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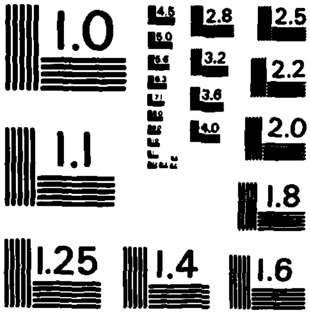
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NAVAL FUEL PROPERTY PROJECTIONS PHASE I — GENERAL TRENDS

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AFLRL No. 179

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Future Naval shipboard fuel properties are assessed from an external approach by evaluating the impact of outside influences on Naval fuel supplies. Historical trends in commercial distillate and resid fuels are reviewed. Energy, crude oil, and petroleum product forecasts are analyzed for their impact on future fuel properties; and linear program refinery model studies are reviewed to determine refinery flexibility in meeting future demand and product quality. Planned refinery construction is summarized and evaluated for effects on future quality. Synthetic fuel penetration into commercial fuel markets is also addressed. Conclusions from each of the above factors and their effects on future shipboard fuel quality are summarized.

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EXECUTIVE SUMMARY

Distillate Fuels

The preferred Navy distillate, MIL-F-16884H, may be subject to some changes in quality due to changing crude quality, product demand distribution, and refining practices. Historical changes in commercial distillate fuel quality in the United States has shown decreased quality in gravity, aniline point, carbon residue, and cetane number. A shift in distillation range as well as reduced crude oil quality may be responsible.

The U.S. serves as a good example of what may happen to fuel properties elsewhere in the world in the future because of the poorer quality crudes which are refined here. The Western Region of the U.S. is a particularly appropriate place to focus on because of its history of exceptionally heavy crude oil and high transportation fuel demand. Distillate fuel properties in the Western Region of the U.S. have shown trends which are comparable to the rest of the U.S. Exceptions to this are viscosity, flash point, and distillation range. Viscosity and flash point have been higher due to a higher distillation range in the Western Region, a trend which is also occurring in the rest of the country. The shift to a higher distillation range may be caused by a higher demand for lighter products including jet fuel and gasoline in the Western Region. Higher distillation ranges may aggravate viscosity, carbon residue, demulsification, pour point, cloud point, sulfur, corrosion, and acid numbers. MIL-F-16884H allows a high distillation 90 percent point and end point by specification. The trend of commercial fuels toward higher distillation range may cause competition in this area and take away fuel quality which has been available in the past for Navy fuels.

Competition for combustion quality has driven cetane number in a downward trend for several years. Commercial diesel fuel average cetane number has fallen below the MIL-F-16884H requirement and nearer the commercial specification. Future cetane numbers will likely be controlled similar to octane numbers for gasoline where little or no give-away is realized and specification is met precisely. High cetane fuel specification will be more costly just as premium unleaded gasoline is more costly than regular unleaded. To reach this degree of control, a more precise method of combustion quality measurement will be necessary.

Although distillate demand is projected to rise from 25 percent to 32 percent of total refined products, this will be more than offset by a decrease in demand for gasoline, causing a decrease in total light products from 68 percent to 64 percent. The feasibility of meeting future demand levels has been demonstrated, in part, in the European and Japanese markets where distillate demand has traditionally been as much as 34 percent, but total light products demand has been much less than in the United States. Exceptionally heavy crudes processed in the U.S. Western Region have produced 65 percent total light products and a large fraction of jet fuel which requires the highest of fuel quality. Total distillate production was only 21 percent in the single year examined, and some imported refined products were necessary to meet demand. The Western Region is able to produce high quality products from very low quality crude because of specially tailored downstream refining capacity. Future demand will call for not only higher total distillates but higher quality in the distribution with more jet fuel and higher pool cetane number requirements.

The refining industry is well aware of market trends and is making long-term adjustments to accommodate low quality crudes and a shift in product distribution. Linear program models of refinery operations demonstrate that technology currently exists which can more than meet future demand slates with high quality products. Higher costs may be associated with rising distillate demand; and therefore, to minimize expenses, a trend toward meeting minimum specifications may occur. A compromise in MIL-F-16884H specifications closer to commercial specifications would likely improve both cost and availability but may not be consistent with special operational requirements.

To meet the future demand slates, existing refinery configurations will have to be upgraded. Distillate quality can be met by additional hydrocracking, hydrorefining, and severe hydrotreating. Segregation of distillate products, improved distillation, advanced catalysts, and imports of refined products may also help meet future demand requirements while at the same time maintaining adequate quality.

Refinery construction plans in the U.S. and throughout the rest of the non-communist world demonstrate a response to future demands. Large percentage increases are planned in catalytic hydrocracking, catalytic hydrorefining, thermal cracking, and hydrogen manufacturing. Downstream refinery capacity outside the U.S. represents a modern flexible refining system not far behind the U.S. in capability and actually leading the U.S. in several categories on a percentage basis in individual countries. Future refinery construction plans will call for even more catalytic hydrocracking and hydrogen manufacturing.

Synthetic fuels will account for no more than a small percentage of future commercial fuel supplies reaching only about 6-8 percent by the year 2000. Degree of penetration into the Navy supply system will largely depend on internal policies. In general, fuels derived from synthetic sources (especially coal) require a great deal of upgrading and are more costly. Syncrudes can be upgraded to specification quality; as the cost of exploration, production, and refining of petroleum fuels approaches the cost of synfuel recovery, larger quantities will be made available.

Resid Fuels

Although resid fuels are being purged from the U.S. Navy fuel supply system, the abundance of commercial resid and resid-containing fuels in the maritime fuel delivery network may impact the quality of the Naval fuels in the future. This may be chiefly in the form of contamination. Anticipated heavy oil upgrading is expected to leave poorer quality resid fuels of lower stability, higher metals, and catalyst fines contamination. This has not been observed in past property trends in the U.S., but this may possibly be due to higher quality imported resids, low resid demand or a shift of low quality resids to alternate uses. Refinery upgrading will lower resid production, particularly in the U.S. but also in the rest of the world.

FOREWORD

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I. INTRODUCTION

An assessment of past and future Navy ship fuels (1)* was performed by N.F. Lynn and E.W. White of the David Taylor Naval Ship Research and Development Center, Bethesda, MD, J.F. Boyle of the Naval Ship System Engineering Station, Philadelphia, PA and R.P. Layne of the Naval Sea Systems Command, Washington, DC. This study included a review of past Navy ship fuels, an internal fuel survey of Naval Distillate Fuel from 1979-1982, a survey of Navy fuel suppliers, and a brief forecast of refining trends. Conclusions indicated a worsening of fuel quality accompanied by changes in fuel specifications and engine design.

A similar objective is undertaken in the current study, that is, to determine the future quality of Navy fuels. A different approach is taken in this effort. The former study reviewed many of the internal factors affecting fuel quality as mentioned above. The current study proposes to analyze external components which will have an impact on the future quality of Navy fuels. The components to be examined include historical commercial fuel quality, forecasts of oil supply and product demand, refinery processing analyses, refinery construction trends, and synthetic fuel penetration. The impact of each of these components on future Navy fuel quality are summarized in the Executive Summary included in this report. The external approach undertaken here will provide a new perspective in assessing future fuel quality to both enhance and compliment the previous work.

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* Underscored numbers in parentheses refer to the list of references at the end of the report.

II. HISTORICAL FUEL PROPERTY TRENDS

A. Navy Distillate Fuels

The preferred fuel for all fossil-fueled surface ship power systems is a distillate (1) meeting requirements established by MIL-F-16884H. This existing specification is presented in abbreviated form in Table 1 and compared to ASTM D 975 Diesel Fuel Oil, Grade 2-D and a proposed Distillate Marine Fuel category ISO-F-DM-R. This specification has evolved from a history of modifications made on shipboard fuel requirements.

To avoid increased maintenance requirements and improve overall system reliability, as well as reduce the number of fuels in the Navy inventory, a movement was started to discontinue use of residual fuels. In 1969, several specifications were released to allow conversion of Navy power systems to a single distillate fuel. These included MIL-F-24374 (Fuel, Distillate, Boiler — which could contain up to 5 percent resid), MIL-F-24376 (Fuel, Reference and Standard Distillate — for research and development) and MIL-F-24397 (Fuel, Navy Distillate - to allow one grade of distillate for fleet wide use). Three years later, MIL-F-24397 was replaced with higher quality MIL-F-16884 (diesel fuel, marine) for economic reasons and this was recently changed to the current specification MIL-F-16884H (Fuel, Naval Distillate). MIL-F-16884H also is standardized with NATO allies, consistent with NATO fuel F-76. Aviation turbine fuel JP-5 (MIL-T-5624L) has remained as the second fossil fuel in the Navy fleet with minor modifications and is used as an acceptable substitute for MIL-F-16884H.

This single distillate fuel for shipboard power systems has been established to meet the unique requirements of the Navy's operation. (1) These include requirements for (1) the ability to operate in all climates and oceans of the world, (2) simplification of supply logistics, (3) rapid refueling capability, (4) capability to ballast fuel tanks with seawater, (5) minimizing of fire hazards, and (6) maintaining fuel stability during extended storage periods. These requirements are unique in that they do not coincide with requirements of commercial shipping fleets. Some of the requirements are shared, such as minimizing of fire hazard, but none are more critical than they are to the Navy's operational capabilities.

TABLE 1. SELECTED CHEMICAL AND PHYSICAL REQUIREMENTS OF THREE FUEL STANDARDS

Property	MIL-F-16884H Fuel, Naval Distillate	ASTM D 975 Diesel Fuel Oil Grade 2-D	Proposed ISO Distillate Marine Fuel Category ISO-F-DM-R
Distillation, (90% point, °C)	357 max	282-338	NS
Distillation, (end point, °C)	385 max	NS	NS
Viscosity (cSt at 40°C)	1.7 - 4.3	1.9 - 4.1	1.5 - 6.0
Flash Point (°C)	60 min	52 min	60 min
Ignition Quality	45 min (a)	40 Min (a)	40 Min (b)
Sulfur (weight %)	1.00 max	0.50 max	1.5 max
Carbon Residue	0.20 max (c)	0.35 max (c)	0.20 max

NS=	Not Specified
(a)=	cetane number
(b)=	cetane index
(c)=	on 10% bottoms
Source:	Reference 1

B. Navy Residual Fuels

The U.S. Navy no longer uses residual fuels as primary ship fuel except in a few cases where the age of the ship precludes investment for conversion to distillate fuel. The transition from coal-fired boilers to liquid fuel was made during the World War I era. During the period from World War I to World War II, the Navy used a residual petroleum fuel known as Bunker C. Bunker C is a heavy, high-viscosity fuel similar to Grade No. 6 fuel oil. During World War II, Bunker C fuel was improved by blending with distillate cutter stock which improved the flow properties. Both the residual fuels were covered under MIL-F-859 as Grade Heavy (Bunker C) and Navy Special Fuel Oil (NSFO) until Grade Heavy was dropped in 1965.

Although not preferred by the Navy now, products resembling Navy Special Fuel Oil and Bunker C are available in the marine fuels market place. Table 2 shows a distribution of residual-type marine fuels sampled from around the world during 1981 and 1982.(2) About 55 percent of the fuels sampled have viscosities between 101 and 250 cSt at 50°C. Over 36 percent of the sampled fuels are more viscous. The difference in viscosity between residual-type fuels is largely due to the amount of cutter stock used. A small amount of distillate cutter stock will substantially reduce viscosity, and therefore provide for ease of handling on board ship.

TABLE 2. SURVEY OF RESID FUELS OF DIFFERENT VISCOSITIES

Viscosity	1981		1982 (1st 8 Months)	
(cSt at 50°C)	Number	Percent	Number	Percent
15-100	54	5.2	124	7.3
101-250	600	58.4	914	53.8
251-400	333	32.4	590	34.7
Greater than 400	41	4.0	72	4.2
TOTAL	1028	100.0	1700	100.0

Source: Reference 2

There are numerous specifications which control residual marine fuels worldwide. Oil companies develop in-house specifications, and national organizations such as the American Society for Testing and Materials (ASTM) and the British Standards Institute (BSI) set standards. Engine builders and trade organizations such as the International Chamber of Shipping (ICS) and the International Council on Combustion Engines (CIMAC) and finally international technical groups such as the International Standards Organization (ISO) also set standards. Not all parties -- engine builders, oil producers, end-users, national groups and international groups -- agree on specifications, especially about Intermediate Fuels Oils (blends of resid and distillate cutter stock). (3) The result is a wide variety of product fuel types each with a different set of fuel properties. The basic constituent for all blended residual marine is the Bunker C or Grade No. 6 type fuel which represents the bottom of the processing barrel. These products are blended with residual that remains after all other desirable fractions are used to supply more sensitive markets.

Because of the proximity of resid fuels to the maritime fuel market used by the Navy, they are included in this investigation of future fuel properties. Contamination of specification Navy fuels by resid is always a distinct possibility when fuel tankers and common lines are used to supply both commercial and military ship needs. Hence, the properties of resid fuels may impact future quality of Navy distillate fuel.

C. Other Marine Fuels

In addition to Intermediate Fuel Oils (IFO) which are blends of resid and cutter stock, several other marine fuel classifications are available in the maritime market. Marine Gas Oil (MGO), Heavy Marine Gas Oil (HMGO) and Marine Diesel Fuel (MDF) have been identified as off-specification alternatives to MIL-F-16884H which are available and currently supplied to major ports around the world. (4) The above descriptions are relatively broad categories for which discrete definitions are not available. Average properties of recently sampled fuels under these descriptions are presented in Table 3.

Fuel suppliers indicated that Marine Gas Oils (MGO) are 100-percent distillates and that Heavy Marine Gas Oils (HMGO) are 100-percent distillates but may have 0.5 vol% residual contamination. Marine Diesel Fuels (MDF) are blends which may contain up to 10 vol% residual fuel. MGO and HMGO are considered primary alternatives for

TABLE 3. AVERAGE PROPERTIES FROM A SURVEY OF ALTERNATE NAVY SHIP FUELS

Property	ASTM Method	Marine Gas Oil	Heavy Marine Gas Oil	Marine Diesel Fuel
Appearance, visual	Visual	B&C	NA	NA
Color, ASTM code	D 1500	L1.5	NA	NA
Sediment & Water, vol%	D 4007	0.00	0.00	0.04
Gravity, API	D 287	34.2	32.4	31.3
Distillation, °F (°C)	D 86			
IBP		399(204)	401(205)	366(186)
FBP		689(365)	712(378)	800(427)
Flash Point,°F	D 93	178	210	209
Cloud Point,°F	D 2500	32	NA	NA
Pour Point,°F	D 97	12	24	23
Viscosity, 40°C, cSt	D 445	3.71	5.8	6.1
Sulfur, wt%	D 2622	.42	0.5	1.12
Carbon Residue,				
10% btms, wt%	D 524	0.57	1.48	0.65
Aniline Point, °F	D 611	154.7	153.1	NA
Hydrogen, wt%	D 3701	13.10	12.8	12.97
Aromatics, wt%	D 2007	38.2	40.6	42.4
Demulsification, minutes	D 1401	1.6	11	22
Neutrality	D 5101	N	N	N
Total Acid Number, mg/KOH	D 974	0.12	0.06	0.11
Copper Strip Corrosion, code	D 130	1A	1A-1B	1A
Ash, wt%	D 482	0.02	0.02	0.01
Asphaltenes, wt%	D 2007	0.00	0.00	0.01
Trace Metals, ppm	D 2788			
Cu		0.4	0.5	0.4
Na		1.2	1.2	1.2
Ca		0.8	0.9	0.8
V		5	7.5	5

B&C = bright and clear
NA = not applicable
N = neutral
Source: Reference 4

specification quality, and MDF is a secondary alternative. It follows that Intermediate Fuel Oil (IFO) blends containing larger portions of residual oils would be of tertiary consideration.

D. Historical Fuel Properties

Past trends in fuel properties are a valuable tool in projecting future fuel quality. Identifying historical patterns in fuel quality establishes a basepoint and direction for future trends. The historical quality of fuel is a function of fuel specification, crude quality, refining trends, and demand for products. Future fuel quality will also be a function of the same factors. An analysis of how the factors have interacted in the past will help identify future trends which may impact availability of specification quality fuels.

It is safe to assume that the average properties of a fuel class available on the market will fall within the specification requirements. When property averages begin to crowd the specification limit, this is a red flag indicator that demand or other factors are beginning to stress supply of the fuel. This stress can be accommodated by adjustments in refining practices such as extra process treatments and special handling. This is usually done at increased cost and ultimately can result in a limit on product availability. Fuel property trends can in this way be a significant factor in projection of future quality and supply.

To determine past trends in fuel properties of Navy shipboard fuels, it is necessary to have a data base of fuel properties which statistically represent what has been available. Such an extended data base which specifically identifies fuels used by the Navy has not been prepared on a yearly basis. Lynn, et al.,(1) reported on fuel property trends of Fuel, Naval Distillate (MIL-F-16884H) over the period from 1979-1982. A special data base was generated for that report from Material Inspection and Receiving reports prepared by government fuel suppliers. For this report, fuel surveys by the Department of Energy (DOE) in cooperation with the American Petroleum Institute (API) were used. (5,6). These surveys extend from 1950 to the present and are the most comprehensive available. Surveys of diesel fuel oils and heating oil covering approximately the past 10 years were selected for review.

Trends of fuels available on a national scale are well represented in these surveys. Navy fuels of interest in this study are shipboard distillate fuels (MIL-F-16884H) and Navy Special Fuel Oil (MIL-F-859). Grade No. 2-D diesel fuel oils (ASTM D 975) and Grade No. 6 fuels (ASTM 396) were selected from the surveys as the fuels which correspond to Navy fuel categories. Although the specification requirements for these fuels do not agree in all respects with Navy fuel requirement, corresponding quality trends for these general fuel categories are evident.

In the diesel fuel surveys, (5) numerical average property data are presented for the 2-D diesel fuels by region. Five regions are reported within the continental United States, Alaska and Hawaii, including Eastern, Southern, Central, Rocky Mountain and Western Regions designated in Figure 1. Except for the the 1983 survey, national average data for 2-D diesel fuels is not tabulated. Therefore, these values were calculated from regional data. A weighting factor was used for each region based on the number of samples reported. Some samples were reported in more than one region because they were marketed in more than one. In the approach used here, these samples were given weighting for each region in which it was reported. This weighting method is only an approximation because actual production levels are not known for the samples reported in the survey. In spot checks against more rigorous data-handling techniques, the results matched closely. This indicates that the data showed good agreement with a theoretical statistical average. The data were also handled as consistently as possible. The surveys from which the data were extracted had various methods of presentation from year to year, and the changes were taken into account and appropriate adjustments made to data collection, reviewing individual sample data as necessary.

A more in-depth study of property trends would include an analysis of variance which shows the distribution of property values around the mean or median value. This type of analysis would show the range of property values and how the range has been changing with time relative to the specification limits in addition to just trends of average values. The level of effort defined for this study has not permitted this to be done for all properties but a range trend has been defined for cetane number.

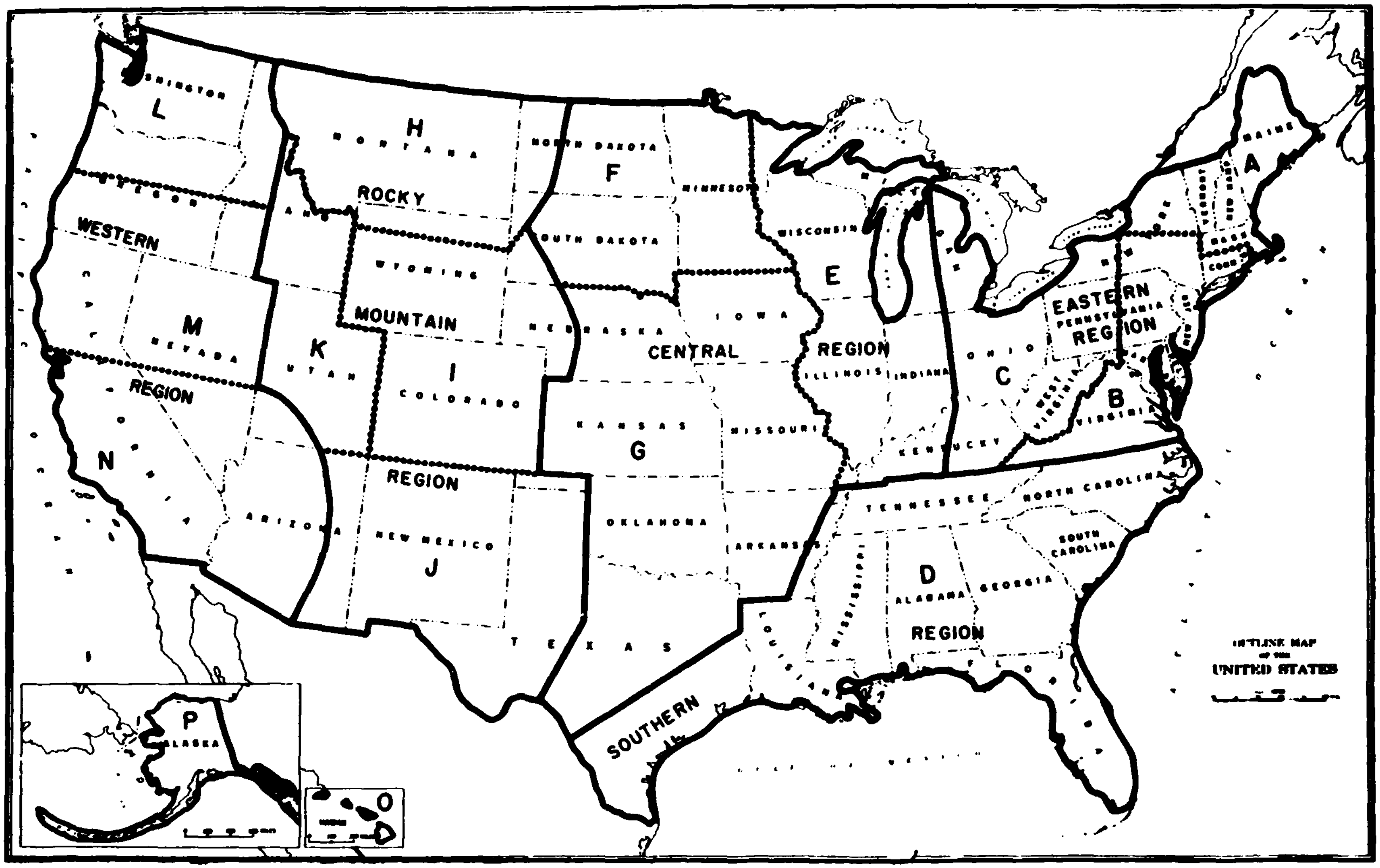

Figure 1. Diesel Fuel Survey Areas

E. Distillate Fuels

National survey properties for Grade No. 2-D diesel fuel oil from 1973-1983 are given in Table 4. Properties reported are API gravity, viscosity, sulfur content, flash point, aniline point, Ramsbottom carbon residue on 10 wt percentbottoms, cetane number, and distillation temperatures for 10 percent, 50 percent, 90 percent, and end points. Average properties for 1983 are compared to specification limits for ASTM D 975 Grade No. 2-D diesel fuel oil and MIL-F-16884H) Fuel, Naval Distillate in Table 5.

Property trends for API gravity, sulfur content, aniline point, and carbon residue are illustrated in Figure 2. A definite downward trend is shown for both gravity and aniline point. These trends may indicate a rise in aromatics concentration which would also be evident in cetane number decrease. Sulfur content has only had a slight overall increase. This trend agrees with an overall trend of increasing aromatics but also indicates the effect of hydrotreating in maintaining a nearly constant sulfur content. Carbon residue remained constant throughout the period from 1972 to 1981 around the 0.10 wt% level until 1982-1983 where it rose nearly 50 percent to 0.15 wt%. A similar observation was made by Lynn, et al. (1) where carbon residue of F-76 Naval distillate fuel abruptly rose from 0.070 wt% to 0.105 wt%, a 50 percent increase, midway through 1979. This abrupt increase may be associated with trends toward higher distillation end point as discussed below. Lynn, et al. (1) also found similar trends for gravity, sulfur, and aniline point in their 4-year study.

Property trends for viscosity, flash point, and cetane number are illustrated in Figure 3. Viscosity hovered between 2.7-2.8 cSt until 1982 and 1983, when it rose to 2.9 and 3.0 cSt respectively. Flash point followed a trend similar to carbon residue and viscosity, abruptly rising in the 1982 to 1983 periods. A rise of several degrees in flash point was experienced in each of these years. Cetane number has shown a steady reduction with some cyclic behavior. Over the 12-year period from 1972-1983 inclusive, nearly 3 cetane numbers were lost, dropping from 48 in 1972 to a 45 cetane average in 1983.

Distillation property trends are illustrated for U.S. 2-D diesel fuel in Figure 4. Distillation temperatures for the 10 percent, 50 percent, and 90 percent and end points are shown. Each of these plots display a similar trend with a steady but somewhat cyclic rise in distillation temperature from 1972 to 198 In 1982 and 1983,

TABLE 4. NATIONAL AVERAGE PROPERTIES FOR GRADE NO. 2-D DIESEL FUEL OILS,1966-1983

Year	No. Samples	Gravity, °API	Viscosity @ 100°F, cSt	Sulfur, wt%	Flash Point,°F	Aniline Point, °F	Carbon Residue On 10%, Wt%	Cetane No.	Distillation, °F ** 10%	50%	90%	EP
1966	237	36.30	2.77	0.204	172.1	148.10	0.089	49.34	439.1	503.2	576.8	622.3
1972	203	35.88	2.80	0.220	170.0	146.44	0.101	47.72	433.8	504.9	583.2	627.1
1973	197	35.51	2.76	0.239	166.2	144.99	0.108	46.94	432.2	503.0	585.1	629.8
1974	205	35.62	2.81	0.251	167.8	146.19	0.107	46.56	433.4	506.1	587.1	634.3
1975	197	35.78	2.75	0.239	165.2	145.28	0.105	47.05	430.2	501.4	585.0	631.6
1976	201	35.72	2.71	0.249	165.9	144.75	0.107	46.75	430.1	501.9	584.9	631.9
1977	181	35.83	2.75	0.243	166.4	145.11	0.100	46.96	431.4	503.1	586.5	633.3
1978	177	35.46	2.71	0.244	165.2	144.62	0.100	46.33	431.1	503.7	588.5	636.8
1979	173	35.18	2.82	0.251	167.3	144.07	0.099	46.26	433.8	506.6	592.2	642.3
1980	171	34.74	2.79	0.259	167.5	143.62	0.099	44.71	436.1	506.4	591.3	638.3
1981	143	35.22	2.75	0.261	167.5	142.81	0.105	46.10	430.9	501.4	587.7	638.3
1982	180	34.36	2.87	0.261	169.8	143.10	0.142	44.65	437.6	509.4	596.9	646.5
1983	250	33.48	3.00	0.275	174.2	139.97	0.149	44.91	440.0	512.8	602.7	654.2

* National averages were calculated from regional average data using the total samples reported for each region as weighting factors, (Ref. 5)

** National survey data reports are given in degrees fahrenheit (°F) and therefore this unit of measurement is used here; to convert to degrees centigrade (°C) use the following equation: (°F - 32) 5/9 = °C

TABLE 5. COMPARISON OF MIL-F-16884H, ASTM D 975 GRADE NO. 2-D AND AVERAGE ASTM GRADE 2-D DIESEL FUEL FOR 1983

	MIL-F-16884H Fuel, Naval Distillate	Mean Grade 2-D 1983 DOE Fuel Survey	ASTM D 975 Grade No. 2-D Diesel Fuel Oil
Gravity, °API	Record	33.5	NS
Viscosity, cSt@ 100°F (37.8°C)	1.7-4.3*	3.00	2.0-4.3
Sulfur, wt%	1.00 (max)	0.275	0.5 (max)
Flash Point, °F (°C)	140 (min)(60)	174(79)	125 (min)(52)
Aniline Point, °F (°C)	Record	140	NS
Carbon Residue, wt% (on 10% bottoms)	0.20 (max)	0.149	0.35 (max)
Cetane Number	45(min)	44.9	40***(min)
Distillation, °F (°C)			
10%	NS**	440(227)	NS
50%	record	513(267)	NS
90%	675(max)(357)	603(317)	540-640(282-338)
EP	725(max)(385)	654(346)	NS

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* 104°F
**NS Not Specified
*** Climate and altitude may require higher cetane ratings

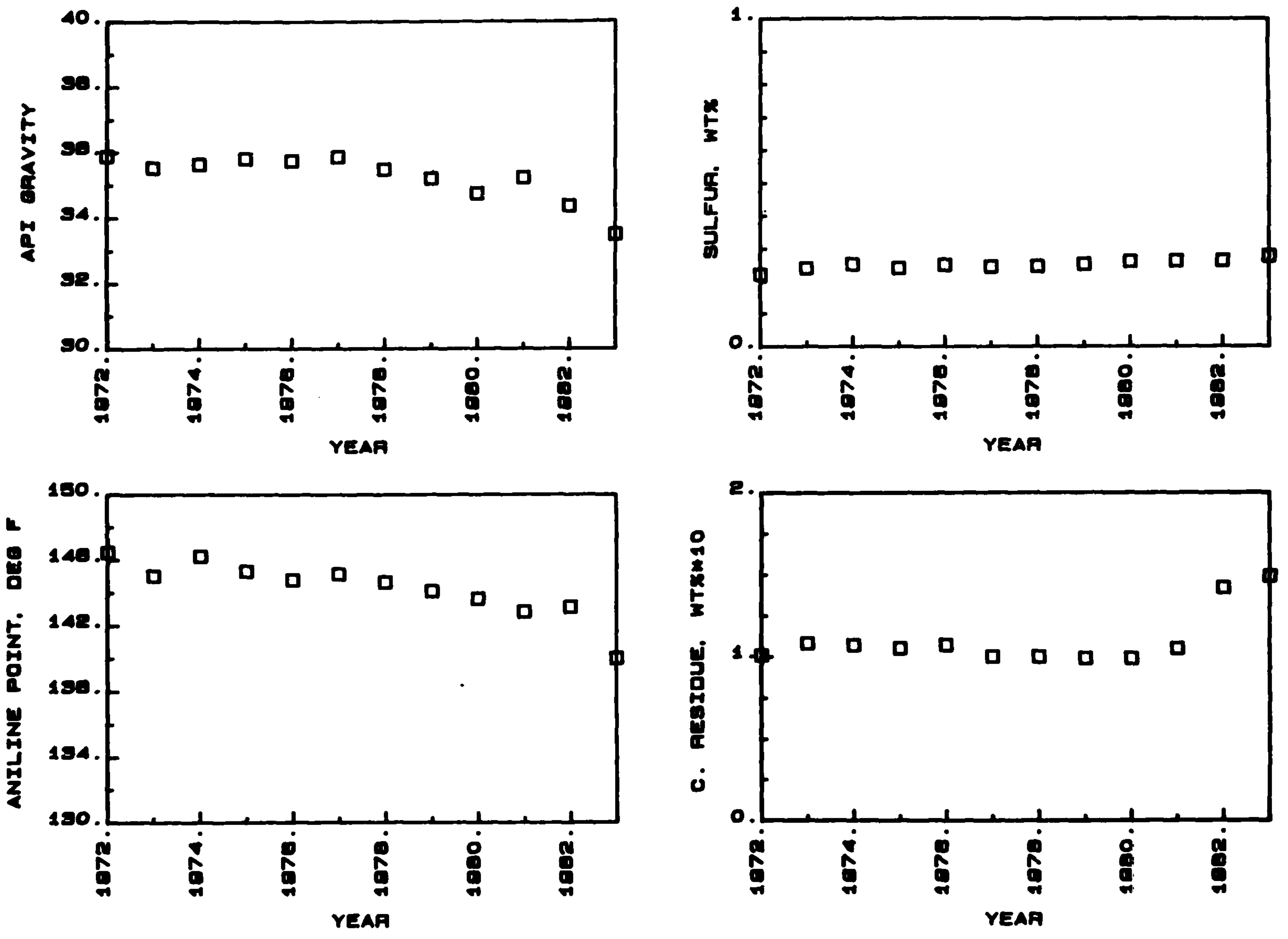

Figure 2. Historical Trends of Mean API Gravity, Sulfur, Aniline Point, and Carbon Residue in U.S. 2-D Diesel Fuel, 1972-1983

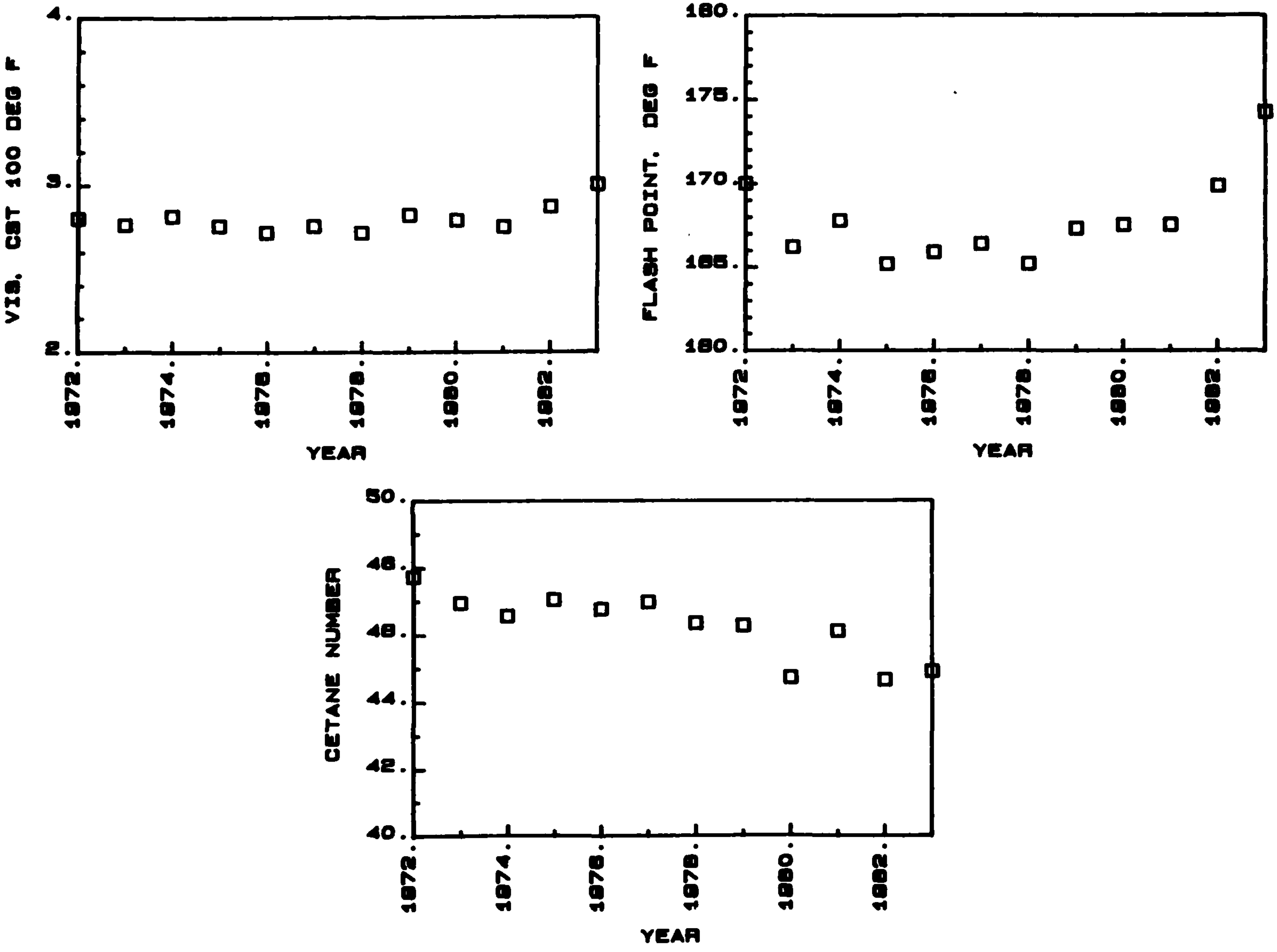

Figure 3. Historical Trends of Mean Viscosity, Flash Point and Cetane Number in U.S. 2-D Diesel Fuel, 1972-1983

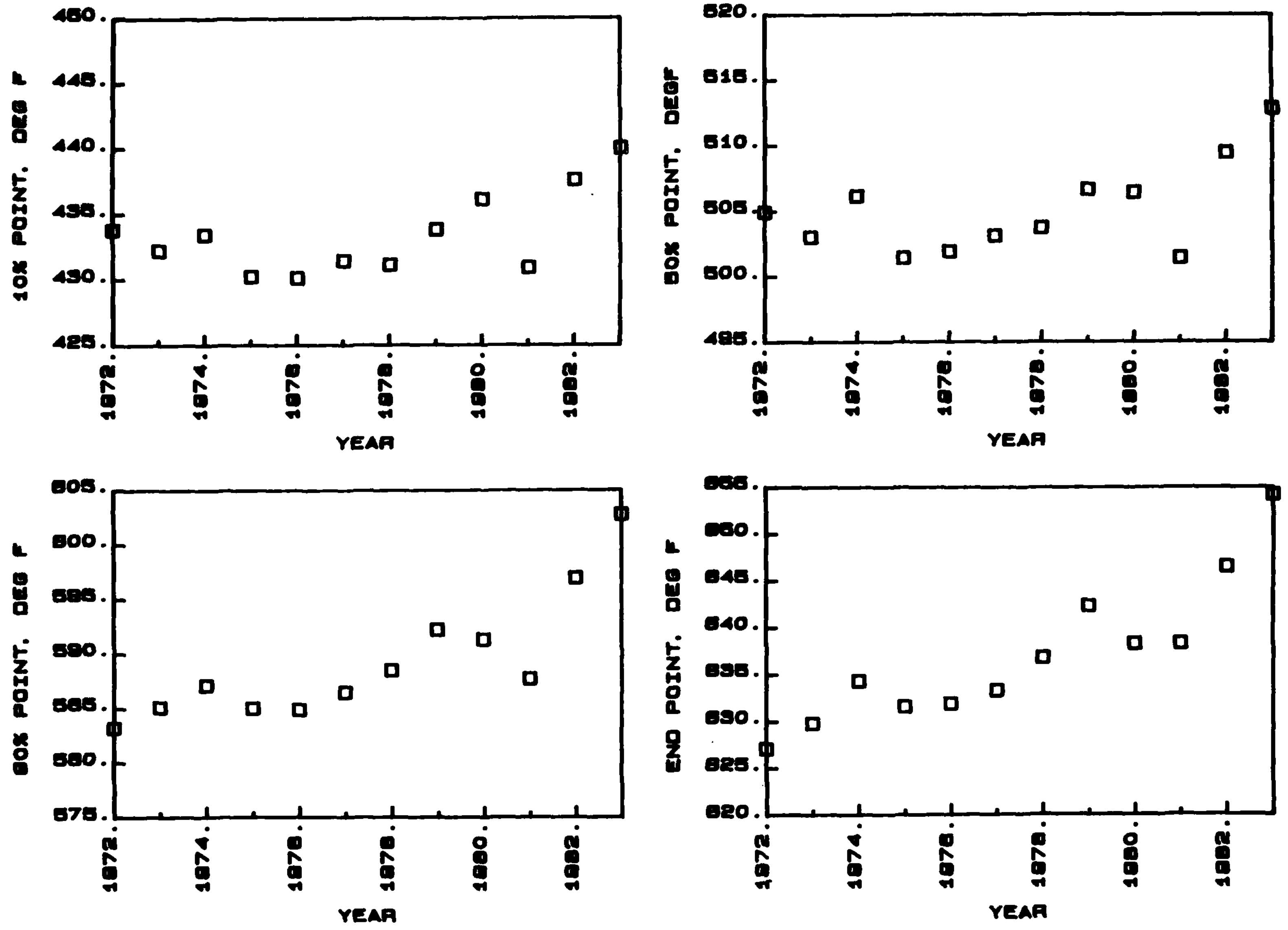

Figure 4. Historical Trends of Mean Distillation Properties of U.S. 2-D Diesel Fuels, 1972-1983

average data for each of the distillation cut point temperatures showed a dramatic rise. The rise in 10% point corresponds with the rise in flash point. The rise in 50 percent, 90 percent and end points in these 2 years also agrees with the rise in viscosity and carbon residue during the same time. The overall trends towards a heavier diesel fuel could be an explanation for lower gravities and reduced aniline points. Heavier distillation range would not necessarily account for all effects observed here, however. Lynn, et al. (1) found similar trends with little or no change in distillation range. Some reduction in fuel quality could also be attributed to poorer quality crude oil. An upward shift in cut point temperatures may actually increase cetane number, for example, if higher boiling distillate fraction contains more paraffinic molecules or even more paraffinic side chains in the aromatic fraction are found present.

It should be pointed out that the average data presented here are numerical averages. Even if the data were precisely weighted according to production or consumption levels, the weighted average would not represent the property value that would be realized if all fuels were pooled together in one batch. Most of the properties reviewed here would require special blending weights applied to actual property values if this were the desired objective. The numerical averages presented do serve a useful purpose in that they represent property values that are found at point of use. This is a more realistic picture; after all, fuels are not all blended together in a single batch. Because of this treatment of the data (numerical average as opposed to batch blending), correlation from one property to another is limited to qualitative trends and cannot be used for quantitative derivations. Directional correlations are the best that can be expected, considering changes in crude quality, processing and distillation trends.

F. Western Region Distillate Fuels

The impact of low quality crude oil on distillate property trends can be observed by examining fuels in the Western Region. Crude oil quality in Petroleum Administration for Defense District (PADD) V -- which is nearly identical to the Western Region identified in Figure 1. -- was over 6 °API lower in gravity than the national averages in 1980. (See Section IV, Table 2). Therefore, it is informative to compare property trends in the Western Region with national trends to see what the impact of lower crude quality might have in the future.

Table 6 presents average properties for 2-D diesel fuels in the Western Region. This may be compared against Table 4 which presents the same data on a national basis. For visual illustrations of how the properties compare, the data from both tables have been plotted in Figures 5-7. Western Region gravity, sulfur content, aniline point, and carbon residue are plotted as triangles, while the national average data are plotted as solid lines in Figure 5. Both gravity and sulfur content were very similar to the national averages. Aniline point for the Western Region was slightly higher than the national average, possibly indicating a less aromatic distillate overall. Carbon residue was slightly lower in the Western Region. Viscosity, flash point, and cetane number comparisons are illustrated in Figure 6. Both viscosity and flash point were definitely higher in the Western Region, while the cetane number trend was very similar to the national trend.

Distillation property comparisons are illustrated in Figure 7. Distillation cut point temperatures at 10 percent and 50 percent were significantly higher in the Western Region than in the nation as a whole. This may explain the difference in both viscosity and flash point for the Western Region fuels. The Western Region has had a higher front end distillation range causing higher flash points and higher viscosities. The 90 percent point and end point temperatures in the Western Region were also quite higher for most of the analysis period; although an increasing trend was evident, the national trend rose more rapidly and matched the values in the Western Region in 1983.

Even though Western Region 2-D diesel fuels had higher boiling ranges and were made from heavier crude oils, their quality as measured by gravity, sulfur content, aniline point, carbon residue, and cetane number closely matched the average 2-D diesel fuel found in the rest of the century. This indicates that refining methods can offset low quality crude oil. This is also discussed later in Section IV and Section V.

G. Cetane Number Range

A more in-depth study of individual property data could reveal not only average values of a given property with time but also the range or standard deviation around the mean that can be determined in an analysis of variance. Mean cetane number and the standard deviation around the mean is graphically illustrated in Figure 8 for 2-D diesel fuel samples with major marketing in coastal regions of the U.S. Data from 1977-

TABLE 6. WESTERN REGION AVERAGE PROPERTIES FOR GRADE NO. 2-D DIESEL FUEL OILS,1966-1983

Year	No. Samples	Gravity, °API	Viscosity @ 100°F, cSt	Sulfur, Wt%	Flash Point, °F	Aniline Point, °F	Carbon Residue on 10% Wt%	Cetane No.	Distillation, °F *			
									10%	50%	90%	EP
1966	30	35.5	3.06	0.245	178.2	150.7	0.082	47.6	446	511	595	643
1972	28	35.5	3.15	0.239	178.6	150.7	0.092	48.1	449	521	598	641
1973	27	35.5	3.02	0.262	170.5	147.6	0.101	47.2	442	513	598	642
1974	29	36.1	3.03	0.287	173.1	150.3	0.108	47.9	441	513	598	645
1975	33	35.5	3.01	0.263	169.2	145.3	0.105	46.1	440	510	593	638
1976	30	36.1	2.91	0.262	174.1	146.3	0.097	47.0	441	511	592	642
1977	25	35.9	2.91	0.246	171.4	144.5	0.089	47.8	438	512	593	638
1978	23	34.7	3.06	0.281	174.0	145.4	0.096	46.0	446	516	600	646
1979	24	35.1	2.96	0.250	171.5	145.7	0.087	46.9	444	514	599	646
1980	24	34.5	3.05	0.275	175.8	146.5	0.086	47.3	454	521	601	646
1981	24	34.1	3.06	0.290	178.2	141.9	0.103	46.4	449	518	601	645
1982	24	33.8	3.15	0.297	179.4	144.4	0.116	44.8	455	523	605	649
1983	29	33.3	3.28	0.302	183.1	143.6	0.122	45.5	457	522	603	651

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* National survey data (Ref. 5) reports are given in degrees Fahreheit (°F) and therefore this unit of temperature measurement is used here; to convert to degrees centigrade (°C) use the following equation: (°F-32) 5/9 = °C.

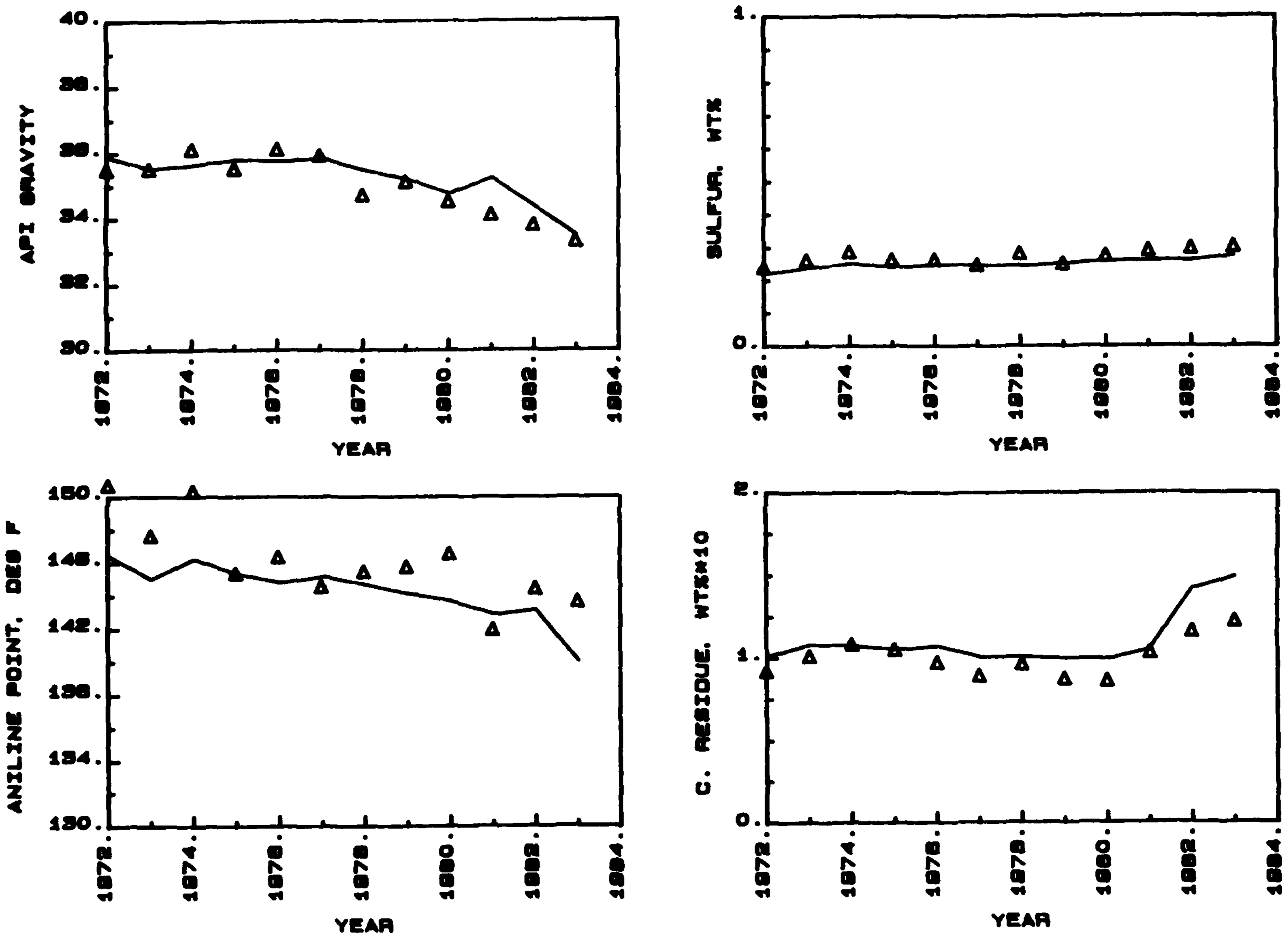

Figure 5. Mean Western Region Gravity, Sulfur, Aniline Point, and Carbon Residue of 2-D Diesel Fuels (Triangles) Compared to National Mean Trends (Solid Lines)

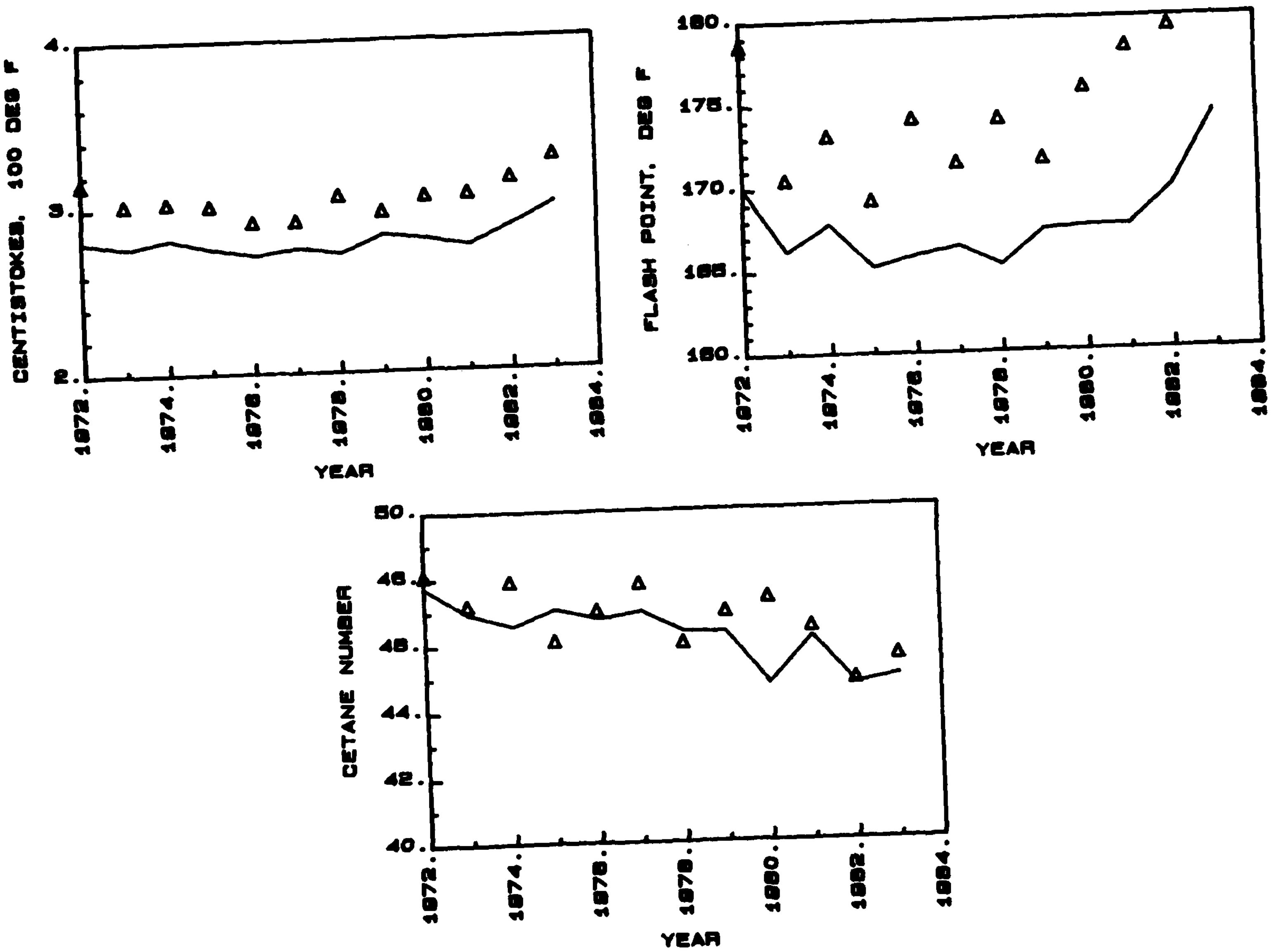

Figure 6. Mean Western Region Viscosity, Flash Point, and Cetane Number of 2-D Diesel Fuels (Triangles) Compared to National Mean Trends (Solid Lines)

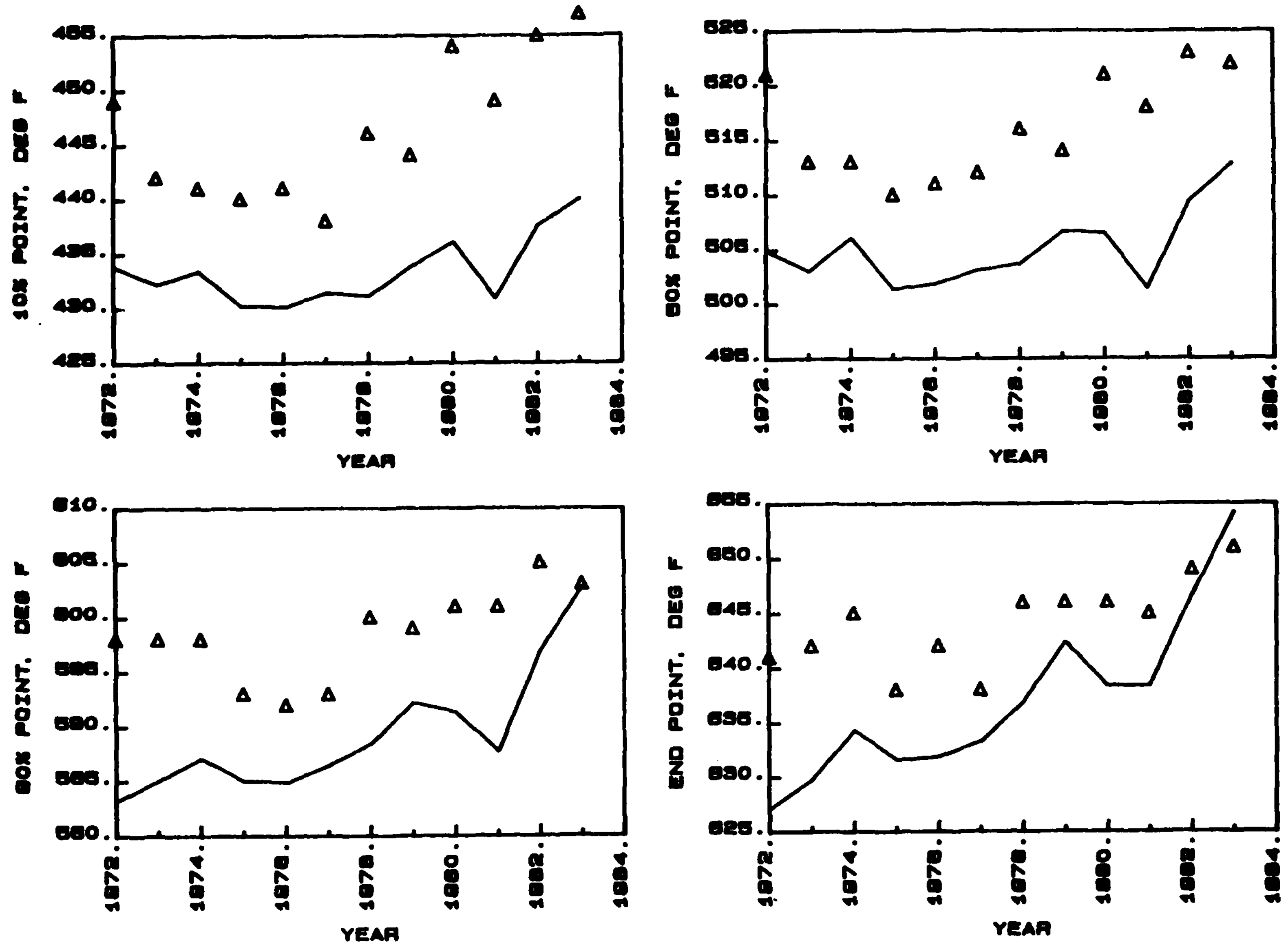

Figure 7. Mean Western Region Distillation Data for 2-D Diesel Fuels (Triangles) Compared to National Mean Trends (Solid Lines)

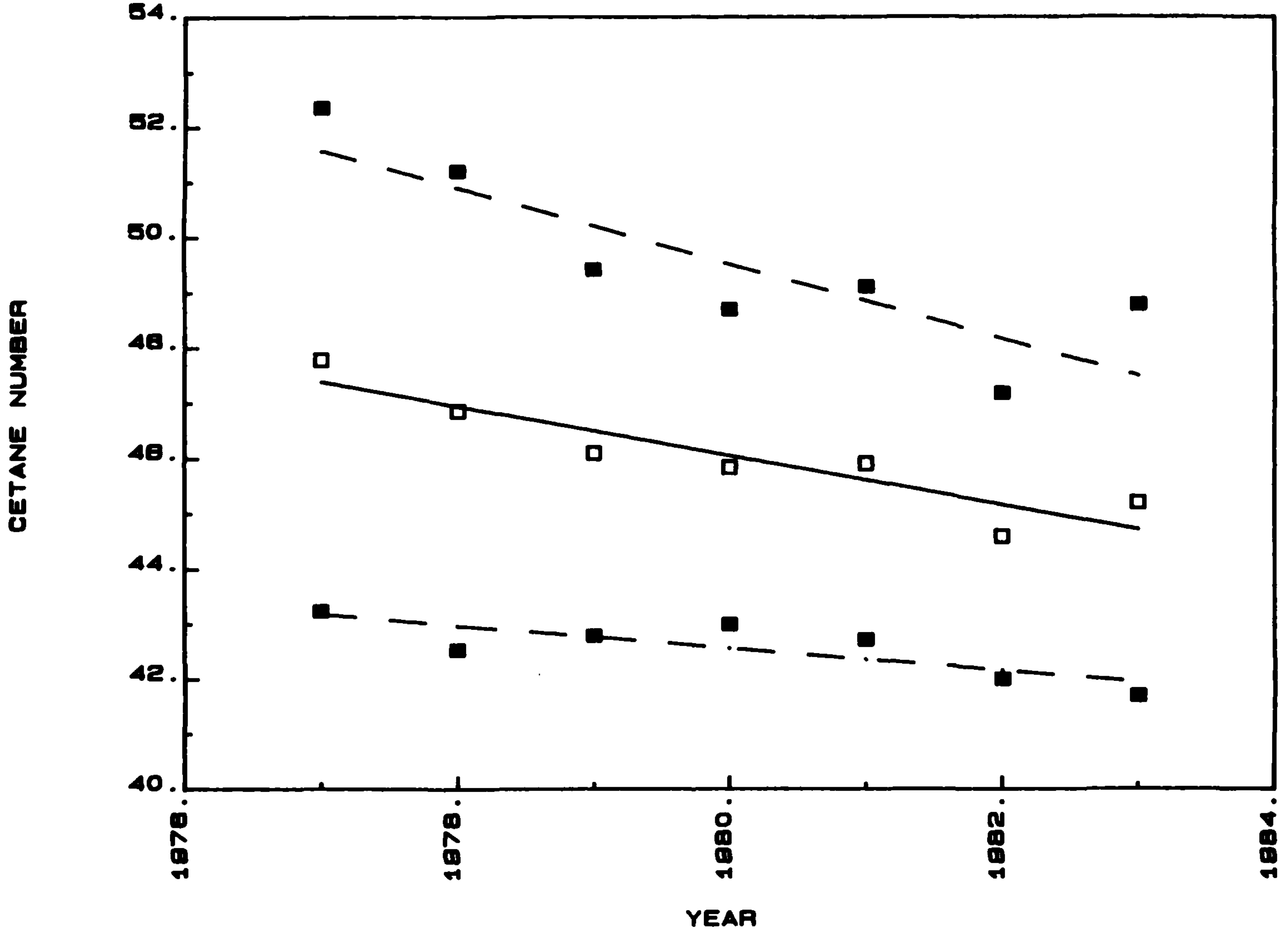

Figure 8. Mean and Standard Deviation of Cetane Number in U.S. Coastal Regions, 1977-1983

1983 are presented. Mean data points are shown by the open square symbols through which a solid linear regression line has also been plotted. The solid square symbols indicate one standard deviation of cetane number range around the mean value. Linear regression lines (dashed) have also been plotted through these data, showing both the upper and lower ranges.

Mean cetane in the coastal regions of the U.S. has suffered a loss of about 2 cetane numbers during the period 1977-1983. The upper range of cetane number has suffered a larger loss of about 3 cetane numbers, while the lower range has decreased only about 1 cetane number over the same time period. This analysis illustrates a tightening of the cetane range as the average value approaches the specification limit. The lower range declines more slowly and in 1983 is near 42 cetane. It is interesting to note that the reproducibility of the cetane measurement is ± 2 cetane numbers, which puts this value very close to the 40 cetane minimum requirement called out in the ASTM specification.

It may be projected that with lower quality crudes, cetane number or combustion quality of diesel fuel will become more valuable. In all probability, the point will be reached where there will be no cetane number give-away similar to the situation with octane number for gasoline. Gasolines meet specification quality precisely in most cases, and there is little or no range of octane above the lower limit. This is due to the extra cost of higher octane numbers. Combustion quality in diesel fuel will soon experience a similar condition. In conjunction with this occurrence, an improved method for determining cetane number or combustion quality should be identified.

H. Residual Fuels

National average properties for Grade No. 6 fuel oil from 1973-1983 are given in Table 7. Properties reported are API gravity, viscosity, sulfur content, Ramsbottom carbon residue on 100 percent oil, ash content, water content by distillation, and sediment by extraction. Average properties for 1983 are compared to specification limits for ASTM D 396 Grade No. 6 fuel oil and MIL-F-859 Navy special fuel oil in Table 8. There is a wide disparity between viscosity requirements of the military and commercial specification. This difference is reconciled with the addition of a certain amount of distillate cutter stock to meet the low viscosity specification. Maximum

TABLE 7. NATIONAL AVERAGE* PROPERTIES FOR GRADE NO. 6 HEATING OILS, 1973-1983

Year	No. Samples	Gravity, °API	Viscosity cSt, 50°C	Sulfur, Wt%	C. Residue On 100%, Wt%	Ash, Wt%	Water, Vol%	Sediment, Wt%
1973	94	11.47	366.4	1.57	9.18	0.043	0.108	0.090
1974	96	12.10	385.6	1.64	8.78	0.039	0.096	0.092
1975	89	13.41	417.3	1.53	8.20	0.035	0.113	0.068
1976	105	13.47	383.4	1.49	8.22	0.043	0.106	0.055
1977	107	14.02	351.5	1.58	8.22	0.038	0.091	0.064
1978	96	14.05	377.0	1.46	8.52	0.032	0.080	0.055
1979	103	13.65	381.2	1.44	7.86	0.031	0.065	0.057
1980	84	13.18	406.8	1.63	9.01	0.036	0.070	0.054
1981	91	12.58	383.4	1.62	7.44	0.042	0.072	0.054
1982	60	12.01	423.9	1.56	7.86	0.044	0.060	0.050
1983	54	12.29	421.7	1.34	7.63	0.056	0.086	0.052

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* National averages were calculated from regional average data using the total samples reported for each region as weighting factors. (Ref. 6)

TABLE 8. COMPARISON OF MIL-F-859E, ASTM D 396 GRADE NO. 6 FUEL OIL AND AVERAGE ASTM GRADE NO. 6 FUEL FOR 1983

	MIL-F-859E Fuel Oil, Burner	Mean Grade No. 6 Fuel, 1983 DOE Fuel Survey	ASTM D396 Grade No. 6 Fuel Oil
Gravity, °API	11.5 (min)	12.3	NS*
Viscosity, cSt@ 50°C	48.3 (max)	421.7	93-650
Sulfur, wt%	3.50 (max)	1.34	NS
Carbon Residue, wt% (on whole oil)	15.0 (max)	7.63	NS
Ash, wt%	0.1 (max)	0.056	NS
Water, vol%	0.5 (max)	0.086	0.5(max)
Sediment, wt%	0.12 (max)	0.052	1.5(max)

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* Not Specified

allowable sediment is much higher for the ASTM Grade No. 6 fuel, but the mean value for No. 6 fuels is well below the military specification.

Property trends for U.S. grade No. 6 fuel oil gravity, viscosity, sulfur, and carbon residue are illustrated in Figure 9 for the period 1973-1983. API gravity rose from 15 to above 14 at the beginning of this period and then fell back to about 12 by the end of the period. Average viscosity was very cyclic throughout the period ranging from 350 to 420 cSt. Sulfur content was also cyclic, but usually fell around 5 wt%. Carbon residue ranged between about 8-9 wt% but actually had a slight decreasing trend. These properties showed little net change during the period but appeared to be variable from one year to the next.

Property trends for No. 6 ash, water, and sediment are illustrated in Figure 10 for 1973-1983. Ash showed somewhat the reverse trend of API gravity with a decrease in the first half of the period followed by an increase in the second half. This agrees theoretically with the gravity trend where low gravity is associated with higher ash content. Both water and sediment have decreased substantially. Each showed nearly a 50 percent decrease which could be attributed to improved contaminant removal techniques although no direct data are available to substantiate this.

Improved heavy oil upgrading techniques are converting more and more of the bottom of the barrel to lighter products. Although this would theoretically leave poorer quality resid for use as fuel, this trend is not evident in the properties monitored here. There may be several reasons for this. In cases where severe upgrading is done, the residual material may be of such poor quality as to be useless for fuel oil use. Resid products from high severity processes would then be directed to other modes of utilization such as feedstocks for hydrogen manufacturing to assist upgrading. In the case of coking, the resid product is solid and has its own market but may also be used for hydrogen production. Much of the demand for resid fuels is met by imports in this country. These imports are from countries with less upgrading capability and therefore higher quality resids are available. Demand for resid has been reduced by fuel users switching from oil to coal. This allows remaining users to select higher quality feeds which then enter the sampling survey.

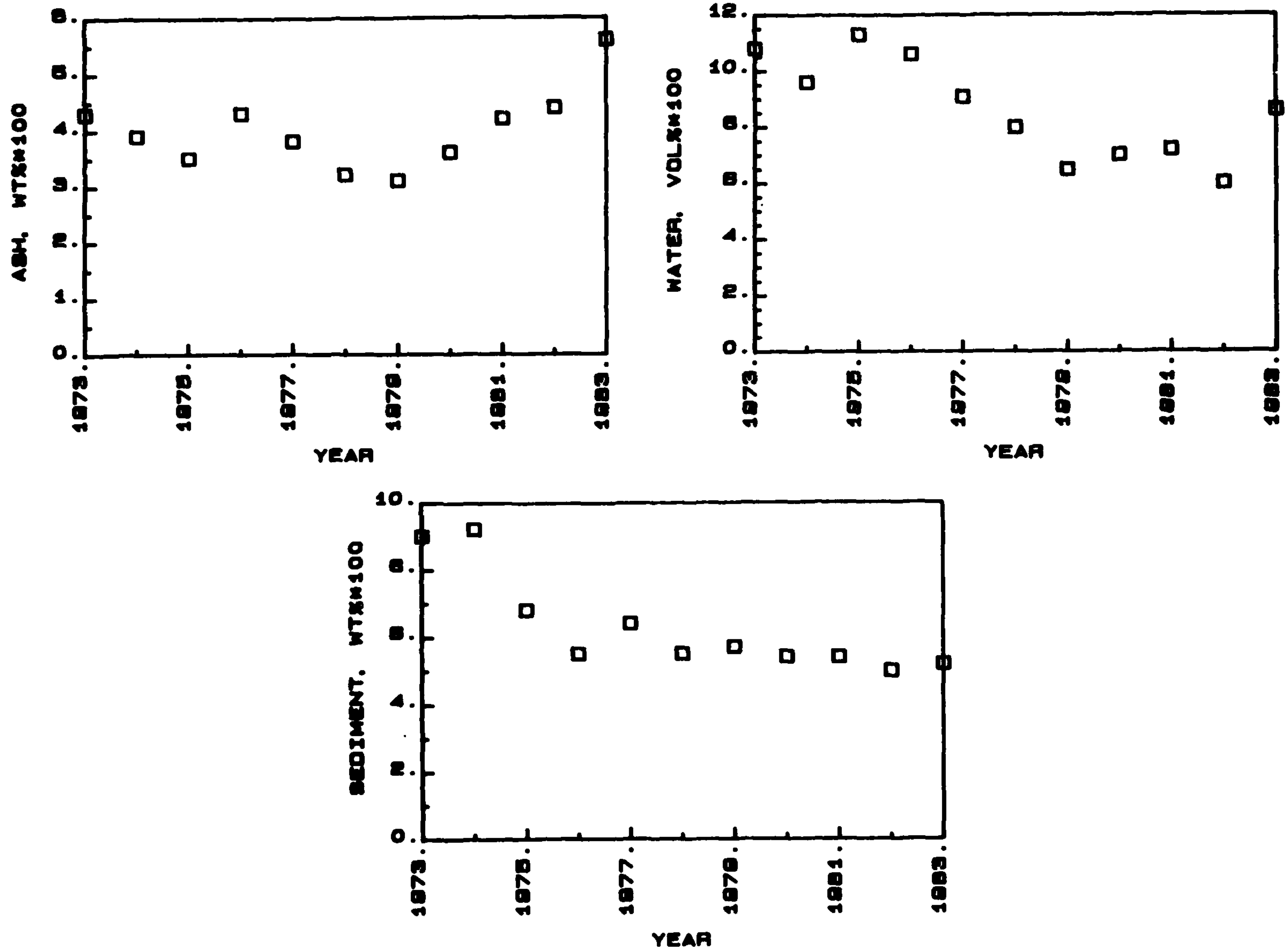

Figure 9. Historical Trends of Mean Ash, Water, and Sediment of U.S. Grade No. 6 Fuel Oils, 1973-1983

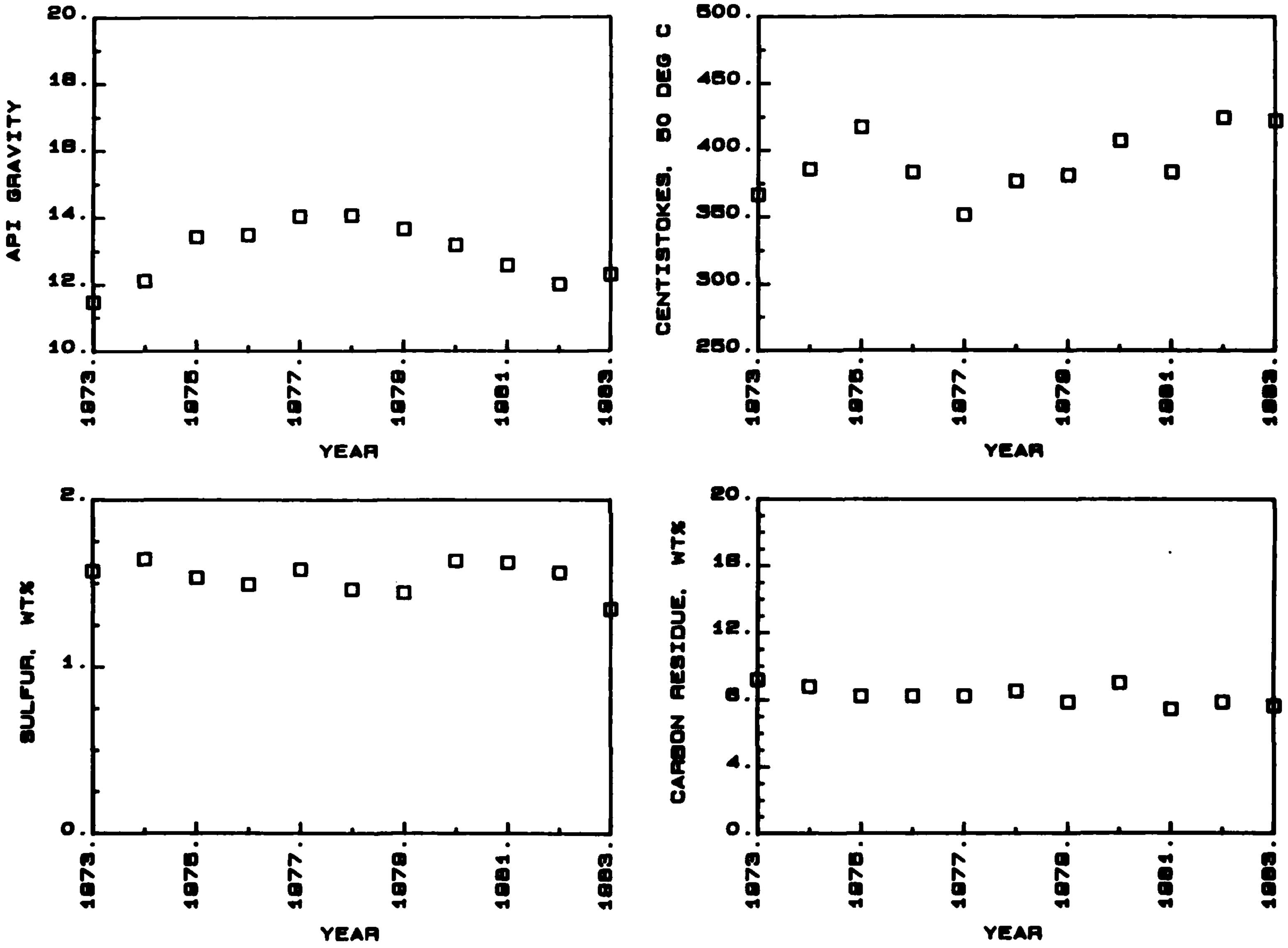

Figure 10. Historical Trends of Mean API Gravity, Viscosity, Sulfur, and Carbon Residue of U.S. Grade No. 6 Fuel Oils, 1973–1983

Other properties of interest in measuring the quality of residual fuels may include elemental analysis (carbon, hydrogen, sulfur, etc.) and the content of catalyst fines which can be entrained in the production during catalytic cracking processing of residual oils. These properties although important to fuel users have not been included in historical surveys and are not discussed here.

III. PRODUCT SUPPLY AND DEMAND FORECAST

A. Forecasting

Forecasting energy supply and demand maybe called more of an art than a science in many respects. This is evidenced by the fact that forecasts are adjusted on a yearly basis as world and national economic, political, and technical events change. Although each of these types of events may have a significant effect on the energy supply and demand picture, they are unpredictable for the most part. Forecasts are based on the most reliable information and trends available at the time. As conditions change, the forecasts must be adjusted accordingly. Despite the degree of uncertainty associated with forecasting methods, it is a necessary element for plannning and investment decisions made by government and industry. As decisions are made, trends change and thus a feedback phenomena occurs which causes even more complications in an already complex situation. It is with these factors in mind that forecasts must be evaluated. Several recent forecasts have been reviewed and evaluated for effects of future oil supply on Navy fuel properties. (7-27) Selected forecast data consulted are identified in the tables which follow.

Fuel properties are associated with local fuel supply conditions. Local conditions are affected by regional conditions which are in turn affected by national and international activities in the oil industry. Changes in oil supply and demand are affected at all levels by energy supply and demand. Stress is placed on oil supply, depending on the availability of other energy alternatives. Therefore, to place the fuel supply and fuel property future in perspective, all of these factors must be considered.

B. World Energy and Oil Demand

Leading world energy and world oil demand trends of the past comprise one of the main ingredients in a forecast. Below are listed some of the past trends and other factors which influence world oil and world energy supply.

- Free world oil demand declined more than 12 percent since a peak in 1979
- Energy as a whole and oil even more so are declining as a percentage of productivity, indicating a basic economic change

- Higher world energy prices have resulted in lower per capita energy use due to conservation and increased efficiency
- Coal and nuclear are providing more and more of the total energy demand.
- The volume of oil produced by non-OPEC countries increased 33 percent since 1973
- Decreased demand recently caused the first price decrease in the two-decade existence of OPEC.

The trends listed above are some of the factors that will influence future energy supply and demand. Some of the factors will continue, such as basic changes in the economy to a less energy-intensive mode of productivity. Other factors may have short-lived effects, including a recession-induced demand decrease, artificial demand decrease due to stock drawdowns, and reversible fuel switching. It is difficult to quantitatively measure the impact and duration of each factor, but these types of factors are used to qualitatively estimate future supply and demand. Table 9 presents free world energy consumption for 1980 and projected consumption for 1985 and 1990. (25) World energy consumption is projected to increase 5 to 10 percent by 1985 and 10 to 20 percent by 1990. Of the total energy consumption in 1980, oil represented over 50 percent of the energy supply. By 1985, oil will supply less than 50 percent of the total energy demand, and this trend will continue to 1990. During this time, oil demand in the world will maintain a nearly constant level. This shift away from energy dependence on oil will relieve some of the supply stress which has been experienced in past years.

C. U.S. Energy and Oil Demand

U.S. energy consumption for 1980 and projected consumption for 1990 and 2000 are presented in Table 10. U.S. energy consumption for 1990 is projected to decrease slightly from the historical rate experienced in 1980. By the year 2000, total energy consumption in the U.S. is projected to increase by 7 to 21 percent over the 1980 level. In Table 11, U.S. oil demand is presented for 1980 and projected values for 1990 and 2000 are also given. By 1990 demand for oil in the U.S. is projected to maintain a constant level or even drop as much as 10 percent below the 1980 level. By the year 2000, demand for oil in the U.S. will decrease slightly or remain a nearly constant.

TABLE 9. FREE WORLD ENERGY CONSUMPTION (QUADS/YEAR)

	1980 (Actual)	1985	1990
Oil	100	94-102	98-112
Energy	188	194-210	214-236

Projections by EIA, Gulf, Socal, PPA/DOE, Tenneco, IEA & Concoco from the 1982 Annual Report to Congress

TABLE 10. U.S. ENERGY CONSUMPTION (QUADS/YEAR)

1980 (Actual)	1990	2000
60.8	57.3-59.5	65.2-73.6

Projections by AEO, ARC, DRI, Chase, PPAE & NEPP from the 1982 Annual Report to Congress

TABLE 11. U.S. OIL DEMAND

	1980 (Actual)	1990	2000
MMBPD	17.1	15.4-17.2	12.7-16.1
Quads/Yr	34.2	30.7-34.4	25.3-32.2

Projections by NEPP, ARC, & DRI from the 1982 Annual Report to Congress

This overall view of world and U.S. demand and consumption projections indicates a relaxation of the stress previously experienced in the last decade. This leveling of demand is encouraging, assuming that adequate supplies will be available. In the past few years, the U.S. has been able to substantially reduce its percentage of imported oil. Of the oil supplied by foreign producers, a substantial fraction has been shifted from Mid-East suppliers to suppliers from Europe and North America. This shift in U.S. supply has done much to secure the availability of oil in the future and added world stability. However, as demand picks up from the recession-induced low level, a larger portion of U.S. supply will again be coming from the Mid-East sector.

D. Crude Oil Quality Projections

The quality of crude oil varies over the world with certain sectors producing higher or lower quality crude oil. Most crude oil fields throughout the world have average gravities which range between 32° and 38° API. Most of these fields are suffering a quality loss at a rate of 1°API during a 10-year period. Europe may be an exception to this generalization due to an influx of high quality North Sea crude recently. The U.S., on the other hand, has suffered a much greater loss in average crude quality in part due to production of North Slope Alaskan crude. This has been a somewhat abrupt change which has been localized in the West Coast region. New discoveries off the coast of California (29, 30) will further impact this trend of decreasing quality in the western region. The U.S. will also be experiencing a decrease in crude oil quality which is being brought about by imports of Mexican crude. Table 12 presents data (24) comparing U.S. crude quality east of the Rockies and in the West Coast. The table shows that from 1981 to 1990 the eastern region will suffer a decrease of 1.6°API in crude oil gravity. The West Coast will experience a somewhat smaller decrease in crude gravity. At the same time, both sulfur and non-distillable fractions of crude are projected to increase.

A similar evaluation of total U.S. refinery feed crude oil properties which includes imported crudes is presented in Table 13. Historical data are presented in this table starting in 1976. Over the period from 1976 to the year 2000, crude oil feed to U.S. refineries is projected to undergo almost a 5°API gravity decrease. Sulfur levels and nondistillable fractions are projected to increase significantly over the same period. The projected decrease in crude oil quality will have an effect both on fuel properties and on refinery processing to accommodate the poorer quality feedstocks.

TABLE 12. U.S. CRUDE QUALITY

	1981	1985	1990
East of Rockies			
°API	34.0	33.6	32.4
%S	0.89	1.09	1.22
% 1000°+F	17.8	18.2	19.2
West Coast			
°API	27.6	26.4	26.3
%S	0.94	0.97	0.98
% 1000°+F	22.2	23.0	23.0

Source: Reference 24

TABLE 13. U.S. REFINING FEED CRUDE OIL PROPERTIES

	Wt% Sulfur	Vol% 1000°+F Material	°API Crude Gravity
1976	.80	16.0	34.8
1978	.85	17.0	34.0
1980	.90	17.7	33.3
1982	.95	18.0	33.0
1984	1.02	18.5	32.8
1986	1.07	18.8	32.7
1988	1.10	19.0	32.3
1990	1.12	19.2	32.0
2000	1.05	19.7	30.0

Source: Reference 24

Mexico became the largest crude supplier to the U.S. in 1983 surpassing Saudi Arabia in total imports and the United Kingdom also surpassed Saudi Arabia and became the second largest U.S. supplier. (31) Mexico has heavy crude oil while the U.K. has higher quality. This trend may be reversed again in the future as product demand rises. Oil to meet new demand will likely come from Arab sources, returning the U.S. to a larger dependence on less politically stable, but higher quality supplies. Mexican expansion of its oil industry may help to offset this somewhat.

E. U.S. Fuel Product Demand

The demand for various fuel products determines the type of refinery processing that will be used on available crude to produce those products. High or low demand of a given fuel product places a correspondingly high or low level of stress on the crude feedstock. This, in turn, is reflected in the quality of fuels that may be derived from a limited quality crude. Historical refined petroleum products supplied in the U.S. are presented in Table 14. As shown in the table, from 1970 there was a constant increase in demand for petroleum products until 1978 when this trend was reversed and continued to decrease until the present. It is expected that petroleum product demand will level off in 1984 or begin to again rise slightly. (17-23) Demand for individual products supplied has followed approximately the same trend as total products supplied with a gradual increase to 1978 followed by a reduction in demand thereafter.

Table 15 shows the historical refined U.S. petroleum product as a fraction of the total products supplied. Over the same time period from 1970 to 1980, there was no significant change in the distribution ratio of products supplied. Starting in 1980, there was a decrease in resid oil supplied with a reduction of almost 50 percent over a 3-year period. During the same time period, the total quantity of light products, i.e., gasoline, jet fuel, and distillate rose from 62 percent of product supplied to almost 70 percent. Over the entire time period of 1970 to 1983, distillate demand remained between 17 and 18 percent. These data were collected from the Annual Energy Review published by the DOE and the Energy Information Administration. (32) When using figures such as these, it should be recognized that various methods of accounting and definitions of products are used so that totals and individual quantities may vary from one method of reporting to the next. The important thing to consider is that each reporting method has been consistent so that relative trends may be identified.

TABLE 14. HISTORICAL U.S. REFINED PETROLEUM PRODUCTS SUPPLIED (MMBPD)

Year	Gasoline	Jet Fuel	Distillate	Resid	LPG & Other	Total
1970	5.78	0.97	2.54	2.20	3.20	14.70
1971	6.01	1.01	2.66	2.30	3.23	15.21
1972	6.38	1.05	2.91	2.53	3.50	16.37
1973	6.67	1.06	3.09	2.82	3.66	17.31
1974	6.54	0.99	2.95	2.64	3.54	16.65
1975	6.67	1.00	2.85	2.46	3.33	16.32
1976	6.98	0.99	3.13	2.80	3.56	17.46
1977	7.18	1.02	3.35	3.07	3.79	18.43
1978	7.41	1.06	3.43	3.02	3.92	18.85
1979	7.03	1.08	3.31	2.83	4.26	18.51
1980	6.58	1.07	2.87	2.51	4.04	17.06
1981	6.59	1.01	2.83	2.09	3.55	16.06
1982	6.54	1.01	2.68	1.69	3.34	15.26
(1983)*	6.60	1.30	2.62	1.39	3.41	15.04

1982 Annual Energy Review DOE/EIA-0384 (82)

* Weekly Petroleum Status Report DOE/EIA-0208 (84-05) (avg. data to 12/83)

TABLE 15. HISTORICAL REFINED U.S. PETROLEUM PRODUCT RATIOS (FRACTION OF TOTAL DEMAND)

Year	Gasoline	Jet Fuel	Distillate	Jet & Distillate	Gasoline, Jet & Dist.	Resid
1970	.393	.066	.173	.239	.632	.150
1971	.395	.066	.175	.241	.636	.151
1972	.390	.064	.178	.242	.632	.155
1973	.385	.061	.179	.240	.625	.163
1974	.393	.059	.177	.237	.629	.159
1975	.409	.061	.175	.236	.645	.151
1976	.400	.057	.179	.236	.636	.160
1977	.390	.055	.182	.237	.627	.167
1978	.393	.056	.182	.238	.631	.160
1979	.380	.058	.179	.237	.617	.153
1980	.386	.063	.168	.231	.617	.147
1981	.410	.063	.176	.239	.649	.130
1982	.429	.066	.176	.242	.671	.111
1983	.439	.086	.174	.262	.699	.092

Projected U.S. refined petroleum consumption to the year 1990 are presented in Table 16. Reference data from 1975 and 1980 through 1982 are also given. This information was also supplied by DOE and the Energy Information Administration (25), but it may be noted that the historical data presented in Table 16 do not necessarily agree with the data presented in Table 14 for the same time period. This is due to different methods of accounting and possibly the use of a different definition basis for products supplied. The EIA projections are that total petroleum consumption will rise sharply beginning in 1984 and then decrease and level off to a value roughly the same as that experienced in 1980 by the end of the decade.

During this time period, gasoline consumption will continually decrease while jet fuel will rise slightly. Distillate demand will rise from 2.9 million B/D in 1983 to 3.9 million B/D in 1990. Although resid demand has fallen in the last few years, it is projected to rise by a large percentage near the end of the decade.

Table 17 reflects the fractional distribution of refined petroleum products consumption over the same time period with historical data from 1975 and 1980 through 1982 for reference. Gasoline ratios are expected to continually drop to 1990. The fraction of distillate to total petroleum product demand has been projected to rise from 19 percent to almost 23 percent by 1990. Middle distillate or jet fuel and distillate will increase from 26 percent to about 30 percent by 1990. Total light products will not increase due to a balance in the decrease of gasoline and the increase in middle distillate demand. Total resid demand is projected to increase from its 1980 level of 17 percent to almost 21 percent in 1990. It can be seen from these projection data that the two fuel categories of interest to the Navy -- of middle distillates and resid fuels -- are expected to rise as a fraction of the total fuel demand.

The above data reflect one set of projections to 1990. Other forecasts were also consulted relative to their projections of the fraction of distillate and resid fuels to 1990 and beyond. Texaco projections of U.S. petroleum demand (28) are presented in Table 18 for 1990 and the year 2000. The percent of distillate to total petroleum demand is projected to rise from a level of 25 percent in 1982 to 27 percent in 1990 and 35 percent in the year 2000. Residual fuel percents will rise from 11 percent in 1982 to 12.6 percent in 1990 but will again drop to an 11 percent level in the year 2000. Projections of SRI International (8) are given in Table 19.

TABLE 16. PROJECTED U.S. REFINED PETROLEUM PRODUCT CONSUMPTION (MMBPD)

Year	Gasoline	Jet Fuel	Distillate	Total Resid	LPG & Other	Total
1975	6.43	1.01	3.14	2.69	3.03	16.30
1980	6.63	1.09	3.23	2.88	3.17	17.00
1981	6.34	1.04	3.01	2.37	3.13	15.90
1982	6.26	1.02	2.83	2.03	2.60	14.75
1983	6.09	1.14	2.93	1.99	3.11	15.25
1984	6.24	1.12	3.39	2.95	3.32	17.00
1985	6.15	1.17	3.79	3.71	3.44	18.25
1986	5.86	1.20	3.87	3.78	3.44	18.15
1987	5.54	1.22	3.84	3.79	3.42	17.80
1988	5.26	1.24	3.82	3.75	3.43	17.50
1989	5.06	1.26	3.84	3.60	3.43	17.20
1990	4.92	1.29	3.92	3.58	3.49	17.20

1982 Annual Energy Outlook DOE/EIA-0383 (82)
"Case A - Middle World Oil Price Forecast"

TABLE 17. PROJECTED U.S. REFINED PETROLEUM PRODUCT CONSUMPTION RATIOS (FRACTION OF TOTAL DEMAND)

Year	Gasoline	Jet Fuel	Distillate	Jet Fuel & Distillate	Gasoline, Jet & Dist.	Resid
1975	.395	.062	.193	.255	.650	.165
1980	.390	.064	.190	.254	.644	.170
1981	.399	.066	.189	.255	.654	.149
1982	.425	.069	.192	.262	.687	.138
1983	.399	.075	.192	.267	.666	.130
1984	.367	.066	.199	.265	.632	.173
1985	.337	.064	.208	.272	.609	.203
1986	.323	.066	.213	.279	.602	.208
1987	.311	.068	.216	.284	.595	.213
1988	.301	.071	.218	.289	.590	.214
1989	.294	.073	.223	.296	.590	.209
1990	.286	.075	.228	.303	.589	.208

1982 Annual Energy Outlook DOE/E14-0383 (82)
"Case A - Middle World Oil Price Forecast"

TABLE 18. TEXACO PROJECTION OF U.S. PETROLEUM DEMAND (MMBPD)

	1982	1990	2000
Mogas	6.5	5.2	4.7
Jet Fuel	1.0	1.2	1.4
Middle Distillate	2.8	3.5	4.6
Residual Fuel	1.7	2.0	1.9
Other	3.3	4.0	4.6
Total	15.3	15.9	17.2
Total Distillate/Total	0.248	0.269	0.349
Residual Fuel/Total	0.111	0.126	0.110

T. Meloe, Chief Economist Texaco, Inc., from the "Impact of Conservation on Future Oil Demand", The Indonesian Petroleum Assoc., 12th Annual Convention, Jakarta, Indonesia, June 1983.

TABLE 19. SRI INTERNATIONAL PROJECTION OF U.S. DEMAND FOR PETROLEUM PRODUCTS (MMBPD)

	1980	1982	1990	2000
Gasoline	6.6	6.4	5.0	4.5
Jet Fuel	1.1	1.1	1.3	1.5
Heating Oil	1.8	1.6	1.6	1.4
Diesel Fuel	1.1	1.1	1.6	1.8
Residual Fuel Oil	2.6	1.7	2.0	1.8
Other	3.6	2.9	2.9	3.3
Total	16.9	14.8	14.4	14.3
Distillate/Total	.237	.257	.313	.329
Resid/Total	.154	.115	.139	.126

SRI International 1983

SRI International expects distillate percentages to rise from 24 to 26 percent in the early decade to 31 percent in 1990 and 33 percent in the year 2000. Resid demand is not expected to rise above its 1980 level of 15 percent. Recent projections by the U.S. Department of Commerce (16) are given in Table 20 for various fuel products as a fraction of total demand. Middle distillates (jet fuel and distillate) are projected to rise from the 1982 level of 25 percent to only 28 percent by the year 2000, while the Department of Commerce projects resid consumption to be 13 percent of the total in the year 2000. Projections by the General Accounting Office (14) are given in Table 21 for years 1985 and 1990. Distillate demand is projected to rise from 24 percent to between 27 and 29 percent by 1985 and between 28 and 32 percent by 1990. In contrast to projections by DOE/EIA the General Accounting Office expects resid demand to be only 7 to 9 percent of the total in 1990.

F. Product Demand Summary and Analyses

Table 22 summarizes the projections from five sources presented here in terms of gasoline ratios, middle distillate ratios, total light product ratios, and resid ratios. These ratios are defined to be the fraction of gasoline, middle distillate, gasoline plus distillate, or resid products compared to the total quantity of products supplied. The figures for 1980 and 1982 consumption ratios are historical figures. In comparing these values among the different forecasters, it can be observed that a slightly different basis was used by each. This indicates the difficulty of measuring current product demand aside from predicting future demand. The historical gasoline and middle distillate ratios are fairly consistent. However, the historical resid ratios of DOE/EIA are much higher than other forecasters. Unlike the other forecasters, DOE/EIA projects resid consumption to increase while other forecasters project resid consumption to decrease.

Gasoline consumption as a ratio of total products appears to have reached a peak in 1982 and will continually decline through the rest of the century. Average values for all forecasters project the middle distillate ratio to consistently increase during the projection years through 1985, 1990, and 2000. Total light product demand ratio reached a peak of 0.68 in 1982 and will fall to between 0.62-0.64 for the projected years. One forecast for 1984 anticipates a total light product demand of 68.4 percent.(23) Resid ratios are projected to increase in 1985 but decrease thereafter. These projections show that the demand for distillate fuels will call for an increasingly

TABLE 20. U.S. DEPARTMENT OF COMMERCE PROJECTED CONSUMPTION RATIOS (FRACTION OF TOTAL DEMAND)

Year	Gasoline	Jet Fuel	Distillate	Jet & Distillate	Resid
1982	.429	.066	.184	.250	.111
2000	.371	.106	.178	.284	.127

PB83-217521
"U.S. Energy for the Rest of the Century, 1983 Edition"

TABLE 21. GENERAL ACCOUNTING OFFICE PROJECTIONS OF 1982, 1985, AND 1990 U.S. PETROLEUM PRODUCT DEMAND (MMBPD)

	1982	1985	1990
Gasoline	6.6	6.0 - 6.5	5.1 - 6.0
Middle Distillates	3.8	4.5 - 4.6	4.8 - 4.8
Residual Fuels	1.7	1.1 - 2.0	1.0 - 1.5
Other	3.4	3.8 - 4.2	4.2 - 4.5
Total	15.5	15.4 - 17.3	15.1 - 16.8
Distillate/Total	.24	.27 -.29	.28 -.32
Residual/Total	.11	.07 -.12	.07 -.09

General Accounting Office
PB83-154286 1983

TABLE 22. PROJECTION SUMMARY OF FUEL CONSUMPTION RATIOS

	Historical		Projections		
Gasoline Ratios	1980	1982	1985	1990	2000
DOE/EIA	0.390	0.425	0.337	0.286	-
Texaco	-	0.425	-	0.327	0.273
SRI	0.391	0.432	-	0.347	0.315
DOC	-	0.429	0.383	0.348	0.371
GAO	-	0.426	0.383	0.348	-
Avg.	0.391	0.427	0.360	0.327	0.320
Middle Distillate Ratios					
DOE/EIA	0.254	0.262	0.272	0.303	-
Texaco	-	0.248	-	0.269	0.349
SRI	0.237	0.257	-	0.313	0.329
DOC	-	0.250	-	-	0.284
GAO	-	0.245	0.279	0.302	-
Avg.	0.246	0.251	0.276	0.296	0.321
Total Light Product Ratios					
DOE/EIA	0.644	0.687	0.609	0.589	-
Texaco	-	0.673	-	0.596	0.622
SRI	0.628	0.689	-	0.660	0.644
DOC	-	0.679	-	-	0.655
GAO	-	0.671	0.662	0.650	-
Avg.	0.636	0.680	0.636	0.624	0.640
Resid Ratios					
DOE/EIA	0.170	0.138	0.203	0.208	-
Texaco	-	0.111	-	0.126	0.110
SRI	0.154	0.115	-	0.139	0.126
DOC	-	0.111	-	-	0.127
GAO	-	0.11	0.10	0.08	-
Avg.	0.162	0.117	0.152	0.138	0.121

larger portion of the crude petroleum barrel in the future. This projected increase will have a large impact on future distillate fuel properties. Resid demand which has taken a temporary dip during the recession years of 1981, 1982, and 1983 will rise again to pre-recession levels and then decrease from that point. In order to reach the demand for lighter products, higher quality resid materials will be converted, and this will leave a poor quality resid to fill the resid demand. Resid fuels of the future may therefore have poorer quality due to these trends.

G. PADD V Product Demand

The total distillate demand in 1978 for PADD V was 24 percent. Of this percentage, 47 percent was jet fuel. (33) Total light product demand was 65 percent. Hydrocracking capacity in the U.S. is concentrated on the west coast to accommodate the heavier than normal crudes refined in that area and still meet product specification. (34) The national demand for distillates was also about 24 percent in 1978. Earlier in the decade, the demand was within one percentage point of this level. In 1978 refinery ouput in PADD V supplied 90 percent of total product demand, producing 21 percent distillates and 64.5 percent total light products. (33) Jet fuel and kerosene was 43 percent of the distillates supplied. This is compared to the 25 to 30 percent national average. The remainder of demand (10 percent) was met by product imports from other PADD areas.

These figures for PADD V supply and demand are very revealing. They show that with an exceptionally low quality crude slate, a high yield of light products could be produced. Existing refining capacity includes a high proportion of conversion processing. Total distillate demand of 24 percent was not met, possibly indicating some limitation, but an exceptional amount of high quality distillate in the form of jet fuel was refined locally.

H. Worldwide Product Demand

Total distillate demand in the U.S. is expected to increase to a level of 30-32 percent of the total demand between 1990-2000. This can be compared to levels found outside the U.S. and Canada in Table 23. Western Europe, Japan and other non-communist countries consumed 33-34 percent of total petroleum products as distillates in 1982. In spite of this high distillate demand level elsewhere in the world, product quality is still maintained at high levels. Traditionally, European diesel fuel has been high quality. This point was brought out in an analysis of estimating worldwide cetane numbers. (35) The cetane index method was found to have a bias which was dependent of cetane number. Fuel suppliers in Britain and Australia reported that the method consistently overestimated cetane in their range of interest from 50-60 cetane. Canadians reported that the method underestimated cetane number in their range of interest from 35-42, cetane numbers while suppliers in the U.S. found only a small bias in the middle range from 42-48 cetane number.

One reason that the Europeans can still make high quality diesel fuel despite a 34 percent distillate demand is that their total demand for light products is less than that for the U.S. -- 55 percent compared to nearly 69 percent for the U.S. in 1982. Western Europe and Japan had a gasoline demand in 1982 which was half that of the U.S. -- 21 percent versus 42 percent as shown in Table 23. Other non-communist countries were similar to Western Europe and Japan in demand for light products in 1982. Adequate distillate quality is made in these countries even with high demand and with less refinery flexibility than in the U.S. (See Section V). This is probably due to a combination of crude selection and less total light product demand. Most of the downstream refining capacity in the U.S. is aimed at gasoline production. Demand distribution within the distillate fraction may also be a factor for countries outside the U.S. where less jet fuel, for instance, may be required which would not take away premium quality from the other distillates.

TABLE 23. WORLD AREA OIL DEMAND DISTRIBUTION, 1972-1982

	United States & Canada		Western Europe & Japan		Other Non-Communist	
Product Ratios	1972	1982	1972	1982	1972	1982
Gasoline	0.380	0.416	0.175	0.211	0.194	0.199
Middle Distillates	0.254	0.270	0.291	0.340	0.289	0.327
Subtotals	0.634	0.686	0.466	0.551	0.483	0.526
Fuel Oil	0.176	0.128	0.407	0.299	0.380	0.334
Other	0.190	18.6	12.7	15.0	13.7	14.0
Totals	1.00	1.00	1.00	1.00	1.00	1.00

Source: OGJ Nov. 14, 1983, p 109.

Canada has a light product demand similar to that found in the U.S. but has even more difficulty meeting distillate quality standards. There are two apparent reasons for this. Nearly 10 percent of total petroleum demand in Canada is met by synthetic crude derived from oil sands. The distillate fraction of this syncrude has a characteristic high-aromatic, low-cetane quality. Refinery flexibility may be the second reason. Canada does not have the extensive flexibility found in the U.S. Because of the extreme cold climates found in Canada, the Canadians are forced to trade cetane number for pour point. The long straight chain paraffins which contribute to cetane quality also cause wax formation. Therefore, although cetane number is necessary for cold-starting capability, pour point requirements are more critical and are reached sometimes at the expense of cetane number.

I. Transportation Diesel Demand

Total distillate demand is comprised of distillates used in electric utilities, industrial applications, railroads and vessels, heating and diesel fuel. Diesel fuel has been growing in its proportion of total distillate demand from 1962 to 1982. There has been a steady increase from 11 to 39 percent demand for diesel out of the total distillate. Diesel is the primary fraction of distillate products which requires a certain combustion quality as measured by cetane number. Railroads and ships would also be considered in this category requiring a minimum combustion quality. Railroad and vessel demand over the last 20 years has remained nearly constant between 100 and 120 million barrels per year over the last 20 years. This increase in the use of distillates requiring a minimum combustion quality has resulted in a net increase in distillate fuel cetane requirements. One forecast (36) projects an increase in minimum pool cetane of 0.8 cetane numbers based on a distribution between burner fuels, heavy-duty diesels and automotive diesels. An evaluation of forecasted diesel fuel consumption (37) based on projected truck, car, farm and off-highway utilization indicates a net pool cetane requirement increase of 0.5 cetane numbers. Therefore, not only is the diesel fuel demand increasing substantially, the projected trends for the use distribution of diesel fuel will require even higher cetane numbers. Ethyl Corporation (37-39) projects an increase in U.S. diesel fuel consumption of approximately 40 percent. In the same forecasts, the consumption of diesel fuel by cars which require a high quality product is expected to be over five times the 1980 level. This forecasted increase is chiefly responsible for an increase in the cetane quality demand.

J. Residual Fuel Demand

Residual fuel demand will be affected by relative prices between natural gas, crude oil, and coal along with the penetration of nuclear energy into the utility market. A moderate price scenario for each of these contributing factors projects the demand for residual fuel in the U.S. to remain at a nearly constant level after a slight rise in the next few years. (20) Nearly half of the residual fuel oil demand is met in this country by imports. Therefore, a flexibility to meet demand in the U.S. has been established through the import market worldwide. The projected world demand for residual oil follows the U.S. trend with a slight increase in the next 2 to 3 years followed by a level demand to 1995.

New residium conversion units will reduce the supply of traditional blendstocks for residual fuel oil. These residum oil conversion units planned in the late 1980's during a rising oil demand period will consume much of the higher quality residual fuels, leaving poor quality resid and resid conversion by-products for fuel consumption. Residual fuel oil quality will therefore change with the level of cracked, non-virgin blendstock in Western Europe and the U.S. rising and causing potential stability problems and possible catalyst fines contamination. In addition, the metals contents are also projected to increase.

IV. REFINERY PROJECTION STUDIES

Refinery projection studies are based on projected crude properties and product slates. These studies are carried out using linear program computer models of refineries which represent actual operation. Projections of expansion of downstream processing equipment are also part of these studies in some cases. Computer models of refinery operations can be modified to include or exclude most types of processing equipment available. They can also make new processing units available as needed for a desired product distribution or for the particular crude being evaluated.

A. Projected and Historical Crude Quality

Average crude quality as represented by API gravity is given by producing area (40) in Table 24. Actual average data are presented for 1975, 1976, 1978, and 1980. Average gravities for each producing area are forecasted for 1985, 1990, and 2000. The U.S. is projected to have the greatest decline in crude API gravity and will have the lowest gravity in 2000 with the exception of crude from the Caribbean area, and much of this Caribbean crude will be imported to the U.S. On the average, crude producing areas outside the U.S. will suffer a decrease in API gravity of about 1° over the next 15 years. Table 25 presents the average API gravity, wt% sulfur, and vol% material boiling above 1000°F (538°C) for total crude oil processed in the U.S. refineries to the year 2000. These data take into account projected crude imports and domestic crude which will be refined within the U.S. (40) It can be seen in Table 24 and Table 25 that U.S. will be processing some of the lowest quality crude of those areas represented. The U.S. is a worse case example of what may happen to crude supply in the future.

The western area represented by PADD V has the lowest quality crude as measured by gravity of any of the refining districts in the U.S. It also processes the crude with largest amount of high boiling material (See Table 25). The crude quality in PADD V in 1980 was actually worse than that which is projected for the U.S. as a whole in the year 2000. (40) Assuming a constant product slate demand, a preview of fuel properties for the year 2000 may be seen by examining the properties of the fuels produced in the western region which corresponds to PADD V. These properties are discussed in Section II, and demand in PADD V is discussed in Section III.

TABLE 24. AVERAGE API GRAVITY IN FREE WORLD CRUDE OIL PRODUCTION (°API)

	Actual				Forecast		
	1975	1976	1978	1980	1985	1990	2000
United States*	34.3	34.2	33.3	32.6	32.2	31.9	29.9
Canada*	37.9	37.8	37.4	37.1	36.9	36.6	36.0
Caribbean	28.0	28.1	27.9	27.6	26.8	25.7	25.0
South America	32.7	32.8	32.8	32.9	33.1	33.3	33.3
Europe	34.9	35.4	35.5	35.5	35.6	35.1	34.6
Japan	35.0	35.0	35.0	35.0	35.0	35.0	35.0
North Africa	38.4	38.2	38.0	38.0	37.9	37.7	37.4
West Africa	36.0	35.0	34.0	34.0	33.8	33.6	33.5
Middle East	32.7	32.8	32.5	32.3	32.3	32.5	32.9
Asia/Oceania	37.9	37.9	37.8	37.7	37.4	37.0	36.8
Total Production	33.6	33.6	33.5	33.3	32.9	32.5	32.0
Total Production less United States	33.7	33.6	33.5	33.5	33.0	32.6	32.3

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* Includes syncrudes

Source: Reference 40

TABLE 25. PROPERTIES OF TOTAL CRUDE OIL PROCESSED IN UNITED STATES REFINERIES

	Disposition Region (PADD)					
	1	2	3	4	5	Total
			°API GRAVITY			
1977	34.1	35.9	35.6	35.4	30.5	34.7
1978	34.4	35.1	35.1	34.9	27.8	34.2
1980	33.0	34.5	34.8	34.9	26.8	33.3
1985	32.3	32.6	32.6	33.5	26.4	32.4
1990	32.1	33.0	32.4	31.6	26.3	31.3
2000	31.6	32.5	27.9	30.9	26.9	29.8
			WEIGHT PERCENT SULFUR			
1977	1.00	0.69	0.68	1.36	0.92	0.78
1978	0.96	0.68	0.73	1.36	0.86	0.78
1980	1.11	0.69	0.85	1.42	0.93	0.87
1985	1.14	0.86	1.16	1.48	0.97	1.07
1990	1.16	1.10	1.23	1.46	0.98	1.18
2000	1.20	1.14	1.02	1.48	1.00	1.14
			VOLUME PERCENT 1000 ° F+ MATERIAL			
1977	17.9	15.5	15.5	16.9	19.7	16.4
1978	18.0	16.1	16.2	17.1	21.3	17.2
1980	19.1	16.5	16.6	17.1	21.9	17.9
1985	19.3	17.5	18.3	17.5	23.0	19.0
1990	20.0	19.1	19.3	18.2	23.0	19.8
2000	22.7	19.6	20.1	18.6	24.0	20.9

Source: Reference 40

B. Distillation Capacity and Downstream Refining Capacity

After years of steady growth to a peak in 1981, the number of refineries is now smaller than at any time since data collection began 65 years ago. (41) The number of operating plants dropped from a high of 303 in 1981 to 220 in 1984. Operating capacity has also fallen about 10 percent and is at the lowest level since 1977. This is due to a large number of shutdowns that have occurred across the country. Many of these shutdowns are temporary and some plants may return to operating status with relatively short notice if petroleum demand or economic circumstances warrant reopening of these refineries. The decrease in demand and removal of the government entitlements program caused the decrease in overall operating refinery capacity. Smaller refineries, established strictly to take advantage of the crude oil entitlements program, have found it uneconomic to remain open with removal of that program and decreased demand. Currently, the refining industry is undergoing a long-term adjustment process which is intended to accommodate a lower crude oil quality and a shift in product distribution. Smaller refineries which have the necessary downstream processing capacity to meet future product demand slates may reopen with an increase in demand which is expected with recovery from the recent recession.

Operable capacity is the total of currently operating capacity plus any capacity which may reach operating status within a 30-day period. Most refineries in the U.S. are operating well below crude distillation capacity. Both crude distillation and vacuum distillation capacity has continued to drop from 1982 to 1984. Thermal operations, catalytic hydrocracking, and catalytic hydrotreating suffered a decrease in 1983 but rose in 1984. This type of downstream refining capacity is aimed at upgrading the heavier, sour crudes that are expected to be more prevalent in the future. Catalytic cracking has been aimed in the past at primarily producing large quantities of gasoline blendstocks as has catalytic reforming. Catalytic cracking is in excess of the current demand, and with projected decreases in gasoline demand, some catalytic cracking operations are being converted to heavy oil cracking to reduce resid production. Catalytic cracking technology will also be adjusted to reduce the conversion to light gasoline products. Through catalyst and operating condition changes, higher conversion to distillate products may be achieved. Sufficient catalytic hydrocracking and catalytic hydrotreating capacity will help to ensure adequate distillate product quality. These are expensive processes and their increased use to meet product quality specifications will be done where economic. One forecast (42) projects significant refinery investments in hydrocracking, hydrotreating, hydrogen plants, coking, hydrodesulfurization, and heavy oil cracking to meet future product demands by the year 2000. These investments are projected to range from $10 to 14 billion. Another forecast (43) projects a 20 percent increase in hydrocracking capacity and thermal operations during the period 1985 to 1990.

Total downsteam capacity in the U.S. exceeded crude distillation capacity for the first time in 1981. Downstream capacity in 1983 was almost 2 million barrels per stream day higher than crude distillation capacity. This trend in increasing refinery complexity is expected to continue into the future to meet new product demand and accommodate lower quality crudes. Other refining trends and worldwide refining capacity is addressed in Section V.

C. Refinery Case Studies

Several case studies have been performed by various organizations to project the effects on refining industry of changing product demand, changing crude quality, and adjustments in refinery conversion capacities. Some of these studies have examined extreme cases in product demand and conversion capabilities within the refinery. These cases can be adjusted to allow investment in required conversion facilities or investment flexibility may be left out. Linear programming models are primarily aimed at determining costs and maximizing profitability.

One such refinery study performed by Wright, Killen and Feldman (43) looked at a base case Gulf Coast refinery without coking or heavy oil upgrading. An average quality crude was processed to produce 63 percent gasoline, 18 percent distillate, and 19 percent resid. The 18 percent distillate product compares to an industry average of about 25 percent. A 1990 case was run with coking capacity where 26 percent distillate, 60 percent gasoline and 5 percent resid were produced. A similar 1990 case with hydrocracking resulted in 26 percent distillate, 60 percent gasoline and 3 percent resid. Overall findings of the study indicated that a substantial increase in middle distillate production could be realized by making sharper cuts in the distillation process. This could amount to as much as a 40 percent increase in distillate production. Another finding was that increasing hydrocracking capacity will enable refineries to meet future needs. Supplementary to this, more severe hydrotreating operating conditions with appropriate catalyst may be used to increase heavy oil conversion.

A study by the Pace Co. (44) projects difficulty in meeting new product distributions within 5 years. The Pace study examined a typical Gulf Coast refinery in the 1985 time frame with reformer, alkylation, FCCU, coker, and hydrotreating units. The maximum yield of distillate was 31 percent matching the forecasted distillate to gasoline ratio of 0.8 used in the study. Pace reported that typical refineries will only be able to produce a distillate to gasoline ratio of 0.75 to 0.85. Product quality was reported not to be a problem as much as product quantity. Downstream hydrotreating was sufficient to bring distillate products within specification in this case with only a small differential in product prices between distillates and other products. Pace reported that hydrocracking capacity represents only 5 percent of total U.S. capacity and that this will increase to meet distillate product demand. In a summary of the work, Pace suggested the following measures necessary to meet future increased distillate demand:

- Increase the hydrocracking installations
- Import diesel and distillate refined products
- Segregate distillate streams for higher cetane diesel fuel
- Use additives to improve cetane number
- Cracking catalyst research

A study done by Bonner & Moore Associates (45) evaluated extreme cases of distillate fuel production. Four cases were studied including a baseline, limited diesel, restricted diesel, and high diesel case. Distillate production ranged from 34 percent to 46 percent of the total products produced and diesel fuel ranged from 12 percent to 24 percent. Conversion capacity was allowed to be added as needed in these cases. The main specification for diesel fuel in these cases was a minimum cetane number of 42. In all cases, this specification quality was met in spite of the large quantities produced by segregating low cetane stocks to heating oil. Cost of distillate products became a major factor in the high diesel case. In this case, distillate cost were nearly 40 percent more expensive than unleaded gasoline as reflected in marginal production costs. Bonner & Moore concluded that there were serious cost barriers to a high percentage diesel production. Marginal costs of distillates would be pushed beyond reasonable levels if demand forced an excessively large yield of diesel from each barrel of crude. This would result from high investment and processing costs.

SwRI investigated the impact of blending synthetic crudes with petroleum crudes on the refining industry. (46) Both shale oil and coal oil crudes were added to petroleum crudes in several regional models. In maximum diesel cases for several regions, the total distillate products ranged from 48 to 52 percent of total products. In these maximum diesel cases, diesel fuel represented 24 to 31 percent of total products. These maximum diesel cases showed both net energy increases and decreases on refinery configuration as compared to the base case. Product quality specifications for diesel fuel were set at 45 cetane blending number. This was met precisely in all the cases with API gravity for the No. 2 diesel fuel from 36.1 to 37.6° API.

Amoco performed a refinery study which evaluated several cases of gasoline to distillate ratio ranging from 1.6 to 0.5 in 1995. (47) At a 0.5 gasoline to distillate ratio, total distillates were 55.4 percent of the total products and diesel fuel was 26.6 percent of total products. Amoco set the specification for diesel fuel at 50 cetane index. The crude charged in these cases was an average U.S. crude mix. The refinery configuration made available the best refining technology. To determine the effects of poor quality crudes, an alternate crude mix consisting of 75 percent U.S. average and 25 percent North Slope was examined. In this case, it was impossible to make the budgeted quantities of diesel fuel and still meet the high 50 cetane specification. However, the budgeted volumes could be made when the specification was lowered to 45. The effect of tightening pour point of diesel fuel from -5°F to -15°F (-20°C to -26°C) was also studied, but negligible refinery energy was associated with control of diesel fuel pour point.

The Exxon Research and Engineering Company (48) studied the effects of changing the proportions of automotive distillate and gasoline produced by petroleum refining. Two base cases were studied where residual fuel oil was produced at a 7 vol% level and at a 20 vol% level. Automotive diesel fuel was incrementally increased for each of the two base cases replacing motor gasoline on a Btu basis. Motor gasoline production was 57 vol% and automotive diesel fuel was 6 vol%, making a total of 63 percent automotive fuel in low fuel oil cases. In the high fuel oil case, motor gasoline was 5 percent and automotive distillate fuel was 49 percent making a total of 54 percent. Exxon concluded that the maximum feasible replacement of diesel fuel is 74 percent on a Btu basis for both cases. This represented a 0.3 gasoline to total distillate ratio. Maximum savings could be realized by producing 46 to 55 percent diesel fuel out of the total motor fuel which corresponded to a 0.49 to 0.66 gasoline to total distillate ratio.

Table 26 summarizes the six refining studies discussed above. In general, distillate products appeared to be quantity limited but not limited by quality. Distillate products could be increased substantially to attain gasoline to distillate ratios of 0.5 to +00.7. However, substantial cost increases occurred at high demand levels. One study reported quality problems which were associated with a high cetane specification product and a poor quality crude. Several recommendations were made to help meet future product demand including segregation of distillate products, improved distillation, hydrocracking, hydrotreating, and imports to offset shortages of refined products.

In the studies reviewed above, diesel fuel was a motor fuel for highway transportation. The trends were interpreted generally as being applicable to all distillate products, including Naval distillate fuel. The studies did not investigate the specific problems hat would be associated with making diesel fuel to Navy specifications to all or part of the production.

D. Regulation of Diesel Fuel Quality

Particulate emissions from diesel-powered vehicles is a subject of growing concern. This concern is accentuated by the penetration of diesel-powered vehicles into the transportation market. Certain studies have shown a correlation of particulate emissions with high boiling hydrocarbons and aromatics. (49-51) It has been suggested that proper control of these properties at the refinery could be a means of controlling particulate emissions. Control of high boiling hydrocarbons through reduction of 90 percent temperatures and reduction of aromatic concentration through low aromatic crude selection, hydrodearomatization processing, or some means of solvent extraction will have two areas of major impact on the refinery and product availability. The first effect will be a reduction in the quantity of material available to produce diesel fuel meeting such restricted requirements. The second effect will be an increase in product cost associated with further handling, storage, and processing. The possibility that such restrictions may be imposed must not be overlooked. The result of taking such measures by regulatory agencies within the government could have a major impact on automotive diesel fuel availability.

If such restrictions were indeed placed on automotive diesel fuel, it would place this product in direct competition with aviation turbine fuels and kerosene-type products.

TABLE 26. REFINING STUDY SUMMARY (EXTREME DIESEL CASES)

Study I.D.	WKF Ltd. Dist.	B&M High Diesel Restricted High Diesel	SwRI Shale, Coal Oil, Max Diesel	Amoco Max Diesel Cases	Exxon Optimized Gaso/Diesel	Pace Max Diesel Coker
Case Year	1990	1995,2000	1995	1995	1990-2000	1985
Crude Oil	33.1 °API, 1.2% S	Proj. PADD Average	Syncrude Petroleum	1995 U.S. Average	35.6°API, 0.7% S	-
Refinery	Gulf Coast Coking, Hydrocracking	Flexible with investment	R. Mtns., Great Lakes, Mid-Continent	1980 Forecast to 1995	Projected to Case Date	Gulf Coast 1985
Refinery Throughput	70,000 B/D	135,000 B/D	52,000 - 125,000 B/D	150,000 B/D	100,000 B/D	90,000 B/D
% Distillates	26	52-54	48-52	49-55	51-57	40
% Diesel	-	22-24	24-31	19-27	34-39	31
% Gasoline	60	18-22	27-35	28-35	19-29	49
Gaso/Dist.	2.31	.40-.50	.54-.73	0.50-0.70	0.34-0.55	.82
Cetane No. (Fuel Oil)	45(40)	42(25)	45(-)	50(40)	45(-)	45(-)
Other Spec.	0.3 sulfur 130°F Flash 0°F pour	0.2 sulfur 125°F Flash 20°F Pour	0.5 sulfur 125°F Flash 20°F Pour	0.3 sulfur	0.1 sulfur 125°F Flash 10°F Pour	
Conclusions	Improve 650°F cut point, segregation, hydrocracking, severe hydrotreat	Large cost difference @ 54% dist. & 24% diesel	No unusual problems 36-37° API diesel	Quality problems w/power crude, optimum diesel fuel = 10% more miles /bbl	Above levels max feasible, max savings @ 34% diesel	Quantity limited not quality, new specs., hydrocracking, diesel imports, segregation

The impact of such a move on Navy shipboard distillates could be devastating with respect to product quality. Once most of the low boiling, low aromatic, distillate products were used for jet fuel, kerosene, and automotive diesel, the remaining distillate material to supply other needs would be much lower quality. The "leftovers" would consist of high aromatic, high boiling, distillate material which would have lower combustion quality, lower stability, and poorer flow properties.

The costs associated with further processing and segregation of special distillate products were assumed to be distributed overall refinery products. The added cost of taking such measures were evaluated by Bonner & Moore Associates for the American Petroleum Institute. (51) These added costs range from less than one dollar per barrel to as much as $14 per barrel in very restricted cases. Availability of restricted quality diesel fuel was as low as 3½ percent of the crude input volume.

V. REFINERY CONSTRUCTION

A. Historical Trends

Refining capacity trends in the United States for past 10 years are presented in Table 27. Total number of operating plants, crude distillation, and downstream processing capacities such as catalytic cracking are listed. (52) Thermal processes include gas oil cracking, thermal cracking, visbreaking, and both fluid and delayed coking. Catalytic hydroprocessing is divided into three categories of hydrocracking, hydrorefining, and hydrotreating. Catalytic hydrocracking includes distillate upgrading, resid upgrading and some lube oil manufacturing. Catalytic hydrorefining includes resid desulfurization, heavy gas oil desulfurization, cat cracker feed pretreatment, and middle distillate refining. Catalytic hydrotreating includes reformer feed pretreatment, naphtha desulfurization, naphtha saturation, straight run distillate hydrotreatment, and lube oil polishing.

Table 27 shows that the number of refining plants decreased during 1981-1984. At the same time refineries were shutting down, new downstream capacity was brought on-line in operating refineries, so that total downstream capacity actually increased in some cases. Vacuum distillation, thermal operation, catalytic hydroprocessing, hydrogen production, and coke production each had a net increase over the last 4 years in spite of numerous plant shutdowns. Each of these processes is aimed at recovering higher quality products from the bottom of the barrel. Hydrogen manufacture, a key to upgrading capacity, is illustrated in Figure 11 for the period 1976-1984. A consistent rise in capacity has occurred with the exception of 1980.

B. Planned U.S. Construction

Planned refinery construction projects in the United States (53) are presented in Table 28. Large percentage gains are planned for thermal cracking (7.75 percent), catalytic hydrocracking (13.36 percent), and hydrogen manufacture (17.99 percent). Coke production will also increase in conjunction with thermal cracking projects. New aromatics or isomerization plants will provide about a 7 percent increase in present capacity. Isomerization will play a prominent role in meeting future octane requirements in anticipation phase-down or phase-out of lead in gasoline. Because of a forecasted reduction in total gasoline demand, new catalytic cracking capacity may

TABLE 27. U.S. REFINERY CAPACITY 1975-1984 MB/STREAM DAY

Year	Plants	Crude MB/CD	Capacity MB/SD	Vacuum Distillation	Thermal Operations	Cat Cracking Fresh Feed (Recycle)	Cat Reforming	Cat Hydrocracking	Cat Hydrorefining	Cat Hydrotreating	Alkylation	Aromatic Isomerization	Hydrogen (MMcfd)	Coke (t/d)
1975	259	14,045	15,464	5,497	1,485	4,677 (934)	3,462	880	1,087	4,907	869	329	-	43,40
1976	256	15,075	15,687	5,673	1,460	4,745 (930)	3,593	893	1,277	5,212	874	335	1,446	44,21
1977	266	16,171	16,913	6,217	1,506	4,932 (890)	3,670	908	1,809	5,568	882	385	1,563	49,31
1978	285	16,849	17,619	6,318	1,497	4,957 (897)	3,782	913	1,945	5,831	888	399	1,665	46,16
1979	289	17,170	18,051	6,532	1,497	4,985 (884)	3,794	887	1,958	5,934	920	388	1,740	45,16
1980	297	17,791	18,709	6,686	1,556	5,304 (817)	3,924	888	1,956	6,341	1,007	464	1,609	48,20
1981	303	18,465	19,370	6,997	1,600	5,531 (871)	4,051	912	2,159	6,625	980	448	1,767	51,45
1982	273	17,669	18,601	6,938	1,703	5,461 (863)	3,978	997	1,849	6,938	965	488	1,886	53,23
1983	225	16,157	17,008	6,877	1,551	5,230 (759)	3,881	939	1,873	6,620	920	486	1,885	55,52
1984	220	15,862	16,689	7,016	1,737	5,170 (737)	3,863	920	2,287	6,651	930	473	2,197	66,32

Source: OGJ Annual Refining Issue 1975-1984.

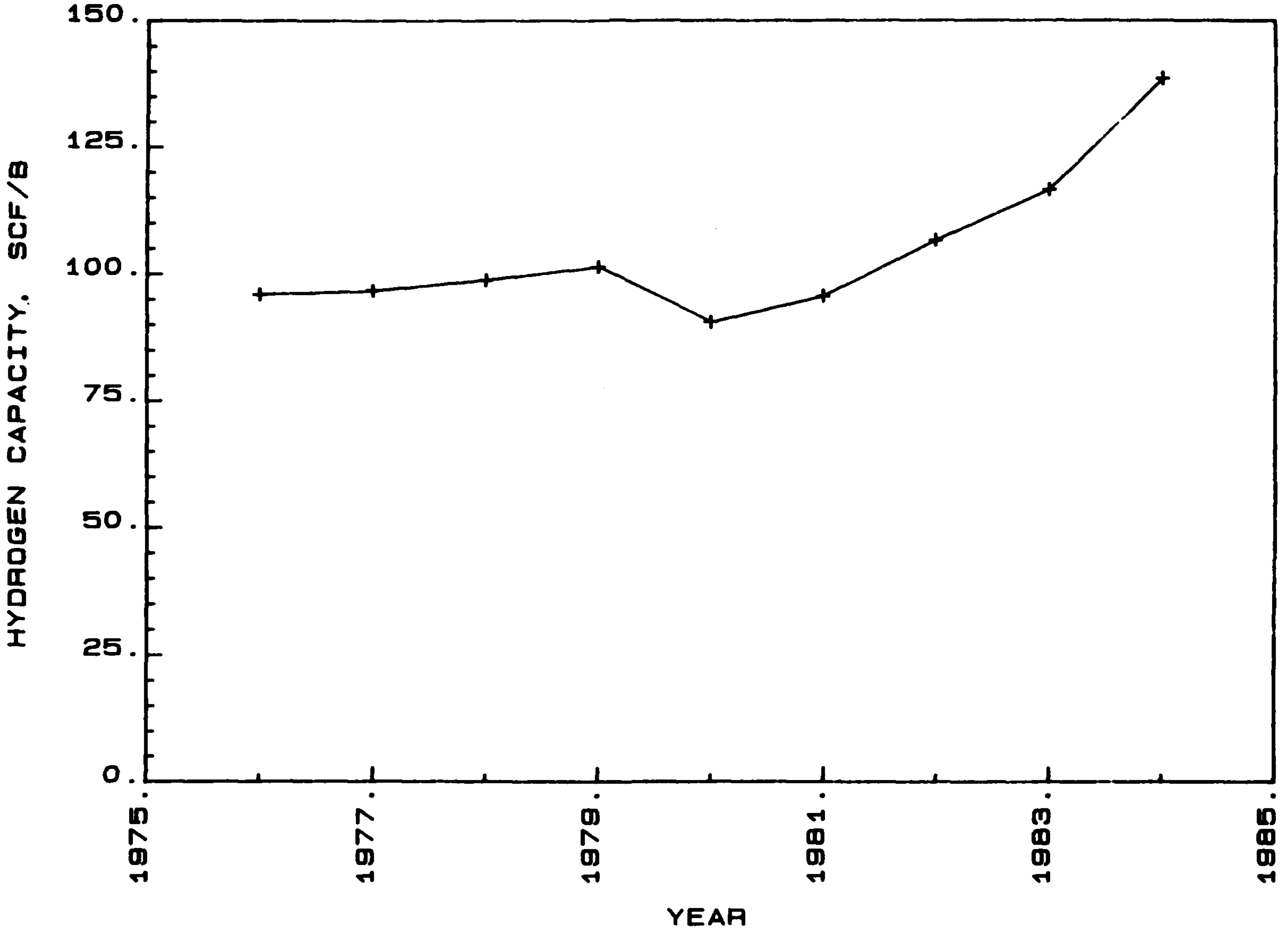

Figure 11. U.S. Hydrogen Production per Barrel, 1976-1984

TABLE 28. PLANNED U.S REFINERY CONSTRUCTION - 1984 (COMPLETION 1984-1987)

	New Capacity B/D	Percent of 1984 Capacity
Crude Distillation	259,000	1.55
Vacuum Distillation	162,200	2.31
Thermal Cracking	134,610	7.75
Catalytic Cracking	59,500	1.01
Cat. Reforming	33,000	0.85
Cat. Hydrocracking	122,900	13.36
Cat. Hydrorefining	67,500	2.95
Cat. Hydrotreating	65,200	0.98
Alkylation	16,600	1.78
Aromatics/Isomerization	32,500	6.87
Hydrogen (MMcfd)	285.5	12.99
Coke (t/d)	3,489	5.26

Source: OGJ Apr. 23, 1984. "Worldwide Construction Report".

not be required and may even be shifted to lower severity for distillate production. High octane demand requiring high severity cracking may compete with low cracking severity for high distillate conversion in some cases. Cat crackers may also be converted to heavy oil crackers which may not be indicated as new construction.

C. Worldwide Refining and Construction

Worldwide downstream refining distribution (54) is given in Table 29. Percentages of crude distillation are given for downstream process capacity in several major oil refining countries and in the non-communist world excluding the United States. The United States leads the world in total downstream capacity percentage with a total of 178 percent of crude distillation. Downstream refining capacity represents the degree of both flexibility and complexity within the refinery. Worldwide comparisons are illustrated in Figure 12 for total downstream capacity.

The United States leads the world in crude distillation capacity and percent of cat cracking, cat reforming, cat hydroprocessing, alkylation, aromatics/isomerization, and coke production. Vacuum distillation percentage is lead by Brazil, Mexico, and Venezuela, reflecting the heavy crude oils produced in those regions. Germany leads in thermal cracking percentage. Japan leads in catalytic hydrorefining and hydrogen manufacturing percentage. Japan adds, on the average, 157 cubic feet of hydrogen per barrel of crude oil. This is a strong indicator of the amount of upgrading which is performed in Japan. Worldwide hydrogen manufacturing comparisons are illustrated in Figure 13 in terms of standard cubic feet of hydrogen per barrel of crude distillation.

A wide difference in refinery flexibility is evident from the data shown in Table 29. The countries listed represent leading refiners worldwide. Other countries as a whole will have less downstream capacity than those shown. Countries with less complex refining systems which import crude can still make high quality products by selecting high quality crudes which require less upgrading. Countries with low quality indigenous crude oil will generally provide the necessary downstream capacity to handle local product demand. Even with the widespread disparity in conversion capacity shown in Table 29, each country can meet product quality because of differences in the quality of crude oil processed and product demand slates.

TABLE 29. WORLDWIDE DOWNSTREAM REFINING DISTRIBUTION - 1984, PERCENT OF CRUDE DISTILLATION CAPACITY

	World Wide*	United States	Canada	Mexico	Venezuela	Brazil	France	Germany	United Kingdom	Italy	India	Singapore	Japan
Crude Distillation (MMB/D)	100.00 (42.659)	100.00 (15.863)	100.00 (1.834)	100.00 (1.269)	100.00 (1.224)	100.00 (1.301)	100.00 (2.670)	100.00 (2.386)	100.00 (2.092)	100.00 (3.050)	100.00 (0.779)	100.0 (1.101)	100.00 (5.020)
Vacuum Distillation	25.05	42.02	32.39	46.73	45.06	49.96	16.87	19.55	27.29	25.93	23.55	14.66	32.28
Thermal Cracking	6.82	10.40	4.55	6.46	2.97	1.24	4.29	13.64	8.46	10.15	10.99	12.17	1.60
Cat. Cracking	9.34	35.37	24.32	23.40	14.61	24.24	9.37	7.73	16.30	8.89	9.55	-	8.82
Cat. Reforming	11.09	23.13	19.74	12.91	0.49	1.66	13.52	16.82	17.67	11.41	1.93	4.63	11.09
Cat. Hydrocracking	1.45	5.51	4.19	1.42	-	-	0.51	3.59	1.95	-	-	1.45	0.74
Cat. Hydrorefining	12.94	13.70	0.63	0.39	22.93	-	12.24	17.19	7.51	12.66	1.77	6.54	38.68
Cat. Hydrotreating	24.79	39.83	43.21	39.56	-	10.20	29.49	34.98	38.43	19.19	9.07	29.23	29.13
Alkylation	0.73	5.57	4.01	0.52	4.83	0.25	0.24	0.42	2.17	1.06	-	-	0.04
Arom./Isomerization	0.98	2.83	2.27	0.36	1.50	0.18	0.50	2.02	1.65	2.05	-	-	0.97
Total Percent	93.19	178.36	135.31	131.75	92.39	87.73	87.03	115,19	121.43	91.34	56.86	68.68	123.35
Hydrogen, (cf/B)	(56.6)	(138.5)	(106.3)	(55.2)	(89.0)	(15.1)	(10.6)	(58.9)	(38.3)	(12.8)	(12.2)	(32.7)	(157.2)
Coke, (100 t/MB)	(21.42)	(418.16)	(27.37)	(-)	(-)	(44.57)	(-)	(72.08)	(90.84)	(-)	(62.93)	(-)	(10.96)

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* Non-communist; excludes U.S.

** Excludes lubes and asphalt

Source: OGJ Dec. 26, 1983, "Worldwide Report"

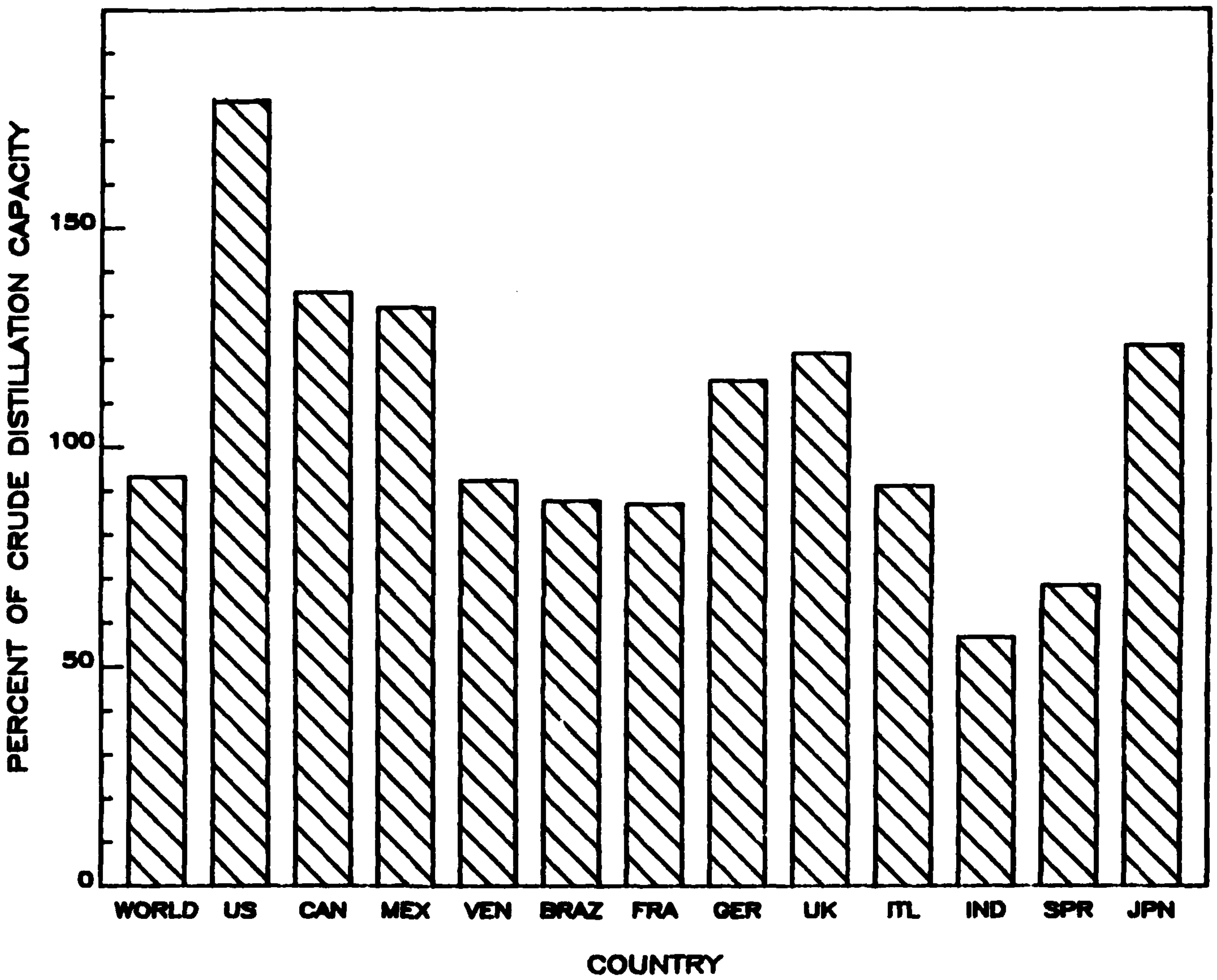

Figure 12. World Downstream Refining Capacity

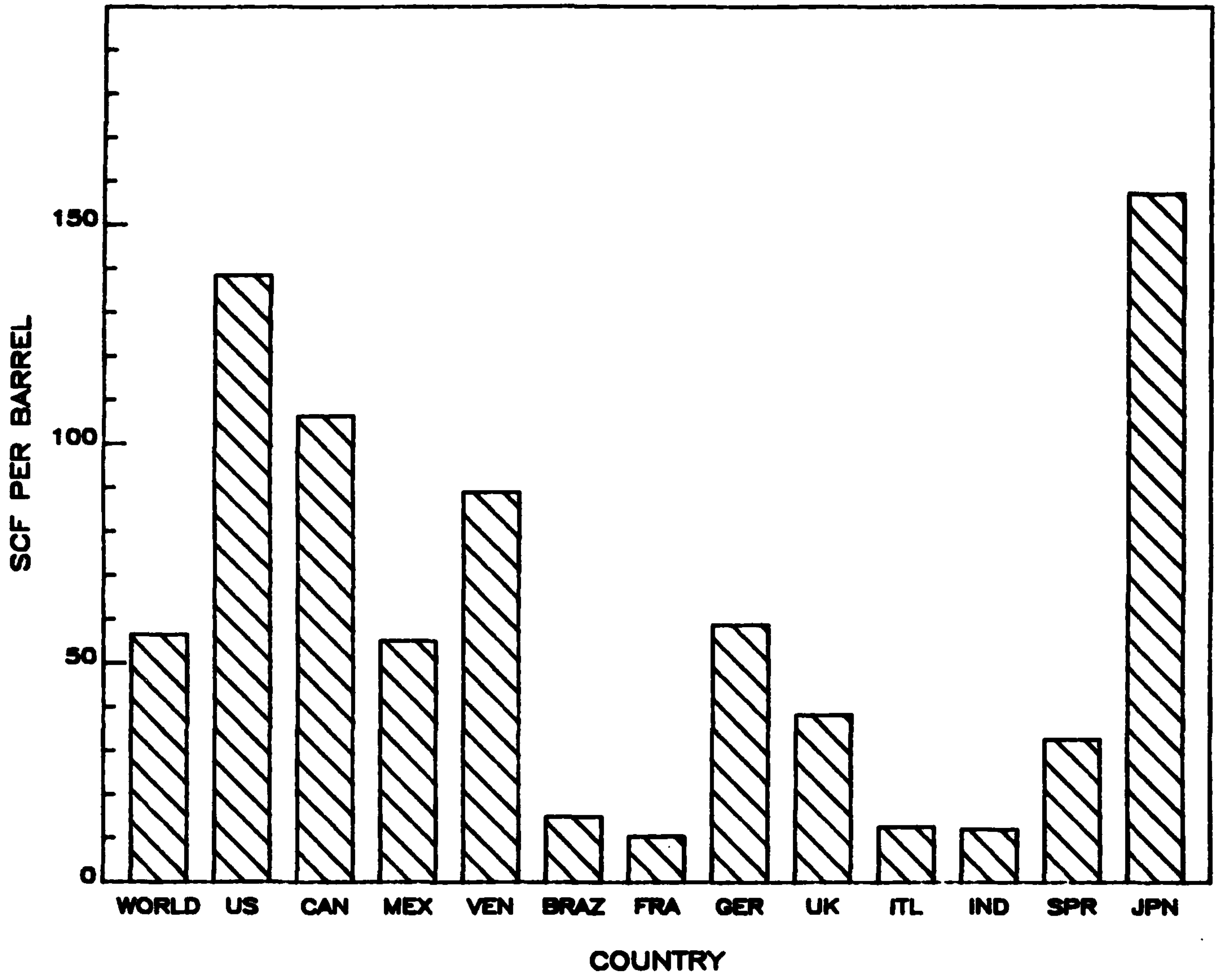

Figure 13. World Hydrogen Manufacturing Capacity
Standard Cubic Feet Per Barrel of Crude

Non-communist countries outside the United States currently plan a substantial increase in existing downstream capacity (54) as shown in Table 30. Worldwide construction increases compared to U.S. planned construction are illustrated in Figure 14. Topping the list of planned expansion is a 61.5 percent increase in catalytic hydrocracking followed by a 58.5 percent increase in coke production. Hydrogen manufacturing will also increase with almost a 28 percent gain. This represents a rate of new hydrogen production of 153 cubic feet per barrel, new distillation capacity. This will make the overall hydrogen capacity 65.6 cubic feet per barrel. The United States is adding new hydrogen capacity (see Table 28) at a rate of 1,102 cubic feet per barrel of new distillation, raising the total rate from 138 to 146 cubic feet per barrel. Substantial gains for each of the other processing categories in Table 30 are planned worldwide. These percentage gains are much greater than those planned in the United States.

D. Future Construction

To meet the future product quality demands, expanded downstream capacity will be required in the U.S. and throughout the world. Decline in overall crude quality and changes in product distribution will call for flexibility in the refinery which can compensate for the changes. The Western Region in the U.S. serves as a good example of low crude quality and high quality product demand. Table 31 compares world, U.S., and California refining capacities. California refining trends are likely to occur throughout the rest of the world in the future. Overall downstream capacity is only slightly greater in California than for the rest of the U.S. Major differences are less cat-cracking but more heavy oil cracking in California. Vacuum distillation, thermal cracking, catalytic hydrorefining, and coke production are from 24 percent to 79 percent greater in California than in the rest of U.S. Major differences between California and the U.S. are catalytic hydrocracking and hydrogen manufacturing which are, respectively, 227 percent and 256 percent greater in California. Future construction must emphasize these areas to accommodate future conditions. Figure 14 shows that both hydrocracking and hydrogen manufacturing are emphasized in planned new construction in the U.S. Worldwide construction is also following this trend along with signficant advances in thermal cracking and coke production.

TABLE 30. PLANNED WORLDWIDE* REFINERY CONSTRUCTION - 1984 (COMPLETION 1984 - 1988)

	Planned Capacity (MB/D)	Percent of 1984 Capacity
Crude Distillation	4,416.28 **	10.34
Vacuum Distillation	1,755.30	16.41
Thermal Cracking	645.88	22.17
Cat. Cracking	720.52	18.06
Cat. Reforming	312.91	6.61
Cat. Hydrocracking	379.99	61.48
Cat. Hydrorefining	659.99	11.94
Cat. Hydrotreating	775.27	7.32
Alkylation	23.24	7.41
Aromatics/Isomerization	93.80	22.43
Hydrogen Mfg. (MMcfd)	675.60	27.97
Coke (Mt/d)	5.35	58.50

---

* Non-communist; excludes U.S.

** Includes capacity of 15 new refineries, a 3.36 percent increase

Source: OGJ Dec. 26, 1983, "Worldwide Report."

Legend
1. Crude Distillation
2. Vacuum Distillation
3. Thermal Cracking
4. Cat. Cracking
5. Cat. Reforming
6. Cat. Hydrocracking
7. Cat. Hydrorefining
8 Cat. Hydrotreating
9. Alkylation
10. Aromatic/Isomerization
11. Hydrogen Manufacturing
12. Coke

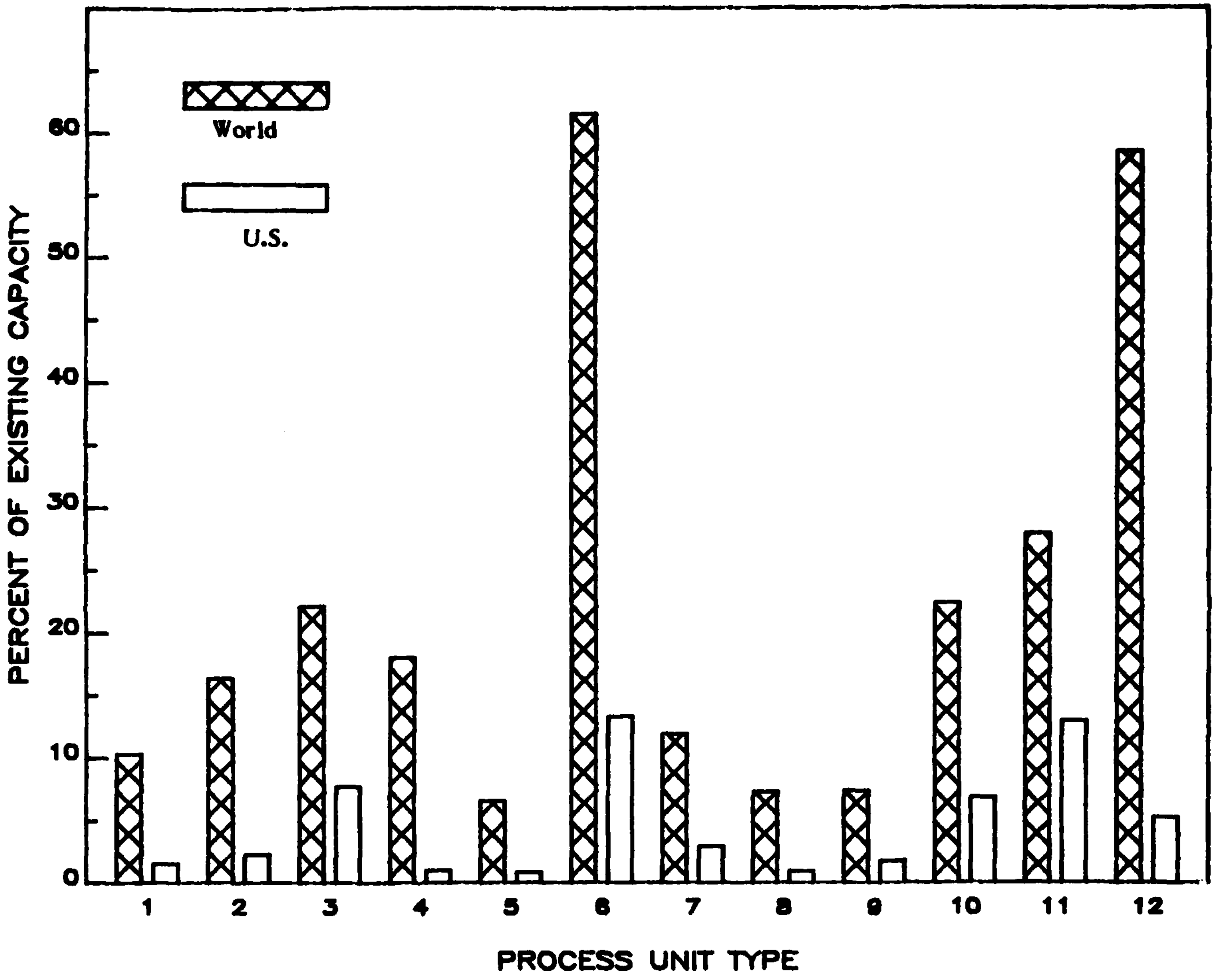

Figure 14. World and U.S. Refinery Construction

TABLE 31. COMPARISON OF WORLDWIDE, U.S. AND CALIFORNIA DOWNSTREAM REFINING CAPACITY

	Percent of Crude Distillation Capacity		
	World Wide*	United States	California
Crude Distillation (MMB/D)	100.00 (42.659)	100.00 (15.863)	100.00 (2.485)
Vacuum Distillation	25.05	42.02	51.99
Thermal Cracking	6.82	10.40	18.63
Cat. Cracking	9.34	35.37	26.055
Cat. Reforming	11.09	23.13	21.23
Cat. Hydrocracking	1.45	5.51	12.51
Cat. Hydrorefining	12.94	13.70	17.83
Cat. Hydrotreating	24.79	39.83	31.68
Alkylation	0.73	5.57	3.90
Arom./Isomerization	0.98	2.83	0.63
Total Percent**	93.19	178.36	184.45
Hydrogen (cf/B)	(56.6)	(138.5)	(354.2)
Coke (100t/MB)	(21.42)	(418.16)	(697.40)

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* Non-communist; excludes U.S.

** Excludes lubes and asphalt

Source: OGJ, Dec. 26, 1983, "Worldwide Report," and Mar. 26, 1984, "Annual Refinery Report"

VI. SYNTHETIC FUEL PENETRATION

In a recent study (55), it was reported that a gap in crude oil supply and product demand could lead to a three million B/D worldwide synthetic fuel industry by the year 2000. The U. S. may produce as much as 1 million B/D by that time. Timing of the synfuel industry development is critical to achieve these projected production levels, because if the fuels are not available as a market develops, it may be lost to fuel-switching or other alternate measures. The U. S. is projected to lead commercialization efforts ahead of Australia, Brazil, Canada, West Germany, and South Africa. Other countries including India, Israel, Jordan, Madagascar, Morocco, and Thailand may also contribute. Currently, 260,000 B/D of synthetic crude oil are produced, mainly by Canada (170,000 B/D from oil sands) and South Africa (90,000 B/D) from indirect liquefaction of coal. A significant but unknown quantity is produced in the Soviet Union and the Peoples' Republic of China.

Sasol produces liquid by indirect liquefaction of coal in South Africa; oil sands extraction is demonstrated in Canada at Suncor and Syncrude; shale oil will soon be in production by Union in Colorado; Tennessee Eastman is producing methanol via coal gasification; and Great Plains is likely to demonstrate natural gas production from coal. Direct liquefaction of coal has been demonstrated as a production method of synthetic fuels. This method was commercially demonstrated in Germany where a production peak of almost 100,000 B/D was reached in 1944. More than ever, the technology is available for commercial production of alternate liquid fuels. As crude oil supplies diminish and the costs of exploration, production, and refining rise, alternate energy sources will be developed to slowly replace shortages in conventional petroleum supply.

The precise timing and quantity of synthetic fuel production is not easily predicted and will depend on favorable economic and political conditions. Recent projections (55-57) of U. S. production range from 30,000 B/D in 1987 to 1 million B/D in 2000. World production projections range from 600,000 B/D in 1990 to 3 million B/D in 2000. Less recent forecast of synthetic fuel production (58-61) indicated larger quantities in the decade of the 1980s. Heavy oil production, which is sometimes classified with synthetic fuels, is currently in excess of 600,000 B/D and is expected to rise in the next decade (61). Selected forecasts for worldwide synthetic fuel, U. S. synthetic fuel, and U. S. heavy oil production are given in Tables 32, 33, and 34,

TABLE 32. POSSIBLE FUTURE WORLD SYNTHETIC FUELS PRODUCTION
(thousands of barrels/day)

Year	Coal Liquefaction	Shale Oil	Tar Sands	M-T-G	Totals
1990	142	88	323	33	56
1995	161	140	360	33	694

Source: Economist Intelligence Unit, Limited (London) 1983

TABLE 33. FORECAST U. S. SYNTHETIC CRUDE SUPPLY
(thousands of barrels/day)

1980	1985	1990	2000
0	100	200	600

Source: ICF Inc., Washington, D.C., 1981

TABLE 34. PROJECTED GROSS DOMESTIC (U. S.) HEAVY OIL PRODUCTION, 1980-2000
(thousands of barrels/day)

1980	1985	1990	1995	2000
609	786	941	1,016	982

Source: Rand Corporation, 1984

respectively. Total production in the U.S. will only represent about 6 percent of the total demand in 2000. A larger percentage is already produced in both Canada and South Africa with adequate fuel quality.

A. Synthetic Fuel Corporation

A key to early synthetic fuel industry development in the United States is the Synthetic Fuels Corporation (SFC). The SFC was planned as an agency to encourage synfuels production when the emphasis was on quantity. Under the Carter administration, the objective was to obtain 2.2 million B/D synfuels production by 1992. The energy industry will, in all probability, not reach this goal, but many projects started at that time. Many may eventually become commercial. Since the 1979 shortages, the world oil situation has shifted to lower consumption. Relative oversupply of petroleum and resulting decline in oil prices have changed the impetus for synthetic fuels development for the near future.

Some companies slowed their pace of development and extended time schedules. When Colony Shale Oil project was shut down by Exxon (62-63) and the Alsands project in Canada was terminated the same week in May 1982 (64), the slow-down became more dramatic.

The SFC completed its organizational phase in 1981 and has recently been functional when encouragement of synfuels development is most needed. (65-66). The announced policy is to be more selective in choosing projects that are first of each type of technology and with reasonable likelihood of success. With the closing of the Colony project which had partial SFC incentives, there are two commercial projects active with SFC participation. These are the Union Oil Company shale oil project in Colorado and the Great Plains coal-gasification plant in North Dakota. In addition, there have been numerous applications made to SFC, from several rounds of solicitations. (67-68) SFC still plans nearly $15 billion in financial assistance awards. (69)

The Union Oil company project at Parachute Creek was first announced in 1980 (70) and further described in 1981. (71) Startup of the facility for 10,000 B/D of shale oil was originally planned for mid-1983, but this schedule has slipped almost a full year. Gary Energy Company has arranged with Union to process about 7,000 B/D of shale oil in its Fruita Colorado plant. Gary plans has built a hydrocracker using Union Oil technology with completion in 1983. Meanwhile, Union Oil Company has licensed their retorting technology to the White River shale project near Vernal, Utah. (72)

With a reduced price in world crude oil, many projects have withdrawn active pursuit of commercial development for the time being. The technology has been established, but due to the economic climate, commercialization efforts have been postponed. It is estimated that 90-95 percent of the synfuels projects planned in 1981 have been tabled or abandoned. (53) Presumably, less-advanced technologies have been abandoned while more fully developed technologies have been tabled temporarily. Although much of the technology is already "waiting in the wings," the tremendous scale and complexity of most synfuel projects will mean a long period of construction before production can actually begin. Most projects will require 5 years or more. In situ production of shale oil may require less lead time because of low front-end capital investment. In situ production from Geokinetics and Occidental may therefore be realized on a much shorter notice and could be the first project to begin production when economic incentives return.

B. Synthetic Fuel Properties

Properties of selected synthetic distillates compared to specifications for Naval distillate fuel are presented in Table 35. (73-80) Distillates derived from coal, shale, and oil sands are presented. Hydrotreated H-coal more closely matches the military specification than do the untreated SRC-II and Exxon Donor Solvent distillates. Hydrotreated H-coal has a much higher ignition quality nearly meeting the military specification, while the untreated coal distillates are well below specification. Low temperature flow properties of direct coal-derived distillates easily meet the specification limit for those properties measured. Stability of the untreated Exxon Donor Solvent liquid was extremely poor, further indicating that hydrotreating is essential to meet stability and ignition quality requirements.

Flow properties as measured by pour point for the indirect liquefaction coal-derived distillates (Sasol II and Fischer-Tropsch) did not meet the specification. End point and cloud point for the Sasol II distillate also did not meet specification. Both fuels did have excellent ignition quality. The shale-derived Paraho II diesel fuel did not meet the cloud point and corrosion test, but otherwise met the Navy distillate specification

TABLE 35. FUEL, NAVAL DISTILLATE SPECIFICATIONS AND PROPERTIES OF SYNTHETIC DISTILLATES

	MIL-F-16884H Specification	ASTM Test Method	Hydrotreated H-Coal Distillate	SRC II Middle Distillate	Exxon Donor Solvent Distillate	Sasol II Diesel Fuel	Fischer-Tropsch Diesel	Paraho II Diesel Fuel Marine	Hydrotreated Oil Sand Coker Distillate
Ignition Quality, Cetane Number (min)	45	D 613	44.3	16.2	21.0	50.1	60+	48.6	41.9
Appearance, 21°C(70°F)	clear, bright	---	---	---	---	---	---	C&B	---
Distillation, °C(°F)		D 86							
50%	record		(480)	(473)	(500)	(434)	(372)	(508)	(508)
90% (max)	357(675)		(595)	(553)	(675)	(643)	(539)	(560)	(602)
EP (max)	385(725)		(670)	(613)	(695)	(760)	(637)	(584)	(633)
Residue plus loss, vol% (max)	3.0		1.0	1.0	---	1.0	---		
Flash Point, °C(°F) (min)	60(140)	D 93	---	(176)	(190)	(160)	(100)	(175)	(183)
Pour Point, °C(°F) (max)	-6(20)	D 97	(-70)	(-54)	(-11)	(5)	(10)	(-10)	(-94)
Cloud Point, °C(°F) (max)	-1(30)	D 2500	---	---	---	(46)	---	(32)	(-27)
Viscosity @ 40°C(104°F) Kinematic, centistokes	1.7-4.3	D 445	2.92	3.68	3.89	2.09	1.40	2.60	3.02
Carbon Residue on 10% bottoms, wt% (max)	0.20	D 524	---	---	1.36	---	---	0.09	---
Sulfur, wt% (max)	1.00	D 129	0.000	0.26	0.09	0.01	0.01	0.00	0.01
Corrosion, 100°C(212°F) (max)	No. 1	D 130	---	---	1A	1A	1	2B	---
Color (max)	3	D 1500	---	---	---	---	---	---	---
Ash, wt% (max)	0.005	D 482	---	---	0.005	---	0.01	0	---
API Gravity, 15.6°C(60°F)	record	D 287	29.2	12.3	16.5	44.2	57	38.7	33.2
Demulsification 25°C(77°F) minutes (max)	10	D 1401	---	---	---	---	---	---	---
Acid Number (max)	0.30	D 974	---	---	---	---	---	0.01	---
Aniline Point, °C(°F)	record	D 611	(131)	---	---	---	(175)	---	---
Accelerated Stability, gm/100mL	1.5	D 2274	---	---	28.0	0.78	---	0.09	---

The hydrotreated oil sand coker distillate does not have sufficient ignition quality but does have excellent flow properties.

While not all the fuels in Table 35 represent an attempt to meet the military specification, it can be seen that many of the specified properties are not easily attained by fuels from synthetic sources. Synthetic fuel properties of concern are ignition quality, flash point, flow properties, carbon residue, corrosion, and stability. Further upgrading of the fuels presented in Table 35 by appropriate refining techniques could result in fuels meeting the military specification.

VII. CONCLUSIONS

A. Historical Fuel Property Trends

1. Although resid fuels are being removed from the U.S. Navy fuel supply system, the abundance of commercial resid and resid-containing fuels in the maritime fuel delivery network may impact the quality of naval fuels in the future, especially in the form of contaminants.

2. Diesel fuels in the U.S. are suffering a decrease in quality as measured by gravity, aniline point, carbon residue, and cetane number. Changes in properties can be atrtributed to a trend toward heavier distillation ranges as well as decreasing crude oil quality.

3. Western Region diesel fuels are made from lower quality crudes and have higher boiling ranges but have comparable quality to other diesel fuel in the U.S. This may be attributed to greater upgrading capability in the Western refining district.

4. Cetane number decrease in Coastal Region diesel fuel is associated with a tightening of the range, approaching the lower specification limit. Cetane numbers will be conserved in the future much like octane numbers are now. A new or improved method of determining combustion quality of diesel fuels will likely be developed to monitor this quality which is increasing in value.

5. Anticipated heavy oil upgrading is expected to leave poorer quality resid fuels. This is not consistent with current property trends possibly due to imported resids, low resid demand, or a shift of low quality resids to alternate uses.

B. Product Supply and Demand Forecast

6. World energy demand will increase, but oil demand is projected to remain nearly constant over the long term. U.S. oil demand is also expected to remain at a near constant level over the long term. These projections indicate less pressure in supply than experienced during the last ten years.

7. Crude oil quality is rapidly decreasing in the world, about 1°API each 10-year period. The U. S. is suffering a greater quality decrease, while crude oil quality in Europe is decreasing less rapidly. Sulfur content and non-distillable resid fractions are also increasing.

8. U.S. gasoline demand is projected to decline from 43 percent of total products to 32 percent by 2000, while distillate and jet fuel rise will be from 25 percent to 32 percent. Total light product demand will decrease from 68 percent to 64 percent of total demand. Resid demand will vary from 12-15 percent of total products.

9. U.S. Western Region (PADD V) demand in 1978 called for 24 percent distillates of which 47 percent was jet fuel and 65 percent total light products. Local refineries met 90 percent of the demand with low quality crude, producing 21 percent distillates of which 43 percent was jet fuel and 65 percent total light products.

10. A larger fraction of distillate demand currently exists in Europe and Japan than is projected in the U.S. for 1900-2000. Acceptable or even higher quality products are made at high distillate demand levels in Europe and Japan but total light product demand is much less than the U.S. — 55 percent compared to 69 percent.

11. Distillate pool cetane number requirement is rising in addition to total demand.

12. Resid demand swings are met by imports in the U.S., but new resid conversion processes will cause future resids to be less stable, heavier, and with higher metal contents.

C. Refinery Projection Studies

13. The U.S. refines some of the lower quality crude oils in the world and is a worse case example of future crude supply and product quality from such crudes.

14. Out of U.S. refining districts, PADD V currently refines lower quality crude than that projected for the U.S. as a whole in the year 2000.

15. The refining industry is undergoing a long-term adjustment to accommodate lower quality crudes and a shift in product distribution.

16. Existing refining technology can produce distillate percentages, ranging from 40 to more than 50 percent while still meeting product quality requirements according to linear program refinery models.

17. High costs may be associated with high distillate production, making distillates more expensive than gasoline.

18. Existing refinery configurations may not be able to meet future product demand without additional processing capacity including hydrocracking or coking and catalytic cracking followed by other hydrorefining to improve distillate production capability. Segregation of distillate products, improved distillation, and imports of refined distillate can also help meet future demand.

19. Regulation of diesel fuel quality through legislation to meet emission standards could have disastrous effects on distillate product supply and costs.

D. Refinery Construction

20. Hydrogen manufacturing capacity in the U.S., a key to product quality upgrading capability, has experienced a steady growth in the last 9 years with the exception of 1980.

21. Large percentage gains are planned in the U.S. for thermal cracking, catalytic hydrocracking, and hydrogen manufacturing.

22. The U.S. leads the world in total downstream capacity, but other world refiners also have large percentage downstream capacities surpassing the U.S. in some areas.

23. Worldwide refinery construction plans emphasize heavy crude refining. Percentage increases for the world are greater than those for the U.S.

24. Future construction requirements can be determined through comparison with existing California downstream capacities. More catalytic hydrocracking and hydrogen manufacture will be required.

E. Synthetic Fuel Penetration

25. Synthetic fuel penetration will represent a small fraction of total fuel supply (6-8 percent) by the year 2000.

26. Synthetic fuels (particularly those derived from coal) do not easily meet Navy specifications for distillate fuel, but can be upgraded using available technology.

VIII. RECOMMENDATIONS

Investigation herein of general trends affecting future fuel naval properties has identified several factors which warrant further study. A continuation of the current study in a more-detailed approach to forecast specific fuel properties is strongly recommended. The objective of such a study would be to identify specific properties and potential problem areas relative to the properties, composition, and availability of Naval distillate fuel in the time frame 1990 to 2000. To accomplish this objective the following specific recommendations are made.

1. Describe U.S. Navy crude oil sources in the world and in the U.S. used to produce MIL-F-16884H.

2. Identify refineries producing MIL-F-16884H

3. Categorize ship fuel processing schemes

4. Forecast crude supply and product demand 1990 to 2000

5. Select crude oils and refinery configurations for 1990 to 2000

6. Tailor a special refinery model to key on general trends identified in this report and perform several refinery model case studies to represent forecasted refinery and crude oil types.

7. Add potential volumes of synthetic crude oils (shale oil, coal liquid, tar sands bitumen) to projected petroleum crude oil slates.

8. Identify critical properties of fuels.

9. Analyze crude and processing combinations to indicate the trade-off between properties, relative cost, and yield.

10. Evaluate effects of specification requirements, engine tolerance, and storage and handling requirements on availability.

In addition to the specific program recommended above, the following recommendations are also made based on the results of this study. Some of the following recommendations may require a physical laboratory test program.

1. Develop a new or improved method of measuring combustion quality of compression ignition fuels.

2. Determine the lower combustion quality limit of diesel engines in the U.S. Navy fleet.

3. Review current fuel specification requirements of MIL-F-16884H which have the potential to limit product availability in the future.

4. Evaluate fuel handling requirements within the fuel distribution system and also in the engine fuel delivery system to determine minimum property requirements.

5. Investigate new diesel fuels which have the potential of expanding future fuel availability.

6. Prepare actual test fuels on a small scale which represent future crude oil compositions and refining configurations to be tested in the laboratory for properties and engine performance.

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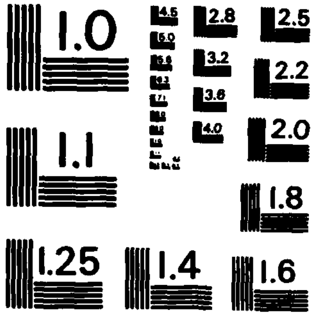

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X. LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

°API	units of gravity defined by the American Petroleum Institute
Arom	aromatics
ASTM	American Society for Testing and Materials
avg.	average
B	barrel
B/D	barrels per day
B&M	Bonner & Moore Associates
bbl	barrel
Braz	Brazil
btms	bottoms
BSI	British Standards Institute
Btu	British thermal unit
C residue	carbon residue
Ca	calcium
Can	Canada
cat.	catalytic
cf	cubic feet
CIMAC	International Council on Combustion Engines
cSt	centistokes
Cu	copper
dist.	distillate
DOC	U.S. Department of Commerce
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
F-76	Nato marine fuel specification
1000°F+	material boiling above 1000 degrees fahrenheit by volume
FBP	Final boiling point
FCCU	fluid catalytic cracking unit
Fra	France
GAO	U.S. General Accounting Office
gaso	gasoline
Ger	Germany
gm	gram
HMGO	Heavy Marine Gas Oil
IBP	initial boiling point
ICS	International Chamber of Shipping
IFO	intermediate fuel oil
Ind	India
ISO	International Standards Organization
Itl	Italy

X. LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (cont'd)

Jpn	Japan
KOH	potassium hydroxide
LPG	liquified petroleum gas
max	maximum limit
MB	thousand barrels
MDF	Marine Diesel Fuel
Mex	Mexico
mg	miligrams
MGO	marine gas oil
MIL-X-XX	military specifications
min	minimum limit
mL	mililiter
MMBPD	million barrels per day
MMcfd	million cubic feet per day
M-T-G	methanol to gasoline
Na	sodium
NATO	North Atlantic Treaty Organization
NSFO	Navy Special Fuel Oil
OGJ	Oil and Gas Journal
PADD	Petroleum Admininstration for Defense District
ppm	parts per million by weight
Quad	quadrillion British thermal units
%S	percent sulfur by weight
Scf/B	standard cubic feet ber barrel
SFC	U.S. Synthetic Fuel Corporation
Spr	Singapore
SRC	solvent refined coal
SRI	SRI International
SwRI	Southwest Research Institute
t	tons
t/d	tons per day
U.K.	United Kingdom
U.S.	United States
V	Vanadium
Ven	Venezuela
Vis	viscosity
Vol%	volume percent
WKF	Wright, Killen, & Feldman, Inc.
Wt%	weight percent

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