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In the early 1970's, the U.S. Navy switched from use of Navy Special Fuel Oil (NSFO NATO F-77 to Naval Distillate Fuel NATO F-76) in shipboard propulsion and electric generating systems. Presently there are two fuels being utilized in shipboard operations. NDF (F-76) is utilized in propulsion and electric generating systems, and JP-5 jet fuel is used for aircraft operations and as an emergency fuel for systems utilizing F-76.

Since the conversion from NSFO to F-76, there has been interest in an additional conversion to a shipboard single-fuel operation. Due to the unique requirement of jet aircraft engines, single fuel, from necessity, would have to be JP-5. Therefore, this study was conducted to determine the potential benefits and problems associated with a shipboard single-fuel operation.

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19. ABSTRACT

All shipboard systems, including boilers, turbine engines, and diesel engines should continue to operate satisfactorily, and in some instances, with increased efficiency with JP-5. The greatest benefit from such a conversion would be the convenience of handling only one fuel, and eliminating the possibility of fuel contamination. The major penalties would include higher fuel cost, and difficulty in procuring adequate supplies of JP-5 to meet the total U.S. Navy shipboard fuel requirements.

EXECUTIVE SUMMARY

<u>Problems and Objectives</u>: In 1967, a movement began within the U.S. Navy to replace a multiplicity of fuels with a single fuel for both ships and aircraft. Although the effort was unsuccessful in its primary objective, a single distillate fuel for ship propulsion resulting eventually in the MIL-F-16884 Naval Distillate Fuel (NDF) used today was developed. Since the conversion to NDF, interest has surfaced periodically to convert further to a single-fuel operation, i.e., one fuel for both aircraft and ship propulsion/power systems. This study considered this goal in view of current systems and situations in order to identify and analyze potential problems and benefits to be derived from a "one-fuel Navy."

<u>Importance of Project</u>: In making a decision of such significance, all aspects must be carefully considered. This study addresses those aspects in order to permit a cautious and conservative changeover.

<u>Technical Approach</u>: Navy personnel were interviewed and technical literature was examined and analyzed to identify any problems and benefits that may result in the conversion to a single-fuel operation. Propulsion systems included the gas turbines (both aircraft and marinized), diesels, and boilers.

<u>Accomplishments</u>: As a result of this program, it was determined that converting surface ships propulsion/electric generating systems to use JP-5 would not be detrimental to fleet operational readiness; however, some diesel engines would experience as much as a 6-percent power loss. Few, if any, operational or maintenance benefits would be realized from such a conversion; range would be reduced about 2.5 percent and fuel costs would increase about 7 percent. Benefits realized were difficult to quantify and would most probably occur in the logistics area through the simplicity of handling only one fuel. Regional shortages in availability could occur.

<u>Military Impact</u>: This report has documented the technical logistic benefits and disadvantages that may occur with the Navy's conversion to a single-fuel operation and estimated the costs of such a conversion. Recommendations have been provided for further study.

FOREWORD/ACKNOWLEDGMENTS

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I. INTRODUCTION

In the late 1960's, the U.S. Navy used three fuels to power its aircraft and nonnuclear ships: MIL-F-859 (Fuel Oil, Burner) included Navy Special Fuel Oil (NSFO), which was a black oil used for generating steam, while MIL-F-16884 (Fuel Oil, Diesel Marine) was specified for the diesel engines used to power smaller craft and for auxiliary power on some ships; MIL-T-5624 (Turbine Fuel, Aviation) covered the JP-5 fuel used for Navy carrier-based jet aircraft. These last two distillate fuels were also acceptable substitutes for use in firing boilers.

In 1967, a movement began to replace this multiplicity of fuels with a single fuel for both ships and aircraft. It was realized that such a fuel must be tailored to satisfy the requirements of the most demanding system, that of the aircraft. At that time, the aviation fuel cost about twice as much as NSFO; moreover, it appeared that there would be insufficient supplies of JP-5 worldwide to meet the demands of both systems. Thus, it was decided not to use JP-5 as a multipurpose Navy fuel.(1)*

That effort did, however, lead to the development of a single distillate fuel for ship propulsion, resulting eventually in the MIL-F-16884 Naval Distillate Fuel (NDF) used today. This fuel has been standardized with the NATO allies as NATO F-76. It is used for powering all nonnuclear ships, with JP-5 considered to be an acceptable alternative.

Since the conversion to NDF/F-76, interest has surfaced periodically to further convert to a single-fuel operation, i.e., one fuel for both aircraft and ship propulsion/power systems. This report summarizes a study to consider this problem in light of current systems and situations to identify and analyze potential problems and benefits to be derived from a "one-fuel Navy." Areas included in the study were the performance requirements of aircraft and ship fuels, the effects on operations and maintenance, the cost of fuels, the supply and demand of fuels, and considerations of the logistics system including transportation and storage.

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

II. FUELS

Fuels considered in this evaluation were NDF [MIL-F-16884H (NATO F-76)] and JP-5 [MIL-F-5624L (NATO F-44)]. (These two fuels are commonly referred to as F-76 and JP-5 in the U.S. Navy, and this convention will be used in this report.) Comparative specification values for these two fuels are presented in TABLE 1.

When comparing F-76 with JP-5 for general use, several areas of difference are of concern; the most notable of these are:

Cloud point/freeze point	Much higher than JP-5
Thermal stability	Not controlled, generally lower
Contaminants, including sulfur	Potentially higher
Viscosity	Higher than JP-5
Hydrogen content	Not controlled, generally lower

Also an FSII additive, fuel system icing inhibitor, is specified for JP-5 but not for F-76.

While the controls on F-76 are adequate for shipboard use, all of the above properties can affect the reliability and/or maintenance requirements of aircraft and, therefore, readiness. JP-5, on the other hand, is inherently a cleaner, more stable fuel capable of operation at significantly lower temperatures as well as higher temperatures. These differences are illustrated below first by looking at the use of F-76 in aircraft, and then JP-5 in ship propulsion systems.

Although the specification requirements for low temperature operations are different, a freeze point of -46°C for JP-5 versus a cloud point of -1°C for F-76, it still suggests a significantly lower temperature capability of about 40° to 45°C since the freeze point is typically just a few degrees above the cloud point. The mission requirements for fuel temperature and the capabilities of pour point depressants are currently being investigated by the Naval Air Propulsion Center (NAPC). This is a mission-aborting problem area: If the fuel temperature falls below

TABLE 1. Comparative Requirements of Diesel and Turbine Fuels

Properties	Test Method*	F-76 MIL-F-16884H	JP-5 MIL-T-5624L
Cetane Number, min	D 613	45	NR**
Explosiveness Percent, max	1151 FED-STD-791	NR	50 Percent
Flash Point, °C, min	D 93	60	60
Cloud Point, °C, max	D 2500	-1	NR
Pour Point, °C, max	D 97	-6	NR
Freezing Point, °C, max	D 2386	NR	-46
Kinematic Viscosity, cSt, at			
40°C, range	D 445	1.7 to 4.3	NR
-20°C, max	D 445	NR	8.5
Distillation, °C (°F)	D 86		
10% Recovered, max		NR	205 (400)
20% Recovered, max		NR	Report
50% Recovered, max		Report	Report
90% Recovered, max		357 (675)	Report
End Point, max		385 (725)	290 (554)
Residue, vol%, max		3	1.5
Cu Corrosivity,	D 130		
3 hrs at 50°C, max		NR	NR
2 hrs at 100°C, max		1	1B
Ash, wt%, max	D 482	0.005	NR
Neutralization Number, mg KOH/g, max	D 974 or D 3242	0.3	0.015
Neutrality	5101 FED-STD-791	Neutral	NR
Particulates, mg/L, max	D 3242 and D 2276	NR	1.05
Specific Gravity	D 1298	NR	0.788 to 0.845
Heating Value, Btu/lb, min	D 240 or D 2382 or D 3338	NR	18300
Hydrogen, wt%, min	D 1018 or D 3343 or D 3701	NR	13.5
Smoke Point, min	D 1322	NR	19.0
Carbon Residue on 10% Bottoms, percent, max	D 524	0.20	NR
Color, max	D 1500	3	NR
Peroxide Number, meq/kg, max	D 3703	NR	1.0
Aromatics, vol%, max	D 1319	NR	25.0
Olefins, vol%, max	D 1319	NR	5.0
Sulfur, wt%, max	D 1266 or D 2622	1.00	0.40
Mercaptan Sulfur, wt%, max	D 3227	NR	0.001
Accelerated Stability, mg/100 mL, max	D 2274	1.5	NR
Thermal Stability,			
Press. drop change, torr. max	D 3241	NR	25
Preheat dep. code, less than		NR	3
Existent Gum, mg/100 mL	D 381	NR	7.0
Filtration Time, minutes, max	MIL-T-5624L	NR	15
Water Reaction Interface Rating, max	D 1094	NR	1B
Water Separation Index, min	D 2550	NR	70
Demulsification at 25°C, minutes, max	D 1401	10	NR
Fuel System Icing Inhibitor, vol%	5327 or 5340 FED-STD-791	NR	0.15 to 0.20

* D = Indicates ASTM test methods.
** NR = No Requirement.

the cloud point, the crystals will plug the fuel filter. The plugged fuel filter can result in a failure to start the engines, or, at altitude in cold weather, fuel starvation and flameout. Because of the high cloud point and the lack of FSII, it is not advised to use F-76 in aircraft at temperatures below 0°C.

The thermal stability of F-76 is not controlled but, when measured by JFTOT "Breakpoint temperature," it is often 25° to 40°C below the limit for JP-5. Operation on a fuel of low thermal stability can lead to deposit formation on the inside flow passages and on the face of the fuel atomizer. The build-up of internal deposits is first realized as a loss of throttle response and/or power. The deposits can also cause nonuniformities in the fuel distribution among atomizers, leading to hot streaks and failures in the hot section. Deposits on the face can distort the fuel spray and cause hot streaks or wall impingement. Studies are currently being sponsored by the Naval Air Propulsion Center to quantitatively relate thermal stability to fouling life.

The presence of particulates and gums due to poor storage stability will plug the fuel filters in aircraft engines and auxiliary power units; these particulates and gums can be filtered out before fueling the aircraft, but the oxidation reactions that caused the particulates to form will continue. The allowable sulfur content in F-76 cannot be tolerated in aircraft engines since it, in conjunction with sodium present in the salt air, leads to a corrosive attack on the high-temperature alloys used in the hot section. In most environments, operations can tolerate the higher viscosity of F-76, but fighter aircraft may have to descend to a lower altitude to relight the engine in the case of a flameout.

The hydrogen content of F-76 is not controlled but, when measured, is often found to be lower by 0.5 to 1.0 wt% than JP-5; this amount is significant, but current inspection and maintenance schedules have been shown to be adequate for most aircraft to prevent operational problems from reductions in liner life.(2,3)

From these factors, it is concluded that the lower quality of F-76 makes it technically unsuited for use as a universal fuel for Navy operations as the specification now stands.

Although a generally more desirable fuel, JP-5 does have three potential problem areas when compared to F-76 for continuous shipboard use: low lubricity, low heating value, and low cetane number. The Naval Air Propulsion Center is currently evaluating the lubricity requirement of the fuel pumps and fuel controls for aircraft along with the capability of additives. The development of similar requirements for ship propulsion systems is currently being considered by the David Taylor Research Center (DTRC).

JP-5 has a lower energy density (Btu/gal.) than F-76. TABLE 2 provides a comparison of average energy contents and specific gravities. The F-76 data came from a data base maintained by the David Taylor Research Center. F-76 does not have a minimum requirement for heat of combustion so it is not routinely measured. The JP-5 data came from a Belvoir Fuels and Lubricants Research Facility (BFLRF) data base. The annual aviation fuel surveys published by the Department of Energy's Bartlesville Energy Technology Center (e.g. 4,5) include JP-5, but the number of samples is small, typically only 3 to 5 per year. The BFLRF data base is more extensive, containing properties of 63 worldwide samples. On the average, there is 2.6 percent less volumetric energy content (Btu/gal.) in JP-5 as compared to F-76.

TABLE 2. Energy Comparison

Property	F-76	JP-5
Specific Gravity	0.844	0.819
lb/gal.	7.076	6.030
Net Btu/lb	18,456	18,356
Net Btu/gal.	129,291	125,965

The lower energy density of JP-5 translates directly into a 2.6-percent reduction in range, but also means an increase in the amount of fuel purchased. Since combustion efficiency in all systems is generally close to 100 percent at all but idle conditions, little opportunity exists for improvements in specific fuel consumption to offset the lower heating value of JP-5. In most engines, the fuel controls can be adjusted to regain maximum power, but a larger volume of fuel will still be required. Burning fuels with lower cetane numbers will result in small increases in thermal efficiency in some diesel engines, but generally not enough to offset the lower heating value. Therefore, should a conversion be made to JP-5, potentially an additional 2.6-percent fuel quantity would be needed to support the Navy requirements.

Minimum cetane number for the F-76 specification is 45.0, while the cetane number of JP-5 often falls below this value, it is not likely that any operational problems will result. In 23 recent JP-5 fuel sample cetane determinations at BFLRF, 18 would not meet the F-76 cetane requirements shown in Fig. 1. This trend is supported by JP-5 survey data from the National Institute for Petroleum and Energy Research (NIPER). Although cetane number is not a reported property for JP-5, it is possible to calculate a "cetane index" according to ASTM D 976 using data that are reported. TABLE 3 gives the calculated values for ten fuels sampled in the 1983 and 1984 NIPER surveys (4,5); six of the fuels would not meet the requirements of the F-76 specification.

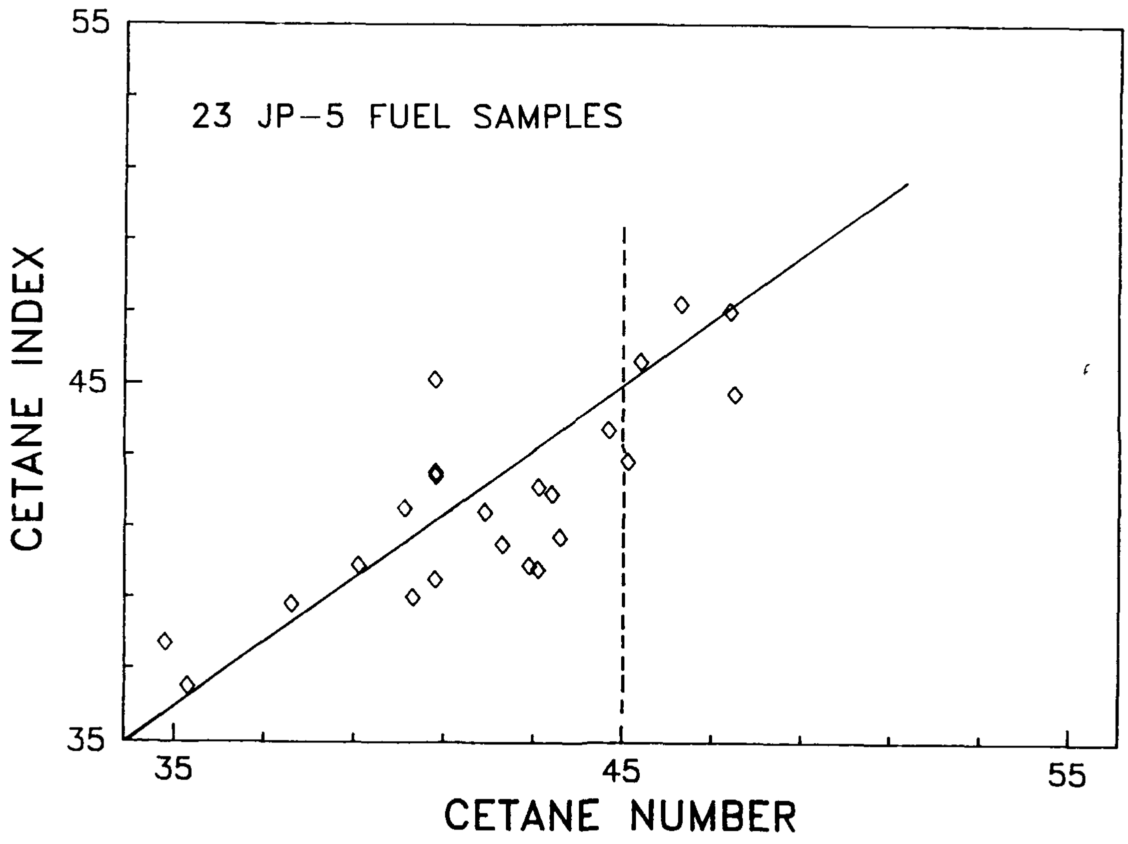

Figure 1. JP-5 cetane number/cetane index

TABLE 3. JP-5 Cetane Index, Calculated From NIPER Surveys

1983	1984
49.5	(41.8)
(41.5)	(35.4)
46.3	48.1
(42.9)	(41.7)
(30.6)	45.0

Parentheses indicate below MIL-F-16884H specification.

This failure to meet the F-76 requirements is probably not as serious as it first seems since the U.S. Army has accepted JP-5 as an alternate fuel for all diesel engines per Army Regulation 703-1. Bowden, et al. provide an annotated bibliography of 23 references on the use of JP-5 in military diesel engines, and conclude that the experience has shown no appreciable ill effects. However, some loss in power was generally noted due to the lower heat content and increased injector leakage.(6) Furthermore, in 1984 the Army lowered the cetane requirement for its diesel fuel, VV-F-800C, DF-2, from 45 to 40; with this relaxation, only four of the fuels in the Army's survey of 23 fuels would not have met the minimum standard.

These problems are at least manageable compared to the problems of using F-76 in aircraft. Thus, of the two fuels, JP-5 is the most obvious choice from a technical standpoint. A compromise fuel would end up being something very close to JP-5. Only a small increase in boiling range could be realized because freeze point is controlled by the heavier fractions and is already one of the limiting factors in availability in some areas. Also, many quality items, such as thermal stability, sulfur, and particulates, would have to be maintained at current JP-5 limits. A cetane requirement would have to be imposed, which might affect cost and availability since many JP-5 fuels cannot currently meet such a requirement. Reducing the F-76 cetane requirement to 40 as the Army has done would help this situation. The remainder of this report will, therefore, concentrate on the implications of the use of JP-5 as the sole fuel for the Navy.

III. SUPPLY AND DEMAND

A. Requirements

In May of each year, the U.S. Navy informs the Defense Fuel Supply Center (DFSC) of its fuel requirements for the upcoming calendar year. DFSC puts out solicitations to industry and awards contracts with fuel suppliers worldwide for specification fuels on the basis of lowest delivered costs. Generally, DFSC contracts with fuel suppliers for a 1- or 2-year contract period. After a contract is in effect, ships can place orders, and oilers, which are responsible to the Navy Petroleum Office (NPO), pick up the product and deliver it to the ships. Ships may also take on fuel from a fixed terminal while in port. If no contract is in effect, ships can procure needed fuel through use of local purchase orders or by other approved methods.

For this study, DFSC fuel records for several years (1980 to 1986) were reviewed for total purchases and fuel pricing information.(7) It should be noted that the figures shown in this report are only those represented by purchases through the Defense Stock Fund. Purchases through bunker contracts (contracts that provide fuel for ships at Ports where there is no Defense Fuel Support Point) could increase the amount of F-76 purchased outside the continental United States (OCONUS) by approximately 10 percent. It should be pointed out that a small amount of the total Navy JP-5 fuel purchased through the stock fund may actually have been utilized by Air Force or Army aircraft refueling at Navy installations. Also, there are small amounts of fuel purchased by Navy aircraft that are not reflected through stock fund purchases. These purchases occur when Navy aircraft refuel at commercial airports with Jet A fuel. These purchases are made through "Into-Plane" contracts.(8)

TABLE 4 depicts total Stock Fund purchases of JP-5 and F-76 for fiscal years 1980 through July 1986.(7) This information is also illustrated graphically in Figs. 2 and 3. Based on data in TABLE 4, fuel purchases through the Stock Fund have averaged 1,075,772,860 gallons for JP-5 and 1,277,911,356 gallons for F-76 per year during the past 7 years. During this period, the price differential between the two fuels averaged approximately $0.05 per gallon higher for the JP-5.

TABLE 4. Total JP-5 and F-76 Stock Fund Purchases

Fiscal Year	JP-5 Total Gallons	% CONUS	F-76 Total Gallons	% CONUS
1986*	1,038,156,517	76	1,071,220,998	57
1985	1,270,515,991	72	1,345,968,709	43
1984	1,005,964,325	70	1,314,568,230	45
1983	1,088,598,000	**	1,406,824,020	**
1982	1,028,874,307	**	1,375,526,445	**
1981	1,064,168,050	**	1,288,563,415	**
1980	1,034,132,831	**	1,142,707,681	**

* Indicates totals only through July.
** Indicates data not available.

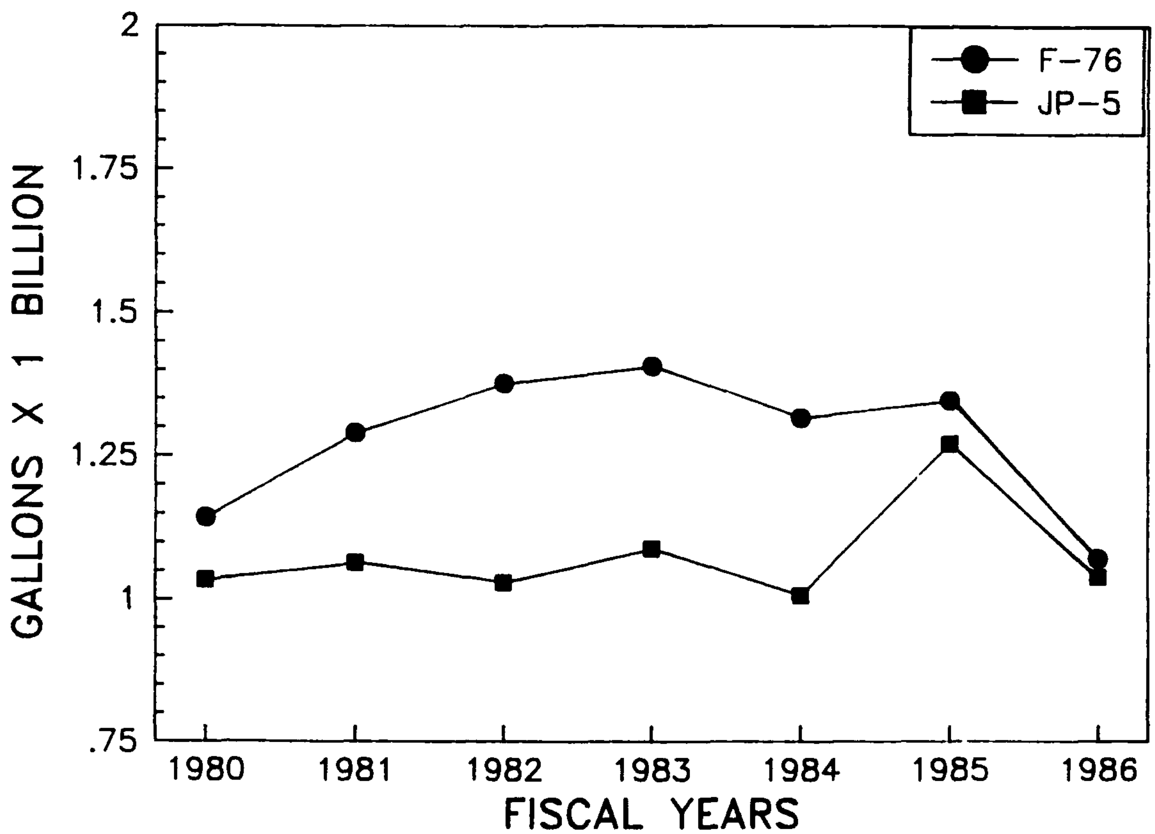

Figure 2. Fuel procurement by years

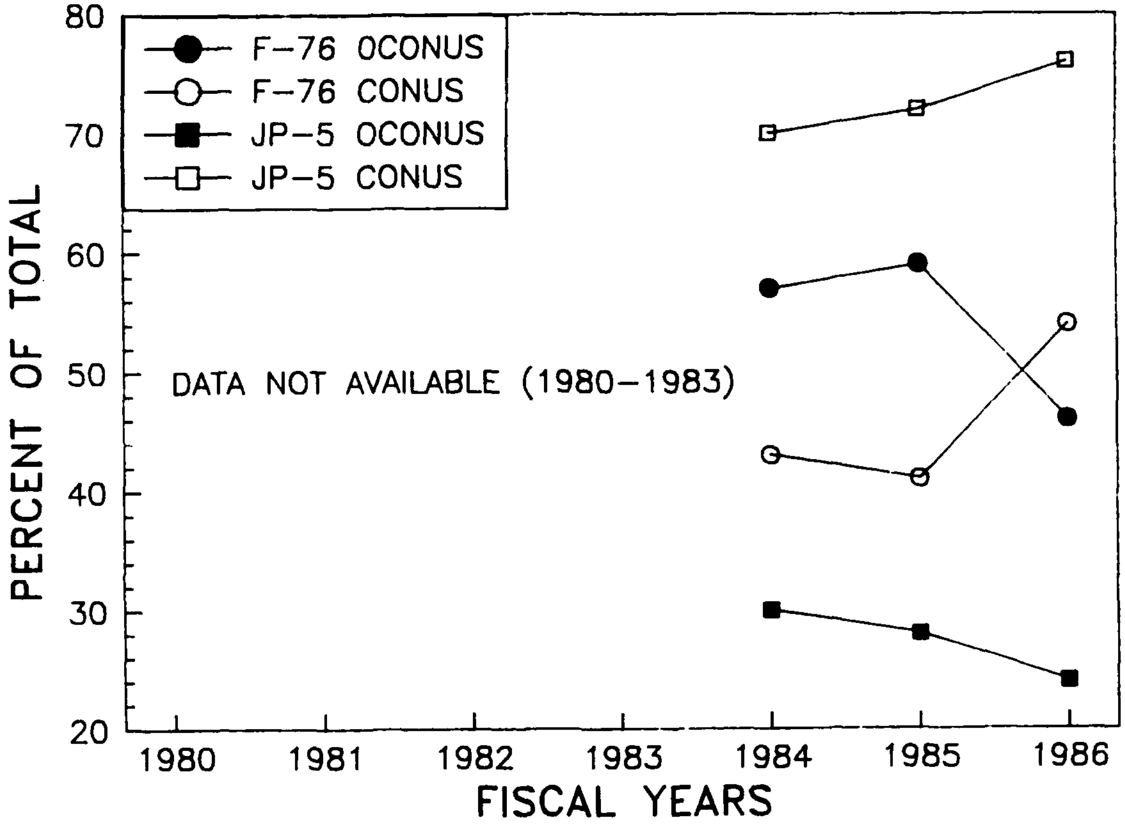

Figure 3. Fuel distribution (CONUS versus OCONUS)

Fig. 4 shows the actual cost of each product (yearly average), which includes transportation, services (lease and storage costs), and losses versus standard prices.(7) In order to stabilize costs for the Military Services throughout the fiscal year, the services are charged the standard price for the fuel. The standard price is established by the office of the Secretary of Defense approximately 18 months before the fiscal year. Standard prices also consist of product, transportation, services, and losses, and are projected based on past experience as well as latest economic assumptions and cost data available. When standard prices exceed stock fund procurement costs, savings are passed on to the services either by cash refund or by lower standard prices in the subsequent year. When standard prices are lower than the stock fund costs, the Defense Stock Fund absorbs the losses. Cash refunds were provided the Navy in all fiscal years represented by these data. Assuming a continuing price differential of $0.05/gal. and taking into account the 2.6-percent lower energy of JP-5, converting to JP-5 would result in an increased fuel cost of approximately $103M per year as illustrated below:

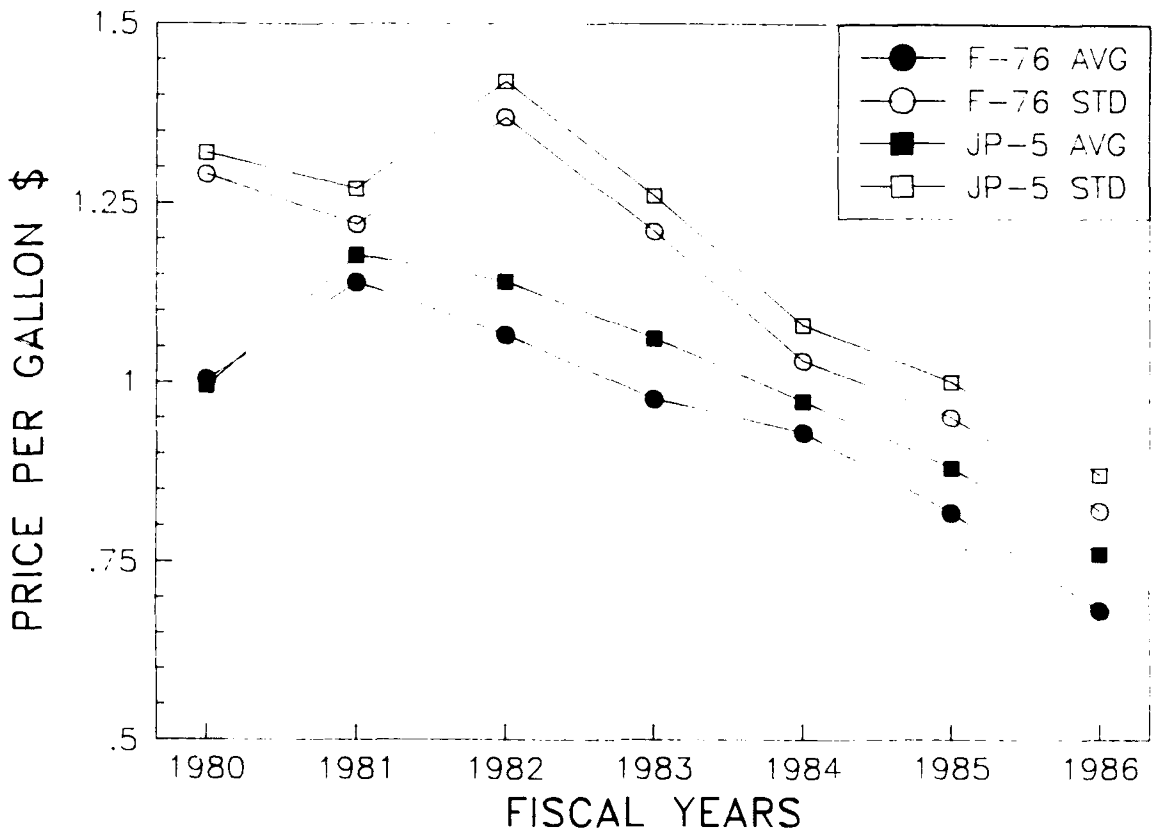

Figure 4. History of fuel prices for JP-5 and F-76

No. Gal. F-76/yr	1,277,911,536	
(price/gal.)	($1.12)	
Approximate Cost		$ 1,431,260,920
2.6-percent additional gallons	33,225,700	
Replacement Fuel (JP-5)	1,311,137,236	
(price/gal.)	($1.17)	
Approximate Cost		$ 1,534,030,566
Approximate Increased Fuel Cost		$ 102,769,646

B. Resources/Refining Capacity

An indication of the potential fuel resources is provided by the response to fuel-purchase bid requests. Requests bring a larger response for F-76 than for JP-5 relative to the amount of each fuel purchased. In each procurement, a few bids are rejected for reasons other than price, most commonly because the capability of the refinery to make fuel of the specified quality is seriously in doubt. Also, some refineries do not bid for technical reasons. For JP-5, trouble meeting the flash point specification is most often cited along with aromatic content. In addition, many of the smaller refineries are less willing than large refineries to make the changes necessary to produce JP-5 because they might lose the contract in a subsequent procurement and would be less able to absorb the loss. Of the reasonable bids received, the JP-5 quantities bid are adequate to meet current needs, but there is very little excess bid. A few years ago, when fuel supplies were tighter, the quantities bid were barely enough, and regional shortages were experienced. In contrast, the F-76 quantities bid have run about three times as much as the actual procurement for several years.

More detailed information is available on contract fuel purchases. Some statistics for 1986 were compiled to determine where the effects of the change would be most critical to the refining industry.(9-11) Fuel purchases for other years show similar patterns, but some differences occur because of the competitive bidding process and because of some year-to-year variations in fuel needs. The data for 1986, shown in TABLE 5, are given by region. The crude capacity of each supplying refinery is listed, along with the contract purchase quantities of F-76 and JP-5. Each fuel is also given as a percent of the refineries crude capacity, which provides a relative measure of the importance of the product to the refinery, and a preliminary basis for estimating whether the refinery could increase its production significantly. The statistic in the final column, termed the "F-76 ratio," is intended to indicate the importance of that refinery in supplying F-76 relative to the overall regional fuel procurement. This ratio is the F-76 procurement divided by the regional total of F-76 plus JP-5 procurements. Sales of other middle distillate fuels, such as nonmilitary jet and diesel, were not included.

An overall examination of TABLE 5 shows that JP-5 is procured primarily in CONUS and the Caribbean regions. F-76 procurement is mostly OCONUS but is distributed more evenly throughout the regions noted.

A regional examination of the statistics in TABLE 5 provides some insights relative to a change in fuels. In the Gulf Coast and Caribbean region, the JP-5 procurement from a number of large

TABLE 5. Refineries and Contract Purchases, Fiscal Year 1986

Refinery	Location	F-76 Purchases: Crude Cap 10^6 B/yr	F-76 Purchases: 10^3 B/yr	F-76 Purchases: % of Crude Cap	JP-5 Purchases: 10^3 B/yr	JP-5 Purchases: % of Crude Cap	JP-5 Purchases: F-76 Ratio %
GULF COAST AND CARIBBEAN:							
Diamond Shamrock	Three Rivers, TX	16.4	0	0	480	5.3	0
Diamond Shamrock	Corpus Christi, TX	31.0	0	0	704	2.3	0
Shell	Pasadena, TX	83.4	0	0	7543	9.0	0
Pride	Abilene, TX	15.6	0	0	347	2.2	0
Mobil	Beaumont, TX	98.5	0	0	1460	1.5	0
Citgo	Lake Charles, LA	117	0	0	300	0.3	0
Exxon	Baton Rouge, LA	166	0	0	4408	2.7	0
Coastal States	Corpus Christi, TX	34.7	298	0.86	1278	3.7	1.2
Amoco	Texas City, TX	146	2381	1.6	0	0	9.6
Puerto Rico Sun	Yabucoa, P.R.	31.0	2625	8.5	322	2.2	10.6
Stewart Petroleum	Punta Cardon, Ven.	96.7	2738	5.7	0	0	11.0
	TOTAL	836	8042	1.0	16842	2.0	32.3
WEST COAST:							
Exxon	Benecia, CA	39.8	0	0	2345	5.9	0
Shell	Martinez, CA	41.4	0	0	5475	13.2	0
Beacon	Hanford, CA	6.3	0	0	274	4.3	0
U.S. Oil & Ref.	Tacoma, WA	11.3	0	0	286	2.5	0
Arco	Ferndale, WA	56.9	550	1.0	2929	5.2	3.2
Mobil	Torrance, CA	45.1	0	0	731	1.6	0
Kern	Bakersfield, CA	7.8	0	0	312	4.0	0
Arco	Long Beach, CA	77.0	4543	5.9	0	0	26.0
	TOTAL	286	5093	1.8	12352	3.9	29.2
EAST PACIFIC:							
Tesoro	Kenai, AK	26.3	0	0	150	0.6	0
Hawaii Ind.	Barbers, HI	22.4	1900	8.5	0	0	93
WEST PACIFIC:							
Kuwait Petroleum	Jeddah, Saudi Arabia	32.9	2978	9.1	2498	7.6	19.9
Kuwait Petroleum	Khor Fakkan, UAE*	27.6	0	0	1571	5.7	0
Shell East	Singapore	168	0	0	1388	0.83	0
Cosmo Oil	Sakaide, Japan	38.1	0	0	316	0.83	0
Nippon Mining	Mizushima, Japan	85.8	0	0	63	0.07	0
Bahrain National	Bahrain	91.3	6135	6.7	0	0	41.0
	TOTAL	444	9114	2.1	5836	1.3	61.0
EUROPE:							
Selm SPA	Priolo, Italy	110	1787	1.6	0	0	32.6
Motor Oil (Hellas)	Greece	37	3699	10.1	0	0	67.4
	TOTAL	147	5486	3.1	0	0	100.0

* Delivery point. Probably made at Shuaiba, Kuwait.

refineries represent a fairly low percent of their crude capacity. Many of them could probably supply more JP-5. Overall, JP-5 procurements are about 2.0 percent of the supplying refineries crude capacity, and there is a large additional capacity not used in these procurements. A JP-5 shortage in this region is not likely.

The F-76 procurements in this region are significant only for the two Caribbean refineries. The effect of losing the F-76 market would be minimal for the region's only other major supplier, the Amoco refinery. The Puerto Rico Sun Refinery makes some JP-5 and may be able to expand its JP-5 production to compensate for a loss of F-76 market.

On the West Coast, JP-5 procurements represent a larger percent of crude capacity than on the Gulf Coast. Unlike the Gulf Coast, the West Coast does not have a large refining capacity from which no procurements are made; most of the effects of the change would have to be absorbed by the current suppliers. However, it is unlikely that many West Coast suppliers could make a large increase in their JP-5 production. The Arco refinery in Ferndale, WA, provides both fuels, and replacement of its F-76 production with JP-5 would require a 19 percent increase in its JP-5 production. The U.S. Oil Refinery at Tacoma is one of the few providing JP-5 at a low fraction of its crude capacity. But its capacity is small; doubling its JP-5 production would bring it up to 5 percent of the crude capacity, but this would only provide half the JP-5 needed to replace the present F-76 production of Arco Ferndale.

Arco's Long Beach refinery is even more critical. Its F-76 supply is one-third of the total California fuel procurement. Mobil's Torrance refinery produced JP-5 at only 1.6 percent of its crude capacity. If this refinery could increase its JP-5 production to 5 percent, it would absorb one-third of the effect of the switch. The ARCO Long Beach refinery, like most others in the area, has a good hydrotreating capacity and could probably make some JP-5. The additional processing and narrower boiling-range product would mean higher cost and significantly lower yield. From the view of the refiner, however, it is not apparent that JP-5 would be the most attractive alternative. For example, if additional processing must be done anyway, cracking and hydrotreating to make gasoline might provide a better return on investment than making JP-5.

The quality of crudes now in use on the West Coast is a related issue. Overall, these crudes tend to produce somewhat more aromatic distillate fuels than the crudes used in the rest of the country. This aromaticity causes cetane numbers to be low. Cetane measurements made a few years ago on some JP-5 from Mobil's Torrance refinery were about 35. Taken together, these considerations indicate that replacing F-76 with JP-5 could involve significant difficulties on the West Coast.

The Eastern Pacific has some surplus JP-5 capacity. The Hawaii Independent refinery produces a large amount of F-76 and Jet A for civilian use. This refinery can produce JP-5, but no purchases were made in fiscal 1986. A small amount of JP-5 was purchased from the Tesoro refinery at Kenai, Alaska.

In the West Pacific/Indian Ocean region, the situation is similar to the Gulf Coast in that alternative JP-5 suppliers appear to be available. Kuwait Petroleum's Jeddah Refinery produces both F-76 and JP-5 at high fractions of its crude capacity. Bahrain National's Bahrain Refinery produces F-76 only, and these two refineries provide a large fraction of the total regional fuel procurements. However, there are other refineries near the Persian Gulf that may have JP-5 capability. Other West Pacific refineries supply JP-5 at low percentages of their crude capacity and could probably supply much more, but they are geographically far distant from the Persian Gulf sources presently used for F-76. Note that almost all of the fuel in both categories in this region come from the Middle East and only relatively small amounts of JP-5 come from the Far East.

In Europe, there is also a large coastal refining capacity, which may provide alternative JP-5 sources. The Motor Oil (Hellas) refinery in Greece would be seriously affected by the change because its F-76 production was such a large fraction of the crude capacity. Its F-76 production was more than half the total European procurement.

IV. LOGISTICS

One of the many responsibilities of the Navy Petroleum Office is to provide fuel contracting requirements to DFSC, coordinate fuel deliveries, and monitor Navy fuel consumption worldwide. DFSC then contracts for fuels worldwide to fulfill the Navy requirements and tasks the Military Sealift Command to transport (by tanker) fuels from refineries to bulk storage depots. Also, some product is transported by tank trucks, rail cars, and pipeline. By these methods, fuel is provided to Navy supply points around the world. There are approximately 350 storage tanks of varying capacities (not including shipboard tanks) worldwide for the storage of F-76. Converting solely to the use of JP-5 would initially require cleaning of these storage tanks in order to maintain aircraft quality JP-5 fuel. Prior experience has shown that average tank cleaning cost is approximately $40,000/tank.(12) Therefore, initial cleaning of these tanks to accept JP-5 fuel would cost approximately $14M.

From the viewpoint of the logistics system, a single fuel operation could potentially have the following benefits:

- Easier for tanker and oiler crews to load and off load only one fuel.
- Reduced workload of tanker and oiler crews in tank cleaning and purging between loads.
- Less possibility of inter-fuel contamination.
- Less bookkeeping on fuel rotation, etc.

In reality, these benefits would be negated if JP-5 for aircraft use needs to be segragated from JP-5 for ship propulsion as discussed in the next section.

V. OPERATIONS: AIRCRAFT

Converting to a single fuel (JP-5) operation should impose no operational problems so long as aircraft-quality cleanliness is maintained in the fuel distribution and storage system. It is Navy policy to not water-ballast fuel tanks containing JP-5. It would, therefore, probably be desirable to segregate the "aviation" JP-5 from the "ship" JP-5 and to prevent the "ship" JP-5 in ballasted tanks from being used in aircraft. There would also be concern about the water ballasting of tankers and oilers and how to keep the "aviation" JP-5 from being stored in water-ballasted tanks. Such efforts will reduce the logistics benefits previously mentioned.

VI. OPERATION: SHIPS PROPULSION/ELECTRIC GENERATING SYSTEMS

A. Boilers

There are considerably more steam-powered surface ships in the Navy inventory than turbine- or diesel-powered vessels. The design fuel for most pressure-fired boilers was JP-5 fuel; therefore, there should be few problems associated with use of JP-5 in operation of this class of boilers, although they only comprise about 4 percent of the boiler inventory.(13,14)

The rest of the boilers, i.e., D-type, were designed to operate on NSFO (NATO F-77). Following the conversion from NSFO to distillate fuels, these systems were converted accordingly. The fireboxes in boilers are basically quite tolerant of distillate fuels providing they are not too volatile. By design for reasons of shipboard safety, JP-5 has a very low volatility for an aviation gas turbine fuel; both JP-5 and F-76 have minimum flashpoints of 60°C. The greatest hazard to boiler operation is explosions when "lighting off" a cold boiler. However, boilers heat up relatively fast and, after reaching auto-ignition temperature (200° to 250°C range) (400° to 500°F), boilers should operate satisfactorily on most any fuel. During this survey, reports of boiler explosions after the Navy converted from NSFO to F-76 were pursued; if such explosions did occur due to this conversion, there is no documentation to support them, nor could the authors find any evidence of explosions when operating a boiler on JP-5.(13)

It is difficult to track "true" cost of boiler repairs since funds are set up for boiler repairs prior to ships coming in for maintenance, and records "usually" are not sufficient to determine if repairs were more or less costly than the pre-established amount. For example, from sources at NAVSSES, it was determined that fireside maintenance (cleaning required due to attacks on refractories and tube metal surfaces as a result of vanadium in the fuel) was reduced drastically when the Navy converted from NSFO to F-76; however, this could not be quantified. Since JP-5 and F-76 fuels are both ashless, further reduction in fireside maintenance probably would not be realized in switching from F-76 to JP-5.

B. Gas Turbine Engines

Gas turbines are used for main ship propulsion in modern destroyers, frigates, cruisers, and large hydrofoils, and for primary service generators on these same destroyers and cruisers.(14) JP-5 has often been used in these ships, both as a temporary fuel, when F-76 has been unavailable, and for extended periods of time. In the Indian Ocean in 1982-83, during the Iranian crisis, Diego Garcia had only JP-5 to supply ships. Ship policies are to "top off" fuel tanks when the level decreases to the 80 percent level. Therefore, after several refuelings, the majority of the fuel onboard the ships in that area was JP-5. Although no documentation is available to support the claims, it has been suggested there was a noticeable increase in wear rate problems in ship fuel transfer pumps and increases in the failure rates observed in engine-driven fuel pumps.(15,16) The general consensus of individuals recalling those incidents was that the failures occurred due to lack of lubricity of the JP-5, which is generally lower than that of F-76 and can vary considerably due to refining techniques. However, since these failures were not documented and inspections were not conducted on the failed components, it is not possible to determine the extent of failures or the possible cause unless controlled laboratory tests are conducted.

A change from F-76 to JP-5 could potentially have a positive impact on the maintenance of the combustion section due to improvements in hydrogen content and thermal stability. The higher hydrogen content of JP-5 will result in less soot production in the combustor and, therefore, a reduction in the radiant heat transfer to the liner. This will result in a lower liner temperatures and hence longer combustor thermal-cycle life.(2) (Note: Combustor life is really determined by the number of thermal cycles, i.e., idle/full power/idle, rather than in terms of operating hours.)

Currently no data are available on the LM2500 and 501K engines to relate liner temperatures/life to fuel hydrogen content, although this is included in current studies sponsored by DTRC. However, these engines are marinized derivatives of the TF39 and T56 engines, respectively, for which there are data and projections on combustor life (2,17) and the associated impact on maintenance requirements.(3)

There is an important distinction in operating duty cycle between aircraft and marine gas turbines. Aircraft gas turbines experience at least one full thermal cycle every mission and most missions are on the order of only a couple of hours, ten for long-haul flights. Main ship propulsion engines rarely go to full power and, beyond that, have relatively few sudden changes in load and speed; thus they experience very few effective thermal cycles. Turbo-generators experience more variations in load, but still operate most of the time at less than half power.

For the TF39, a reduction in fuel hydrogen content of 1 wt% is predicted to reduce the liner thermal-cycle life by about 20 percent.(17) The sensitivity of combustor life to hydrogen content for the LM2500 is expected to be much less than for the TF39 because the LM2500 operates at much lower pressures and temperatures than the TF39. The T56 is predicted to suffer about a 30 percent loss for the same case(2); the 501K loss would be somewhat less than this because of a slightly lower pressure ratio.

Since changing from F-76 to JP-5 implies an increase in fuel hydrogen content, the combustor life ratios should increase by the inverse of these factors. However, the real question of cost savings is determined by whether these increases in liner life have an impact on maintenance and overhaul schedules. The combustor liner on the LM2500 is not a maintenance item, and the life is much longer than the overhaul schedule. Quite the opposite is true for the 501KC in which the combustor liners are major maintenance items. The failure, however, is related to a coking or fouling problem with the atomizers, which then disrupts the fuel spray causing "hot streaks" and liner burnout. The use of JP-5 with its better thermal stability should reduce this problem, but there are currently no data to quantify this possibility. (This, too, is included in the aforementioned DTRC program.) Also, the Navy has not done a study on the actual maintenance costs of the problem; the current product improvement program to address this was justified on readiness. A cost study could be done by NAVSSES Philadelphia if requested by a Navy authority.

Thus, it is concluded that a conversion to JP-5 would not result in any cost benefits from reduced maintenance on the LM2500; however, there is a potential for cost savings in the 501KC maintenance, at least until product improvements on the fuel atomizers are implemented to reduce atomizer coking. This savings could not be quantified within the scope of this study. The potential problem of accelerated wear of fuel pumps could be controlled by lubricity additives, but would have to be evaluated against detrimental effects on the performance of water coalescers.

C. Diesel Engines

Fuel pump and injector failures also reportedly occurred on diesel engines as well as gas turbines on ships using JP-5 fuel supplied by Diego Garcia during the Iranian crisis in 1982-83. Again, these failures were not documented nor was failure analysis conducted. Therefore, the quantity and cause of failure are only speculation.(15) This potential problem area should be further documented and given special attention in the DTRC program.

The lower cetane number of many JP-5 fuels, e.g., 35, could cause problems with the cold-starting characteristics and the durability of some diesel engines, primarily two-cycle, high-speed diesels. Medium-speed diesels can generally operate satisfactorily on fuels with lower cetane number than high-speed diesels, and they are located within the warm environs of a ship's hull where there is a greater capacity for starting aids. High-speed engines are used in smaller boats, some of which are stored on the deck of a larger ship and expected to be used in emergencies or on short notice. They are more exposed to the environment and have less opportunity for extensive starting aids. A lower cetane number also means that the ignition delay period will be longer. This results in higher peak pressures once combustion takes place and can lead to durability problems if an engine is already near its design limit for power output. Two-cycle engines, of which the Navy has many, are particularly sensitive to injection timing and ignition delay. Problems of this type are included in the DTRC program, but only one JP-5 is included in the fuel matrix, which is oriented toward middle distillates of lower quality than present-day F-76.

In the meantime, it is possible to draw on past experience with using JP-5 in diesel engines to gain confidence in its acceptability. As mentioned earlier in this report, Bowden, et al.(6) provide an annotated bibliography of 23 references consisting of technical notes, letters, and reports on the subject of using JP-5 in military diesels. TABLE 6 is reproduced from that report and summarizes the engine test experience on JP-5; note that several different types of injection systems are covered and that no unusual wear or damage was noted. The first 10 entries in TABLE 6 refer to efforts beginning in 1965 when the Naval Civil Engineering Laboratory (NCEL) examined four heavy-duty diesels as part of an overall study to reduce the number of fuels stocked by the Navy. These engines were primarily from construction equipment. The last entry in TABLE 6 is particularly important since 75 percent of the high-speed diesels in the 1985 Navy inventory were Detroit Diesel Allison 2-cycle engines in this same general family of design.(18) No unusual wear or damage was found after 250 hours of operation, but there was a power loss (no value given by Bowden, et al.) caused both by the lower heat content and by pumping losses in the injectors due to the lower viscosity. An earlier performance test of a DDA 6V-53T on a JP-5 showed a 6-percent average loss in maximum power output as compared to the reference diesel fuel.(6)

The test fuels noted in TABLE 6 include a JP-8 and MP-1. The former is similar to JP-5 but with lower viscosity and higher volatility; MP-1 was a multipurpose fuel developed by the Navy for use in Antarctica in turbines, diesels, and space heaters, again having a higher volatility and lower viscosity than JP-5. The successful use of these fuels provides further support for the use of JP-5.

Bowden, et al., also mentions that from 1980 through 1983, all Army equipment operating in the Panama area out of Fort Clayton ran on JP-5 because diesel fuel (VV-F-800) was unavailable. There were no reported problems.(8)

TABLE 6. Engine-Dynamometer Testing of JP-5 and JP-8 Fuels (From Ref. 6)

Engine	Injection System	Fuel	Test Hours	Results	Conducted by
Continental Mtrs SD-802	Roose Master Pump CAV Injectors	JP-5	500	No damage or unusual wear	NCEL*
Continental Mtrs SD-802	Roose Master Pump CAV Injectors	DF-2	359	Timing gear failed—no damage or unusual wear	NCEL
Detroit Diesel 3-71	GMC Unit Injectors	JP-5	500	No damage or unusual wear	NCEL
Detroit Diesel 3-71	GMC Unit Injectors	DF-2	500	No damage or unusual wear	NCEL
International UD-18A	IHC Injection System	JP-5	500	No damage or unusual wear	NCEL
International UD-18A	IHC Injection System	DF-2	500	No damage or unusual wear	NCEL
Cummins Model JT-6	Cummins PT Injection	JP-5	500	No damage or unusual wear	NCEL
Cummins Model JT-6	Cummins PT Injection	DF-2	500	No damage or unusual wear	NCEL
Caterpillar 50-kW	Caterpillar Injection	DF-A	500	Parts in excellent condition, 0.8% loss in pumping capacity	NCEL
Caterpillar 50-kW	Caterpillar Injection	MP-1	500	Parts in excellent condition, 2.0% loss in pumping capacity	NCEL
CUE† 1790	Am. Bosch APE1BB	JP-5	250	Less wear and deposits than with DF-2	AFLRL**
AVDS-1790-2C (RISE)	Am. Bosch Rotary	JP-5	400	Performance was satisfactory	TCM***
DD 6V-53T	GMC Unit Injectors	JP-8	240	No damage or unusual wear	AFLRL

* NCEL - U.S. Naval Civil Engineering Laboratory, Port Hueneme, CA.
** AFLRL - Belvoir Fuels and Lubricants Research Facility (SwRI), formerly U.S. Army Fuels and Lubricants Research Laboratory.
*** TCM - Teledyne Continental Motors.
† - Cooperative Universal Engine.

One potential advantage to using JP-5 instead of F-76 in diesel engines is the lower sulfur content. Recently, Frame, et al. conducted an extensive literature search and survey of fleet data on the effects of fuel sulfur or wear.(19) Although they reported several instances of reductions in iron in the lubricating oil when low sulfur fuels were used, the authors cautioned against simple extrapolations of lower oil iron content and higher ring/cylinder wear to extended engine life since there are so many complex interactions of fuel sulfur with temperature, load, and oil alkalinity. In some tests, there did seem to be a direct correlation, but not on all engine types examined. Most reasons for engine rebuild are difficult to relate directly to corrosive ring and liner wear.(19)

Fuel sulfur has often been related to corrosive wear of the ring and bore, but the strongest effects are at lower operating temperatures; thus, engines with short-duty cycles would benefit the most from a reduction in fuel sulfur. Higher oil alkalinity (TBN) and shorter drain intervals are common ways to to extend engine life when using fuels with higher sulfur. It was not possible to determine Navy practice, so it was not possible to determine the real benefit from using lower sulfur fuels. This is another problem area that should be addressed in the DTRC program, but again, fuels of higher quality, in this case containing lower sulfur, would need to be included in the matrix of test fuels.

VII. OVERALL ASSESSMENT

During the course of this survey, the following problems/benefits associated with converting to JP-5 for aircraft and ships propulsion/electric systems were identified:

A. Problems

- The lower cetane number of JP-5 could create low-temperature starting problems for diesel engines; this would be less of a problem for medium-speed engines located inside the hull than for small boats stored on deck and other small craft more susceptible to ambient temperature. Experience has not shown any engine durability problems, but cold-start is less documented.

- The use of JP-5 in high-speed diesel engines can result in power losses as much as 6 percent, depending on the engine design; the greatest contributing factor to this loss of power is the lower viscosity of JP-5 leading to increased leakage in the fuel injectors. The lower heat content of JP-5 also contributes to the power loss, but small improvements in thermal efficiency can offset this in some diesel engines.

- The use of JP-5 can also lead to accelerated wear of fuel-lubricated parts of the fuel system due to its lower lubricity; this includes transfer pumps, high-pressure pumps on both diesel and turbine engines, and injectors on diesel engines. Although some studies have not identified these problems, they generally have not covered long-term effects, i.e., greater than 500 hours.

- The average energy density (Btu/gallon) of JP-5 fuel was found to be 2.6 percent less than F-76 (TABLE 2). Therefore, based on the FY80-86 average yearly fuel (F-76) purchases, this would result in an increased requirement of over 25 million gallons of JP-5 per year to compensate for the energy differential between F-76 and JP-5. Increasing the fueling rate can theoretically recover the power loss due to the lower energy content, but the increased pumping losses in the injectors due to the lower viscosity may prevent this, resulting in a nonrecoverable power loss as much as 5 percent, depending on the engine.

- During the period FY80 through FY86, DFSC had no difficulties in procuring F-76. However, this is not true for JP-5. Reportedly, DFSC had periodic shortages of JP-5 in three out of four major purchasing areas (Mediterranean, U.S. West Coast, and U.S. Gulf Coast). Most of the refineries around the world that are now supplying F-76 do so in large volumes, and a switch to JP-5 would have a major impact on them if they were unable to make JP-5. From TABLE 5, it appears the greatest supply difficulties resulting from replacing F-76 with JP-5 would occur in the West Coast region, which supplies about one-third of the total JP-5 procurement.

- Assuming adequate quantities of JP-5 are available, DFSC fuel pricing history has shown JP-5 costs to be approximately $0.05/gal. more than F-76. Based on average yearly fuel purchases mentioned earlier, this could result in an increased fuel cost of approximately $103M per year.

- To provide adequate storage and cleanliness for JP-5, approximately 350 fuel storage tanks now utilized for F-76 would require cleaning at an estimated cost of $14M.

- Fuel flexibility/ability to use alternate fuels could be impaired. Currently JP-5 is authorized as alternate/emergency fuel when F-76 is not available, but there are many parts of the world where F-76 and JP-5 are not available and the Navy has no bunkering agreements. Spot purchases of emergency fuels that will meet the ships needs would preserve JP-5 for aviation use.

B. Benefits

- Transportation, storage, and accountability would be easier with a single fuel.

- Possibility of fuel contamination with other fuels would be eliminated.

- Easier to rotate inventory—First in/First out.

- Reduced maintenance of 501K fuel atomizers.

- Potential increases in diesel engine life due to lower fuel sulfur content in JP-5 with resultant reduction in corrosive wear of bore and rings.

The first three of these benefits could not be realized if JP-5 for aviation use needs to be segregated from that for ship use because of contamination by water ballasting. Even if they could be realized, these three benefits are difficult to quantify in order to compare with the project costs.

Generally speaking, increases in life ratio of combustors in ship gas turbines will not result in savings in maintenance costs because the combustors do not determine overhaul times.

Because atomizer fouling is a major maintenance item on the 501K turbines, a change to JP-5 should result in a cost savings, but this had not been quantified at NAVSSES at the time of this study.

One potential side benefit of using JP-5 is due to the better storage stability characteristics. Launch boats and other systems that are not used very often can suffer in reliability if their fuel supply deteriorates to the point of plugged filters or poor performance. Hence, fueling these craft with JP-5 should improve their reliability.

VIII. CONCLUSIONS

Converting the propulsion and electric generating systems of ships to use of JP-5 would not be detrimental to fleet operational readiness. However, few, if any, operational or maintenance benefits would be realized from such a conversion. Benefits realized would most probably occur in the logistics area through the simplicity of handling only one fuel. These benefits are very difficult to quantify, and may not be fully realized if it is still desirable to fully segregate the fuel to be used for aviation from ship fuel.

Due to the higher cost of JP-5, increased fuel requirement, and the necessity of cleaning numerous fuel storage tanks, such a conversion would, at least initially, be very costly for the U.S. Navy. It also seems unlikely that the higher volumes of JP-5 would result in significant price reductions; in some markets the price may increase due to increased refining requirements.

The concept of a compromise fuel does not seem practicable since it would have to be very close to JP-5 in all the areas that affect cost and availability, namely: contaminants, aromatics, and freeze point. Competing restrictions on viscosity between the aviation gas turbines and the surface diesels will severely limit availability and a compromise would have to be developed. Furthermore, a specification for cetane would have to be imposed, which could further affect cost and availability, at least in some regions. Thus, the result could be even more expensive than JP-5, and some flexibility in fuel utilization would be lost.

IX. RECOMMENDATIONS

The major deficiency of this study is the inability to quantify the benefits of converting to JP-5 as a single Navy fuel. There is also a lack of data on the long-term effects of JP-5 on performance and durability—both positive and negative aspects, i.e., expected reductions in diesel engine wear, deposits, fouling, and oil degradation but possible increases in the wear of fuel-lubricated parts and power loss.

It is therefore recommended that the DTRC program on fuel flexibility give consideration to looking at the use of JP-5 in the diesels, in addition to the current focus on commercial and low quality marine fuels. The study should include long-term effects on the durability of engines, pumps, injectors, and the lubricating oil.

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STRBE-BT 2
AMSTR-ABCE (MR COOK) 1
FORT BELVOIR VA 22060-5606