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Jet Fuel Property Changes and Their Effect on Producibility and Cost in the U.S., Canada, and Europe

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FOREWORD

The authors are indebted to a number of persons and organizations for furnishing and reviewing data on crude and product supply and demand projections in Canada and Europe. Particular acknowledgement is made for contributions from the U.S. Air Force Wright Aeronautical Laboratories Fuels Branch, the National Research Council of Canada, and the NATO Petroleum Planning Council.

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SUMMARY

This report presents input information and results of a technical and economic analysis using model petroleum refineries conducted by Exxon Research and Engineering Company under NASA contract. The objective was to determine the effect of variations of jet fuel (aviation turbine fuel) properties on the refinery output and costs of jet fuel. The study used optimization programs to determine minimum cost paths for petroleum product production. Realistic features of the analysis lay in the consideration of the complete range of competing refinery products and the flexibility to adjust refining process capacities or add advanced processes, where economically warranted. The study was international in scope and utilized models for the industry in the United States, Canada and Europe. Supply and demand schedules (projected to 2010 in the United States) allowed for the introduction of shale and coal liquids in the East United States and tar sands liquids in Canada.

Three types of calculations were performed: (1) "Producibility" studies determined the influence of jet fuel properties on the maximum output of jet fuel. For each region, calculations covered a range of crude feedstocks, refinery configurations, and competing product mix variations. (2) "Cost Saving" studies determined the influence of jet fuel properties on the reduction of refining costs. For these calculations, refinery models from the producibility studies, linked together to simulate a region, were required to meet projected supply and demand based on best available forecasts. (3) "Conversion" studies determined the refining cost increases for conversion of military jet fuel from wide-cut to kerosene-based (JP-8 for JP-4 in the United States, for example). These calculations used U.S. and Europe regional models.

The results of the analysis are dependent on the regional refining and product demand assumptions and the 1981 economic bases used. Certain general observations can be made. Except in the West U.S., no changes in jet fuel properties were required to meet all projected demands, even allowing for deteriorating crude qualities and changes in competing product demand. In the West U.S., some relaxation of jet fuel properties or extensive use of cracked stocks appears to be required beyond 1990. Generally, the relaxation of aromatics or freezing point, or the inclusion of cracked stocks will increase the output of jet fuels by up to a factor of three. Similarly, the same variations will reduce the refining costs by up to \$10.00/m^3 (4¢/gallon) of jet fuel. The jet fuel relaxations also reduce refining energy requirements, by up to 4%. Conversion study results show that military use of kerosene rather than wide-cut jet fuel will increase costs on the order of hundreds of millions of dollars annually in the U.S. and Europe. These costs can be substantially reduced if the kerosene jet fuel properties are relaxed or if the higher volumetric energy of the kerosene fuel reduces the military fuel demand.

An important finding of the analysis is that the inclusion of cracked stocks in jet fuels can provide the same, if not greater, advantages in producibility and cost reduction as relaxation of aromatics and freezing point. On a limited basis, refiners are now using hydrocracked distillate streams, which have excellent properties, to produce jet fuel. However, refiners do not now manufacture jet fuels using distillates from catalytic cracking or coking units. These fuels may have poor storage or thermal stability characteristics, but an assessment of these properties was beyond the scope of this program.

1. INTRODUCTION

Deteriorating crude quality plus the rapid growth in demand for middle distillates have had a marked impact on jet fuel properties. For example, specifications for commercial aviation turbine fuel, Jet A(1), permit an extension of the aromatics limit, smoke point limit or both, if reported by the supplier. Over the five-year period from 1977 to 1982, jet fuels with reportable aromatics and/or smoke points increased from 5% to 20% of samples tabulated in DOE's annual survey(2,3). Projections indicate that crudes will continue to decline in quality and that the demand for distillates will continue to increase(4). Concurrently, the demand for gasoline and heavy fuel oil will decline, forcing refineries to shift to processes that increase distillate production. The ability of refiners to meet jet fuel demand in the forecast environment is uncertain, and the production of a jet fuel conforming to all current specifications may require the use of more costly processing, unavailable at most refineries today.

The relaxation of jet fuel properties, such as freezing point, aromatics and smoke point, or the use of blending stocks from certain cracking processes can make additional refinery streams available for jet fuel production. These can aid in meeting increased jet fuel demand or can reduce the cost of producing jet fuel.

This report presents input information and results of a technical and economic analysis to determine the effects of property relaxation and cracked stock addition on jet fuel output and costs using optimization programs. The study covered the United States, Canada, and Europe. Three types of calculations are discussed. The first is a determination of the effect of property variations on jet fuel output ("producibility") for cases with a range of feedstocks, refinery configurations, and product distributions. The second is a determination of the effect of property variations on jet fuel costs ("cost savings") for refinery models which simulated a region and were required to meet present and future (to 2010) product demands. The third is a determination of the refining cost differences between military wide-cut and kerosene jet fuels ("conversion"), using regional models. Preliminary results of the producibility and cost savings calculations for the United States were presented at a NASA alternative fuels conference(5).

The body of this report consists of 11 sections outlined as follows.

1. Introduction.

2. Bases Used describes the model inputs for the United States, including product demands, properties of jet fuels and other major fuels, feedstock properties and quantities, refinery model configurations, and economic assumptions.

3. Producibility presents the results of the calculations of maximum jet fuel output and yield for representative U.S. refineries and changes in jet fuel production which could be realized with property relaxation and cracked stock addition.

4. Cost Savings presents the results of the calculations of cost savings associated with jet fuel property relaxation and cracked stock use.

5. Canada describes the model inputs unique to Canada and presents the results of the producibility and cost savings results for Canada.

6. Europe describes the model inputs unique to Europe and presents the results of the producibility study for Europe.

7. Military Fuel Conversion describes the model inputs required for the military fuel conversion study and presents the cost results for Europe and the United States.

8. Summary of Results and Concluding Remarks.

9. Recommendations for Future Work.

10. Glossary lists fuel and refining terms used in this report.

11. References.

2. BASES USED FOR THE UNITED STATES

This study has investigated the producibility increases and cost decreases associated with the relaxation of jet fuel properties. The time frame considered was from 1978, the base period year, up to 2010.

Producibility and cost changes were calculated using computer models similar to those used in refining industry planning studies. The models were furnished with input information on product demands, crude feedstock qualities, and types, costs and yields of refinery processes. The computer program simulated the operation of complete refineries, calculating the processing and blending of product streams by appropriate chemical and physical equations. By linear programming methods, an optimum solution was determined among various alternative refining paths to satisfy the required demands at minimum cost.

This section discusses the bases which were utilized in conducting the U.S. portion of the study and defines the refinery-crude models that were developed. After the models were established, they were verified on a regional basis by comparing refining process capacities predicted with 1978 historic data.

2.1 UNITED STATES REGIONS

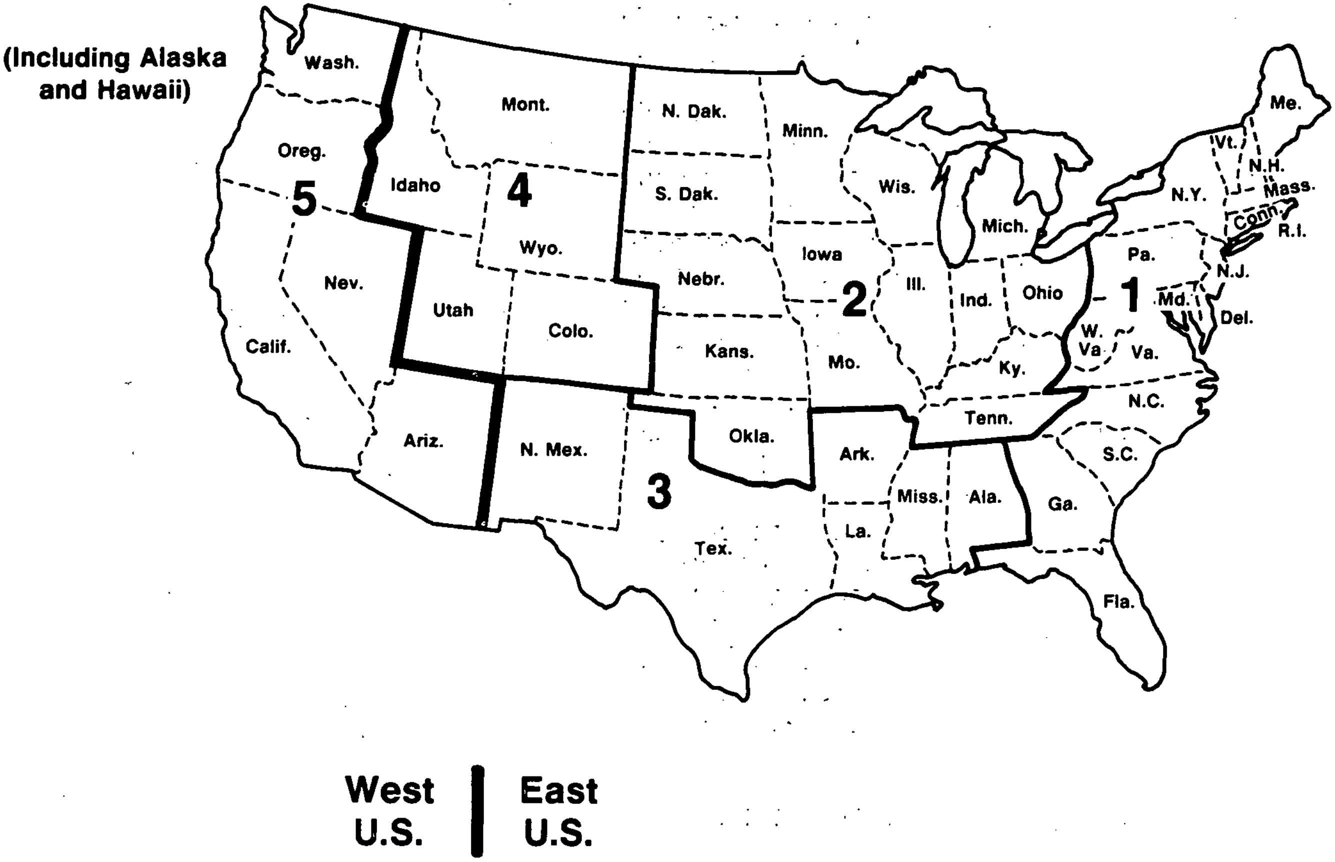
The U.S. was divided into two geographic regions for study purposes. The division was based on what are termed Petroleum Administration for Defense Districts, or PADDs, as shown in Figure 1. The two regions used were PADDs 1-4 and PADD 5. PADDs 1-4 are termed the East and PADD 5 the West. PADD 5 includes the Pacific coast states, two states in the southwest, Hawaii and Alaska. The East includes the rest of the country. This grouping is based on crude and product logistical considerations. For example, there is considerable shipment of crudes and petroleum products within PADDs 1-4, with PADD 3 being a net exporter of both crudes and products to PADDs 1 and 2. There is, however, little interchange of either crude or products between PADD 5 and the remainder of the U.S.

Each region was characterized by different crude blends and product demands. The use of shale-oil or coal-derived crude oils was investigated only in the East.

2.2 PRODUCT DEMANDS

The primary product demand forecast used was that produced for the National Petroleum Council's (NPC) Refinery Flexibility Study(6). This forecast, formulated in 1980, represented the composite outlook of

FIGURE 1
REFINERY STUDY REGIONS FOR THE UNITED STATES



over 30 oil companies and government agencies, research, educational and financial institutions. The NPC forecast was augmented by that from a more recent industry forecast when consumption trends in the early 1980s indicated that the NPC study was overpredicting the demand of certain products. Demands for years beyond the NPC and industry forecast were made by extrapolation. Separate forecasts were generated for the two regions investigated, the East and West.

The forecasts used showed that overall demand for kerosene jet fuel and diesel fuel increases over the study period, while the demand for gasoline, heating oil, and heavy fuel oil declines. The forecasts for the East and West U.S. are presented in Tables 1 and 2, respectively.

Overall product trends are described by the three ratios at the bottom of the Tables. The Gasoline/Distillate Ratio (G/D) includes diesel plus heating oil in the denominator but excludes jet fuel. The Naphtha/Total Distillate Ratio (N/TD) includes as naphtha, gasoline, Jet B (JP-4), and feed to chemical plants and, as total distillate, diesel, heating oil, and Jet A. The Jet A percentage illustrates the jet fuel yield on crude required to satisfy demand and it approximates the fraction of Jet A in the total product demand. There are several pronounced differences in product demand characteristics between East and West U.S. worthy of note. First, Jet A is a larger fraction of the total product demand in the West, reaching 16.1% vs. 9.5% in the East in 2010. Second, the West has a higher G/D throughout the study period.

More recent forecasts project the same basic trends as shown in Tables 1 and 2, but with moderated rates of change for diesel and gasoline. This results in higher N/TD in projected periods than were used in this program. However, the range of N/TD covered in this study was broad enough to encompass all projections. Results can be considered on an N/TD basis regardless of timing. The changes projected for 1990 may be applied to 1995 or even 2000, for example.

2.3 KEROSENE JET FUEL PROPERTIES

Property parameters for the jet fuels and the specification for Jet A (ASTM D1655) are presented in Table 3. Five jet fuel types were studied to determine the effect of property relaxation on producibility and cost. The major study fuel changes were the relaxation of freezing point and aromatics content (and the related smoke point), the inclusion of cracked stocks in the jet fuel, or a combination of both changes.

TF-1 represented average property 1978 kerosene jet fuel consumed in the U.S. as reported by DOE(7). Most properties show considerable margins from the specification limits. Only virgin components, that is, streams without substantial chemical processing or cracking, could be blended to produce TF-1. TF-1 properties were used in the model verification runs and served as the base fuel in producibility and cost savings determination.

TABLE 1

EAST U.S. PRODUCT DEMANDS

1000 m^3/d

	1985	1990	2000	2010
LPG	43	43	43	43
Benzene, Toluene, Xylene (BTX)	15	15	15	15
Chem Feed	107	157	234	278
Regular Gasoline	587	498	320	275
Premium Gasoline	147	124	80	69
Jet A	102	118	137	152
Jet B (JP-4)	23	23	24	24
No. 1 Diesel	18	16	13	14
Diesel	182	257	411	482
Heating Oil	163	142	96	75
Lubes	27	30	33	35
Low Sulfur Fuel Oil (LSFO)(1)	52	30	33	28
Regular Sulfur Fuel Oil (RSFO)	46	29	28	24
Asphalt	53	63	76	83
Total	1565	1545	1543	1597
Gasoline/Distillate Ratio(4)	2.0	1.5	0.8	0.6
Naphtha(2)/Total Distillate Ratio(3)	1.9	1.5	1.0	0.9
Jet A as Percentage of Crude Feedstock	6.3	7.4	8.6	9.2

Notes:

(1) LSFO < 1.0% sulfur.
(2) Naphtha includes BTX, Chem Feed, Gasoline, Jet B.
(3) Total Distillate includes Jet A, Diesel, Heating Oil.
(4) Distillate includes Diesel and Heating Oil.
(5) Cubic meters/d x 6.2893 = bbl/d.

TABLE 2

WEST U.S. PRODUCT DEMANDS

1000 m^3/d

	1985	1990	2000	2010
LPG	7	7	7	8
BTX	3	4	5	5
Chem Feed	5	6	8	8
Regular Gasoline	114	96	86	75
Premium Gasoline	28	24	21	19
Jet A	34	41	47	54
Jet B (JP-4)	7	7	7	7
No. 1 Diesel	1	1	1	1
Diesel	28	44	57	71
Heating Oil	25	24	20	16
Lubes	6	7	8	9
LSFO	49	32	31	25
RSFO	43	31	30	22
Asphalt	10	12	14	15
Total	360	336	342	335
Gasoline/Distillate Ratio	2.6	1.8	1.7	1.1
Naphtha/Total Distillate Ratio	1.8	1.2	1.0	0.8
Jet A as Percentage of Crude Feedstock	9.0	11.6	13.0	15.2

Notes:

(1) Cubic meters/d x 6.2893 = bbl/d.

TABLE 3

PROPERTIES OF U.S. KEROSENE FUELS FOR STUDY

Property	Spec. D1655-83a	TF-1	TF-2	TF-3	TF-4	TF-5	ERBS
Aromatics, Vol. % Max	20 (1)	18	18	23	33	35	Report (2)
Smoke Pt., Min.	20 (1)	21.5	21.5	20	14	13	Report (2)
Freezing Pt., °C, Max.	-40	-43	-43	-43	-29	-29	-29
Flash Pt., °C, Min.	38	43	43	43	43	43	38-48
Sulfur, Wt. % Max	0.3	0.05	0.28	0.28	0.28	0.28	0.3
Dist. 10%, °C Max.	204	190	204	204	204	204	204
Density, Max.	0.84	0.84	0.84	0.84	--	--	Report (2)
Cracked Stocks allowed	--	No	Yes	Yes	No	Yes	--

Notes:

(1) Aromatics to 25 Vol % and smoke point to 18 mm permissible if reported by the supplier.
(2) No limits specified but measurements to be reported.

TF-2 had nearly all the same properties as TF-1. The major difference was that TF-2 could contain cracked stocks, such as those from hydrocracking, catalytic cracking and thermal cracking processes. While the current specification does not exclude these blending stocks, they are not used in practice. It is recognized that cracked stocks may affect certain properties adversely, especially those related to stability and lubricity. The exception to this generalization is hydrocracked stocks, which have good stability characteristics and which are blended into jet fuel by some producers in the West U.S. Stability and lubricity parameters are unpredictable and were not considered in the blending calculations. For TF-2, sulfur was allowed to increase to the specification value, less a measurement tolerance, and the 10% distillation point was allowed to increase to the specification value.

TF-3 has a higher aromatics level, and with it, smoke point. Cracked stocks could be used to blend this fuel. This fuel complied with the reportable provisions of ASTM D1655.

TF-4 and TF-5 represented further relaxations of aromatics and smoke point and a relaxation in freezing point from -43 to -29°C. Property changes of this type could be realized through the addition to jet fuel of heavier fractions normally used in diesel fuel and heating oil, which would raise the final boiling point of the resulting jet fuel. Because of the addition of these heavier stocks, TF-4 and TF-5 had no maximum density requirement. TF-4 could contain only virgin blending components while TF-5 could contain cracked stocks. The properties of TF-5 were formulated to resemble the properties of the Experimental Research Broad Specification (ERBS) fuel proposed at a workshop in 1977 as an extreme test fuel(8). The properties of ERBS are also noted in Table 3.

2.4 PROPERTIES OF OTHER MAJOR REFINERY FUELS

This section presents descriptions of other major refinery fuels. Two sets of properties are presented: those of the 1978 base period which were used in the model verification runs and those used for the study of future time periods.

Gasoline. Two grades of gasoline were considered for each time period shown in Table 4. For the 1978 verification run, these grades were leaded regular and unleaded regular. For all other time periods, 1985 through 2010, unleaded regular and unleaded premium were used.

Leaded premium was not considered. The substitution of unleaded premium for leaded regular grade increased the overall octane level of the gasoline pool. Any bias thereby introduced was considered to be minimal.

TABLE 4

BASE PERIOD AND PROJECTED PROPERTIES FOR GASOLINE

Fuel Property	1978 Fuels Leaded Regular	1978 Fuels Unleaded Regular	1985 and Beyond Fuels Unleaded Regular	1985 and Beyond Fuels Leaded Premium
Research Octane Number	94	92	92 min.	96 min.
Motor Octane Number	84	82	82 min.	86 min.
Octane Index (1)	89	87	87 min.	91 min.
Reid Vapor Pressure, kPa	80	80	90 max.	90 max.
Vapor Lock Index (2)	15	15	16 max.	16 max.
Lead Level, g/L	3.2	0	0	0

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(1) Octane Index is defined as:

$$\frac{\text{Research Octane No.} + \text{Motor Octane No.}}{2}$$

(2) Vapor Lock Index is defined as:

Reid Vapor Pressure + (0.13) (Percent off at 70°C)

A slight increase in Reid Vapor Pressure and consequently Vapor Lock Index was assumed for future periods. This trend was identified in recent industry studies which have shown a high level of vehicle tolerance for fuels with relatively high volatilities.

Heating Oil (No. 2). Heating oil properties are presented in Table 5. The 90% distillation point has been increasing, and for the future, No. 2 heating oil was assumed to equal the ASTM specifications of 338°C (640°F)(9). The 10% distillation point has been moving upward less rapidly and was projected to be 227°C (440°F). The sulfur level was projected to reach 0.3%, with pollution regulations being the determining factor. The cloud point was set to be -12°C (+10°F) and the flash point to be 46°C (115°F), the specification value of 38°C (100°F) plus an allowance for property degradation attributable to storage and handling. The specific gravity was assumed to decline to 30° API, the ASTM specification.

Diesel Fuel. The diesel fuel quality targets are presented in Table 6. The projected 10% and 90% distillation values for No. 2 diesel fuel were the same as those specified for heating oil. As with heating oil, the 90% point has been increasing. At 338°C (640°F), the projected 90% point is still lower than many 90% values encountered worldwide. Sulfur, also increasing upwards with time, was assumed to be 0.3%, again, the same as heating oil. The cetane number has been decreasing sharply in recent times. In this study the cetane index was used to blend cetane number. Cetane index minimum was set at 42 to insure meeting an ASTM standard of 40 minimum cetane number. The flash point and viscosity values reflect base period levels(10) and the cloud point was the same as for heating oil.

Residual Fuel. For the purposes of computer modeling, residual fuel was assumed to be present in high and low sulfur forms, shown in Table 7. Low sulfur residual fuel had a maximum sulfur target of 0.6% and the high sulfur, 2.3%. The kinematic viscosity of the low sulfur fuel was assumed to be 200 centistokes at 50°C, and the high sulfur, 450.

TABLE 5

BASE PERIOD AND PROJECTED PROPERTIES FOR NO. 2 HEATING OIL

Fuel Property	1978 Fuel *	1985 and Beyond Fuel
10% Distillation Point, °C	220	227 max.
90% Distillation Point, °C	307	338 max.
Sulfur, %	0.23	0.3 max.
Specific Gravity, °API	35	30 min.
Cloud Point, °C	-17	-12 max.
Flash Point, °C	73	46 max.

* Average property values presented in or averaged from Ref. 9.

TABLE 6

BASE PERIOD AND PROJECTED PROPERTIES FOR NO. 2 DIESEL FUEL

Fuel Property	1978 Fuel*	1985 and Beyond Fuel
10% Distillation Point, °C	218	227 max.
90% Distillation Point, °C	303	338 max.
Sulfur, %	0.23	0.3 max.
Cetane Index, ASTM D976-80	46	42 min.
Flash Point, °C	75	60 min.
Viscosity @ 38°C, cSt	2.6	2.8
Cloud Point, °C	-15	-12 max.

* Average property values presented in or averaged from Ref. 10.

TABLE 7

BASE PERIOD AND PROJECTED PROPERTIES FOR RESIDUAL FUEL OIL

Fuel Property	1978 Fuels Low Sulfur	1978 Fuels High Sulfur	1985 and Beyond Fuels Low Sulfur	1985 and Beyond Fuels High Sulfur
Maximum Sulfur Level, %	0.6	2.3	0.6	2.3
Maximum Viscosity @ 50°C, cSt	200	450	200	450

2.5 CRUDE BLENDS

Many hundreds of crudes, both domestic and foreign, are consumed in the U.S. For this study, these crudes were represented by five blends in the East and four blends in the West, described by sulfur level and the amount of 566+°C (1050+°F) residuum in the crude. The formulation used was adopted from the National Petroleum Council's Refinery Flexibility study(6).

The properties of crudes used in the U.S. are shown in Table 8. Low sulfur crudes were those containing less than 0.5% sulfur, high sulfur crudes contained more than 1% sulfur and intermediate sulfur crudes were in between. Light crudes had less than 15% boiling above 566°C (1050°F), while heavy crudes had more than 15% boiling above 566°C (1050°F). It should be noted that the definition of light and heavy crudes used here is not based upon API gravity, which has been used frequently to differentiate crude types. The low sulfur crude is a light crude. As illustrated in Table 8, crude properties in the two regions were different, even for crude blends having the same name.

Sulfur level, the residuum content and other crude characteristics have important processing implications. The sulfur specification of Jet A is 0.3, but the sulfur level of the average property base period fuel, TF-1, is 0.05%. Clearly, if the sulfur level of the kerosene cut used for formulating Jet A is greater than the TF-1 value, sulfur will have to be reduced. Normally, treatment with hydrogen in the presence of a catalyst under "mild" processing conditions (total pressure less than 3450 kPa (500 psi) and hydrogen-to-oil volume ratio of 12 (70 scf H_2/bbl)) will effectively remove sulfur.

The fraction boiling above 566°C (1050°F) has additional processing implications. This residuum fraction can be made into residual fuel oil by blending with a lower boiling flux. However, residual fuel oil is a low value product, and projections show a declining demand for

TABLE 8

PROPERTIES OF CRUDE BLENDS USED IN UNITED STATES STUDIES

	Wt% Sulfur	Vol% 566°C+ (1050°F+)	Vol% Aromatics in Kerosene Fraction	Crude Naphtha/ Distillate Ratio
East U.S.				
Low Sulfur	0.26	7.8	16.3	0.71
Medium Sulfur				
Light	0.77	9.0	19.1	0.84
Heavy	1.00	17.3	21.6	0.56
High Sulfur				
Light	1.70	12.5	21.0	0.77
Heavy	2.42	24.1	18.9	0.31
Coal Liquids	0.012	-	35.0	2.22
Shale Liquids	0.017	-	26.0	0.58
West U.S.				
Low Sulfur	0.14	12.3	17.4	0.80
Medium Sulfur				
Light	0.79	10.0	22.9	0.69
Heavy	1.07	18.8	24.3	0.43
High Sulfur				
Heavy	1.73	25.7	21.2	0.35

fuel oil, its place being taken in the industrial market by coal and even gas, and in the power generation market by these fuels plus nuclear. The residuum in crudes can be processed in refineries possessing resid destruction processes to produce more valuable products such as gasoline, diesel fuel, heating oil and in our formulation, jet fuel.

The aromatics level of the kerosene cut has important effects on processing. The Jet A specification calls for an aromatics level of 20 volume percent, with a reportable extension to 25% aromatics. The base period fuel has an aromatics property maximum of 18%. Consequently, crudes with a kerosene cut containing more than this level of aromatics will require processing (or blending with streams with lower aromatics levels) to reduce aromatics to the target value. One type of processing used is aromatics extraction, a well established process which uses SO_2 to remove aromatics from kerosene. Another is aromatics saturation in which severe hydrotreatment converts the aromatics compounds into cycloparaffins with one or more rings. This process operates at pressures greater than 6900 kPa (1000 psi) and hydrogen-to-oil volume ratios of 35 (200 scf H_2/bbl). Mild hydrotreatment for sulfur removal cannot reduce aromatics.

The kerosene from all crudes was cut to have a freezing point of -45°C. This permitted the blending of high freezing point stock to reach the -43°C target for TF-1, 2 and 3, and the -29°C target of TF-4 and 5.

Crude shale and coal liquids were used in some East U.S. runs. Properties for these synthetic refinery feedstocks are shown in Table 8. Although the sulfur levels of both syncrude liquids are low and the vacuum residuum content nonexistent, the aromatics levels of both are high. The N/TD ratio of shale liquid is low, favoring its use in distillate products, while the comparable ratio for coal liquids is high, favoring the production of gasoline.

The crudes and gas liquids consumed in the East and West U.S. are shown in Tables 9 and 10, respectively. Again, the NPC formulation was used. These data show that the overall make up of the crudes in the East and in the West differ considerably. In the East, for example, low sulfur crude constitutes 40 to 50% of the total crude during the forecast period, while high sulfur heavy crude constitutes no more than 25% for the forecast period. In contrast, between 30 and 40% of total crude in the West is high sulfur heavy. In both regions, crude composition is projected to become heavier, more aromatic and higher in sulfur with time. For the regional model calculations, changes in crude composition with time were handled by changing the volume fraction of the blends and by introducing coal and shale liquids in future (low product G/D) time periods.

TABLE 9

EAST U.S. CRUDE AND GAS LIQUIDS REQUIREMENTS

1000 m^3/d

Crudes	1985	1990	2000	2010
Low Sulfur	746	663	582	535
Medium Sulfur Light	62	47	44	42
Medium Sulfur Heavy	73	67	73	71
High Sulfur Light(1)	428	479	472	437
High Sulfur Heavy	204	228	270	324
Synthetics				
Coal Liquids	-	-	13	94
Shale Liquids	2	7	37	46
Other				
Butanes	40	40	40	40
Natural Gas Condensates	69	69	69	69
	1624	1600	1600	1658

Notes:

(1) Adjustable crude.
(2) Cubic meters/d x 6.2893 = bbl/d.

TABLE 10

WEST U.S. CRUDE AND GAS LIQUIDS REQUIREMENTS
1000 m^3/d

	1985	1990	2000	2010
Crudes				
Low Sulfur	72	61	57	47
Medium Sulfur Light	34	33	35	36
Medium Sulfur Heavy	123	112	115	112
High Sulfur Heavy(1)	117	113	120	125
Other				
Butanes	2	4	4	4
Natural Gas Condensates	31	31	31	31
	379	354	362	355

Notes:

(1) Adjustable crude.
(2) Cubic meters/d x 6.2893 = bbl/d.

Published projections for the use of shale liquids and coal liquids have varied considerably. In the late 1970s and early 1980s, it was estimated that almost 20% of total crude feedstock would be synthetic crudes by 2000, and that this percentage would increase to over 30% by 2010. Some current projections do not identify any significant synthetic crude usage well into the next century other than that from small shale plants now under construction. In this study, very limited availability of crude shale liquids to refiners from these plants was assumed as early as 1985, and increased availability to nearly 3% of total crude run by 2010. Availability of crude coal liquids to refiners was assumed to begin around 2000 and to increase rapidly to almost 6% of crude runs by 2010. Synthetic crude was assumed to be consumed only in the East, reflecting the known shale and coal deposits in this region.

In the regional refinery modeling for the determination of cost savings, one crude in each region was free to vary as needed for material balance purposes. This crude is termed the adjustable or swing crude. In the East, the adjustable crude was the high sulfur light crude, and in the West, it was the high sulfur heavy crude. The volumes of other crudes were fixed as shown in the tables.

2.6 REFINERY-CRUDE MODELS

Two types of refinery models were assembled. The first type consisted of individual refinery-crude models that simulated one crude blend processed by one refinery of a specified complexity. These models were used to determine increases in jet fuel yield attributable to jet fuel property relaxation.

Individual refinery-crude models were used because (a) significant differences in jet fuel yield are known for different types of crude, and (b) refineries of different complexities can affect the jet fuel yield, even if the same crude is run in each. Running one average crude in one average refinery masks the constraints that real refineries face, such as crude quality changes and available processes.

The second type of model consisted of these individual models linked together to form a regional model. Regional cost savings attributable to jet fuel property relaxation were calculated with these models. Cost savings depend on the interrelations of the large market supply and demand factors and are best calculated for the region as a whole.

For the refinery-crude models, three types of refineries were considered. They were the hydroskimmer, the low conversion refinery and the high conversion refinery. The hydroskimmer is essentially an atmospheric distillation unit, or pipestill, with hydrotreating capability.

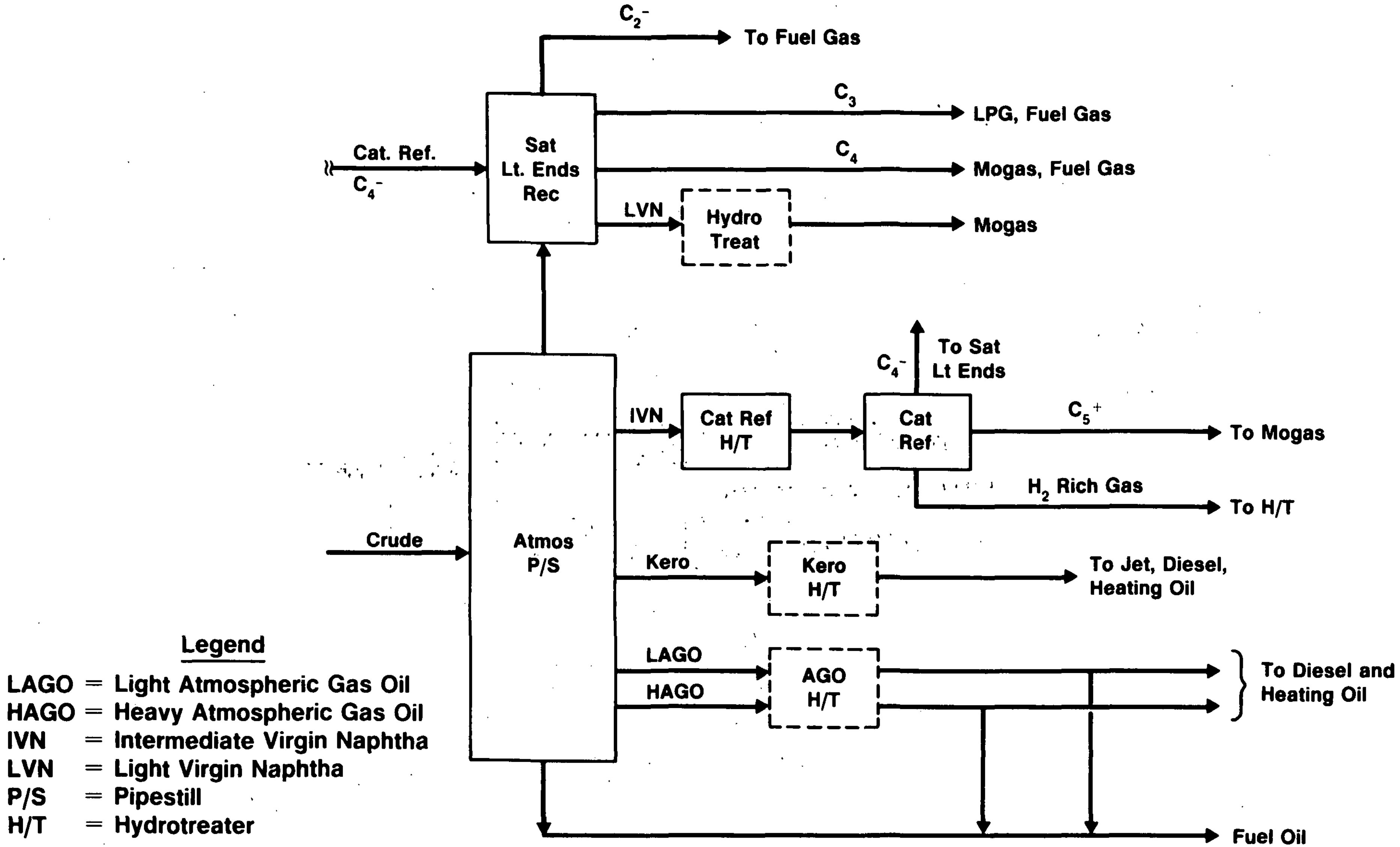
The low conversion refinery adds catalytic cracking and vacuum distillation capability to the hydroskimmer. The high conversion refinery has the capability to convert all of its residuum to lighter, more valuable products through the use of resid destruction processes.

A diagram for the hydroskimmer is presented in Figure 2. Crude oil is first distilled in an atmospheric pipestill. The bottom or highest-boiling cut, atmospheric residuum, serves as the basis for heavy fuel oil. Lower-boiling-point fractions shown by lines higher on the pipestill are the heavy atmospheric gas oil (HAGO) and light atmospheric gas oil (LAGO). These cuts are hydrotreated when high and intermediate sulfur crudes are run and blended in diesel fuel and heating oil and, if required for viscosity control, into fuel oil. When low sulfur crude is run, LAGO and HAGO bypass hydrotreating.

The next cut up the pipestill is kerosene which can be used in jet fuel, diesel or heating oil. When high and intermediate sulfur crudes are used, the kerosene is first hydrotreated. Intermediate boiling range naphtha is next. It is catalytically reformed for octane number improvement after first being hydrotreated for almost complete removal of sulfur, a catalyst deactivator. The reformer produces reformate (a high octane blending component for motor gasoline), light ends, and a hydrogen-rich stream that is used in the hydrotreaters. Petroleum molecules containing four carbon atoms or less (C_4^-) which have been produced by the cat (catalytic) reformer along with the pipestill overhead are sent to the light ends recovery unit to recover propane for LPG, or fuel gas, butane for gasoline or fuel gas and light virgin naphtha (LVN) for gasoline blending. LVN is hydrotreated when high and intermediate sulfur crudes are run. The hydroskimming refinery makes a high yield of heavy fuel oil since it has no equipment to convert material boiling above the boiling range of distillate products to gasoline or distillate.

The Low Conversion Refinery, shown in Figure 3, adds vacuum distillation, catalytic cracking, and alkylation units to the hydroskimming scheme to reduce heavy fuel and increase lighter products. In this refinery, atmospheric residuum is diverted from fuel oil to a vacuum pipestill and the distillation process repeated, this time at low pressure. The vacuum residuum is blended in heavy fuel oil. The vacuum gas oil is often hydrotreated and catalytically cracked. Vacuum gas oil is not hydrotreated when low sulfur crude is run. Catalytic cracking is the central process in a low conversion refinery. The cat cracker converts a heavier boiling part of the crude, 315^{o}-505^{o}C (600^{o}-1050^{o}F), into fractions which can be blended into gasoline and the distillates. In the U.S., catalytic crackers are normally operated to maximize the production of the light boiling fractions blended into gasoline.

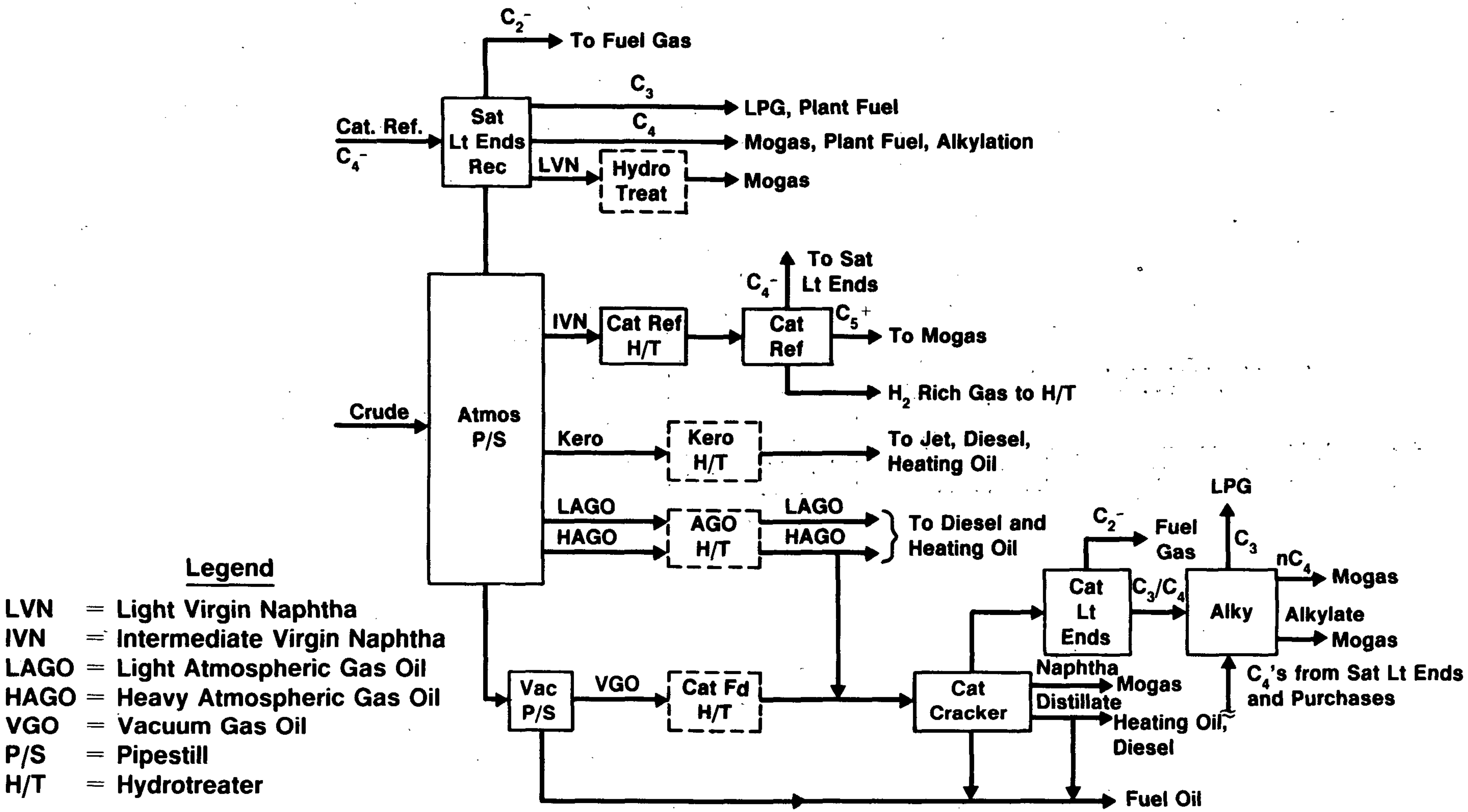
FIGURE 2
HYDROSKIMMING REFINERIES



NOTE: Hydrotreaters in Dashed Boxes Are Not Required for Low Sulfur Crude

0185-0-015

FIGURE 3
LOW CONVERSION REFINERIES



Legend

LVN = Light Virgin Naphtha
IVN = Intermediate Virgin Naphtha
LAGO = Light Atmospheric Gas Oil
HAGO = Heavy Atmospheric Gas Oil
VGO = Vacuum Gas Oil
P/S = Pipestill
H/T = Hydrotreater

NOTE: Hydrotreaters in Dashed Boxes Are Not Required for Low Sulfur Crude
Not Shown Are Sulfur Recovery, Hydrogen Generation and Hydrogen Recovery Process Facilities

0185-0-016

The catalytic cracker produces light ends, catalytic naphtha, catalytic distillate and fractionator bottoms. The fractionator bottoms are blended in fuel oil. Catalytic distillate is used as a blend or flux to reduce the high viscosity of the vacuum residuum, and it also finds dispositions in diesel fuel and heating oil. The naphtha is a moderate octane number gasoline stock.

The catalytic gases go to light ends recovery. The C_3/C_4 cut, rich in olefins and isobutane, is alkylated to produce a high octane gasoline blending component called alkylate. Since the isobutane content of the cat C_3/C_4 stream is insufficient to convert all the olefins contained therein, the butanes from the saturated light ends system are also fed to the alkylation unit to increase isobutane availability. Butane from natural gas plant operations may also be purchased to alkylate surplus olefins and to blend into gasoline. Normal butane from alkylation is used for direct mogas blending, and propane is used for LPG. Catalytic C_2^- (methane and ethane) is used as plant fuel or can be fed to steam reforming to make hydrogen.

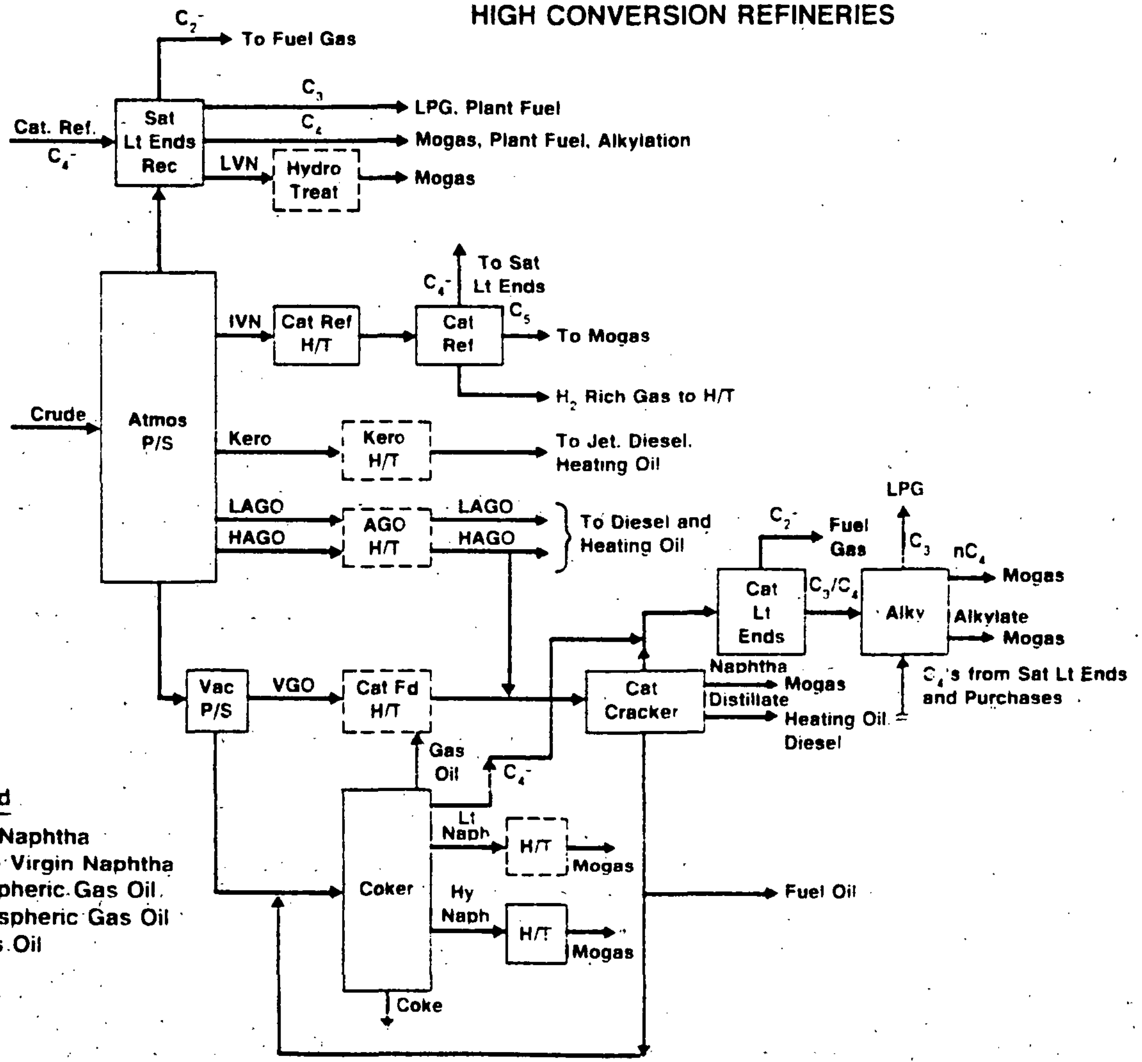
The dispositions of the atmospheric pipestill cuts are nearly identical to those in the hydroskimmer except that Heavy Atmospheric Gas Oil (HAGO) can be fed to the cat cracker to increase gasoline yield at the expense of distillate.

The key difference between the High Conversion Refinery and the other types is its ability to destroy all the residuum and convert it largely into lower boiling, more valuable products. One process for accomplishing this is delayed coking, shown in the flow sheet for this refinery in Figure 4. Residuum from the vacuum pipestill is converted into light and heavy naphtha which, after hydrotreatment as appropriate, is blended into gasoline. Coker gas oil, after hydrotreatment as needed, is shown being used as cat cracker feed. Alternatively, it can be blended into distillates and into jet fuel. The C_4^- gas goes to the cat light ends recovery system and the solid coke is sold as a product.

Table 11 summarizes the commercial processes and the refinery types in which they are used. Note that the high conversion refinery also has access to hydrocracking (not shown in Figure 4), a process in which heavier petroleum molecules are cracked in the presence of hydrogen to yield mostly a naphtha cut which is used in gasoline. Some distillate is also produced by this process. Visbreaking, a mild thermal process that converts a portion of the resid to distillate, is also available. All three types of refineries could also invest in aromatics removal by aromatics extraction or severe kerosene hydrotreatment if economically warranted.

In addition, the conversion refineries could invest in certain advanced processes as shown in Table 12. These processes were not in widespread use in 1978 but are considered to be demonstrated or commercial technology now. One important process is a form of hydrocracking

FIGURE 4
HIGH CONVERSION REFINERIES



Legend

LVN = Light Virgin Naphtha
IVN = Intermediate Virgin Naphtha
LAGO = Light Atmospheric Gas Oil
HAGO = Heavy Atmospheric Gas Oil
VGO = Vacuum Gas Oil
P/S = Pipestill
H/T = Hydrotreater

NOTE: Hydrotreaters in Dashed Boxes Are Not Required for Low Sulfur Crude
Not Shown Are Sulfur Recovery, Hydrogen Generation and Hydrogen Recovery Process Facilities

0185-0-017

TABLE 11

CURRENT PROCESSES AND REFINERY TYPES

Process	Hydroskimmer	Low Conversion	High Conversion
Atmospheric Distillation	X	X	X
Vacuum Distillation		X	X
Naphtha Reforming	X	X	X
Catalytic Cracking		X	X
Hydrotreating			
Mild Kerosene H/T	X	X	X
Severe Kerosene H/T(1)	X	X	X
Naphtha H/T	X	X	X
Gas Oil H/T	X	X	X
Alkylation		X	X
Visbreaking			X
Delayed Coking			X
Hydrocracking for Naphtha			X
Aromatics Extraction(1)	X	X	X
Steam Reforming H_2	X	X	X
Sulfur Plant	X	X	X

Notes:

(1) Model must invest if it chooses these processes.

TABLE 12

ADVANCED PROCESSES(1)

Process	Low Conversion	High Conversion
Hydrocracking for Jet Fuel	X	X
FLEXICOKING		X
Resid Hydroconversion		X
H_2 Pressure Swing Adsorption	X	X
H_2 Partial Oxidation	X	X

Notes:

(1) Model must invest if it chooses to use these processes.

that emphasizes the production of kerosene for use in jet fuel (hydrocracking for jet or "jet hydrocracking") from vacuum gas oil, using special catalysts and operating conditions. The kerosene produced by this process is suitable for blending into jet fuel since it possesses a low aromatics concentration and a low freezing point.

Flexicoking is a process, not unlike delayed coking, that destroys residuum. It differs from delayed coking in that it is a continuous process and it converts virtually all of its coke to a low energy content gas which can be used to supply energy to the process and other refinery process units.

Resid hydroconversion converts residuum to naphtha, distillates and a gas oil under especially severe hydrotreatment conditions. Both conversion models could invest in a hydrogen recovery process called pressure swing adsorption and in hydrogen production by partial oxidation of residuum.

Specific crudes were matched to refinery types as shown in Table 13. Generally, the light crudes were run in low conversion refineries, the heavy crudes in high conversion refineries. The high conversion refineries, although capital intensive, can run the lowest quality heavy crudes, which usually have the lowest cost. Because of their extensive processing capability, high conversion refineries would normally be expected to have the highest yields of light products from any quality crude.

The low sulfur crude was run into all three refinery types. This is an excellent crude for the simple hydroskimmer since it will have a high yield of light products. It is also a good crude for the conversion refineries for the same reason. One hydroskimmer in each region also ran a heavy crude and was in fact an asphalt plant. The lighter products are, for the most part, by-products from this refinery.

2.7 ECONOMIC CONSIDERATIONS

Constant 1981 dollar costs were developed for each process utilized by the models. Cost calculations centered on determining differences associated with property relaxation. Consequently, costs that would not be expected to change with relaxation were not needed. Operating costs for new units included investment related costs and throughput related costs. For existing units there were only throughput related costs, which were costs that could change with relaxation. Non-operating costs associated with capital recovery were applicable to new units. Components of these costs are noted below:

TABLE 13

U.S. REFINERY-CRUDE MODELS

	Hydroskimmer	Low Conversion	High Conversion
Low Sulfur	X	X	X
Medium Sulfur Light		X	
Medium Sulfur Heavy			X
High Sulfur Light (1)		X	
High Sulfur Heavy	X		X

Notes:

(1) East only.

Throughput-Related Costs (Existing and New Units)

- Fuel and Utilities
  (power, steam, cooling water, treated water)

- Chemicals and Catalysts.

Investment-Related Costs (New Units Only)

- Salaries, Wages, Benefits

- Supplies, Taxes, Administration, General Expense.

An annual capital recovery charge of 20% of investment per year was used for new units. The bases impacting on this calculation include:

Centroid of investment one year before startup
16-year project life
No inflation included in operating costs
Sum-of-the-years digits depreciation
50% combined federal and state income taxes
No investment credits
No salvage value
No working capital

Processes which involve investment are all those listed in Table 12 and those indicated in Table 11.

No working capital items such as crude and product inventory were included in costs since the basis for such items is highly location/situation dependent. These costs could represent a significant addition to the average refining costs. Power costs were indexed to fuel cost. All other operating costs were given typical 1981 values. Judgment was used to set raw materials costs and by-product values. Values for major products were not required since each series of cases was run at a constant major product production, except for jet fuel in producibility runs. Marginal crude costs reflect 1981 price estimates for petroleum. Raw material and by-product costs were set approximately in cost parity with this crude price assumption. Propane, LPG, purchased butanes, coke and sulfur were set at a cost consistent with crude costs.

A 30% "contingency" was used for investments. The contingency covers many items which will be required to construct new facilities but which were not defined in modeling.

2.8 MODEL VERIFICATION

Before the producibility and cost savings calculations were made, the regional models were tested to compare predicted regional process capacity utilization with historic values as reported for 1978 in the NPC Refinery Flexibility Study(6).

Crude blends, natural gas liquids and condensate were made available to the refineries linked together in the regional models. The refineries "competed" for crudes made available to more than one refinery type. Consumption of each crude blend was set at 1978 levels, except for the high sulfur light blend in the East and the high sulfur heavy blend in the West. These crudes were "swing" crudes and were allowed to vary as needed to permit the regional model to achieve material balance. The refineries also competed to supply finished products to satisfy 1978 regional demands. The products from each refinery were constrained to meet 1978 qualities as described in this report in Tables 4 through 7.

The crude inputs and product outputs determined for the East U.S. verification run are shown in Table 14. The calculations, constrained to meet the regional crude feedstock supply and product demands, selected optimized production paths, using seven of the eight representative refinery-crude models in the East U.S. The hydroskimming refinery supplied with low sulfur crude was excluded by the computer as noncompetitive economically compared to the two higher conversion refineries running the same crude. The calculated volume of the adjustable high sulfur, light crude turned out to be within 96% of the actual 1978 value and overall crude volume was over 99% of the actual 1978 volume.

The comparison of calculated process capacities for verification of the East U.S. region is shown in Table 15. The available capacities should not be less than those used by the model. The comparison indicates that 1978 actual capacities were adequate except for vacuum distillation, cat feed hydrotreating and hydrogen manufacturing.

It is not surprising that vacuum distillation used in the simulation exceeded reported capacity. A $343^{o}C$ ($650^{o}F$) atmospheric pipestill cut point between gas oil and residuum had been assumed for modeling purposes. In practice, many units employ higher cut points, reducing the volume of atmospheric bottoms available for vacuum distillation. The actual vacuum distillation requirement will therefore be less than predicted by the model.

The excess of cat feed hydrotreating consumption in the model run was probably due in part to the lower cut point for atmospheric bottoms used in the model compared to existing refineries. There is ample distillate hydrotreating capacity to process heavy distillates boiling above $343^{o}C$ ($650^{o}F$), which have been included in cat cracking feed in our simulation.

TABLE 14

VERIFICATION RUN SUPPLY AND DEMAND FOR EAST U.S.

1000 m^3/d[3]

Refinery - Crude Model	Low Sulfur Low Conversion	Low Sulfur High Conversion	Medium Sulfur Light Low Conversion	Medium Sulfur Heavy High Conversion	High Sulfur Light Low Conversion	High Sulfur Heavy Hydroskimming	Heavy Sulfur Heavy High Conversion	Total
Feed								
Crude[1]	15.9	1118.9	110.4	54.2	373.8	55.9	201.7	1930.8
Isobutane	0.1	12.8	1.5					14.4
Normal Butane		15.6		0.3	7.1	0.1	3.8	26.9
NGL and Condensate	1.4	40.2	18.5	5.7	0.1		9.7	75.6
Total Input	17.4	1187.5	130.4	60.2	381.0	56.0	215.2	2047.7
Products								
LPG	0.8	32.4	7.9					41
BTX[2]		15.0						15
Leaded Gasoline	4.1	288.0	67.5	17.8	170.2	8.3	85.1	641
Unleaded Gasoline	5.2	288.6		5.1	19.8		26.2	345
Jet A	1.3	81.3	11.6	0.8				95
Jet B (JP-4)			5.8	17.2				23
No. 1 Fuels		37.0						37
No. 2 Diesel	2.5	88.5		9.3	7.0		17.6	125
No. 2 Heating Oil	1.5	110.4	21.2		120.6	10.8	36.5	301
Low Sulfur Fuel Oil		88.4	1.6					90
High Sulfur Fuel Oil	1.5	25.5	13.9	8.0		16.3	25.9	91
Lubes and Waxes		33.0						33
Asphalt					46.7	16.3		63
Other Products		59.0						59
Coke, ktons/D							15.0	15
Sulfur, ktons/D		0.7	0.4	0.2	2.8	0.1	2.6	6.8

Notes:

(1) Volume of high sulfur light crude predicted by model was 374 km^3/d versus 388 km^3/d 1978 historic. Split of low sulfur and high sulfur heavy crudes between refineries established by model.
(2) Benzene, toluene, xylenes.
(3) Cubic meters/d x 6.2893 = bbl/d.

TABLE 15

PROCESS UNIT VERIFICATION FOR EAST U.S.

1000 m^3/d (2)

Refinery	Capacity Predicted Low Sulfur Low Conv	Low Sulfur High Conv	Medium Sulfur Light Low Conv	Medium Sulfur Heavy High Conv	High Sulfur Light Low Conv	High Sulfur Heavy Hydroskim	High Sulfur Heavy High Conv	Total	Capacity Available(1)
Atmospheric Distillation	15.9	1118.8	110.5	54.1	373.8	55.9	201.7	1930.7	2053
Naphtha Hydrotreater	2.5	152.7	21.6	4.5	71.4	7.8	38.1	298.6	438
Cat Reforming	2.5	152.4	9.6	0.6	50.7	5.7	26.8	248.3	391
Gas Oil Hydrotreating									
Cat Feed			31.1	11.4	116.4		29.0	187.9	132
Distillate		54.6	22.3	5.0	95.3	12.6	51.1	240.9	306
Total GO H/T		54.6	53.4	16.4	211.7	12.6	80.1	428.9	438
Vacuum Distillation	5.9	412.9	41.0	28.6	163.4	31.6	113.9	797.3	727
Cat Cracking	6.0	374.5	37.3	15.0	135.9		41.7	610.3	662
Hydrocracking		18.3		10.2			41.5	70.0	70
Visbreaking		3.1		7.9				11.0	11
Coking							36.3	36.3	96
Alkylation	0.5	37.9	4.9	1.7	7.6		6.3	59.1	61
LVN Isomerization			11.0					11.0	11
H_2 Mfg - kMT/d		0.5	0.1	0.3	0.6		1.4	2.9	1.5
Sulfur Recovery - kMT/d		0.7	0.4	0.2	2.8	0.1	2.6	6.8	

Notes:

(1) Available capacity as per National Petroleum Council, Refinery Flexibility, December, 1979.
(2) Cubic meters/d x 6.2893 = bbl/d
kMT/d = thousands of metric tons/d

Predicted hydrogen manufacturing capacity exceeded reported capacity. Our simulation assumed that all hydrogen required for cat feed hydrotreating and hydrocracking must be manufactured. In actual operations, some of the hydrocracking and cat feed hydrotreating units were designed to consume lower purity hydrogen offgas from catalytic reforming. Also, some purification capacity was available to upgrade more dilute hydrogen streams, such as reformer hydrogen and spent naphtha and distillate hydrotreater gas streams to high purity levels for hydrocracking and cat feed hydrotreating.

The West U.S. regional model was also verified with 1978 data. Table 16 shows the feedstock supply and product demand representations. Utilization of the high sulfur heavy crude was 98% of the actual 1978 crude run, and overall feedstock volume was 99% of actual 1978 levels. Only five of the seven refineries were used. Jet fuel was made in the three high conversion refineries, each of which ran a different crude. This occurred because the high conversion refineries could produce jet fuel at the lowest cost and insufficient low sulfur crude was available to make all jet fuel. The regional crude mix was more evenly divided than in the East. The hydroskimming and low conversion refineries could not compete economically with the high conversion refinery for low sulfur crude.

Predicted and available process unit capacities are presented in Table 17. Here again, predicted capacities exceeded those available for vacuum distillation and cat feed hydrotreating. The reasons were the same as in the East.

The agreement between historic actual capacity and the capacities predicted by the models show that the regional models assembled could simulate the U.S. regions well, giving confidence that the individual and regional models would give meaningful results in this study.

TABLE 16

VERIFICATION RUN SUPPLY AND DEMAND FOR WEST U.S.

1000 m^3/d

Refinery	Low Sulfur High Conversion	Medium Sulfur Light Low Conversion	Medium Sulfur Heavy High Conversion	High Sulfur Heavy Hydroskimming	High Sulfur Heavy High Conversion	Total
Feed						
Crude(1)	118.3	25.8	130.7	26.7	75.0	376.5
Isobutane		0.2	0.8			1.0
Normal Butane			0.9		1.1	2.0
NGL					1.7	1.7
Total Input	118.3	26.0	132.4	26.7	77.8	381.2
Products						
LPG	2.6	0.2	2.1	0.2	1.5	6.6
BTX(2)					1.1	1.1
Chemicals Feed	4.9	3.5				8.4
Leaded Gasoline	28.5	7.1	52.5	0.5	18.8	107.4
Unleaded Gasoline	36.5	1.0	9.2	1.9	9.3	57.9
Jet A	9.5		16.9		3.8	30.2
Jet B		2.9	8.7	0.1	0.3	12.0
No. 1 Diesel	2.4	1.9				4.3
No. 2 Diesel	25.9	3.4	9.1		2.3	40.7
No. 2 Heating Oil				3.6	3.7	7.3
Low Sulfur Fuel Oil	2.3	2.8	26.9	3.2	3.4	38.6
High Sulfur Fuel Oil		2.4		6.2	30.1	38.7
Lubes and Waxes	2.1					2.1
Asphalt				9.5		9.5
Coke, kMT/D	2.6		5.4		0.3	8.3
Sulfur, kMT/D	0.1	0.1	0.8		0.5	1.5

Notes:

(1) Volume and distribution between refineries of high sulfur heavy crude established by model. Volume of crude predicted by model was 102 km^3/d versus 104 km^3/d 1978 historic.

(2) Benzene, toluene, xylenes.

TABLE 17

PROCESS UNIT VERIFICATION FOR WEST U.S.

1000 m^3/d

Refinery	Capacity Predicted Low Sulfur High Conversion	Medium Sulfur Low Conversion	Medium Sulfur High Conversion	High Sulfur Hydroskimming	High Sulfur High Conversion	Total	Capacity Available(1)
Atmospheric Distillation	118.3	25.8	130.7	26.7	75.0	376.5	431
Naphtha Hydrotreating	20.0	0.1	14.8	2.1	5.8	42.8	102
Cat Reforming	17.7	0.1	11.9	2.1	5.8	37.6	82
Gas Oil Hydrotreating							
Cat Feed		8.0	20.9		19.2	48.1	28
Distillate	6.8	2.2	31.7	5.3	10.5	56.5	57
Total GO H/T	6.8	10.2	52.6	5.3	29.7	104.6	85
Vacuum Distillation	49.4	10.9	76.1	15.3	48.4	200.1	177
Cat Cracking	42.1	7.4	19.4		18.3	87.2	87
Hydrocracking	7.3		33.5		9.5	50.3	50
Visbreaking							15
Coking	10.8		15.7		0.8	27.3	52
Alkylation	2.3	0.5	2.2		1.4	6.4	10
H_2 Mfg - kMT/D	0.2		1.0		0.4	1.6	
Sulfur Recovery - kMT/D	0.1	0.1	0.8		0.5	1.5	

Notes:

(1) Available capacity as per National Petroleum Council, Refinery Flexibility, December, 1979.
(2) Cubic meters/d x 6.2893 = bbl/d.

3. PRODUCIBILITY RESULTS FOR UNITED STATES MODELS

3.1 INTRODUCTION

This Section examines the effect of jet fuel property relaxation on the maximum yield of jet fuel that could be achieved at constant cost, subject to constraints.

Determinations were made at specific Gasoline/Distillate (G/D) ratios using selected crudes run in refineries of different complexities. Distillate was defined as No. 2 diesel fuel plus No. 2 heating oil specified in a ratio of 85 to 15, reflecting the fact that most refiners produce heating oil and diesel fuel as a common product. The total volume of gasoline plus distillate was fixed at 13.5 km^3/d (85 kB/d). Jet A was considered to be a separate product and was not included in the distillate. Production of LPG and sulfur could vary. Volumes of other products, such as Jet B and residual fuel oil, if made, were fixed. Approximately 15.9 km^3/d (100,000 bbl/d) of crude was required for this volume of products but crude volume was allowed to vary (i.e., if more jet fuel were made with relaxation, the refinery could run more crude).

The jet fuel property variations were those defined by the study fuels TF-1 through TF-5 (Table 3). The property limits of all other fuels were invariant. Base property jet fuel (TF-1) marginal cost was set at a level of $13.2/$m^3$ (5¢/gallon) greater than the marginal cost of No. 2 diesel fuel. The marginal cost is the cost to produce the last increment of fuel. Once established for a given G/D, the TF-1 marginal cost was used for each successive relaxation, TF-2 through TF-5. At a given G/D, the identical marginal cost was used for the corresponding runs in East U.S. refineries in which coal liquids or shale liquids replaced a portion of the crude.

The Gasoline/Distillate ratios investigated were:

East: 2.0, 1.2, 0.9

West: 2.6, 1.9, 1.2

The approximate years to which these G/Ds correspond are:

East: 1985, 1995, 2000

West: 1985, 1990, 2010

The property limits of the five jet fuels studied determined the blending components which could be used by the model. Those which were utilized most often to formulate the different study fuels are summarized below:

TF-1 - Kerosene
TF-4 - Kerosene + Gas Oil
TF-2 - Kerosene + Hydrocracker Kerosene
TF-3 - Kerosene + Hydrocracker Kerosene
TF-5 - Kerosene + Gas Oil + Cat Cracked/Hydrocracked/Thermally Cracked Kerosene.

Normally, TF-1 was formulated entirely or almost so from kerosene, adjusted for aromatics as needed. Relaxation of freezing point and aromatics to the TF-4 limits enabled gas oil, which has a higher aromatics content and higher freeze point than kerosene, to be blended into jet fuel. Generally, the model added the maximum amount of gas oil until the freezing point or aromatics targets were met.

Kerosene produced from hydrocracking supplemented virgin kerosene in formulating TF-2. The model attempted to minimize the amount of kerosene produced from jet fuel hydrocracking since this process required investment. It used conventional naphtha hydrocracking, which required no investment, to the extent permitted by G/D. Additionally, at high G/D, distillate stocks of all types were available since distillate demand was low. Consequently, potential distillate blend stocks such as cat crackate and coker distillate could be blended into jet fuel. Because of the properties of these streams, they were blended most frequently into the most relaxed study fuel, TF-5.

Crude coal and shale liquids were made available to conversion refineries in the East in separate runs. Fourteen per cent of the crude was replaced, successively, by an equivalent quantity of coal liquids and shale oil liquids.

Coal liquids contained more aromatics (35%) and had higher Naphtha/Distillate ratio (2.22) than any crude considered. Shale liquids had a lower N/D ratio (0.58) and the shale kerosene, a lower aromatics level (26%) than coal liquids.

The kerosene cuts of both coal and shale liquids could be blended into jet fuel, the distillates and residual fuel oil. Although neither shale nor coal liquids contained vacuum residuum, both contained an atmospheric resid fraction boiling between 343°-566°C (650-1050°F). For coal liquids, this cut could be blended into fuel oil or be sent to resid hydroconversion. For shale, this cut could serve as catalytic cracker feed, but its use in hydrocracking was not modeled.

3.2 PRODUCIBILITY IN EAST U.S.

3.2.1 - General Findings

Producibility results are presented in two ways. First, yields of jet fuels are plotted for each case as a percentage of the refinery crude feedstock volume. Second, volume outputs are shown as relative values, or volume yields, referenced to the volume of jet fuel produced for a baseline case (TF-1 at high G/D). Since the refinery models permit additional crude to be run if favorable, the volume increases on the relative volume basis will be greater than those compared on a percentage of input basis.

Figure 5 shows the percentage yield results by eight separate bar graphs, one for each of the refinery-crude models in the East U.S. The bars represent the liquid volume percent of jet fuel produced relative to the quantity of crude feedstock input. Each row of plots compares similar crude types, and each column similar refinery types. Within each plot, the bars are grouped to compare percentage yields for the set of TF-1 through TF-5 study fuels at each of three G/D ratios. Table 18 shows volume producibility information for the East U.S. models on the basis of normalized volumes.

At the high and intermediate G/D ratios, relaxation and the addition of cracked stocks resulted in increases in jet fuel producibility. The magnitude of the increases depended upon crude properties and the extent of relaxation. At the low G/D ratio, not only were TF-1 yields lower than at the high G/D, but improvements in jet fuel production with study fuels were smaller and often not possible. This resulted because the kerosene that could have been blended into jet fuel was needed to meet the specifications and the volume requirements of the distillate fuels and because there was no product for disposal of excess naphtha. The latter problem was termed a "naphtha block."

In most cases, high conversion refineries could produce greater jet fuel yields than low conversion refineries and both could produce greater yields than the hydroskimmers.

Figure 6 and Table 19 present corresponding results for the U.S. East for cases where coal liquids were substituted for 14% of the petroleum feedstocks. Jet fuel yields were similar to, but generally less than for the petroleum cases at the higher G/D ratios. However, at the low G/D, yields decreased substantially, because coal liquids contain a very high percentage of naphtha, reducing the availability of kerosene for jet fuel and aggravating the naphtha disposal problem encountered in the petroleum cases.

FIGURE 5
JET FUEL YIELD BASED ON CRUDE RUN, EAST U.S.

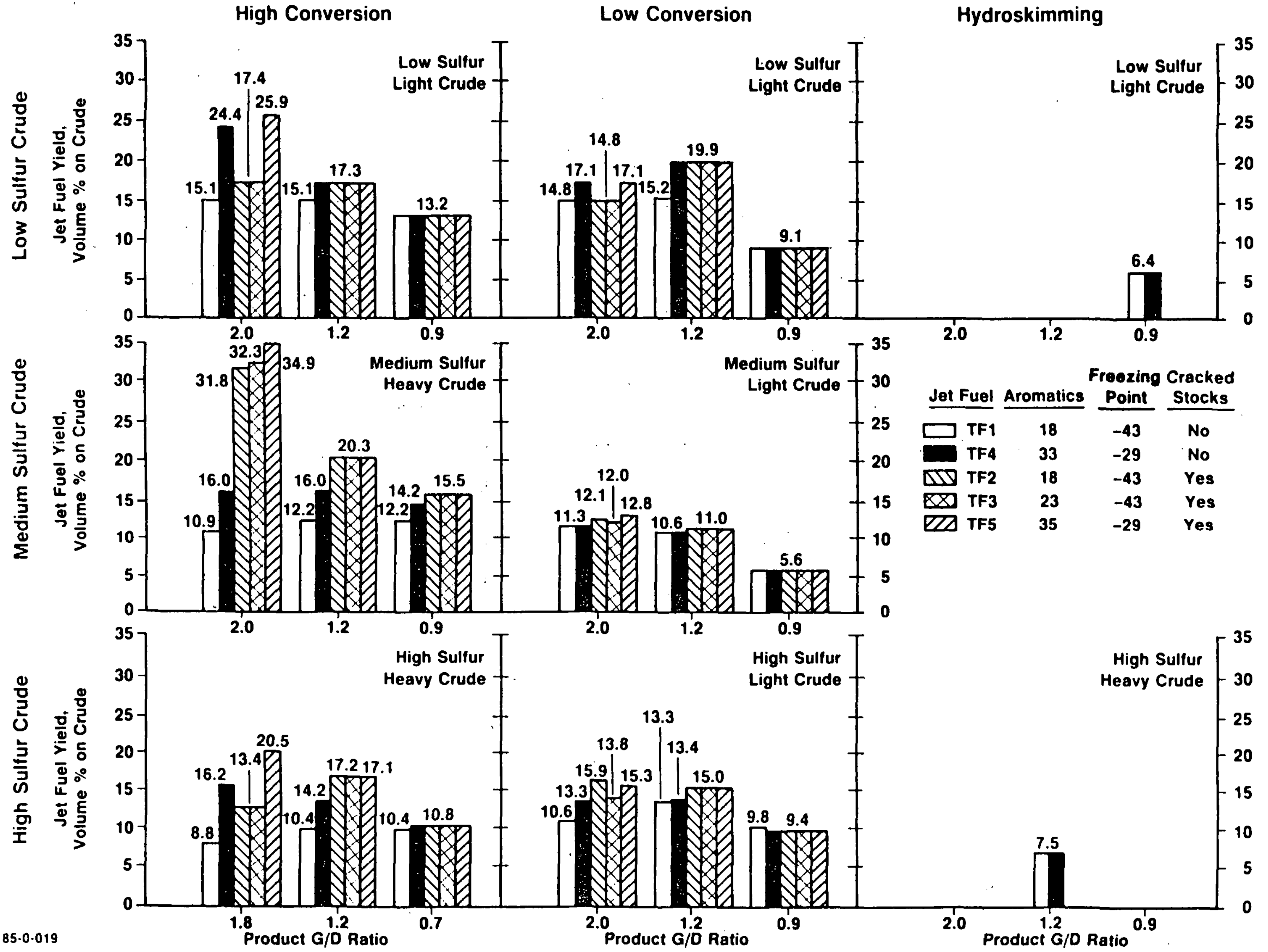


TABLE 18

RELATIVE JET FUEL VOLUME PRODUCED, EAST U.S.

G/D Ratio	2.0					1.2					0.9				
Jet Fuel	TF-1	TF-4	TF-2	TF-3	TF-5	TF-1	TF-4	TF-2	TF-3	TF-5	TF-1	TF-4	TF-2	TF-3	TF-5
Low Sulfur/High Conversion	1.00	1.85	1.15	1.15	1.95	1.00	1.20	1.20	1.20	1.20	0.90	0.90	0.90	0.90	0.90
Low Sulfur/Low Conversion	1.00	1.20	1.00	1.00	1.20	1.05	1.45	1.45	1.45	1.45	0.60	0.60	0.60	0.60	0.60
Low Sulfur/Hydroskimmer	-	-	-	-	-	-	-	-	-	-	1.00	1.00	-	-	-
Medium Sulfur/High Conversion	1.00	1.65	3.80	3.95	4.45	1.15	1.55	2.15	2.15	2.15	1.20	1.40	1.50	1.50	1.50
Medium Sulfur/Low Conversion	1.00	1.00	1.10	1.10	1.20	0.95	0.95	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50
High Sulfur/High Conversion(1)	1.00	2.00	1.60	1.60	2.70	1.25	1.70	2.15	2.15	2.15	1.25	1.25	1.25	1.25	1.25
High Sulfur/Low Conversion	1.00	1.30	1.65	1.40	1.55	1.30	1.30	1.55	1.55	1.55	0.95	0.90	0.90	0.90	0.90
High Sulfur/Hydroskimmer	-	-	-	-	-	1.00	1.00	-	-	-	-	-	-	-	-

Notes:

(1) G/D ratios for this refinery were 1.8, 1.2 and 0.7.

FIGURE 6
JET FUEL YIELD BASED ON CRUDE RUN WITH 14% COAL LIQUIDS, EAST U.S.

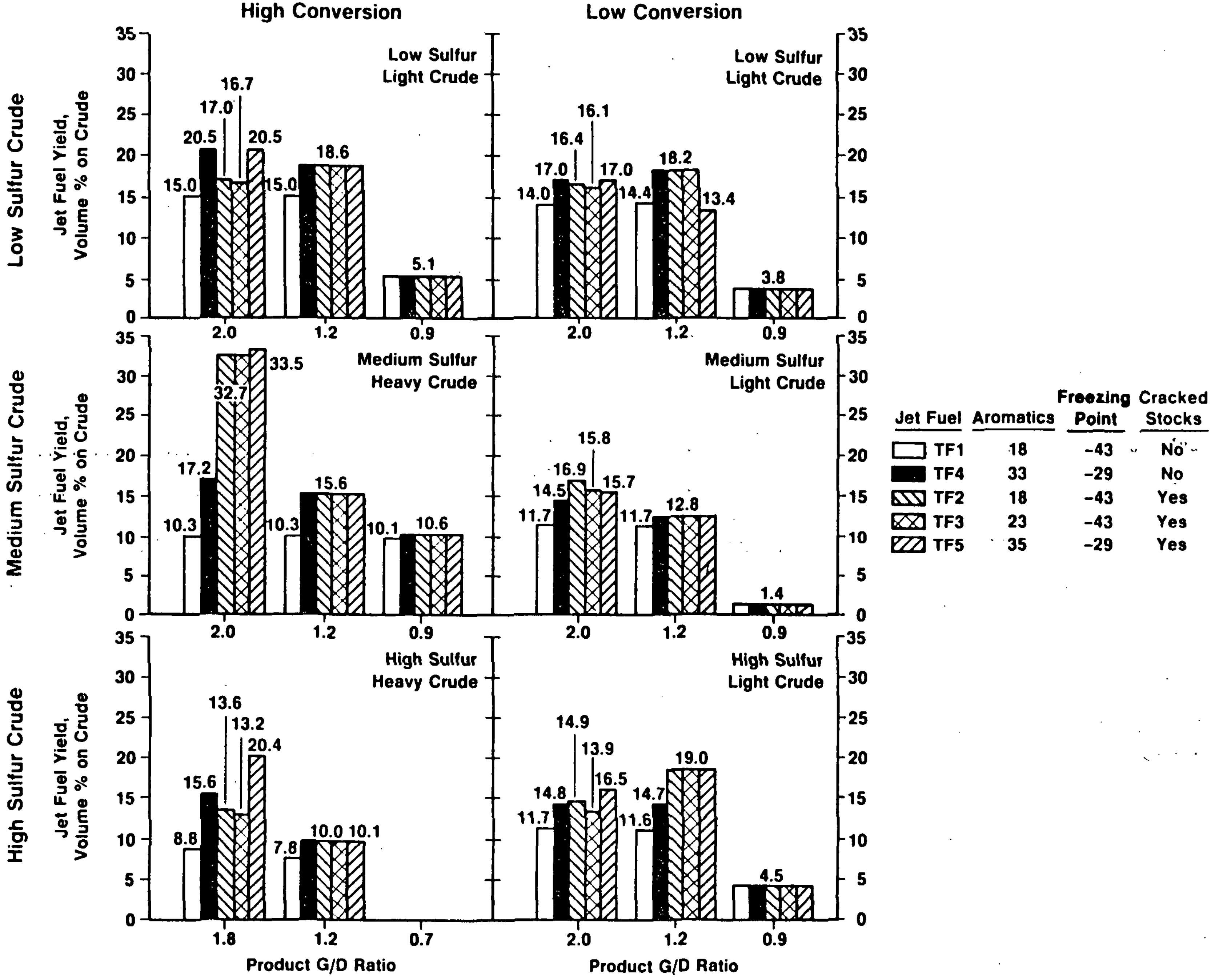


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TABLE 19

RELATIVE JET FUEL VOLUME PRODUCED WITH 14% COAL LIQUIDS, EAST U.S.

G/D Ratio	2.0					1.2					0.9				
Jet Fuel	TF-1	TF-4	TF-2	TF-3	TF-5	TF-1	TF-4	TF-2	TF-3	TF-5	TF-1	TF-4	TF-2	TF-3	TF-5
Low Sulfur/High Conversion	1.00	1.50	1.25	1.15	1.50	1.05	1.35	1.35	1.35	1.35	0.30	0.30	0.30	0.30	0.30
Low Sulfur/Low Conversion	1.00	1.30	1.25	1.20	1.30	1.05	1.40	1.40	1.40	1.00	0.25	0.25	0.25	0.25	0.25
Medium Sulfur/High Conversion	1.00	1.85	4.40	4.40	4.55	1.05	1.65	1.65	1.65	1.65	1.00	1.05	1.05	1.05	1.05
Medium Sulfur/Low Conversion	1.00	1.25	1.50	1.40	1.40	1.00	1.15	1.15	1.15	1.15	0.15	0.15	0.15	0.15	0.15
High Sulfur/High Conversion(1)	1.00	2.00	1.70	1.60	2.70	0.90	1.15	1.15	1.15	1.15	-	-	-	-	-
High Sulfur/Low Conversion	1.00	1.35	1.35	1.25	1.50	1.00	1.35	1.80	1.80	1.80	0.40	0.40	0.40	0.40	0.40

Notes:

(1) G/D ratios for this refinery were 1.8, 1.2 and 0.7.

When shale liquids were substituted for 14% of the petroleum (see Figure 7 and Table 20), only minor changes in yield occurred at the high G/D. At the low G/D, yields were reduced from the petroleum levels for the high conversion refineries. At the intermediate and low G/D ratios, the low conversion refineries generally produced more jet fuel when shale oil was included in the feed than when only petroleum was used. When petroleum only was run, the inability to dispose of residual fuel was a constraining influence on jet fuel production since it prevented more crude from being run to make additional jet fuel. Shale oil contains no vacuum resid. When the feed consisted of 86% petroleum and 14% shale oil, additional quantities of this feed could be run, producing additional jet fuel before a resid block or other limitations were reached.

It may be of interest to recognize the projected regional requirements for jet fuel yield. Table 1 shows that the forecast jet fuel demand for the East U.S. ranges from 6.3% of the crude feedstock in 1985 to 9.2% in 2010.

3.2.2 - Discussion of Model Results

Major factors affecting producibility increases, blendstocks used and limiting properties associated with jet fuel property changes are discussed here.

In Section 3.1, it was shown how, in general, the refinery streams are blended for each of the study fuels TF-1 to TF-5. Producibility results may be examined in more detail by discussing the calculated blending for the optimized solutions. Consider, as an example, the percent yields shown for the high conversion refinery supplied with low sulfur crude (upper left plot in Figure 5). For this model, TF-1 production was limited by kerosene availability in the crude and by freezing point. Relaxation to TF-4 permitted gas oil to be added to kerosene to increase jet fuel yield until freezing point was limiting. The use of cracked stocks (TF-2) resulted in a smaller yield increase. Relaxation to TF-3 produced no gain since aromatics were not limiting. Further relaxation to TF-5 resulted in a slight yield increase as hydrotreated coker distillate supplemented the kerosene and gas oil used to prepare TF-4.

At the intermediate G/D, freezing point and kerosene availability again limited TF-1 production. Relaxation to TF-4 or TF-2 produced the same small increase in yield. Since no properties were restrictive, further relaxation did not increase jet fuel yield.

At the low G/D, no properties were limiting and kerosene availability limited jet fuel production. Running additional crude could have produced more jet fuel but the naphtha simultaneously generated could not be disposed of, resulting in a naphtha block. Thus, jet fuel production could not be increased.

FIGURE 7
JET FUEL YIELD BASED ON CRUDE RUN WITH 14% SHALE LIQUIDS, EAST U.S.

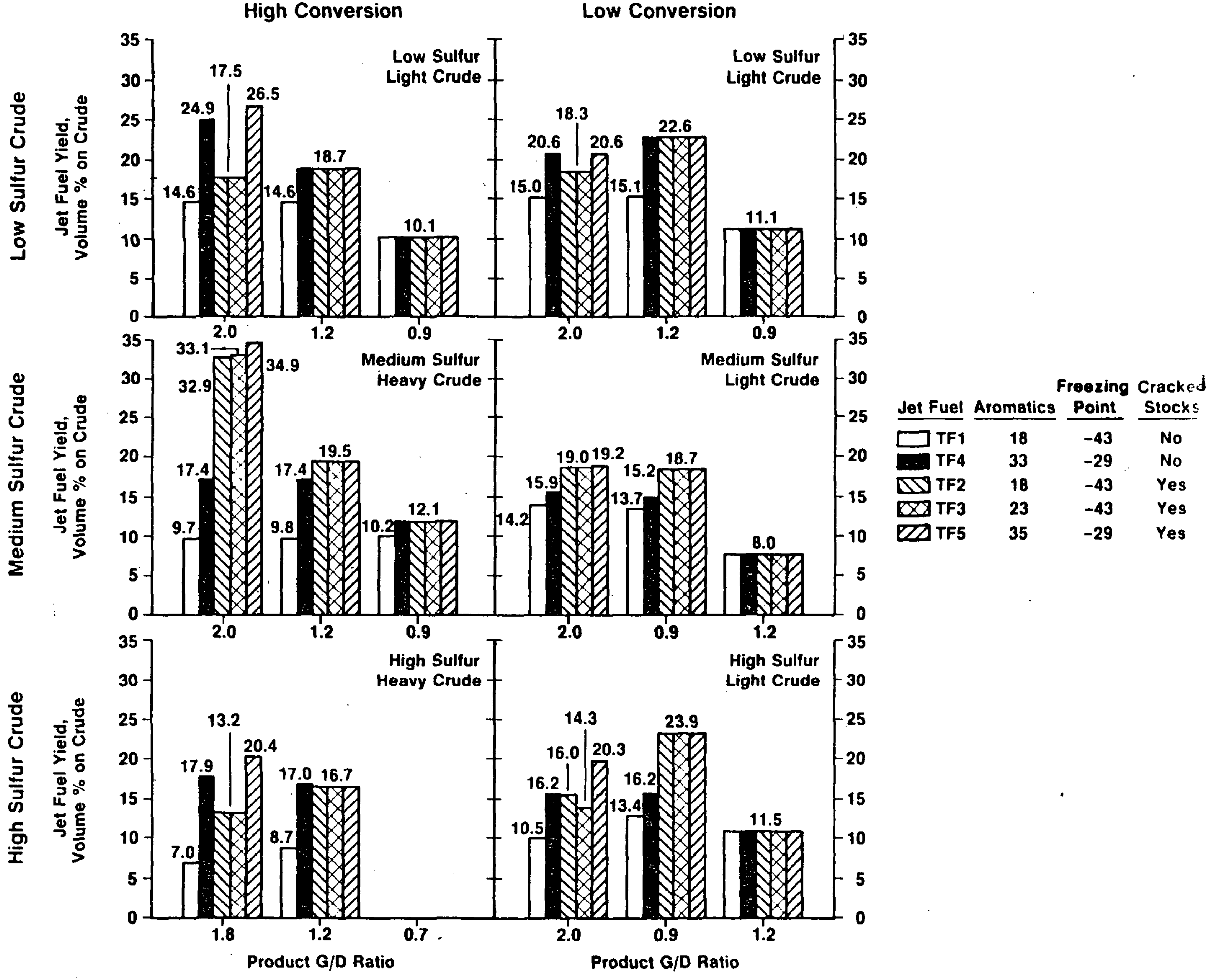

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TABLE 20

RELATIVE JET FUEL VOLUME PRODUCED WITH 14% SHALE LIQUIDS, EAST U.S.

G/D Ratio	2.0					1.2					0.9				
Jet Fuel	TF-1	TF-4	TF-2	TF-3	TF-5	TF-1	TF-4	TF-2	TF-3	TF-5	TF-1	TF-4	TF-2	TF-3	TF-5
Low Sulfur/High Conversion	1.00	1.95	1.20	1.20	2.15	1.00	1.40	1.40	1.40	1.40	0.65	0.65	0.65	0.65	0.65
Low Sulfur/Low Conversion	1.00	1.45	1.25	1.25	1.45	1.00	1.65	1.65	1.65	1.65	0.70	0.70	0.70	0.70	0.70
Medium Sulfur/High Conversion	1.00	2.00	4.65	4.65	5.15	1.10	2.00	2.30	2.30	2.30	1.10	2.00	2.00	2.00	2.00
Medium Sulfur/Low Conversion	1.00	1.15	1.40	1.40	1.40	0.95	1.10	1.40	1.40	1.40	0.50	0.50	0.50	0.50	0.50
High Sulfur/High Conversion(1)	1.00	2.90	2.00	2.00	3.50	1.30	2.80	2.70	2.70	2.70	-	-	-	-	-
High Sulfur/Low Conversion	1.00	1.65	1.65	1.40	2.20	1.30	1.65	2.70	2.70	2.70	1.10	1.10	1.10	1.10	1.10

Notes:

(1) G/D ratios for this refinery were 1.8, 1.2 and 0.7.

The substitution of coal liquids for 14% of the low sulfur crude (upper left plot in Figure 6) did not change jet fuel yield by more than 7.5% from the petroleum cases at the high and intermediate G/D ratios, but reduced it by over 60% at the low G/D. In this case the high naphtha content of the coal liquids aggravated the naphtha block which existed in the petroleum case at the low G/D. The inclusion of a similar level of shale liquids (upper left plot in Figure 7) had little effect at the high G/D, increased yield by no more than 8% at the intermediate G/D, and lowered yield by 25% at the lowest G/D. Jet fuel yield at the low G/D was constrained by the fact that shale oil hydrocracking was not an option available to the model.

For the low conversion refinery supplied with low sulfur crude (upper center plot in Figure 5), yield and yield improvement results were similar to those for the high conversion refinery with a few exceptions. At the high G/D, property relaxation (TF-4) produced only a small increase in jet fuel yield, and incorporation of cracked stocks (TF-2) produced no increase because freezing point was still limiting. At the intermediate G/D, hydrocracking was economically warranted to provide a low sulfur, low viscosity flux for residual fuel. This made virgin and/or cracked stocks available for blending into jet fuel. Consequently, the yields of most jet fuels at this G/D were greater than for the high conversion refinery, where a comparable use of distillate as fuel oil flux could not occur since the high conversion refinery did not produce residual fuel oil.

For the hydroskimming refinery supplied with low sulfur crude (upper right plot in Figure 5), a refinery with no conversion capacity, the G/D of products is determined by the G/D or naphtha/distillate ratio of the crude. For this refinery, a product G/D of 0.9 could be realized. As shown in Table 8, this crude had a naphtha/distillate ratio of 0.7. No other product G/Ds could be run for this refinery. Because this refinery cannot produce cracked stocks, TF-2, 3 and 5 were not studied, nor were the effects of introducing coal and shale liquids determined, since it is unlikely that syncrudes would be run in refineries lacking conversion equipment. Virgin kerosene was the only component in jet fuel. Jet fuel production was limited by the kerosene level in the low sulfur crude and by the competition for kerosene by the distillate products of diesel fuel and heating oil. No TF-1 properties were critical. Consequently, property relaxation did not increase jet fuel yield.

The medium and high sulfur crudes had higher aromatic contents in the kerosene fractions than the low sulfur crudes (compare Table 8). Hence the models required aromatics reduction, which raised the marginal cost of TF-1, allowing considerable leeway for investment when relaxed property fuels were blended. Investment was economic in jet hydrocracking, especially at high G/D, and several-fold increases in jet yield resulted when cracked stocks were allowed.

For the high conversion refinery supplied with medium sulfur, heavy crude (center left plot in Figure 5), the inclusion of cracked stocks tripled the jet fuel yield, improving the yield more than with property relaxation. Hydrocrackate was responsible for most of this increase. Aromatics and freezing point constrained jet fuel production. Relaxation of the aromatics constraint to the TF-3 level permitted a small further increase in jet production. TF-3 production was freezing point limited. Relaxation to TF-5 increased yield even further. The TF-5 pool contained virgin kerosene, hydrocracked kerosene, gas oil and cat crackate. This refinery-crude model was the only case in the East U.S. that showed some yield increases, although small, at the low G/D.

For the low conversion refinery supplied with medium sulfur, light crude (center plot in Figure 5), severe hydrotreatment was used to make TF-1, and kerosene availability was limited. There were no yield improvements at any G/D level with TF-4 and only small increases with the other study fuels. With the substitution of coal liquids or shale liquids (center right plots in Figures 6 and 7), however, this model showed modest yield responses to all study fuels at the high and intermediate G/D ratios.

For the high conversion refinery supplied with high sulfur, heavy crude (lower left plot in Figure 5), relative yield increases were similar to those for the same refinery with low sulfur crude. Baseline (TF-1) yields, however, were about half those with the low sulfur crude. The TF-5 fuel was blended with distillates from cat cracking and Flexicoking, as well as the virgin and hydrocracked kerosene and gas oil. The high aromatics streams could be used since aromatics were not a problem with TF-5 properties.

The substitution of coal liquids for 14% of the high sulfur heavy crude (lower right plot in Figure 6) resulted in decreases in yield of less than 4% at the high G/D and up to 42% at the intermediate G/D. No jet fuel was produced at the low G/D. This occurred because at this ratio, all kerosene was required to meet diesel fuel and heating oil volume and none was available for jet fuel. With the substitution of shale liquids (lower right plot in Figure 7), again, no jet fuel could be produced at the low G/D. The heavy shale fractions could be cat cracked only and the refinery encountered severe problems satisfying distillate demand without exceeding gasoline demand.

The cases for the high conversion refinery supplied with high sulfur, heavy crude were the first calculations in the study. They were investigated at G/D ratios of 1.8, 1.2 and 0.7. The highest and lowest of these ratios were lower than used for the other East refineries. It is likely that these low G/D values influenced the producibility results obtained, especially when synthetic crudes were used.

For the low conversion refinery supplied with high sulfur, light crude (lower center plot in Figure 5), relative yield increases were similar to those for the same refinery with the low sulfur crude. However, as with the high conversion model, the baseline (TF-1) yields were appreciably lower.

For the hydroskimmer supplied with high sulfur, heavy crude (lower right plot in Figure 5), the important product was asphalt, and the lighter products could be considered by-products. This refinery-crude model ran effectively at a G/D of 1.2, the intermediate G/D used in East runs. Because the kerosene from heavy, high sulfur crude had an aromatics level of 21.2%, TF-1 was formulated from mildly and severely hydrotreated virgin kerosene. However, jet fuel production was limited by the need to use kerosene in distillates to meet the 227°C (440°F) volatility constraint. Relaxing aromatics to the TF-4 level (33% aromatics) made severe hydrotreating unnecessary, which reduced cost. However, jet production could not be increased because of the continuing need to divert kerosene to the distillates for volatility considerations. Thus, this refinery exhibited no flexibility whatsoever to change yields.

3.3 PRODUCIBILITY IN WEST U.S.

3.3.1 - General Findings

Figure 8 shows the jet fuel yields for the refinery-crude models in the West U.S. as a percentage of crude run. Table 21 summarizes the second comparison of producibility results, the relative volumes of jet fuel, normalized with respect to the volume of the baseline fuel (TF-1) at current refinery demands (high G/D). Seven refineries were investigated, one less than in the East, since one less crude blend was considered in the West. Also one fuel, TF-3, was not studied since findings for this fuel in the East proved to be the same as for TF-2. West refineries operated at higher G/D ratios than in the East, but the average jet fuel yields required were higher than in the East. No synthetic crudes were run in the West.

Results in the West were affected by the higher aromatics levels and lower crude Naphtha/Distillate ratios. While relaxation of properties usually resulted in small to modest yield increases, the addition of cracked stocks usually produced far larger increases in yield. Especially pronounced were yield increases for medium and high sulfur heavy crudes. Their high aromatics levels required investment to meet the TF-1 aromatics requirement. Because these crudes had low Naphtha/Distillate ratios, the naphtha blocks prevalent at the low G/D in the East did not develop. Consequently, refineries running these crudes had their greatest yield increases at low G/D ratios. The medium sulfur, light crude had a high virgin jet yield because of a high kerosene content.

FIGURE 8
JET FUEL YIELD BASED ON CRUDE RUN, WEST U.S.

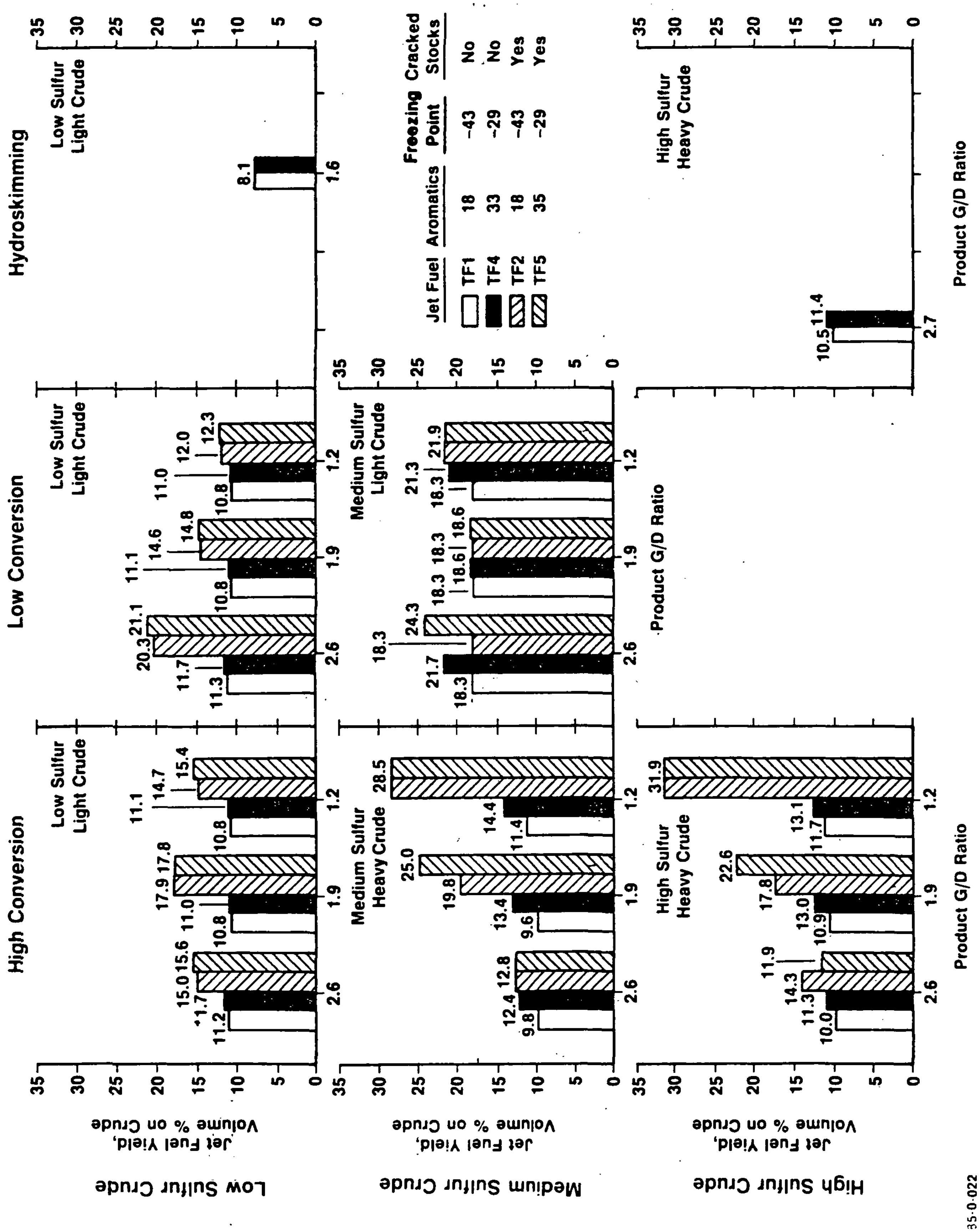

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TABLE 21

RELATIVE JET FUEL VOLUME PRODUCED, WEST U.S.

G/D Ratio	2.6				1.9				1.2			
Jet Fuel	TF-1	TF-4	TF-2	TF-5	TF-1	TF-4	TF-2	TF-5	TF-1	TF-4	TF-2	TF-5
Low Sulfur/High Conversion	1.00	1.00	1.35	1.40	0.95	0.95	1.70	1.70	0.95	1.00	1.35	1.40
Low Sulfur/Low Conversion	1.00	1.10	2.05	2.15	1.00	1.00	1.40	1.40	1.00	1.00	1.10	1.15
Low Sulfur/Hydroskimmer(1)	-	-	-	-	1.00	1.00	-	-	-	-	-	-
Medium Sulfur/High Conversion	1.00	1.30	1.35	1.35	1.00	1.40	2.30	3.10	1.00	1.30	3.10	3.10
Medium Sulfur/Low Conversion	1.00	1.25	1.00	1.45	1.00	1.00	1.00	1.00	1.00	1.25	1.30	1.30
High Sulfur/High Conversion	1.00	1.10	1.40	1.15	1.00	1.25	1.80	2.50	1.15	1.30	4.00	4.00
High Sulfur/Hydroskimmer(2)	1.00	1.10	-	-	-	-	-	-	-	-	-	-

Notes:

(1) G/D Ratio = 1.6
(2) G/D Ratio = 2.7

3.3.2 - Discussion of Model Results

Producibility results may be examined in more detail by considering first, as an example, the yields of the high conversion refinery supplied with low sulfur crude (upper left plot in Figure 8). For this model, the low kerosene content in the crude and high freezing points of virgin blend stocks constrained producibility. Freezing point limited TF-1 production. Relaxation from TF-1 to TF-4 at the high G/D resulted in a very small increase in yield. All available kerosene was blended to jet fuel. Only a small volume of high freezing point gas oil could be added before the TF-4 freezing point limitation was reached. Additional cut point flexibility in the model would undoubtedly have resulted in a somewhat greater increase in relaxed property jet fuel volume. Incorporation of cracked stocks increased yield to a greater extent with kerosene from naphtha hydrocracking added to virgin kerosene. The TF-2 pool was freezing point and aromatics critical. Relaxation to TF-5 increased yield only very slightly above TF-2 as limited quantities of gas oil could be added to the pool until the TF-5 freezing point targets were met.

At the intermediate G/D, relaxation to TF-4 increased producibility negligibly due to gas oil freezing point properties. Use of kerosene from naphtha hydrocracking and cat cracker output increased jet yield with TF-2 more than shown for the high G/D case. Relaxation to TF-5 did not increase producibility since no properties were limiting in TF-2.

At the low G/D, TF-1 production was limited by the availability of kerosene in the crude and by freezing point. Yield and improvements, however, were similar to those calculated for the high G/D.

For the low conversion refinery supplied with low sulfur crude (upper center plot in Figure 8), the yield increases associated with jet fuel changes were very similar to those of the high conversion refinery. In fact, most yields were identical, except that the low conversion refinery realized higher yields at the high G/D when cracked stocks were allowed (since jet hydrocracking was needed with the low conversion but not the high conversion refinery), and the high conversion refinery had higher yields at the lower G/D ratios. This refinery also required the addition of cracked stocks to increase yields significantly.

The hydroskimming refinery supplied with low sulfur crude (upper right plot in Figure 8) had little flexibility and could be run at only one G/D. A G/D of 1.6 was chosen since it was within the range of G/D ratios used for other refineries, and it resulted in smooth refinery operation. Virgin kerosene was the only component in TF-1 and TF-4. No properties were critical, and there was no incentive for relaxing jet properties.

As in the East U.S. cases, the medium and high sulfur crudes had high aromatic contents in the kerosene fractions, requiring aromatics reduction in the baseline case. This also influenced the effects of the jet property relaxations on yield increases.

The high conversion refinery supplied with medium sulfur, heavy crude (center left plot in Figure 8) showed yield results at high G/D similar to those for the same refinery with low sulfur crude. The baseline TF-1 was aromatics critical rather than freezing point critical. Results at the other G/D ratios were different from the low sulfur case. For this refinery, turbofuel production was highest at the low Gasoline/Distillate ratio. At this G/D, investment in jet hydrocracking was economically justified. Use of jet hydrocrackate in TF-2 and TF-5 increased production significantly. No naphtha block existed at the low G/D. Turbofuel production generally decreased as G/D increased because investment in jet hydrocracking was not justified at either the intermediate or high G/D. All of the vacuum gas oil was processed by either cat cracking or naphtha hydrocracking in these cases to meet the increased gasoline demand.

The low conversion refinery supplied with medium sulfur, light crude (center plot in Figure 8) had the highest baseline (TF-1) yield of any case investigated in the United States. Moreover, it was the only West U.S. case that produced only small increases with the inclusion of cracked stocks (TF-2). At the high and intermediate G/D ratios, hydrocracking was not justified. There were some yield improvements at the high G/D, where gas oils could be added for the TF-4 and TF-5 fuels. At the intermediate G/D, competition for distillate products limited the yield increases to negligible amounts. At the low G/D, hydrocracked kerosene was available to provide moderate yield increases for TF-5.

The results for the high conversion refinery supplied with high sulfur, heavy crude (lower left plot in Figure 8) were similar to those of the same refinery and medium sulfur crude with one notable exception. At the high G/D, jet fuel yield increased for TF-2 through blending with hydrocracked kerosene and coker distillate. Further relaxation to TF-5 had the unusual result of decreasing the yield compared to TF-2. Here, the model was able to reduce costs by backing-out processing rather than by increasing the quantity of jet fuel produced.

For the hydroskimming refinery supplied with high sulfur, heavy crude (lower right plot in Figure 8), a G/D of 2.7 was chosen because it resulted in reasonable refinery operation. The high sulfur heavy hydroskimming refinery produced asphalt and heavy fuel oil in addition to the light refinery products. Maximum turbofuel production increased moderately when properties were relaxed. TF-1 was a blend of hydrotreated virgin kerosene and dearomatized kerosene from the aromatics extraction process. In the TF-4 case, aromatics extraction of virgin kerosene was no longer required due to the relaxed maximum aromatics and minimum smoke limits. An increased quantity of virgin kerosene was blended to jet fuel in the TF-4 case because there was no longer the volumetric reduction in the aromatics extraction process. In the TF-1 case, the extract from aromatics extraction was blended to heavy fuel oil. In the TF-4 case, slightly more crude was run and atmospheric bottoms replaced this material in the heavy fuel oil pool.

3.4 PROPERTIES OF COMPETITIVE DISTILLATES

Many of the same blend stocks that were used to blend jet fuel were also used to blend diesel fuel and heating oil. Aromatics have poor diesel cetane properties and high density (low API gravity). Consequently, diesel fuels and heating oils prepared from crudes with high aromatics-content kerosenes were frequently cetane critical and heating oil gravity critical. Therefore, a competition existed between jet fuel and the other distillates for the same molecules. Relaxation of cetane or gravity properties would make it easier to produce jet fuel. With jet fuel property relaxation, the poorer quality kerosene used to blend the distillates could be blended into jet fuel and the superior jet kerosene could be blended into the distillates, improving their properties and perhaps removing the criticality.

Other properties which were frequently limiting for the distillates were flash point, cloud point, 10% distillation and sulfur. The latter occurred most frequently with high sulfur crudes and to a lesser extent with medium sulfur crudes.

The distillate produced by hydrocracking was usually used at low G/D to meet the volume requirements of the distillates. Distillate from hydrocracking had excellent properties and its use would frequently improve one or more distillate properties which were critical at a higher G/D. The process of choice at low G/D was hydrocracking for jet fuel. Kerosene, suitable for use in jet fuel and the distillates, constituted about 60-65% of the output of this process. However, this process was expensive from both investment and operating bases. One reason for this was that augmented hydrogen production capacity must be provided at additional expense when hydrocracking was installed. Processes that are efficient, low cost distillate producers are needed.

3.5 SUMMARY OF PRODUCIBILITY RESULTS

The wide range of producibility results obtained using different refinery-crude models showed that modeling one "average" refinery running an "average" crude can produce misleading results since the average refinery will not be constrained in the same way as real refineries. Key findings of the producibility calculations are summarized below.

- Relaxation of aromatics and freezing point or use of cracked stocks increased jet fuel yield for conversion refineries from an overall average of 12% to as high as 35% of the crude volume.
    - In the East, yield increases were generally greatest for the high conversion refinery at high G/D. Relaxation of properties or the use of cracked stocks were equally effective in increasing yield. At a G/D of less than 1, however, producibility was limited by specifications of distillates and excess naphtha production.
    - In the West, yield increases were also greatest for the high conversion refinery. However, the use of cracked stocks was usually more effective than property relaxation in increasing yield. Also, for some refineries, yield increases were greatest at the low G/D cases because there was no naphtha block and investment in conversion processes was warranted.
- Property relaxation had little or no effect on hydroskimmer producibility.
- Hydrocracking for jet fuel was needed in low G/D cases for distillate volume and quality.
- Substitution of coal liquids for 14% of petroleum had little effect at higher G/Ds but sharply reduced jet fuel yield at lowest G/D. High naphtha content of coal liquids accentuated the need to meet distillate volume and qualities and the naphtha disposal problem at low G/D.
- Use of 14% shale liquids produced small changes at the high G/D, but increased yield for low conversion refineries at intermediate and low G/Ds since a residual fuel block was relieved.

4. REGIONAL COST SAVINGS RESULTS FOR THE UNITED STATES

4.1 INTRODUCTION

This section describes the cost savings which can be realized with jet fuel property relaxation. Cost savings were determined using regional models. As described in Section 2.8, regional Linear Programming (LP) models were established by linking together the individual refinery-crude LP models used for producibility determinations.

Crude blends, crude shale and coal liquids and gas condensate were provided to appropriate refineries. Syncrudes could be run in East U.S. refineries only. Generally, the overall crude mix became more aromatic, heavier and higher in sulfur with time. The high sulfur, light crude in the East and the high sulfur, heavy crude in the West were allowed to vary for material balance purposes. The refineries competed for crudes and liquids supplies.

The regional models were run using the product demands shown in Tables 1 and 2. Production of coke and sulfur were allowed to vary as needed. Individual refineries in each regional model were not constrained to meet the regional product demands. Instead, the refineries competed for available crude and to supply finished products so that in the optimum solution the marginal costs of each refinery supplying a given product were equal. A marginal cost is the cost of the last increment of fuel produced. The regional model was run to yield the lowest overall costs. When optimized for lowest costs, certain high cost refineries may run no crude at all. However, five refineries must be run in the East, and four in the West, corresponding to the number of crude blends consumed in each region.

While Gasoline/Distillate ratio is a widely understood parameter, the Naphtha/Total Distillate ratio (N/TD) is the more encompassing ratio affecting results. Naphtha includes benzene, toluene, xylene (BTX), chemical feed, gasoline and Jet B (JP-4). Total Distillate includes diesel fuel, heating oil and Jet A. The latter was excluded from Distillate in producibility determinations because it was the fuel being maximized and its volume could change from run to run.

Processing equipment present in 1978 was made available in aggregate to the regional models. The models could invest in additional refining capacity if this lowered overall costs. Also, if overall costs were minimized, the model could invest in advanced processes listed in Table 12 and described in Section 2.6. All cost savings runs used a 1981 constant dollar basis, assuming no inflation, no changes in crude and other raw material costs and constant unit operating and investment costs.

To determine cost savings in a given year, the model was first run to produce jet fuel meeting TF-1 qualities. A solution representing overall regional costs in dollars resulted. Then the model was run producing jet fuel meeting TF-2 property levels. The total cost in this case was lower than that realized when TF-1 was being produced. The difference between these two cost values represented the regional savings due to relaxing jet fuel properties to TF-2. Dividing regional savings by the quantity of jet fuel produced resulted in savings on a "per cubic meter," "per barrel," or "per gallon" basis. This complete process was then repeated for each relaxation, always comparing results to the TF-1 solution. Implicit in this calculation is that all cost savings accrued to jet fuel. Each run also established a marginal cost for each product. Refiners use the marginal cost value to guide their production of a particular fuel.

Not every refiner produces jet fuel. This means that the jet fuel yield of those refiners that produce jet fuel must be greater than the regional average. Cases that adjust for the crude available to jet fuel producers were called "limited participation." Requiring a greater yield of jet fuel created a greater strain on those refiners producing it, which translated to increased refining costs. Consequently, under limited participation relaxation of properties resulted in greater savings than if all refiners made jet fuel.

While product demands have been presented for four different time periods, they also represent four different Naphtha/Total Distillate ratios. As was noted earlier, recent forecasts project more moderate rates of change than used here for gasoline and diesel fuel. Thus, the Naphtha/Total Distillate ratio forecast for 2000 might not be reached until a later period, such as 2010. Expressed on a N/TD basis, results will be applicable to any time period corresponding to the N/TD used.

4.2 COST SAVINGS IN THE EAST U.S.

4.2.1 - Annual Cost Savings

The annual cost savings in the East U.S. for jet fuel property relaxation are presented in Table 22. Savings range from a low of about $15 million in 1985 to a potential high of over $230 million in 2010. For limited participation cases it was assumed that 2/3 of the crude run in the East participated in the production of jet fuel in 1985 and 1990. The value of 2/3 is about midrange between the 75% and 45% values for participation in jet fuel production reported by two recent studies (11,12). The extent of participation in the limited participation cases was increased to 3/4 in 2000 and to 4/5 in 2010. This was done because the forecast Jet A demand could not be met with TF-1 at the 2/3 participation limit in 2000 and 2010 due to the low N/TD ratios in those years.

TABLE 22

ANNUAL COST SAVINGS FOR EAST U.S.

$ MILLION/YR

	Participation	TF2	TF3	TF4	TF5
1985	Full	15.5	15.5	17.8	17.8
	Limited (2/3)	53.5	53.6	64.1	64.1
1990	Full	39.0	39.0	47.5	47.5
	Limited (2/3)	90.7	91.5	100.0	108.7
2000	Full	63.3	64.0	72.5	74.9
	Limited (3/4)	110.3	110.6	119.3	124.7
2010	Full	103.7	103.8	106.1	110.9
	Limited (4/5)	223.0	223.1	225.4	231.8

The most striking aspect of the cost savings data was that the savings increased substantially with time and also as participation in the Jet A market was limited. These increases in cost savings came about because the demand for kerosene as well as other distillate products grew with time. Limiting participation further stressed competition for kerosene, increasing the savings for relaxation of Jet A properties. High costs were associated with the production of Jet A at the low N/TD ratios of future periods. Within this high cost regime, even minor relaxations could produce large cost savings, but the differences in savings between relaxed property fuels were small. Savings were nearly equal for all relaxations. All relaxations from TF-1 eliminated aromatics reduction costs. In addition, in the relaxed cases, less crude was consumed due to reduced use of plant fuel previously required for aromatics reduction.

Other interesting trends are also shown in Table 22. First the savings obtained by relaxing fuel properties for the study fuel that excluded cracked stocks, TF-4, always exceeded those for TF-2 and TF-3, which contained cracked components with little property relaxation. In contrast, the producibility studies for the East U.S. showed that cracked stocks had as great an impact on yield as property relaxations. Second, cost savings for TF-2 and TF-3 were identical or nearly so, which showed there was little benefit for aromatics relaxation when hydrocracked components are available. Likewise, cost savings obtained for TF-4 and TF-5 were also essentially the same. This showed that once properties were relaxed substantially there was little incentive for blending cracked stock to the jet pool. In each case the relaxation that resulted in the least savings, TF-2, produced about 80 to 95% of the savings realized with TF-5, the relaxation that produced the highest savings.

4.2.2 - Cost Savings per Unit Volume

Because property relaxation and inclusion of cracked stocks in jet fuel were the only refining changes, all cost savings could be expressed in terms of jet fuel production. Table 23 summarizes the cost savings on the basis of dollars per cubic meter or cents per gallon of kerosene jet fuel produced. Cost savings on this basis appear slight, \$0.44 to \$4.15/m^3 (0.2 to 1.6¢/gallon), but comparison to the tens to hundreds of millions of dollars in Table 22 shows that small cost savings per unit volume lead to considerable cost reductions annually for the region.

4.2.3 - Cost Savings as a Function of Production Level

The cost savings due to jet fuel property relaxation were not equally distributed over the total range of jet fuel production volume. In general, savings increased as jet fuel production volume increased.

TABLE 23

AVERAGE COST SAVINGS FOR EAST U.S.

		TF-2		TF-3		TF-4		TF-5	
	Participation	$/m³	¢/gallon	$/m³	¢/gallon	$/m³	¢/gallon	$/m³	¢/gallon
1985	Full	0.44	0.2	0.44	0.2	0.50	0.2	0.50	0.2
	Limited (2/3)	1.45	0.5	1.45	0.5	1.70	0.6	1.70	0.6
1990	Full	0.94	0.4	0.94	0.4	1.13	0.4	1.13	0.4
	Limited (2/3)	2.14	0.8	2.14	0.8	2.33	0.9	2.52	0.9
2000	Full	1.26	0.5	1.26	0.5	1.45	0.5	1.51	0.6
	Limited (3/4)	2.20	0.8	2.20	0.8	2.39	0.9	2.52	0.9
2010	Full	1.89	0.7	1.89	0.7	1.89	0.7	2.01	0.8
	Limited (4/5)	4.03	1.5	4.03	1.5	4.09	1.5	4.15	1.6

Figure 9 shows that savings that resulted from relaxing jet properties from TF-1 to TF-5 in 1985 as a function of the volume of jet fuel produced. It is seen that no cost savings from property relaxation developed until the Jet A demand increased beyond roughly $75000m^3/d$ in the full participation case. The plateau between 75000 and $89000m^3/d$ represents the average cost savings for this increment of jet fuel. The savings continued to increase with Jet A demand. The cross-hatched area represents the total daily savings which would result from a relaxation to TF-5 in this case. The area under the curve is equal to an average savings of $\$0.50/m^3$ of Jet A produced, the value shown in Table 23. When the limited participation case was considered, 2/3 for 1985, the savings started at a lower Jet A demand level. The resulting area under the curve (diagonal lines) is greater and the average is higher, $\$1.70/m^3$ Jet A produced, than in the full participation case. Graphs very similar to Figure 9 could be established for each time period and each fuel studied.

The stair-like appearance of this Figure is a direct result of its method of development. Cases were run at selected Jet A demand increments in order to generate data that showed savings as a function of demand.

4.2.4 - Marginal Costs

A marginal cost is the cost for producing the last increment of a specific product. In general, the higher the marginal cost the more difficult it will be to produce that product. As conditions change (for instance, as product properties are relaxed), marginal cost changes for the same product will indicate whether that product is easier or more difficult to produce under the revised condition.

Marginal costs are overly sensitive to model input parameters, such as the cost of crude, processing, and the quantity and mix of all products produced. They should be used only to indicate trends.

Table 24 presents marginal costs of selected products for the TF-1 and TF-5 runs at full and limited participation for each study year. The marginal costs for other jet property relaxation levels fall between those presented. The four products that were selected, regular unleaded gasoline, Jet A, diesel, and regular sulfur fuel oil (RSFO), are representative of all segments of the demand barrel.

Because N/TD ratios decreased with time, the marginal cost of gasoline decreased with time and the marginal costs of distillate products increased. The rising marginal costs of the distillate products tended to make them more expensive than the other products, with Jet A being the most expensive. These effects were accentuated in the limited participation cases. The marginal cost of regular gasoline decreased from one of the highest marginal cost products in 1985 to the lowest in

FIGURE 9
TF-5 SAVINGS FOR PRODUCTION INCREMENTS, EAST U.S. REGION, 1985

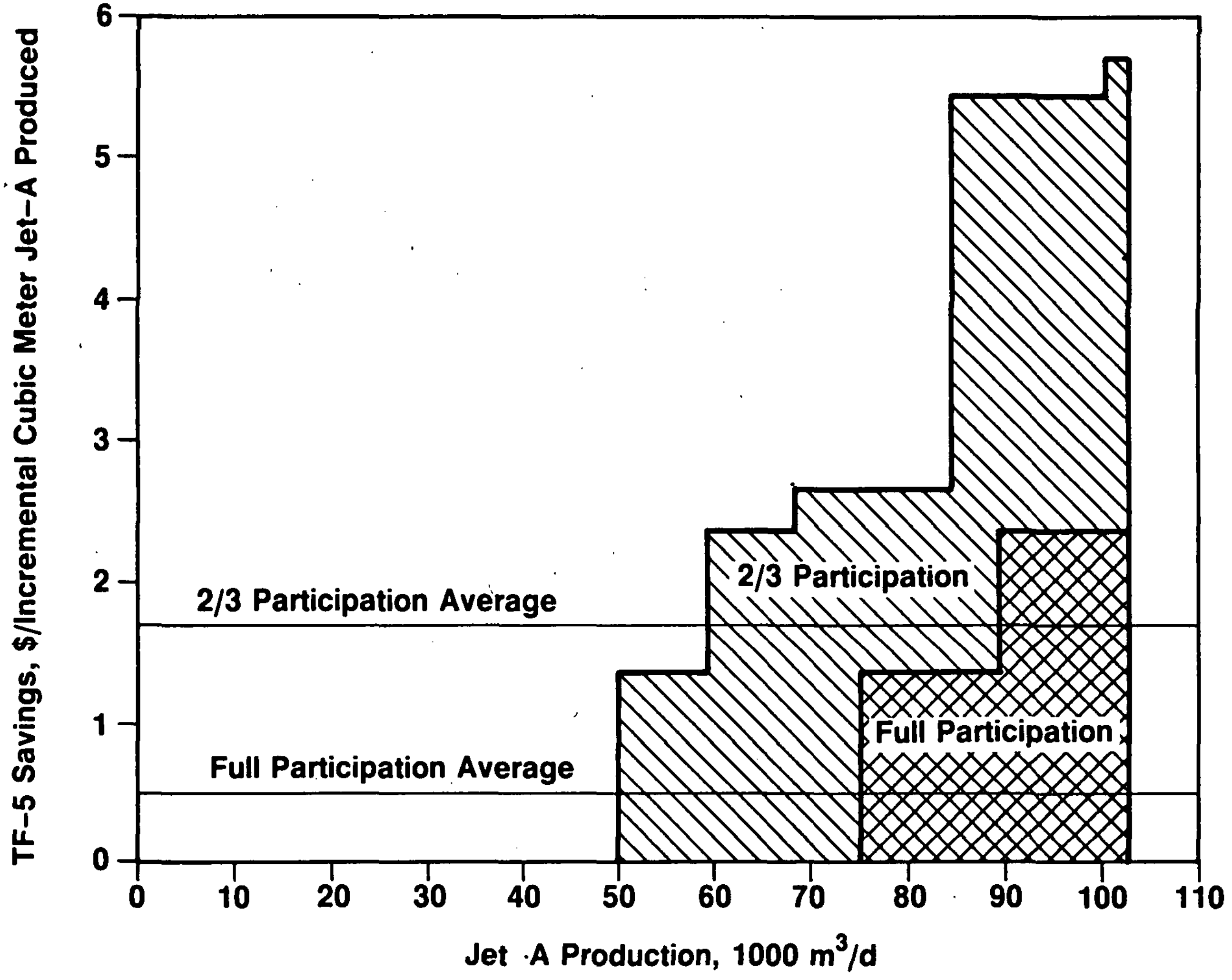


TABLE 24

MARGINAL COSTS FOR EAST U.S.

		1985		1990		2000		2010	
Full Participation		$\$/m^3$	\$/gallon	$\$/m^3$	\$/gallon	$\$/m^3$	\$/gallon	$\$/m^3$	\$/gallon
TF1	Gasoline	266.4	1.01	263.8	1.00	241.4	0.91	215.0	0.81
	Jet Fuel (Jet A)	265.0	1.00	270.5	1.02	292.4	1.11	310.3	1.17
	Diesel	261.2	0.99	263.7	1.00	285.5	1.08	303.5	1.15
	RSFO	231.9	0.88	232.3	0.88	227.7	0.86	219.6	0.83
	Jet - Diesel	3.8	0.01	6.8	0.02	6.9	0.03	6.8	0.02
TF5	Gasoline	265.8	1.01	264.0	1.00	241.9	0.92	215.0	0.81
	Jet Fuel	263.2	1.00	264.8	1.00	286.7	1.09	305.3	1.16
	Diesel	261.9	0.99	263.5	0.99	285.3	1.08	303.8	1.15
	RSFO	232.2	0.88	232.2	0.88	227.3	0.86	219.7	0.83
	Jet - Diesel	1.3	0.01	1.3	0.01	1.4	0.01	1.5	0.01
Limited Participation									
TF1	Gasoline	265.0	1.00	262.3	0.90	227.1	0.86	210.1	0.79
	Jet Fuel (Jet A)	269.7	1.02	271.8	1.03	310.3	1.17	340.9	1.29
	Diesel	263.0	0.99	264.9	1.00	294.1	1.11	298.7	1.13
	RSFO	232.3	0.88	232.7	0.88	233.1	0.84	214.3	0.81
	Jet - Diesel	6.7	0.03	6.9	0.03	16.2	0.06	42.3	0.16
TF5	Gasoline	264.9	1.00	262.9	0.99	228.4	0.86	210.4	0.80
	Jet Fuel	264.3	1.00	266.0	1.01	297.0	1.12	308.8	1.17
	Diesel	263.0	0.99	264.5	1.00	295.3	1.12	307.3	1.16
	RSFO	232.5	0.88	232.7	0.88	224.3	0.85	218.8	0.83
	Jet - Diesel	1.3	0.01	1.5	0.01	1.7	0.01	1.5	0.01

2010, dropping below that of RSFO and substantially below the distillate products. It is this result that leads one to question whether extrapolation of product demands beyond the year 2000 is practical. It might be expected that the demand for distillate will weaken if its cost increases relative to that of gasoline.

RSFO marginal costs were also relatively stable with time since the value of bottoms product, which constituted the bulk of the RSFO pool, was not sensitive to changes in N/TD ratio. The marginal cost changes which did occur were emphasized in the 2010 case since the N/TD ratio was extreme in that year.

As expected, relaxation from TF-1 to TF-5 reduced the marginal cost of jet fuel. This fuel change also had a very slight effect on the marginal costs of other products. The most noteworthy effect of the fuel change was the reduction of the cost differential between jet fuel and diesel.

The U.S. refining industry is now geared largely toward the production of gasoline, conforming to the current high N/TD environment. Cat cracking and hydrocracking capacity as now installed in the U.S. are oriented toward the production of naphtha. If, as forecasts suggest, the U.S. N/TD will drop with time, this capacity must become more distillate oriented. To a limited extent, naphtha/distillate ratio can be reduced by changing the catalyst and operating conditions in existing cat crackers and hydrocrackers. However, further projected declines in N/TD ratio warrant the development of processes that are more cost-effective than current technology for the production of distillates. The marginal costs presented here illustrate the incentives for this development.

4.2.5 - Jet Fuel Pool Compositions and Critical Properties

Each crude blend was run in only one refinery type. In cases when one blend could have been run in more than one refinery type, the highest conversion refinery available was always selected by the model. For example, the low sulfur crude, which could be run in all three refinery types, was run only in the high conversion refinery.

The regional models used for the cost saving study produced jet fuel by the optimized blending of component refinery streams. The study output provided an opportunity to examine the critical properties of jet fuel produced from each crude.

The crudes used and the specific blendstocks from those crudes contributed directly to determining which jet fuel properties were critical, i.e., at the specified property limit. Tables 25 through 28 show the crudes and blendstocks used to prepare 1985, 1990, 2000 and 2010 East jet fuel pools under limited participation. The rows show, for

TABLE 25

JET FUEL POOL COMPOSITION AND CRITICAL PROPERTIES EAST U.S. - 1985 LIMITED PARTICIPATION, VOL%(1)

TF-1	Low Sulfur	Med. Sulfur Light	Med. Sulfur Heavy	High Sulfur Light	High Sulfur Heavy
Kerosene	66.1	3.8		10.7	11.5
Gas Oil	1.8				
Raffinate		0.5		4.1	1.3
Synthetics	0.2				
	68.1 (F)	4.3 (A)		14.8 (A)	12.8 (A)
TF-2					
Kerosene	57.6			11.4	10.8
Gas Oil	1.8			0.2	0.4
Hydrocrackate	6.1		0.9	4.5	5.1
Cat Crackate			0.1	0.2	0.7
Synthetics	0.2				
	65.7 (F)		1.0 (F)	16.3 (F,A)	17.0 (F,A)
TF-3					
Kerosene	57.7			12.9	10.6
Gas Oil	1.8				
Hydrocrackate	5.8		0.9	3.0	5.4
Cat Crackate			0.1	0.5	1.1
Synthetics	0.2				
	65.5 (F)		1.0 (F)	16.4 (F)	17.1 (F)
TF-4					
Kerosene	64.8				
Gas Oil	35.1				
Synthetics	0.1				
	100.0				
TF-5					
Kerosene	57.9				
Gas Oil	28.4				
Hydrocrackate	5.7				
Cat Crackate	8.0				
	100.0				

Notes:

(1) Critical properties are: (F) = Freezing Point
(A) = Aromatics

TABLE 26

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES EAST U.S. - 1990 LIMITED PARTICIPATION, VOL%(1)

TF-1	Low Sulfur	Med. Sulfur Light	Med. Sulfur Heavy	High Sulfur Light	High Sulfur Heavy
Kerosene	51.1	2.5		22.7	11.5
Gas Oil	1.3				
Raffinate		0.4		8.6	1.3
Synthetics	0.6				
	53.0 (F)	2.9 (A)		31.3 (A)	12.8 (A)
TF-2					
Kerosene	44.5		1.9	22.0	10.5
Gas Oil	1.2				0.5
Hydrocrackate	0.7		0.7	6.7	9.6
Cat Crackate			0.1		1.0
Synthetics	0.6				
	47.0 (F)		2.7 (F,A)	28.7 (A)	21.6 (F)
TF-3					
Kerosene	44.4		1.0	23.3	10.3
Gas Oil	1.2				
Hydrocrackate	0.8		0.7	6.0	9.5
Cat Crackate				0.8	1.1
Synthetics	0.6				
Coker					0.3
	47.0 (F)		1.7 (F)	30.1 (F)	21.2 (F)
TF-4					
Kerosene	37.2		4.1	7.3	7.6
Gas Oil	32.2			6.4	5.2
	69.4 (F)		4.1	13.7 (F)	12.8 (F)
TF-5					
Kerosene	49.1				
Gas Oil	29.7				
Hydrocrackate	0.8				3.4
Cat Crackate	14.0				1.1
Synthetics	0.6				
Coker					1.3
	94.2 (F)				5.8 (F)

Notes:

(1) Critical properties are: (F) = Freezing Point
(A) = Aromatics

TABLE 27

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES EAST U.S. - 2000 LIMITED PARTICIPATION, VOL%(1)

TF-1	Low Sulfur	Med. Sulfur Light	Med. Sulfur Heavy	High Sulfur Light	High Sulfur Heavy
Kerosene	44.1	2.5		24.9	13.3
Gas Oil	0.8	0.3			
Raffinate		0.5		9.5	1.5
Synthetics	2.6				
	47.5 (F)	3.3 (F,A)		34.4 (A)	14.8 (A)
TF-2					
Kerosene	44.1	1.5	1.5	15.1	
Hydrocrakate	0.8	4.5	0.8	17.2	9.4
Cat Crackate	0.9		0.1		1.0
Synthetics	2.2	0.9			
	48.0 (F)	6.9 (F)	2.4 (F,A)	32.3 (F)	10.4 (F)
TF-3					
Kerosene	44.1	1.5	1.9	15.2	
Hydrocrackate	0.8	4.5		17.4	9.6
Cat Crackate	0.9		0.1		1.0
Synthetics	2.1	0.9			
	47.9 (F)	6.9 (F)	2.0 (F)	32.6 (F)	10.6 (F)
TF-4					
Kerosene	44.1		2.4	7.0	10.3
Gas Oil	29.8				2.0
Synthetics	1.7	2.7			
	75.6 (F)	2.7 (F)	2.4	7.0	12.3
TF-5					
Kerosene	44.1		1.5		6.8
Gas Oil	17.6				
Hydrocrackate	0.6	4.5			
Cat Crackate	17.1		0.4		1.0
Synthetics	2.1	0.8			
Coker			0.5		3.0
	81.5 (F)	5.3	2.4 (F)		10.8 (F)

Notes:

(1) Critical properties are: (F) = Freezing Point
(A) = Aromatics

TABLE 28

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES EAST U.S. - 2010 LIMITED PARTICIPATION, VOL%(1)

TF-1	Low Sulfur	Med. Sulfur Light	Med. Sulfur Heavy	High Sulfur Light	High Sulfur Heavy
Kerosene	39.7	0.7		14.0	14.4
Gas Oil	0.9			1.0	0.9
Raffinate	-	1.8		14.2	2.5
Synthetics	4.1	1.6		4.2	
	44.7 (F,A)	4.1 (F,A)		33.4 (F,A)	17.8 (F,A)
TF-2					
Kerosene	38.7	1.3	2.4	1.8	8.9
Hydrocrackate	1.1	4.0	1.3	2.1	34.5
Cat Crackate	1.1				
Synthetics		0.9	0.2		0.6
Coker					1.7
	40.9 (F)	6.2 (F)	3.9 (F,A)	3.9 (F)	45.1 (F)
TF-3					
Kerosene	38.7	1.3	3.1	2.1	8.1
Hydrocrackate	1.1	4.0	0.8	2.3	34.5
Cat Crackate	1.0		0.2		
Coker					1.1
Synthetics		0.9	0.1		0.7
	40.8 (F)	6.2 (F)	4.2 (F)	4.4 (F)	44.4 (F)
TF-4					
Kerosene	38.7		3.1	12.1	17.4
Gas Oil	25.6				
Synthetics		3.0	0.1		
	64.3	3.0	3.2	12.1	17.4
TF-5					
Kerosene	38.7		3.1	5.2	12.3
Gas Oil	15.2				
Hydrocrackate	1.1	4.1	3.4		
Cat Crackate	7.5			1.8	
Coker	1.1		1.2		3.2
Synthetics		2.1			
	63.6	6.2	7.7	7.0	15.5

Notes:

(1) Critical properties are: (F) = Freezing Point
(A) = Aromatics

each study fuel, the jet fuel components or blendstocks. The columns show the proportion of each crude source used. The total blend for each crude source has a letter in parentheses denoting if freezing point, aromatics, or both were critical. No letter denotes that the blend properties were not at their specification limits.

The jet fuel components have been grouped into six categories. These are:

Kerosene.	Includes both hydrotreated and non-hydrotreated virgin kerosene stocks. Kerosene from all crudes was cut to a -45°C freezing point. Aromatics levels of the kerosene fraction are shown in the listing of crude blend properties in Table 8.
Gas Oil.	Includes both hydrotreated and non-hydrotreated Atmospheric Gas Oil. Gas oils had freezing points ranging from -18°C to +3°C and aromatics levels ranging from 24 to 35%.
Raffinate.	Is from the aromatics extraction process, with the same -45°C freezing point as kerosene and an aromatics level of 10%.
Hydrocrackate.	Is the kerosene cut from hydrocrackers, with a freezing point of -46°C, and an aromatics content of 7%.
Cat Crackate.	Includes heavy cat naphtha (-57°C freezing point, 40% aromatics) and light cat cycle oil (freezing point -18°C, aromatics 75%).
Coker Stocks.	Are coker gas oils with -32°C freezing point and 20 to 60% aromatics, depending on crude source.
Synthetics.	Includes shale kerosene with a freezing point of -34°C. Coal naphtha and kerosene have -47°C freezing point. Naphtha contains 15% aromatics; gas oil has a -29°C freezing point and contains 40% aromatics. Kerosene aromatics levels are presented in Table 8.

An examination of Table 25 provides an example of the blending of jet fuel and the impact of study fuel changes. As shown in the table, 68% of TF-1 in 1985 was produced from low sulfur crude. Kerosene with a 16.3% aromatics level (Table 8) was the largest component. The low aromatics level of this kerosene allowed the blending of both gas oil and a trace of shale liquid until the jet pool from this refinery became freezing point critical. The remaining TF-1 was produced from medium and high sulfur crudes. Kerosene was the primary component, augmented with low aromatics raffinate to offset the high aromatics contents of the virgin kerosenes. To minimize costs, only sufficient raffinate was produced so that these pools were aromatics critical. They were not freezing point critical.

TF-2 had essentially the same properties as TF-1 except that cracked stocks were allowed. The model blended virgin kerosene, hydrocrackate and minor quantities of cat crackate. A total of four refineries contributed to the jet fuel pool. For the high sulfur crudes, the use of hydrocracker stocks with their low aromatics content permitted the elimination of aromatics extraction and allowed for gas oil and cat crackate to be added until these pools were freezing point and aromatics critical. Kerosene from the low sulfur crude refinery constituted a major fraction of jet fuel. The favorable properties of hydrocrackate were offset by those from gas oil and shale liquids which were added until freezing point became critical.

The composition of TF-3 was nearly the same as that of TF-2. The relaxation of aromatics level allowed the blending of increased levels of cat crackate. While all of the pool remained freezing point critical, the aromatics relaxation was sufficient so that no aromatics limitation existed.

TF-4 was produced entirely from the low sulfur crude. The relaxation of freezing point and aromatics allowed over one-third of the pool to be composed of gas oil, yet neither freezing point nor aromatics were limiting.

TF-5 was also produced entirely from low sulfur crude. Property relaxation allowed over one-quarter of TF-5 to be composed of gas oil and nearly 10% from cat crackate.

The jet fuel pool compositions for 1990 and 2000 (Tables 26 and 27) show the same general trends as those for 1985. A greater contrast is seen in the results for 2010 (Table 28), which show the effects of increased fuel demand and decreased product Naphtha/Total Distillate ratio. At the TF-1 level, a greater percentage of the jet demand must be satisfied with crudes other than the low sulfur crude, which constituted a smaller percentage of crude consumed in 2010 than in 1985. The percentage of the overall jet pool from the low sulfur crude decreased from 68% in 1985 down to 44% in 2010. As the demand for distillate increased, the competition for kerosene blendstocks in the distillate pools also increased. Therefore, as can be seen, more gas oils and synthetic stocks were included in the jet pool to make the required volume of jet fuel. These lower quality stocks were included to the limits of the property constraints, making freezing point and aromatics critical in the whole jet fuel pool.

The TF-2 relaxation allowed for the inclusion of hydrocracker kerosene into the jet pool. The low aromatics level of this stock allowed cat crackate and synthetics to be blended into the pool as well. The TF-3 relaxation had little effect on either the crudes or blendstocks used to make the jet fuel.

Unlike the 1985 case, the TF-4 relaxation required the use of crudes other than the low sulfur crude for jet production due to the higher volume of jet fuel required. The property relaxation allowed for the addition of more gas oil and synthetic stocks in the jet pool. The aromatics relaxation allowed for the production of jet fuel using the medium sulfur heavy crude, which was not used in the TF-1 case due to the high aromatics content of its virgin kerosene. Neither freezing point nor aromatics were critical. Relaxation of freezing point and aromatics to the TF-5 level allowed the inclusion of a significant amount of gas oils in the low sulfur crude jet pool. As in the TF-4 relaxation, the increased volume resulting from the inclusion of the gas oils caused most of the jet fuel to be produced from the low sulfur crude. The TF-5 aromatic relaxation also permitted blending of cat cracker stocks into the high sulfur light crude jet pool.

The fraction of the jet fuel pool that was property-critical for the cases just discussed is shown in Table 29. Note that for TF-1, the 1985 pool is about two-thirds freezing point critical, one-third aromatics critical. This breakdown shifts to half and half by 2000. All the pool components are both freezing point and aromatics critical or TF-1 by 2010. However, with property relaxation, the percentage of the pool that was aromatics critical dropped sharply. For TF-2 this was due to the use of hydrocrackate, and for TF-4, the aromatics levels of the kerosene cuts were lower than the aromatics limit of 33%. Yet, even after these relaxations, a large fraction of the pools still remained freezing point critical in certain years. The use of another kerosene stream with different cut points might make a smaller percentage of the jet pool freezing point critical. This was an option which was not modeled.

Full participation tables corresponding to Tables 25 through 28 are not included to avoid repetition. However, a summary of the critical properties for full participation is given in Table 30. The data are similar to those for limited participation, but they show the effect of greater crude availability from which jet fuel could be made. For TF-1, the percentages of the pool that were aromatics critical were about one-half those of the limited participation cases. Further, the aromatics limitation became virtually non-existent simply by allowing cracked stocks to be present, TF-2. For further relaxations, aromatics were never critical, and even freezing point criticality was virtually non-existent for TF-4 and TF-5.

4.2.6 - Qualities of Other Products

As Jet A properties were relaxed, there was an effect on diesel and heating oil because jet fuel property relaxation primarily resulted in a redistribution of blendstocks between jet fuel and the other distillate pools. The effect of jet relaxation on other distillates was most

TABLE 29

PERCENT OF POOL CRITICAL FOR PROPERTY - EAST U.S. (LIMITED PARTICIPATION)

	TF-1		TF-2		TF-3		TF-4		TF-5	
	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics
1985	68	32	100	33	100	0	0	0	0	0
1990	53	47	71	32	100	0	96	0	100	0
2000	51	52	100	2	100	0	79	0	95	0
2010	100	100	100	4	100	0	0	0	0	7

TABLE 30

PERCENT OF POOL CRITICAL FOR PROPERTY - EAST U.S. (FULL PARTICIPATION)

	TF-1		TF-2		TF-3		TF-4		TF-5	
	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics
1985	84	16	100	0	100	0	0	0	0	0
1990	76	24	100	0	100	0	0	0	0	0
2000	63	37	100	0	100	0	0	0	10	3
2010	51	49	100	0	100	0	0	0	0	0

pronounced in the TF-4 relaxation, which, though substantial, did not allow cracked stock to be blended to Jet A. Therefore, to take advantage of relaxed properties it was necessary to switch heavier virgin distillate stocks, which traditionally go to diesel and heating oil, into Jet A. This resulted in the distillate product pools having a much higher percentage of cracked stock than was the case with TF-1 or any of the other relaxations.

Another change occurred in the distillate product pools with time as a result of decreasing N/TD ratio. In the later years, since supplies of virgin distillate blendstocks were not adequate to meet the increased distillate demand, it was necessary to increase the percentage of process stock in the distillate product pools. This would occur irrespective of any Jet A relaxation. However, as mentioned above, it is exacerbated in the TF-4 case. These process stocks, most of which had higher aromatics content than their virgin counterparts, produced distillate product pools which had generally poorer cetane and cloud point properties. These pools tended to be flash point limited because of the inclusion of more volatile blendstocks.

Jet fuel property relaxations had minimal impact on the critical qualities in the gasoline pool and only minor impact on the fuel oil as property relaxation resulted in minor adjustments to flux stock. This is because the volume of potential jet fuel blendstocks in the gasoline and fuel oil pools was small relative to the total volume of those pools.

Gasoline was limited by research octane and vapor lock index in all cases. In a very few cases in the later years, gasoline made from medium sulfur heavy crude was also limited by motor octane or octane index, the average of research and motor octane. In no case was Reid vapor pressure limiting.

Fuel oil was sulfur limited in all cases. In the latter years an increasing portion of the fuel oil pool was viscosity limited as well. However, in no case was the entire fuel oil pool viscosity critical.

4.2.7 - Processing Considerations

Jet fuel property relaxation had some impact on the utilization of existing capacity as well as on the need for new facilities. In most cases, however, this impact tended to be relatively small.

Since relaxation had almost no effect on the volume of crude run, the impact on the utilization of existing pipestill capacity was minimal. In the later years, relaxation reduced crude run by 0.1%. In the early years, it had little or no effect.

Aromatics extraction was required by TF-1 in all years. This requirement grew from 2400m^3/d (15000 bbl/d) in 1985 to 18900m^3/d (119000 bbl/d) in 2010 for full participation. In the limited participation cases, aromatics extraction increased from 8000m^3/d (50000 bbl/d) in 1985 to 36400m^3/d (229000 bbl/d) in 2010. Extraction was not required for the production of any of the relaxed property fuels.

Investment in jet hydrocracking was required over the study period, and the requirements for this process increased as N/TD ratio declined. However, differences in requirement as a function of jet fuel property relaxation were relatively small because jet hydrocracking was needed to meet distillate volume.

It is also interesting that the model chose not to invest in two processing options that were available and entered into the producibility runs, severe kerosene hydrotreating and resid hydroconversion. This occurred because the Jet A demands as a percentage of crude run were much lower in the cost savings run than in the producibility runs, where jet fuel production was maximized, and therefore the more severe processing was justified.

4.2.8 - Energy Savings

Jet fuel property relaxation resulted in only limited energy savings as the data in Table 31 show. These savings were essentially the same for all four relaxations.

The total feedstock energy content is shown for both the full and limited participation cases. In the full participation cases, energy content tracked the forecast refining industry demands. In the limited participation cases, the assumed increase in participation overwhelmed the relatively small changes in demand. These data have been shown for only the TF-1 case since differences between cases were small. In all cases, the average feedstock energy content was 37.82 TJ/m^3 (5.7 x 10^6 Btu/bbl).

Plant fuel is also shown for the TF-1 case. While it was nominally 6% of feed on an energy content basis, it decreased with time. As N/TD ratio decreased for the future time periods, atmospheric gas oil was used directly for distillate blending rather than for conversion in the cat cracker to light products. This reduced the level of conversion and hence the fuel consumption.

Fuel savings show how much plant fuel was saved in the TF-5 case relative to TF-1. Fuel savings for the other relaxation levels have not been shown since these savings were essentially the same irrespective of the relaxation level chosen. Relative savings increased with time (i.e., decreasing N/TD ratio) and with limited participation.

TABLE 31

ENERGY USE SUMMARY - EAST U.S.

	1985	1990	2000	2010
Full Participation				
Feedstock Energy Content (TJ/d)(1)	57,485	56,609	56,683	58,693
Plant Fuel (TJ/d)(1)	3,650	3,529	3,270	3,155
(% of Feed)	6.3	6.2	5.8	5.4
Fuel Savings (TJ/d)(2)	4.9	18.0	30.2	27.0
(% of Feed)	0.008	0.032	0.053	0.046
(% of Fuel)	0.1	0.5	0.9	0.9
Limited Participation(3)				
Feedstock Energy Content (TJ/d)(1)	39,670	39,253	43,843	48,158
Plant Fuel (TJ/d)(1)	2,516	2,458	2,580	2,733
(% of Feed)	6.3	6.3	5.9	5.7
Fuel Savings (TJ/d)(2)	9.5	32.7	33.1	66.6
(% of Feed)	0.024	0.083	0.076	0.138
(% of Fuel)	0.4	1.3	1.3	2.4

Notes:

(1) Represents TF-1 Case (values in tera joules/calendar day).
(2) Equals fuel savings for TF-5 relative to TF-1.
(3) Assumed participation 1985 (2/3); 1990 (2/3); 2000 (3/4); 2010 (4/5). Values apply only to those refiners making jet fuel.

4.3 COST SAVINGS IN THE WEST U.S.

In the West U.S., only four crude blends were considered as opposed to five in the East. TF-3 was not investigated in the West since the Eastern runs showed that its cost savings and producibility behavior were virtually identical to those of TF-2.

For the West U.S. in 2000 and 2010, the regional calculations showed that it is not possible to meet the projected demand for jet fuel with the baseline TF-1. By 2010, there is a shortfall even with the relaxed property fuel TF-4. Table 32 shows the percentage of jet fuel demand which could be met with these fuels. Because demand could not be met with TF-1 in years beyond 1990, it was not possible to calculate cost savings due to relaxation for 2000 and 2010 using a basis consistent with earlier years in the West U.S., and all time periods in the East U.S. As a consequence, a basis change was required in the West for 2000 and 2010. For these years two new fuels were defined, TF-1A and TF-4A. These fuels had identical properties to TF-1 and TF-4, respectively, except that the blending of hydrocracked stocks was allowed. With the addition of hydrocracked stocks, Jet A volume could be met with all fuels in all years. TF-1A differed from TF-2 in that cracked stocks of all types were allowed in TF-2, but only hydrocracked stocks were allowed in TF-1A.

Sensitivity cases to show the effect of limiting the participation of refiners in the production of jet fuel were run for the West U.S. In 1985, a 3/4 level of participation was assumed. In 1990, the lower N/TD ratio made it even more difficult to meet Jet A demand with TF-1. The minimum participation level was 94% in 1990. Since 94% participation was very close to full participation, limited participation sensitivity cases were not run for 1990, and full participation was assumed. Limited participation level of 3/4 and full participation cases were run for both 2000 and 2010, where the baseline fuel became TF-1A.

4.3.1 - Annual Cost Savings

The annual cost savings for each of the relaxed property jet fuels are presented in Table 33. For 1985, cost savings are included for full, 4/5 and 3/4 participation cases. The 4/5 participation case is an additional sensitivity run used only for the cost savings study.

Annual cost savings for the West U.S. in 1985 and 1990 were two to four times greater than those observed for the East U.S. The lower N/TD ratios, the poorer crudes, and the relatively higher levels of Jet A demand made it more difficult to make jet fuel in the West than in the East.

TABLE 32

PERCENTAGE OF JET FUEL DEMAND ACHIEVABLE FOR WEST U.S.

Study Fuel	Full Participation TF-1	Full Participation TF-4	Full Participation TF-1A	Limited Participation TF-1	Limited Participation TF-4	Limited Participation TF-1A
1990	100	100	100	-	-	-
2000	94	100	100	71	76	100
2010	79	86	100	59	64	100

TABLE 33

ANNUAL COST SAVINGS FOR WEST U.S.
$ Million/yr

BASIS: TF-1

	Participation	TF-2	TF-4A	TF-5
1985	Full	70.9	67.9	73.5
	Limited (4/5)	71.7	69.2	78.7
	Limited (3/4)	111.1	111.2	122.0
1990	Full	136.0	138.6	147.7
2000	Full	Demand cannot be met with TF-1.		
2010	Full	Demand cannot be met with TF-1.		

BASIS: TF-1A

	Participation	TF-2	TF-4A	TF-5
2000	Full	0.4	15.0	16.5
	Limited (3/4)	1.6	12.0	15.8
2010	Full	1.7	4.3	6.1
	Limited (3/4)	1.8	0.6	3.0

In 1985, as participation was reduced, annual cost savings increased. Limiting participation had the same effect on the model as increasing Jet A demand level since a relatively smaller volume of crude was available to make the same volume of jet fuel. Increasing Jet A demand made Jet A more costly to produce to TF-1 quality and the potential for savings greater with property relaxation. The increase in savings was not sizable until participation fell below 4/5. As participation approached 3/4, both the cost to produce jet fuel and the savings from property relaxation increased sharply.

Cost savings due to property relaxation increased from 1985 to 1990 as the N/TD ratio decreased and demand for Jet A increased. In both 1985 and 1990 the level of cost savings for all relaxations was approximately equivalent, with a slight advantage for TF-5. Note that the producibility studies for the West U.S. showed that the inclusion of cracked stocks (TF-2) was almost always more effective than property relaxation in increasing yield.

As noted above, TF-1 could not meet jet fuel demand in 2000 and 2010. The base fuel used for these years was TF-1A. Also, TF-4A replaced TF-4. By allowing hydrocrackate into the jet pool, the refineries realized greater flexibility to blend jet fuel. This overcame the shortage of virgin kerosene for meeting jet fuel volume. The base case fuel TF-1A closely resembled TF-2 in composition. Although TF-2 could contain cracked stocks from all cracking types (catalytic, thermal and hydrocracking) hydrocracked stocks constituted the vast majority of the cracked stocks used in TF-2. Since the two fuels were nearly identical, savings with TF-2 were negligible in 2000 and 2010. Cost savings with TF-4A and TF-5 were also very small.

4.3.2 - Cost Savings per Unit Volume

Table 34 shows the savings expressed on a unit volume basis. For 1985 and 1990 average cost savings for the West U.S. were 4 to 12 times greater than the corresponding savings for the East U.S.

For 2000 and 2010, average cost savings using the hydrocracked fuels as a basis were very slight. Nevertheless, there are advantages in the use of the relaxed property fuel (TF-4) in reducing the required investment in jet fuel hydrocracking. This can be shown by examples based on the year 2000 cases. Table 35 lists calculated investments in jet fuel hydrocracking processes with several study fuels. For full participation, the use of TF-1A as formulated by the model requires the greatest quantity of hydrocrackate and a process investment of $120 million. With TF-1, 94% of the required jet fuel demand is met with the virgin component fuel (Table 32). Makeup of the shortfall reduces the hydrocracking investment to $20 million. With TF-4, all demands are met with virgin stocks and no jet hydrocracking is necessary.

TABLE 34

AVERAGE COST SAVINGS FOR WEST U.S.

BASIS: TF-1

		TF-2		TF-4		TF-5	
	Participation	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon
1985	Full	5.66	2.1	5.41	2.0	5.85	2.2
	Limited (4/5)	5.72	2.2	5.53	2.1	6.29	2.4
	Limited (3/4)	8.87	3.4	8.87	3.4	9.75	3.7
1990	Full	9.18	3.5	9.31	3.5	9.94	3.8
2000	Full	Demand cannot be met with TF-1.					
2010	Full	Demand cannot be met with TF-1.					

BASIS: TF-1A

		TF-2		TF-4A		TF-5	
	Participation	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon
2000	Full	0.03	0.01	0.88	0.3	0.94	0.4
	Limited (3/4)	0.07	0.03	0.50	0.2	0.69	0.3
2010	Full	0.06	0.02	0.25	0.1	0.31	0.1
	Limited (3/4)	0.06	0.02	0.03	0.01	0.13	0.05

TABLE 35

HYDROCRACKING INVESTMENT PROJECTED FOR WEST U.S., 2000

	HYDROCRACKING INVESTMENT, $ Million/yr	
	Full Participation (100% Crude Available)	Limited Participation (75% Crude Available)
TF-1A	120	290
TF-1 (Max Virgin)	20	210
TF-4 (Max Virgin)	0	170

If limited participation of 75% is assumed, there are demand shortfalls even with TF-4. Table 35 shows that hydrocracking investment is required with all the fuels, but the TF-1A cost of $290 million is reduced to $210 million with TF-1 and to $170 million with TF-4.

4.3.3 - Marginal Costs

Marginal costs for the West U.S. in four study years are presented in Table 36 for the same four products that were shown in the East U.S. The same trends are apparent. With declining N/TD ratio, the marginal costs of naphtha based products such as gasoline declined and the marginal costs of distillate products such as jet fuel and diesel increased. RSFO generally remained stable with time.

As in the East, relaxation of jet fuel properties reduced the jet fuel-diesel cost differences. The high cost difference between Jet A and diesel in the 1985 limited participation and 1990 full participation cases illustrate a stressed situation in which the West is struggling to meet Jet A demand. In such cases, the marginal costs in the linear program become unrealistically high. The average costs of Jet A were, however, reasonable.

4.3.4 - Jet Fuel Compositions and Critical Properties

In the West U.S., where four crude blends were available, the model always selected the highest conversion refinery available to process a given crude. Thus, high conversion refineries were used for the low sulfur, medium sulfur heavy and high sulfur heavy crudes. The low conversion refinery was used for the medium sulfur light crude which was not made available to the high conversion refinery. The high sulfur heavy hydroskimmer, which was economically viable in the East because of the need for asphalt, was not in the West. The high conversion refineries were always selected because they offered the greatest number of processing options, including operation in the low conversion mode.

The Table arrangement is similar to those of Tables 25 to 28 for the East U.S. Tables 37-40 show the crudes and blendstocks used to prepare 1985, 1990, 2000, and 2010 West U.S. jet pools. The discussion which follows emphasizes 1985 and 2010 since these contain the greatest contrasts.

In Table 37 (1985 Limited Participation), it can be seen that, unlike the East where low sulfur crude predominated, all of the available crudes were used to make TF-1. The poorer crudes had to be used in order to meet the volume of jet fuel required. Since the other crudes had kerosenes that were high in aromatics, a significant amount of aromatics extraction was required to meet the aromatics target for TF-1. The high sulfur heavy crude required aromatics extraction to meet smoke point rather than aromatics specifications.

TABLE 36

MARGINAL COSTS FOR WEST U.S.

		1985		1990			2000		2010	
Full Participation		$\$/m^3$	$/gallon	$\$/m^3$	$/gallon		$\$/m^3$	$/gallon	$\$/m^3$	$/gallon
TF-1	Gasoline	243.6	0.92	228.1	0.86	TF-1A	234.5	0.39	218.5	0.83
	Jet Fuel (Jet A)	264.1	1.00	348.2	1.32		268.9	1.02	278.4	1.05
	Diesel	254.2	0.96	246.9	0.93		263.2	1.00	275.5	1.04
	RSFO	243.0	0.92	230.3	0.87		242.5	0.92	240.4	0.91
	Jet - Diesel	9.9	0.04	101.3	0.39		5.7	0.02	2.9	0.01
TF-5	Gasoline	244.1	0.92	238.6	0.90	TF-5	228.8	0.37	215.8	0.82
	Jet Fuel	255.8	0.97	260.3	0.98		271.6	1.03	279.9	1.06
	Diesel	253.9	0.96	257.7	0.98		268.3	1.02	277.5	1.05
	RSFO	243.0	0.92	242.1	0.92		241.3	0.91	241.9	0.92
	Jet - Diesel	1.9	0.01	2.6	0.01		2.3	0.01	2.4	0.01
Limited Participation										
TF-1	Gasoline	230.9	0.87	-	-	TF-1A	229.5	0.87	217.4	0.82
	Jet Fuel (Jet A)	347.3	1.31	-	-		274.3	1.04	281.8	1.07
	Diesel	242.8	0.92	-	-		268.5	1.02	279.4	1.06
	RSFO	230.9	0.37	-	-		242.3	0.92	242.1	0.92
	Jet - Diesel	104.5	0.39				5.3	0.02	2.4	0.01
TF-5	Gasoline	241.7	0.92	-	-	TF-5	227.4	0.86	217.1	0.82
	Jet Fuel	256.9	0.97	-	-		274.0	1.04	281.9	1.07
	Diesel	254.6	0.96	-	-		270.1	1.02	279.7	1.06
	RSFO	243.0	0.92	-	-		242.2	0.92	242.1	0.92
	Jet - Diesel	2.3	0.01				3.9	0.02	2.2	0.01

TABLE 37

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES WEST U.S. - 1985 LIMITED PARTICIPATION, VOL%(1)

TF-1	Low Sulfur	Med. Sulfur Light	Med. Sulfur Heavy	High Sulfur Heavy
Kerosene	16.8	10.5	31.2	15.6
Gas Oil	1.5	0.3	0.8	0.3
Raffinate		3.7	3.5	15.8
	18.3 (F)	14.5 (A)	35.5 (A)	31.7
TF-2				
Kerosene	15.6	0.6	34.6	10.2
Gas Oil	1.0			
Raffinate		0.3		
Hydrocrackate	2.5		20.8	12.8
Cat Crackate	1.6			
	20.7 (F,A)	0.9 (A)	55.4 (A)	23.0
TF-4				
Kerosene	16.8	11.9	35.6	34.6
Gas Oil	1.1			
	17.9 (F)	11.9	35.6	34.6
TF-5				
Kerosene	12.2	4.5		34.3
Gas Oil	1.7			8.4
Hydrocrackate	2.4	2.3	22.3	7.6
Cat Crackate	3.4		0.8	0.1
	19.7 (F)	6.8	23.1	50.4

Notes:

(1) Critical properties are: (F) = Freezing Point
(A) = Aromatics

TABLE 38

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES WEST U.S. - 1990 FULL PARTICIPATION, VOL%(1)(2)

TF-1	Low Sulfur	Med. Sulfur Light	Med. Sulfur Heavy	High Sulfur Heavy
Kerosene	15.4	10.6	30.7	16.2
Gas Oil	1.3	0.3	0.8	0.3
Raffinate		4.5	3.4	16.5
	16.7 (F)	15.4 (A)	34.9 (A)	33.0
TF-2				
Kerosene	13.3	2.0	32.0	12.2
Gas Oil	0.7			
Hydrocrackate	0.9	1.0	21.3	15.3
Cat Crackate	0.8		0.5	
	15.7 (F)	3.0	53.8	27.5
TF-4				
Kerosene	11.2	16.1	35.0	35.7
Gas Oil	0.8	0.8		0.4
	12.0 (F)	16.9 (F)	35.0	36.1
TF-5				
Kerosene	0.3	0.9	27.0	35.7
Gas Oil	0.4	1.3		11.3
Hydrocrackate				12.6
Cat Crackate	1.4	2.5	2.8	3.8
	2.1 (F)	4.7 (F,A)	29.8	63.4 (F)

Notes:

(1) Critical properties are: (F) = Freezing Point
(A) = Aromatics

(2) Full participation data only available since demand could not be met with limited participation.

TABLE 39

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES WEST U.S. - 2000 LIMITED PARTICIPATION, VOL%(1)

TF-1A	Low Sulfur	Med. Sulfur Light	Med. Sulfur Heavy	High Sulfur Heavy
Kerosene	8.0	5.8	18.7	16.4
Gas Oil	0.4	0.1	3.0	
Hydrocrackate		3.1	24.5	20.0
	8.4 (F)	9.0	46.2 (F)	36.4
TF-2				
Kerosene	7.8	5.6	15.0	16.9
Gas Oil	0.4	0.1	0.9	1.0
Hydrocrackate		3.1	23.6	21.6
Cat Crackate	0.2	0.1	0.6	
Coker			3.1	
	8.4 (F,A)	8.9	43.2 (F)	39.5
TF-4A				
Kerosene	1.7	6.5	9.1	24.4
Gas Oil	0.1	0.6	3.5	11.1
Hydrocrackate		2.4	22.5	18.1
	1.8 (F)	9.5 (F)	35.1 (F)	53.6 (F)
TF-5				
Kerosene		5.7	9.4	23.4
Gas Oil		0.1	1.3	11.3
Hydrocrackate		0.8	23.3	19.1
Cat Crackate		1.3	0.6	
Coker			3.7	
		7.9 (F)	38.3 (F)	53.8 (F)

Notes:

(1) Critical properties are: (F) = Freezing Point
(A) = Aromatics

TABLE 40

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES WEST U.S. - 2010 LIMITED PARTICIPATION, VOL%(1)

TF-1A	Low Sulfur	Med. Sulfur Light	Med. Sulfur Heavy	High Sulfur Heavy
Kerosene		5.1	7.4	20.2
Gas Oil		0.4		6.7
Hydrocrackate		3.2	28.7	28.3
		8.7	36.1	55.2
TF-2				
Kerosene		3.8	2.3	20.4
Gas Oil			0.4	2.4
Hydrocrackate		2.2	29.8	29.1
Cat Crackate		0.2	3.6	
Coker			3.6	5.2
		6.2 (A)	36.7 (F)	57.1 (A)
TF-4A				
Kerosene		5.0	5.1	25.0
Gas Oil		0.2		7.9
Hydrocrackate		3.2	28.6	25.0
		8.4	33.7	57.9 (F)
TF-5				
Kerosene		2.8		21.0
Gas Oil		0.5	1.1	5.2
Cat Crackate			0.6	0.4
Hydrocrackate		3.2	28.6	27.3
Coker			3.5	5.8
		6.5 (F)	33.8	59.7 (F)

Notes:

(1) Critical properties are: (F) = Freezing Point
(A) = Aromatics

The 1985 TF-2 pool added hydrocracked kerosene to eliminate almost all of the aromtics extraction necessary to meet the aromatics requirement. In contrast to the East, a larger portion of the pool was hydrocracked kerosene since more naphtha hydrocracking was available in the West. The TF-4 pool could use virgin kerosenes almost exclusively. The TF-5 pool replaced kerosenes with hydrocracked stocks for the most part. Again, in contrast to the East U.S., where only low sulfur crudes were used in making jet fuel, all crudes contributed to the pool composition. Only the streams produced from the low sulfur crude were freezing point critical.

Table 38 gives the pool composition for 1990 full participation because there were no limited participation runs for that year.

In 2000 TF-1A containing hydrocrackate replaced all virgin TF-1 (Table 39). The quantity of jet fuel prepared from low sulfur crude continued to decrease, responding to its reduced availability with time, the processing options available, the extent of relaxation and its use in the other distillates. None of this crude was used to prepare TF-5.

By 2010 (Table 40), no jet fuel was prepared from low sulfur crude. Since TF-1A included a large portion of hydrocracked stocks, which had good aromatics and freezing point properties, there were no critical properties for this pool. The TF-2 pool differed from that in the East in that the higher aromatics content of the virgin kerosenes made aromatics critical rather than freezing point.

Freezing point was critical for the large fraction of TF-4A produced from the high sulfur heavy crude. This resulted from the addition of gas oil to that pool, which reduced the requirement for more expensive hydrocracker kerosene. Most of the TF-5 pool was freezing point critical. Like the TF-4A pool, with aromatics not being limiting, gas oil was added to the pool until freezing point was critical in order to minimize the need for hydrocracker kerosene.

The percentage of the jet fuel pool which was critical in freezing point and aromatics for limited and full participation in the West are presented in Tables 41 and 42, respectively.

The primary difference between the East U.S. (Tables 29 and 30) and West U.S. jet pools was the effect of the higher aromatics content of the West crudes. In the 1985 limited participation TF-1 and TF-2 pools, aromatics were critical in a greater percentage of the pools in the West (50-77%) than in the East (32-33%). However, after 2000, the use of the TF-1A fuel eliminated aromatics as a critical property. With TF-2, however, the use of the high aromatics virgin kerosenes in the West resulted in a larger percentage of the pool being aromatics critical than in the East: 63% in the West and 47% in the East in 2010.

TABLE 41

PERCENT OF POOL CRITICAL FOR PROPERTY - WEST U.S. (LIMITED PARTICIPATION)

	TF-1*		TF-2		TF-4		TF-5	
	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics
1985	18	50	21	77	18	0	20	0
1990	-	-	-	-	-	-	-	-
	TF-1A				TF-4A			
2000	54	0	51	8	100	0	100	0
2010	0	0	37	63	58	0	66	0

* For 2000 and 2010, TF-1A and TF-4A were used.

TABLE 42

PERCENT OF POOL CRITICAL FOR PROPERTY - WEST U.S. (FULL PARTICIPATION)

	TF-1*		TF-2		TF-4*		TF-5	
	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics
1985	24	59	27	27	23	0	27	0
1990	17	50	16	16	29	0	70	5
	TF-1A				TF-4A			
2000	12	39	12	39	100	0	100	0
2010	58	0	60	0	56	0	100	0

* For 2000 and 2010, TF-1A and TF-4A were used.

The TF-4, TF-4A, and TF-5 relaxations eliminated aromatics as a critical requirement in both the East and the West. However, as gas oil was blended into the pool to make volume and replace the kerosene, the jet pool became freezing point critical.

4.3.5 - Qualities of Other Products

As Jet A properties were relaxed, there was an effect on diesel and heating oil because jet relaxation resulted in a redistribution of blendstocks between jet fuel and the other distillate pools. For 1985 and 1990 cases, when TF-1 was relaxed to TF-2 or TF-5, significant amounts of hydrocracked stocks moved from diesel and heating oil to the jet fuel pool. Virgin kerosene moved out of jet fuel to replace the hydrocracked material in the diesel and heating oil pools. The same poor aromatics and freezing point characteristics of virgin distillate blendstocks from West crudes that adversely impacted on jet properties also affected diesel and to a lesser extent heating oil. Diesel cetane and cloud point were the most prevalent limiting properties in the pre-2000 period. In the later years, when hydrocracked stocks were allowed in the base period fuel (TF-1A), there was generally less shifting of material between Jet A and the other distillate pools when properties were relaxed. Many properties were critical for both diesel and heating oil, including cetane, cloud point, volatility and flash point. The number of distillate pools with limiting properties was not a significant function of the extent of relaxation.

As in the East, the Jet A relaxations in the West had essentially no impact on the critical qualities of either the gasoline or fuel oil pools because the volume of potential jet fuel blendstocks in the gasoline or fuel oil pools were small relative to the total volume of those pools. Gasoline was limited by research octane and vapor lock index in all cases and, in a few cases, by motor octane.

Low sulfur fuel oil was both sulfur and viscosity limited in all cases. Regular sulfur fuel oil was viscosity limited in all cases. RSFO was sulfur limited in the East but not in the West because vacuum bottoms in the West were lower in sulfur than those in the East.

4.3.6 - Processing Implications

Jet fuel property relaxation had some impact on the utilization of existing capacity as well as the investment for new facilities. For most processes, however, this impact tended to be small. The significant impact associated with the use of hydrocrackate in TF-1A and TF-4A was discussed in Section 4.3.2.

As expected, jet fuel property relaxation had the greatest impact on processes related to Jet A blendstocks. These processes included mild kerosene hydrotreating (H/T), aromatics extraction, severe kerosene H/T, and jet hydrocracking.

Aromatics extraction and severe hydrotreatment were required when TF-1 was produced in 1985 and 1990. Except for a small amount used when producing TF-2 in 1985, these aromatics reduction processes were not required when relaxed property jet fuels were produced. Elimination of these processes caused the high cost savings calculated for TF-2 through TF-5.

In the 2000 TF-1A full participation case, investment was made for jet hydrocracking. When properties were relaxed, the amount of jet hydrocracking was reduced. In the 2000 limited participation case, investment for mild kerosene H/T was made for TF-1A but was backed out when properties were relaxed. By 2010 increased investment for jet hydrocracking was required to meet Jet A demand. When properties were relaxed, cost savings were realized by backing out mild kerosene H/T and/or distillate H/T.

4.3.7 - Energy Savings

Jet fuel property relaxation resulted in only limited energy savings as the data in Table 43 show. These savings were similar for all three relaxations.

The total feedstock energy content is shown for both the full and limited participation cases. Energy content tracks the forecast refining industry demands. These data have been shown for only the TF-1 and TF-1A cases since differences between cases were small.

Plant fuel is also shown for the same cases. It was roughly 7% of feed on an energy content basis. Plant fuel increased from 1985 to 1990 and from 2000 to 2010 because distillate production became more difficult with time. Plant fuel dropped from 1990 to 2000 because of the change from TF-1 to TF-1A since the heat requirement for aromatics reduction in TF-1 was eliminated.

Fuel savings show how much plant fuel was saved in the TF-5 case relative to the TF-1 cases. Fuel savings for the other relaxation levels have not been shown since these savings were similar irrespective of the relaxation level chosen. Relative savings were higher in 1985 and 1990 than in 2000 and 2010 because jet fuel was more difficult to make with TF-1 than TF-1A.

4.4 SUMMARY OF COST SAVINGS RESULTS

Key findings of the cost savings calculations to meet future jet fuel demands in the East and West regions of the United States are as follows:

TABLE 43

ENERGY USE SUMMARY - WEST U.S.

	1985	1990	2000	2010
Full Participation				
Feedstock Energy Content(1)				
(TJ/d)	13,816	12,845	13,167	12,924
Plant Fuel(1)				
(TJ/d)	937	905	899	931
(% of Feed)	6.8	7.0	6.8	7.2
Fuel Savings(2)				
(TJ/d)	17.0	22.4	16.4	4.1
(% of Feed)	0.12	0.17	0.12	0.03
(% of Fuel)	1.8	2.5	1.8	0.4
Limited Participation(3)				
Feedstock Energy Content(1)				
(TJ/d)	10,714	---	10,355	10,239
Plant Fuel(1)				
(TJ/d)	727	---	733	733
(% of Feed)	6.8	---	7.1	7.2
Fuel Savings(2)				
(TJ/d)	19.2	---	11.3	0.8
(% of Feed)	0.18	---	0.11	0.1
(% of Fuel)	2.6	---	1.5	0.01

Notes:

(1) Represents TF-1(A) Case (values in tera joules/calendar day).
(2) Equals fuel savings for TF-5 relative to TF-1(A).
(3) Assumed participation of 3/4. Values apply only to those refineries making jet fuel.

- Demand could be met in the East U.S. with baseline, virgin component jet fuel, although by 2010, appreciable aromatics reduction is required.
- Demand could not be met in the West U.S. with baseline, virgin component jet fuel in 2000 and 2010. The use of 40 to 60 volume percent hydrocracked kerosene as a jet fuel component is required.
- Cost savings were greater in the West U.S. than in the East U.S. due to poorer crudes, higher jet fuel yield requirements, and lower N/TD ratios.
- Both relaxation of properties and inclusion of cracked stocks contributed toward cost savings. In the East, property relaxation resulted in slightly greater savings than using cracked stocks in baseline property jet fuel.
- Quantitative annual cost savings for the entire United States (TF-5 substitution, limited participation) ranged from $186 million in 1985 to $256 million in 1990, expressed in constant 1981 dollars.

5. PRODUCIBILITY AND COST SAVINGS STUDIES FOR CANADA

This report section describes the increases in production and decreases in cost that can result from relaxation of jet fuel properties in Canada. The subsections that follow present:

1. The bases used for the Canadian investigations.
2. The effect of relaxation on producibility.
3. The effect of relaxation on cost.

5.1 BASES USED FOR CANADA

5.1.1 - Regions Studied

Much crude processed in eastern Canada is imported, and most crude processed in western Canada is domestic. The properties of many petroleum products sold in the east differ from those sold in the west. For modeling purposes, Canada was divided into two regions, each of which had separate refinery-crude models and product-demand and quality schedules. The provinces included in each region are shown in Figure 10 and are listed below.

EAST CANADA	WEST CANADA
Newfoundland	Alberta
New Brunswick	British Columbia
Nova Scotia	Manitoba
Prince Edward Island	Northwest Territories
Quebec	Ontario
	Saskatchewan
	Yukon

5.1.2 - Product Demand Forecasts

Product-demand forecasts for Canada were obtained from the projections of the Canadian National Energy Board(13), supplemented by information from Canada's Bureau of Energy, Mines, and Resources. The latter data were furnished through the cooperation of the National Research Council of Canada.

Canadian modeling was undertaken for 1990 and 2000. The regional Canadian product demands for these two future time periods are shown in Table 44. These projections were used directly for the cost savings calculations and indirectly to establish product Gasoline/Distillate (G/D) ratios for the producibility studies. As in the U.S., distillate was defined as diesel plus heating oil and excluded jet fuel. As can be seen from Table 44, the G/D ratio was projected to increase

FIGURE 10
CANADIAN REGIONS

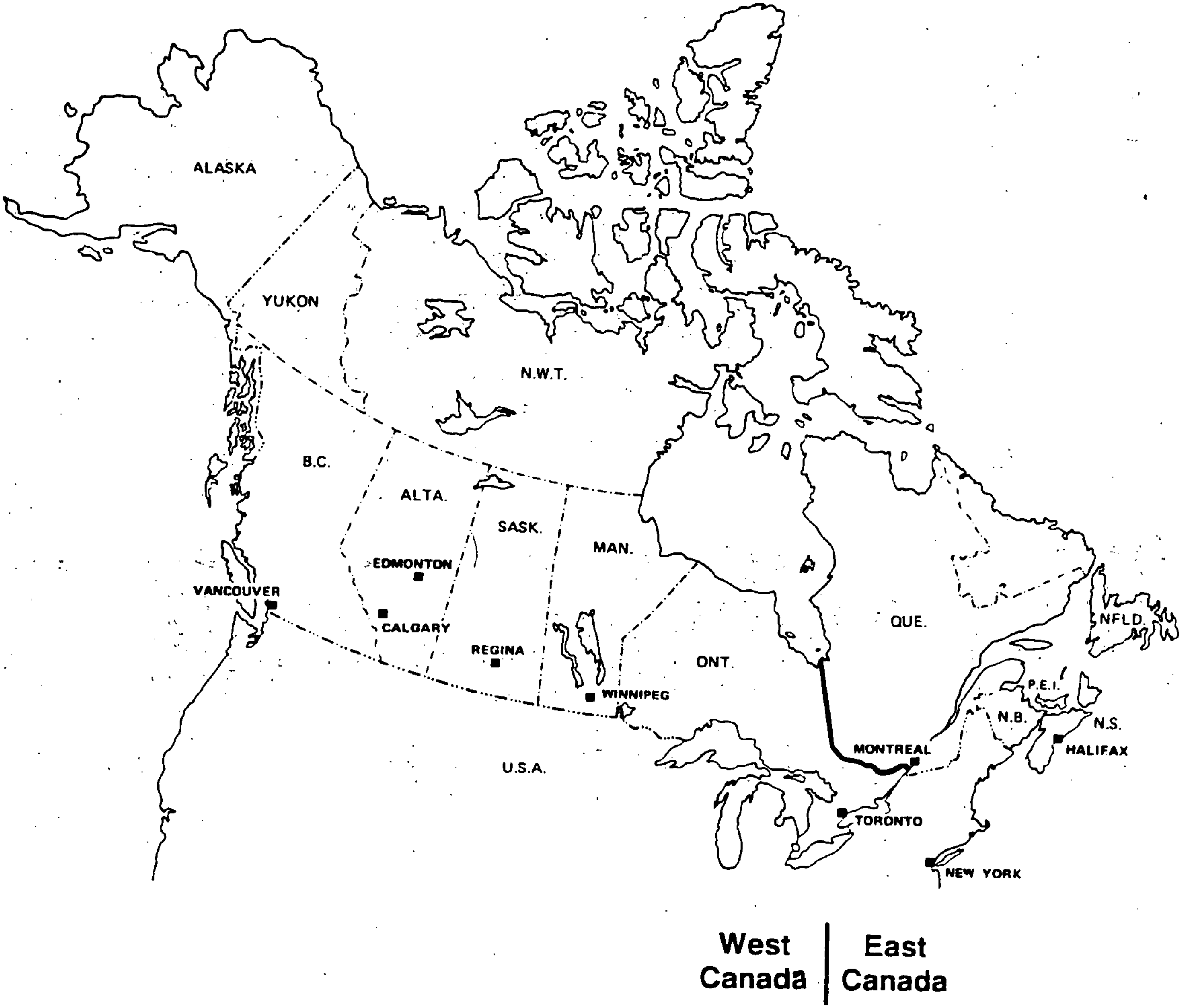


TABLE 44

PRODUCT DEMANDS - CANADA

1000 m^3/d

	1990		2000	
	East	West	East	West
LPG	1.9	4.4	2.2	4.8
Chem Feed	4.4	8.9	4.9	9.5
Regular Gasoline	21.8	52.3	22.1	55.3
Premium Gasoline	5.6	13.7	5.7	14.5
Jet A/A-1	3.3	5.7	4.4	7.0
Jet B	0.9	4.1	1.3	5.1
Diesel	14.3	36.1	17.3	49.1
Heating Oil	10.3	7.2	4.6	8.3
Lubes	0.8	2.4	0.9	3.0
Low Sulfur Fuel Oil (LSFO)(1)	0.5	0.3	0.5	0.3
Regular Sulfur Fuel Oil (RSFO)	11.3	8.6	11.0	6.0
Asphalt	3.3	7.0	4.0	8.9
Gasoline/Distillate Ratio	1.1	1.5	1.3	1.2
Total Naphtha/ Total Distillate(1) Ratio	1.2	1.6	1.3	1.3

Notes:

(1) LSFO $\leq$ 1.25% sulfur.
(2) Total naphtha includes chem feed, regular and premium gasoline, and Jet B; total distillate includes Jet A/A-1, diesel and heating oil.
(3) Cubic meters/d x 6.2893 = bbl/d.

with time in the East, from 1.1 to 1.3, and decrease with time in the West, from 1.5 to 1.2. These G/D ratios are similar to the East U.S. G/D ratio of 1995. The G/D ratio affects the cost and producibility of jet fuel. Lower product G/D ratios tend to increase the cost of producing jet fuel since there is increased competition for the distillate cuts.

Even more important than G/D as a factor affecting study results is the product Naphtha/Total Distillate ratio. The N/TD ratios in Table 44 include naphtha-based Jet B and chemical feedstocks as well as gasoline in the numerator. Since Jet B and chemical feedstocks were minor components of the Canadian product slate, the N/TD ratio and its change with time differed little from the G/D ratio.

5.1.3 - Kerosene Jet Fuel Properties

The jet fuel properties used for Canada are presented in Table 45. The thrust of the Canadian portion of this study was to investigate increasing jet fuel aromatics levels associated with the expanded use of synthetic crude from Canadian oil sands. Also considered was a relaxed flash point in which some volatile stocks previously used in gasoline production could be used in jet fuel to increase yield. The properties for the base and relaxed fuels used were developed by the National Research Council of Canada.

The base fuel, CF-1, represented the production specification corresponding to kerosene jet fuel consumed in Canada (ASTM D1655 with the reportable extensions of aromatics and smoke point). The freezing point value was an average of Jet A-1 (specification maximum of -47°C) consumed in the winter and Jet A (specification maximum of -40°C) used in the summer. CF-2 represented a relaxation of the flash point, aromatics and smoke point from the CF-1 property limits and permitted the inclusion of cracked stocks into the pool. Freezing point was not varied. Some Canadian refineries blend hydrocracked stocks into jet fuels, considering these streams equivalent in quality to virgin (unprocessed) streams. The refinery model calculations, however, excluded hydrocracked as well as other cracked streams from CF-1. In addition, for the study, the synthetic crude blendstocks were considered as virgin streams. In actuality, Canadian oil sands are processed in a coking unit at the production facility prior to transport as refining feedstocks.

Relative to the base U.S. study fuel, TF-1, the base period Canadian fuel, CF-1, was higher in aromatics, poorer in smoke point, lower in flash point and had a higher sulfur level. Relative to the most relaxed U.S. study fuel, TF-5, the relaxed Canadian fuel, CF-2, had lower aromatics, a better smoke point, a worse flash point and a slightly higher sulfur level.

TABLE 45

PROPERTIES OF CANADIAN TURBINE FUELS

	Specification CAN 2-3.23M81	Base Kerojet Fuel CF-1	Relaxed Kerojet Fuel CF-2	Relaxed Kerojet Fuel CF-1A	Relaxed Kerojet Fuel CF-2A
Flash Point, °C (min)	33	40	35	40	35
Freezing Point, °C (max)	-47(1)	-45	-45	-45	-45
Aromatics, vol% (max)	22	23	28	23	28
Smoke Point, mm (min)	25	19	16	19	16
Sulfur, wt% (max)	0.2	0.3	0.3	0.3	0.3
Density, g/cc (16°C)					
(max)	0.84	0.84	0.84	.84	.84
(min)	0.775	0.775	0.60	.775	.60
Cracked Stocks Allowed		No	Yes	Yes	No

Note:

(1) -47°C November through April, -40°C May through October.

Limited calculations were also conducted with the additional jet fuels CF-1A and CF-2A. CF-1A had the same properties as CF-1, except that cracked stocks were permitted; CF-2A had the same properties as CF-2, except that cracked stocks were excluded.

5.1.4 - Properties of Other Major Refinery Fuels

The properties for diesel and heating oil are presented in Table 46. There were regional differences in sulfur, cetane, cloud point and density. Gasoline properties are shown in Table 47. Although leaded gasolines are now extensively consumed in Canada, current indications are that only unleaded gasolines will be produced during the study period. Fuel oil properties are shown in Table 48. While two grades are shown, most of the fuel oil produced in Canada is the high sulfur grade.

5.1.5 - Crude Blends

Information on crudes currently used and anticipated to be used in Canada was obtained from Canada's Bureau of Energy, Mines and Resources through the cooperation of the National Research Council of Canada. Based on this information, projected crude slates were developed for the study periods and are shown in Table 49.

The models used for the U.S. East were used as the basis for the Canadian models. Modifications to these models were made to reflect the different yields and qualities of the Canadian crudes.

Synthetic crudes are anticipated to comprise a substantial fraction of the crude run by 2000 in both the East and West. This projection was based on Canadian national policies designed to minimize the importation of foreign crudes in favor of domestic production. The synthetic crudes were modeled using the assumption that these crudes will be produced from oil sands. In addition, it was assumed that production and yields will be similar to current operations in Canada. These are extraction of bitumen from oil sands, coking the bitumen, hydrotreating the coker products, and combining the hydrotreated coker products into a synthetic crude. Synthetic crude contained no 566°C+ (1050°F+) material and was similar to coker stocks from conventional crude operations. Coker stocks were thus used as a modeling basis, but any significant differences in qualities between those stocks and the synthetic crude stocks were incorporated in the models. A modeling limitation was that the gas oil from synthetic crude could not be processed in a jet hydrocracker. As in the U.S., only virgin gas oil could be jet hydrocracked. Synthetic crude could, however, be processed in the naphtha hydrocracker in the high conversion refinery.

TABLE 46

PROJECTED PROPERTIES FOR CANADIAN DIESEL FUEL AND HEATING OIL

	East		West	
	Diesel Fuel	Heating Oil	Diesel Fuel	Heating Oil
Sulfur, wt%	0.4	0.5	0.2	0.2
Cetane Number (min)	45	-	43	-
Flash Point, °C (min)	52	46	52	46
Viscosity @ 37.8 °C, cSt (min)	2.3	-	2.3	-
Cloud Point, °C (max)	-12	-11	-18	-16
Density, g/cc (16°C)	0.855	0.871	0.86	0.855

TABLE 47

PROJECTED PROPERTIES FOR CANADIAN GASOLINE

	Unleaded Regular	Unleaded Premium
Research Octane Number (RON) (min)	93	97
Motor Octane Number (MON) (min)	85	87
Octane Index(1) (min)	89	92
Reid Vapor Pressure, kPa (max)	100	100
Vapor Lock Index(2) (max)	16	16

Notes:

(1) Octane Index is defined as (RON + MON)/2
(2) Vapor Lock Index is defined as:
Reid Vapor Pressure + (0.13)(% Off at 70°C)

TABLE 48

PROJECTED PROPERTIES FOR CANADIAN RESIDUAL FUEL OIL

	Low Sulfur	High Sulfur
Sulfur, wt% (max)	1.25	2.8
Viscosity @ 50°C, cSt (max)	440	600

TABLE 49

CANADIAN CRUDE AND GAS LIQUIDS REQUIREMENTS(1)

1000 m^3/d

	1990	2000
East Canada		
Crudes		
Low Sulfur(2)	22.3	41.5
High Sulfur Light	42.6	2.1
High Sulfur Heavy	17.0	8.1
Synthetics	-	29.1
Gas Liquids	1.9	1.9
Total East Canada	83.8	82.7
West Canada		
Crudes		
Low Sulfur(2)	104.9	88.4
High Sulfur Heavy	15.9	27.7
Synthetics	34.7	63.0
Gas Liquids	7.6	7.6
Total West Canada	163.1	186.7
Total Canada	246.9	269.4

Notes:

(1) Represents total Canadian crude requirements. Only 75% of crude supplies in East Canada and 50% of crude supplies in West Canada were available for jet fuel production.

(2) Adjustable crude.

The categorization of crudes differed from that used in the U.S. in that no Canadian medium sulfur crude was defined and the low sulfur designation extended up to 1% sulfur vs. 0.5% in the U.S. Light crudes were those which contained up to 20% residuum (fraction boiling above 566°C) in Canada, compared to 15% in the U.S. The average properties of the crudes in each category are shown in Table 50. Some Canadian crude blends had higher sulfur levels and greater percentages of residuum than encountered in U.S. crudes, and one Canadian petroleum crude blend had a higher aromatics level than any U.S. crude blend. The Canadian petroleum crudes had generally higher N/D ratios than their U.S. counterparts. Synthetic crude possessed low sulfur, no 566°C+ residuum, and higher aromatics than any conventional Canadian or U.S. crude. The synthetic crude N/D ratio was 0.2, the lowest studied. Note, in contrast, the extremely high N/D for the proposed U.S. coal liquid feedstock (Table 8).

5.1.6 - Refinery-Crude Models

Canadian refinery process capacity in place at the end of 1982 is shown for the two regions in Table 51. This information was obtained from published sources and the Canadian Bureau of Energy, Mines, and Resources.

The Canadian refinery processes and flow sheets were analogous to those described for the U.S. The three types of refineries developed for the models in the U.S. study (hydroskimming, low conversion, and high conversion) are present in the Canadian refining industry, as summarized in Table 52. However, since hydroskimmers comprised such a small fraction of the refining capacity in Canada, they were omitted from the study. An adequate representation was made instead with only two refinery configurations.

Table 53 presents the refinery-crude combinations that were used to represent East and West Canada. As can be seen, in East Canada, low conversion refineries processed the low sulfur and high-sulfur light crudes. The high conversion refinery processed the high-sulfur heavy crude. In West Canada, the low conversion refinery processed the low sulfur crude, the high conversion refinery processed the high-sulfur heavy crude. Synthetic crude was available to all refinery types.

Because the models used for Canada were derived from those used in the U.S., a separate model verification run was not undertaken.

TABLE 50

PROPERTIES OF CANADIAN CRUDE BLENDS

East Canada	Wt% Sulfur	Vol% 560°C+ (1050°F+)	Vol% Aromatics in Kerosene Fraction	Crude Naphtha/Distillate Ratio
Low Sulfur	0.54	9.5	17.8	0.95
High Sulfur				
Light	1.64	15.8	20.3	0.75
Heavy	2.59	29.0	29.0	0.56
West Canada				
Low Sulfur	0.57	9.6	17.2	0.94
High Sulfur				
Heavy	2.96	27.7	16.6	0.57
Synthetic Crude	0.05	0	30.4	0.20

TABLE 51

CANADIAN REFINING CAPACITY - 1982, 1000 m^3/d

	East Canada	West Canada
Atmospheric Distillation	143.0	215.0
Vacuum Distillation	52.0	56.0
Catalytic Reforming	24.0	37.0
Cat Cracking	24.0	49.0
Hydrocracking	8.9	3.0
Coking	-	4.5
Visbreaking	3.3	1.4
Naphtha Hydrotreating	24.0	46.0
Distillate Hydrotreating	35.0	27.0
Gas Oil Hydrotreating	1.4	0.8
Alkylation	0.5	7.6
Naphtha Isomerization	0	0.5

TABLE 52

DISTRIBUTION OF CANADIAN REFINERY CAPACITY AMONG REFINERY TYPES

Refinery Types	East Canada		West Canada	
	Percent of Crude Run	Number of Refineries	Percent of Crude Run	Number of Refineries
Hydroskimming	14	2	4	4
Low Conversion	63	6	58	14
High Conversion	23	2	38	6
Totals	100	10	100	24

TABLE 53

CANADIAN REFINERY-CRUDE MODELS

	Low Conversion	High Conversion
East Canada		
Low Sulfur	X	
High Sulfur Light	X	
High Sulfur Heavy		X
West Canada		
Low Sulfur	X	
High Sulfur Heavy		X

Synthetic crude from oil sands was available to all of the refinery-crude models.

5.2 PRODUCIBILITY

5.2.1 - Introduction

The producibility determinations for Canada were undertaken using the same general methodology as was used in the U.S. The study investigated the effect of jet fuel property relaxation at specific Gasoline/Distillate ratios corresponding to the selected future time periods, as follows:

	1990	2000
East Canada	1.1	1.3
West Canada	1.5	1.2

While the U.S. G/D ratios decreased significantly with time, the Canadian G/D ratios changed only moderately. The East Canada G/D actually increased in the future.

As in the U.S., distillate was defined as diesel fuel plus heating oil. Jet fuel was considered to be a separate product. In East Canada distillate was composed of a 60/40 diesel/heating oil ratio at the low G/D and an 80/20 ratio at the high G/D. In West Canada, the distillate proportions were an 85/15 ratio for both G/D ratios. The differences reflected product demand projections and the sale of some diesel fuel as heating oil in Canada.

The total volume of gasoline plus distillate was fixed at 13500m^3/d (85000 bbl/d) which, after accounting for the production of other products, required the processing of approximately 15900m^3/d (100,000 bbl/d) of crude.

For the East Canada low G/D cases, about 8% of the crude run was synthetic crude to account for the possibility that, while the regional impact of synthetic crude may be negligible, any individual refinery might process small amounts of synthetic crude. In the East Canada high G/D runs, synthetic crude was increased to 35% of crude run. In the West, synthetic crude accounted for 21% and 34% at G/D ratios of 1.5 and 1.2, respectively. These values were based on Energy, Mines and Resources projections.

The marginal cost of producing CF-1 was set at a level of \$13.2/m^3 (5¢/gallon) higher than the marginal cost of diesel. This differential was the same as was used in the U.S. The jet fuel marginal cost established for CF-1 at each G/D was used for the relaxed property fuels as well. A marginal cost is the cost for producing the last production increment.

The blending components that were utilized most frequently to formulate the prime study fuels are summarized as follows:

CF-1 Kerosene (virgin and synthetic)
Raffinate from aromatics extraction
Gas oil
Heavy virgin naphtha

CF-2 Kerosene (virgin and synthetic)
Gas oil
Heavy virgin naphtha
Kerosene, distillate and naphtha from catalytic, thermal and hydrocracking

Blend stocks from cracking processes and high sulfur crudes were hydrotreated as appropriate.

The large volume of high aromatics kerosene from synthetic crude required that aromatics reduction processing be used to produce CF-1 in all but the East Canada low G/D cases, where synthetic crude constituted only 8% of crude run. Aromatics extraction was the lowest cost process available in the model for this purpose. Only small quantities of gas oil and heavy virgin naphtha were usually blended to CF-1, the former until freezing point became limiting, the latter until flash point became limiting. The use of naphtha was not feasible in the U.S. but was possible in Canada since Canadian fuels had lower flash points than those in the U.S. Decreasing the initial boiling point of the distillate fraction rather than using a naphtha cut might have resulted in greater producibility increases than found with flash point relaxation. The computer model did not have this capability, however.

Relaxation of aromatics and flash point to CF-2 levels permitted elimination of aromatics reduction processing. In addition to kerosenes from conventional and synthetic crudes, hydrocracker kerosene and distillate from cat cracking and coking and heavy naphtha from cat cracking were the most frequent choices to blend CF-2.

5.2.2 - East Canada Refineries

Producibility results are presented for Canada in two ways, similar to the presentation for the U.S., discussed in Section 3.2. Figure 11 shows the yield as the percentage of refinery crude input. Separate plots represent the producibility for the three East Canada refinery-crude models. The bar graphs within the plots compare results or the two study fuels at the two G/D ratios of 1.1 and 1.3, corresponding to 1990 and 2000. Table 54 compares producibility in the second way, on the basis of output volume, normalized with respect to the volume of CF-1 at a G/D of 1.1 for East Canada. The Table includes results for West Canada normalized with respect to CF-1 at a G/D of 1.3, to be discussed later in this Section.

FIGURE 11
JET FUEL YIELD BASED ON CRUDE RUN, EAST CANADA

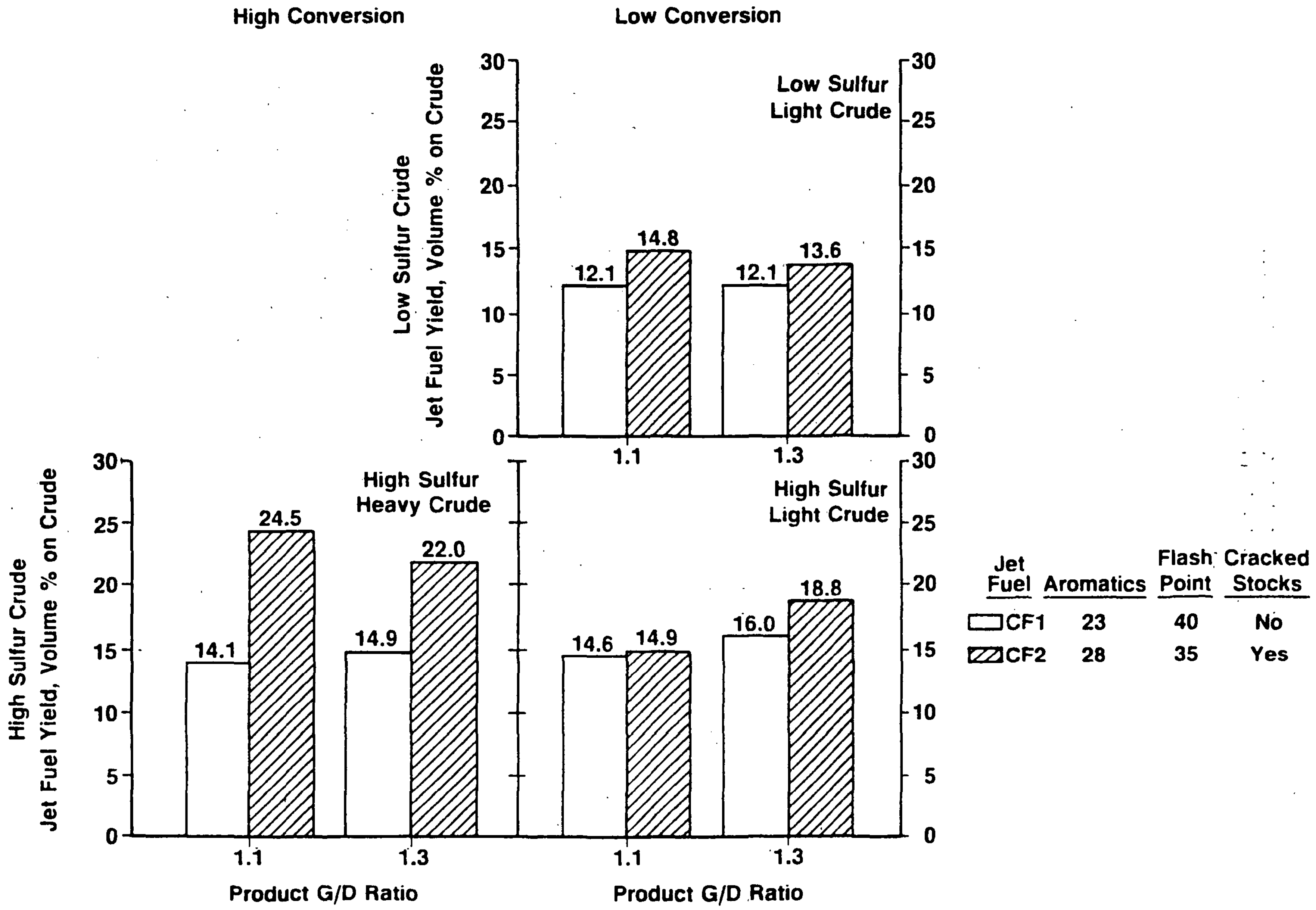


TABLE 54

RELATIVE JET FUEL VOLUME PRODUCED, CANADA

	East Canada							
G/D Ratio	1.1				1.3			
Jet Fuel	CF-1	CF-1A	CF-2	CF-2A	CF-1	CF-1A	CF-2	CF-2A
Low Sulfur - Low Conversion	1.00	1.20	1.30	1.00	0.95	1.05	1.10	0.95
High Sulfur Light - Low Conversion	1.00	-	1.05	-	1.10	-	1.30	-
High Sulfur Heavy - High Conversion	1.00	2.00	2.00	1.05	1.10	1.70	1.80	1.20

	West Canada							
G/D Ratio	1.5				1.2			
Low Sulfur - Low Conversion	1.00	-	1.35	-	0.90	-	0.95	-
High Sulfur Heavy - High Conversion	1.00	-	1.25	-	1.05	-	1.10	-

The regional average yield required to meet the jet fuel demand in East Canada is projected to be 4.0% in 1990 and 5.4% in 2000. Note that the yields of the individual refinery-crude models in Figure 11 are all well above this projected average.

Producibility results for East Canada may be examined in more detail by discussing the calculated blending for the optimized solutions. Consider first the low conversion refinery supplied with low sulfur crude (upper right plot in Figure 11). The baseline CF-1 yield at 1.1 G/D was limited by both freezing and flash point. Relaxation to CF-2 increased yield since hydrocrackate was added to the jet pool and slightly more crude was run producing additional kerosene.

At the high G/D ratio, the jet pool was limited by aromatics, flash, smoke and freezing points. The refinery at this G/D used more catalytic cracking and did not invest in as much jet hydrocracking as the low G/D CF-1 case because of a higher demand for gasoline and greater use of synthetic crude (35% vs. 8%), which had a lower naphtha content than the low sulfur crude it replaced. Investment in aromatics extraction was required since the aromatics level and smoke point of the synthetic crude kerosene did not meet the jet targets. Relaxing jet properties to the CF-2 level allowed the jet fuel pool to meet the relaxed smoke and aromatics targets without investment in aromatics extraction. The yield of jet fuel increased slightly because of the addition of jet hydrocracker kerosene, cat naphtha and cat cracker distillate to the jet pool. This added disposition for the catalytic cracker products also allowed additional crude to be processed. The increase in producibility at this G/D ratio was less than that at the low G/D ratio because at the higher ratio more cat cracking was needed to meet the requirements of naphtha-based products.

For the high conversion refinery supplied with high sulfur, heavy crude (lower left plot in Figure 11), yield and yield improvements were greater than those for the previously-discussed low conversion example. Investment in aromatics extraction was required at both G/D cases for the baseline, CF-1, fuel. Less jet hydrocracking was required since the lower crude N/D ratio of the high sulfur heavy crude, along with the added bottoms conversion capacity in this refinery, provided the required volume of distillate products. In fact, no hydrocracking was necessary at the high G/D.

Relaxing jet fuel to the CF-2 level increased jet fuel yield substantially, about 50 to 70 percent. The high conversion refinery blended coker products as well as other process stocks into the CF-2 jet fuel. As in the low conversion case, the yield increase at the high G/D was less than that at the low G/D because of the naphtha requirements that diverted jet fuel gas oil components to the cat cracker and hydrocracker.

For the low conversion refinery supplied with high sulfur, light crude (lower right plot in Figure 11), yields were greater than in the comparable low sulfur crude case because the high sulfur light crude had a lower crude N/D ratio. Therefore, to meet naphtha-based product demand, the crude run was larger, the difference being reflected in the higher jet yield. At the low G/D, relaxation to CF-2 did not have a significant effect since the low crude N/D ratio required that gas oil be used as cat cracker feed to supply the naphtha-based products rather than as jet hydrocracker feed. At the high G/D, relaxation to CF-2 permitted a moderate increase in yield because the refinery could shift kerosene from diesel to jet fuel.

5.2.3 - East Canada Sensitivity Cases

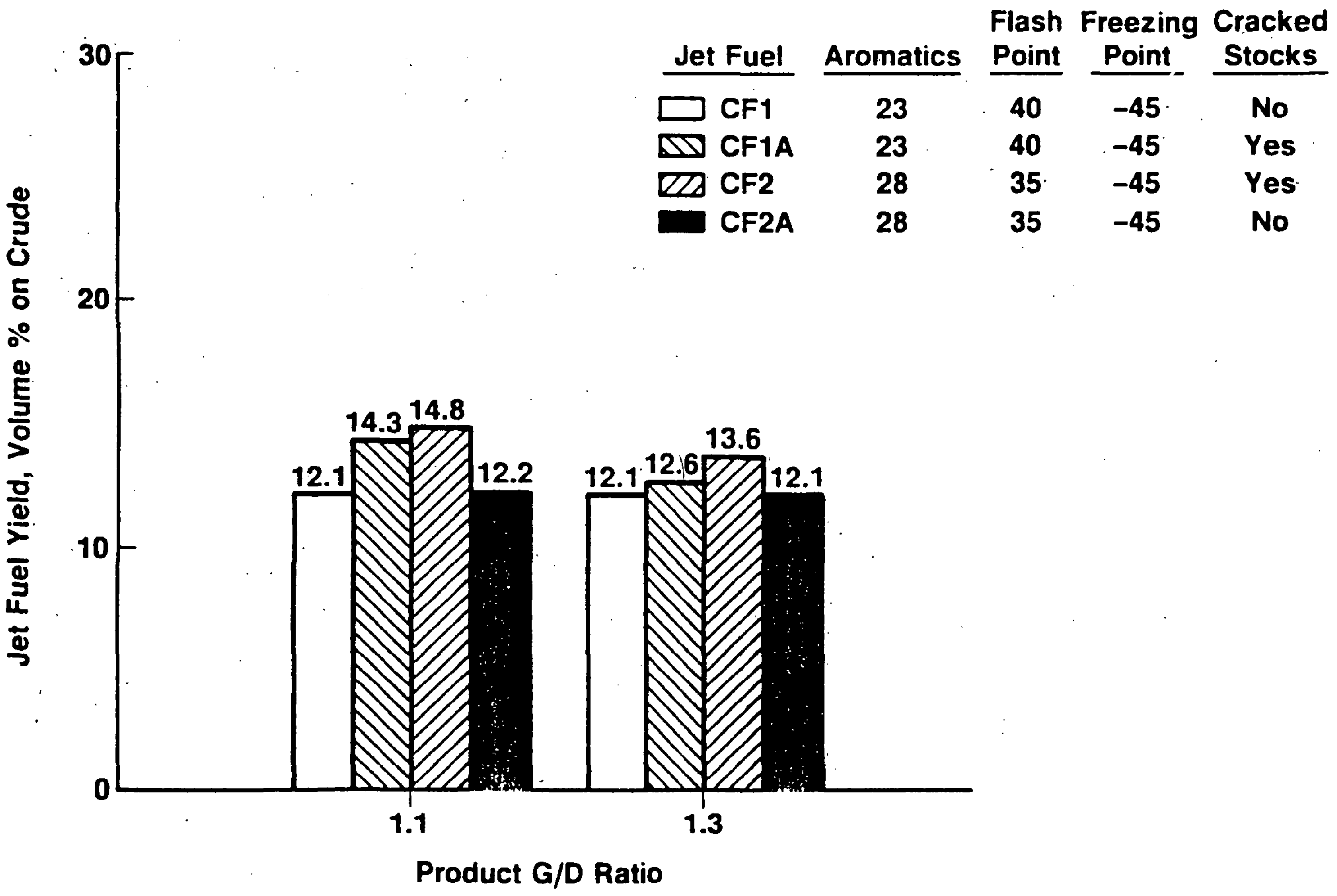
The differences between the base CF-1 jet fuel and the CF-2 jet fuel included both property relaxations (relaxed flash and aromatics), and the ability to blend cracked stocks into the jet pool. Sensitivity runs were undertaken to evaluate independently the contributions of relaxation and cracked stocks. For these runs, two new jet fuels were defined. These fuels were CF-1A, which had the base CF-1 properties but allowed cracked stocks, and CF-2A, which had the relaxed CF-2 properties but did not allow cracked stocks. The cases selected were the low sulfur crude-low conversion refinery and the high sulfur heavy crude-high conversion refinery.

Figure 12 shows the results of these sensitivity cases for the low sulfur-low conversion refinery. The figure shows that at both G/D ratios, the yield of CF-2A is identical to that of the baseline CF-1. On the other hand, the yield of CF-1A is nearly equal to the increased yield with CF-2. Thus, the sensitivity calculations indicated that the inclusion of cracked stocks accounts for all, or nearly all, of the yield improvements. The fact that CF-2, the combined-change study fuel, actually gave higher yields than CF-1A, the fuel with cracked stocks only, suggests that there is a favorable influence when property relaxation and use of cracked stocks are combined. No doubt this comes from the ability of the model refinery to dispose of additional cat cracker streams in the jet fuel when the aromatics limits are relaxed.

The results for the high sulfur heavy-high conversion refinery are shown in Figure 13. The sensitivity comparison agrees with that for the low conversion refinery. Because property relaxation eliminates the need for aromatics extraction, CF-2A shows a small increase in yield over CF-1. However, again almost all of the yield improvement appears to come from the inclusion of cracked stocks, as CF-1A yields are nearly equal to those of CF-2.

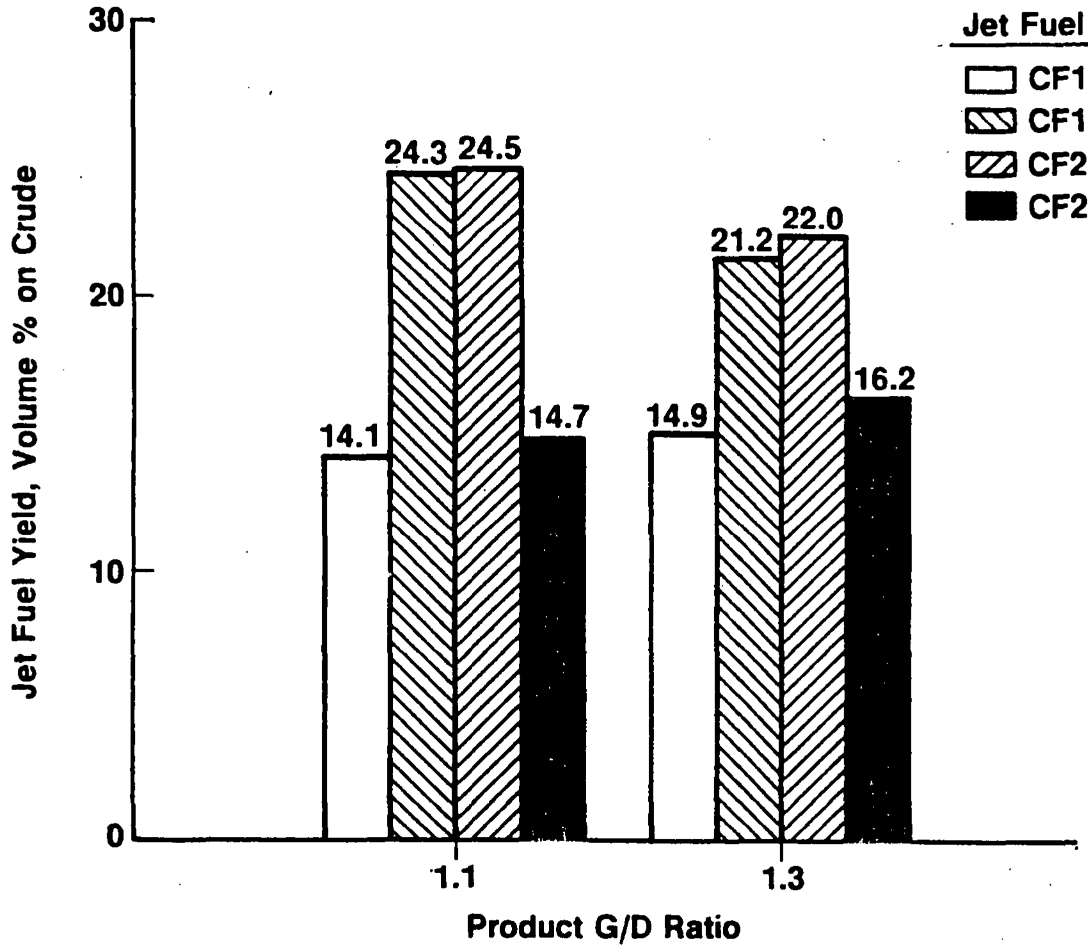
These sensitivity studies were applied to only two models. However, the trends shown would probably also apply to the other refineries and to West Canada. These trends indicate that allowing cracked stocks in the jet pools was the major contributor to the increases in producibility experienced for the CF-2 cases. Cracked stocks are not excluded from jet fuel by specification, but are typically not included due to concerns over stability.

FIGURE 12
JET FUEL YIELD FOR SENSITIVITY CASE, EAST CANADA LOW SULFUR CRUDE—LOW CONVERSION REFINERY



Jet Fuel	Aromatics	Flash Point	Freezing Point	Cracked Stocks
☐ CF1	23	40	-45	No
▧ CF1A	23	40	-45	Yes
▨ CF2	28	35	-45	Yes
■ CF2A	28	35	-45	No

FIGURE 13
JET FUEL YIELD FOR SENSITIVITY CASE, EAST CANADA HEAVY HIGH SULFUR CRUDE—HIGH CONVERSION REFINERY



Jet Fuel	Aromatics	Flash Point	Freezing Point	Cracked Stocks
☐ CF1	23	40	–45	No
▧ CF1A	23	40	–45	Yes
▨ CF2	28	35	–45	Yes
■ CF2A	28	35	–45	No

5.2.4 - West Canada Refineries

Producibility studies were conducted for West Canada refinery-crude models at G/D ratios of 1.5 and 1.2, which correspond to the years 1990 and 2000, respectively. The yield of jet fuel as a percentage of the total crude run for each refinery model is shown in Figure 14. The regional average yield required to meet the projected jet fuel demand in West Canada is 3.5% in 1990 and 3.7% in 2000. Note that the yields of the individual refinery-crude models in Figure 14 are all well above these projected averages. The relative volumes of jet fuel are included in Table 54.

The low conversion refinery supplied with low sulfur crude (upper right plot in Figure 14) made less jet fuel than the East Canada cases, primarily because of the higher product G/D ratio, the amount of synthetic crude that was processed, and the amount of fuel oil demand. The first two items increased the need to use catalytic cracking to meet the naphtha volume required. Once the fixed fuel oil demand was met, a fuel oil block was created since additional crude could not be run.

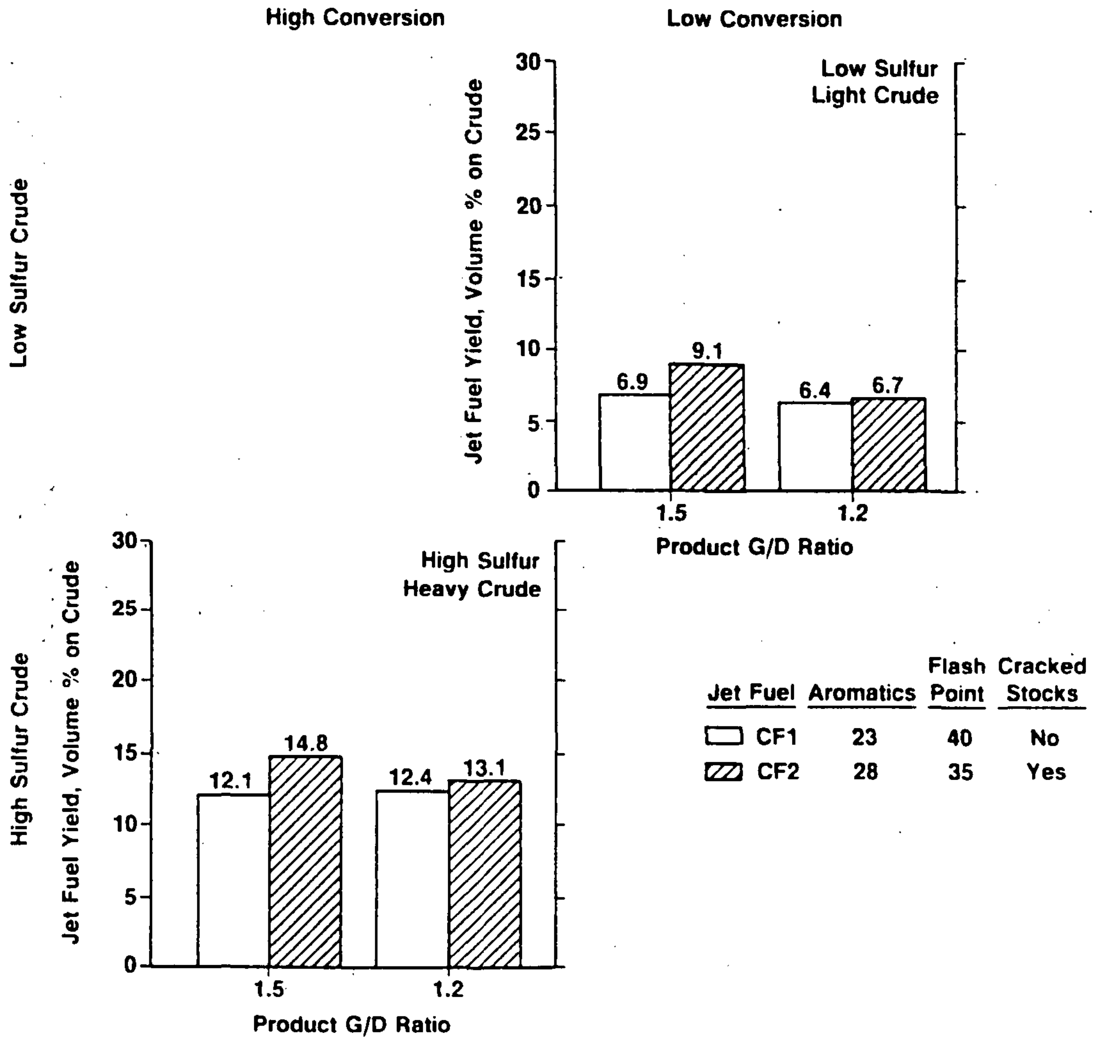
Relaxing the jet fuel to the CF-2 level at the high G/D increased yield moderately. Higher jet fuel producibility resulted primarily from the addition of the cat blendstocks. This added disposition for the cat cracker stocks allowed some additional crude to be run, which also contributed to the increase in jet fuel.

Relaxing to the CF-2 level at the low G/D increased jet yield very slightly, because the product G/D ratio required that the naphtha blendstocks be used to produce gasoline and hydrocracker kerosene be used to improve diesel cetane number.

The high conversion refinery supplied with high sulfur, heavy crude (lower left plot in Figure 14) produced more jet fuel than the West Canada low conversion model. It produced less jet fuel than the corresponding East Canada high conversion refinery model because of a greater disparity between crude N/D ratio and product G/D ratio. The West Canada high sulfur heavy crude had a much lower crude N/D ratio than did the corresponding East Canada crude and processed a higher percentage of synthetic crude, which also had a low crude N/D ratio. The net effect was that the West Canada high conversion refinery had to produce naphtha blendstocks in preference to distillate blendstocks.

For the high G/D, CF-1 fuel case, the refinery required aromatics extraction to meet the jet fuel property limits. For the low G/D baseline case, because the aromatics extract outlets were limited, severe kerosene hydrotreatment was required in addition. This optional process was rarely found to be economic in the U.S. studies. With the relaxation to CF-2, the aromatics reduction processes were not required. However, yield improvements were small because the large percent of synthetic crude with poor cetane values required diversion of kerosene, otherwise useful for jet fuel, to the diesel pool.

FIGURE 14
JET FUEL YIELD BASED ON CRUDE RUN, WEST CANADA



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5.2.5 - Summary of Canada Producibility Results

Key findings of the producibility calculations for Canada are summarized below:

- **The relaxation of aromatics and flash point and the use of cracked stocks increased jet fuel yields from an overall average of 12% to as high as 24% of the crude volume at anticipated 1990 G/D ratios. Yields increased to a maximum of 22% at G/D ratios anticipated for 2000 when synthetic crude constituted about one-third of the feed to each refinery.**

- The increase in the use of synthetic crude projected for 2000 constrained jet fuel yield and relaxation-associated yield increases. The very low naphtha content of synthetic crude forced some distillate, potentially available for jet fuel blending, to be cracked to naphtha to satisfy gasoline demand. The poor quality of synthetic crude distillates also limited jet production. In some cases, jet blendstocks, such as kerosene, were required in the diesel fuel and heating oil pools to offset the low cetane and high gravity of the synthetic crude distillate.

- Most producibility increases resulted from adding cracked stocks to the jet pool. Property relaxation had a smaller effect. Moreover, most of the property relaxation effect was from aromatics relaxation. Relaxing flash point had little effect on jet fuel producibility since high product G/D and low crude N/D required that naphtha be used as a gasoline blendstock.

5.3 REGIONAL COST SAVINGS

5.3.1 - Introduction

Cost savings associated with jet fuel property relaxation were determined regionally in Canada as they were in the U.S. Two future time periods were investigated, 1990 and 2000.

In a procedure analogous to that of the U.S. study (Section 4.1), individual refinery-crude models were linked together to form East and West regional models. East Canada was made up of three models and West Canada was composed of two. Actual 1981 Canadian process capacities were available to each region. Through investment, the models could utilize a particular process not in existence in 1981, or add additional capacity after all existing capacity was utilized. The model minimized cost within each region. All costs were developed in constant value 1981 U.S. dollars.

Synthetic crude from oil sands was available to all of the refinery-crude models. While the total regional synthetic crude supply was fixed, the amount run by any individual refinery type was not limited. Crude and other supplies, available to each region, were set at projected levels presented in Table 49. The volume of low sulfur crude in each region was allowed to vary for material balance purposes. Each refinery in the region blended products independently but the total regional product production met the projected demand shown in Table 44. Production of coke and sulfur were allowed to vary as needed.

The cost to produce the complete refinery slate was determined successively with baseline (CF-1) and relaxed property (CF-2) jet fuel. The difference in cost between these runs represented regional savings; the savings divided by the jet fuel volume provided savings per unit of production.

Not all Canadian refiners produce jet fuel. To reflect this fact, the resources available for jet fuel production were limited to 75% and 50% of the total available refining capacity in East and West Canada, respectively. These participation levels were provided by the Canadian National Research Council. The U.S. results indicated that cost savings are greater where limited participation is considered; however, full participation runs for comparison were not made for the Canadian regions.

5.3.2 - Annual Cost Savings

Annual cost savings from property and processing changes (CF-1 to CF-2) in East and West Canada are shown in Table 55. Savings increased with respect to time and were largest in the West.

The high aromatics level of synthetic crude directly affected cost savings. Synthetic crude kerosene had an aromatics content of 30%, above the CF-1 property limit of 23% and the CF-2 limit of 28%. When synthetic crude was used to make jet fuel, aromatics reduction technology, usually aromatics extraction, was required. Relaxation to CF-2 could frequently eliminate aromatics reduction processing and this produced the majority of the cost savings.

Savings were lowest in the 1990 East Canada case where no synthetic crude was used. In the 2000 East Canada case, synthetic crude constituted 35% of the crude run, and relaxation increased savings by nearly an order of magnitude over the 1990 case.

Savings were considerably higher for West Canada for both years because of the high percentage of synthetic crude in the feedstocks, which made elimination of aromatics reducing through relaxation of jet fuel to CF-2 very cost effective.

TABLE 55

CANADA ANNUAL COST SAVINGS FOR RELAXATION FROM CF-1 TO CF-2, MILLION U.S.$/YR

	1990	2000
East Canada	0.7	7.7
West Canada	9.7	17.2
Total Canada	10.4	24.9

5.3.3 - Cost Savings per Unit Volume

Table 56 summarizes the cost savings on the basis of dollars per cubic meter or cents per gallon of kerosene jet fuel produced. As in the U.S. studies, cost savings on this basis are small even though the regional cost savings are in millions of dollars annually.

TABLE 56

CANADA AVERAGE COST SAVINGS FOR RELAXATION FROM CF-1 TO CF-2

	1990		2000	
	$/m^3	¢/gallon	$/m^3	¢/gallon
East Canada	0.57	0.2	4.72	1.8
West Canada	4.59	1.7	6.73	2.5
Total Canada(1)	3.08	1.2	5.91	2.2

(1) Demand weighted average cost savings.

5.3.4 - Sensitivity Cases

The previous sections presented cost savings with a study fuel that combined jet fuel property relaxation and the addition of cracked stocks. Sensitivity runs were undertaken to separate the cost savings due to property relaxation from those of cracked stock addition.

The same two additional study fuels, CF-1A and CF-2A, introduced in the producibility sensitivity study were utilized (see Table 45). CF-1A was equivalent to CF-1 except that blending of cracked stocks was allowed. CF-2A was equivalent to CF-2 except that blending of cracked stocks was not allowed. Therefore, with CF-1 as the base fuel, CF-1A showed the effects of allowing cracked stocks only and CF-2A revealed the effects of property relaxation only.

Results for the cost saving sensitivity runs are summarized in Table 57. The West Canada 1990 scenario was investigated since it had significant cost savings, and a substantial level of synthetic crude utilization.

TABLE 57

COST SAVINGS FOR SENSITIVITY CASE
WEST CANADA 1990

Relaxation. CF-1 to	Annual Cost Savings, Million U.S. $/Yr.	Average Cost Savings $/m^3	¢/gallon
CF-2	9.7	4.59	1.7
CF-1A	4.7	2.26	0.9
CF-2A	6.3	3.02	1.1

For the West Canada 1990 scenario, the allowance of cracked stocks (CF-1 to CF-1A) and the relaxation of properties (CF-1 to CF-2A) individually resulted in cost savings of 48% and 65% of the savings realized by the combined effect (CF-1 to CF-2), respectively. Therefore, for this case, both relaxation and the allowance of cracked stocks played significant roles in the reduction of refining costs.

Of the properties relaxed with CF-2A, the aromatics/smoke point relaxation may have contributed more strongly to cost savings than the flash point relaxation. The reduction in investment for aromatics extraction was directly related to the aromatics/smoke point relaxation. Further sensitivity cases would be required to determine the relative importance of each property relaxation more precisely.

5.3.5 - Marginal Costs

A marginal cost is the cost for producing the last increment of a specific product. In general, the higher the marginal cost, the more difficult it will be to produce that product. Marginal costs are more sensitive than average costs to model input parameters, such as the quantity and mix of products produced and the cost structure used, and should be used only to indicate trends.

Table 58 presents marginal costs of selected products for the CF-1 and CF-2 cases for each study year. The four products that were selected are representative of all segments of the demand barrel.

In the East Canada 1990 cases, the marginal costs of Jet A/A-1 and diesel were greater than those of gasoline. This resulted from a high crude N/D coupled with a low product N/TD. Marginal costs of naphtha-based products were low due to a relatively low product demand

TABLE 58

CANADA MARGINAL COSTS

		1990		2000	
		$\$/m^3$	\$/gallon	$\$/m^3$	\$/gallon
East Canada					
CF-1	Gasoline	237.7	0.90	256.0	0.97
	Jet Fuel (Jet A/A-1)	274.2	1.04	250.9	0.95
	Diesel	272.3	1.03	246.5	0.93
	RSFO	226.4	0.86	228.9	0.87
	Jet - Diesel	1.9	0.01	4.4	0.02
CF-2	Gasoline	237.7	0.90	256.6	0.97
	Jet Fuel	273.6	1.04	246.5	0.93
	Diesel	272.3	1.03	246.5	0.93
	RSFO	226.4	0.86	230.2	0.87
	Jet - Diesel	1.3	0.01	0.0	0.0
West Canada					
CF-1	Gasoline	268.6	1.02	268.6	1.02
	Jet Fuel (Jet A/A-1)	249.1	0.94	254.1	0.96
	Diesel	239.0	0.90	241.5	0.91
	RSFO	215.1	0.81	214.5	0.81
	Jet - Diesel	10.1	0.04	12.6	0.05
CF-2	Gasoline	269.2	1.02	268.6	1.02
	Jet Fuel	241.5	0.91	246.5	0.93
	Diesel	239.0	0.90	242.1	0.92
	RSFO	217.0	0.82	215.7	0.82
	Jet - Diesel	2.5	0.01	4.4	0.01

along with an abundance of naphtha blendstock. Marginal costs of distillate-based products were high due to a relatively high product demand along with a scarcity of distillate blendstocks. In the East Canada 2000 scenario, and in all of the West Canada cases, gasoline had the highest marginal cost. Crude N/D ratios were lower and product N/TD ratios were higher in these cases than in the East Canada 1990 cases.

Relaxation from CF-1 to CF-2 reduced the marginal cost of jet fuel to some extent in all cases. Changes in the marginal costs of other products were slight. The most noteworthy effect of the relaxation, as in the U.S. regions, was the reduction of the marginal cost difference between jet fuel and diesel fuel.

5.3.6 - Jet Fuel Pool Compositions and Critical Properties

The crudes used and the specific product blending components from those crudes contributed directly to determining which jet fuel properties were critical, i.e., at the specified property limit. In Canada, each crude could be run in only one refinery and in the cost saving runs the model determined which crudes contributed to the regional jet pool. Three crude blends were available in East Canada and two in West Canada. Product blending component properties were generally the same as those in the U.S. with the exception of synthetic crude.

The crudes and blendstocks used to prepare jet fuel are shown in Table 59 for East Canada and Table 60 for West Canada. The arrangement of the table and the blendstock categories correspond to those described for the U.S. in Section 4.2.5. The Canadian components include naphtha, which is a hydrotreated virgin steam from the atmospheric distillation unit. The synthetic crude kerosene component in Canada is derived from processed oil sands (Table 50), whereas in the U.S. it came from oil shale and coal liquids. The total blends in Tables 59 and 60 have letters in parentheses denoting if flash point, freezing point, aromatics, smoke point, or combinations, were critical.

Generally, the CF-1 pool consisted of virgin kerosene, with small quantities of naphtha added until the flash point became limiting. Frequently gas oil was added until freezing point, aromatics and/or smoke point targets were met. When synthetic crude was used, synthetic crude kerosene, adjusted for aromatics by extraction, was also present.

CF-2 aromatics and smoke point targets were met by blending combinations of gas oil, coker, and cat cracker components into virgin kerosene and sometimes hydrocracker kerosene. When synthetic crude was used, aromatics reduction was no longer required, and synthetic crude kerosene was added until property targets were met. Again, small quantities of naphtha were often added until flash point became limiting.

TABLE 59

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES

EAST CANADA - 1990, VOL%(1)

	Low Sulfur Low Conversion	High Sulfur Light Low Conversion	High Sulfur Heavy High Conversion
CF-1			
Kerosene	42.8	55.5	
Gas Oil	0.5	0.4	
Naphtha	0.4	0.5	
	43.7 (FL,FZ)	56.4 (FL,FZ)	
CF-2			
Kerosene	42.7		45.3
Cat Crackate	3.5		7.1
Coker Stocks			0.1
Naphtha	0.6		0.7
	46.8 (FL,FZ)		53.2 (FL,FZ)

EAST CANADA - 2000

	Low Sulfur Low Conversion	High Sulfur Light Low Conversion	High Sulfur Heavy High Conversion
CF-1			
Synthetic Crude Kerosene	20.6	0.7	15.6
Kerosene	42.0	1.6	9.9
Raffinate	2.6		6.2
Naphtha	0.5	0.1	0.2
	65.7 (FL,S)	2.4 (FL,A)	31.9 (FL,A,S)
CF-2			
Synthetic Crude Kerosene	62.8		18.3
Kerosene	10.7		
Gas Oil	0.1		
Hydrocrackate			3.3
Cat Crackate			3.7
Naphtha	0.8		0.3
	74.4 (FL,A)		25.6 (FL,A)

Notes:

(1) Critical properties are:
(FL) = Flash Point
(FZ) = Freezing Point
(A) = Aromatics
(S) = Smoke Point

TABLE 60

JET FUEL POOL COMPOSITIONS AND CRITICAL PROPERTIES WEST CANADA - 1990, VOL%[1]

	Low Sulfur Low Conversion	High Sulfur Heavy High Conversion
CF-1		
Synthetic Crude Kerosene	14.3	14.3
Kero	58.5	4.6
Gas Oil	1.5	
Raffinate		6.0
Naphtha	0.6	0.2
	74.9 (FL,FZ,S)	25.1 (FL,S)
CF-2		
Synthetic Crude Kerosene	38.9	13.5
Kerosene	10.0	11.8
Gas Oil		10.7
Hydrocrackate		8.1
Cat Crackate	0.5	4.1
Coker Stocks		1.8
Naphtha	0.6	
	50.0 (FL,FZ)	50.0
	WEST CANADA - 2000	
CF-1		
Synthetic Crude Kerosene	29.0	27.7
Kerosene	14.9	2.2
Gas Oil	0.5	3.1
Raffinate	9.4	12.5
Naphtha	0.4	0.3
	54.2 (FL,FZ,S,A)	45.8 (FL,S,A)
CF-2		
Synthetic Crude Kerosene	22.3	19.3
Kerosene	3.6	17.2
Gas Oil		15.5
Hydrocrackate	0.1	12.0
Cat Crackate		6.4
Coker Stocks		3.3
Naphtha	0.3	
	26.3 (FL,A)	73.7 (FL, A)

Notes:

(1) Critical properties are: (FL) = Flash Point
(FZ) = Freezing Point
(A) = Aromatics
(S) = Smoke Point

The percentages of the total jet pools which were flash, freeze and aromatics critical are summarized in Table 61. Almost 100% of each pool was flash point critical. In the 2000 projection, due to the influx of synthetic crude, nearly all jet fuel was aromatics critical in addition.

5.3.7 - Qualities of Other Products

The properties of other products were dominated by the use of synthetic crude from oil sands. For example, in East Canada, 2000, when synthetic crude was 35% of the crude run, all of the diesel pool was cetane critical and maximum density critical when CF-1 was produced. Synthetic crude contained a high percentage of aromatic molecules which had high density and poor cetane properties. Density was the most frequently limiting property for heating oil.

The jet fuel property relaxation had almost no impact on the critical qualities in either the gasoline or fuel oil pools. This was because the volume of potential jet fuel blendstocks in the gasoline or fuel oil pools was small relative to the total volume of those pools. Gasoline was limited by motor octane number and vapor lock index in all cases. In a few cases, gasoline was also limited by research octane number.

In the East Canada 1990 cases, when no synthetic crude was available, the heavy fuel oil pools were sulfur and viscosity critical. In the East Canada 2000 and in West Canada in both 1990 and 2000, when synthetic crude was used, the heavy fuel oil pools were no longer at these property limits. Synthetic crude did not contain vacuum resid. Vacuum resid from conventional crudes is typically a high sulfur and high viscosity fuel oil blendstock. In cases with significant synthetic crude runs, some vacuum resid was replaced primarily by cat cracked distillates in the fuel oil pool.

5.3.8 - Processing Considerations

Property relaxation had a significant impact on the use of aromatics extraction. In East Canada, 2000, and both of the West Canada years, aromatics extraction was utilized in the CF-1 cases to allow kerosene from synthetic crude to be blended into the jet fuel pool. The relaxation of the aromatics property with CF-2 eliminated the need for this process.

5.3.9 - Energy Savings

Energy savings which resulted from property relaxation are shown in Table 62. Information regarding the total feedstock energy content and the plant fuel used is shown for the CF-1 cases. The plant fuel savings shown in Table 62 are the decrease in plant fuel consumed due to jet property relaxation.

TABLE 61

PERCENT OF POOL CRITICAL FOR PROPERTY - CANADA

	East Canada					
	CF-1			CF-2		
	Flash	Freeze	Aromatics	Flash	Freeze	Aromatics
1990	100	100	0	100	100	0
2000	100	0	34.3	100	0	100

	West Canada					
	CF-1			CF-2		
	Flash	Freeze	Aromatics	Flash	Freeze	Aromatics
1990	100	74.9	0	50	50	0
2000	100	54.2	100	100	0	100

TABLE 62

ENERGY USE SUMMARY FOR CANADIAN REFINERIES PRODUCING JET FUEL

	1990	2000
East Canada		
Feedstock Energy Content(1)(2)		
TJ/d	2270	2243
Plant Fuel(1)(2)		
TJ/d	157	140
% of Feed	6.9	6.3
Fuel Savings(3)		
TJ/d	0.2	3.9
% of Feed	0.01	0.17
% of Fuel	0.2	2.8
West Canada		
Feedstock Energy Content(1)(2)		
TJ/d	2928	3365
Plant Fuel(1)(2)		
TJ/d	187	222
% of Feed	6.4	6.6
Fuel Savings(3)		
TJ/d	1.6	8.5
% of Feed	0.06	0.25
% of Fuel	0.9	3.8

Notes:

(1) Only energy utilized by refineries producing jet fuel are presented. Refinery participation levels of 75% for East Canada and 50% for West Canada are assumed.
(2) Represents CF-1 case (values in tera joules/calendar day).
(3) Fuel savings for CF-2 relative to CF-1.

The effect of property relaxation on energy savings increased with time due to the increased synthetic crude run. In both East and West Canada 2000, relaxation allowed the product requirements to be met without aromatics extraction. Other energy intensive processes, such as hydrocracking and naphtha reforming, were also reduced in some cases. The energy savings contributed to the overall cost savings noted previously for these cases.

5.3.10 - Summary of Cost Savings Results

Key findings of the cost savings calculations in Canada are as follows:

- The forecast jet fuel demand in Canada can be met with a fuel having baseline CF-1 properties, although aromatics reduction will be needed if synthetic crude use increases as projected.
- Total cost savings calculated for a relaxed property and processing jet fuel were U.S. $10.4 million/yr and $24.9 million/yr in 1990 and 2000, respectively.
- The largest cost savings were associated with the cases that had the greatest synthetic crude run. The high aromatics content of the synthetic crude kerosene required the use of aromatics reduction processing to meet the baseline fuel (CF-1) aromatics level. Relaxation to the CF-2 level allowed the jet fuel to be produced without aromatics reduction thereby realizing a cost savings.
- Limited sensitivity calculations showed that both property relaxation and allowing cracked stocks in jet fuel were significant contributors to total cost savings.

5.4 EFFECT OF SYNTHETIC CRUDE

Since synthetic crude is already an important crude source in Canada and is projected to play an even more significant role in the future, this section highlights the effects synthetic crude had on the results of this study.

It should be noted again that the synthetic crude represented in this study assumed the type of synthetic crude currently produced in Canada. This is based on extraction of bitumen from oil sands, coking the bitumen, and hydrotreating the coker products. The two critical attributes of the synthetic crude that affected jet producibility and cost were its low naphtha to distillate ratio, and its high aromatics content in the distillate range. The effects of these characteristics are summarized below.

1. Low Naphtha/Distillate Ratio

   - Jet fuel producibility and the improvement with property relaxation were limited in cases with high product G/D ratios. This resulted from the need to crack heavier cuts into the naphtha range to produce naphtha blendstocks to satisfy the gasoline demand, which in turn limited the opportunities to produce additional distillates.

   - In some cases, the synthetic crude was processed in the high conversion refinery despite the lack of need for the bottoms conversion capability of this refinery. The synthetic crude was processed there in order to take advantage of the ability to hydrocrack the synthetic crude gas oil for naphtha products.

2. Aromatics Content of Distillates

   - The high aromatics content of distillates limited jet producibility in some cases because the diesel pool was cetane critical. This limited the flexibility to divert jet blendstocks, such as conventional kerosene, to the jet pool since they were required in the diesel pool to offset the low cetane number of synthetic crude distillate.

   - The high aromatics content of synthetic crude kerosene required investment in aromatic reduction processes, such as aromatics extraction, to meet jet smoke and aromatics targets in base (CF-1) cases. Much of the cost savings associated with property relaxation resulted from the elimination of the need for this type of processing. It should be noted that although synthetic crude kerosene has high aromatics levels, it also has a very low freezing point. This increased producibility to some extent by allowing additional high freezing point blendstocks to be included in the jet pool.

6. PRODUCIBILITY STUDIES FOR EUROPE

This Section of the report describes the increase in production that can result from relaxation of jet fuel properties in Europe. The study fuels in Europe were based on the military kerosene jet fuel designated F-34 by the North Atlantic Treaty Organization (NATO) European forces. Regional cost savings were not determined for Europe. The linked regional models for cost analysis were developed for Europe, however, and they were used for a study of the conversion of NATO forces from wide-cut to kerosene jet fuel, presented in the next Section of this report.

The properties of typical F-34 (designated JP-8 by the U.S. Air Force) are essentially identical to those of Jet A-1, the commercial jet fuel consumed in Europe. (The military fuel contains an additive package, the civilian does not.) Thus the results of this and the following Sections have significant application to commercial jet fuel usage in Europe. The subsections that follow present the bases used for Europe and the results of the producibility study.

6.1 BASES USED FOR EUROPE

6.1.1 - Regions Studied

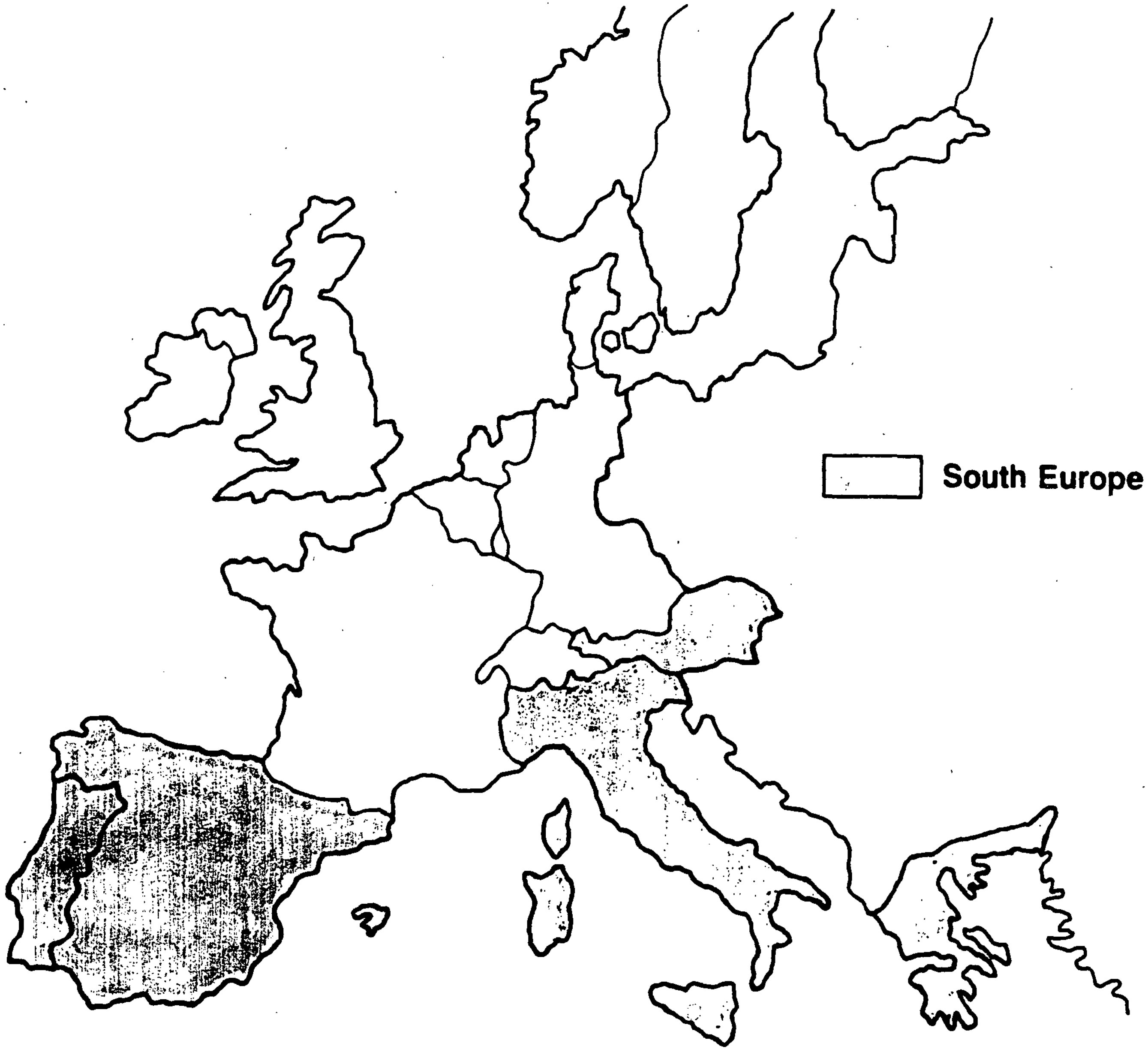
Europe was divided into two geographic regions, North and South, for study purposes. South Europe included countries on the Mediterranean Sea, and North Europe included all other Western European countries. France was included in North Europe. Countries included in the regions are listed below and shown in Figure 15.

North Europe	South Europe
Belgium*	Austria
Denmark*	Greece*
Finland	Italy*
France*	Portugal*
Germany*	Spain*
Ireland	Turkey**
Netherlands*	
Norway*	
Sweden	
Switzerland	
United Kingdom*	

* Signifies NATO member nation.

** Signifies NATO member nation not investigated.

FIGURE 15
EUROPEAN REGIONS



6.1.2 - Product Demands

Demands for major refinery products for civilian and military markets in North and South Europe are shown in Tables 63 and 64, respectively. Fiscal year 1981 demands in Europe for military diesel and military gasoline were furnished by personnel of the Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Military F-40 and F-34 demands and participation levels were obtained from AGARD's Working Group 16. Diesel Fuel Marine (DFM) demand was provided by the Naval Energy Management Office. The demands for civilian fuels were developed from a forecast by Chem Systems, Inc. and were regionalized and adjusted for product imports and exports by Exxon Research personnel. Military fuel demands were assumed to be constant with time as they did not depend directly upon economic factors. The emergency demand scenarios assumed that demands for military fuels would triple, and the increases in demand in the emergency scenario relative to the normal demand reflect military consumption. Only the normal demand schedules were used for the producibility study.

Military and civilian kerosene jet fuel demands are shown as a combined total in Tables 63 and 64, in the row labeled Jet A-1/F-34. The Total Naphtha/Total Distillate ratio (N/TD) shown in the tables is defined as in the U.S. studies, where naphtha includes gasolines, chemical feedstocks, and F-40 military jet fuel, and distillate includes the diesels, heating oil, and F-34. A lower N/TD tends to make production of distillate and kerosene based jet fuel more difficult and costly.

6.1.3 - Jet Fuel Properties

Four study fuels were formulated. These fuels were designated as Military Fuel 1 through Military Fuel 4 (MF-1 through MF-4). The specifications and properties for all of these fuels are presented in Table 65.

MF-1 was an average property, wide-cut or naphtha NATO F-40 jet fuel (designated JP-4 by the U.S. Air Force). The properties for this fuel were based on inspections of over 2000 batches of JP-4 delivered to the U.S. Air Force worldwide during the period July, 1980 to June, 1981(14). Minor adjustments to the published values were made in aromatics and smoke point to facilitate modeling. This fuel was used as the base case for the subsequent conversion studies.

MF-2 was designed to be an average property F-34 kerosene jet fuel. Since F-34 and Jet A-1 have very similar properties, they can be considered to be the same for modeling purposes. MF-2 properties were based on those of Jet A-1 consumed over a 12-month period at major airports in the U.K., France, Italy and Greece. These countries accounted for about 55% of all jet fuel produced in Europe in 1981(15).

TABLE 63

MAJOR REFINERY PRODUCT DEMANDS - NORTH EUROPE

1000 m^3/d

	1985		1995	
	Normal	Emergency	Normal	Emergency
Regular Gasoline	104.1	104.2	112.9	113.0
Premium Gasoline	193.3	193.3	208.3	208.3
Chem Feed	133.9	133.9	144.5	144.5
F-40	4.3	12.9	4.3	12.9
Jet A-1/F-34	62.6	76.3	74.7	88.4
Diesel	381.9	382.4	364.9	365.4
Diesel Fuel Marine	0	0	0	0
Heating Oil	67.4	67.4	64.4	64.4
LSFO	70.1	70.1	54.1	54.1
RSFO	154.1	154.1	124.3	124.3
Total Naphtha/ Total Distillate Ratio(1)	0.85	0.84	0.93	0.92

Notes:

(1) Total naphtha includes chem feed, regular and premium gasoline, and F-40 jet fuel; total distillate includes Jet A-1/F-34, diesel and heating oil.

TABLE 64

MAJOR REFINERY PRODUCT DEMANDS - SOUTH EUROPE

$1000\ m^3/d$

	1985		1995	
	Normal	Emergency	Normal	Emergency
Regular Gasoline	36.1	36.7	46.1	46.7
Premium Gasoline	66.9	66.9	84.3	84.3
Chem Feed	24.8	24.8	39.0	39.0
F-40	4.1	12.4	4.1	12.4
Jet A-1/F-34	9.1	11.8	30.2	32.9
Diesel	109.9	109.9	135.1	135.1
Diesel Fuel Marine	1.1	3.3	1.1	3.3
Heating Oil	19.4	19.4	23.8	23.8
LSFO	14.5	14.5	39.7	39.7
RSFO	89.4	89.4	95.4	95.4
Total Naphtha/ Total Distillate Ratio(1)	0.95	0.98	0.91	0.93

Notes:

(1) Total naphtha includes chem feed, regular and premium gasoline, and F-40 jet fuel; total distillate includes Jet A-1/F-34, diesel and heating oil.

TABLE 65

SPECIFICATIONS AND PROPERTIES OF MILITARY AND EUROPEAN TURBINE FUELS

	Specification						
	JP-4/F-40	JP-8/F-34	Jet A-1	MF-1	MF-2	MF-3	MF-4
Freezing Point, °C (max)	-58	-50	-50	-60	-51	-49	-43
Flash Point, °C (min)	-	38	38	-	43	42	42
Aromatics, vol% (max)	25	25	20	17	17	23	23
Smoke Point, mm (min)	20	19	25	25	25	20	20
Sulfur, wt% (max)	0.4	0.3	0.3	0.04	0.04	0.28	0.28
Reid Vapor Pressure, kPa (max)	21	-	-	21	-	-	-
Reid Vapor Pressure, kPa (min)	14	-	-	14	-	-	-
Density, g/cc (16°C) (max)	0.80	0.84	0.84	0.80	0.84	0.84	0.84
Density, g/cc (16°C) (min)	0.75	0.78	0.78	0.75	0.78	-	-
% Distilled @ 204°C (min)	-	-	-	90	20	10	10
% Distilled @ 227°C (min)	-	-	-	95	50	-	-
% Distilled @ 288°C (min)	-	-	-	100	90	90	90
Cracked Stocks Allowed	-	-	-	No	No	Yes	Yes

MF-3 was a relaxation of MF-2. Properties relaxed included aromatics, smoke point and freezing point. This fuel met all F-34 specifications, except freezing point. MF-3 met the specifications of Jet A-1 which is widely available in Europe and Canada. MF-3 also allowed for the incorporation of cracked stocks derived from hydrocracking, cat cracking, and thermal cracking.

MF-4 describes the property limits resulting when the F-34 freezing point was relaxed to create a fuel similar to Jet A as used in the U.S. The actual qualities chosen for this fuel were those of TF-3 studied in the East U.S.

6.1.4 - Properties of Other Major Refinery Fuels

Distillate fuels relevant to European modeling were civilian and military diesel fuel (which were assumed to have identical properties), heating oil and Diesel Fuel Marine (DFM), a fuel used by U.S. Navy and NATO ships worldwide (NATO designation F-76). Properties of these fuels are presented in Table 66.

The properties of military gasoline and civilian regular grade gasoline were assumed to be the same. Premium grade gasoline was also consumed in the European civilian market. It was assumed that the current strong trend for the reduction of lead in gasoline in Europe resulted in a reduction from the current 0.4 g/L for all grades to 0.15 and 0.25 g/L for regular/military and premium, respectively. Gasoline properties are presented in Table 67.

The properties of Regular Sulfur Fuel Oil and Low Sulfur Fuel Oil are shown in Table 68. The property information for European civilian fuels was assembled through the cooperation of personnel of Esso Petroleum Company, Ltd., Abingdon, England.

6.1.5 - Crude Blends

Projected crude slates for Europe were developed by identifying crudes now consumed and projecting changes in consumption for the study period. The crudes were categorized using the same scheme as was used for the U.S. High sulfur crudes contained 1% or more sulfur, low sulfur crudes contained less than 0.5%. Heavy crudes were those with 15% boiling above 566°C (1050°F).

Crudes consumed in North Europe were described by three blend types: low sulfur, high sulfur light and high sulfur heavy. The quantities of crude consumed are shown in Table 69. The low sulfur crude constitutes about 50% of the crude consumed throughout the study period. The high sulfur heavy blend declines from 20% of the total in 1985 to 5% in 1995. In South Europe, crude blends had the same designations. However, low sulfur blend constitutes just under 15% of the total consumed,

TABLE 66

PROPERTIES OF MILITARY AND EUROPEAN CIVILIAN DISTILLATE FUELS

Property	Military Diesel Fuel Civilian Diesel Fuel	Diesel Fuel Marine	Heating Oil
Cetane Index, min ASTM D976-66	45	45	-
Flash Point, °C min	55	60	55
% Distilled @ 227°C, min(1)	10	-	10
% Distilled @ 338°C, min(2)	70	85	70
Cloud Point, °C max	-6 and -3(3)	-1	-13 and -10(4)
Sulfur, wt% max	0.3	1.0	0.5
Density, g/cc max	0.85	-	0.85
Pour Point, °C max	-	-7	-

Notes:

(1) Corresponds to ASTM D-86 10% point.
(2) Corresponds to ASTM D-86 90% point.
(3) Diesel cloud point of -6°C was used for North Europe and -3°C for South Europe.
(4) Heating oil cloud point of -13°C was used for North Europe and -10°C for South Europe.

TABLE 67

PROPERTIES OF MILITARY AND CIVILIAN GASOLINES

	Military Gasoline Regular Grade Gasoline	Premium Grade Gasoline
Research Octane Number, min	91	98
Motor Octane Number, min	82	88
Octane Index, min(1)	86.5	93
Reid Vapor Pressure, kPa max	90	90
Vapor Lock Index, max(2)	18	18
Lead Level, g/L	0.15	0.25

Notes:

(1) Octane index is defined as (Research Octane No. + Motor Octane No.)/2.
(2) Vapor lock index is defined as: Reid Vapor Pressure + (0.13)(% Off @ 70°C).

TABLE 68

EUROPEAN FUEL OIL PROPERTIES

	Regular Sulfur Fuel Oil	Low Sulfur Fuel Oil
Sulfur, wt% max	3.0	1.3
Viscosity @ 100°C, cSt max	60	60

TABLE 69

EUROPEAN CRUDE AND NATURAL GAS CONDENSATE REQUIREMENTS(1)

1000 m^3/d

	1985	1995
North Europe		
Low Sulfur	657.3	709.1
High Sulfur Light(2)	358.7	487.7
High Sulfur Heavy	244.2	62.8
Natural Gas Condensate	30.5	30.5
Total North Europe	1290.7	1290.1
South Europe		
Low Sulfur	53.7	71.6
High Sulfur Light	271.4	262.0
High Sulfur Heavy(2)	84.7	227.7
Natural Gas Condensate	1.6	1.6
Total South Europe	411.4	562.9
Total Europe	1702.1	1853.0

Notes:

(1) Represents total European crude requirements. Only 85% of crude supplies in North Europe and 60% in South Europe were available for jet fuel production.
(2) Adjustable crude.

high sulfur heavy grows from 20% to 40% between 1985 and 1995, and the high sulfur light blend constitutes between 65% and 45% of total crude over the study period. The North Europe high sulfur light crude and the South Europe high sulfur heavy crude could vary as needed for material balance purposes.

The representations of crudes used in the East U.S. were modified as required to simulate the crudes consumed in Europe. The modifications reflected significant yield and quality differences between U.S. and European crudes. In addition, any effect on processing produced by these modifications were also modeled. The properties of the crudes specific to Europe are presented in Table 70. Values for sulfur, residuum content, kerosene aromatics level and crude naphtha/ distillate ratio fell within the envelope of U.S. and Canadian crudes.

6.1.6 - Refinery - Crude Models

European refinery crude models were developed from their U.S. counterparts. In Europe, cat cracking capacity is only 25% of that in the U.S., and consequently hydroskimmers are a major refinery type. European refineries, however, have three times as much visbreaking capacity as in the U.S. Because visbreakers were included in North American high conversion refineries only, a hydroskimmer with residuum conversion capability was developed for Europe. In North Europe, the modified hydroskimmer possessed visbreaking and coking capability, while in South Europe it had visbreaking capability only. Also, because European cat crackers produce relatively more distillate than their North American counterparts, the European cat cracker representation was modified to reflect this difference.

Table 71 presents European process capacities and Table 72 shows the distribution of refinery capacity among the four refinery types as a percentage of distillation capacity and by number of refineries in 1982. The distribution of crudes to refineries was developed using the projected crude runs and the breakdown of refinery types. The heavy crudes were fed to the high conversion refinery and the light crudes to the hydroskimmers and low conversion refineries, as shown in Table 73.

The cut point of the kerosene fraction from the model atmospheric pipestill (refer to Figures 2 to 4) was adjusted to reflect the lower initial boiling points encountered in Europe. Initial boiling points in Europe are typically in the 160-166°C (320-330°F) range while in the U.S. they are in the 177-182°C (350-360°F) range. This shift in cut point permitted jet fuel and high European distillate demand to be met more easily.

Because the European models were derived from the U.S. models which had already been verified, no separate verification was made for Europe.

TABLE 70

PROPERTIES OF EUROPEAN CRUDE BLENDS

North Europe	Wt% Sulfur	Vol% 566°C+ (1050°F+)	Vol% Aromatics in Kerosene Fraction	Crude Naphtha/ Distillate Ratio
Low Sulfur	0.22	7.8	17.5	0.66
High Sulfur				
Light	1.58	12.5	20.0	0.65
Heavy	2.80	23.3	19.3	0.58
South Europe				
Low Sulfur	0.17	7.8	12.1	0.59
High Sulfur				
Light	1.80	12.5	20.2	0.60
Heavy	2.01	23.3	19.0	0.63

TABLE 71

EUROPEAN REFINING CAPACITY - 1982

1000 m^3/d

	North Europe	South Europe	Total Europe
Atmospheric Distillation	1698.1	877.7	2575.8
Vacuum Distillation	504.0	165.4	669.4
Catalytic Reforming	263.9	79.5	343.4
Cat Cracking	163.8	46.1	209.9
Hydrocracking	15.6	1.4	17.0
Coking	20.7	5.1	25.8
Visbreaking	155.8	58.8	214.6
Naphtha Hydrotreating	354.6	128.8	483.4
Distillate Hydrotreating	397.5	127.2	524.7
Gas Oil Hydrotreating	31.8	46.1	77.9
Alkylation	11.1	6.0	17.1
Naphtha Isomerization	11.8	2.4	14.2

TABLE 72

DISTRIBUTION OF EUROPEAN REFINERY CAPACITY AMONG REFINERY TYPES

	North Europe		South Europe	
Refinery Types	Percent of Capacity	Number of Refineries	Percent of Capacity	Number of Refineries
Hydroskimming (H/S)	20	34	47	21
H/S with Coking and/or Visbreaking	23	24	15	9
Low Conversion	29	20	22	7
High Conversion	28	15	16	5
Totals	100	93	100	42

TABLE 73

EUROPEAN-REFINERY CRUDE MODELS

North Europe	Hydroskimmer	Modified Hydroskimmer	Low Conversion	High Conversion
Low Sulfur	X		X	
High Sulfur Light		X		
High Sulfur Heavy				X
South Europe				
Low Sulfur		X		
High Sulfur Light	X		X	
High Sulfur Heavy				X

6.2 PRODUCIBILITY

6.2.1 - Introduction

The producibility determinations for Europe were undertaken using the same general methodology that was used for the U.S. and Canada. The study investigated the effect of jet fuel property and processing changes at specific Gasoline/Distillate ratios corresponding to the selected future time periods, as follows:

	1985	1995
North Europe	0.6	0.7
South Europe	0.7	0.8

In contrast to the United States and West Canada, the European G/D ratios increased with time, although the change was moderate.

Distillate was defined as diesel fuel plus heating oil which were produced at an 85/15 ratio. Jet fuel was considered to be a separate product. The total volume of gasoline plus distillate was fixed at 13500 m^3/d (85000 bbl/d) which, after accounting for the production of other products, required the processing of approximately 15900 m^3/d (100,000 bbl/d) of crude.

The European producibility runs used MF-2 as the baseline jet fuel and MF-4 as a single relaxed-property study fuel. With the exception of cracked stocks, MF-4 is similar to Jet A now consumed in the U.S. For the commercial market, the producibility determinations illustrated the change in jet fuel production possible if current Jet A-1 properties were relaxed to those of Jet A produced in the U.S with the reportable aromatics/smoke point limit extension. From a military point of view, these determinations illustrated how much additional kerojet could be produced if F-34 properties were relaxed to MF-4 levels.

The blending components that were utilized most frequently to formulate the two study fuels are summarized below.

MF-2	Kerosene Raffinate from aromatics extraction Severely hydrotreated kerosene
MF-4	Kerosene Gas oil Components from catalytic, thermal and hydrocracking

Most European crudes possessed aromatics levels in excess of the MF-2 target and aromatics reduction processing was required. Relaxation to MF-4 removed the requirement for aromatics reduction and allowed the addition of gas oil and cracked stocks.

6.2.2 - North Europe

Producibility results are presented for Europe in two ways, similar to those for the United States (Section 3.2) and Canada. Figure 16 shows the yield as the percentage of refinery crude input. Separate plots represent the producibility for the four North Europe refinery-crude models. The bar graphs within the plots compare results for the two study fuels at the two G/D ratios of 0.6 and 0.7, corresponding to 1985 and 1995. Table 74 compares producibility in the second way, on the basis of volume output, normalized with respect to the volume of MF-2 produced at a G/D of 0.6 for North Europe. The Table includes results for South Europe, normalized with respect to MF-2 at a G/D of 0.7, to be discussed later in this Section.

For reference, the individual refinery-crude model results may be compared to the regional jet fuel yield required to meet demand projections. These are 4.9% for 1985 and 5.8% for 1995, in North Europe.

Producibility results for North Europe may be examined in more detail by discussing the optimized solutions. Consider first the low conversion refinery supplied with low sulfur crude (upper center plot in Figure 16). Baseline fuel yield with MF-2 at a G/D of 0.6 was very low because the virgin kerosene was used to meet distillate cloud point targets and jet fuel production was constrained. The refinery invested in jet fuel hydrocracking for distillate production. Aromatics extraction of the virgin kerosene was needed to meet the jet fuel smoke point target. The jet fuel pool was smoke point and freezing point critical.

When the jet properties were relaxed to the MF-4 level, yield increased from 1.2% to 4.8%, a 300% increase. Aromatics extraction was no longer required, and only freezing point was critical. The jet pool consisted of virgin kerosene, with a small amount of gas oil. The refinery was able to produce more jet fuel by investing in additional jet hydrocracker capacity and by running additional crude.

At the 0.7 G/D ratio, less distillate was produced, which eased the competition for kerosene and more virgin kerosene was available for jet fuel. MF-2 yield was higher by a factor of 2.5 compared to the lower G/D case. The jet pool consisted of virgin kerosene and kerosene raffinate from aromatics extraction, and was smoke point critical. Since there was a lower demand for distillate products, jet hydrocracking was not utilized.

When the jet fuel properties were relaxed to MF-4, yield increased but not to the level of the lower G/D because less investment in jet hydrocracking was justified to meet the distillate demand.

FIGURE 16
JET FUEL YIELD BASED ON CRUDE RUN, NORTH EUROPE

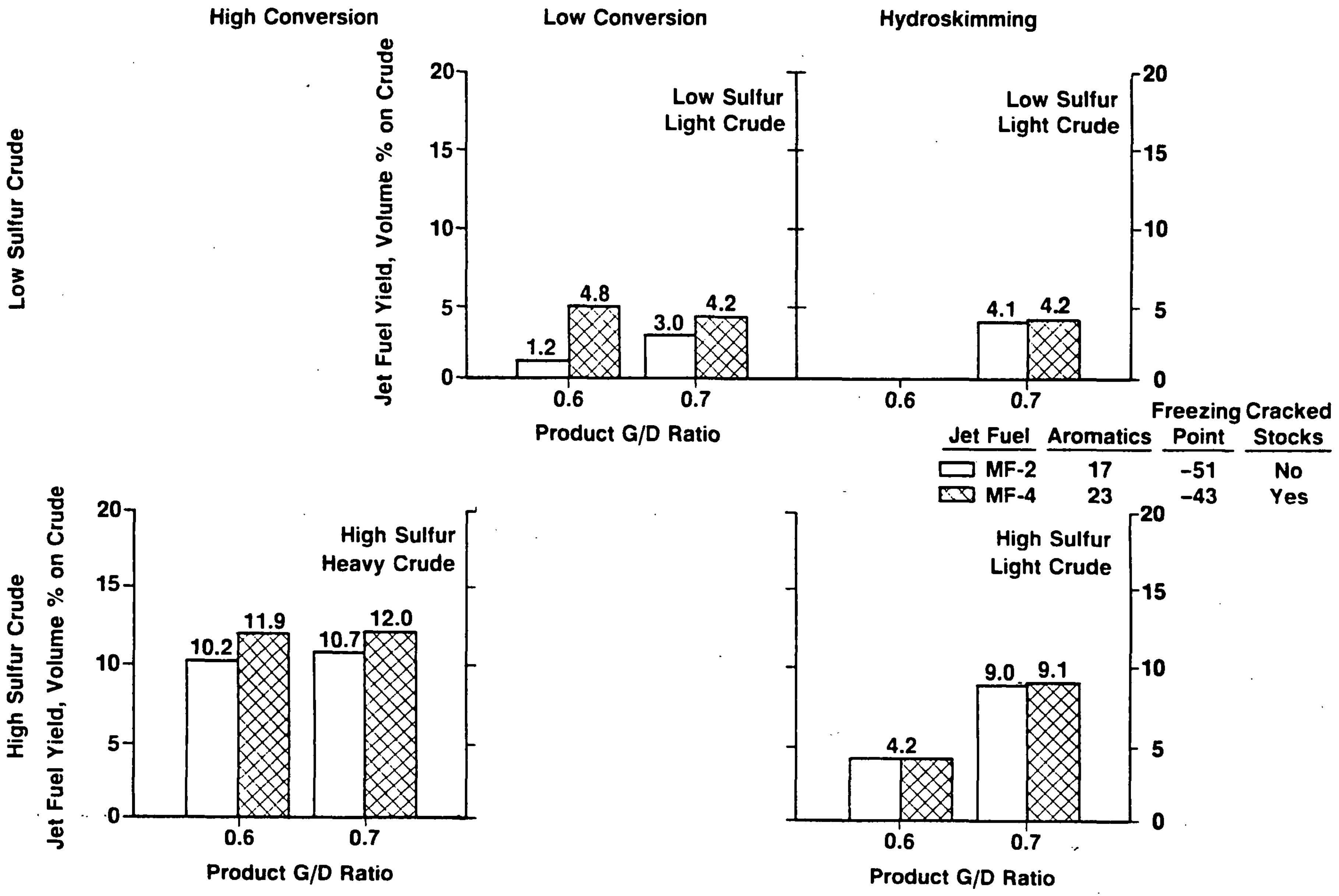


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TABLE 74

RELATIVE JET FUEL VOLUME PRODUCED, EUROPE

North Europe

G/D Ratio	----- 0.6 -----		----- 0.7 -----	
Jet Fuel	MF-2	MF-4	MF-2	MF-4
Low Sulfur - Low Conversion	1.00	4.30	2.65	3.75
Low Sulfur - Hydroskimmer	-	-	1.00	1.01
High Sulfur Heavy - High Conversion	1.00	1.25	1.05	1.20
High Sulfur Light - Modified Hydroskimmer	1.00	1.00	2.45	2.50

South Europe

G/D Ratio	----- 0.7 -----		----- 0.8 -----	
Jet Fuel	MF-2	MF-4	MF-2	MF-4
Low Sulfur - Modified Hydroskimmer	1.00	1.02	-	-
High Sulfur Heavy - High Conversion	1.00	1.45	1.15	1.70
High Sulfur Light - Low Conversion	1.00	1.35	1.00	1.20
High Sulfur Light - Hydroskimmer	1.00	1.00	-	-

For the hydroskimming refinery supplied with low sulfur crude (upper right plot in Figure 16), only one G/D ratio, 0.7, was run since this type of refinery has no conversion capacity and has little flexibility to alter yields. At G/D of 0.6, the refinery could not meet the distillate demand.

The hydroskimmer produced more MF-2 than the low conversion refinery supplied with the same crude. The cat cracker in the low conversion refinery converted low value fuel oil components into naphtha and distillate so less virgin naphtha and distillate was needed to meet product demands. This decreased both crude usage and the quantity of kerosene available for jet fuel blending in the low conversion refinery.

Relaxing jet properties to MF-4 in the hydroskimmer resulted in a negligible yield increase. Since the property relaxation included smoke point relaxation, the aromatics extraction of virgin kerosene was no longer necessary but only slightly more virgin kerosene was available for the jet pool.

For the high conversion refinery supplied with high sulfur, heavy crude (lower left plot in Figure 16), yields in all cases were substantially higher than those for the other North European models. In the baseline MF-2 case, the model could invest, at the G/D of 0.6, in jet hydrocracking, severe kerosene hydrotreatment, and aromatics extraction. The high sulfur content of the kerosene raffinate limited its use in jet fuel blending.

Relaxing the jet fuel properties to MF-4 improved the yield moderately. The model took advantage of the property relaxation by eliminating severe kerosene hydrotreating and aromatics extraction. The increased volume resulted from the addition of the cracked stocks into the jet pool, including the cat naphtha which could be included since the flash point was relaxed slightly for MF-4.

At G/D ratio of 0.7, MF-2 yield was slightly higher than at the lower G/D ratio since the lower distillate demand allowed the shift of some virgin kerosene from the distillate to jet pools. The results of relaxation of jet fuel properties to MF-4 were similar to those for the lower G/D.

The modified hydroskimming refinery supplied with high sulfur, light crude (lower right plot in Figure 16) could operate at two G/D ratios because it added coking capability. At the 0.6 G/D ratio and the base MF-2 jet property level, yield was 4.2%. The model utilized mild kerosene hydrotreating to meet the sulfur target and severe hydrotreating and aromatics extraction to meet the smoke and aromatics targets. Distillate cloud point targets were met by the use of virgin kerosene, decreasing its availability for jet fuel use. With relaxation of jet fuel to MF-4 quality, severe hydrotreatment and aromatics extraction were not required, but jet fuel producibility did not increase because the virgin kerosene was needed in the distillate pools for both volume and quality.

At the 0.7 G/D ratio, jet fuel yields were higher by a factor of two. This increase relative to the 0.6 G/D ratio case was a result of the higher G/D ratio allowing additional crude to be run and kerosene to be diverted from the distillate pools to the jet pool. Relaxation to the MF-4 properties at this G/D again removed the requirement for severe hydrotreatment and aromatics extraction, but it made little additional jet fuel because virgin kerosene was unavailable.

6.2.3 - South Europe

Producibility studies were conducted for South Europe at G/D ratios of 0.7 and 0.8, which correspond to the years 1985 and 1995. The yield of jet fuel as a percentage of the total crude run for each refinery model is shown in Figure 17. The relative volumetric jet fuel yields are included in Table 74. Most European jet fuel is produced in North Europe. The regional average demand requirements for South Europe are relatively low, 2.2% for 1985 and 5.4% for 1995.

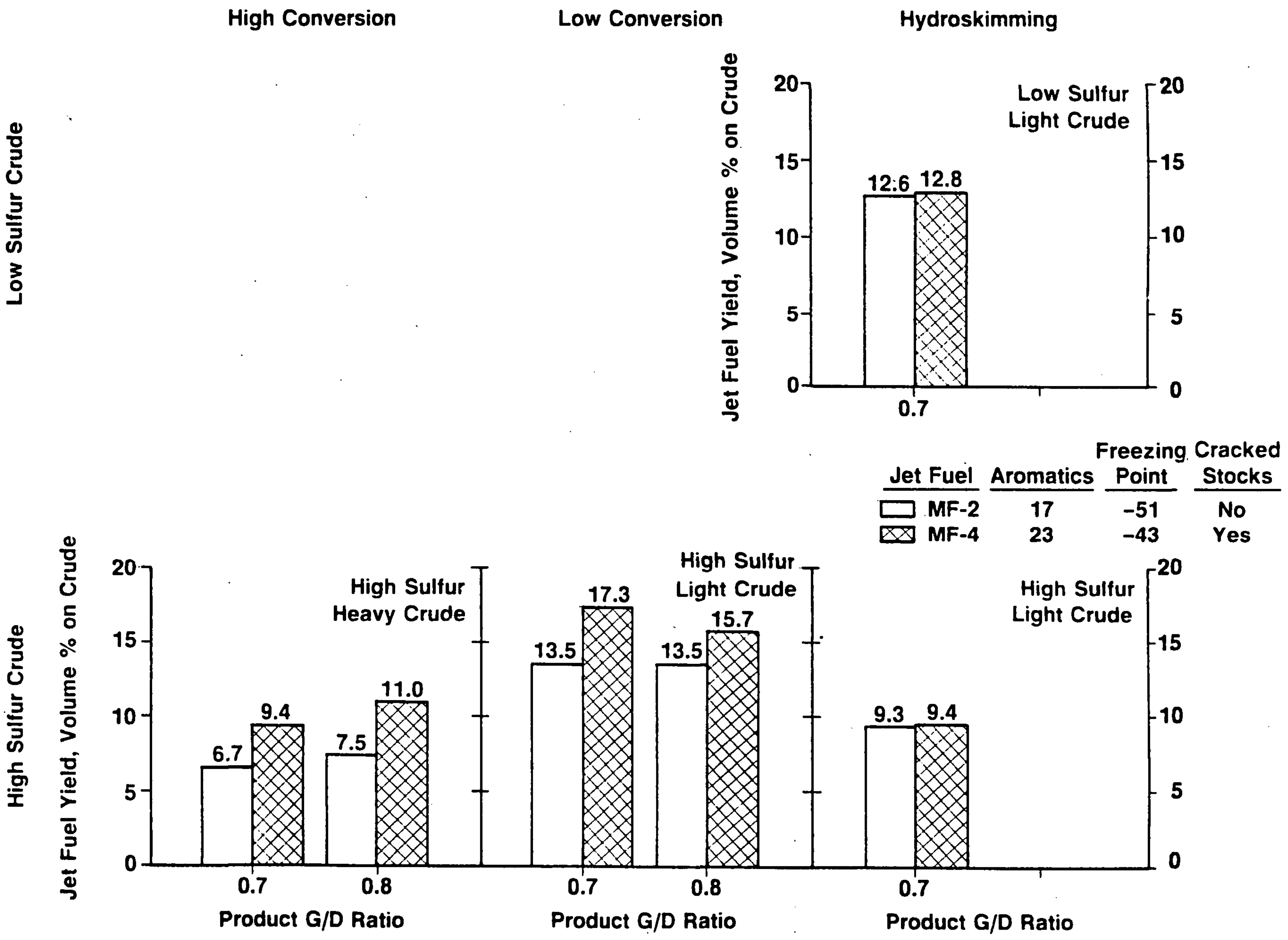
The South Europe modified hydroskimmer supplied with low sulfur crude (top right plot in Figure 17) added visbreaking as its only bottoms conversion capability and operated at one G/D ratio. The yields for this refinery-crude model were over three times greater than those of the corresponding North Europe model. This was a result of two differences between the cases. First, the North Europe low sulfur crude had a higher ratio of naphtha to distillate which caused increased competition for the kerosene cut as the refinery attempted to produce the low G/D ratio product slate. Second, the South Europe hydroskimmer made significantly more fuel oil than did the North Europe refinery, reflecting the greater fuel oil demand in South Europe. The production of larger quantities of fuel oil allowed the South Europe hydroskimmer to run more crude which allowed it to make more jet fuel.

Relaxing jet properties to the MF-4 level for the modified hydroskimmer allowed more gas oil to be blended into the jet pool to increase yield slightly.

For the high conversion refinery supplied with high sulfur, heavy crude (lower left plot in Figure 17), the relatively poor qualities of the crude limited the jet fuel yields compared to the corresponding North Europe model. For the baseline MF-2 at a G/D of 0.7, the model invested in severe kerosene hydrotreatment and aromatics extraction. Relaxation of jet fuel properties to MF-4 removed the requirements for severe hydrotreatment and extraction. In addition, the relaxed properties allowed blending of cat naphtha and cat distillate to the jet pool, thereby increasing the volume produced.

At the 0.8 G/D ratio, the increased jet yield of MF-2 was attributable to the lessened demand for distillate products which allowed the model to shift components to the jet pool. Relaxation of jet fuel properties to the MF-4 property level increased yield further due to the lessened demand for distillate products, and, therefore, the decreased competition for kerosene.

FIGURE 17
JET FUEL YIELD BASED ON CRUDE RUN, SOUTH EUROPE



5-0-026

The low conversion refinery supplied with high sulfur light crude (lower center plot in Figure 17) could make several times more jet fuel than the low conversion refinery in North Europe. The South Europe high sulfur, light crude had a lower G/D than the low sulfur crude run in the North Europe low conversion refinery. Consequently, the South Europe refinery could run more crude and make more jet fuel before naphtha disposal became limiting. Further, Gasoline/Distillate ratios in the South were higher than in the North, permitting even more crude to be run and more jet fuel to be made before a naphtha block developed. Also, fuel oil demand was greater in the South than in the North so again, more crude could be run before fuel oil became constraining. Additionally, the distillate pool was not cloud point critical with this crude as it was in the North, so kerosene diverted to distillate blending in the North was available for jet fuel production in this South Europe refinery.

The increased jet producibility at the relaxed property level of MF-4 at the G/D of 0.7 was a result of an increase in jet hydrocracking. Gas oil was shifted from cat cracking to jet hydrocracking. This reduction in naphtha production due to the reduced catalytic cracking utilization, allowed the refinery to run additional crude to produce the naphtha volume required and provide additional virgin kerosene for jet fuel production.

At the 0.8 G/D ratio, production of MF-2 was the same as for the lower G/D. A significant difference was that this case utilized catalytic cracking and excluded jet hydrocracking. Catalytic cracking was required to produce naphtha to meet the higher gasoline demand. The lower distillate demand could be met by lower cost means than by jet hydrocracking.

Relaxing the jet fuel properties to MF-4 increased yield but to a lesser extent than that at the 0.7 G/D level because catalytic cracking was required to meet the increased naphtha demand at the higher G/D, utilizing feedstock that would have been available for jet hydrocracking.

The hydroskimming refinery supplied with high sulfur, light crude (bottom right plot in Figure 17) operated at 0.7 G/D only. In order to meet the smoke and aromatics targets, this refinery invested in aromatics extraction and severe kerosene hydrotreating. It utilized severe hydrotreating to a greater degree, since disposal of extract from aromatics extraction was limiting.

Relaxing properties to the MF-4 level resulted in a negligible increase in producibility. The model backed out the aromatics reduction processes and swapped some blendstocks with the distillates.

6.2.4 - Summary of Europe Producibility Results

Key findings of the producibility study for Europe are summarized below:

- The high aromatics levels of the crudes used in Europe required aromatics extraction and/or severe hydrotreatment to meet baseline military kerosene jet aromatics and smoke point targets.
- Jet fuel yield and yield increases with property relaxation were limited by the need to meet the required distillate demands and the use of kerosene to meet distillate properties, especially cloud point in the North.
- Producibility increases were greatest for the conversion refineries and were generally very small for the hydroskimmers.
- Jet fuel yields were generally higher in South Europe than in North Europe because of better crude qualities, and a better match of crude and product G/D ratios.

7. MILITARY FUEL CONVERSION STUDY RESULTS

This Section of the report presents the results of the study on the refining cost of the conversion of wide-cut, or naphtha, military jet fuel (designated F-40 in NATO Europe and JP-4 in the U.S.) to kerosene jet fuel (designated F-34 in NATO Europe and JP-8 in the U.S.).

7.1 EUROPE

The increases in military jet fuel costs due to conversion were determined using regional optimization models which linked together individual European refinery-crude models. This was the same technique used for the cost savings calculations in the U.S. (Section 4.1) and Canada. The cost savings calculations for relaxed-property fuels were not performed for Europe. Instead, for the military fuel conversion studies, the European regional models were first run to produce military jet fuels meeting the baseline F-40 quality, or MF-1 (Table 65). A solution representing overall refining costs resulted. Then the model was run supplying the same military fuel demand but at the baseline F-34 quality, or MF-2. The difference between these two cost values represented the regional cost increase for the conversion to kerosene from wide-cut fuel, for the selected case. Subsequent calculations processing MF-3 or MF-4 determined cost increases for conversion to these relaxed-property kerosene fuels.

It was assumed that 85% of the crude and natural gas condensate in North Europe and 60% in South Europe (Table 69) could be used for jet fuel production. The refinery product demands used in the conversion study were those shown in Tables 63 and 64, where the emergency demand scenarios assumed that the normal military demands were tripled. The demands for F-40 in the Tables were first applied to MF-1 and then to the converted MF-2 to MF-4 in the calculations. Civilian fuel Jet A-1 was always represented by MF-2, even when military kerojet was relaxed. Further, it was assumed that investments in processing equipment which lowered overall costs could be made if economically warranted.

When the military fuels were converted from wide-cut to kerosene types, the Naphtha/Total Distillate ratios (N/TD) in Tables 63 and 64 always decreased. The extent of the change depended on the region. In North Europe, the decrease was of the order of 0.01 to 0.04 for both normal and emergency demands. In South Europe, the normal ratios decreased by 0.04 to 0.06, the emergency ratios by 0.11 to 0.16. The change in N/TD was great enough that the N/TD for F-34 was greater than that for F-40 in the normal case but lesser in the emergency case. In general, as the product N/TD decreases, the cost of the kerosene-based products increases.

7.1.1 - Increased Annual Costs

Additional annual costs which would be incurred if NATO forces in Europe converted from F-40 to an equal volume of F-34 or the relaxed kerosene fuels are shown in Table 75. The columns labeled MF-2 represent the cost in millions of U.S. dollars/year to convert to current property F-34. The other columns represent the cost of converting to relaxed property kerosene fuels, MF-3 and MF-4.

For normal product demands, additional annual costs in 1981 dollars would not exceed $125 million in 1985 and $101 million in 1995. Use of either relaxed fuel by NATO forces would reduce the cost increase by about $25 million in both 1985 and 1995, a 20% saving in 1985 and a 25% saving in 1995.

Under emergency military demands, use of F-34 rather than F-40 would increase costs by about $435 million annually in both 1985 and 1995. Under emergency conditions, three times as much jet fuel would be required annually. This volume change was responsible for most of the cost increase, the remainder representing the cost of producing military jet fuel under increasingly stressed refining conditions. The substitution of the relaxed-property kerosene fuels, MF-3 and MF-4, would reduce the annual conversion cost by $75 million in the 1985 period to $120 million by 1995. There were only slight differences between the MF-3 and MF-4 costs. This shows that there were little cost benefits from the relaxation of freezing point, which is the difference between MF-3 and MF-4. In the same way, from an analysis of the jet fuel pool compositions in the European producibility studies, it was evident that aromatics relaxation rather than freezing point was also instrumental in increasing jet fuel yields.

As noted previously, if the N/TD decreased due to the conversion or military emergency, the cost of kerosene-based products increased. The converse held if the N/TD increased. The decrease in conversion costs with time in North Europe and the increase in South Europe reflected these considerations. The cost data showed especially large increases for MF-2 in the South Europe 1995 emergency demand case, suggesting that production of this fuel was difficult and costly.

Changes in four of the basic assumptions used could affect the results. First, civilian Jet A-1 properties were always assumed to be identical to those of MF-2, i.e., civilian jet fuel properties were not relaxed even when military fuel properties were relaxed. If the relaxed properties were used or if blending of cracked stocks were allowed for Jet A-1, conversion costs for military jet fuel would be lower. Second, to reflect the fact that not all European refiners produce jet fuel, only 85 and 60% of total crude was available for jet fuel production in North and South Europe, respectively. If higher participation levels had been assumed, conversion costs would have been lower. Third, the

TABLE 75

ANNUAL COST INCREASES FOR CONVERSION FROM F-40 TO AN EQUAL VOLUME OF F-34 IN EUROPE, $ MILLION/YR

	Normal Demand			Emergency Demand		
	MF-2	MF-3	MF-4	MF-2	MF-3	MF-4
1985						
North Europe	73	60	60	288	249	248
South Europe	52	40	40	147	113	112
Total Europe	125	100	100	435	362	360
1995						
North Europe	42	30	29	177	139	138
South Europe	59	46	45	260	181	177
Total Europe	101	76	74	437	320	315

regional models used to calculate conversion costs did not reflect national policies which could interfere with optimization of the region on a strictly economic basis. These policies include national tax and price control to protect the local industries. Fourth, it was assumed that investments would be made if justified by cost reduction, and it was further assumed that these investments were made instantaneously. Because refinery investments take time, this suggests that some civilian demands might experience a temporary shortfall until new processing were made operational. Capital recovery charges associated with these investments are included in the conversion costs.

7.1.2 - Cost Increases per Unit Volume

Table 76 illustrates cost increases for converting from JP-4 to military kerojet on a dollar per cubic meter and a cents per gallon basis. These data are useful in assessing the relative costs of the conversion, as distinct from costs arising from the demand increases. Note, for example, that in South Europe in 1985, the emergency scenario reduces the average conversion cost per unit volume slightly. In all other cases, the emergency demand conversion costs per unit volume are 30 to 45% higher than the corresponding normal demand costs.

While cost savings calculations were not conducted for the European regions, examination of Table 76 can provide qualitative estimates of cost savings. For example, the average cost of conversion for 1985 North Europe normal demand decreased by $8/m^3 for the military fuel substitution of MF-3 for MF-2. A cost savings of at least this unit amount might be assumed if both civilian and military jet fuels were relaxed to the MF-3 qualities. Other estimates of cost savings may be made from comparison of the marginal cost tables of the U.S. and European regions.

7.1.3 - Marginal Costs

A marginal cost is the cost for producing the last increment of a specific product. In general, the higher the marginal cost the more difficult it will be to produce that product. As conditions change (for instance, as product properties are relaxed), marginal cost changes for the same product will indicate whether that product is easier or more difficult to produce under the revised condition.

Marginal costs are overly sensitive to model input parameters, such as the cost of crude, processing, and the quantity and mix of all products produced. Marginal costs should be used only to indicate trends.

Table 77 presents marginal costs of selected products for the MF-1, MF-2, MF-3, and MF-4 runs for North Europe. The civilian jet fuel, Jet A-1, was always represented by MF-2 in the calculations; only the military fuel was converted to relaxed-quality jet fuels. Marginal

TABLE 76

AVERAGE COST INCREASES FOR CONVERSION FROM F-40 TO AN EQUAL VOLUME OF F-34 IN EUROPE

	Normal Demand					
	MF-2		MF-3		MF-4	
	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon
1985						
North Europe	47.2	17.9	39.0	14.8	39.0	14.8
South Europe	34.6	13.1	26.4	10.0	26.4	10.4
1995						
North Europe	27.0	10.2	19.5	7.4	18.9	7.1
South Europe	39.6	15.0	30.8	11.7	30.2	11.4

	Emergency Demand					
	MF-2		MF-3		MF-4	
	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon
1985						
North Europe	61.6	23.3	53.5	20.2	53.5	20.2
South Europe	32.7	12.4	25.2	9.5	24.5	9.3
1995						
North Europe	38.4	14.5	30.2	11.4	29.6	11.2
South Europe	57.9	21.9	40.2	15.2	39.0	14.8

TABLE 77

MARGINAL COSTS - NORTH EUROPE

	1985				1995			
	Normal Case		Emergency Case		Normal Case		Emergency Case	
	$/m^3$	¢/gallon	$/m^3$	¢/gallon	$/m^3$	¢/gallon	$/m^3$	¢/gallon
MF-1								
Gasoline	254.1	96.2	253.5	95.9	269.8	102.1	269.8	102.1
Jet A-1 (MF-2)	283.6	107.4	283.6	107.4	277.4	105.0	278.0	105.2
F-40 (MF-1)	237.7	90.0	237.7	90.0	252.2	95.5	252.2	95.5
Diesel	273.6	103.6	274.2	103.8	267.9	101.4	267.9	101.4
RSFO	234.0	88.6	234.0	88.6	230.8	87.4	230.8	87.4
Jet A-1 - Diesel	10.0	3.8	9.4	3.6	9.5	3.6	10.1	3.8
MF-2								
Gasoline	252.8	95.7	234.0	88.6	266.7	100.9	259.1	98.1
Jet A-1 (MF-2)	284.3	107.6	292.4	110.7	278.6	105.5	284.3	107.6
F-34 (MF-2)	284.3	107.6	292.4	110.7	278.6	105.5	284.3	107.6
Diesel	274.8	104.0	283.0	107.1	269.2	101.9	274.2	103.8
RSFO	234.6	88.8	237.1	89.8	232.7	88.1	231.4	87.6
Jet A-1 - Diesel	9.5	3.6	9.4	3.6	9.4	3.6	10.1	3.8
F-34 - Diesel	9.5	3.6	9.4	3.6	9.4	3.6	10.1	3.8
MF-3								
Gasoline	252.8	95.7	232.7	88.1	266.7	100.9	259.7	98.3
Jet A-1 (MF-2)	284.3	107.6	293.1	110.9	278.6	105.5	284.3	107.6
F-34 (MF-3)	276.1	104.5	284.9	107.9	270.4	102.4	276.1	104.5
Diesel	274.8	104.0	283.6	107.4	269.2	101.9	274.2	103.8
RSFO	234.6	88.8	237.1	89.8	232.7	88.1	230.8	87.4
Jet A-1 - Diesel	9.5	3.6	9.5	3.5	9.4	3.6	10.1	3.8
F-34 - Diesel	1.3	0.5	1.3	0.5	1.2	0.5	1.9	0.7
MF-4								
Gasoline	252.8	95.7	232.7	88.1	265.4	100.5	259.1	98.1
Jet A-1 (MF-2)	284.3	107.6	293.1	110.9	279.2	105.7	284.3	107.6
F-34 (MF-4)	275.5	104.3	284.9	107.9	270.4	102.4	275.5	104.3
Diesel	274.8	104.0	283.6	107.4	269.8	102.1	274.2	103.8
RSFO	234.6	88.8	237.1	89.8	232.7	88.1	231.4	87.6
Jet A-1 - Diesel	9.5	3.6	9.5	3.5	9.4	3.6	10.1	3.8
F-34 - Diesel	0.7	0.3	1.3	0.5	0.6	0.3	1.3	0.5

cost changes generally were governed by changes in N/TD. Marginal costs of the nonmilitary fuels changed little from case to case, except for the civilian jet fuel, Jet A-1, whose marginal costs increased in the emergency scenarios. The Table also lists the marginal cost differences of Jet A-1 minus diesel and F-34 minus diesel. Note the substantial decrease in the F-34 to diesel difference with relaxation to MF-3 and MF-4. This implies that a concurrent relaxation of the civilian Jet A-1 (making a common military-civilian jet fuel in Europe) would reduce marginal costs of all jet fuels and reduce the overall conversion costs.

The marginal costs for South Europe (Table 78) also illustrate the effect of N/TD. However, the MF-2 marginal cost in the 1995 emergency case was almost 40% higher than that in the normal case. This suggests strongly that MF-2 was close to its maximum level of production, where small changes in demand can produce very large changes in marginal cost. The difference between the marginal cost of MF-2 and diesel was also very large, attesting further to the stressed kerojet production situation. Relaxation to MF-3 or MF-4 not only greatly reduced the marginal cost and cost differential of the military fuel, but it also reduced the cost of the civilian jet fuel, which remained at the MF-2 qualities. When exceptional stress, such as that illustrated here is encountered, alternate coverage steps, for example, "importing" jet fuel from North Europe rather than producing it locally, may be favored.

7.1.4 - Conversion Costs on an Equal Energy Basis

The discussion of the F-40 to F-34 conversion in the previous sections assumed that the volumetric demands for these wide-cut and kerosene-based fuels would be equal. The data in Table 79 show that the volumetric energy contents of the F-34 study fuels (MF-2 to MF-4) were 7 to 9% greater than those of the baseline F-40 fuel (MF-1). Properties of the fuels were calculated by the refinery model program. Since the optimized fuel blends were not necessarily at their specification limits, the same study fuel type could have slight differences in density or energy content in the two European regions.

If one assumes that there are no differences in the combustion efficiencies of these two fuels, the volumetric demand for F-34, in the limit, could be 7 to 9% lower than for F-40 for the same total energy requirements.

The demands for F-40 and the corresponding "equal energy" demands for F-34 are shown in Table 80. The costs of converting to the smaller volume of kerosene fuel were estimated by applying the marginal costs of the fuels affected to the changes in volume for the case. The resulting annual cost increases are shown in the "Equal Energy" portion of Table 81. In the 1995 South Europe emergency MF-2 case, the marginal costs were substantially higher than the average cost, producing uncertainties in calculation, and a range has been presented. Average cost increases on a unit basis are presented in Table 82.

TABLE 78

MARGINAL COSTS - SOUTH EUROPE

	1985				1995			
	Normal Case		Emergency Case		Normal Case		Emergency Case	
	$/m^3$	¢/gallon	$/m^3$	¢/gallon	$/m^3$	¢/gallon	$/m^3$	¢/gallon
MF-1								
Gasoline	224.5	85.0	229.6	86.9	234.0	88.6	234.6	88.8
Jet A-1 (MF-2)	244.0	92.4	247.2	93.6	254.7	96.4	256.0	96.9
F-40 (MF-1)	212.6	80.5	219.5	83.1	218.9	82.9	221.4	83.8
Diesel	235.8	89.3	239.0	90.5	244.6	92.6	245.3	92.9
RSFO	213.2	80.7	207.5	78.6	201.9	76.4	200.0	75.7
Jet A-1 - Diesel	8.2	3.1	8.2	3.1	10.1	3.8	10.7	4.0
MF-2								
Gasoline	223.9	84.8	222.6	84.3	228.3	86.4	205.0	77.6
Jet A-1 (MF-2)	245.3	92.9	251.6	95.2	259.7	98.3	359.7	136.2
F-34 (MF-2)	245.3	92.9	251.6	95.2	259.7	98.3	359.7	136.2
Diesel	236.5	89.5	242.1	91.7	249.1	94.3	245.3	92.9
RSFO	213.8	80.9	210.1	79.5	201.3	76.2	188.7	71.4
Jet A-1 - Diesel	8.5	3.4	9.5	3.5	10.6	4.0	114.4	43.3
F-34 - Diesel	8.5	3.4	9.5	3.5	10.6	4.0	114.4	43.3
MF-3								
Gasoline	223.9	84.8	222.6	84.3	228.9	86.7	218.2	82.6
Jet A-1 (MF-2)	245.3	92.9	251.6	95.2	259.1	98.1	271.1	102.6
F-34 (MF-3)	237.7	90.0	243.4	92.1	250.9	95.0	262.9	99.5
Diesel	236.5	89.5	242.1	91.7	249.0	94.3	259.1	98.1
RSFO	213.8	80.9	210.1	79.5	201.3	76.2	197.5	74.8
Jet A-1 - Diesel	8.8	3.4	9.5	3.5	10.1	3.8	12.0	4.5
F-34 - Diesel	1.2	0.5	1.3	0.4	1.9	0.7	3.8	1.4
MF-4								
Gasoline	224.5	85.0	222.6	84.3	228.9	86.7	218.9	82.9
Jet A-1 (MF-2)	245.3	92.9	250.9	95.0	259.1	98.1	270.4	102.4
F-34 (MF-4)	237.1	89.8	243.4	92.1	250.3	94.8	261.0	98.8
Diesel	236.5	89.5	242.1	91.7	249.0	94.3	259.1	98.1
RSFO	213.8	80.9	210.1	79.5	201.3	76.2	197.5	74.8
Jet A-1 - Diesel	8.8	3.4	8.8	3.3	10.1	3.8	11.3	4.3
F-34 - Diesel	0.6	0.3	1.3	0.4	1.3	0.5	1.9	0.7

TABLE 79

CALCULATED ENERGY PROPERTIES OF MILITARY FUELS - EUROPE

	Fuel	North Europe	South Europe
Density, kg/m^3	MF-1	742	731
	MF-2	803	791
	MF-3	803	791
	MF-4	803	803
Gravimetric Energy Content			
MJ/kg	MF-1	43.7	43.7
(% Difference from MF-1)	MF-2	43.3 (-1.1)	43.3 (-1.1)
	MF-3	43.3 (-1.1)	43.3 (-1.1)
	MF-4	43.3 (-1.1)	43.3 (-1.1)
Volumetric Energy Content			
GJ/m^3	MF-1	32.4	31.9
(% Difference from MF-1)	MF-2	34.7 (7.2)	34.2 (7.4)
	MF-3	34.6 (6.8)	34.2 (7.2)
	MF-4	34.6 (6.8)	34.7 (8.6)

TABLE 80

MILITARY FUEL DEMANDS FOR EQUAL ENERGY CONVERSION EUROPE, 1985 AND 1995, 1000 m^3/d

	Normal Demand				Emergency Demand			
	F-40	F-34			F-40	F-34		
	MF-1	MF-2	MF-3	MF-4	MF-1	MF-2	MF-3	MF-4
North Europe	4.3	3.9	4.0	4.0	12.7	11.8	11.9	11.9
South Europe	4.1	3.8	3.8	3.7	12.3	11.4	11.4	11.3

TABLE 81

ANNUAL COST INCREASES FOR CONVERSION FROM F-40 TO F-34 IN EUROPE, $ MILLION/YR

	Equal Volume Basis						Equal Energy Basis					
	Normal Demand			Emergency Demand			Normal Demand			Emergency Demand		
	MF-2	MF-3	MF-4	MF-2	MF-3	MF-4	MF-2	MF-3	MF-4	MF-2	MF-3	MF-4
1985												
North Europe	73	60	60	288	249	248	42	32	32	191	160	159
South Europe	52	40	40	147	113	112	25	15	10	64	35	19
Total Europe	125	100	100	435	362	360	67	47	42	255	195	178
1995												
North Europe	42	30	29	177	139	138	11	1	1	83	52	51
South Europe	59	46	45	260	181	177	30	20	13	141-174	97	77
Total Europe	101	76	74	437	320	315	41	21	14	224-257	149	128

TABLE 82

AVERAGE COST INCREASES FOR CONVERSION FROM F-40 TO AN EQUAL ENERGY OF F-34 IN EUROPE

	Normal Demand					
	MF-2		MF-3		MF-4	
	$\$/\mathrm{m}^3$	¢/gallon	$\$/\mathrm{m}^3$	¢/gallon	$\$/\mathrm{m}^3$	¢/gallon
1985						
North Europe	29.2	11.0	22.1	8.4	22.1	8.4
South Europe	18.0	6.8	10.8	4.1	7.3	2.8
1995						
North Europe	7.6	2.9	0.7	0.3	0.7	0.3
South Europe	21.6	8.2	14.4	5.4	9.5	3.6

	Emergency Demand					
	MF-2		MF-3		MF-4	
	$\$/\mathrm{m}^3$	¢/gallon	$\$/\mathrm{m}^3$	¢/gallon	$\$/\mathrm{m}^3$	¢/gallon
1985						
North Europe	44.2	16.7	36.9	14.0	36.7	13.9
South Europe	15.4	5.8	8.4	3.2	4.6	1.7
1995						
North Europe	19.2	7.3	12.0	4.5	11.8	4.4
South Europe	33.8 - 41.8	12.8 - 15.8	23.2	8.8	18.7	7.1

The F-40 to F-34 conversion on an equal energy basis resulted in lower overall costs for conversion relative to conversion on an equal volume basis. In 1985, for example, conversion costs for Europe were approximately 40 to 60% of those on an equal volume basis. It is worth noting that in North Europe in 1995 (see Table 81), cost savings due to relaxation and reduced volumetric demand nearly equaled the cost increases of conversion.

It is recognized that due to mass limitations of some military aircraft and some mission requirements, full advantage cannot be taken of the higher kerosene fuel volumetric energy content. Consequently the increased annual costs probably lie between the equal volume and equal energy values shown in Table 81.

7.1.5 - Summary of European Conversion Study Results

Key findings of the study to determine the refining cost increases for conversion of NATO Europe from wide-cut to kerosene military jet fuel are summarized below:

- Under the assumptions used, conversion of NATO forces in Europe from F-40 to an equal volume of F-34 is possible, although at a cost penalty of $125 million/year in 1985 and $100 million/year by 1995.
- Relaxation of F-34 aromatics content to levels typical of current civilian Jet A/A-1 with reportable aromatics extensions and the use of cracked stocks would lower these increases by about $25 million in 1985 and 1995.
- Under tripled military fuel demands, conversion costs would rise to $435 million in both years. Relaxation would reduce conversion costs by $75 million in 1985 and by $120 million in 1995.
- If the demand for military kerosene jet fuels were reduced to account for the 7 to 9% higher volumetric energy content compared to that of wide-cut fuels, normal conversion costs could be reduced to as little as 40 to 60% of the equal-volume demand conversion costs.

7.2 UNITED STATES

The military fuel conversion study was also conducted for the United States regions. The methodology used was essentially the same as that used in Europe. Individual U.S. refinery crude models were linked to form East and West optimization models, the same as those established or the cost savings study (Section 4.1). The study fuels were the same as those defined for Europe (Table 65), except that the reference fuels are designated in the U.S. as the wide-cut JP-4 and the kerosene JP-8.

The regional models were first run to produce military jet fuels meeting the baseline JP-4 quality, or MF-1. The same models were then run to process the same volumetric demands of military jet fuel converted to JP-8, or MF-2 to MF-4. As in the European calculations, differences between the cost results of the kerosene fuel cases and the wide-cut baseline case gave the costs of conversion.

Conversion was studied for 1985 and 1995, for both normal and emergency demands. In the latter scenario, demands for military fuels tripled. Civilian Jet A was always represented by TF-1 (Table 3) even when military kerojet was relaxed. The participation factor was not considered. It was assumed that all refiners could produce military fuels since a number of refiners, in addition to those that produce commercial Jet A, produce fuels for use by the armed forces. It was further assumed that refinery investments which lowered overall costs would be made if economically warranted.

7.2.1 - Product Properties, Demands and Crude Blends

The properties and specifications of military jet fuels used were the same as those used for Europe and shown in Table 65. Military diesel fuel had the same properties as U.S. No. 2 diesel (Table 6) and military gasoline was the same as U.S. unleaded regular grade (Table 4). Diesel Fuel Marine (DFM) properties are shown in Table 66. The properties of all other civilian products were those used in other U.S. modeling.

The product demands used in this modeling effort for the East and West U.S. are shown in Tables 83 and 84, respectively. Fiscal year 1981 military demands in the U.S. for JP-4 and military diesel were furnished by personnel of the Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. The military gasoline demand was set at 0.1% of the 1985 demand for unleaded regular gasoline in each region. Military fuel demands were assumed to be constant with time as they do not depend directly upon economic factors. Emergency demand scenarios were developed by assuming that demands for military fuels would triple in such an emergency. Civilian fuel demands were the same as or interpolated from demands used in U.S. modeling. The wide-cut or naphtha jet demand is shown by JP-4/JP-8. These demands differ slightly from those shown in Tables 1 and 2 due to the availability of more current information when conversion modeling was undertaken. In Tables 1 and 2, DFM was considered to be part of the diesel demand. For this work, however, it was broken out as a separate product. DFM demand was provided by personnel of the David W. Taylor Naval Ship Research and Development Center, Annapolis, MD and the Naval Petroleum Office, Cameron Station, VA. Military diesel demand was included in the civilian demand.

TABLE 83

EAST U.S. PRODUCT DEMANDS FOR CONVERSION STUDY

1000 m^3/d

	1985		1995	
	Normal	Emergency	Normal	Emergency
Regular Gasoline	587.0	588.1	424.2	425.3
Premium Gasoline	147.1	147.1	106.1	106.1
Chem Feed	107.0	107.0	191.9	191.9
Jet A	102.1	102.1	128.5	128.5
JP-4/JP-8	26.1	78.3	26.1	78.3
No. 1 Diesel	18.0	18.0	14.5	14.5
Diesel	179.0	182.0	344.2	347.2
Diesel Fuel Marine	3.0	9.1	3.0	9.1
Heating Oil	163.0	163.0	115.7	115.7
LSFO	52.0	52.0	37.8	37.8
RSFO	46.0	46.0	28.6	28.6
Naphtha/Total Distillate Ratio (JP-4)	1.90	1.97	1.26	1.33
Naphtha/Total Distillate Ratio (JP-8)	1.74	1.55	1.17	1.06

TABLE 84

WEST U.S. PRODUCT DEMANDS FOR CONVERSION STUDY

1000 m^3/d

	1985		1995	
	Normal	Emergency	Normal	Emergency
Regular Gasoline	113.5	113.7	90.5	90.6
Premium Gasoline	28.4	28.4	22.7	22.7
Chem Feed	5.2	5.2	7.0	7.0
Jet A	34.3	34.3	43.7	43.7
JP-4/JP-8	7.8	23.4	7.8	23.4
No. 1 Diesel	1.0	1.0	1.0	1.0
Diesel	25.8	26.7	47.4	48.3
Diesel Fuel Marine	2.5	7.5	2.5	7.5
Heating Oil	25.3	25.3	21.9	21.9
LSFO	48.7	48.7	31.8	31.8
RSFO	43.1	43.1	30.5	30.5
Naphtha/Total Distillate Ratio (JP-4)	1.78	1.83	1.14	1.21
Naphtha/Total Distillate Ratio (JP-8)	1.55	1.27	1.00	0.85

Naphtha/Total Distillate ratios for the demand scenarios considered are also shown in Tables 83 and 84. The emergency demand scenario increased the N/TD ratio from normal demands facilitating distillate production. However, assuming conversion to JP-8 tended to reduce N/TD ratio, making distillate and jet fuel production more difficult. The East always had a higher N/TD ratio than the West. This resulted in distillates being easier and less expensive to make in the East.

The qualities of U.S. crudes used were the same as those shown in Table 8 and the quantities were the same as shown in Tables 9 and 10. The high sulfur light crude in the East and the high sulfur heavy crude in the West could vary as needed. Sufficient quantities of these crudes were assumed available to accommodate the approximately 5% increase in crude usage occurring with the emergency demand scenarios.

7.2.2 - Increased Annual Costs

Additional annual costs which would be incurred if the U.S. Air Force converted from JP-4 to an equal volume of JP-8 are shown in Table 85. The columns labeled MF-2 represent the cost in millions of dollars/year to convert to JP-8 possessing current typical properties. The other columns represent the cost of converting to relaxed property kerosene jet fuels, MF-3 and MF-4. In certain emergency cases, no costs are included for MF-2 because it was not possible to meet the total demand for all products in these cases and shortfalls occurred. These will be discussed later. In a realistic situation, the shortfalls would probably be covered with product imports.

Civilian jet fuel demand was met using TF-1 except in the West 1995 cases when TF-1A was used. TF-1A was also used in the Cost Savings calculations reported in Section 4.3, for years beyond 1990. Use of TF-1A avoided a Jet A shortfall. The properties of TF-1A were identical to those of TF-1 except that hydrocracked stocks were allowed in TF-1A. Hydrocracked stocks were not allowed into MF-2.

For base product demands, additional annual costs in constant 1981 dollars were $296 million in 1985 and $463 million in 1995. Use of either relaxed fuel reduced conversion costs in 1985 by about $121 million, or about 40%. In 1995 relaxation reduced conversion costs by $146 million or about 30%. In Europe, differences in cost increases with the relaxed-property fuels MF-3 and MF-4 were slight. In the U.S., they were essentially zero. This result suggests that for the U.S., there also was no benefit from the relaxation of freezing point, which was the only difference between MF-3 and MF-4.

TABLE 85

ANNUAL COST INCREASES FOR CONVERSION FROM JP-4 TO AN EQUAL VOLUME OF JP-8 IN U.S., $ MILLION/YR

	Normal Demand			Emergency Demand		
	MF-2	MF-3	MF-4	MF-2	MF-3	MF-4
1985						
East U.S.	159	104	104	597	326	326
West U.S.	137	71	71	*	199	199
Total U.S.	296	175	175	*	525	525
1995						
East U.S.	324	206	206	*	694	694
West U.S.	139	111	111	*	337	336
Total U.S.	463	317	317	*	1031	1030

* Product shortfall prevents calculation of increased costs.

Under emergency military demands converting to either relaxed fuel in 1985 increased costs by $525 million annually and by just over $1000 million annually in 1995. Cost calculations for conversion to MF-2 could not be made because of product shortfalls which occurred in the West in 1985 and in both regions in 1995. The basis change to TF-1A in the West 1995 reduced the cost differences between military kerojets.

7.2.3 - Cost Increases per Unit Volume

Table 86 illustrates cost increases for converting from JP-4 to military kerojet on a dollar per cubic meter and a cents per gallon basis. In general, average costs with the relaxed property fuels were 50 to 65% of those for the baseline MF-2. In the West 1995, the basis change allowed hydrocracked stocks to be blended into Jet A, freeing virgin stocks for blending into JP-8. Average costs were about 80% with the relaxed property fuels compared to the baseline for this case.

7.2.4 - Marginal Costs

Marginal costs for the U.S. East and West are shown in Tables 87 and 88, respectively. Also shown are the differences in marginal cost between Jet A and diesel as well as between JP-8 and diesel. As noted previously, marginal cost is the cost producing the last increment of a specific product. Marginal costs indicate the difficulty of producing a product, not necessarily the average cost of the product.

As in Europe, marginal cost changes reflected the Naphtha/Total Distillate ratio. If the ratio declined with conversion or time, the marginal cost of distillate products increased and the marginal cost of naphtha-based products decreased. The converse occurred with an increasing N/TD ratio.

In the East U.S., conversion from JP-4 to JP-8 (MF-2) increased the marginal costs of both Jet A and JP-8 and the difference in marginal cost between Jet A and diesel. The MF-2 minus diesel value was greater than the Jet A minus diesel value, reflecting the greater difficulty in producing baseline specification JP-8 than Jet A. Relaxation to MF-3 or MF-4 removed most cost pressure.

In the West, conversion from JP-4 to JP-8 (MF-2) produced severe stress as shown by the large marginal cost increases in 1985 for both Jet A and JP-8 and the very large differences between these fuels and diesel. In 1995, when the baseline civilian jet fuel is TF-1A, cost increases and jet fuel to diesel differences were much less severe. Relaxation to MF-3 or MF-4 relieved most of the cost pressure for both years.

TABLE 86

AVERAGE COST INCREASES FOR CONVERSION FROM JP-4 TO AN EQUAL VOLUME OF JP-8 IN THE U.S.

	Normal Demand					
	MF-2		MF-3		MF-4	
	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon
1985						
East U.S.	16.7	6.3	10.9	4.1	10.9	4.1
West U.S.	48.0	18.2	24.9	9.4	24.9	9.4
1995						
East U.S.	34.0	12.9	21.7	8.2	21.7	8.2
West U.S.	48.7	18.4	38.9	14.7	38.9	14.7

	Emergency Demand					
	MF-2		MF-3		MF-4	
	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon
1985						
East U.S.	20.9	7.9	11.4	4.3	11.4	4.3
West U.S.	*	*	23.3	8.8	23.3	8.8
1995						
East U.S.	*	*	24.3	9.2	24.3	9.2
West U.S.	*	*	39.4	14.9	39.4	14.9

* Product shortfall prevents calculation of increased costs.

TABLE 87

MARGINAL COSTS - EAST U.S.

	1985				1995			
	Normal Case		Emergency Case		Normal Case		Emergency Case	
	$/m³	¢/gallon	$/m³	¢/gallon	$/m³	¢/gallon	$/m³	¢/gallon
MF-1								
Gasoline	267.5	101.3	268.9	101.8	261.2	98.9	261.6	99.0
Jet A (TF-1)	261.8	99.1	259.0	98.0	271.3	102.7	271.2	102.7
JP-4 (MF-1)	251.4	95.2	257.4	97.4	250.7	94.9	253.5	96.0
Diesel	260.5	98.6	257.7	97.5	266.8	101.0	266.3	100.8
RSFO	230.2	87.2	228.5	86.5	232.6	88.0	229.5	86.9
Jet A - Diesel	1.3	0.5	1.3	0.5	4.5	1.7	4.9	1.9
MF-2								
Gasoline	266.5	100.9	263.5	99.7	256.7	97.2	-	-
Jet A (TF-1)	264.6	100.2	272.9	103.3	276.6	104.7	-	-
JP-8 (MF-2)	271.0	102.6	284.0	107.5	285.8	108.2	-	-
Diesel	261.6	99.0	263.1	99.6	270.6	102.4	-	-
RSFO	230.6	87.3	230.9	87.4	232.3	87.9	-	-
Jet A - Diesel	3.0	1.2	9.8	3.7	6.1	2.3	-	-
JP-8 - Diesel	9.4	3.6	20.9	7.9	15.2	5.8	-	-
MF-3/4								
Gasoline	266.6	100.9	264.3	100.1	256.7	97.2	251.5	95.2
Jet A (TF-1)	262.8	99.5	265.8	100.6	274.0	103.7	279.4	105.8
JP-8 (MF-3/4)	262.8	99.5	265.7	100.6	272.5	103.1	279.0	105.6
Diesel	261.4	99.0	264.0	99.9	270.6	102.4	277.0	104.9
RSFO	230.5	87.3	231.3	87.6	232.3	87.9	229.4	86.8
Jet A - Diesel	1.4	0.5	1.8	0.7	3.4	1.3	2.4	0.9
JP-8 - Diesel	1.4	0.5	1.7	0.7	1.9	0.7	2.0	0.7

TABLE 88

MARGINAL COSTS - WEST U.S.

	1985				1995			
	Normal Case		Emergency Case		Normal Case		Emergency Case	
	$/m^3	¢/gallon	$/m^3	¢/gallon	$/m^3	¢/gallon	$/m^3	¢/gallon
MF-1								
Gasoline	244.7	92.6	245.4	92.9	237.4	89.9	241.4	91.4
Jet A (TF-1/1A)	263.6	99.8	263.7	99.8	265.2	100.4	265.8	100.6
JP-4 (MF-1)	233.8	88.5	241.3	91.3	227.2	86.0	239.4	90.6
Diesel	253.5	95.9	253.8	96.1	259.1	98.1	259.7	98.3
RSFO	243.0	92.0	243.0	92.0	242.4	91.8	242.3	91.7
Jet A - Diesel	0.1	3.9	9.9	3.7	6.1	2.3	6.1	2.3
MF-2								
Gasoline	233.5	88.4	-	-	236.2	89.4	-	-
Jet A (TF-1/1A)	323.8	122.6	-	-	267.7	101.3	-	-
JP-8 (MF-2)	353.5	138.8	-	-	280.7	106.3	-	-
Diesel	248.0	93.9	-	-	263.5	99.7	-	-
RSFO	234.5	88.8	-	-	242.6	91.9	-	-
Jet A - Diesel	75.8	28.7	-	-	4.2	1.6	-	-
JP-8 - Diesel	105.8	44.9	-	-	17.2	6.6	-	-
MF-3/4								
Gasoline	241.2	91.3	241.1	91.3	236.0	89.3	222.4	84.2
Jet A (TF-1/1A)	265.2	100.4	269.2	101.9	267.6	101.3	277.0	104.9
JP-8 (MF-3/4)	257.0	97.3	260.7	98.7	266.2	100.8	276.8	104.8
Diesel	255.3	96.7	258.8	98.0	260.9	98.8	274.6	103.9
RSFO	243.2	92.1	242.7	91.9	242.6	91.8	241.8	91.5
Jet A - Diesel	9.9	3.7	10.4	3.9	6.7	2.5	2.4	1.0
JP-8 - Diesel	1.7	0.6	1.9	0.7	5.3	2.0	2.2	0.9

7.2.5 - Product Shortfalls

As mentioned previously, the optimization program results indicated that the required demand schedule (Tables 83 and 84) could not be met in most of the emergency demand cases for the conversion of MF-1 to MF-2. A quantitative summary of the shortfalls is given in Table 89. Shortfalls did not occur when the relaxed property fuels, MF-3 or MF-4, were produced.

Product shortfalls occurred in the three cases with the lowest product N/TD. If this ratio declines in years after 1995 as projected, shortfalls could become even larger.

7.2.6 - Conversion Costs on an Equal Energy Basis

The data in Table 90 show that the volumetric energy contents of the JP-8 study fuels were 6 to 8% greater than those of the baseline JP-4. Thus, as in Europe, demands could be reduced by this amount (Table 91). The costs of converting to a smaller volume of kerosene jet fuel were estimated by applying the marginal costs of the fuels affected to the changes in volume demand for each case. The resulting annual cost increases are shown in the "Equal Energy" portion of Table 92. For some MF-2 cases, the marginal costs were higher than the average costs, adding uncertainty to the estimate, and a range has been presented. Average cost increases on a unit basis are presented in Table 93.

The data in Table 92 show that in the limit, the costs attributable to conversion can be reduced if the differences in energy content are considered. Because of uncertainties due to high marginal costs and shortfalls, comparisons are only approximate. For normal demands, equal energy conversion costs for the U.S. ranged from 15 to 55% of the equal volume conversion costs. It is worth noting that for the East U.S. in 1985, savings due to relaxation and reduced volumetric demand exceed the conversion cost. Hence, negative cost increases are shown in Table 92 to indicate cost reductions relative to the JP-4 case. However, as was pointed out for Europe, equal energy conversion cannot be fully achieved, and the actual cost for conversion would probably fall between the equal volume and equal energy values shown in Table 92.

7.2.7 - Summary of U.S. Conversion Study Results

Key findings of the study to determine the refining cost increases for conversion of the U.S. Air Force from wide-cut to kerosene military jet fuel are summarized below:

- Under the assumptions used, conversion of the U.S. Air Force from JP-4 to an equal volumetric demand of JP-8 is possible, although at a cost penalty of $300 million in 1985 and $460 million by 1995.

TABLE 89

PRODUCT SHORTFALLS - MF-2 EMERGENCY DEMAND, 1000 m^3/d

	Demand	Produced	Shortfall	% Produced
East U.S.				
1995				
Jet A	128	104	24	81
West U.S.				
1985				
No. 1 Diesel	1	-	1	-
Jet A	34	16	18	47
JP-8 (MF-2)	23	21	2	91
1995				
JP-8 (MF-2)	23	21	2	91

TABLE 90

CALCULATED ENERGY PROPERTIES OF MILITARY FUELS - U.S.

	Fuel	East U.S.		West U.S.	
Density, kg/m^3	MF-1	742		754	
	MF-2	802		802	
	MF-3/4	814		826	
Gravimetric Energy Content					
MJ/kg-net	MF-1	43.7		43.5	
(% Difference from MF-1)	MF-2	43.3	(-1.1)	43.3	(-0.5)
	MF-3/4	43.0	(-1.6)	43.0	(-1.1)
Volumetric Energy Content					
GJ/m^3-net	MF-1	32.7		33.1	
(% Difference from MF-1)	MF-2	35.0	(7.0)	35.0	(5.7)
	MF-3/4	35.3	(8.0)	35.6	(7.8)

TABLE 91

MILITARY FUEL DEMANDS FOR EQUAL ENERGY CONVERSION - U.S. 1985 AND 1995, 1000 m^3/d

	Normal Demand			Emergency Demand		
	JP-4	JP-8		JP-4	JP-8	
	MF-1	MF-2	MF-3/4	MF-1	MF-2	MF-3/4
East	26.1	24.3	24.2	78.2	73.1	72.5
West	7.8	7.3	7.2	23.4	22.1	21.6
	33.9	31.6	31.4	101.6	95.2	94.1

TABLE 92

ANNUAL COST INCREASES FOR CONVERSION FROM JP-4 TO JP-8 IN U.S., $ MILLION/YR

	Equal Volume Basis				Equal Energy Basis			
	Normal Demand		Emergency Demand		Normal Demand		Emergency Demand	
	MF-2	MF-3/4	MF-2	MF-3/4	MF-2	MF-3/4	MF-2	MF-3/4
1985								
East	159	104	597	326	10	-70	40-230	-320
West	137	71	*	199	30-130	10	*	0
Total U.S.	296	175	*	525	40-140	-60	*	-320
1995								
East	324	206	*	694	70-150	20	*	140
West	139	111	*	337	70-100	50	*	140
Total U.S.	463	317	*	1031	140-250	70	*	280

* Product shortfall prevents calculation of increased costs.

TABLE 93

AVERAGE COST INCREASES FOR CONVERSION OF JP-4 TO AN EQUAL ENERGY OF JP-8 IN THE U.S.

	Normal Demand				Emergency Demand			
	MF-2		MF-3/4		MF-2		MF-3/4	
	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon	$\$/m^3$	¢/gallon
1985								
East	1.1	0.4	-7.9	-3.0	1.6 to 8.7	0.6 to 3.3	-12.2	-4.6
West	1.1 to 4.9	0.4 to 1.8	3.7	1.4	*	*	0	0
1995								
East	7.9 to 16.9	3.0 to 6.4	2.3	0.9	*	*	5.3	2.0
West	26.2 to 37.5	9.9 to 14.2	19.1	7.2	*	*	17.7	6.7

* Product shortfall prevents calculation of increased costs.

- Relaxation of JP-8 aromatics and smoke point to levels typical of civilian Jet A with the reportable limit extensions and the use of cracked stocks would reduce these added costs by \$125 million in 1985 and \$145 million in 1995.
- Under tripled military fuel demands, shortfalls of both civilian and military jet fuels would arise if the conversion occurs. The relaxation of the JP-8 properties would alleviate the emergency-demand shortfalls at a cost of \$525 million in 1985 and \$1030 million by 1995.
- If the demand of military kerosene fuels were reduced to account for the 6 to 8% higher volumetric energy content of these fuels compared to that of wide-cut fuels, normal conversion costs could be reduced to as little as 15 to 55% of the equal-volume demand conversion costs.

8. SUMMARY OF RESULTS AND CONCLUDING REMARKS

This report presents the results of a technical and economic analysis of the effect of jet fuel property variations on output and refining costs of jet fuels in the United States, Canada, and Europe. In addition, the models were applied to determine the costs of conversion of military jet fuel from wide-cut (naphtha-based) to kerosene-based in Europe and the United States. Key results and concluding remarks are presented below.

8.1 UNITED STATES PRODUCIBILITY

These studies investigated the effects of the substitution of several jet fuels with relaxed properties or cracked stocks for current, average-quality jet fuel on the maximum output of jet fuel. Cases covered variations of crude feedstocks, refining capabilities, and refinery product distribution expressed as the Gasoline-to-Distillate ratio (G/D). Key results are as follows.

- In hydroskimming refineries, which had no conversion capabilities (cracking or boiling point reduction), property relaxation had little or no effect.
- Relaxation of aromatics and freezing point or use of cracked stocks increased jet fuel yield for conversion refineries from an overall average of 12% to as high as 35% of the crude volume.
    - In the East, yield increases were generally greatest for the high conversion refinery at high G/D. Relaxation of properties or the use of cracked stocks were equally effective in increasing yield. At a G/D of less than 1, however, producibility was limited by the competition from distillate fuels and excess naphtha (gasoline).
    - In the West, yield increases were also greatest for the high conversion refinery. However, the use of cracked stocks was usually more effective than property relaxation in increasing yield. Also, for some refineries, yield increases were greatest at the low G/D cases because there was a better balance of refinery output and product demands. Also, investment in conversion processes was justified.
- Substitution of coal liquids for 14% of petroleum had little effect at higher G/D ratios but sharply reduced jet fuel yield at the lowest G/D. The high naphtha content of coal liquids accentuated the difficulties in meeting distillate demands and qualities and naphtha disposal at low G/D.

- Substitution of shale liquids for 14% of petroleum produced small changes at the high G/D but increased yield for low conversion refineries at intermediate and low G/Ds because shale liquids have no residual fuel content to limit production.

8.2 UNITED STATES COST SAVINGS

These studies investigated the effects of the substitution of several jet fuels with relaxed properties or cracked stocks for current, average-quality jet fuel on the refining costs of jet fuel. Cases covered two composite regions, East U.S. and West U.S., required to meet supply and demand projections to 2010. Key results are as follows.

- The forecast jet fuel demands could be met in the East U.S. with baseline, virgin component jet fuel, although by 2010, appreciable aromatics reduction is required.
- Demand could not be met in the West U.S. with baseline, virgin component jet fuel in 2000 and 2010. The use of 40 to 60 volume percent hydrocracked kerosene as a jet fuel component is required.
- Cost savings were greater in the West U.S. than in the East U.S. due to poorer crudes, higher jet fuel yield requirements, and lower product naphtha-to-total distillate ratios.
- Both relaxation of properties and inclusion of cracked stocks contributed toward cost savings. In the East, property relaxation resulted in slightly greater savings than using cracked stocks in baseline property jet fuel.
- Quantitative annual cost savings for the entire United States for substitution of a jet fuel with both property relaxation and cracked stocks ranged from $186 million in 1985 to $256 million in 1990, expressed in constant 1981 dollars.
- Substitution of relaxed-property jet fuels reduced refining energy by up to 2.5% of the plant fuel requirements.

8.3 CANADA PRODUCIBILITY

These studies were similar in approach to the corresponding U.S. cases. The substituted Canadian jet fuels relaxed flash point as well as aromatics content. Canadian crudes included a portion of tar sands liquids in all cases. Key results are as follows.

- The relaxation of aromatics and flash point and the use of cracked stocks increased jet fuel yields from an overall average of 12% to as high as 24% of the crude volume at anticipated 1990 G/D ratios. Yields increased to a maximum of 22% at G/D ratios anticipated for 2000 when synthetic crude constituted about one-third of the feed to each refinery.

- The increase in the use of synthetic crude projected for 2000 constrained jet fuel yield and relaxation-associated yield increases. The very low naphtha content of synthetic crude forced some distillate, potentially available for jet fuel blending, to be cracked to naphtha to satisfy gasoline demand. The poor quality of synthetic crude distillates also limited jet production.

- Most producibility increases resulted from adding cracked stocks to the jet pool. Relaxation of aromatics had a smaller effect and relaxation of flash point had virtually no effect.

8.4 CANADA COST SAVINGS

These studies were similar in approach to the corresponding U.S. cases. The Canadian calculations covered two regions, East Canada and West Canada, using supply and demand projections to 1990. Key results are as follows.

- The forecast jet fuel demands in Canada can be met with baseline, virgin component jet fuel, although aromatics reduction will be needed if synthetic crude use increases as projected.

- Quantitative cost savings in Canada for substitution of a relaxed property were U.S. $10.4 million/yr and $24.9 million/yr in 1990 and 2000, respectively.

- The largest cost savings were associated with the cases that had the greatest synthetic crude run. The high aromatics content of the synthetic crude kerosene required the use of aromatics reduction processing to meet the baseline fuel (CF-1) base jet fuel aromatics level. Relaxation of properties and inclusion of cracked stocks allowed the jet fuel to be produced without aromatics reduction, thereby realizing a cost savings.

- Limited sensitivity calculations showed that both property relaxation and allowing cracked stocks in jet fuel were significant contributors to total cost savings.

8.5 EUROPE PRODUCIBILITY

These studies were also similar in approach to the corresponding U.S. cases, but the relaxed property jet fuels in Europe were substituted for a baseline military jet fuel rather than for a civilian fuel. Since baseline military fuel was similar to commercial Jet A-1 and the relaxed property fuel was similar to Jet A consumed in the U.S., European producibility results also had commercial relevance. Key results are as follows.

- The high aromatics levels of the crudes used in Europe required aromatics extraction and/or severe hydrotreatment to meet baseline military kerosene jet fuel aromatics and smoke point targets.

- Jet fuel yield and yield increases with property relaxation were limited by the need to meet the required distillate demands and the use of kerosene to meet distillate properties, especially cloud point in the North.

- Producibility increases were greatest for the conversion refineries and were generally very small for the hydroskimmers.

- Jet fuel yields were generally higher in South Europe than in North Europe because of better crude qualities and a better match of crude and product G/D ratios.

8.6 EUROPE CONVERSION

These studies investigated the effects of the substitution of military kerosene fuel (F-34) for wide-cut (F-40) on the refining costs for jet fuel. Cases covered two composite regions, North Europe and South Europe, required to meet supply and demand projections for 1985 and 1995. Additional calculations assumed an emergency where demands for all military fuels are tripled. Key results are as follows.

- Under the assumptions used, conversion of NATO forces in Europe from F-40 to an equal volumetric demand of F-34 is possible, although at a cost penalty of $125 million/yr in 1985 and $100 million/yr by 1995.

- Relaxation of F-34 aromatics content to levels typical of current civilian fuel (Jet A/A-1) with reportable aromatics and the use of cracked stocks would lower these increases by about $25 million in 1985 and 1995.

- Under tripled military fuel demands, conversion costs would rise to $435 million in both years. Relaxation would reduce conversion costs by $75 million in 1985 and by $120 million in 1995.

- If the demand of military kerosene jet fuels were reduced to account for the 7 to 9% higher volumetric energy content compared to that of wide-cut fuels, normal conversion costs could be reduced to as little as 40 to 60% of the equal-volume demand conversion costs.

8.7 UNITED STATES CONVERSION

These studies investigated the effects of the substitution of military kerosene fuel (JP-8) for wide-cut (JP-4) on the refining costs for jet fuel. Cases used the regional models established for the U.S. costs savings studies with supply and demand projections for 1985 and 1995. The emergency scenarios used in the European conversion studies were also included in the United States. Key results are as follows.

- Under the assumptions used, conversion of the U.S. Air Force from JP-4 to an equal volumetric demand of JP-8 is possible, although at a cost penalty of $300 million in 1985 and $460 million by 1995.
- Relaxation of JP-8 aromatics and smoke point to levels typical of current civilian Jet A with the reportable limit extensions and the use of cracked stocks would reduce these added costs by $125 million in 1985 and $145 million in 1995.
- Under tripled military fuel demands, shortfalls of both civilian and military jet fuels would arise if the conversion occurs. The relaxation of the JP-8 properties would alleviate the emergency-demand shortfalls at a cost of $525 million in 1985 and $1030 million by 1995.
- If the demand of military kerosene fuels were reduced to account for the 6 to 8% higher volumetric energy content of these fuels compared to that of wide-cut fuels, normal conversion costs could be reduced to as little as 15 to 55% of the equal-volume demand conversion costs.

8.8 CONCLUDING REMARKS

The producibility and cost savings analyses showed that present-quality jet fuel can meet projected future demands, even allowing for deteriorating crude qualities and changes in product competition. One important exception is the West U.S. region, where jet fuel demand shortfalls can occur after 1990. A plausible approach for this region is the use of hydrocracked stocks blended into jet fuel to increase the output. A few refiners in this region are already manufacturing jet fuel in this manner. Hydrocracking will also be required in some regions to meet diesel fuel volume and quality.

The study results also showed that, although demands can be met by present-quality fuels, in most cases relaxation of aromatics and freezing point offers advantages in increasing output and decreasing refining cost. An interesting finding is that the use of cracked stocks in jet fuels is an alternative to relaxation of properties that will provide the same, if not greater, advantages in producibility and cost savings. Cracked stocks include process streams from catalytic cracking and coking. Their inclusion in jet fuels requires further research, since laboratory tests have shown that these components may have low storage and thermal stability. Existing data on cracked stocks and blending correlations are not available for storage and thermal stability. Hydrocracked streams, however, have excellent stability properties and are considered equivalent to virgin, nonprocessed streams.

The conversion analysis showed a cost on the order of hundreds of millions of dollars a year, for the wide-cut to kerosene military jet fuel conversion. These costs can be reduced substantially by the substitution of kerosene fuels with relaxed properties and cracked stocks. Volumetric demands of the military fuels can be reduced, cutting costs, if the higher energy of the kerosene fuels can be used. Conversion costs can be made more attractive if commonality is considered, that is, the relaxation of both the military and civilian fuels to reduce refining and distribution costs. This analysis, however, was outside the scope of the study.

The wide range of producibility and cost results illustrated that regional variations cannot be represented effectively by a single average refinery configuration. Verification of the U.S. models by comparison of calculated with historic crude and product volume and property data as well as published process capacities gave confidence that the models used provided a realistic simulation. The power of the models to utilize these parameters successfully suggests that further modeling refinements may allow additional questions to be answered. These are discussed in the following section.

9. RECOMMENDATIONS FOR FUTURE WORK

The results of this study point to several areas where further refinements to the computer models may be desirable. These are given below:

- Wider distillation cut points. Raising the kerosene final boiling point will raise the freezing point of the entire cut and will probably also increase the aromatics level. In the present models when freezing point and aromatics were relaxed, a heavier gas oil cut was blended. However, changing the kerosene cut point so the kerosene properties met the product properties might have resulted in larger producibility increases than were obtained by adding gas oil. Lowering the initial boiling point of the kerosene cut would be another way of lowering the flash point rather than adding naphtha. This might produce a larger increase in yield than was obtained in Canadian modeling.

- Cracked stock stability data. Hydrocracked stocks are generally considered to possess thermal and storage stability characteristics similar to corresponding virgin stocks. Similar stocks from other cracking processes even after mild hydrofining are generally considered to have poorer stability characteristics. The use of these stocks could be limited by stability considerations. Existing cracked stock stability data or correlations of species associated with instability could be incorporated into the models.

- Model refinery kerosene competition. Many modern integrated refineries divert portions of the kerosene cut to products that have a higher value than jet fuel. This reduces the quantity and frequently the quality of kerosene available to produce jet fuel. For example, linear paraffins may be removed leaving the kerosene enriched in aromatics. Jet fuel produced using kerosene from which linear paraffins have been extracted could exceed the aromatics property target. Also, less kerosene would be available for jet fuel blending. The extraction of linear paraffins could be modeled and the jet fuel producibility determined.

- Limitations on individual refinery product slates. When one crude could be run in more than one refinery type, the refinery with the highest conversion level was always chosen by the model. Also, the preferred crude for jet fuel production usually possessed the lowest aromatics level. When feasible, the model made as much jet fuel as possible using this crude. To increase the realism of regional refinery modeling, each refinery could be required to produce a specified fraction of major products, in keeping with refinery capabilities. Since less efficient refineries would be in use, it is possible that cost savings associated with relaxation could be greater than the fully optimized cost savings determined.

- Updated process representation. New yield, efficiency and cost information are available due to advances in processes, such as resid hydroconversion. These changes may make certain alternative processing more desirable economically.

- Reduced requirements for aromatics-relaxed jet fuels. Relaxation of aromatics levels produced fuels with a higher volumetric energy content than unrelaxed fuels. On an equal energy basis, a smaller quantity of relaxed aromatics fuel would be required, adding further to the savings. Thus, savings due to relaxation can be categorized as being due to the use of lower cost blendstocks and the need for a reduced quantity of relaxed property fuel. Only the former cost savings were determined. The latter remain to be quantified.

- Balancing virgin and hydrocracked fuel requirements. Because of the shortfall of baseline, virgin-component jet fuel (TF-1) to meet demands in the West U.S. beyond 1990, the models used a hydrocracked baseline fuel (TF-1A) for the cost savings calculations. Investment in hydrocracking can be reduced if some of the demand is met with the virgin-component fuel blended into TF-1A. The virgin/hydrocrackate blend ratios and cost savings reported here for the maximum virgin TF-1A fuel were calculated by hand and were not optimized. Use of the regional model would produce a maximum virgin TF-1A fuel optimal solution.

10. GLOSSARY

This glossary defines many of the terms used in this report that may not be familiar to an informed reader outside the petroleum refining industry.

ALKYLATE - The desired product of the alkylation process, used primarily as a gasoline blendstock. It consists of isoparaffins and has a high octane rating.

ALKYLATION - A petroleum process that combines light olefins (propylene, butylenes) with isobutane using a catalyst to produce a high octane gasoline blendstock (alkylate).

AROMATICS - Organic compounds that contain one or more benzene rings.

AROMATICS EXTRACTION - A petroleum process in which a petroleum stream is contacted with a solvent for the purpose of removing aromatic compounds. Two product streams result, the desired raffinate stream, which is low in aromatics, and the extract stream, in which the aromatics are concentrated.

ASPHALT - Black to dark-brown material that is solid or semi-solid at ambient conditions. It is produced primarily from the residual product from vacuum distillation. Asphalt can only be made from selected crudes.

ATMOSPHERIC PIPESTILL (APS) - A primary distillation unit for separating crude oil into various components having different boiling points. It usually consists of a furnace and a distillation tower operating at essentially ambient pressure levels. Thermal decomposition of the petroleum limits the maximum temperature to about 345°-400°C. Therefore, only products that boil below this range can be separated. The higher boiling material can be further separated under vacuum. (See VACUUM PIPESTILL.)

AVIATION TURBINE FUEL - (See JET FUEL)

BOTTOMS - The product remaining after the removal of the highest boiling material in distillation of a petroleum stream. The boiling range of the bottoms depends on the feed to the distillation unit and the amount of material distilled off. In an atmospheric pipestill, this would be the material that boils higher than about 343°C (650°F).

BTX (BENZENE/TOLUENE/XYLENES) - Aromatic compounds removed from reformate and used as feedstock to chemical plants.

CAT CRACKING (See FLUID CATALYTIC CRACKING)

CAT FEED - Petroleum stream usually in the distillate or gas oil boiling range processed in a Fluid Catalytic Cracker.

CETANE NUMBER - A measurement that indicates the ignition quality of diesel fuel. High cetane number indicates good diesel fuel. Cetane number is defined as the percentage of cetane in a mixture of cetane and methyl naphthalene that has the same ignition quality in an engine as the fuel under test.

CHEMICAL FEEDSTOCKS - Light products, such a naphthas or gases, used as raw materials for chemicals or plastics.

CLOUD POINT - The temperature at which paraffin wax or other solid substances begin to crystallize out or separate from solution when a petroleum oil is chilled under test conditions.

COAL LIQUIDS - The hydrocarbon liquid produced by the liquefaction of coal by altering the ratio of carbon to hydrogen atoms in the coal. The liquefaction process usually involves the addition of hydrogen to the coal under high temperature and pressure. Coal liquids usually contain a high level of aromatics.

COKE - A black, solid, carboniferous residue produced when petroleum products are thermally cracked and the light hydrocarbon fractions are removed.

COKING (See FLUID/FLEXICOKING/DELAYED) - A thermal cracking process in which heavy oils are heated and cracked to produce lighter fractions and coke.

CONVERSION - The ability of a process or entire refinery to alter the boiling point characteristics of a feed (or crude oil). It usually implies the conversion of heavier boiling fractions into lighter boiling fractions by some cracking process.

CRACKING - A generic term to describe the breaking up of large hydrocarbon molecules into smaller molecules by either heat, pressure and/or catalysts. In some cases, the cracking is done in the presence of hydrogen.

CRITICAL (PROPERTY) - In linear programming, a constraint (such as a property specification of a product) that is at its limit and involves a cost to stay within the limit.

CRUDE OIL - A naturally occurring, complex hydrocarbon liquid, which usually contains a wide range of compounds from the very light, boiling at less than 37°C (100°F), to the very heavy, boiling at greater than 815°C (1500°F).

CUT (FRACTION) - A stream removed from a distillation unit or conversion unit, such as an atmospheric pipestill, that has a particular boiling range (e.g., a 177/260°C cut would contain compounds that boil between 177°C and 260°C).

CUT POINT - The boiling temperature division between adjacent cuts or fractions that defines the boiling range of the cuts.

DELAYED COKING - A process in which a heavy petroleum stream is thermally cracked to produce lighter products and coke. This process involves heating the feed stream to high temperature then transferring it to a drum where the cracking reactions take place. The coke settles from the liquid and remains in the drum. The liquid product, which has now been cracked to lighter components, is removed from the drum as a vapor. The coke is removed from the drum by mechanical or hydraulic means.

DENSITY - Mass of a substance per unit volume.

DIESEL FUEL - A petroleum distillate product, usually boiling between 177°C (350°F) and 343°C (650°F), used as a fuel for vehicular and stationary diesel engines. It is similar to heating oil, although diesel fuel typically must meet more stringent product specifications, such as minimum cetane number, maximum sulfur levels, and a more controlled distillation range.

DISTILLATE - Generically, distillate is any product of distillation. In the petroleum industry this commonly refers to products that boil at a higher temperature than naphthas and at lower temperatures than vacuum gas oils (usually between 177°C and 343°C). Streams such as kerosene and atmospheric gas oils are examples of distillates.

END POINT (FINAL BOILING POINT) - The temperature at which all of the material in a particular cut would have vaporized.

ENERGY CONTENT - The combustion energy of a fuel per unit mass or volume, determined under standard test conditions. In this study, energy contents are reported as net or lower heats of combustion, which adjust test values for the heat of vaporation of water in the exhaust products.

EXTRACT - The stream from an extraction process, such as Aromatics Extraction, in which the compounds to be removed or extracted are concentrated. In Aromatics Extraction, the aromatic compounds are concentrated in this stream.

FLASH POINT - The lowest temperature at which an oil or fuel gives off sufficient vapor to form a mixture that will ignite, under standard test conditions.

FLEXICOKING - A process in which a heavy petroleum stream is thermally cracked to produce lighter products and coke gas. This process combines Fluid Coking with the gasification of the coke with steam and air in a separate vessel to produce a fuel gas.

FLUID CATALYTIC CRACKING - A process that cracks gas oils into lighter streams using heat and a catalyst. The solid catalyst particles are maintained in a hot fluidized bed into which the oil stream is introduced. The feed is cracked and the lighter products are removed. Coke forms on the catalyst, which is removed to another vessel where the coke is burned off to supply heat to the process.

FLUID COKING - A process in which a heavy petroleum stream is thermally cracked to produce lighter products and coke. This process involves heating the feed and introducing it into a hot fluidized bed of coke particles. The coking reactions take place on the coke particles, which are removed to another vessel and burned to provide heat to the process. Excess coke is removed and can be used as fuel.

FLUX STOCK - Any blendstock added to a product pool, especially fuel oil, in order to meet a quality specification. For instance, kerosene is used as a flux in fuel oil in order to meet sulfur and viscosity specifications.

FRACTION (See CUT)

FREEZING POINT - The temperature at which crystals of hydrocarbons formed on cooling disappear when the temperature of the fuel is allowed to rise. The Freezing Point test is used to detect the separation of solids in aviation fuels at temperatures likely to be encountered during flight or on the ground.

FUEL GAS - Gaseous products, primarily methane and ethane, produced during the processing of petroleum and used as fuel in the refinery.

FUEL OIL - A residual petroleum product that is sold as a liquid fuel, primarily to industrial users. Various grades are sold, categorized primarily by the amount of sulfur contained in the fuel.

GAS OIL (LIGHT/HEAVY) - Any distillate stock heavier than kerosene obtained during the fractionation of crude oil. Common descriptors and corresponding approximate boiling ranges are:

- LAGO (Light Atmospheric Gas Oil): 204/302°C (400/575°F)
- HAGO (Heavy Atmospheric Gas Oil): 302/343°C (575/650°F)
- LVGO (Light Vacuum Gas Oil): 343/454°C (650/850°F)
- HVGO (Heavy Vacuum Gas Oil): 454/565°C (850/1050°F)

GASOLINE (MOTOR/AVIATION) - A refined petroleum product that is suitable for use as a fuel in an internal combustion engine. Motor gasoline (Mogas) is used in automobile engines and is graded according to octane level (regular/premium) and whether lead is used as an octane improver (leaded/unleaded). Aviation gasoline (Avgas) is used in airplane engines and is usually a high octane leaded fuel.

GASOLINE/DISTILLATE RATIO - A ratio of the volume of gasoline products (regular and premium, leaded and unleaded) to the volume of distillate products (diesel fuel and heating oil).

GRASS ROOTS - A term referring to new refinery equipment, which may be one process unit or a whole refinery.

HEATING OIL - A petroleum distillate product, usually boiling between 232°C (450°F) and 343°C (650°F) and primarily used as a home heating fuel.

HIGH CONVERSION REFINERY - Petroleum processing plant, or refinery, that contains processes capable of extensive conversion of the heavy boiling portion of the crude oil into lighter boiling components. Specifically, this refinery would contain a residuum conversion process, such as Coking, in addition to the processes in a Low Conversion Refinery.

HYDROCARBON - Organic compound that contains both carbon and hydrogen atoms.

HYDROCRACKING - A process that cracks large hydrocarbon molecules into smaller molecules at high temperature, high pressure, and in the presence of a catalyst and hydrogen. Typical feeds are distillates and gas oils. Depending upon the process conditions, the primary products can be either in the naphtha boiling range or distillate boiling range.

HYDROCRACKATE - Naphtha and distillate boiling range products from Hydrocracking process.

HYDRODESULFURIZATION - Process that removes sulfur compounds from petroleum streams by the addition of hydrogen, in the presence of a catalyst, to form hydrogen sulfide.

HYDROGENATION - The chemical addition of hydrogen to a petroleum stream, usually in the presence of a catalyst. Hydrogen addition can be used to saturate olefins and aromatics, remove sulfur and improve other properties depending upon the feed stream and process conditions.

HYDROSKIMMING - A term referring to the least complex refinery type. It usually only contains crude oil distillation (APS), naphtha reforming and product hydrotreating as the primary processing steps. It is not capable of any significant conversion of the boiling ranges of the petroleum products.

HYDROTREATING (See HYDROGENATION)

INITIAL BOILING POINT (IBP) - Boiling point of the lowest boiling component of a particular cut.

INVESTMENT - Monies used to purchase materials (i.e., equipment) and labor for the construction of a process unit or units.

ISOMERIZATION - Process that converts one hydrocarbon into another hydrocarbon having the same molecular weight but a different structure. It is usually used to convert low octane straight chain isomers of pentane and hexane (as those contained in light virgin naphtha) to higher octane branched isomers for blending into gasoline or to convert n-butane to iso-butane.

JET FUEL - A petroleum product used in jet aircraft turbine engines, which is highly specified to meet stringent product properties. The principal types of jet fuel are wide-cut or naphtha-based (JP-4, Jet B, or F-40), boiling in the range of 40 to 260°C, and kerosene-based (JP-8, Jet A, Jet A-1, or F-34), boiling in the range of 150 to 290°C. Typical product properties that are specified for jet fuel are distillation range, flash point, freezing point, combustion quality as measured by smoke point, thermal stability, and maximum contamination level (such as sulfur).

KEROSENE - Petroleum stream obtained from APS that boils between about 177°C (350°F) and 260°C (500°F). Typical dispositions are to aviation turbine fuel (jet fuel), diesel and heating oil. Kerosenes are sometimes used as flux stocks in fuel oils.

LIGHT ENDS - The low boiling portion of a petroleum fraction, generally pentane and lighter components.

LINEAR PROGRAMMING (LP) - Mathematical technique used to optimize the economic allocation of resources to activities within a given set of constraints. Computerized programs using that technique are utilized to optimize refinery operations such that desired products are made at the lowest cost.

LIQUID PLANT FUEL - Liquid petroleum streams used as fuel in a refinery. It is similar to fuel oil, although specific properties may differ.

LIQUEFIED PETROLEUM GAS (LPG) - Light hydrocarbon material, gaseous at atmospheric conditions, held in the liquid state by pressure to facilitate storage, transport and handling. Commercial LPG consists of propane and/or butane.

LOW CONVERSION REFINERY - Petroleum processing plant, or refinery, that contains processes capable of conversion of distillate and gas oil fractions of the crude oil into lighter boiling components such as naphtha. This refinery would usually contain APS, VPS, naphtha reforming, and Fluid Catalytic Cracking as the primary processes.

LUBES - Lubricating oils produced by processing the vacuum gas oil or residuum cut of the crude oil.

MARGINAL COST - In Linear Programming, the cost to produce the last increment of a particular product. In general, the higher the marginal cost, the more difficult it is to produce that product.

MOGAS (See GASOLINE)

NAPHTHA - Petroleum stream whose initial cut point is in the C_5 (pentane) range (37°C; 100°F) and final cut point is about 163-204°C (325-400°F). Naphthas are usually split into Light (C_5/71°C) and Heavy (71/177°C) fractions.

NAPHTHA/DISTILLATE RATIO - The ratio of the volume of components of a crude boiling in the naphtha range, to the volume of components boiling in the distillate range.

NAPHTHA/TOTAL DISTILLATE RATIO - The ratio of the volume of all naphtha products (gasoline, BTX, Chemical Feed, and Jet B) to the volume of all distillate products (diesel fuel, heating oil, and Jet A).

NATURAL GAS CONDENSATE - The pentane and heavier hydrocarbons produced as a condensate in natural gas processing.

OCTANE NUMBER (RON/MON) - A number indicating the antiknock combustion quality of gasoline under specific conditions. There are several different octane tests that simulate different operating conditions. Two of the most common of these are the Research test, which gives the Research Octane Number (RON), and Motor test, which gives the Motor Octane Number (MON). Since these tests both simulate important, and yet different operating conditions, an Octane Index (RON + MON/2) is often reported for a given fuel. This is the rating posted on service station pumps in the U.S.

OLEFINS - Hydrocarbons with double bonds, which are more reactive than paraffins leading to poor stability properties.

PARAFFINS - Hydrocarbons that are linear, branched, or cyclic in structure, with the maximum number of hydrogen atoms per carbon (saturated). Linear paraffins are also called normal paraffins. Cyclic paraffins are frequently termed naphthenes in the petroleum industry.

PARTICIPATION - This term refers to the percentage of crude oil available in a region that can be used to make a specific product such as jet fuel, since not all refineries make all products.

PIPESTILL (See APS and VPS)

POOL - Generic term used to represent the blending of several stocks into a final product or group of products.

POUR POINT - The lowest temperature at which oil will pour or flow when it is chilled under prescribed conditions.

PROCESS STOCKS - Generic term used to represent any petroleum stream that has been significantly altered on a molecular level in a refining process. Streams that have been only fractionated in an APS, VPS, or have only been mildly treated for sulfur removal, are not considered Process Stocks. (See VIRGIN.)

RAFFINATE - The stream from an extraction process, such as Aromatics Extraction, that remains after the compounds which are more soluble in the solvent are extracted. In Aromatics Extraction, the raffinate is the stream with the low aromatics content.

REFORMATE - Primary product from Naphtha Reforming process. It consists of naphtha boiling range material that is highly aromatic and therefore has a high octane rating. It is used primarily as a gasoline blendstock. Selected aromatic compounds are sometimes removed and used as chemical plant feedstock. (See BTX.)

REFORMING (NAPHTHA) - Process that converts molecular structure of naphtha to obtain product with higher octane for blending to gasoline. The process is usually catalytic and operates at elevated temperature and pressure. The process is also a significant producer of hydrogen which is then usually used in the refinery in the hydrotreating processes.

REFORMING (STEAM) - Process that produces hydrogen from hydrocarbon feeds such as fuel gas or naphtha. The process reacts hydrocarbons and steam making hydrogen and carbon dioxide at elevated temperatures in the presence of a catalyst. The carbon dioxide is removed and the hydrogen product concentrated and compressed to the pressure required in the process units that utilize it (such as hydrotreaters).

REID VAPOR PRESSURE - A measure of the vapor pressure of a petroleum stream at 100°F (37°C).

RESIDUUM - The material remaining as unevaporated liquid or solid from processes involving distillation or cracking. The term is often used interchangeably with BOTTOMS.

RESID HYDROCONVERSION - Process that converts the heavy boiling fraction of crude oil into lighter fractions. It usually operates at elevated temperatures and pressure in the presence of a catalyst in a hydrogen rich atmosphere.

SHALE OIL - Hydrocarbon stream that is produced by the processing of oil shale, which is a sedimentary rock that contains organic matter. The oil can be liberated by heating in a retorting operation and subsequently treated with hydrogen to improve its quality.

SMOKE POINT - A measure of kerosene burning cleanliness. Using a standard laboratory lamp, it is expressed in terms of flame height in millimeters before smoking starts.

SPECIFIC GRAVITY - The ratio of the weight in air of a given volume of a sample at a stated temperature to the weight in air of an equal volume of distilled water at the same temperature.

STABILITY - Generic term used to describe the resistance of some hydrocarbons to decompose into less desirable components that adversely affect the performance of a fuel. (See THERMAL STABILITY.)

SWEET - A term used to describe a petroleum fraction that is relatively free from corrosive and malodorous sulfur compounds.

SWEET CRUDE - Crude oil containing low levels of corrosive and malodorous sulfur compounds. This description usually indicates that little if any chemical removal of sulfur compounds is required in product streams.

SYNTHETIC CRUDE - Hydrocarbon liquid that resembles crude oil produced from resources such as tar sands, coal, or oil shale. Quality of the synthetic crude depends upon the resource used and the processing employed to produce and upgrade the synthetic crude.

TAR SANDS (OIL SANDS) - Naturally occurring deposits of sands that contain substantial amounts of petroleum-like hydrocarbons. Unlike conventional crude oil, the hydrocarbons must be physically or thermally extracted from the sand. Usually, the resource is mined and a synthetic crude produced by the extraction and treating of the hydrocarbons.

THERMAL CRACKING - A process in which a petroleum stream is heated to a temperature high enough to induce decomposition of larger molecules to produce lighter products.

THERMAL STABILITY - The tendency of a fuel to resist formation of oxidation deposits when thermally stressed in a standard apparatus under flowing conditions at a specified residence time and temperature.

THROUGHPUT - The volume of feedstock charged to a process unit frequently per unit of time.

VACUUM PIPESTILL (VPS) - A distillation unit for separating residuum (bottoms) from the atmospheric pipestill into streams having different boiling points (vacuum gas oils and vacuum resid). It usually consists of a furnace and a distillation tower. Because the unit is operated under vacuum (i.e., less than ambient pressure), separation of components with high atmospheric pressure boiling points is possible at temperatures below about 345-400°C (650-750°F) to minimize thermal decomposition of the petroleum.

VIRGIN - A petroleum product that has been fractionated from crude oil, but not processed or changed in any other way. The definition is sometimes expanded to include streams that have been mildly processed for the removal of sulfur compounds.

VISBREAKING - A process in which a heavy petroleum stream is thermally cracked to produce lighter products. The process is similar to Thermal Cracking, but usually less severe (lower temperature and residence times) and produces a lower percentage of light products. Originally, process was used to reduce (or "break") the viscosity of fuel oil in order to meet specifications.

VISCOSITY - A measure of the resistance to flow of a fluid.

YIELD - The amount of a desired product obtained from a process, usually expressed as a percentage of the feedstock or total products.

11. REFERENCES

1. American Society for Testing and Materials, D1655-83a, "Standard Specification for Aviation Turbine Fuels," in 1984 Annual Book ASTM Standards, Volume 05.01, Philadelphia, 1984.

2. E. M. Shelton and C. L. Dickson, "Aviation Fuels, 1983," NIPER-134 PPS, 84/2, April, 1984.

3. R. Friedman, "Trends of Jet Fuel Demand and Properties," in Assessment of Alternative Aircraft Fuels, NASA Conf. Publ. 2307, 1984, pp. 1-10.

4. R. B. Whyte, Ed., "Alternative Engine Fuels - Executive Summary," AGARD-AR-181-Vol. I, July, 1982.

5. G. M. Varga, Jr., A. R. Cunningham, J. F. Gorgol, A. J. Graf, and G. A. Oliver, "The Effect of Property Changes on Jet Fuel Producibility and Costs," in Assessment of alternative Aircraft Fuels, NASA Conf. Publ. 2307, 1984, pp. 11-22.

6. National Petroleum Council, Committee on Refinery Flexibility, J. McAfee, Chairman, "Refinery Flexibility," December, 1980.

7. E. M. Shelton, "Aviation Turbine Fuels, 1978" BETC/PPS-79/2, U.S. Department of Energy, May, 1978.

8. J. P. Longwell, Ed., "Jet Aircraft Hydrocarbon Fuels Technology," NASA Conf. Publ. 2033, 1978.

9. E. M. Shelton, "Heating Oils, 1978," BETC/PPS-78/4, U.S. Department of Energy, 1978.

10. E. M. Shelton, "Diesel Fuel Oils, 1978," BETC/PPS-78/5, U.S. Department of Energy, 1978.

11. "Aviation Turbine Fuels. An Assessment of Alternatives" Ad Hoc Committee on Alternative Aviation Turbine Fuels, Commission on Engineering and Technical Systems, National Research Council, National Academy Press, 1982, p. 29.

12. C. L. Blake, "The Impact of Petroleum, Synthetic and Cryogenic Fuels on Civil Aviation," DOT/FAA/EM-82/29, U.S. Department of Transportation, June, 1982, p. 10.

13. National Energy Board of Canada, "Canadian Energy Supply and Demand. 1980-2000," June, 1981.

14. 2nd Lt. W. E. Harrison, III, "The Chemical and Physical Properties of JP-4 for 1980-1981," AFWAL-TR-82-2052, June, 1982.

15. International Energy Annual, Table 15, "World Output of Refined Petroleum Products in 1981," U.S. Department of Energy DOE/EIA-0219(81).

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15. Supplementary Notes

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16. Abstract

This study determined the effects of changes in properties and blending stocks on the refinery output and cost of jet fuel in the U.S., Canada, and Europe. The study utilized computerized refinery models that minimized production costs and incorporated a 1981 cost structure and supply/demand projections to the year 2010. Except in the West U.S., no changes in jet fuel properties were required to meet all projected demands, even allowing for deteriorating crude qualities and changes in competing product demand. In the West U.S., property changes or the use of cracked blendstocks were projected to be required after 1990 to meet expected demand. Generally, relaxation of aromatics and freezing point, or the use of cracked stocks produced similar results, i.e., jet fuel output could be increased by up to a factor of three or its production cost lowered by up to $10/m^3 (4¢/gallon). High quality hydrocracked stocks are now used on a limited basis to produce jet fuel. The study also addressed the conversion of U.S. and NATO military forces from wide-cut to kerosene-based jet fuel. This conversion resulted in increased costs of several hundred million dollars annually. These costs can be reduced by relaxing kerosene jet fuel properties, using cracked stocks and/or taking into account the greater volumetric energy content of kerosene jet fuel.

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