Future Aviation Turbine Fuels

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This paper discusses an Air Force program which is being conducted to establish the properties of an aviation turbine fuel which will result in adequate fuel availability for the Air Force at an acceptable cost. Results of recent processing studies on alternative hydrocarbon sources from coal and shale oil are presented, together with combustor studies directed to determining the effects of property variations on combustor performance, durability, and level of harmful emissions. Also, results of a recent survey are given showing projected increases in turbine fuel availability resulting from turbine fuel property changes. A projection of the chemical and physical properties of the future Air Force aviation turbine fuel is presented.

I. Introduction

THE Department of Defense (DOD) consumes approximately 3.4% of the total U.S. demand for petroleum. The Air Force usage accounts for 57% of the DOD consumption with approximately 82% being consumed as jet fuel (see Fig. 1). The Air Force jet fuel demand, which reached a peak in 1969, has steadily declined to the present level as a result of the cessation of the Southeast Asia conflict and strict conservation measures. The cost of this fuel to the Air Force has increased greatly since the 1973 oil embargo. The bill in 1973 was slightly over one-half billion dollars for 112 million barrels of JP-4, whereas it is now approximately 1.6 billion dollars or about 6% of the Air Force annual budget for only 80 million barrels (see Fig. 2).

The proven U.S. domestic reserves of petroleum crude oil are approximately 40 billion barrels. Currently, the U.S. consumes about 6.6 billion barrels of oil per year, of which 45% is imported. Current projections are that by 1980 over 50% of the petroleum consumed by the U.S. will be imported. This excessive dependence upon nondomestic sources has obvious and serious implications with respect to the U.S. defense posture.

Approximately 50% of the petroleum used annually in the U.S. is consumed by ground transportation vehicles, aircraft, and railroads. The transportation area requires a portable fuel that is safe, can be easily handled, and has a respectable heating value. The petroleum derived fuels used today are ideal; substitutes such as hydrogen, methane, methanol, etc., have significant deficiencies, such as low-energy densities, which make them unattractive for aircraft applications. Aircraft in the inventory today and those under development, both military and commercial, are still being designed to use hydrocarbon fuels of the kind now being used. If one looks at the longevity of the B52, KC135, and F4 and extrapolates that to newly developed aircraft, it would appear that conventional aircraft will be in the inventory well into the 1990's. So also will be the need for today's hydrocarbon-type fuels.

Although it is expected that nuclear, solar, geothermal, and other types of energy will eventually replace petroleum as the energy source in many areas, the U.S. growth of total petroleum products needs over today's consumption is projected by almost every source. With diminishing petroleum resources, the development and growth of a major synthetic liquid fuels industry to meet the nation's liquid hydrocarbon needs well into the year 2000, when renewable energy sources will be developed, is imperative.

At the present time, there is a great deal of emphasis by both the Department of Energy and industry to develop the technology to produce hydrocarbon liquids from sources such as coal and oil shale which are available in huge quantities in this country. In addition, much research is being conducted to utilize heavy crudes (low pour point viscous oils) and residues (tar-like solids) which heretofore have been too costly to extract and process. Also, the North Slope crude, which is currently impacting the west coast refineries is more highly aromatic and heavier than conventional crudes and thus

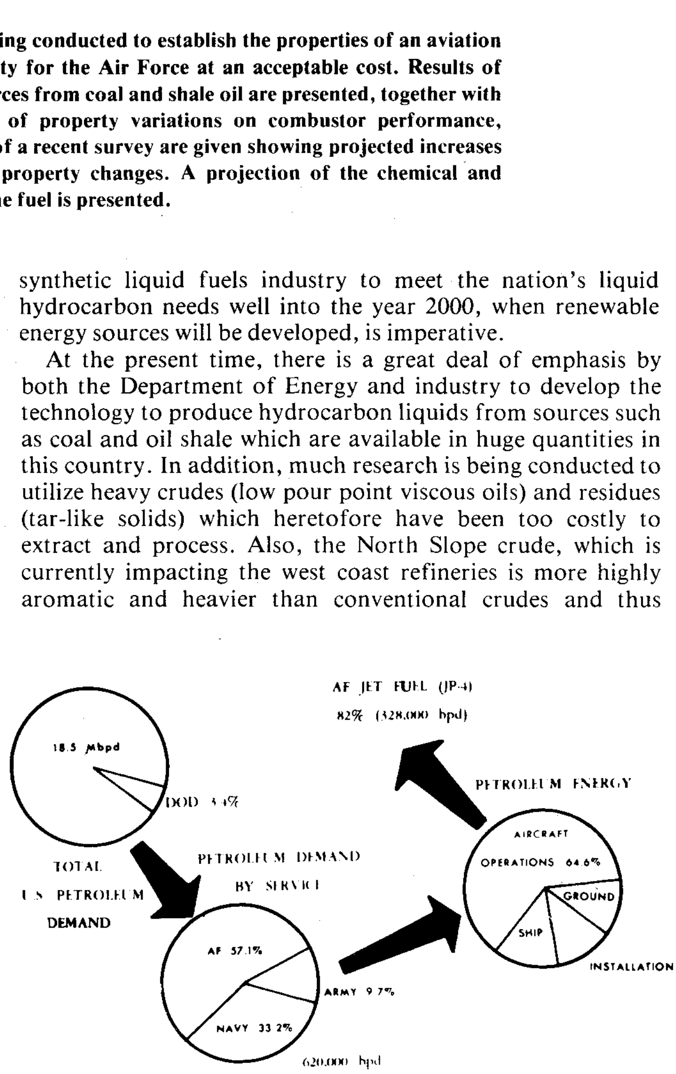

Fig. 1 Air Force jet fuel requirements.

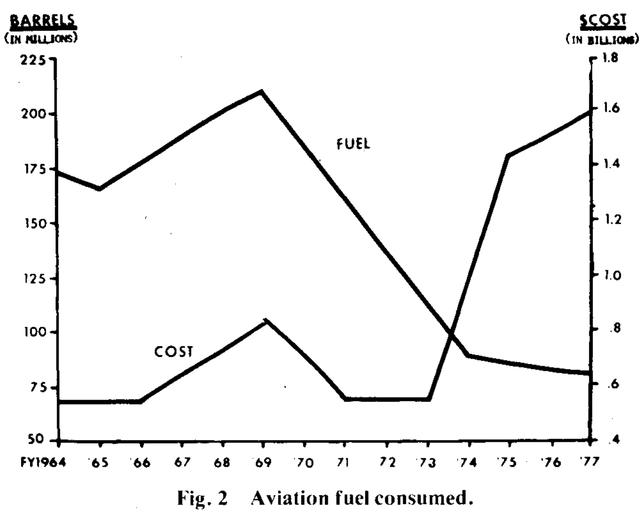

Fig. 2 Aviation fuel consumed.

Presented as Paper 78-268 at the AIAA 16th Aerospace Sciences Meeting, Huntsville, Ala., Jan 16–18, 1978; submitted Feb. 21, 1978.

Index categories: Alternate Fuels; Airbreathing Propulsion; Combustion and Combustor Design.

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results in different refinery process economics for a conventional slate of products.

Each of these energy sources, while basically hydrocarbons, differ drastically as to compound types, mineral content, etc., and therefore each will have specific processing problems. Liquid hydrocarbons from coal, oil shale, and tar sands will also be much more deficient in hydrogen than conventional crude. Hydrotreating (generic classification of processes involving hydrogen addition) is the most costly and energy consuming operation in refining and is expected to become much more expensive in the future. Refining energy costs on coal liquids, for example, could be relaxed by one-third if restrictions on aromatic content were relaxed. Refining costs are proportional to refinery energy costs. Therefore, a substantial cost saving on refined products such as jet fuel would be achieved if the amount of hydrotreating in processing both petroleum and nonpetroleum feedstocks is reduced.

The specification for JP-4, the standard U.S. Air Force jet fuel, was defined at a time when this product was both inexpensive and plentiful. While there have been refinements to the fuel specification to keep pace with engine development, JP-4 has basically maintained the critical properties first specified to insure availability and to fulfill aircraft operational performance requirements. A clear understanding of the relationship between fuel characteristics and aircraft system performance, engine durability, emissions, and survivability may result in dramatic cost reductions for a broadened specification fuel, but these reductions can only be realized with assurance that aircraft performance is not adversely affected.

II. Aviation Turbine Fuel Technology Program

The Air Force Aero Propulsion Laboratory (AFAPL), which has prime responsibility for military aviation turbine fuels in the Department of Defense, initiated an Aviation Turbine Fuel Technology Program early in 1974 to establish the properties of an aviation turbine fuel which will result in adequate fuel availability for the Air Force at an acceptable cost. This program involves extensive work on fuel analysis, combustion, fuel system effects, and overall fuel property/aircraft system tradeoff research. Two approaches are being pursued in this program: 1) relax specifications to reduce the level of processing required on conventional petroleum crudes and the lower quality crudes which are expected to be used in the near future; and 2) investigate the acceptability of fuel produced from alternate sources such as coal, oil shale, and tar sands to meet the same relaxed specifications as for petroleum derived fuels. Figure 3 depicts the overall nature of the program. Fuel processing will be of primary importance to ascertain per-gallon fuel costs. The impact of reduced levels of refining on all aircraft system components must be determined. These include fuel system (pump, filters, heat exchangers, etc.) and airframe (fuel tank size and design, impact on range, etc.) considerations as well as turbine engine mainburner and augmentor impact (exhaust emissions). It is anticipated that the optimum turbine fuel for Air Force use will be a compromise among these various considerations.

The primary emphasis of the program to date is in the areas of fuel processing, fuel analysis, and combustion effects. The fuel processing work has been conducted through contractual efforts with industry, whereas the fuel analysis and combustion efforts have been conducted both in-house by the AFAPL and through contractual efforts.

The AFAPL initiated an Air Force/NASA funded contract with Exxon Research and Engineering in May 1974 to investigate alternative domestic hydrocarbon resources which could potentially be used as feedstocks for the production of jet fuel. The conclusions of this study were that this country had sufficient resources of oil shale and coal to meet this country's hydrocarbon fuel needs for centuries and that, of

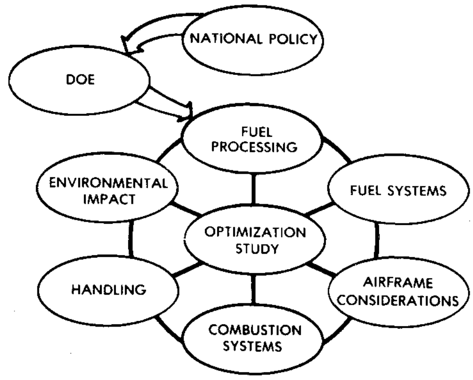

Fig. 3 U.S. Air Force aviation turbine fuel technology program.

Table 1 Effect of hydroprocessing severity on compound type distribution

Crude type	Compounds	Feedstock	800psi	1500psi	2200psi
Paraho shale oil	Aromatics	40.2	23.5	16.4	1.6
	Paraffins	33.2	47.5	47.6	47.7
	Naphthenes	26.6	29.0	36.0	50.7
Tosco II shale oil	Aromatics	29.9	19.3	7.5	2.1
	Paraffins	25.8	50.3	51.8	52.0
	Naphthenes	44.3	30.4	40.7	45.9
Occidental shale oil	Aromatics	38.9	21.5	12.1	4.8
	Paraffins	35.9	47.1	48.3	47.4
	Naphthenes	25.2	31.4	39.6	47.8
Synthoil coal oil	Aromatics	51.9	50.2	24.0	1.6
	Paraffins	0.5	1.4	8.2	15.9
	Naphthenes	47.6	48.4	67.8	82.5
H-coal coal oil	Aromatics	44.8	35.7	20.2	2.9
	Paraffins	1.4	5.0	10.0	4.6
	Naphthenes	53.8	59.3	69.8	92.5

the two, oil shale was the more attractive for the production of jet fuel. The primary reasons for these conclusions were that shale oil is economically and technically closer to commercialization and more nearly resembles petroleum than do coal liquids. During the experimental phase of the program, hydrocarbon liquids produced from three shale oil conversion processes (Paraho, TOSCO II, and Occidental In-Situ) and two coal liquefaction processes (H-Coal and Synthoil) were fractionally distilled and catalytically hydrotreated at varying severities. Two commercially available catalysts were used: a nickel-molyb-denum-on-alumina catalyst supplied by American Cyanamid Co. and a cobalt-molybdenum-on-alumina catalyst supplied by Nalco Chemical Co. A kerosene fraction was distilled from each synthetic crude oil sample and hydrotreated at 800, 1500, and 2200 psi in an experimental hydrogenation system. The liquid hourly space velocity (LHSV) was varied from about 0.2 to 1.0 at each of these pressures. Parameters such as hydrogen consumption as well as final product analysis were determined for all conditions. Table 1 gives a comparison of the characteristics of the products from the five synthetic crudes when run under identical hydrogenation conditions. All three shale oils resulted in specification turbine fuel when hydrotreated at 1500 psi. The coal liquids however required a hydrotreat pressure of 2200 psi to approach a specification product (density was exceeded). It should be noted that both shale oils and coal liquids reacted similarly when hydrotreated; namely, the unsaturated aromatics compounds were converted to naphthenes. However, since the coal liquids contain very little paraffins in the starting material, the processed liquid is highly naphthenic compared to the shale oil product (which is mixed base). This may result in some unusual combustor or smoke emission effects and requires further investigation when sufficient coal derived fuel samples become available. Future developments, however, may result in catalysts which do not cause this effect.

Because of the unavailability of refined petroleum and synthetic fuels meeting the range of parameters desired for various experimental efforts, a great deal of emphasis has been placed on blending fuels to simulate refined petroleum and synthetic fuels. Table 2 gives a mass spec analysis of the initial to 563°F feed fraction for the five synthetic liquids tested in the Exxon program. Table 3 gives an analysis of the blend materials being used in the Combustor Fuel Effects Tasks. These materials, when blended with base JP-4 and JP-8 fuels, result in fuels which have physical and chemical properties similar to hydroprocessed shale oils.

Bonner and Moore Associates, Inc., under an Air Force contract, recently conducted a study to determine the most critical jet fuel specification requirements where relaxation could be expected to have an impact on availability, and to estimate the effects that changes in these critical specifications would have on the refining industry's willingness to offer jet fuel for sale. The principal tool used in this study was a confidential survey of the U.S. refining industry. Survey respondents accounted for 21% of the U.S. jet fuel production. Survey answers were on 1975 crude availability and product prices. Independent estimates were not derived for different types of kerosene-based jet fuels. Increases in availability for one such fuel due to relaxing specifications for it alone would tend to come almost entirely at the expense of the other kerosene-based jet fuels. Results of the survey indicate that for kerosene-type jet fuels, increases of 20% could be realized by relaxing freeze point and final boiling point, and increases of about 28% could be realized by relaxing aromatics, smoke point, freeze point, and final boiling point. For naphtha-type jet fuels, an increase of 24% by relaxing freeze point is indicated. This study was based on the assumption that jet fuel availability, for a particular refinery, increases at the expense of reduced availability of other products without affecting the price of the other products. In areas which are short of crude supplies or crude capacity, these assumptions are not valid. If additional crude can be obtained and crude processing capacity is available, the assumptions are valid since all products will tend to be priced on the basis of constant profit margins which are based on replacing products by running additional crude.

The results of the Bonner and Moore and Exxon study and recent processing studies conducted by NASA and the Department of Energy form the basis for selection of the turbine fuel property variations currently being studied in the Air Force's Aviation Turbine Fuel Technology Program. These property variations are shown in Table 4.

The primary emphasis in the experimental portion of the program is to establish a combustion technology base necessary for the development of aircraft jet fuels. The initial work involved determining the effects of fuel hydrogen and nitrogen content using a T56 single combustor modified to operate at conditions representative of a wide variety of engines in the U.S. Air Force inventory. Hydrogen content was varied (12.7 to 14.5% by weight) by the addition of alkylbenzene in a base JP-4, nitrogen content was varied (0.1 to 1.0% by weight) by the addition of pyridine. Results of the hydrogen variation effects on combustion liner temperature at low pressure cruise conditions are presented in Fig. 4. These data, which are typical, show significant increases in combustor liner temperature due to the more luminous flame produced as hydrogen content is decreased. The effect of hydrogen content variations on smoke emission for various combustor inlet temperatures is shown in Fig. 5. It should be noted that the 756 K combustor inlet condition might be expected to result in a somewhat higher increase in smoke number than the 644 K inlet. However, because of test facility limitations, a lower fuel/air ratio was required to maintain a 1200 K exhaust temperature, resulting in a lower absolute smoke emission. The effects of fuel bound nitrogen conversion to NO_x, found by calculating the percent conversion required to produce the additional NO_x in the exhaust are shown in Fig. 6.

The present combustor efforts in the program involve three contractual programs, two initiated in FY77 and one planned for FY78, to investigate the effect of fuel property variations

Table 2 Hydrocarbon analysis of syncrudes, initial boiling point to 563°F feed fractions

	Paraho	Tosco II	Garrett	Synthoil	H-coal
Paraffins	33.2	25.8	35.9	0.5	1.4
Monocycloparaffins	4.6	28.3	5.9	38.8	43.4
Dicycloparaffins	11.3	9.3	10.5	8.5	8.3
Tricycloparaffins	10.3	6.4	8.4	0.0	1.6
Total Paraffins	59.3	69.8	60.7	47.8	54.7
Alkylbenzenes	18.4	17.0	16.5	21.2	24.2
Indans	11.6	7.9	10.7	21.4	17.2
Indenes	5.0	2.7	4.1	7.7	0.2
Naphthalenes	5.2	2.3	7.6	1.6	3.2
Total Aromatics	40.2	29.9	38.9	51.9	44.8

Table 3 Hydrocarbon analysis of blend materials, wt. %

	Xylene	2040 Solvent	Gulf mineral seal oil
Paraffins			43.5
Cycloparaffins			30.2
Dicycloparaffins			9.9
Tricycloparaffins			4.6
Total paraffins			88.2
Alkylbenzenes	100.00	35.5	4.0
Indans/Tetralins		6.8	4.8
Indenes		0.09	1.4
Naphthalene		18.6	0.9
Naphthalenes		39.0	0.14
Acenaphthylenes		...	0.44
Tricyclic Aromatics		...	...
Total aromatics	100.00	99.99	11.68

Table 4 Turbine fuel property variations

H_2 content	12.7–14.5%
Aromatic type	Single, double, triple ring
Vapor pressure	0–2.5 psi
End point	450–625°F

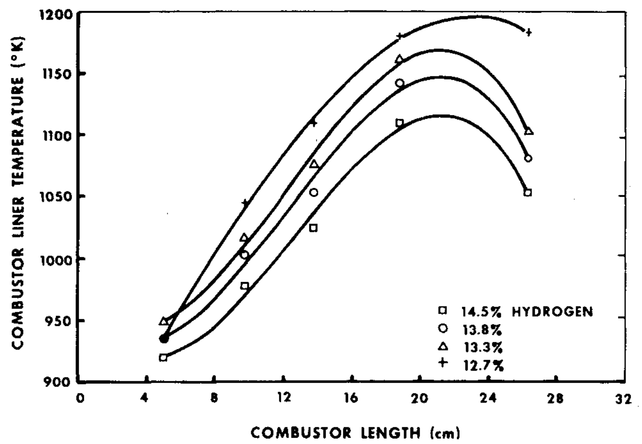

Fig. 4 Fuel hydrogen content effect on combustor liner temperature.

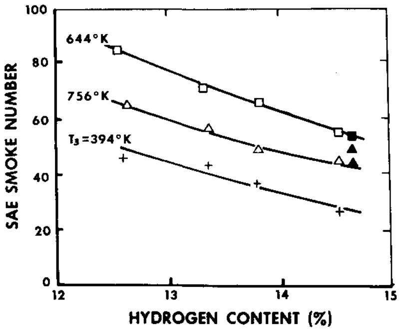

Fig. 5 Fuel hydrogen content effects on smoke emission.

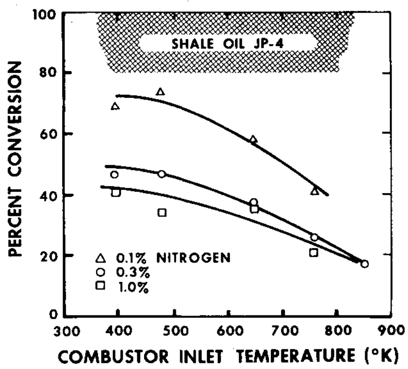

Fig. 6 Fuel bound N_2 conversion to NO_x.

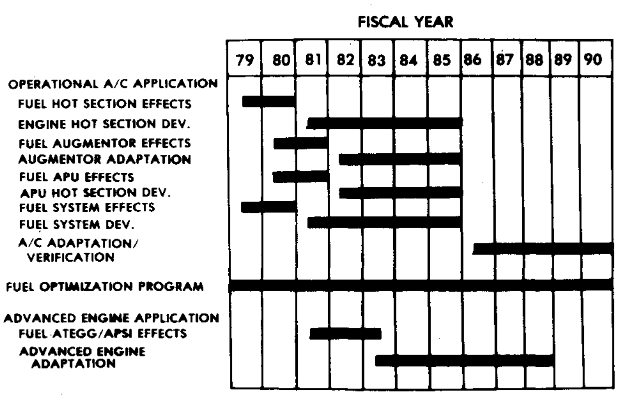

Fig. 7 Aircraft alternate propulsion technology.

on the three classes of combustors presently in the Air Force inventory. General Electric Co. is in the process of assessing the effects of hydrogen content variation, volatility, aromatic type, and end boiling point on the performance and durability of the low-pressure can (J79) and full annular type (F101) combustors. The FY78 program will involve the high-pressure can-type combustors. The results of these efforts, as well as Fuel/Engine/Airframe Optimization Study effort to be initiated in FY78, will be used to determine the specific direction of the overall program in the future.

The Fuel/Engine/Airframe Optimization study will first determine the extent to which fuel properties can be varied without detrimental effects to any U.S. Air Force aircraft/mission. The effects on fuel cost/availability will also be assessed. The second part of the program will be directed towards establishing fuel properties which will minimize U.S. Air Force aircraft system life cycle costs. It is anticipated that this will consist of a tradeoff between fuel properties with associated fuel cost saving, increased availability, and aircraft system costs associated with modifications required to utilize the broadened specification fuel. This tradeoff study will be the primary analytical program used to provide specific guidance to all experimental and developmental efforts planned for the Aviation Turbine Fuel Technology Advanced Development Program to be initiated in FY79, shown in Fig. 7.

Table 5 Future fuel specifications

Final BP, max., °F	600
Flash pt., min.-max., °F	90-130
Freeze pt., max., °F	−30
Net heat of combustion, min., Btu/lb	18,300
Aromatics, vol. %, max.	35
Nitrogen, wt. %, max.	0.005
Hydrogen, wt. %, min.	13.0

III. Future Fuel Characteristics

The Advanced Development Program is structured so that an interim fuel specification will be defined three years after program initiation. This interim specification, which is projected to be similar to the JP-8 specification, should serve as a guide to the engine and aircraft manufacturers as well as to the fuel processing industry. The program is then expected to lead to a significant fuel specification change in approximately 10 years. The projected properties of this fuel are shown in Table 5.

IV. Conclusions

The Air Force, the largest user of petroleum within the Department of Defense, has an ongoing Aviation Turbine Fuel Technology Program to develop the specification for a fuel which will maximize the availability and minimize the cost of turbine fuel in the future. This fuel optimization program is a complex effort involving compromises between fuel cost/availability and aircraft system performance/modification cost penalties. This program is structured to insure that the Air Force can utilize fuel produced from any domestic hydrocarbon resource without any degradation to aircraft system performance. Shale oils have been determined to be the most attractive synthetic feedstock for the production of turbine fuel because they more closely resemble petroleum crude, are easier and less expensive to process, and closer to commercialization than are coal liquids.

The Air Force Aviation Turbine Fuel Technology Program is expected to result in the definition of an interim fuel specification within three years, which is projected to be similar to specification grade JP-8. It is also anticipated that as a result of information obtained early in the program minor changes will be made in the current JP-4 specification which will result in increased fuel availability or decreased cost. The program is then expected to lead to a significant fuel specification within 10 years. A validated fuel specification will insure confidence in the projected usage of fuel processed from petroleum and alternate energy sources with respect to engine performance, compatibility with combustion systems and fuel system components/elements and the level of harmful emissions.

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