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Aviation Turbine Fuels: An Assessment of Alternatives

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Abstract: It is NASA's intent that its research and technology program be able to provide the data base needed to facilitate use of broadened-specification aviation turbine fuels should that be required as a result of a future disruption in petroleum supplies. This report contains the results of the assessment of the NASA program taking into account the general outlook for aviation turbine fuels, the effect that broadening permissible aviation turbine fuel properties could have on the overall availability of such fuels, the fuel properties most likely to be affected by use of lower grade petroleum crudes, and the research and technology required to ensure that aviation turbine fuels and engines can function satisfactorily with fuels having a range of fuel properties differing from those of current specification fuel.

Descriptors: \*Jet engines, \*Aviation fuels, Jet engine fuels, Technology assessment, Refining, Flashpoint, Performance evaluation

Identifiers: \*Alternative fuels, NTISNASNRC, NTISNASA, NTISNASIOM, NTISNASAE

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# **Aviation Turbine Fuels**

## **An Assessment of Alternatives**

Report of the  
Ad Hoc Committee on Alternative Aviation Turbine Fuels  
Aeronautics and Space Engineering Board  
Commission on Engineering and Technical Systems  
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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## INTRODUCTION

In order to improve aircraft performance and reduce cost of commercial airline operation in a highly competitive market, airframe and engine manufacturers have continuously striven to produce a more cost-effective aircraft based on the latest available research and technology. Since the end of World War II, all aircraft turbine engine developments have been based on fuel falling well within allowable aviation turbine fuel specification limits. Thus, succeeding generations of aircraft turbine engines have been designed to operate optimally within these limits and tend to be sensitive to significant variations in critical fuel properties. For the most part, this sensitivity is due to continuing efforts to produce more thrust and lower fuel consumption per pound of engine weight.

As aromatic content of aviation turbine fuels has increased due to continuing changes in the character of petroleum feedstocks available to refiners, new and difficult problems became evident to commercial aircraft operators and the owners of turbine-powered general-purpose aircraft. These problems were characterized by increased smoke in engine exhausts, as well as by expectations of increased maintenance of engine hot parts.

This situation has brought increased attention to potential problems of this type that could occur in the future should it become necessary to broaden the aviation turbine fuel specification limits to compensate for a reduction in availability of aviation turbine fuel meeting current specifications for both commercial and military aircraft. There have been some indications of this possibility.

An earlier study by a major aircraft manufacturer involving an analysis of 60 samples of Jet A fuel in 1979 concluded that, although only three of the samples were at specification limits, the average aromatic content of Jet A fuel, for example, was moving closer to the maximum specification limit with each passing year.

A more recent analysis of data on 676 samples of Jet A turbine fuel samples recorded by the Department of Energy and reported for the period 1969-1979 indicated the same increasing trend in annual median values toward specification limits of various fuel properties of aviation turbine fuel such as aromatic content, smoke point, and freezing point. An increasing number of the individual samples were at specification limits in one or more important performance parameters. As the required refinery output began to decrease concurrent with a lessening of overall refinery-product demand, the aviation turbine fuel samples tested in 1980 and 1981 showed fewer such incidents; whether this is a temporary or a longer term reversal of trend is not yet clear.

As available raw feedstocks continue to be composed of heavier and less desirable crudes, it will become increasingly more costly

and difficult to refine them to current aircraft turbine fuel specification limits. In order to keep refining costs for such fuels within reasonable limits, it may be necessary to broaden the current specifications for aviation turbine fuels by the turn of the century or even sooner, and well before the introduction of the next completely new generation of commercial aircraft and turbine engines that will succeed the new generation soon to enter the worldwide commercial air fleet.

Experience of the last decade suggests the probability of continued disturbance of the worldwide pricing and potential availability of raw crudes from certain overseas sources. This trend may well continue to be dependent in part on domestic and overseas raw crude supply and ongoing demands for the refined petroleum product in this and other nations. Furthermore, added problems associated with unpredicted international crises involving U.S. military forces in this decade and beyond point to the desirability of continuing parametric studies of aviation turbine fuel with broader properties that would not sacrifice fuel efficiency or operational safety and that could be produced from lower quality crudes.

Ongoing research and development activity by NASA, the Department of Defense, and the aviation industry has been a key element in maintaining the nation's preeminence in the worldwide sale and use of aviation products, particularly aircraft and engines based on current U.S. aviation turbine fuel specifications.

With the development and worldwide spread of air commerce, a large percentage of the aviation turbine engines in operation overseas are of U.S. manufacture and thus are dependent on fuel produced to the same basic specification as that used in the United States. U.S. specifications generally set the standard for the Western world. Thus, the overall aviation fuel problem is a matter of serious international as well as national concern.

In light of these considerations, continuation of ongoing NASA and DOD programs on aviation turbine fuels is essential. The improvements perceived to be necessary must be made so that current and proposed turbine engines and components will be able to function satisfactorily and with little or no adverse effect on service life and safety of the equipment. Attention must also be given to related aircraft fuel-handling systems, particularly ground systems.



## EXECUTIVE SUMMARY

In the next 20 years, the United States will be faced with a particularly difficult problem in supplying all elements of the economy, including transportation, with adequate liquid fuels. In particular, recent events and projected trends foreshadow great uncertainty about the future availability, cost, and quality of aviation turbine fuel.

Thus the National Aeronautics and Space Administration (NASA) foresees a possibility, should a future emergency arise, for use of aviation turbine fuel with a wider range of properties than is permissible under current specifications. It is looking into its research and technology programs with a view to meeting that potential need. The National Research Council (NRC), through the Aeronautics and Space Engineering Board (ASEB) of the Assembly of Engineering, was asked by NASA to conduct an examination of those programs in that light.

An ad hoc committee was formed by the ASEB specifically to assess the appropriateness and adequacy of the current and planned NASA research and technology program in alternative aircraft turbine fuels and its relationship to similar programs in other government agencies. The committee comprised experts selected for their knowledge and experience in research, development, production, economics, and use of aircraft turbine fuels. Its members represented the petroleum refinery, aircraft, engine, and airline industries, as well as related research and development activities in government, industry, and academe.

As a basis for its assessment, the committee assumed that greater energy independence will be a continuing objective of the United States for the foreseeable future and that, consistent with this objective, efforts will continue both to reduce consumption of petroleum-derived fuels and to increase supplies of fuel from synthetic crudes. In developing its conclusions and recommendations, the committee considered the general outlook for future aviation turbine fuels, the effect that broadening permissible aviation turbine fuel properties could have on the overall availability of such fuels, the aviation turbine fuel properties most likely to be affected by use of lower grade petroleum crudes or proposed synfuels, and the research and technology required on aviation turbine fuels and aviation turbine engines to accommodate the range of fuel properties likely to be encountered in the future.

At the conclusion of its two meetings, after consideration of the information presented, the committee concluded that, although current data indicated that adequate quantities of aviation turbine fuel could be made available in the future at a probable increase in price, it was not possible to assume that there would not be a future disruption in the supply of suitable quality aviation turbine fuel.

In the face of such uncertainty, the committee concluded that a carefully planned and coordinated national program of aviation turbine fuel and engine research, technological development, and testing should be developed.

In assessing the adequacy and appropriateness of the existing NASA program, the committee identified typical operational problems related to future fuel, engine and aircraft interactions as a basis for evaluating both a base research and technology program and a proposed augmentation thereof.

The committee concluded that the existing NASA base research and technology program on alternative aviation turbine fuels and their effects on related propulsion system components is sound, but inadequate in certain respects.

For example, the level and scope of the base research and technology program was deemed inadequate to provide the data base for the quantitative decisions likely to be required later in this decade and in the next, in connection with the cost and complexity of engine/aircraft modifications required to cope with possible wider specification aviation turbine fuels, and the added costs of refining future less desirable crudes into suitable fuels meeting today's specifications.

Though commercial and military large-size aircraft turbine engines spring from a common base, there are increasing differences in the direction that specific engine developments take. In commercial turbine engines, the effort is toward higher thrust, longer operational life, and improved fuel consumption; in military engines, it is toward ever higher performance, altitude, and maneuver capability. For this reason, the missions of NASA and the Department of Defense are closely related though essentially different. In any case, there is a continuing need for close cooperation between DOD and NASA during the planning and program execution phases of this work.

The proposed NASA augmentation of the base program on alternative turbine fuels and engine technology consists of a Phase I effort that would begin in FY 1983 at a cost of \$48 million and a Phase II program that would be initiated in FY 1987 at a projected cost of \$54 million. With regard to the augmented program,

the committee concluded that the Phase I effort should be undertaken immediately as proposed; and that interpretation and verification of the initial results from the Phase I program should be in hand prior to proceeding with an updated Phase II effort, to the extent deemed necessary at that time.

In addition, if a Phase II program is found necessary at the conclusion of the Phase I effort, it should take into account the latest actual data and forecast trends of the aviation turbine fuel supply-demand situation existing at that time.

In arriving at these primary conclusions, the committee further agreed that a program of research and technological development in aviation turbine fuels and associated propulsion systems should be considered a vital national investment and worthy of continued and expanded support in view of the importance of air transportation to the economic well-being and military defense of this country.

In view of the relatively high cost of large aircraft engine research and development, the committee agreed that such work can best be accomplished by experienced scientists and engineers within NASA who are devoted to the overall rapid advancement of basic and generally applicable aviation turbine fuel and engine technology. This would also implement NASA's legislated mandate to support the national aviation community as a whole, while at the same time providing the industry with the basic developments needed to maintain its preeminence in the increasingly competitive domestic and world marketplace. Such activities support and augment the individual companies' research, development, and test efforts dedicated primarily to resolving technical problems that are a part of the early engine development program. These are also an ongoing important part of advancing the state of the art for a particular new engine design. Later, such funds are devoted to a continuing modification and improvement in economy and performance of a successful aircraft engine series.

In recognition of this, as well as the fact that NASA's research and technology programs in aircraft engines and fuels have in the past resulted in important improvements to current engine technology, particularly during the last 6 years, the committee concluded that NASA's current and planned program in these areas could not effectively be accomplished by any single engine company and that any group of such companies could not do so without the possibility of running counter to antitrust legislation. Although the committee did not address this situation in detail, it could well be a factor requiring further attention in future.

Underlying this view was recognition of the fact that there has been a sudden and probably irreversible 10-fold increase in the cost of aviation turbine fuel during the past decade. This, too, has had a major effect on the continued and earlier rapid increase in the worldwide use of air transportation. There has been an annual aircraft fuel bill of about \$9.75 billion for the 9 billion gallons of aviation turbine fuel consumed annually by the major U.S. air carriers. Under air traffic conditions that prevailed prior to the air controllers' strike, which occurred during the course of this study, it is estimated that each 1-percentage-point improvement in aircraft fuel consumption that can be achieved by the U.S. commercial air fleet up to the year 2000 through use of new technological developments in modified and new aircraft represents a saving of

nearly 1.8 billion gallons of fuel and \$1.9 billion at current fuel prices. Although the NASA alternate fuels program does not seek increased engine efficiency as its principal objective, more fuel-flexible and fuel-efficient new and/or modified engines that incorporate results of other NASA programs, such as the Aircraft Energy Efficiency effort, must be compatible with the turbine fuel available throughout their operational life. Furthermore, since the Department of Defense currently uses more than 6.5 billion gallons of aviation turbine fuel annually, improvements in fuel consumption by military aircraft with no sacrifice in aircraft performance or maintenance would also result in significant savings each year.

## CONCLUSIONS AND RECOMMENDATIONS

The U.S. national master energy plan, although not so specifically stated, is viewed as including the following elements:

1. Greater energy independence will be a continuing objective of the United States.
2. To reduce fuel consumption during this decade, the United States will rely on public and industrial cooperation to ensure more fuel-efficient transportation and more energy-efficient homes, industrial equipment, and buildings and will support further research and development needed to realize cost-competitive forms of alternative fuel production.
3. During the 1990s, synfuels could become available in sufficient quantities to permit a start toward reducing United States dependence on foreign oil, but only if the mining and processing of our large shale oil deposits are given adequate and continuing priority as one of the long-term national goals.
4. Beyond 2000, significant quantities of syncrudes could be available on such a basis and the trend toward increasing use of renewable energy sources could be well under way.

Even should the apparent current stability of the ongoing supply-demand situation for all types of fuels continue into the foreseeable future, the possibility of a future disruption in supply cannot be dismissed. In the face of such uncertainty, the committee considers that a continuing effort in alternative fuels and related aviation engine turbine development by NASA as well as the military services is justified.

### Conclusions

U.S. demand for refinery petroleum products for transportation has slowed considerably, and this trend is expected to continue through the end of this decade. Gasoline demand will make up proportionately less of total refined products demand than it has in the past because of conservation, better automobile gas mileage, and conversion to diesel. The demand for aviation turbine fuel is expected to increase annually by 1.7 percent between 1980 and 1990 and 1.8 percent between 1990 and 2000, and the demand for several

products other than heating-fuel-type middle distillates will also increase.

It is expected that the aviation turbine fuel supply will meet anticipated demand unless an unforeseen world supply-demand dislocation occurs.

The gasoline:distillate ratio is expected to decrease from 1.7 in 1980 to 0.7-1.0 in 2000. In general, estimates of oil availability in the 1980s vary and are uncertain. It is possible that there will be no serious supply problem between now and the year 2000. However, there is a real prospect that economic or political developments, or even natural disasters, can occur that could put oil in short supply.

Several world or national dislocation (risk realization) scenarios are considered plausible. A proper NASA research program will help blunt or negate the effects of such possible incidents.

The prevailing thinking within the petroleum industry is that the U.S. crude slate will involve heavier feedstocks and generally those higher in sulfur content. This trend is expected to continue in the foreseeable future and is likely to be accelerated in emergency situations. Thoughtful national decision-making demands that preparations be made to cope with all reasonable contingencies. If a fuel shortage should occur as a result of a future emergency, the technological developments and operational testing accomplished in advance would aid in determining acceptable variations from the then current turbine fuel specifications without costly modification of equipment or major reductions in aircraft turbine engine service life.

Allowing some reasonable aircraft turbine fuel specification flexibilities combined possibly with some aircraft engine and related fuel system modifications and new refinery processes, it is now considered that adequate aviation turbine fuels can be made available even during moderate world supply-demand dislocations.

Assuming a short supply of oil, it appears that a broader specification for aviation turbine fuel, or one that would permit a higher percentage of selected new crudes to be processed into turbine fuel than current specifications permit, could result in more readily available turbine fuel. It should be recognized, however, that the competitive demands for the middle distillate cut of the barrel of crude--for diesel fuel, heating oil, etc.--will escalate prices for all such products and may deny turbine fuel its share of the middle distillate product slate. In such a situation, aviation turbine fuel can be made available under the present specification, but with greater difficulty and at a relatively higher price. Like all other services and products, air transportation demand varies with price. If the price of air transportation rises too high because of fuel costs, passenger traffic will fall off, thus reducing demand for aviation turbine fuel. In case of a major national emergency, air transportation will be even more critical and equipment that can safely operate on a broadened specification fuel will be vital. However, the costs involved for the refining industry, the aviation

engine industry, and commercial aviation in such a situation are both large and not yet clearly understood.

Although the broadening of the specifications to permit more extensive use of aromatics and other occasional new crude components in aviation turbine fuels can be accomplished if the need is sufficient, the complex interactions involved in doing so are not yet clearly understood. Recent laboratory, field test, and very limited ongoing operational use of turbine fuels that have exceeded the current turbine fuel specification limits in only one of the several characteristics listed in Table C-10, particularly aromatic content, have resulted in increased luminosity during burning, increased smoke and exhaust particulates, and some coking under certain engine operating conditions. Continuing emphasis is required on improving methodologies to qualify new fuels through bench scale tests, component tests, and other relatively smaller scale tests well prior to carrying out the more expensive but essential full-scale engine tests both on the ground and in the air.

For example, in a future emergency situation that would require a sudden broadening of the aviation turbine fuel specification, the use of Jet B instead of Jet A fuels would probably be most practical because some engines and aircraft already are certified for Jet B. However, if such substitution became necessary, critical safety aspects associated with continued use of Jet B would need to be fully investigated.

In addition, new referee fuels are needed to serve as widely accepted standards for qualifying engine and fuel systems components. At present, it is understood that a closely defined worst-case referee fuel is not available, one that has that combination of worst properties that could be allowed for use in modern high-energy-output turbine engines operating on probable future fuels. Such approved referee fuels could be used by the National Aeronautics and Space Administration and the Department of Defense as well as by the engine and aircraft manufacturers in future qualifying test work on the performance of American aircraft turbine engines throughout their operational life.

Future supply-demand deficits can be further reduced by utilizing domestic and imported crudes that are heavier in gravity and higher in sulfur. Refiners will need to install facilities to process these lower quality crudes and, at the same time, provide conversion facilities to increase aviation turbine fuel production. This trend has already started but could be accelerated if turbine fuel specifications were broadened. These combined actions could improve fuel availability and provide more operational flexibility for refiners, but with as yet unknown effect on flight safety and turbine engine maintenance and service life.

## Recommendations

The NASA Research and Technology Base program in aviation turbine fuels is sound but is not sufficient as now constituted to furnish the technological information and data base needed to deal with commercial aviation turbine fuel/engine problems when they arise in the future.

The base program in alternative aviation turbine fuels must continue to emphasize fuel compatibility with current and proposed engines and NASA's continuing work in improving the overall efficiency of turbine engines. Apart from this, the continuing base fuels program must be able to provide critical data required to respond to emergency operational situations involving aviation turbine fuels and turbine engines that might occur as a result of future disruptions in turbine fuel supply. At present, such disruptions would force the expanded use of JP-4 and Jet B fuels certified for use in current aircraft turbine engines. Related problems such as flash point would then need to be addressed. In any case, the uncertainty in the future supply of acceptable aviation turbine fuel is ample reason to continue and augment the NASA Research and Technology Base program in aviation turbine fuels and related areas.

NASA should continue research and technology efforts on commercial aviation turbine fuels and engines and related aircraft and ground-handling systems to permit use of lower quality turbine fuels with minimum penalty in engine performance, service life, and no degradation in flight safety in current turbine engines and their improved derivatives as well as in turbine engines yet to be designed and developed.

An appropriate level of aviation turbine fuel and aircraft engine research, technological development, and testing should be supported to (a) provide the technical data base that U.S. national policy decision makers will need to ensure that national air transportation requirements can be met promptly in emergency situations and (b) facilitate successful use of broadened specification fuel in current and future aviation turbine engines with little or no degradation of aviation engine performance, service life, and safety.

NASA is responsible for providing major contributions to the technological data base needed for decisions concerning temporary waivers or permanent changes in commercial aviation turbine fuel specifications either directly or, preferably, through related appropriate trade-off studies. It is also responsible for maintaining sufficient capability in commercial aviation turbine fuel and engine technology to support foreseeable national needs.

Considerable effort is required to determine the feasibility of using broadened specification fuels in both current and future aircraft fuel systems and engines. Moreover, when aviation turbine fuel properties do not meet turbine engine/aircraft requirements,



additional studies must be made to determine whether the mismatch can be corrected by altering the fuel or modifying the equipment in use. Finally, although primary responsibility for establishing turbine fuel specifications lies elsewhere, for example with the American Society for Testing Materials (ASTM), it is important that NASA continue to provide data for this and related purposes.

NASA should continue its Research and Technology Base program in commercial aviation turbine fuel and related areas, with increased emphasis on specific areas, and proceed to augment the base program with the proposed Phase I effort. The Phase II program should begin only when a continuing assessment of the early progress and preliminary results of the Phase I effort and the fuel supply-demand situation at that time indicate a need for such a program augmentation.

Some aviation turbine fuel properties are approaching critical specification limits. (See Appendix C for the description and several types of general properties of aviation turbine fuels.) There are indications that refinery feedstocks are becoming lower in quality, having heavier components and higher sulfur contents than those previously used. This trend is expected to continue in the foreseeable future and is likely to be accelerated in emergency situations. Aromatic content of crude oils showed a steady increase until 1980 and has slowed since then. A study by Boeing Aircraft Company accurately predicted this possibility, indicating that, although the trend of increasing average aromatic content of aviation turbine fuels would level off, continuing concern about a possible emergency situation suggests the following type of effort is still needed. Such fuel components have varying degrading effects on the performance and/or service life of aviation turbine engines and associated fuel system components. In view of these trends, it is important that essential research and technology be continued to ensure that in an emergency situation, adequate data are available to provide a valid base for the temporary use of some lower quality fuels in existing aviation turbine engines. This is needed to provide a valid assignment of the effects of such fuels on performance, service life, and flight safety effects.

In this connection, several committee members noted that continued use of fuel with properties below and outside current specification limits would likely be more costly over the life of a modern aircraft even if the fuel could be produced at a slightly lower cost. The reason for this is that aircraft turbine engines generally are designed to operate most effectively when using a fuel that meets or exceeds the standard aircraft turbine fuel specification. Tests have shown that extending the current fuel-specification limits are likely to result in increased engine maintenance costs as well as a suspected increase in engine exhaust pollution products such as  $\text{NO}_x$  and smoke.

Recognizing the probability that such wide-specification fuel might have to be used should supply of light crude oil for manufacture of aviation turbine fuel be reduced or curtailed, the committee

considered that it would be useful to analyze on a cost-effective basis the trade-offs between modifications in existing specification limits of aviation turbine fuel and their effect on aircraft performance, operation, and maintenance over the projected life of typical current and proposed aircraft turbine engines. Studies of this type have, in the past, proved successful in producing an improved and more competitive product. Such upgrading, resulting from both NASA's efforts and the aircraft engine industry's own follow-on proprietary work, has led to the successful utilization of domestically designed and produced turbine engines in aircraft developed in this country and abroad.

NASA should continue to provide the broad technological data on aviation turbine fuels and engines needed for decisions concerning possible temporary waivers or permanent changes in commercial aviation turbine fuel specifications, particularly for use during periods of national emergency.

The aviation turbine fuel situation in foreign countries cannot be ignored by the United States. U.S. flag airlines operate worldwide. Foreign countries use American-made aircraft and also operate in this country. However, if scarcity of turbine fuel, specification quality products in foreign countries continues or worsens, the development of technology to handle broader-specification aviation turbine fuels can be helpful in facilitating the use of such fuels in U.S. aircraft operating in those countries and elsewhere. This is an important factor in view of the favorable balance of payments realized from sales of U.S. aircraft in foreign markets.

NASA, in concert with other appropriate agencies in the United States, should maintain an awareness of the aviation problems and needs of foreign countries, particularly with respect to aviation turbine fuel and engine/airframe compatibility so that U.S. technology can react appropriately.

From all indications, there is good communication and exchange of information on existing programs of NASA and the Army, Navy, and Air Force organizations engaged in research and technology on aviation turbine fuels and engines.

The committee agreed, however, that increased coordination and information exchange are essential between NASA and the DOD on aviation turbine fuel and engine activities in the early program-planning stage. This is important to ensure that future programs will be able to achieve maximum productivity from the relatively limited resources available for this work in NASA and the three military services.

NASA, in concert with the Army, Navy, and Air Force, should give greater attention to exchanging information in the early planning stage on proposed programs in aviation turbine fuel and related engine research and technology.

Should the congressionally-mandated NASA aeronautical research and technology program be terminated and industry were to undertake the effort, the committee believes that the work would not be done as effectively. In addition, the results would not be broadly appli-

cable, the cost would be greater, and the government would have no capability for obtaining an objective evaluation of the aeronautics research conducted by the private sector.

If industry should undertake some of the research, it might not be inclined to do it on as broad a base as has NASA. In addition, research and development results obtained by one company would not likely be applicable in others. Furthermore, much of the work would be categorized as proprietary within individual companies so that results could not be broadly disseminated or made available for general use by the industry as a whole. The process probably would not be as effective as the present NASA system, because each aircraft and engine manufacturer would feel compelled to conduct much of the same NASA-type of aeronautical research and development to maintain a competitive position. Duplication of effort would cause greater operating expense for each manufacturer and would be reflected in increased costs of their products and services.

NASA, through implementation of sound and well-conceived programs, should retain its leadership role in stimulating the national aeronautics research and technology effort, involving the industrial, military, and academic elements of the U.S. aviation community.

2  
BACKGROUND

Recent history and projected trends point to considerable uncertainty concerning the future availability, cost, and quality of aviation turbine fuels. (See Appendix C for a description of these fuels.) The average aromatic content of Jet A fuel, the commonly used commercial air carrier fuel, has increased from 16 percent in 1969 to 18 percent in 1979 because of the necessarily increased proportion of high-aromatic crude oils being used as feedstocks as lighter crude availability continues to decrease. The aromatic content is limited to a maximum of 20 percent by the current Jet A fuel specification; however, Jet A produced from some of the available crude oil, such as Alaskan North Slope and heavy Arabian crudes, can exceed this limit. To avoid a shortfall in supply, aircraft turbine fuels with aromatic contents as high as 25 percent are permitted by certification, provided the product in excess of 20 percent is reported to the user. Military fuels allow 25 percent aromatics without special provisions.

Unless U.S. refineries are modified to permit the use of poorer quality feedstocks, the percentage of reportable fuels may increase further. To counteract this trend, the refining industry must add heavy front-end costs to current refinery equipment to improve these poorer quality feedstocks through hydrogenation. Since fuel for aircraft transportation is only 6 percent or so of the barrel, to do so may add to the already high cost of aviation turbine fuel.

The price of aviation turbine fuel has escalated rapidly since 1973. The cost of producing turbine fuel to current specifications may continue to rise even without the addition of costly hydrogenation facilities as less desirable feedstocks necessarily are used and as more energy-intensive refining processes are required. Rising production costs can be an increasing incentive to broaden aviation turbine fuel specifications to minimize refinery energy consumption and reduce total fuel costs; however, these must be balanced against possible increases in aircraft and engine costs, airline maintenance costs, and potential increases in fuel consumption.

The middle distillate portion of the refinery product slate, which represents the boiling fraction that includes kerosene turbine fuel and broadened diesel and heating oils, is predicted to increase from a current share of about 25 percent to between 40 and 50 percent of the slate by the year 2000. As the demand for middle distillates increases, the refineries may be unable to meet it with conventional distillation and the current finishing processes, which maximize gasoline production. The refineries may have to make up the middle distillate shortfall by cracking higher-boiling-point heavy gas oils and residual oils or possibly through a reduced need to produce high-octane gasoline. The heavy gas oils contain larger amounts of aromatic compounds and, therefore, middle distillates produced by cracking

these heavy materials will contain a larger concentration of aromatics than those obtained by conventional distillation of the crude. It would thus be necessary for the refinery to employ hydrocracking (a catalytic process combining cracking and hydrogen addition) or coking to produce current specification turbine fuel. Hydrocracking can be a very energy-intensive process. The thermal efficiency of producing hydrogen required for this process from coal, for example, is only about 55-60 percent. The thermal losses in the production of hydrogen combined with the thermal losses during hydrocracking result in an overall thermal efficiency of less than 50 percent. Hydrogen is currently produced as a byproduct in refineries that employ reforming, a process that upgrades gasoline octane number by hydrogen removal. However, as the refinery product mix shifts to more middle distillates and less gasoline, insufficient by-product hydrogen will be available from the reforming process, and the refinery will have to install new processing equipment to produce the additional hydrogen required for hydrocracking. Specification Jet A produced by hydrocracking heavy gas oil will consume about 1.5-2.0 times the processing energy required in producing Jet A from conventional distillation and finishing processes. The quantity of energy consumed will be even greater to convert alternative liquid hydrocarbon sources, such as oil shale or coal, to current specification Jet A fuel.

Unless refineries incorporate the energy-intensive processes required to upgrade the hydrogen content of the fuel, jet fuels may have higher aromatic content because of (1) changes in available feedstock properties and (2) dependence on cracking of higher aromatic content, higher boiling fractions to increase the distillate fraction. Refineries may be reluctant to install the required processing equipment for a number of reasons: (1) the size of the aviation turbine fuel market and potential "value added" profit may not provide a sufficient return on investment, (2) government environmental regulations may prevent or delay the installation of new equipment, and (3) less stringent specifications of other middle distillate products may discourage refineries from producing specialized fuels such as Jet A. On the other hand, demand for all middle distillate products may provide sufficient incentive for some refiners to install hydrogen-upgrading equipment or for smaller local refineries to market their own product at nearby airport terminals.

However, continued or more severe government environmental restrictions on emission standards for equipment operated with other middle distillate products (i.e., diesel, No. 2 heating oil) could very well cause the refining industry to install processing equipment aimed at better-quality middle distillate products. In that case, the increased processing costs will be spread over a wide range of products.

While the future supply and demand situation for aviation fuels is marked by uncertainty for the foreseeable future, disruptions in fuel supply and/or quality are viewed as likely to occur with increasing frequency. The development of technology that would

permit turbine-powered aircraft to use hydrocarbon fuels with the broadest possible range of properties appears to be a sound approach to greater flexibility and reliability in the supply of aviation turbine fuel in the future and would help provide acceptable alternatives within the next decade or so.

Broadening aviation turbine fuel properties will not necessarily assure an increase in fuel availability. Minimizing processing energy consumed in the production of turbine fuel may permit some increase in total product yield from a barrel of crude, but the turbine fuel users must still compete with the other fuel consumers for their share of the total supply. Nevertheless, the ability to use a turbine fuel produced to less stringent specifications would provide the aviation community with the advantageous flexibility of using fuels that might otherwise not be acceptable.

It is also important that the aviation turbine engines and associated fuel systems to be used in the next major series of commercial transport and general purpose aircraft be able to utilize a fuel produced from crude stocks that are expected to be available during the expected operational life of 15-20 years of such aircraft beginning in the late 1990's. Although this time period would appear to be too remote for current concern, a careful examination indicates that the research, development, and test of improved engine components can take 5-7 years, followed by 3-5 years of intensive full-scale engine development and test, preferably before detailed design of the follow-on aircraft series to the current series of new aircraft recently placed in production here and abroad is undertaken. Meanwhile, the continued dynamic worldwide search for ways to reduce airline operational costs will cause the turbine engine manufacturer to press forward vigorously in the quest for improved critical engine components that, when certified by the Federal Aviation Administration, can and will, no doubt, be retrofitted to existing turbine engines in our own domestic airline fleet and, overseas, in commercial aircraft and turbine engines of American origin.

Although this type of limited development work is often done by the aircraft engine manufacturer for application to a specific series of engines in service and still in limited production, the basic generic work undertaken by NASA and the DOD has been the principal reason why this nation has maintained its preeminent technical lead in the world marketplace for over half a century. NASA should continue to press forward with vigor and foresight in basic and applied research in aviation turbine fuels and engines that can be optimized for use of the fuels expected to be available at least two decades in advance of their prospective operational use.

It is considered essential, therefore, that NASA's proposed plan and program, described elsewhere in this report, be continued, not only on current fuels, at or beyond current specification limits, but also on aviation turbine fuels derived from alternate sources such as shale oil deposits and coal liquids. This is considered particularly important, as these fuels could enter aviation turbine fuel supply channels toward the end of this decade and beyond to an

ever increasing degree. Inherently, this type of research and development work can be accomplished only in an orderly step-by-step development process.

It should also be noted that the degree to which aviation turbine fuel specifications may need to be changed is a complex issue involving (1) interactions between results of essential research, technological development, and flight test of aviation engines and related fuel systems based on fuel blends that will possibly come into common use in later years; of particular importance are those critical engine components most subject to degradation caused by fuel blends verging on and exceeding current aviation turbine fuel specification limits; (2) proposed and potential improvements in the refinery processing of middle distillate fuels from increasingly less desirable feedstocks; and (3) the up-front capital required not only by the refinery industry, but also by the commercial aircraft industry and airlines. The capital requirements cannot be defined, pending trade-offs between increasingly expensive fuel over the operational life of the aircraft, the considerable cost of modification kits needed for existing engines to reduce fuel consumption, and the higher cost of new engines and aircraft more adapted to the new fuels.

An effective research and development program, as discussed in Chapter 3 of this report, might well lead to the ultimate saving of many tens of billions of dollars to be reflected in lower passenger fares over the proposed life of the current and ongoing domestic and worldwide commercial airline fleets and the growing number of general purpose business aircraft utilizing modern turbine engine machinery of the latest type. Such savings would not only aid in reducing the cost of air transportation for the traveling public, more rapid movement of the world's mail, and express and air freight, but also would conserve billions of barrels of turbine fuel in the remainder of this century and beyond.

### History

In the early 1970s, concern rapidly increased over the effects that diminishing domestic oil reserves might have on the future growth of the air transportation industry. In light of this concern, in 1974 the Aeronautics and Space Engineering Board (ASEB) Committee on Aircraft Fuels Conservation recommended, among other things, that NASA devote a significant research effort to the study of future fuels for jet aircraft. As the result of decisions made by the Deputy Administrator of NASA, the NASA Lewis Research Center responded by initiating a research and technology base program on alternative hydrocarbon fuels for turbine aircraft.

This effort was planned to identify the potential allowable range of properties of future turbine fuel derived from either petroleum

or nonpetroleum sources and to determine the effects of varying fuel properties on the performance and durability of the combustors, fuel systems, and other engine components of aviation turbine engines.

As a result of the committee's recommendation urging a joint effort, the Air Force and Navy initiated a complementary program to address future military aviation fuels. The joint program brought together activities of mutual interest to NASA and the military departments associated with both commercial aviation and military aviation turbine fuels.

Since the mid-1970s, the NASA activities in its turbine fuel program have been coordinated with industry by means of NASA symposia and workshops and through NASA participation in various technical committees of the Coordinating Research Council (CRC) and the American Society for Testing Materials (ASTM). NASA workshops on "Jet Aircraft Hydrocarbon Fuels Technology" and on "Fuel Thermal Stability" were held in 1977 and 1978, respectively, to identify specific research needs. NASA also participated in a 1978 NATO/AGARD sponsored lecture series concerned with aviation fuel problems. A NASA symposium was held in April 1980 to review programs and recent results of research efforts in aviation turbine fuel development being conducted by NASA, DOD, and interested groups in industry.

As part of the planning process for an expanded program in aircraft fuels, a special meeting of the Propulsion Subcommittee of NASA's Aeronautics Advisory Committee was held in March 1980 with representatives of airlines, airframe and engine manufacturers, and petroleum refiners to review the current content of the new NASA fuels initiative and provide additional views on the program structure. In general, broad support was expressed for the NASA program by the subcommittee members and by the industry representatives in attendance at the meeting.

Despite the generally broad support expressed for the NASA research effort on alternative turbine fuels, there remained a great deal of uncertainty about the availability of fuel meeting the existing Jet A specification limit, particularly beyond the current decade. NASA has been encouraged by petroleum experts and others to continue its research effort to provide options for future turbine fuel property variations, regardless of the interpretation of the supply and demand trends. At the same time, a need for trade-off studies was recognized, taking into account the interrelationships of such factors as fuel properties, cost, and energy consumption associated with fuel production, engine and fuel system development, operating costs, fuel consumption and efficiency, and performance. A study recently made by the Boeing Aircraft Company focused attention on the probability that the supply of aviation turbine fuel would meet anticipated demands for the next two decades and with current-specification fuel; however, the number of exceptions granted in a future emergency situation would probably need to be increased as a function of likely increased demand for all types of middle distillate products.



To obtain further assistance and guidance on this problem, NASA requested the National Research Council, through its Aeronautics and Space Engineering Board, to examine the agency's plan for its alternative aviation turbine fuels and related engine technology programs to determine their appropriateness and adequacy in the light of projected aviation turbine fuel supply-demand estimates and taking into account other similar or related research and technology programs being conducted or planned by activities outside of NASA.

Consistent with past recommendations, procurements were initiated by NASA during FY 1980 for refinery trade-off studies that would consider a broad range of refinery feedstocks and complexities of refining processes and fuel products as a basis for developing a forecast matrix extending to the year 2010. These data are being used to evaluate trade-offs between aviation turbine fuel properties and refinery yield, energy, and cost. The studies are utilizing the expertise of the petroleum industry as well as established modeling/optimization techniques to evaluate multiple plausible scenarios for aviation fuels and competing products and thereby provide initial guidance for a planned new NASA initiative on alternative fuels.

## TRENDS IN SUPPLY AND DEMAND FOR PETROLEUM FUEL

The committee was not able to perceive a clear or complete national policy that could be used as a backdrop against which to evaluate NASA programs on turbine fuel and engine technology. Thus, the committee proceeded under assumptions that (1) the policy of the United States in the 1980s is to depend entirely on conservation, utilization, exploration, and international availability at a price that will help to keep petroleum supply and demand forces in balance on the supply side; (2) during the 1990s, synthetic crudes would begin to come on line, and foreign oil imports, barring an emergency, would begin phasing down at about the same rate that synthetic crude production would increase; (3) by the year 2000 there would be significant synthetic crude available and energy provided from renewable alternative sources (e.g., nuclear, biomass, solar) would begin to be introduced. This is the fuel supply picture that the committee visualized for the United States.

It was not a committee objective to generate its own projections of supply and demand for turbine fuel as so many such projections already have been made. Consequently, the committee brought together and reviewed several credible forecasts of crude oil production and use in order to develop a consensus on probable scenarios for future supply and demand of petroleum and turbine fuel in the United States. Readers interested in more detailed information on this subject are encouraged to consult the original sources referenced in the Bibliography in this report for the data used in the projections, as well as for further references bearing on other aspects of this report.

The need for alternative fuels is, of course, prompted by the future supply-demand relationship of petroleum fuels. There is current agreement that crude oil supplies will diminish in time, but opinions are more divergent regarding the rate of decrease (none as high as some publicized only a year or two ago), the demand for various products, and when appreciable supplies of synthetic fuels will reach the market.

Barring political, economic, or military crises, most current fuel supply-demand forecasts indicate there should be sufficient total liquid hydrocarbons available through the year 2000. From the supply-demand forecasts presented to the committee, marked deterioration in aviation fuel quality does not appear likely in the current decade. Questions remain with regard to individual products. For example, will gasoline and heating oil usage decrease sufficiently to compensate for the expected large increase in diesel oil demand, and a smaller increase in turbine fuel? Also, what changes in refinery processes will be required?

## Historical Summary and Projection

Since 1973, the world oil supply situation has been in a state of turmoil and uncertainty due to changing political conditions, especially in the Middle East. The shortfall in world oil supplies in 1973 and 1974, occasioned by an embargo and production cutbacks by producing countries, and the accompanying jump in world oil prices first introduced the "energy crisis." The cutbacks were lifted relatively soon, and oil supply-demand balances eased. Then came two serious shocks to world oil supplies: the Iranian revolution in 1979 and the war between Iran and Iraq. Shortfalls in supply--and more important, fear of shortfalls and eventual shortages--sent oil prices skyrocketing. By the summer of 1981, supplies were ample once again and surpluses beginning to appear. Oil prices--particularly prices in spot markets--have been weakening. The supply-demand imbalance and uncertainty are likely to continue at least into the next century. Considering energy efficiency improvement, utilization of other forms of energy, and, possibly, slower economic growth, the world need for petroleum crude should increase less than 2 percent per year for the remainder of this century, with the major increase occurring after 1990. This amounts to an increase of approximately 1 million barrels per day annually. On the basis of this projection, cumulative oil production of approximately 500 billion barrels would be required over the years 1980-2000 to satisfy world oil consumption.

World petroleum production and consumption projections, prepared by the National Petroleum Council in 1980, are presented in Tables 1 and 2, respectively. More recent projections by the American Petroleum Institute (API) and its member companies show reduced U.S. consumption estimates for 1985 and 1990 of about 16.5 million barrels/day (MMB/D) in place of the value of 18.8 million barrels/day as shown in Table 2. U.S. dependency on imported petroleum crude, as evidenced in Table 3 (also National Petroleum Council, 1980), is expected to increase from 4.7 million barrels/day (or 27.9 percent) in 1972 to 8.8 million barrels/day (or 45.8 percent) projected for 1990. Although the 1990 projection includes syncrude derived from shale (coal-derived syncrude production would be insignificant before 2000), a large portion of the domestic petroleum crude supply will depend upon imports. It is anticipated that the supply of oil may continue to be generally tight, and the real price of oil may point upward, with a possible occasional shift in supply-demand imbalance caused by domestic as well as international economic or political factors. Figure 1, prepared from Energy Information Agency (DOE) data, is indicative of the large variation in projected supply estimates from the year 1960 to 2020.

**TABLE 1 World Petroleum Liquids Production Projections  
(millions of barrels per day)**

	Actual		Projected		
	1972	1978	1982	1985	1990
<b>OECD</b>	14.2	14.7	15.9	16.0	16.8
U.S.	11.6	10.8	10.3	10.1	9.9
Canada	1.8	1.6	1.7	1.6	1.8
West Europe	0.4	1.8	3.3	3.8	4.5
Other	0.4	0.5	0.6	0.5	0.6
<b>OPEC</b>	27.4	30.1	30.2	30.8	32.5
Venezuela	3.3	2.2	2.3	2.2	2.2
Indonesia	1.1	1.6	1.7	1.7	1.6
Algeria	1.1	1.2	1.2	1.1	1.1
Libya	2.2	2.0	2.1	2.1	2.2
Nigeria	1.8	1.9	2.2	2.2	2.2
Iran	5.0	5.2	3.2	3.3	3.6
Kuwait	3.1	1.9	1.9	1.9	2.1
Saudi Arabia	5.8	8.3	9.1	9.4	10.2
Iraq	1.5	2.6	3.1	3.5	3.8
United Arab Emirates	1.2	1.8	2.0	2.0	2.2
Other	1.3	1.4	1.4	1.4	1.3
<b>Non-OPEC</b>	3.4	4.7	6.8	8.0	10.1
Mexico	0.6	1.3	2.6	3.1	4.2
Other	2.8	3.4	4.2	4.9	5.9
<b>Subtotal</b>	45.0	49.5	52.9	54.8	59.4
<b>Sino-Soviet</b>	9.0	14.0	14.8	15.6	17.3
<b>Total</b>	54.0	63.5	67.7	70.4	76.7

SOURCE: National Petroleum Council, "Refinery Flexibility," 1980.

**TABLE 2 World Petroleum Consumption Projection  
(millions of barrels per day)**

	Actual		Projected		
	1972	1978	1982	1985	1990
<b>OECD</b>	37.5	41.4	41.4	42.5	43.3
U.S.	16.4	18.8	18.4	18.8	18.9
West Europe	14.1	14.6	14.6	14.8	15.3
Other	7.0	8.0	8.4	8.9	9.1
<b>Non-OECD</b>	7.3	10.0	12.0	13.1	15.9
<b>Subtotal</b>	44.8	51.4	53.4	55.6	59.2
<b>Sino-Soviet</b>	8.0	12.2	13.9	15.4	17.2
<b>Total</b>	52.8	63.6	67.3	71.0	76.4

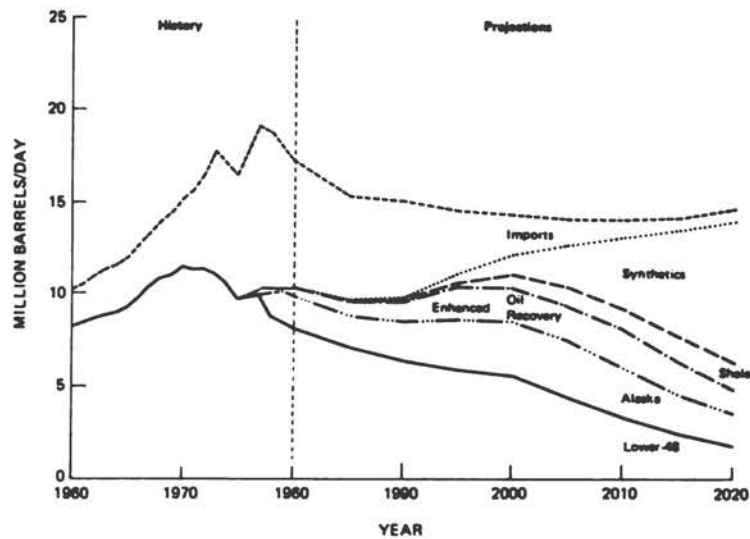
SOURCE: National Petroleum Council, "Refinery Flexibility," 1980.

**TABLE 3 U.S. Petroleum Supply Forecast (millions of barrels per day)**

	Actual		Projected		
	1972	1978	1982	1985	1990
<b>Domestic Production</b>					
Crude Oil and Condensate	9.4	8.7	8.3	8.2	8.0
NGL	1.7	1.6	1.5	1.4	1.3
Syncrude Production	0.0	0.0	—	0.1	0.5
<b>Subtotal</b>	11.2	10.3	9.8	9.7	9.9
<b>Imports</b>					
Crude and Unfinished Oils	2.3	6.4	6.4	6.8	6.6
Products and NGL	2.4	2.0	2.0	2.2	2.2
<b>Subtotal</b>	4.7	8.4	8.4	8.9	8.8
<b>Processing Gain and Stock Change</b>	0.7	0.5	0.5	0.5	0.5
<b>Total Petroleum Supply</b>	16.8	19.2	18.8	19.1	19.2

SOURCE: National Petroleum Council, "Refinery Flexibility," 1980.

FIGURE 1. Liquid fuels supply/crude.



Trend in Crude Oil Type

Table 4 shows actual and projected supply of high-sulfur and low-sulfur-content crude oil between 1969 and 1990. In 1969, sweet crude oil made up 64.5 percent of total crude oil refined in the United States. It is projected to decrease to roughly 40 percent in 1990. This trend is likely to continue to the year 2000.

TABLE 4 Sweet/Sour Crude Oil Supply Projection (millions of barrels per day)

	Actual		1978		Projected		1985		1990	
	1969		MMB/D	%	1982	%	MMB/D	%	MMB/D	%
	MMB/D	%	MMB/D	%	MMB/D	%	MMB/D	%	MMB/D	%
<b>Domestic</b>										
Sweet	6.1	57.0	4.9	32.5	3.9	26.6	3.7	24.8	3.6	23.8
Sour	3.1	29.0	3.8	25.0	4.4	29.9	4.5	30.2	5.0	33.1
Subtotal	9.2	86.0	8.7	57.5	8.3	56.5	8.2	54.0	8.6	56.9
<b>Foreign</b>										
Sweet	0.8	7.5	3.3	22.0	2.8	19.0	2.8	18.8	2.4	15.9
Sour	0.7	6.5	3.1	20.5	3.6	24.5	3.9	26.2	4.1	27.2
Subtotal	1.5	14.0	6.4	42.5	6.4	43.5	6.7	45.0	6.5	43.1
<b>Total</b>										
Sweet	6.9	64.5	8.2	54.5	6.7	45.6	6.5	43.6	6.0	39.7
Sour	3.8	35.5	6.9	45.5	8.0	54.4	8.4	56.4	9.1	60.3
Total	10.7	100.0	15.1	100.0	14.7	100.0	14.9	100.0	15.1	100.0

SOURCE: National Petroleum Council, "Refinery Flexibility," 1980.

## Trend in Product Demand and Supply

Table 5 shows actual and projected product demand between 1978 and 1990. It is generally expected that an increasingly larger proportion of world oil consumption will be used for transportation, owing to the absence of any other major competing fuel. These demand projections may be considered optimistic based on FAA current forecasts of civil turbine engine aircraft activity.

The marketplace will have a strong influence on the mix of products coming from the refineries. In the United States, demand for gasoline has always exceeded that for the middle distillates; this relationship should change markedly and will probably reverse in time should the relative proportion of diesel fuel and gasoline change in favor of diesel. Most refineries outside the United States produce more distillates and heavy fuels than gasoline.

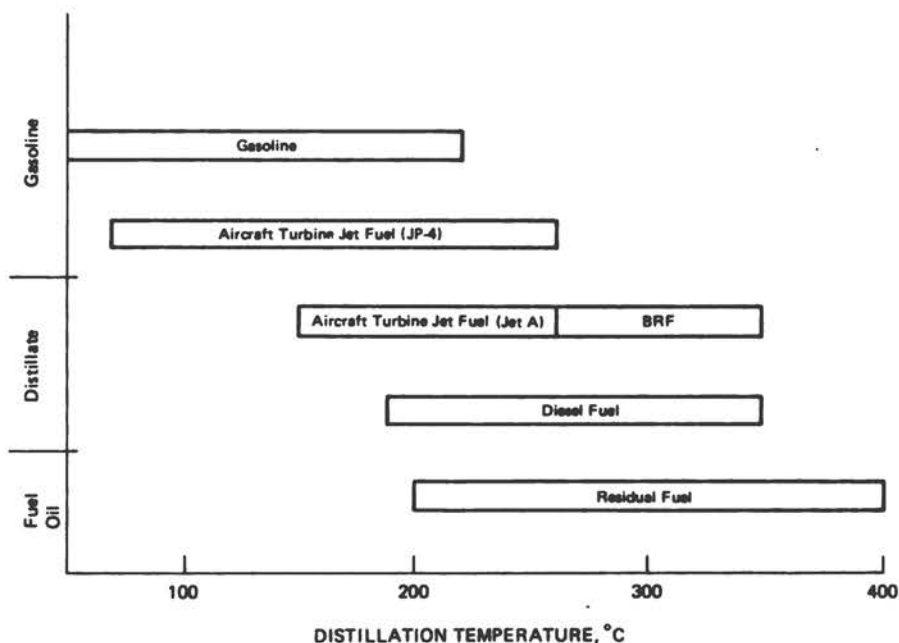
The principal products discussed in this report--gasoline, distillates, and heavy fuel oil--have overlapping distillation ranges, as shown in Figure 2. The limits shown are dictated by product specifications. A typical crude will contain less than 50 percent of cuts boiling below 350°F, while the demand for such lighter products as noted in Table 5 exceeds 80 percent of the total demand. Consequently, cuts boiling above 350°F (i.e., gas oils and residuals) are cracked into these lighter products.

TABLE 5 Domestic Product Demand Projection  
(millions of barrels per day)

	Actual 1978	1982	1985	1990
Motor Gasoline	7.4	6.9	6.7	6.1
Jet Fuel: Naphtha type	0.2	0.2	0.2	0.1
Kerosene type	0.9	0.9	1.0	1.2
Special Naphtha	0.1	0.1	0.1	0.1
Kerosene and Heating Oil #1	0.2	0.2	0.2	0.2
Distillate Fuel Oil	2.4	2.2	2.2	2.1
Diesel Fuel	1.0	1.2	1.5	2.0
Residual Fuel Oil	3.0	2.6	2.6	2.3
Liquefied Gases	1.4	1.6	1.7	1.8
Petrochemical Feedstocks	0.6	0.8	0.9	1.1
Miscellaneous	1.6	1.7	1.7	1.9
<b>Total Domestic Demand</b>	<b>18.8</b>	<b>18.4</b>	<b>18.8</b>	<b>18.9</b>

SOURCE: National Petroleum Council, "Refinery Flexibility," 1980.

FIGURE 2. Distillation range of major fuel products (typical initial and final boiling points).



Note that JP-4 fuel is largely blended from gasoline fractions, while Jet A light diesel fuel and heating oil share the same distillation range. The kerosene-type distillate represented by Jet A must also be blended into residual fuel for viscosity control to provide a suitable product for burning under boilers. The cross-hatched area of the Jet A bar represents the extension of its distillation into the higher boiling range of diesel fuel. This is the principal broadened specification jet fuel referred to in this report as offering increased potential availability.

Table 6 shows that late 1979 projections of several organizations who are constantly updating estimates of turbine engine jet fuel (Jet A) demand for the years between 1979 and 2000, derived from data published by the National Petroleum Council, Federal Aviation Administration, Commerce Department, and Chevron, Exxon, and Shell Corporations. Military demands, published by the Department of Defense, are included on these commercial projections for comparison. The DOD data in Table 6 represent only consumption of military aviation turbine fuel within the continental United States. The aviation kerosene fraction is approximately 40 percent of the total DOD jet fuel consumption shown in the table.



**TABLE 6 Kero-Jet-A Demand/Consumption in Continental United States  
(1,000 barrels per day)**

	1979	1980	1985	1990	1995	2000
DOE/(EIA)	822	875	791	893	893	963
FAA		816	822	912		
Commerce	833					1,200
NPC	('78) 858	892 (est)	1,034	1,203		
Chevron		842	845	875		911
EXXON		800		1,193		1,250
Shell		800	825	1,000		
<b>DOD All Jet CONUS Only</b>						
Peacetime		201	209	207		
Limited Engagement (Vietnam)		400	418	414		
Major War		703	732	724		

It is significant to note in Table 7 the wide variation in the 1990 projections of domestic crude oil and natural gas liquids production, made by 17 different sources and compiled in a recent report by the American Petroleum Institute. The studies reviewed for the report show a potential 1990 range of 5.3 to 11.4 million barrels a day of crude oil and natural gas liquids production. A majority of the estimates fall within a range of 8.5-9.7 million barrels a day.

**TABLE 7 Comparison of Current Forecasts of 1990  
Domestic Production Crude Oil Plus Natural Gas Liquids  
(millions of barrels per day)**

Gulf Oil Corporation	8.3-11.4
Professor Edward Erickson	10.0
National Academy of Sciences	7.5- 9.9
Data Resources, Inc.	9.8
Department of Energy-P&E	7.1- 9.7
Chase Econometrics	9.7
Department of Energy-EIA	9.0- 9.6
National Petroleum Council	8.5- 9.4
PIRIWC	9.0
Bankers Trust	8.7
Congressional Budget Office	8.6
Standard Oil Company of California	8.6
Shell Oil Company	8.6
Arthur D. Little, Inc.	8.5
Texaco, Inc.	8.2
Office of Technology Assessment	5.3- 7.6

SOURCE: American Petroleum Institute, "Two Energy Futures: A National Choice for the 80's," May 1981.

Both suppliers and operators should prepare for the advent of synfuels, whether from coal or shale. Characteristics of such fuels that might effect airplane or engine design and operation should be investigated by NASA.

SUMMARY OF VIEWS OF INDUSTRY REPRESENTATIVES  
ON ALTERNATIVE AVIATION TURBINE FUELS

In order to obtain as broad a perspective as possible on the future supply and demand of jet fuel, representatives of the industries involved in the production, supply, and use of turbine fuel were invited to present their views. At two separate meetings (April 22-24 and June 2-4, 1981) in Washington, D.C., representatives of the petroleum, airframe, aircraft turbine engines, and airline industries; government agencies--DOE, FAA, DOC, NASA, Army, Navy, Air Force--and the National Petroleum Refiners Association made presentations to the committee. The following sections summarize the views of industry representatives on the committee.

Petroleum Industry Members' Views

In the next 20 years, the United States will face particularly difficult problems in supplying transportation users with adequate liquid fuels, as U.S. crude production from the lower 48 states is expected to continue to decline. This will be only partially offset by expanded production from Alaska and the Outer Continental Shelf. Crude imports of one-sixth to one-third of total requirements could still be needed by the year 2000, depending on how rapidly a synthetic fuel industry is established. In that regard, some recent estimates suggest that synthetic liquids from shale and coal could grow to 10 percent of the input to refineries by the end of the century.

The U.S. refining industry currently consists of about 300 refineries operated by 174 companies, of which 20 companies with 114 refineries have 75 percent of the total capacity of 18.5 million barrels/day. These 20 companies plus about 17 other small refiners have adequate processing capability for military and civilian turbine fuels. However, kerosene-type turbine fuels for civilian use are produced almost entirely by the 20 companies, each of which has a refinery capacity larger than 200,000 barrels/day.

Today, because of reduced product demand, the U.S. refining industry is operating at only about 70 percent of capacity compared with a normal 90 percent. As a consequence, a number of smaller, uneconomic refineries are being shut down. (Seven closings were announced in May 1981 alone.) This trend is expected to continue as loss of high-quality crude and shifts in product demands make small refineries too expensive to convert or to operate.

Kerosene-type aircraft fuels are particularly sensitive to the continued dependence on petroleum because of their critical specifi-

cation requirements (as compared with other middle distillate products) and the shifting pattern of U.S. demand for transportation fuels from gasoline to distillates. The principal distillate to experience a growth in demand is diesel fuel, with the increasing numbers of diesel-powered buses, trucks, and passenger cars; a compounded annual growth rate of 5 percent is expected. Aircraft fuel demand is expected to show a 2 percent annual growth rate. While heating oil demand is expected to decline, the net overall effect on distillates is about 1.9 percent annual growth.

The expected decline in gasoline demand from its recent 6.6 million barrels/day level to about 4.2 million barrels/day by 2000 as cars become more fuel-efficient or convert to diesel engines will have a dramatic effect on petroleum refining. The U.S. refining industry, traditionally organized to maximize gasoline production--the ratio being about 1.7 barrels of gasoline for each barrel of distillate--faces the prospect of a reversed product pattern of about 0.9 barrels of gasoline per barrel of distillate. A higher middle distillate:gasoline production ratio is common in most foreign refineries.

Moreover, overall domestic crude availability is expected to decline by 1-2 million barrels/day, and the market for residual fuels will dwindle as other more available fuels replace petroleum for electric power generation.

How the petroleum industry will respond to these changing patterns of crude input and product demand is illustrated by the current example of Pascagoula refinery of the Chevron Oil Company. Faced with the prospect of refining a heavy high-sulfur crude, Chevron has installed conversion and hydrocracking capacity to minimize yield of heavy fuel oil and maximize yield of middle distillates. The investment, at a cost of \$1 billion at one refinery, has not increased overall capacity and is only justified because of lower crude cost (light crudes usually carry a premium price) and a greater yield of higher valued products.

The declining quality of marginal crudes, of which heavy oils and bitumens are examples, is reflected in the declining quality of kerosene cuts from which jet fuel is made. The principal quality deficiency is the hydrogen:carbon ratio, resulting in higher aromatics content of turbine fuel. The trend of increasing aromatics in turbine fuel, begun in 1973, may well continue unless processing steps are installed either to extract aromatics or hydrogenate them. Increasing the distillation range of kerosene fractions to include more heavy ends will increase turbine fuel availability but will also increase aromatics. Higher aromatic content leads to increased luminosity during the burning process. This in turn leads to higher metal temperatures, which are already critical. To offset this condition, it is necessary to operate at reduced engine power settings to accept reduced service life of hot section components.

On the other hand, the inclusion of more light ends in the kerosene fraction, limited by flash point, has the opposite effect of lowering aromatics. Incidentally, it is evident that flash point

flexibility exists at present because pipeline operators have imposed arbitrary flash point limits on turbine fuel moving to terminals and airports.

Unfortunately, there is increasing competition for the products in the boiling range of kerosene turbine fuel. For example, the automobile industry is suggesting the use of a lighter diesel cut for trucks and cars to meet environmental requirements. Another pressure on kerosene as a blending stock is created by moves to lower the sulfur content of diesel fuel. At the same time, the needs of the air transport industry must continue to be met. Thus, both availability and quality of aviation fuel will be under threat during the next few decades.

Because the United States will remain so heavily dependent on crude imports during the next 10 years, the National Petroleum Council, in its role as an adviser to the government, has recommended measures to cope with import disruptions of varying severities. Most of the shortfall in products would be taken in motor gasoline. Some of the gasoline fractions would be blended into aviation fuel to increase availability about 20 percent merely by having refineries blend to 38°C flash point specification instead of the 44°C flash point currently in effect for pipeline shipments. Under the most severe case studied--total crude import cutoffs from the Middle East, i.e., a 3.2 million barrels/day loss to the United States and a 7.8 million barrels/day loss to the rest of the Free World--aviation fuel would still be produced to 85 percent of normal demand, although refineries would be operating at only about 60 percent of capacity.

By the year 2000, the United States should be considerably less vulnerable to a loss of crude imports if the synthetic fuel industry has developed to the extent now expected. Nevertheless, under an emergency scenario involving crude cutoffs in this time period, aviation fuel supplied to civil transportation would require either military fuel (Jet B) or broadened specification kerosene-type fuel involving some heavy ends normally blended into diesel fuel.

The processes to make more distillates by cracking heavy feedstocks are expensive and energy-intensive. A thermal conversion process uses minimum energy but produces distillates lower in hydrogen (i.e., higher in aromatics and olefins). A hydrocracking process uses additional energy and produces products still containing aromatics but low in sulfur and olefins. In either case, it is possible to upgrade the kerosene jet fuel by additional hydrogenation, if this last step is necessary. Meeting current specifications for jet fuel aromatic content obviously carries an economic penalty, the size of which depends on the extent to which investments and operating costs are incurred for producing the desired hydrogen level. Thus, from either source--cuts from marginal crudes or conversion processes--the kerosene jet fuel is deficient in hydrogen and will tend to become a more costly product to manufacture to current standards.

A favorable impact on jet fuel prices might result from broadening specifications due to the combination of increased potential

supply and lower refining costs. With the full functioning of world-wide free market competitive forces, prices of jet fuel, as well as other petroleum products, would reflect refining costs and the balance between supply and demand.

It will be necessary for users of jet fuel and other distillates to compete for these products. Competitive pressure will increase as demands increase and would be further aggravated if quality requirements for passenger car diesel fuel were made more stringent. Broadening of specifications will permit jet fuel users to compete more effectively with users of other distillates. Broadening of specifications could lower refining costs and permit existing suppliers more price latitude in competing for turbine fuel business, but might also provide incentive for new suppliers to enter the business. All these factors will increase the supply base and help users negotiate more attractive prices; however, until recently there had been no negotiation of fuel prices since early 1973.

Of the synthetic sources that will supplement petroleum crude, shale oil is the most attractive as potential jet fuel. Several shale projects are under way now in western Colorado, and, by the year 2000, shale alone may provide 8 percent, about 1.3 million barrels/day, of the projected input to U.S. refineries. Most of the plants will involve on-site upgrading of the kerogen removed from shale rock to provide a suitable syncrude for pipelining to a refinery. The upgrading involves arsenic removal and hydrotreating to remove nitrogen and sulfur. The result is a paraffinic crude superior in many ways to typical petroleum crudes. For example, the low yield of residual oil from upgraded shale oil means that less conversion capacity is needed to make distillates from it than from petroleum crude. The jet fuels producible from shale syncrude--JP-4 or kerosene-type--are equal or superior to jet fuels from petroleum. Upgrading shale rock to high-quality syncrude is an expensive process in capital investment and operating costs, as it involves hydrogenation.

A look ahead to the next century clearly suggests increasing replacement of petroleum by synthetic crudes from shale or coal. Transportation will require all the liquid products not devoted to petrochemicals or specialties. Although the most significant long-term U.S. energy reserve is coal, the liquids from coal will be better suited for gasoline than for jet fuel, because they are even more hydrogen-deficient than heavy oils and bitumens. Nevertheless, the available resources of shale and coal provide assurance that alternative aviation fuels will be available for the next century when petroleum's dominance is ended.

In this connection, wide use of coal liquids for this purpose may be delayed because of currently projected high costs for converting some types of coal into feedstock liquids that can be refined to meet the aviation turbine fuel specification. Continuing research on process development can help to ameliorate this situation.

## Aircraft Industry Members' Views

The aircraft components that are affected by turbine fuel properties are fuel tanks; fill, vent, delivery, and scavenge pipelines; transfer pumps; fuel quantity gaging; and fuel temperature sensors. It is important to ensure that the fuel properties, if changed, will not adversely affect the operation of the fuel system or the engine.

Before examining the effect on aircraft systems of changing existing turbine fuel specifications, it is important to note that the detailed specification requirements, although numerous, nevertheless define only a limited number of the fuel's properties. Other physical and chemical properties also influence the fuel's compatibility with the engine and airframe. Unspecified properties--lubricity, conductivity, dielectric strength, and hygroscopicity, to name a few--can cause problems in compatibility with the airframe. Problems caused by these unspecified properties often are detected only during in-service operation of the airplane. Frequently, solution of these problems is achieved by modifying the materials of the airframe fuel system or requiring an appropriate fuel additive.

NASA's involvement in this class of problems should be in the fundamental research part of the Research and Technology Base program. Here the fuel characterization, i.e., the fuel properties dependent on crude stocks, and the interaction of the fuel with other materials can be determined.

The elements of the turbine fuel specifications with the greatest influence on availability and perhaps on turbine fuel price are flash point, vapor pressure, freezing point, and end boiling point. The freezing point, which is related to the end point and the crude stock composition, influences the lower temperature operation of the airplane. The concern caused by increasing the freezing point is that, as an airplane operates for extended periods at low ambient temperatures, the fuel will begin to solidify, impairing the capability of the fuel system to supply fuel to the engines. The magnitude of the problem depends primarily on the ambient temperature encountered during flight, the duration of the flight at low temperatures, and the geometry of the fuel tanks. Airplanes operating over short ranges, at low altitudes, and having large tanks with greater volume-to-surface ratios have less critical freezing point problems. Small business jets flying long ranges have greater problems.

An increase in freezing point temperature could result in more frequent flight diversions to lower altitudes or greater Mach numbers. Such diversions can result in reductions in fuel-burn efficiency and in the ability to accept altitude changes within the air traffic control system, and can create flight safety problems. If the frequency of diversion is significant, some remedial actions might be considered to reduce it. These include:

- o Development of better data to correlate the freezing point of fuel and the onset of fuel delivery problems in aircraft fuel systems.

- o Installation of fuel temperature sensors in aircraft that operate in low-temperature environments to indicate the need to alter flight altitude or aircraft speed when extremely low fuel temperatures are encountered.

- o Installation of a temperature-sensitive fuel-pumping system that would circulate the fuel within or between fuel tanks to keep it from solidifying when extremely low ambient temperatures are encountered.

- o Development of a low-temperature atmospheric model to better predict the frequency of low-fuel-temperature encounters.

If a significant increase in freezing point becomes necessary or is desired to assure turbine fuel availability and to reduce the cost of jet fuel, more extreme measures are required to solve the problem. Pasion and Thomas (1976) examined several methods for heating fuel in airplane fuel tanks. They concluded that significant rises in freezing point (10°C to 20°C) are possible with "moderate" change in the airframe. Such in-flight changes could consist of adding heat to the fuel by using air conditioning bleed air, engine fuel oil, accessory oil, or electric power as a heat source. In addition, a source of ground-based heat is essential if fuel stocks used for refueling drop to close to freezing point prior to or during refueling operations.

Incorporating a fuel-heating system in an airframe during the design stage can be accommodated with only small penalties beyond the added weight and complexity of the system itself. On the other hand, retrofitting that same change in an existing airplane can be extremely difficult and costly and, in some cases, practically impossible. Since fuel tank heating systems entail cost and weight, there must be evidence that the cost of the airframe changes will be justified by lower fuel-burn costs.

It has been estimated that a 10°F increase in jet fuel freezing point will permit up to a 20 percent increase in jet fuel availability. A 20°F decrease in jet fuel flash point is estimated to permit as much as a 10 percent increase in availability of jet fuel. However, the tolerance of the airplane and its engine to changes in freezing point and flash point is considerably different. A small increase in freezing point could be made without a change in the airframe, provided the actions described in the earlier discussion were taken. Such an increase in freezing point is likely to result in some increase in the number of flight diversions to accommodate low fuel temperatures. On the other hand, problems created by a large increase in freezing point could be very difficult to overcome because of the major modifications and resultant high cost that



might be required to accommodate low fuel temperatures, especially in existing aircraft.

Problems associated with relaxation of the turbine fuel flash point are easier to resolve, but not without risks. Commercial turbine-powered airplanes are normally certified to operate with JP-4, JP-5, Jet A, Jet A-1, and Jet B. Table 8 compares the freezing and flash points of the types of fuels mentioned above and other important characteristics.

TABLE 8 Important Characteristics of Aviation Turbine Fuels

Specification Limits	JP-4	JP-5	Jet A	Jet A-1	Jet B
Freezing Point, °F (°C)	-72(-58)	-51(-46)	-40(-40)	-52(-47)	-58(-50)
End Point, °F (°C)	-	554(290)	572(300)	572(300)	-
Flash Point, °F (°C)	-	140(60)	100(38)	100(38)	-
Reid Vapor Pressure, psi	2-3	-	-	-	2-3

A more productive specification change for increasing jet fuel availability is to lower the flash point. There are virtually no major aircraft or airframe system problems associated with current lower flash point fuels. A typical flash point for JP-4 (and Jet B) is 0°F; for Jet A, 100°F is typical. In any case, there are public concerns about fuel handling and crash survivability that would have to be dealt with before the flash point specification could be changed, since flash point is one measure of flammability.

Fuel volatility properties, which are specified in part by vapor pressure and are related to the lower distillation temperatures, have an effect on airplane operation. Fuel pump performance can be severely affected by rapid vapor evolution. A combination of lower fuel flow rates, high fuel temperature, and high altitude increases the possibility of developing vapor lock in the fuel delivery lines. These pockets of vapor start to form at high points in the fuel lines and can prevent the delivery of fuel to the engine. It is possible to minimize the problem through use of vapor bleed lines that delivery vapor to the engine fuel pump. Relaxation of a broadened fuel specification's vapor pressure limit would increase the occurrence of vapor formation and require recertification of the airplane.

A more important fuel volatility effect is boiling of the fuel within the fuel tanks. This occurs with a hot fuel at altitude. The loss of fuel can be significant. For a commercial transport (based on results from Pasion and Thomas), approximately 3 percent of the fuel load can be lost on an extremely hot day (1 day per year representing a 0.3 percent probability) with a turbine fuel having a

vapor pressure of 10 psi for above-current-specification levels. This example is for a fuel with a relatively high vapor pressure. A fuel boil-off of 3 percent on a 0.3 percent probability hot day is less than 1 percent when averaged over the year. Thus, the problem created by increasing the specification vapor pressure, although appearing to be small, then becomes a significant cost factor when all airline operations are considered. Modification of the aircraft fuel system by fuel tank pressurization to reduce boil-off (see Appendix C--JP-3 fuel), although possible, is not desirable because of the complexity of such pressurization systems, the effect on wing fatigue life, and the increase in fire hazard.

In ground storage prior to physical transfer to aircraft fuel tanks, environmental control aspects concerning vapors from high-vapor-pressure fuels in ground storage also increases capital investment and operating expenses for suitable vapor recovery systems. Though the amount lost in this way in fuel stored and transferred to aircraft is small, several state and local governments have taken action to reduce or prevent this source of environmental pollution.

The effect on the airframe of broadened aviation turbine fuel specifications can be summarized as follows:

- o A small increase in freezing point might be accommodated without airframe change. Larger increases require hardware changes that could be particularly difficult for retrofit. However, the modifications themselves generally tend to be within the present state of the art.
- o Lowering the flash point to the levels of JP-4 requires no changes in the aircraft or engine.
- o Increases in the turbine fuel vapor-pressure limit should not go beyond the point at which the costs of boil-off fuel losses are no longer compensated by lower fuel costs.

#### Large Aircraft Turbine Engine Industry Members' Views

Broadening turbine fuel specifications in the direction of diesel fuel or heavy ends generally leads to decreased hydrogen content, increased aromatic and naphthalene content, and decreased volatility, fluidity (i.e., increased viscosity), and thermal stability. Government and company-sponsored turbine engine and component tests have clearly shown that these changes in fuel chemistry and/or physical properties significantly reduce combustor-liner life, increase smoke and chemical emissions, reduce ignition and relight envelopes, and increase carbon deposition and the fouling of fuel nozzles. Important questions also have been raised about

deleterious effects on combustion efficiency, hot section erosion and corrosion, and fuel pump wear.

It should be noted that broadening in the direction of gasoline or light ends has no known negative effect on the engine proper. This change will, however, reduce the flash point of the fuel and increase fuel flammability, which under certain circumstances may compromise flight safety.

Because the life cycle of turbine engines is so long, the adverse effects of changing fuel specifications are liable to persist far into the future. Most of the engines that will be flying in the year 2000 are already under development or in production, and introduction of brand new technology for a fuel-tolerant engine would take about 10 years. The warranty situation for commercial and military aircraft engines also considerably complicates the consequences of using nonspecification fuels in service. All these factors place a premium on anticipation of and preparedness for likely changes in fuel composition.

On the positive side, the engine manufacturers have identified several promising approaches that would reduce or eliminate the harmful effects of fuel alterations. These include techniques to reduce the temperature and/or increase the durability of combustor parts, improve the stoichiometry of the combustion process, enhance the atomization of fuel sprays, and reduce the exposure of liquid fuel to destabilizing heat loads. Several of these ideas are being incorporated in experimental engines (e.g., the NASA Energy Efficient Engine and the DOD Advanced Turbine Engine Gas Generator programs), and many can be retrofitted into existing engines, although at the expense of increased cost, weight, and complexity of the engine, some too complex for practical operational use.

In the event that the petroleum industry supply situation provides strong incentives for change, several requirements must be met to permit sensible decisions and systematic planning for engine management. To begin with, it must be known how existing and development aircraft turbine engines will respond to foreseeable changes in fuel composition. Further, suitable fuel-tolerant technology must be understood and proven in detail. This will require at least full-scale demonstration testing. Finally, since unknown future fuel properties are the basis of these problems, it would be highly desirable to make early identification of a target (i.e., likely or perhaps worst-case) blend, similar to the NASA Experimental Referee Broad Specification Fuel. It would then be possible to construct a program that would allow engines to be qualified to burn that fuel within a specified period of time and, in fact, to give overall direction to the propulsion industry in quantifiable terms. It is strongly recommended that the latter course of action be followed, if possible.

Other points are worthy of mention in this section with regard to the large turbine engine industry. First, turbine fuels derived from shale oils thus far made available for engine testing have met existing specifications and revealed no operational differences.

The jet engine industry is, therefore, optimistic about this potential source of aviation fuels. Second, the nature of turbine engine development is such that confidence finally rests upon performance in actual service. In the interest of all parties concerned, provision for this must be made if any alteration of aviation fuels is contemplated.

#### Small Aircraft Turbine Engine Industry Members' Views

Concerns for future usage of alternative fuels in small turbine engines as applied to general aviation turboprops and turbofan fixed-wing aircraft, helicopters, and auxiliary power units (APU) are primarily related to the prospect of heavier fuels with increased aromatics and lower hydrogen content, which tend to cause increased soot/carbon formation, exhaust smoke, and degradation of hot section durability. Other changes in fuel properties such as increased viscosity, higher distillation temperatures, and reduced thermal stability can also present problems associated within sufficient atomization for low-temperature/high-altitude starting, reduced combustion efficiency at low power, and fuel nozzle plugging, respectively.

Combustion systems in most small turbine engines differ from the conventional straight-through-flow type used in the large high-thrust engines. Many small engines employ a reverse-flow annual combustor and, in the case of one manufacturer, a single, aft-mounted can-type combustor is employed. The fuel injection systems generally consist of one or more pressure atomizers or airblast nozzles. In some of the smaller gas turbine engines, the fuel is injected into the inner periphery of the combustor by a rotating slinger.

Smaller turbine engines with high surface:volume ratios in combustors can be more sensitive to heavier turbine fuels with regard to engine durability and performance than larger high-thrust engines. Large surface area:volume ratios present greater difficulty in cooling the combustor walls as flame radiation increases from the higher concentration of soot/carbon formed in burning the more highly aromatic fuels. Also, small engine turbine blades tend to be relatively more sensitive to erosion due to carbon particles in the gas stream. Furthermore, the small fuel atomizer sizes used in smaller engines are less tolerant to internal deposits that can form as a result of thermal instability of the fuel and cause plugging of critical flow passages. Plugged fuel nozzles can cause wide variations in the turbine inlet gas temperatures that severely degrade hot section durability.

The combustion development approaches best suited to provide greater fuel flexibility with small gas turbines are those that retain the basic simplicity of this class of engine and are largely refinements in the current designs, such as optimization of fuel:air

ratio distribution, more thorough mixing of fuel and air, improvements in fuel atomization, more effective combustor wall cooling, and increased energy for ignition. The development process leading to accommodation of broadened properties in turbine fuels becomes complicated by possible conflicts in design; for example, a lean, well-mixed primary zone to reduce smoke formation normally would be expected to impair the lean limit of flame stability. Thus far, the effects of these design changes on small combustors have been assessed only to a rather limited degree as compared with the more extensive program efforts expended on the combustion systems for large engines.

General aviation aircraft and helicopters operate out of major air terminals as well as the many small airports and unimproved landing areas that have limited refueling facilities. Consequently, small turbine engines are quite likely to encounter the need to use alternate fuels as substitutes in emergency situations. In addition to the approved civil aviation turbine fuels (Jet A, Jet A-1, and Jet B), many small turbine engines are approved to use aviation gasoline for limited flight operation. Also, special purpose (e.g., agricultural) aircraft are certified for use of diesel fuel over limited flight envelopes. In this respect, the small aircraft turbine engines may be able to provide some advance information, based on flight experience, and on fuels with broadened properties beyond current specification limits. However, sufficient records are not yet available to assess adequately the effects of alternate fuels on engine durability.

The low fuel consumption of small turbine engines offers a decided advantage over large engines with respect to the lesser quantities, and attendant lower costs, of experimental fuels required for long-term evaluation of hot section durability effects. However, over all, the test certification costs of alternative fuels for small turbofan, turboprop, turboshaft, and APU engines will be substantial because of the wide variety of engine models and many aircraft installations involved.

#### Airline Industry Members' Views

Because the world air transportation system has been and will continue to be dependent on liquid hydrocarbon fuel, and with no alternative fuel source available in the quantities required, the airlines were forced to absorb the 10-fold increase in cost of turbine fuel since 1973. This, in turn, has dramatically increased airline operating costs. These, together with escalated labor costs, have been reflected in increased air fares. Although there have been dips in airline traffic in the past, recent total airline traffic has decreased even in spite of deregulation. This could be

indicative of public reaction to fare increases, even though this nation has become increasingly dependent on air transport for most personal trips longer than 500 miles.

With regard to relaxation of fuel specifications:

1. The airlines should be able to tolerate a rise in freezing point if given sufficient time to modify long-range airplanes. Meanwhile, refiners might take advantage of the margin that exists between average freezing points of fuel as delivered and the current specification limit to increase availability. Freezing points must remain below ambient ground temperatures to facilitate refueling and permit overnight layovers.

2. The average flash point of fuels as delivered is well above the specification minimum. Closer adherence to specification limits could presumably increase availability. While no changes in aircraft or engines would be required to tolerate small decreases in flash points until current specification limits are reached, decreases below these limits could reduce operating safety. Experience with JP-4 exhibited potentially greater hazards than with Jet A; perhaps they would be even greater with a mix. Although airlines may still use JP-4, and probably would in a national emergency, its earlier use was abandoned because of several accidents and public pressure. The airlines would not like to return to use of JP-4, and any reduction of fuel flash point below 100°F should be approached with extreme caution for reasons of safety.

3. Refiners have suggested that further increases in the aromatic content of fuels could improve the availability of turbine fuel. Combustion of fuels with more aromatics produces higher metal temperature, particularly in the combustor wall, and more smoke in the exhaust plume. The turbine engine operates at very high temperatures; small temperature increases can cause a disproportionate reduction in the useful life of hot section parts. These parts comprise the most expensive part of the engine. If it proves necessary to permit increased aromatic content to make sufficient turbine fuel available, research to improve tolerance to higher temperatures while continuing to meet smoke regulations would be in order.

4. When the demand for finished fuels is close to or greater than the feedstocks available to the refiners, as has occurred in recent years, the number of fuel samples at or near specification limits in certain critical fuel properties increases and can cause ongoing and long-term increased smoke and maintenance problems, particularly in engines well along in their service life. However, modifications of operating procedures, and certainly of fuel specifications to allow for such contingencies, is not considered acceptable.

With the drive for greater fuel efficiency, care must be exercised that improved tolerance to fuel specification relaxations does not increase fuel consumption or fuel and hot part deterioration rates.

Research efforts on broader specification fuels should give priority to engines currently in operation or committed to production. If changes in fuel specifications could permit development of more-fuel-efficient engines, great emphasis should be placed on such lines of research.

5  
SUMMARY OF GOVERNMENT  
RESEARCH AND TECHNOLOGY PROGRAMS  
ON  
AVIATION TURBINE FUELS

Aviation turbine fuel is manufactured and procured to specifications that set limits on selected physical and chemical properties of the fuel that have been found to be critical to the successful use of the fuel in various aviation turbine engines and aircraft, including commercial, general aviation, and military types. Such specifications are set out to assure that all fuels conforming to them can safely be used without harm to the specified types of engine and aircraft and that the quality of any fuel used in those engines and aircraft will be maintained within the specified narrow limits without regard to the source of the fuel.

NASA, through its research and technology programs, has played a major role in providing to the aviation community a base of technical data and information on the interaction of aviation turbine fuels, engines, and airframes. This information, provided to the agencies having responsibility for development of turbine engine fuel specifications, is a significant contribution to such developments.

At the same time, as a result of over half a century of working cooperatively with industry and academe, NASA has developed a series of technical publications that transmit the results of its ongoing research, exploratory development, initial flight test, and related technical work in a form that has been most useful to interested elements of industry and academe, as well as other potential users. Scientific and technical reports generated by NASA, both within its own research and test centers as well as by contracts or grants to industry and academe, have established a recognized standard of excellence for such work.

NASA periodically arranges tours of its research centers and conducts workshops and seminars in which its scientists and engineers report on their work principally to representatives from industry, academe, and other government agencies. In addition, small teams of highly qualified NASA engineers and scientists are occasionally invited to visit aerospace companies that request special training or updates on activities within the centers. This material includes information on important new work under way in NASA. Such information exchange often contributes to more rapid progress in the development of successful commercial aeronautical products. Many companies have been able to use information from NASA on new work in a proprietary way to form the basis for development of new or improved products that has enabled them to compete more successfully in the domestic and international aeronautical product marketplace.

The overall effort required to assess the feasibility of using broad-property turbine fuels in both in-service and future aircraft



fuel systems and turbine engines is considerable. Engine performance and durability over the expected service life of the aircraft must be evaluated to ensure component and system reliability, maintainability, safety, and environmental acceptability with the use of these fuels. Furthermore, it is necessary to consider economic and engineering trade-off factors that take into account the effects of fuel property changes on: (1) projected turbine fuel supply and relative cost; (2) refinery energy consumption, processing requirements, and return on investment; and (3) investment modification and operating costs for both current and future transport and general-aviation-type aircraft. For current in-service aircraft, it is important to establish the degree to which turbine fuel properties may be varied from those currently in use without resorting to prohibitively costly equipment modifications or having to accept significant reductions in service life or increases in fuel consumption, but with no reduction in safety.

A long lead time is required to obtain and successfully transfer research and technology results into practical applications. NASA has conducted an increasingly productive research and technology program on aviation turbine fuels and related propulsion systems. This program, which has accelerated particularly since the advent of the Organization of Petroleum Exporting Countries (OPEC), is intended to provide technical data needed as a basis for improvements in aircraft turbine engine performance and service life and safety despite use of aviation turbine fuels derived from raw crudes of lower quality and more complex composition.

The NASA effort consists of a Research and Technology Base Program and a proposed augmentation program that would have two phases. Each of these is described below, together with a brief description of similar programs being conducted by the three military services.

#### National Aeronautics and Space Administration Programs

The overall objective of the NASA alternative fuels program is to evolve the advanced technology needed to permit broadened property fuels, as refined from petroleum and alternative sources, to be used in current and future commercial and general aviation turbine-powered aircraft.

All the relevant influences that affect fuel consumption cost and supply are not well understood at this time. As more experience is gained in analyzing the interrelationships involved, the supply-demand factor in worldwide fuel pricing will be dealt with more systematically and with better effect for the consumer. One important factor in certain of the ongoing calculations is the vital data base NASA supplies to engine and airframe manufacturers, as well as to interested airline operators. This information will also aid the turbine fuel-processing industry in arriving at investment and operating decisions relating to manufacture of aviation turbine fuels.

In this connection, the committee agreed that NASA also has an important responsibility to provide a sound and objective technology data base for the decision makers in government who are primarily responsible for establishing policy, regulations, and specifications for aviation activities. In order to meet its responsibility competently and effectively, it is essential that NASA maintain a continuing program of aeronautics research to keep its staff engaged at the forefront of new research and technological development, which benefits all users.

Typical problems associated with the fuel composition/aircraft interaction considered by the committee in assessing the NASA program are described below.

#### Hot-Section Deterioration and Performance

Problems involve liner heating and damage and formation of deposits that break off to cause turbine vane and blade erosion and also cause temperature field deterioration from spray nozzle deposits. Emission of smoke must be minimized. Relevant fuel properties are aromatics content, hydrogen content, aromatics boiling point and structure, and thermal stability.

This class of problems is complex and susceptible to control by both added capital and process costs in the refining of increasingly heavy crudes and the need for consequent advancements in combustion and fuel system technology. A general goal should be, at least, to match current engine durability and performance with fuels of minimally modified specifications.

#### Fuel Freezing Point and Pumpability

These problems limit the inclusion of high-boiling-point material in the fuel blend. Control by exclusion of high-freezing-point fractions or by fuel heating requires further study, but at a lower level priority than hot sections problems.

#### Fuel Flash Point

While lowering fuel flash point is probably the most effective means of reducing fuel cost and increasing supply, there are logistic problems in delivering specification flash point fuel as well as operational safety problems in reducing flash point below current specifications. Such problems do not appear to require a major research and technology program at this time. However, setting flash point below current levels does not prevent the trend toward increasing aromatic content of turbine fuel, but does start to come to a point of diffusion that will call for a technical solution. Hence, suitable research and development may be required at a later date.

In addition to the above general comments, following are the more specific assessments of the principal elements of the NASA

overall Research and Technology Base program on aviation turbine fuels and engines.

### Research and Technology Base Program

The objective of the NASA Research and Technology Base program is a fundamental knowledge of the characteristics of aviation fuels and their effects on the performance, durability, reliability, and safety of airframe and engine components and systems. Fuels characterization research at present focuses on extending our limited knowledge of the probable range of properties of predicted future turbine fuels, as well as providing better understanding of the interrelationship of fuel-property characteristics and the chemical composition and molecular structure of such fuels.

The program also focuses on identifying and tentatively evaluating advanced generic subcomponent-component technologies that will serve as the technology base for improving performance, durability, and fuel flexibility in future combustors and aviation turbine fuel systems. In this work, special attention is being given to new and improved fuel injector concepts, liner-cooling technology, advanced materials, fuel-heating problems, and advanced combustor concepts. NASA's Research and Technology Base program has in the past resulted in continuous and important improvements in aviation turbine engines, and will continue to do so as a consequence of the supportive program of research and development described above.

In view of the uncertainty underlying the future supply-demand situation of aviation turbine fuels, NASA has proposed an augmentation of the Research and Technology Base program that would focus on alternative aviation turbine fuels. In view of the long lead time required to move a new aircraft design from research through development to production, certification, and early operation, it is essential that the Research and Technology Base program on fuels and engine components be accelerated if it is to have any substantial effect on the next generation of commercial and general aviation aircraft. This is also true to a lesser extent in the development of modification kits for engines in current operational use in order to ensure compatibility and improve engine performance and fuel efficiency.

Those features of the present NASA Research and Technology Base program that appear to be of most relevance to the proposed augmented fuels program are the NASA pilot plant capable of catalytically hydrogenating small quantities (1 liter) of subspecification hydrocarbons to produce aviation turbine fuel, the fuel characterization and testing programs to correlate physical properties and combustion mechanisms, and the combustion component studies.

The current NASA program represents an impressive buildup of capability during the last 6 years. Contributions of basic knowledge and preliminary assessments of technological approaches to fuel-related problems are being made; however, the level and scale of the effort are not adequate to define quantitatively the technological

options and trade-offs needed for the period beginning in the late 1980s and extending beyond the 1990s. Study of the complex fuel combustor system, for example, requires an augmented effort, in the judgment of the committee.

#### Phase I Program: An Augmentation

The program was proposed to have two phases, the first of which was to be initiated in FY 1982 with two major targets: (1) to establish a data base and assess the extent to which in-service aircraft engines and fuel systems can use broadened property fuels refined from heavier crudes with higher sulfur content or from alternative sources; and (2) to evolve and evaluate advanced generic technical concepts to permit use of such broadened property fuels by future aircraft.

The need to expand the existing fundamental research to achieve increased fuel availability and flexibility was stated as the main purpose of an augmented program. This objective would be accomplished in the Phase I effort by implementing the following:

Systems Analysis: This includes an extensive fuel properties sensitivity study involving all segments of the aviation industry--airframe manufacturers, engine manufacturers, airlines, and fuel suppliers. An appropriate data base will be developed. The magnitude and timing of this effort seems reasonable. The scheduled early completion of the fuel trend and trade-off studies is important in establishing background on cost and supply sensitivities relating to fuel composition.

Test Fuels: This program would define research fuels, characterize them, and acquire sufficient quantities to permit extensive component and engine testing.

Definition and acquisition of test fuels is a necessary component of the proposed experimental program. It is an appropriate and adequate effort although it is difficult to make a judgment on the proper cost and scope of effort at this time.

In-Service Engine/Fuel System Assessment: This phase of the work would involve extensive component and engine testing. Potential problem areas would be identified and appropriate information used to expand the data base to prevent recurrence of these problems in typical operational usage of turbine engines.

Because of long fleet life of aircraft and engines, an adequate data base on major in-use systems is essential. A Department of Defense (DOD) program focused on use of aviation turbine fuel in military aircraft will complement this work and close coordination and information exchange should continue to be maintained between the NASA and DOD programs.

In addition to measurement of liner temperature and related problems, deposit formation and subsequent shedding should also be

studied. Similarly, effect of fuel composition on formation of nozzle deposits has been identified as an important element of durability and requiring study.

An optimum strategy for carrying out engine durability studies is of special importance, as cyclic durability studies are very expensive and applicable only to a particular engine configuration. While the program focus should be on the causes of deterioration, it was agreed that well-chosen cyclic tests should be made. Some of this work should also be done during the earlier programmed component technology development program.

This part of the program is appropriately focused on the high-priority durability and emission aspects of the engine fuel interaction.

Component Technology Development: Technology to resolve problems and to provide improved performance and flexibility will be studied and the new components tested.

The goal of acquiring a data base that will allow commercial development of practical combustors capable of matching the durability of current engine fuel systems is strongly endorsed. Emphasis is to be placed on establishing the full potential of single-stage combustor designs that are compatible with present and planned advanced engines.

Fuel System Technology Demonstration: New components will be integrated in a complete system and the unit tested.

The program on aviation turbine fuel systems is considered to be of lower priority, as a substantial technology base exists for dealing with aviation-turbine-fuel-system-related problems.

In the program on aircraft fuel systems, priority should be given to a study of the effect of fuel composition on freezing point and viscosity and on the response of elastomers and sealants to fuel composition. Better techniques for modeling atmospheric temperature and its interaction with fuel temperature are also needed. Where state-of-the-art technology is available for design of aviation turbine fuel systems, studies by NASA in this area are currently of low priority.

#### Phase II Program: An Augmentation

The second phase of the program, planned for initiation in FY 1986, has as its major target the verification and demonstration of advanced technologies in full-scale component, engine, and fuel system tests.

Specific outputs from the two-phase program would include: (1) determination of the impact of broadening turbine fuel properties on aircraft engine performance, life, and emissions; (2) establishment of a data base on refinery and air transportation sensitivities to broadening properties of turbine fuel; and (3) evolution of advanced fuel-flexible aircraft engine technology, including the development

of retrofit technology. This information will be intended to enable turbine fuel users to better define acceptable fuel properties for in-service aircraft during supply emergencies and to establish optimum fuel properties for the future based on technical and economic constraints and on supply availability.

The Phase II program is, by its nature, dependent on the results of Phase I and is, therefore, less clearly defined. The committee believes that early interpretation of Phase I results and further consultation with appropriate industrial and government groups, as well as updated information on the aviation turbine fuel supply-demand situation, would be required to justify and to properly define the scope and substance of Phase II, an expensive but vital effort. NASA should plan to investigate the need to conduct extensive full-scale engine tests on a case-by-case basis, taking into account military requirements as well as industrial full-scale test capability and programs.

#### NASA Program Funding

The committee agreed with the allocation of funds proposed for NASA's Research and Technology Base program and Phase I of the augmented program as outlined above. Figures 3 and 4 include these elements, as well as the proposed cost of Phase II on System Technology Demonstration. Although, as stated, the committee consensus calls for further work on the first two elements of the program prior to commitment on Phase II, the committee agreed that independent full-scale engine and aircraft fuel system tests should be performed to the extent necessary to verify expected improvements in fuels, propulsion systems, and components expected to result from the continuing Research and Technology Base program and a carefully integrated Phase I program. Further details of this program are included as Appendix B.

Figure 3. Fuels R&T funding profile.

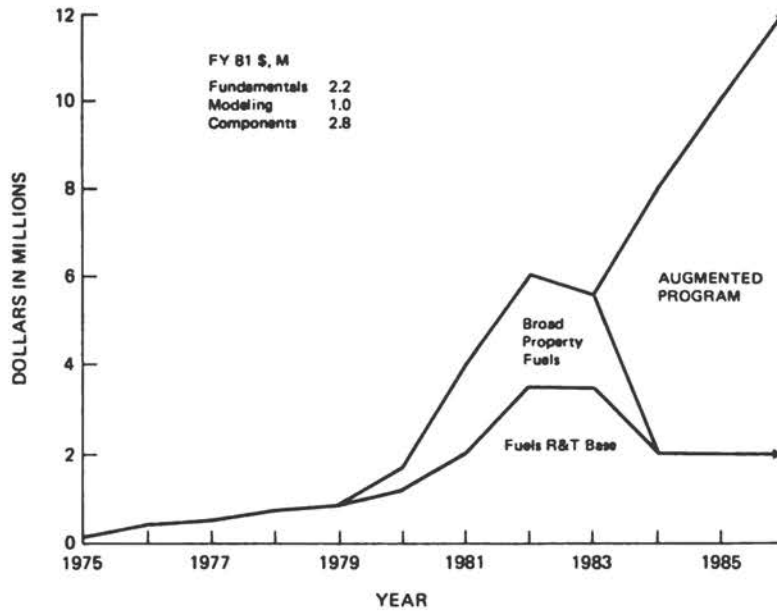
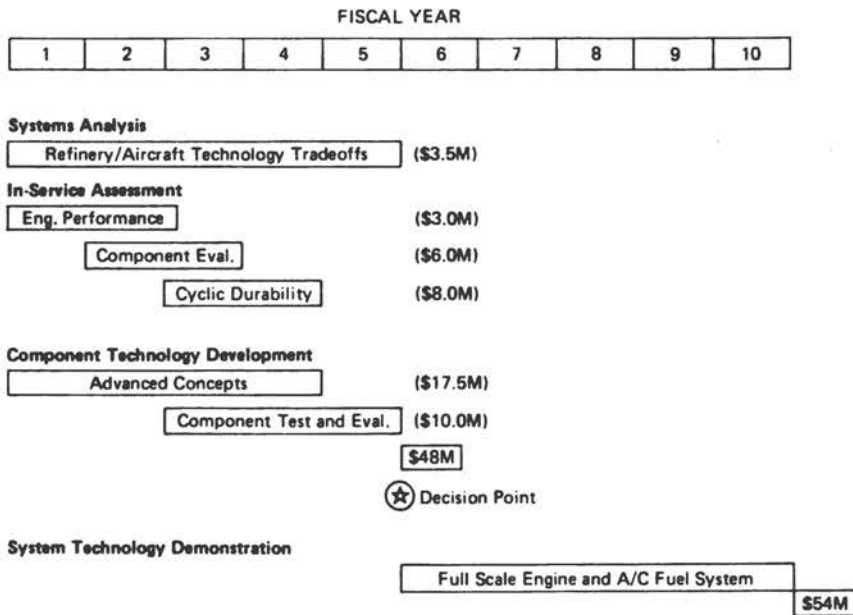


Figure 4 Augmentation Program.



## Department of Defense Programs

The DOD uses large quantities of aviation turbine fuels--6.5 billion gallons in FY 1981. The principal consumer is the Air Force, which currently is using about 240,000 barrels/day. There is concern about the future quality, quantity, and availability of these fuels for use in aircraft demanding peak performance. To resolve these concerns, the military services have embarked on an extensive program of aviation turbine fuels research and technology. These have received increased funding in the past few years. These programs have as their objective the following:

- o Evaluation of the tolerance of existing aeropropulsion and related fuel systems to a wide variety of fuel properties and the identification of alternate fuels that can be qualified in existing equipment and that lead to a larger pool of potential fuels and fuel sources.
- o Development of methods, procedures, and equipment modification leading to increased fuel economy.
- o Development of new and faster fuel qualification procedures.

It is clear that all but a few of the research programs funded by the military are intended to accomplish these objectives without substantial retrofitting of existing equipment. It should be noted that the operation and maintenance requirements for aviation turbine engines used in military aircraft are different from the requirements of turbine engines used in commercial aircraft. As a result, special research and development effort is required by the military to support its exacting flight missions. Such requirements emphasize high performance under rigorous combat conditions rather than economy of operation, long operating life, and passenger safety which constitute the basic requirements for commercial aircraft.

All the military services have active programs evaluating shale-derived fuels. The early results have been encouraging, but extensive testing of the type required for complete turbine engine and fuel system qualification is difficult because sufficient quantities of fuel are not readily available. This program includes a full range of research component testing, full-scale engine evaluation, safe-to-fly tests (delayed by unavailability of test fuels), and, finally, operational validation.

Another program of interest to the committee is the Aviation Research and Development Command (AVRAD COM) research sponsored by the Department of the Army. This work includes a study of the effects of broadened fuel specifications on combustor and turbine performance for smaller turbine engines.

The unclassified results of the extensive research program under way in aviation turbine fuels in each military service have been shared with NASA and made available to the aviation industry. As



most of the research is unclassified, the results can be used without delay when they are pertinent.

At the same time, it should be noted that the differences between commercial and military aviation operations--characterized, for example, by commercial aviation's major concern with increased flight safety, longer engine life, and better fuel economy--make it necessary that the military services, as well as NASA, support separate but well-coordinated research and technology programs directed toward meeting the special and different needs of commercial and military aviation.

The committee judged that the coordination of the on-going programs of NASA and the DOD is basically sound and vitally important, but there is room for improvement in the coordination of proposed research during the early planning stage.



## APPENDIX A

### STATEMENT OF COMMITTEE TASK AND METHOD OF IMPLEMENTATION

#### Committee Task

In response to the request of the National Aeronautics and Space Administration, an ad hoc committee was formed by the Aeronautics and Space Engineering Board to assess the appropriateness and adequacy of the current and planned NASA Research and Technology Base program in alternative aviation turbine fuels and its relationship to somewhat comparable programs of the Department of Defense and other government agencies.

Several critical aspects of the problem were considered:

- o the general outlook for future aviation turbine fuels, i.e., future supply and demand for these fuels relative to the competing middle distillate refinery products (heating oil, diesel fuel, etc.);
- o the effect that broadening aviation turbine fuel specification limits will have on overall availability of such fuels;
- o the turbine fuel properties/characteristics most likely to be affected when using synfuels or lower grade petroleum crudes;
- o turbine engine and aircraft fuel system technology required to enable aviation turbine engines to accommodate a range of properties likely to be encountered in the future.

Within this general task statement, specific questions were posed for consideration by the committee. These were:

- o Is there a fuel-supply/demand problem?
- o What is the magnitude of the problem?
- o Is the ongoing NASA Research and Technology Base program adequate?
- o What should be the scope and pace of an expanded program?
- o How far should NASA carry technology development?
  - component technology?
  - full-scale demonstration?

In addition to consideration of the specific issues and questions, the committee also addressed the following two related issues having to do with coordination and exchange of information on the

aviation turbine fuel and engine research programs of government and industry:

o Is there adequate coordination between NASA and other government agencies (DOD/USA, USN, USAF; DOT/FAA; DOE) involved in the aviation turbine fuel supply-demand and research technology areas?

o Do existing mechanisms ensure adequate exchange of information and coordination of effort between government and industry in turbine fuel and engine research and technology? If not, what recommendations can be made for improvement?

### Methodology

To accomplish its task, the committee received briefings and reviewed currently available information, projections, and assumptions regarding supply and demand of turbine fuel and other products competing for the same fraction of middle distillate feedstock. From the above information, the committee postulated a general outlook that, in its view, described the most likely situation regarding quality and quantity of turbine fuel for the foreseeable future.

With this as background, the committee reviewed and evaluated the current and planned NASA programs in alternative aviation turbine fuels and related engine technology to determine whether the programs were appropriate and adequate, taking into account similar or related programs being conducted by aircraft engine and airframe companies, the petroleum industry, and other interested industrial, academic, and government organizations.

Changes were recommended in the NASA programs that, in the view of the committee, would enhance the effectiveness of the NASA effort to solve or prevent anticipated problems in jet aircraft propulsion systems caused by variations in fuel specifications that might be necessitated by future imbalances in aviation turbine fuel supply and demand.

## APPENDIX B

### SUMMARY OF KEY QUESTIONS

The five questions and answers presented here summarize the findings of the committee with respect to the key issues considered in this report.

#### Question 1. Is there a fuel supply-demand problem?

There will be problems in meeting demands for aviation turbine fuels during the next 20 years and longer, but these problems will relate more generally to shortages of petroleum for all products and to shifting product yield requirements than they will specifically to shortages of turbine fuel. The committee considers two scenarios.

A "normal" situation can be anticipated with reasonably adequate supplies of petroleum available from domestic and foreign sources. However, conservation of energy and the high cost of petroleum will reduce total refinery crude runs and will force a change in refinery product yield distribution. Lower quantities of motor gasoline and residual fuel oil will be in demand, and higher yields of middle distillate products, including kerosene-type turbine fuel, will be required. Most existing refinery processing capability for conversion of heavy fractions is designed for increasing yields of motor gasoline and may not be usable to obtain significant improvement in yields of turbine fuel and other middle distillates. More extensive use of hydrocracking, in combination with more residuum conversion, probably will be required to increase yields of turbine fuel and other distillate products. The fact that available crudes are becoming heavier further increases the need for new processing investments. In this "normal" situation, modifications in turbine fuel specifications to permit the use of heavier or more aromatic components could improve supply in individual refining or short-term situations, but would not be very significant in distillate/turbine fuel supply because the increased yield of turbine fuel would come at the expense of other distillate products unless more hydrocracking is done in the future.

The second scenario is the "emergency" situation in which a disruption in worldwide crude availability causes a severe shortage in the United States. If aviation turbine fuels were assigned a disproportionate share of the available petroleum, either by economic or arbitrary means, a broadening of product specifications probably would be necessary. The use of Jet B instead of Jet A fuels would probably be most practical, first because this would have a large effect on supply availability and second because engines and aircraft already are certified for Jet B, although safety aspects would need to be considered.

Modifications in turbine fuel distribution practices and in specifications to permit the use of lighter components could improve supply availability. This benefit of increased yield would come at the expense of gasoline, which is expected to be in long supply in contrast to distillates. Adding lighter components lowers the flash point, but provides increased yield to the extent that flash point can be decreased below the current specifications of 100°F (38°C). New problems arise, primarily in handling and safety, because there is limited commercial experience base for use of fuels of this type.

Military turbine engine combat aircraft have a wider range of extremes for operational performance requirements, have shorter operational life expectations, and have far less time between overhaul than commercial or transport aircraft. Because of this, the experience gained by the military in using JP-4 fuel is insufficient to predict with confidence the results of using JP-4 in commercial service, where as much as 60,000 hours of average operating life for aircraft is expected at very high utilization rates.

In the event of a national security emergency, it would be vital to have a JP-4 data base for use in planning and executing the operation of the Civil Reserve Aircraft Force (CRAF), utilizing commercial transport and cargo aircraft for military missions.

The complexities of turbine fuel properties and their potential impact on engine components, together with the uncertainty of future petroleum supply sources, greatly affect the nature of the fuel supply-demand problem at the present time.

Alternative sources of turbine fuels and other petroleum products, such as shale oil or coal liquids, will not be significant as volume or quality considerations until at least 1995-2000.

#### Question 2. What is the Nature and Magnitude of the Problem?

Because of the decline in total crude reserves and increasing demands for distillates, including turbine fuels, relative to other refining products, the total yield of distillates based on crude is expected to increase about 35 percent during the next 20 years. Moreover, this trend is expected to continue beyond the year 2000. This changing product demand presents a significant requirement for modified new refining facilities.

While forecasts of product demands in the long term vary considerably, there is substantial agreement that gasoline and residual fuel demands will decrease and distillate demands increase. There is full agreement that quality of crude feedstocks will decrease. Both factors imply that specification quality turbine fuel will be maintained only by processing at higher cost than at present. The problem of adequate supply of turbine fuel must be considered in the context of demand for all middle distillate products.

Unlike the short-term outlook, broadening the specification by increasing use of light ends for turbine fuel is unlikely to improve yield or quality in the long term, simply because industry will have to overcome the current barriers that prevent refining to the flash point specification limit. On the other hand, broadening the specification by increasing use of heavy ends has possible cost and availability benefits. The quality deficiencies that accompany increased heavy ends--higher aromatic content and freezing point--can both be overcome by increased refining at higher cost. The broadened specification should permit normal market forces to operate in offering aviation turbine fuel of lower cost to users, but this may not always happen because of other economic factors affecting fuel price. For example, this has not occurred in the past few years when airlines have paid the same or higher prices for "reportable" fuel that did not meet the ASTM D-1655 Jet A specification with regard to aromatics, smoke point, and/or freezing point. Until government price controls were removed in early 1981, normal market forces did not operate in connection with airline fuel prices.

The emergency scenario of a crude feed disruption has not been analyzed in depth for the year 2000 time frame. Refiners then may have no alternative for protecting aviation turbine fuel supplies except to offer increased light ends, increased heavy ends, or both. Jet B is an obvious emergency fuel, and a lowered flash point kerosene deserves full investigation. However, the existence of the capability to burn a broadened specification fuel containing increased heavy ends underscores the importance of this concept in meeting emergency, as well as normal supply situations of the future.

Question 3. Is the Ongoing NASA R&T Program Adequate?

The current program represents an impressive buildup of capability during the last 6 years. Contributions of a basic nature and preliminary assessment of technological approaches to fuel-related problems are being generated; however, the level and scale of the effort is not adequate to quantitatively define the technological options and trade-offs needed for the late-1980 to post-1990 period. Study of the complex fuel combustor system, in particular, requires an augmented program.

Question 4. What should be the scope and pace of an augmented program?

This question was addressed by study of the proposed Phase I and Phase II programs.

Phase I            5 years        \$48 million

Systems Analysis                                    \$2.2 million

The magnitude and timing of this program seems reasonable. Early completion, as scheduled, of the fuel trend and trade-off studies is important in establishing background on cost and supply sensitivities relating to fuel composition.

Test Fuels \$3.5 million

Definition and acquisition of test fuels is a necessary component of the proposed experimental program. It is appropriate and adequate, although the cost and effort are difficult to predict at this time.

In-Service Data Base and Assessment \$17.0 million

Because of long fleet life, an adequate data base on major in-use systems is essential. A DOD program focused on military aircraft will complement this work.

In addition to measurement of liner temperature and its related problems, the problem of deposits formation and subsequent shedding should also be studied with respect to combustor durability and turbine erosion.

Similarly, the effect of fuel composition on formation of nozzle deposits was identified as an important element of durability and worth study.

An optimum strategy for carrying out engine durability studies is of special importance, as cyclic durability studies are very expensive and their results are difficult to interpret. While the program should be focused on the causes and prevention of deterioration, it was agreed that well-chosen cyclic tests should be made. Some of this work should also be done in the component technology development program.

This part of the program is appropriately focused on the problems of engine durability and the degradation of performance with increased operational service, which results in higher visibility of unburned particulates in exhaust emission.

Component Technology Development \$26.1 million

The goal of acquiring a data base that will allow commercial development of practical combustors capable of matching the durability of current engine fuel systems was strongly endorsed. Emphasis was placed on establishing the full potential of single-stage combustor designs that are compatible with planned advanced engines.

The \$5.5 million program on aviation turbine fuel systems was considered to be of lower priority, since a substantial technology base exists for dealing with aviation turbine fuel system problems.

In the program on aviation turbine fuel systems, priority problems should include study of the effect of fuel composition on freezing point and viscosity and on the response of elastomers and



sealants to fuel composition. Better techniques for modeling atmospheric temperature and its interaction with fuel temperature are also needed. Where state-of-the-art technology is available for design of aviation turbine fuel systems, studies by NASA in this area are of low priority.

Phase II is, by its nature, dependent on the results of Phase I and is, therefore, less clearly defined. Early interpretation of Phase I results and participation of related industrial and government groups in definition of the Phase II program are required.

Overall, the program matches the needs and priorities for research in this area, as indicated in the body of the report.

Question 5. How far should NASA carry technology development?

New technologies should be demonstrated to the point where the information acquired will allow use of those technologies in the development of commercial engines. An example is the testing of new combustor fuel combinations in full-scale engines in order to establish sufficient confidence to allow incorporation in commercial development programs. Such programs are compatible with the findings and recommendations of the ASEB workshop on the role of NASA in aeronautics.<sup>1</sup>

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<sup>1</sup> The Role of NASA in Aeronautics--A Workshop, 7 volumes.

## APPENDIX C

### AVIATION TURBINE FUELS-- TYPES AND GENERAL PROPERTIES

The following section presents descriptions of various types and general properties of aviation turbine fuels currently in use in U.S. commercial and military turbine-powered aircraft.

#### Types

##### 1. JP-1 Through JP-4

The history of aviation turbine engine fuel dates back to 1944, with the introduction of JP-1. This  $-76^{\circ}\text{F}$  freeze point fuel, having a  $300^{\circ}\text{F}$ - $500^{\circ}\text{F}$  boiling range, could not be produced in sufficient quantities to meet military requirements. In an effort to increase availability, a wider cut fuel, JP-2, was authorized in 1945. JP-2 was used only for experimental purposes as viscosity restrictions limited its production. The availability problems posed by JP-1 and JP-2 resulted in the adoption of JP-3 in 1947. JP-3 was produced by blending gasoline with kerosene. It was found that, while fuel requirements could be met, the relatively high Reid vapor pressure of 7 psi caused excessive losses in the order of 20 percent by venting of liquid and vapor in high-rate-of-climb aircraft and at high altitudes. For these reasons, a specification for JP-4, which essentially is a low-vapor-pressure JP-3, was issued in 1951 and at present is the standard U.S. Air Force aviation turbine fuel.

While the fuel specifications have been refined to keep pace with engine development, JP-4 has basically maintained the critical properties first specified to ensure availability and to fulfill aircraft performance requirements. JP-4 is a wide-cut mixture of heavy naphtha and kerosene, with  $140^{\circ}\text{F}$ - $460^{\circ}\text{F}$  boiling range. It possesses a maximum freezing point of  $-72^{\circ}\text{F}$  and a Reid vapor pressure of 2 to 3 psi at  $100^{\circ}\text{F}$ , a compromise volatility that assures availability with reduced vaporization loss. Related to the volatility is an expected low flash point from approximately  $-20^{\circ}\text{F}$  to  $0^{\circ}\text{F}$  and an explosive range from approximately  $-20^{\circ}\text{F}$  to  $90^{\circ}\text{F}$  under equilibrium conditions at standard sea level ambients of temperature and pressure.

##### 2. JP-5

The need for a less fire-hazardous fuel aboard aircraft carriers was responsible for the adoption of JP-5 by the U.S. Navy in 1951. It is considered the standard U.S. Navy fuel. Properties of JP-5

affecting ignitability are a boiling range of 300°F-550°F, a freezing point of -51°F, and a flash point requirement of 140°F minimum. Also, the higher viscosity limit for JP-5 as compared to JP-4 reduces the starting capability at low temperature.

The narrow boiling range of JP-5 and the 140°F minimum flash point requirement are severe limitations in the production of this fuel.

### 3. Jet A and Jet A-1

In 1958, the American Society for Testing and Materials (ASTM) formulated commercial aviation turbine fuel specification D-1655. Requirements for Jet A and Jet B (JP-4) were specified. Jet A was used almost exclusively for commercial carriers within the Continental United States in order to enhance ground and flight safety. Its properties include a 100°F minimum flash point requirement and a freezing point of -40°F. Long-range, high-altitude aircraft operations made it necessary to formulate a lower freezing point kerosene. Approximately 1 year later, Jet A-1, having identical properties to Jet A except for a -58°F freezing point requirement, was added to the commercial specification.

### 4. JP-8

Efforts to evaluate the use of a safer fuel than JP-4 for combat operations, as well as ground handling, were intensified at the time of the Southeast Asia conflict. Combat losses directly related to fuel fires or explosions supported the basis for evaluation of a more combat safe fuel.

JP-8, which is essentially commercial Jet A-1 with fuel system icing inhibitor and corrosion inhibitor added, was selected for tests in 1967. Initially, considered as a possible replacement fuel for JP-4 in Southeast Asia, its expanded use for U.S. Air Force application worldwide has been proposed. Significant and favorable volatility property of JP-8 is a minimum flash point of 100°F, which normally exceeds ground-handling temperatures. Also, it appeared that JP-8 would be available in the quantities required. Thus, JP-8 emerged as a prime candidate fuel. At present, because of availability and cost factors, its use has been limited to U.S. Air Force bases in the United Kingdom. In the mid-1970s, efforts were started and are continuing at present to make JP-8 the standard fuel of the NATO air forces in Europe.

### 5. Special Applications

Grade JP-5 is the preferred fuel for presidential aircraft. Alternate fuels in their order of preference are Jet A-1, Jet A, and JP-4. Grade JP-5, used specifically for AF No. 1, contains Fuel System Icing Inhibitor (FSII).

Properties of general interest in current aviation turbine fuels are given in Tables C-1 through C-8. The values for Jet A-1 will indicate what properties may be expected for JP-8. A DOD conversion, in competition with the commercial airlines for kerosene-type fuel, may shift properties toward higher volatility. On the other hand, demand in other industries for the gasoline-type fractions may offset any shift due to increased kerosene demand.

The advantage/disadvantage factors (safety, cost, low-temperature operation, engine starting, smoke, etc.) associated with JP-8 are in between those of JP-4 and JP-5. This is important because, when direct comparisons between JP-4 and JP-8 are not available, JP-4 and JP-5 may be used. For example, the J79 engine low-smoke combustor showed a 5-point increase in smoke number for JP-5 compared to JP-4, and, as there were no smoke data for JP-8, the expected increase in smoke number for JP-8 would be 5 or less.

Flash point range, not average, is given in Table C-5, and the effects of both the minimum and maximum have to be considered. Low flash is the worst case for fire safety. High flash is the worst case for cold starting.

All turbine fuels have about the same gravimetric (Btu/lb) heating values, but the kerosene fuels have substantially higher volumetric (Btu/gal) heating values as shown in Table C-6. Grade JP-8 (Jet A-1) will increase range per mission, but probably at the sacrifice of payload in current systems. This increased heating value may have more benefit in the design of future systems.

Grades JP-4 and Jet B have the same distillation requirement. The same holds also for Jet A, Jet A-1, and JP-8 (Table C-7). Grade JP-5, with a 140°F minimum flash point, has only a 135°F typical boiling range, which accounts for its limited availability (Table C-8).

TABLE C-1 Density, lb/gal, 60°F

Fuel	Minimum-Maximum	Typical
JP-4	6.25-6.68	6.36
Jet B	6.25-6.68	6.36
Jet A	6.46-6.99	6.77
Jet A-1	6.46-6.99	6.77
JP-8	6.46-6.99	6.77
JP-5	6.56-7.03	6.83

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

TABLE C-2 Viscosity, Centistokes, -30°F

Fuel	Maximum	Typical
JP-4	—	2.83
Jet B	—	3.08
Jet A	15	8.78
Jet A-1	15	8.64
JP-8	15	8.64
JP-5	16.5	10.50

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

TABLE C-3 Freezing Point, °F

Fuel	Maximum	Typical
JP-4	-72	below -80
Jet B	-58	below -76
Jet A	-40	-51
Jet A-1	-52	-59
JP-8	-58	-59
JP-5	-51	-56

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

TABLE C-4 Composition, Volume Percent

Fuel	Aromatics		Olefins		Naphthalenes	
	Maximum	Typical	Maximum	Typical	Maximum	Typical
JP-4	25	13.2	5	1.0	3	0.90
Jet B	20 (22*)	13.2	5	1.5	3	1.20
Jet A	20 (25*)	17.5	5	1.2	3	1.99
Jet A-1	20 (25*)	18.5	—	0.8	3	1.13
JP-8	25	18.5	5	0.8	3	1.13
JP-5	25	19.5	5	0.8	3	1.60

\*When reported to user.

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

TABLE C-5 Flash Point, °F

Fuel	Minimum	Maximum	Typical Refinery Product Range
JP-4	—	—	Subzero
Jet B	—	—	Subzero
Jet A	100	—	102-148
Jet A-1	100	—	128-146
JP-8	100	—	128-146
JP-5	140	—	140-158

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

TABLE C-6 Heat of Combustion

Fuel	Btu/lb		Btu/gal	
	Minimum	Typical	Minimum	Typical
JP-4	18,400	18,707	115,000	118,977
Jet B	18,400	18,707	115,000	119,977
Jet A	18,400	18,574	118,864	125,747
Jet A-1	18,400	18,546	118,864	125,556
JP-8	18,400	18,546	118,864	125,556
JP-5	18,300	18,578	120,048	126,884

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

TABLE C-7 Distillation, Specification Maximum Temperature, °F

	JP-4, Jet B	Jet A, Jet A-1, JP-8, JP-5
Initial Boiling Point	—	—
10% Recovered	—	400
20% Recovered	290	—
50% Recovered	370	450
90% Recovered	470	—
End Point	—	572

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

TABLE C-8 Distillation, Typical Boiling Range, °F

Fuel	Initial Boiling Point	End Point	Difference
JP-4	140	446	306
Jet B	140	446	306
Jet A	342	514	172
Jet A-1	351	504	153
JP-8	351	504	153
JP-5	338	516	178

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

TABLE C-9 Smoke Point

Fuel	Minimum	Typical
JP-4	20	25.7
Jet B	20 (18)*	25.7
Jet A	20 (18)*	22.5
Jet A-1	20 (18)*	24.5
JP-8	19	24.5
JP-5	19	20.9

SOURCE: U.S. Air Force, USAF RPT AFAPL-TR-74-71, "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4," June 1975.

Grade JP-4 has an average initial boiling point (IBP) of 140°F at 1 atmosphere, and IBP's as low as 115°F can be expected. IBP is significant, as the trend to increased usage of the fuel as a coolant for airframe equipment is driving fuel temperatures beyond the IBP of JP-4, resulting in increased boil-off and cavitation problems.

Grade JP-4 has a 2-3 psi vapor pressure requirement at 100°F, while the kerosene fuels have no vapor pressure requirement. All the fuels discussed above have the same thermal stability requirement.

It also should be noted that smoke point is the principal test employed to define fuel combustion characteristics. Typical or average values exceed specification minimums. However, Jet A-1 or JP-8 display higher smoke point values for a given aromatics level compared with Jet A if Table C-9 is compared with Table C-1.

Unlike Jet A, Jet A-1, and Jet B, military fuels specify a minimum hydrogen content, 13.6 percent for JP-4 and JP-8 and 13.5 percent for JP-5. Hydrogen content is a compositional parameter that has been shown by some combustor rig tests to correlate more closely with liner temperature and smoke output than aromatic content of fuel. The reasons for these results are twofold: the poor precision of the aromatics test and also its inability to discriminate between paraffinic-type aromatic compounds (e.g., alkyl benzenes) and cycloparaffinic-type aromatic compounds (e.g., tetralin); the latter tend to produce more soot and radiation when burned.

Essential properties of U.S. commercial and military aviation turbine fuels are summarized in Table C-10.



**TABLE C-10 Essential Properties of U.S. Commercial and Military Aviation Turbine Fuels**

Fuel Specification	ASTM Test, D	Wide Cut		Kerosene Type			
		Jet B D-1655	JP-4 MILT 5624	Jet A, A-1 D-1655	JP-5 MILT 5624	JP-7 MILT 38219	JP-8 MILT 83133
<b>PROPERTIES</b>							
<b>I Heating Value</b>							
Specific Gravity 60/60F	1298	0.751-0.802	0.751-0.802	0.775-0.840	0.788-0.845	0.779-0.806	0.775-0.840
Net Heat of Combustion Btu/lb, min	2382 or 1405	18,400	18,400	18,400	18,300	18,700	18,400
<b>II Composition, Burning Behavior</b>							
Aromatics, Vol %, max	1319	20(22)*	25	29(25)*	25	5	25
Hydrogen, Wt %, min	1018 or 3343	-	13.6	-	13.5	-	13.6
Sulfur, Wt %, max	1266 or 1522	0.3	0.4	0.3	0.4	0.1	0.4
Smoke Point, mn, min	1322	25	20	25	19	-	25
Smoke Point, mn and } min	1322	19	-	18	-	-	20
Naphthalenes, Vol % } max	1840	3	-	3	-	-	3.0
Luminometer No., min	1740	45	60	45	50	75	-
<b>III Volatility</b>							
Flash Point, F, min	56 or 93	-	-	100	140	140	100
Vapor Pressure, lb	323	3 max	2-3	-	-	-	-
Distillation, F	86	-	-	-	-	-	-
IBP/EP	-	-	-	-572	-550	360/550	-572
10/20 %	-	-290	-290	400/-	400/-	385/403	400/-
50/90 %	-	370/470	370/470	-	-	-500	-
<b>IV Cold Handling</b>							
Freezing Point, F, max	2386	-58	-72	-40;-58/A-1	-51	-46	-58
Viscosity, cSt @ -4F, max	445	-	-	8	-	-	8
@ -30F, max	-	-	-	-	16.5	15	-
<b>V Thermal Stability (JFTOT)</b>							
Heater Tube Rating	3241	<3	<3	<3	<3	Res.)	<3
Pressure Drop, mm Hg, max	3241	25	25	25	25	Coker)	25
<b>VI Storage/Corrosion</b>							
Existent gum, mg/100 ml, max	381	7	7.0	7	7.0	5.0	7.0
Potential Residue mg/100 ml	-	-	-	-	-	-	-
16 hours, max	873	-	-	-	-	10.0	-
Acidity mg KOH/g, max	3241	-	0.015	0.1	0.015	-	0.015
Copper Strip Corrosion, 2 hr	-	-	-	-	-	-	-
212 F, max	130	No. 1	No. 1b	No. 1	No. 1b	No. 1b	No. 1b

\*When reported to user.

SOURCE: A. Korosi and J. N. Rubin, "Hydroprocessing of Light Pyrolysis Fuel Oil for Kerosene Type Jet Fuel," U.S. Air Force AFWAL-TR-80-2012, February 1980.

## APPENDIX D

### THE ROLE OF THE REFINERY AND SUMMARY DESCRIPTION OF PRINCIPAL APPLICABLE PETROLEUM REFINERY PROCESSES

The essential role of the worldwide refinery network is to process any type of carbonaceous liquid compounds such as petroleum crude, shale oil, or coal liquid into products that satisfy the needs of the customer. Although all refineries serve the same basic purpose, each works to improve its input crudes and other raw feedstocks to compete with other refineries in the production of those products.

In general, all domestic and foreign refineries employ the same basic refining processes and use the same types of equipment. Within well-established limits, refineries are so constructed that they are able to vary the sources and amount of input crude mix to meet the needs of the marketplace.

The basic process unit in a refinery is the atmospheric distillation or fractionation tower, in which the heaviest of the crude distills closest to the bottom of the tower, with the distribution of the lighter portions of the crude condensing out toward the top of the tower. However, a refinery cannot normally produce more of any given distillate product than is available in the raw crude unless special processing units are available to convert intermediary streams, such as the atmospheric gas oil or the vacuum gas oil, to produce desired products. As the need for even more carefully blended end products, such as aviation jet fuel, diesel fuel, and home heating oil, requires more of the middle distillate of the available raw crude than the basic fractionation tower can produce, other means are needed. Large corporate research and development laboratories continue the long and urgently needed process of developing new and improved ways of converting the less desirable and less valuable parts of the heavy fractions in the fractionation tower into new and lighter molecular combinations. Several of the processes most commonly used are described below.

In the catalytic cracking process, oil vapors heated to about 1,000°F are passed over a silica-alumina catalyst, which causes the heavier oil fractions to crack into lighter ones (gasoline and distillate fuels); these lighter fractions are then sent to a fractionating tower for distillation. The used catalyst goes to a regenerator, where it is activated for further use by the burning off of the carbon (coke) deposited on the catalyst in the cracking process.

Hydrocracking is used to convert either heavy gas oils or residual stocks into high-quality products. It employs a series of high-pressure reactors to mix hydrogen with oil vapors at tempera-

tures up to 1,100°F. The process combines the use of a silica-alumina cracking catalyst with platinum or nickel as the hydrogenating agent and obtains high yields of good-quality gasoline or distillates.

Catalytic reforming is a continuous process that uses platinum or platinum and rhodium on alumina as a catalyst to rearrange molecules, upgrading low-octane naphthas into high-octane gasolines or producing aromatics--benzenes, toluenes, xylenes--for petrochemical use. Hydrogen is a by-product of reforming.

Polymerization occurs when a higher boiling point hydrocarbon is formed from two lower boiling point compounds.

Alkylation is a process for combining smaller dissimilar molecules into larger ones in the presence of sulfuric acid or hydrofluoric acid to provide high-octane components for premium motor gasoline or aviation gasoline.

Coking is a thermal cracking process in which a heavy feedstock is heated to about 900°F-1,000°F under moderate pressure to produce a high-quality gas oil suitable for use in catalytic cracking. Gas, gasoline, and coke are produced as secondary products.

Hydrogen manufacturing is accomplished in the refinery through a catalytic process that decomposes natural or refinery gas. Hydrogen may also be manufactured from coal or coke by a gasification process and subsequent separation from other by-product gases.

Hydrogen treating (hydrotreating or hydrogenization) is a series of processes using cobalt-molybdenum catalysts on a wide variety of petroleum stocks to improve the quality of final products by removing sulfur from petroleum or nitrogen from syncrudes. Hydrogen is added at higher temperatures and pressures.

Blending is the final step in producing gasoline and fuel oils. It involves mixing two or more fractions having different properties to obtain a final fuel with the desired specification. This can be done "off-line" in blending tanks or "on-line" in a refinery's pipelines.

## APPENDIX E

### GLOSSARY OF SPECIAL TERMS

- ASTM: American Society for Testing and Materials
- CONAES: Committee on Nuclear and Alternative Energy Strategies,  
National Research Council
- DOC: Department of Commerce
- DOE: Department of Energy
- DOT: Department of Transportation
- EIA: Energy Information Administration
- EPA: Environmental Protection Agency
- FAA: Federal Aviation Administration
- NPC: National Petroleum Council
- OECD: Organization for Economic Cooperation and Development
- OPEC: Organization of Petroleum Exporting Countries
- USGS: U.S. Geological Survey
- Alaskan North Slope: The Alaskan coastal plain between the Brooks Range and the Beaufort Sea.
- British thermal unit (Btu): The amount of heat required to raise the temperature of 1 pound of water 1°F.
- Capitalized outlays: Expenditures that, for accounting purposes, are not charged wholly in the time period incurred but allocated over future time periods.
- Cracking: Breaking down an organic compound with a high molecular weight to form compounds of lighter molecular weights.
- Crude Petroleum: A naturally occurring mixture, consisting predominantly of hydrocarbons and/or of sulfur, nitrogen, and/or oxygen derivatives of hydrocarbons, which is removed from the earth in liquid state or is capable of being so removed. Crude petroleum is commonly accompanied by varying quantities of extraneous substances such as water, inorganic matter, and gas.
- Distillate fuel oil: A light fuel oil distilled off during the refining process. Included are products known as No. 1 and No. 2 heating oils, diesel fuels, and No. 4 fuel oil. These products are used primarily for space heating on-and off-highway diesel engine fuel (including railroad engine fuel) and electric power generation.
- Enhanced gas recovery (EGR): Increased recovery of natural gas from a reservoir through the external application of physical or chemical processes. An example of an EGR process is hydraulic fracturing.
- Enhanced oil recovery (EOR): The recovery of oil from a petroleum reservoir resulting from application of a recovery process beyond secondary oil recovery. Examples of an EOR process are steam or CO<sub>2</sub> injection, chemical flooding, miscible flooding, and thermal recovery.
- Feedstock: A raw material used in production. For example,

petroleum distillates used for producing petrochemicals are referred to as petrochemical feedstocks.

Heavy crude oil: Crude oil containing a weighted average gravity of 20.0 degrees API or less corrected to 60°F.

Heavy fuel oil: A liquid product produced in refining crude oil that is used as fuel, instead of asphalt for road building or tar for roofing. (See residual fuel oil.)

High-Btu gas: High-Btu gas is predominantly methane with a heat content greater than 800 Btu per cubic foot. High-Btu gas can be produced from coal through chemical reactions (coal gasification). Natural gas, a high-Btu material, has a heat content in the range of 900 to 1,100 Btu per cubic foot.

Light oil: Natural gas liquids and all light oil products, including gasoline, distillates, and jet fuel.

Liquefied petroleum gas (LPG): A gas containing certain specific hydrocarbons that are gaseous under normal atmospheric conditions, but can be liquefied under moderate pressure at normal temperatures. The principal examples of LPG are propane and butane.

Low-Btu gas: A fuel gas produced from coal or other material with a heat content of 100 to 250 Btu per cubic foot.

MB/D: Thousand barrels per day.

MMB/D: Million barrels per day.

Medium Btu gas: A gaseous fuel produced from coal or biomass with a heat content of 300 to 750 Btu per cubic foot that can be used in boilers or direct heat applications.

Natural gas liquids: Those portions of reservoir gas that are liquefied at the surface in lease separators, field facilities, or gas-processing plants--natural gas plant liquids (NGPL). Includes ethanes, propanes, butanes, pentanes, and natural gasoline.

Natural gas production, dry: The natural gas remaining after the natural gas liquids have been removed. As usually presented, it represents the amount of natural gas production that is available to be marketed and consumed.

Oil shale: A range of sedimentary shales containing organic matter (kerogen) that can be converted into crude shale oil, gas, and carbonaceous residue by destructive distillation.

Organization for Economic Cooperation and Development (OECD): A 24-member body composed of the United States, Canada, Japan, the western European countries, Australia, and New Zealand. The organization's purpose is to promote mutual economic development and to contribute to the development of the world economy.

Organization of Petroleum Exporting Countries (OPEC): A cartel of oil-exporting nations consisting of Venezuela, Ecuador, Indonesia, Algeria, Libya, Nigeria, Gabon, Iran, Kuwait, Saudi Arabia, Iraq, the United Arab Emirates, Qatar, and the Neutral Zone.

Refinery utilization rate: The percent of total crude oil throughput capacity at which a refinery is operated.

- Reid vapor pressure: The measure of pressure exerted on the interior of a special container (Reid vapor pressure apparatus), under a specified test condition of 100°F.
- Residual fuel oil: Topped crude oil obtained in refinery operations, including ASTM grades No. 5 and No. 6, heavy diesel, Navy Special, and Bunker C oils used for generation of heat and/or power.
- Shale oil: A liquid similar to conventional crude oil that is obtained by processing organic mineral (kerogen) in oil shale, a sedimentary-type rock.
- Sour crude oil: A crude that contains sulfur in amounts greater than 0.5 to 1.0 weight percent or that contains 0.05 cubic feet or more of hydrogen sulfide (H<sub>2</sub>S) per 100 gallons.
- Sweet crude oil: A crude that does not contain hydrogen sulfide and has below 0.5 weight percent sulfur content with only a minor portion of the sulfur content being present as mercaptan compounds.
- Syncrude: The liquid hydrocarbons produced from organic deposits, such as oil shale, tar sands, and coal.
- Syngas: A high-Btu gas resulting from the manufacture, conversion, or reforming of petroleum hydrocarbons or coal. Syngas may be easily substituted for, or interchanged with, pipeline-quality natural gas. (See High-Btu gas.)
- Synthetic Natural Gas (SNG): Gas manufactured from coal, petroleum, or biomass. SNG from naphtha is the most common today. (See High-Btu gas.)
- Tar sands: Consolidated or unconsolidated rocks with interstices containing bitumen that ranges from very viscous to solid. In a natural state, tar sands cannot be recovered through primary methods of petroleum production.
- Waiver: An agreement by a purchaser of a petroleum product to accept a supplier's product that fails to meet one or more of the physical, chemical, or performance requirements of the product specification to which it was procured.

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