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ADVANCED FUEL SYSTEM TECHNOLOGY FOR UTILIZING BROADENED PROPERTY AIRCRAFT FUELS

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AIRCRAFT FUELS

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ABSTRACT

Consideration of a number of uncertain factors which may influence the future availability of high quality, reasonably priced aviation fuels suggests that the effect of potential changes in aircraft fuels be examined. In view of possible future crude sources and characteristics some changes in fuel properties may be desirable to provide a more flexible and reliable fuel supply as well as minimizing fuel processing in the refinery. However, before any change can be considered, the impact on the entire air transportation industry including the costs of developing and operating new technology must be carefully assessed and compared with perceived benefits related to fuel supplies. This paper identifies some possible changes in fuel properties based on current trends and projections, examines the effect of those changes with respect to the aircraft fuel system and describes some technological approaches to utilizing those fuels. Fuel system research activities are also described which are being conducted to establish a data base for broadened property fuels that can be used in future technical and economic tradeoff studies.

I. INTRODUCTION

The purpose of this report is to assess the impact of potential future fuel properties on aircraft fuel systems and present the status of advanced fuel system technology to use these fuels. Current projections of world petroleum reserves indicate that crude production will likely reach a peak before the year 2000^{1,2}. On the other hand, demand for jet fuels and other products in the same kerosene and mid-distillate boiling range is expected to increase. As lighter, more attractive crude supplies are depleted, the remaining heavier crudes will require more processing and refinery energy consumption to produce fuels meeting current aviation fuel specifications. Furthermore, the increased demand for the mid-distillate products may require energy intensive refinery conversion processing to increase the yield of the products in this boiling range. Synthetic crudes produced from oil shale and coal may expand

supplies, but these feedstocks will require more processing than low-quality petroleum crudes.

One option available to the air transportation industry which could reduce the impact of increased processing costs and refinery energy consumption is to permit the relaxation of jet fuel specifications^{3,4}. However, this approach would require some new developments in engine and aircraft fuel system technology to address the overall conservation of energy in both the air transportation and petroleum refining industries. In the United States, NASA, along with other government agencies and private industry, has been conducting research to establish the data base necessary to optimize future jet fuel characteristics in terms of refinery energy consumption and tradeoffs in jet aircraft and engine design⁵. These studies will examine the benefits of relaxing jet fuel properties in terms of fuel flexibility, availability and reduced refinery processing costs as opposed to the development and operational costs associated with new technology.

This report will examine the supply and demand outlook for jet fuels with particular emphasis on trends which may impact jet fuel characteristics. Fuel properties of most concern to the aircraft fuel system will be identified and the significance of changes in these properties will be examined. The status of fuel system technology to use broadened property fuels will be reviewed and finally, possible future options for the commercial air transportation industry will be discussed.

II. JET FUEL SUPPLY OUTLOOK

Current Conditions

Commercial turbine aircraft in the United States operate almost exclusively on a kerosene jet fuel, American Society for Testing and Materials (ASTM) D 1655 Jet A. Jet A is produced principally by the distillation of a specified boiling range fraction from petroleum followed by a mild finishing process to reduce the sulfur content. The boiling range of Jet A is identified in Figure 1 and compared with other major petroleum products which share a portion of the same boiling range fraction. The military kerosene jet fuel, JP-5 used by the U.S. Navy, has a higher flash point than

Jet A which is dictated by its use aboard aircraft carriers. The gasoline and naphtha jet fuels have much wider boiling ranges, incorporating the lighter or "naphtha" portion of petroleum and overlapping the lower boiling portion of Jet A. The naphtha jet fuels are primarily JP-4 used by the U.S. Air Force and its commercial equivalent Jet B, which is seldom used in the U.S. today. Number 2 diesel and home heating oils overlap much of the Jet A boiling range, but also extend to a higher final boiling temperature, incorporating heavier components. By overlapping most of the Jet A boiling range, diesel and heating oils are in direct competition for the Jet A fraction of the crude.

The distillation and finishing processes used in the production of most jet fuels have little effect on the hydrocarbon type composition of the fuel. Thus the composition-related characteristics and properties of the fuel products are strongly dependent on the properties of the crude feedstocks from which they are derived. In the past, refiners have had some flexibility in selecting feedstock material which would be most suitable for their desired product mix and often the refinery itself would be tailored to a specific type or mix of crudes. However, with the present supply situation, refiners often accept whatever crudes are available; and as a result, jet fuels may be produced from crudes with less desirable compositions. This is best illustrated by an examination of the trends in aromatics composition. Aromatic compounds are organic rings which are deficient in hydrogen and have poor combustion characteristics. A survey of 420 worldwide crudes⁶ showed that 20 percent cannot be used to produce jet fuel by simple distillation and finishing processes without exceeding the current specification of 20 percent aromatics in the fuel product.

A waiver is currently in effect which permits the limited use of Jet A fuels with aromatics concentrations as high as 25 percent when reported by the supplier (known as "reportable" fuels). This waiver was originally introduced in 1974 in an attempt to improve jet fuel availability at a time when crude supplies were limited. Since that time, United Airlines has maintained records of the purchases of Jet A fuel that meet specifications only through the use of this waiver (unpublished ASTM bulletin). Figure 2 illustrates this trend by plotting percent of "reportable" fuels to total fuels purchased. While the percent of "reportable" fuels oscillates, reflecting shifts in the availability of low and high aromatic crudes at refineries, the peak values have increased markedly. The peak experienced in 1978 was attributed to the introduction and use of Alaskan North Slope crude in refineries located primarily on the

western coast of the United States. This event illustrates the sensitivity of jet fuel properties to crude characteristics since the North Slope crude has a high aromatics concentration. The reduction in "reportable" fuel deliveries in early 1979 is believed to result from a more widespread distribution of the North Slope crude resulting in a lower fraction of this crude being processed by individual refineries.

Projected Trends

Recent studies and projections of the U.S. petroleum product demand⁷⁻⁹ indicate that gasoline demand will begin to decrease during the 1980's as automobile efficiency increases, annual mileage decreases, and the number of Diesel-powered vehicles increases. The increase in Diesel-powered vehicles is also expected to cause a substantial increase in mid-distillate fuel consumption. Jet fuel demand will also increase in the same time period. The results of these forecasts would be a significant change in the ratio of the gasoline to mid-distillate demand.

As the demand for mid-distillates increases, U.S. refineries may be unable to produce all of the middle distillate products needed by conventional distillation and finishing processes. If this situation occurs, refineries may be required to make up the middle distillate shortfall by cracking higher-boiling, heavy gas oils. The middle distillates produced by cracking heavy gas oils will have characteristically high aromatics concentrations which may necessitate the use of hydrocracking (a catalytic process combining cracking and hydrogen addition) to produce Jet A which will meet current aromatics specifications. Hydrocracking is a relatively energy-intensive process that consumes a considerable amount of hydrogen. Hydrogen is currently produced as a by-product in refineries that employ reforming, a process that upgrades gasoline octane number by hydrogen removal. However, as the ratio of gasoline to mid-distillate products decreases, the hydrogen produced in the reformer may be insufficient and the refinery will be required to manufacture more hydrogen for hydrocracking purposes⁹. Current specification Jet A produced by hydrocracking heavy gas oil will consume 4 to 5 times the processing energy required to produce Jet A from conventional distillation and finishing processes.

Any difficulties in meeting future changes in product demands may be further aggravated by the trend toward lower quality crude feedstocks discussed earlier. As the more desirable crude supplies are consumed, the remaining high aromatic, heavier crudes will require more processing and more energy to convert to acceptable products.

Figure 3 summarizes future jet fuel production alternatives. As the supply

of petroleum crude diminishes, the next likely domestic source of fossil fuel will be shale oil and coal liquids. Either source will produce acceptable jet fuel products¹⁰, but both will require more extensive processing than most petroleum crudes. Shale oil, with a lower aromatic content than coal liquids, is more attractive; however, shale oils contain large concentrations of undesirable organic nitrogen which must be removed by relatively severe hydrotreating (catalytic hydrogen addition). Organic nitrogen compounds act as catalyst poisons and can seriously shorten the useful life of many catalysts routinely used in refinery operations. Initially, small quantities of shale oil may be blended with other petroleum feedstocks, but significant commercial quantities of shale oil are not likely for 10 to 20 years. The use of coal syncrudes, which have very high concentrations of aromatics, will require even more severe hydrogenation than shale oils for the production of jet fuels. However, the commercial production of coal liquids will probably lag the development of shale oils.

Thus, future jet fuels may have higher aromatic content because of (1) changes in available feedstock properties and (2) increases in jet fuel production by cracking of higher-boiling fractions. Increasing amounts of "reportable" fuels could appear in the market and more frequent shortages in jet fuel could occur as a result of increasing competition with other mid-distillate users. Use of the energy intensive refinery processes required to upgrade the hydrogen content and quality of the fuel to current specifications will certainly increase the cost of producing the fuel. Rising production costs will be an increasing incentive to consider changes in jet fuel specifications in order to minimize refinery energy consumption and reduce total fuel costs.

Certainly, the aircraft industry should consider and assess all potential alternatives regarding the future availability of jet fuel. The continued use of current specification fuels is most desirable to maintain performance and durability of current aircraft and engine components, but this also involves some risk with regard to availability and potentially higher refinery energy consumption and fuel production costs. Conversely, allowing relations in jet fuel properties beyond current limits could provide a more flexible, reliable fuel supply with minimum refinery energy consumption and associated costs, but also with possible adverse effects on aircraft and engine durability, performance and emission characteristics. A comprehensive data base is required to establish the economic and technical tradeoffs between future fuel properties

in terms of refinery, airframe, engine and airline operating technologies.

III. POTENTIAL CHANGES IN JET FUEL PROPERTIES

Properties of Significance to Aircraft Fuel Systems

Table I lists several aviation turbine fuel specifications which are of concern to the aircraft fuel system. The specifications are from voluntary consensus standards published by the ASTM¹¹. The ASTM specification contains additional properties which impact fuel system design, but which are not of primary concern to the technology activities described in this paper. For the purposes of this paper the aircraft fuel system will be defined as the aircraft components and systems that are involved with the storage of fuel aboard the aircraft and the delivery of fuel through boost pumps, check valves, transfer lines, main pumps, filters, flow controls, heat exchangers, manifolds, and nozzle to the combustor.

The volatility specifications shown in the table are particularly important since they have a direct impact on jet fuel yield in the refinery. In the engine, the volatility, defined by the 10 percent recovered temperature, is critical to good fuel atomization in the combustor; the fuel must include sufficient light ends to assure easy starting while avoiding excessive heavier fractions which would be difficult to vaporize. In the aircraft fuel system, volatility is also significant as an indicator of potential "boiloff" fuel losses through tank vents at high altitude pressures. The final boiling point is a measure of the inclusion of heavier components which influence specific gravity, heat of combustion, freezing point and other properties. The flashpoint is established on the basis of safety considerations associated with fuel handling and storage. Consistent specific gravity within the indicated limits is important to assure proper fuel metering by the fuel control.

The fluidity specifications are established to ensure reliable engine and fuel system operation at the minimum temperatures which can be encountered at a high aircraft cruising altitude. As indicated in Table I, ASTM also identifies a type A-1 jet fuel which is similar to type A except for a lower freezing point specification of -47°C. The significance of the freezing point limit will be discussed later in this paper. Fuel freezing point is also of potential importance to refinery jet fuel yield because of the sensitivity of freezing point to higher-boiling heavier fractions. For some crudes, an increase in jet fuel yield by including higher boiling fractions in the jet fuel blend is limited by the freezing point specification. Viscosity is related to pumpabil-

ity and is also a factor in fuel spray atomization.

Specifications on fuel composition are established with regard to combustion performance and materials compatibility concerns. Fuels with high aromatics content tend to burn with a smoky luminous flame and produce soot and carbon deposition in the combustor.¹² In the fuel system, aromatics cause swelling of many elastomeric materials used for gaskets, sealants, etc. Sulfur compounds, particularly mercaptans, may also damage components. Materials compatibility technology will be discussed later.

Fuel thermal stability is a measure of the ability of the fuel to withstand thermal stress in the fuel system without chemical degradation. Thermal stability is particularly sensitive to trace levels of certain elements, such as nitrogen, copper, sulfur and others, and may be affected by some aromatic compounds. This requirement will be discussed later in this paper.

Potential Property Changes

A NASA workshop held in 1977¹³ recommended some characteristics of a broadened property jet fuel to be used for experimental engine and fuel system research. Compared to current Jet A fuel, the future fuel would have (1) an increased aromatic content, as much as 35 volume percent, (2) a higher final boiling point, (3) a higher freezing point, up to -29°C, and (4) a thermal stability that is marginal by present standards. The properties designated for the future broad-property fuel tend to be similar to those of the current number 2 Diesel fuels.

In general, the fuel properties were selected because of the sensitivity of refinery jet fuel yield to the property or in anticipation of potential changes in crude quality. The trend toward heavier, more aromatic crudes coupled with changes in refinery processing to meet increased mid-distillate demand, as discussed earlier, suggest that future jet fuel yield may be seriously limited by current aromatics specifications. An increase in final boiling point along with freezing point, which are closely interrelated, is seen as a means for increasing potential refinery yield by including higher boiling fractions in the jet fuel product.¹⁴ These higher boiling fractions typically contain higher aromatics concentrations, thus reinforcing the potential increase in aromatics already suggested. The higher-boiling fractions also contain increased concentrations of trace elements which may degrade the thermal stability of future fuels.

The changes discussed above also take into consideration the possible introduction of limited quantities of syn-crude material. The inclusion of some shale oil into refinery feedstocks may

result in higher levels of organic nitrogen compounds in the jet fuel product which would degrade thermal stability. Also, high nitrogen levels in jet fuels may lead to environmentally unacceptable levels of oxides of nitrogen emissions¹². However, because of the sensitivity of many refinery catalysts to nitrogen poisoning, some preprocessing of shale oil syncrudes to reduce nitrogen levels before introduction into the refinery is expected. Nonetheless, any relaxation of thermal stability requirements that would allow higher nitrogen concentrations in jet fuels would be beneficial in terms of reduced processing costs to remove the nitrogen. The primary effect on jet fuels of the introduction of coal syncrudes would be an increase in aromatics content. Any other effects would be heavily dependent on the characteristics of the coal used and the nature of the liquefaction process.

An additional jet fuel property which could significantly increase potential jet fuel yield if it were changed is the flashpoint temperature. A reduction in flashpoint would permit inclusion of additional lighter fractions in jet fuel and would tend to mitigate some problems such as higher freezing point and viscosity resulting from the addition of higher boiling fractions, thus reducing demands on advanced technology. This change has been considered by the ASTM and was the subject of a symposium held by the ASTM in 1978¹⁵. Some reduction in flashpoint may be reasonable; however, in consideration of the handling hazards associated with lower flashpoints no change is likely at this time.

The discussion in this paper of potential changes in future jet fuel properties has been limited to those properties which are expected to have a major impact on fuel system design requiring the evolution of advanced technology. However, due to the close interrelationship of fuel properties, changes in these properties would also result in changes in many other fuel characteristics. These include water separability, electrical conductivity, lubricity, and others. Changes in some fuel properties may also change the effectiveness of some approved jet fuel additives.

IV. HIGHER FREEZING POINT FUELS

Effect of Fuel Freezing Point

Fuel stored in aircraft integral wing tanks can reach very low temperatures during long range, high-altitude flights as a result of heat transfer to the surrounding environment. The heat flux, largely convective, is dependent on the total air temperature which in turn varies with the static air temperature and Mach number. Figure 4 illustrates the variation of fuel temperature

in a typical commercial aircraft on a long-range mission representative of an extreme winter condition. The information in the figure was obtained from a Boeing Company computer program which has been developed for the prediction of in-flight fuel temperatures¹⁶. The total air temperature schedule shown in Figure 4 is based on a flight profile with cruise at a Mach number of 0.84 and an altitude static temperature of -72°C . Calculations for initial fuel temperatures of 12° and -21° are shown. After about six hours of flight time, there is no longer an influence of initial fuel temperature, and the fuel temperature eventually approaches the total air temperature. Fuel temperature variations predicted by the model have been compared to measured fuel temperatures and the trends shown in Figure 4 have been verified.

Figure 5 shows a correlation of in-flight minimum fuel temperatures for Boeing 707 and 747 aircraft flying polar route missions. The data were obtained from about 1100 missions, each greater than 7400 kilometers¹⁷. The probability that the temperature of fuel in the tank will fall below a given minimum value is plotted against minimum fuel temperature. The differences in temperature between the two types of aircraft are mainly attributed to differences in flight Mach number or flight path. In-flight problems with freezing fuel have not been documented. Situations have occurred, however, where gage-warnings of low fuel temperature have prompted flight crews to accelerate to a higher Mach number, or to divert to warmer, low altitude air masses. Such diversions are costly in terms of operation at less than optimum altitude-speed combinations or increased path length. A margin of 3° to 5° above the specification freezing point is required as a minimum fuel temperature during flight.

Because aviation turbine fuels are complex mixtures of many compounds, freezing or crystallization occurs over a range of temperatures rather than at a single definite temperature. The higher molecular weight, straight-chain or normal paraffins and some hydrocarbons with symmetrical molecules crystallize first in the form of waxes. If temperatures are further lowered, a waxy matrix builds up, trapping other constituents of the fuel which are still liquid, until a nearly solid structure is formed. The specification test used for aviation fuels is based on observations of the temperature at the disappearance of crystals in a stirred fuel sample removed from a freezing bath and warmed after first crystals are formed. This procedure defines a conservative melting point, independent of supercooling. Other tests have been defined to measure low temperature fluidity of fuels, some of which attempt to relate low temperature behavior to a desired operating

characteristic¹⁸. These include measurement of viscosity-temperature relations, filter or pumping pressure drop, and flow rate through tubes or capillaries under pressure or vacuum. Most of these methods were devised for testing diesel or fuel oils for winter service, but they may have eventual application to jet fuels.

In order to better identify the low temperature performance of fuels in an aircraft system, a full-scale apparatus designed to represent a section of an airplane wing tank was used. The apparatus, shown in Figure 6, included the capability to cool the upper and lower tank surfaces to simulate the wing surface temperature history typical of a given flight profile. Instruments measured temperature gradients and other parameters. At an appropriate point during the test, fuel withdrawal was initiated and the mass fraction of fuel remaining in the tank as unpumpable solids was reported as the percent holdup. Figure 7 is a photograph of the interior of the simulator tank after completion of a test in which the fuel was cooled to an average temperature of -26°C , two degrees above the measured freezing point of the test fuel. The fuel slush covering the bottom of the tank represents a holdup of 8.8 percent.

The fuel tank simulator has been used to investigate the performance of a series of test fuels having a range of freezing points from -28° to -52°C . Each fuel was derived from known petroleum or shale oil sources to examine the effect of hydrocarbon type composition on performance. Analysis of the data suggested two regimes of behavior: a low holdup regime below 10 percent, in which the minimum average temperature was well above the fuel freezing point, and a high holdup regime, greater than 10 percent, in which the minimum average fuel temperature is at, or below, the fuel freezing point. The low holdup regime is of most practical interest since it represents a situation in which the bulk fuel temperature would not indicate any frozen fuel, yet due to the large temperature gradient near the lower surface, fuel temperatures just above the lower skin may be below the freezing-point. As shown in Figure 8, the holdup data for the low holdup regime correlated with a fuel temperature 0.6 centimeters above the lower tank surface. The curves in Figure 8 indicate little effect of fuel source on fuel holdup, but suggest a strong correlation of the fuel temperature corresponding to a holdup of one percent or less and the fuel freezing point. Thus, fuel freezing point temperature may in fact be a good indicator of incipient fuel freezing if the fuel temperature is measured at an appropriate position near the lower tank surface. These results are reported in detail in reference 19.

Technology For Higher Freezing Point Fuels

Several potential fuel system technology approaches to using higher freezing point fuels have been analytically evaluated for NASA by the Boeing Commercial Airplane Company²⁰. These approaches included the use of insulation to reduce heat transfer from the aircraft fuel, and the addition of heat to the fuel in the tank during flight to prevent fuel freezing. The studies incorporating heat addition considered waste heat recovery systems as well as auxiliary heat generation systems. The sketch in Figure 9 indicates the various approaches which were examined.

The calculated effect on fuel temperature of two levels of heat addition to the fuel is indicated in Figure 10 for a typical long-range, wide-bodied aircraft. A heat addition rate of 62 kilowatts per tank would be required to maintain the fuel temperature above -29°C , while an input of 108 kilowatts per tank would maintain the fuel temperature above -18°C . Additional calculations indicated that the use of wing tank insulation (without heat addition) could reduce initial cooldown rates, but would have very little effect on the minimum fuel temperature for long duration flights. The use of insulation in conjunction with fuel tank heating could reduce heat input requirements for higher freezing point fuels, but performance penalties associated with increased weight and increased drag or decreased fuel tank volume must also be considered.

After detailed consideration of the advantages and disadvantages of the heat sources identified in Figure 9, two approaches were selected for further study, the lubricating oil heat exchanger and the engine-drive electrical heater²¹. The lubricating oil heat exchanger system shown schematically in Figure 11 represents a minor modification to the fuel system that could be implemented with relatively low risk and cost. This system uses heat rejected by the engine lubricating oil as a heat source and involves the addition of a second oil-to-fuel heat exchanger. When the fuel heating system is not in operation, the fuel control relieves excess fuel flow back to the engine fuel pump. When fuel heating is needed, a three-way recirculation valve diverts the excess flow through the second heat exchanger and back to the fuel tanks. The maximum amount of heat available is dependent on engine operating condition but is relatively constant throughout the cruise portion of the flight. The maximum heat available will also vary with different engines, and future high performance engines may have less heat rejection from the engine oil than current engines. The calculated fuel temperature for a long-range extreme winter flight using this system is shown in Figure 12.

In the example shown, the fuel heating rate averages 50 kilowatts per engine-tank combination increasing the minimum fuel temperature to -31°C . The advantages of this system are that it has little or no effect on the engine or fuel system operation, and that weight, performance and cost penalties are small. The primary disadvantage, however, is the limited heat available from this system corresponding to a small increase in fuel freezing point limit.

The second approach to fuel heating which has been studied uses an electrical system to divert a small portion of the engine energy to fuel heating. A schematic of this approach is shown in Figure 13. Suitable engine-driven generators have been developed for auxiliary power generation on some current military aircraft. To eliminate the hazards of directly heating fuel with electric heaters, a heat transfer medium such as an ethylene-glycol solution would be used. The transfer fluid reservoirs and heaters would be centrally located and the fluid would be pumped out to heat exchangers in the fuel tanks. The primary advantage of this system is that it can provide practically any amount of heating power desired, thus accommodating a substantial increase in fuel freezing point. Also, the system could be easily adapted for ground power heating. Disadvantages include the relatively major fuel system modifications needed to incorporate the system and the small but appreciable aircraft performance penalty due to the added weight and engine power drain of the system.

Research And Technology Status

Design studies of both the lubricating-oil heat exchanger system and the electrical heating system have indicated that these concepts represent two feasible approaches to heating system technology. However, much additional data will be required before systems such as these can be realistically considered for future aircraft designs. Experimental studies currently in progress using a fuel heating system simulator will provide some of the needed information. The simulator, shown in Figure 14, adds a fuel heat exchanger and recirculation loop to the fuel tank simulator described earlier (fig. 6) and can simulate either of the two heating system concepts. The current studies will provide data on heat transfer rates, fuel tank behavior with heat input, and system dynamics, which will aid in modeling the system performance. This information will be sufficient for engineering evaluations of the systems, but demonstrations of the concepts in full-scale hardware will be required before actual development of this technology is likely to occur.

Several additional issues such as ground handling of higher freezing point

fuels and the effects of these fuels on turbine-powered general aviation aircraft must also be examined and resolved. Special provisions for storage and distribution systems as well as aircraft parking may be required at airports in northern latitudes if jet fuel freezing points change significantly.

V. LESS STABLE FUELS

Effect Of Fuel Thermal Stability

An important fuel characteristic which must be considered by both fuel system designers as well as fuel suppliers is the chemical stability of the fuel at the elevated temperatures which it may encounter in the fuel system. The term "thermal stability" refers to the resistance of the fuel to chemical alteration or degradation under thermal stress which could produce gums, insolubles or other deposits in the fuel system. The mechanisms which lead to the production of these deposits are only partially understood, but there is general agreement that autoxidation, from oxygen in the fuel, is the primary mechanism in initiating deposit formation. Much of the chemistry involves free radicals, and any fuel constituent that tends to form free radicals easily will likely be instrumental in fuel degradation. Small concentrations of some metals and heterocompounds containing nitrogen, sulfur, and oxygen have been shown to be detrimental.

Thermal instability was first identified as a problem in aviation gas turbine engines in the 1950's, but the development of commercial supersonic aircraft in the 1960's focused much more attention in the area²². In a supersonic aircraft, the fuel serves as a heat sink for wing surfaces which are aerodynamically heated and is susceptible to thermal degradation. With current fuels and fuel systems, thermal stability may become a problem at Mach numbers above 2.5.

In the subsonic aircraft, fuel tank temperatures are much cooler, but elevated fuel temperatures are encountered in the lubricating oil heat exchanger (where the fuel is used to cool the engine oil) and in the combustor fuel manifold and nozzles. Fuel thermal instability may cause fouling deposits in the heat exchanger that can interfere with heat transfer resulting in excessive lubricating oil temperatures. Thermal deposits in fuel manifolds and spray nozzles can cause nonuniformities in fuel spray patterns in the combustor. These can result in higher pollutant emissions, increased combustor liner temperatures, and hot spots in turbine inlet temperature profiles leading to durability problems and increased engine maintenance costs. Current efforts to improve gas turbine fuel efficiency are resulting in higher cycle pressure ratio engines with higher combustor inlet tem-

peratures which tend to aggravate stability problems. Also, current trends toward more complex fuel injection systems with closer spray nozzle tolerances and multiple injectors with lower pilot fuel flow rates lead to conditions which promote fuel thermal degradation or are more sensitive to its effects.

Several test methods have been developed for characterizing jet fuel thermal stability. One of these, identified as the Jet Fuel Thermal Oxidation Tester (JFTOT), is illustrated in Figure 15. In the JFTOT, the test fuel is passed over an electrically heated tube and any degradation products which are formed deposit on the tube or are trapped by a downstream filter. Pass-or-fail criteria are established on the basis of pressure drop across the filter or observation of a change in deposit color or reflectance on the heated tube. A more quantitative assessment of fuel stability can be obtained by conducting JFTOT tests over a range of heater tube temperatures and determining the tube temperature or "breakpoint" temperature where the fuel just meets the stability criteria.

Meeting jet fuel thermal stability criteria is not typically a problem in current refineries. Except for isolated incidents, problems related to thermal deposits have not been observed in operating aircraft gas turbine engines. Generally, the refinery processing needed to meet other jet fuel specifications such as sulfur content, acidity, color, or smoke point will render a product that will also meet stability criteria. However, several potential changes in future fuels may contribute to decreased thermal stability. Jet fuels with higher final boiling points typically include higher concentrations of heterocompounds and trace metals which may degrade stability. This could be aggravated by the overall trend in petroleum crudes toward heavier, more aromatic crudes and the potential for increased use of cracking of heavier fractions to provide mid-distillate fuels.

The inclusion of shale oil syncrude as a refinery feedstock could have a considerable effect on fuel stability due to its high organic nitrogen content. Typical shale syncrudes may have 1 to 2 weight percent of fuel nitrogen. Figure 16 from reference 23 shows the effect of nitrogen level in oil-shale-derived fuels on the breakpoint temperature as determined by the JFTOT. Current specifications require jet fuels to meet stability criteria at 260°C. These data suggest that fuels derived from synfuels with nitrogen levels as low as 0.005 percent by weight may not meet stability criteria. An important consideration in examining Figure 16 is that the lower nitrogen content fuels are a result of increased hydrogenation severity in processing the shale syn-

crude. The increased hydrogenation severity required to reduce the nitrogen content should also reduce the concentrations of other unstable species such as oxygen containing organics or olefinic hydrocarbons.

Technology for Less Stable Fuels

Several approaches to handling fuels with reduced thermal stability are already in use, including fuel system design guidelines and fuel additive technology. Design guidelines generally focus on reducing fuel exposure to high temperatures. Typically, maximum fuel temperature limits are established on the basis of experience, and fuel system components such as heat exchangers or fuel nozzle struts are designed to maintain the desired fuel temperature. Figure 17 from reference 24 suggests a correlation between fuel temperature referenced to breakpoint temperature and fuel nozzle valve performance for an F101 engine fuel nozzle operating on two test fuels. These data were acquired in accelerated cyclic tests on a fuel system simulator, and the time to an arbitrarily selected change in a nozzle flow characteristic was used as a measure of performance. When components lack the design flexibility to meet fuel temperature limits, alternative approaches such as insulation of fuel manifolds or heat shields may be required. Some advanced multizone combustors in which the fuel flow to a zone is shut off for a period of time may require purging systems to prevent fuel nozzle coking.

Another approach to using turbine fuels with poorer thermal stability characteristics is through the use of additives. Antioxidant additives are available which suppress oxidation by interrupting the free radical chain reaction to form stable products. It should be recognized, however, that if fuels become more unstable the effect of antioxidants will be diminished because of the increasing ability of the fuel to form free radicals. Another group of additives which may be helpful are known as metal deactivators. Several metals frequently present in trace concentrations serve as catalysts in free radical formation steps. Metal deactivators serve to remove these metal ions from participation in the reaction process. However, the use of some additives may result in the formation of an insoluble sludge and a dispersant may be needed to maintain the sludge in solution. Additives may be helpful in dealing with potentially less stable future fuels, but the use of additives alone is not likely to provide a solution.

The current pass-or-fail specification criteria have proved satisfactory for maintaining high quality fuels when fuel stability has not been a limiting property. However, trends in fuel characteristics may lead to less stable fuels, and an improved stability test

may be needed to avoid unnecessary constraints on jet fuel production. Two problem areas have been identified: first the need for a more quantitative determination of fuel stability, and second, the need for a better correlation between laboratory test results and engine fuel system performance. The first need has led to modifications to current specification test apparatus, as well as revised procedures that may improve the quantitative determination of deposit or insolubles formation. The second need has led to test programs being conducted to develop relationships between laboratory test results and the performance of heat exchangers (ref. 25). Results such as the correlation shown in figure 17 that included fuel breakpoint temperatures may lead to improved relationships between test results and fuel nozzle performance.

Research and Technology Status

A number of organizations in the U.S. are currently conducting research directed toward an improved understanding of the chemistry and mechanisms leading to thermal deposits. Many of these studies are examining potential stability problems associated with fuels derived from synthetic crude sources. A workshop was held at the NASA Lewis Research Center in 1978 (ref. 26) to review ongoing research and to provide recommendations for future activities. A specific recommendation was to establish a generalized test apparatus that could be used to relate laboratory screening tests to actual performance. Several research programs have been initiated to design and build fuel system simulators for this purpose. Variables to be considered include the effects of wall temperature, fuel Reynolds number, fuel inlet temperature and pressure on deposit formation rate. Detailed chemical characterization of the deposits will also be obtained.

A substantial amount of additional effort will be required before any significant change in fuel thermal stability can be considered. The nature of the fuel instability must be understood and the techniques to deal with it must be exhaustively studied in component and engine tests. These programs will require expensive, long-term, cyclic tests unless reliable techniques for accelerated tests can be devised. Taking these factors into consideration, it would appear that major changes in jet fuel thermal stability are unlikely in the near future, but that research efforts must be initiated today to provide an alternative to increased fuel processing to meet current specification criteria.

VI. NON-METALLIC MATERIALS COMPATIBILITY

Increased aromatic content of future jet fuels may present a problem with

regard to compatibility with non-metallic materials used as gaskets, sealants, adhesives and coatings in aircraft fuel systems. Elastomers typically swell when exposed to aromatics, and standard design procedures take this into account. However, some data have been acquired²⁷ which indicate a significant loss in elasticity after exposure to a fuel with higher aromatics content. Figure 18 compares results for an elastomer exposed to Jet A with 20 percent aromatics and two higher aromatics content blends. It should be noted that these aging tests were conducted at an elevated temperature of 150°C; the loss in elasticity was less severe at lower temperatures. Another study, reported in reference 28, involved the examination of a wide variety of non-metallic aircraft materials. With some exceptions, most materials were found to be reasonably tolerant of a JP-4 base fuel with aromatics levels up to 35 volume percent and sulfur levels up to 1 weight percent.

Both of the cited studies found an indication of potential problems with some materials. Followup studies should investigate these specific cases more thoroughly and examine as many classes of materials as possible. In addition to aging tests with specific fuels, cyclic tests where aromatics concentrations are varied are needed. Compatibility problems with some materials may be identified, but many elastomer compounds can be tailored to specific fuel properties so that undesirable effects would be minimized for a given fuel in a given application.

VII. CONCLUDING REMARKS

A number of factors related to the future supply and cost of aviation turbine fuels have been identified. The turbine fuel properties of most significance to the aircraft fuel system have been examined, and trends and potential future changes in these properties have been discussed. Finally, the effects of several of these property changes have been identified, and some of the fuel system technology approaches which are being studied to use these future fuels were also described. The research activities described herein are not meant to be a complete survey of all of the fuel related efforts being conducted by the government and industry, but merely to illustrate some of the more significant fuel system problem areas that must be addressed in considering broadened property fuels.

It must be recognized that broadening jet fuel properties will not necessarily insure an increase in jet fuel availability. Minimizing processing energy consumed in refining jet fuel may result in some increase in product yield from a barrel of crude, but the jet fuel users must still compete with the other

fuel consumers for their share of the total supply. Nevertheless, the ability to use a jet fuel with less stringent specifications would provide the aircraft industry with the flexibility of using fuels that might otherwise not be acceptable.

Potential changes in future aircraft fuels could take many forms ranging from gradual changes over a period of many years to the establishment of radically new or different fuels such as liquid hydrogen or liquid methane. Two factors which severely constrain any potential changes are: (1) the very long lead times associated with the development and implementation of new aircraft technology and (2) the very long service lifetimes of aircraft. Thus any significant changes in fuel characteristics will be paced by the hardware development to accommodate the fuels, and the introduction of any changes must include provisions for the continuing operation of the existing fleet of aircraft. The approach to the latter problem would, of course, depend on the degree of change in fuel properties, but under some circumstances a dual fuel system for either an interim or a longer period might be a reasonable alternative. Certainly any potential changes must be considered on a worldwide as well as a national scale. Aircraft must have the flexibility to operate on fuels which are economically available throughout the international system.

The overall effort required to assess the feasibility of using broad property fuels in both in-service and future aircraft fuel systems and engines will be considerable. Not only performance but also durability over the extended service life of the aircraft must be evaluated to insure component and system reliability, maintainability, safety and environmental acceptability with the use of these fuels. Eventually, extensive economic and engineering tradeoff studies will be needed to evaluate the effects of broadening fuel properties on the overall fuel production and air transportation system. These tradeoff studies will require an extensive technological data base, and with the long lead times associated with new aircraft technology it is imperative to begin this effort now.

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TABLE I. - SELECTED AVIATION TURBINE FUEL SPECIFICATIONS FROM ASTM D 1655-79

VOLATILITY	
Distillation Temperature (max.), °C	
10% recovered	204
Final boiling point	300
Flashpoint (min.), °C	37.8
Specific gravity (15°C/15°C)	0.75 - 0.840
FLUIDITY	
Freezing point (max.), °C	-40 ^a
Viscosity at -20°C (max.), cS	8
COMPOSITION	
Aromatics (max.), Vol. %	20 ^b
Sulfur, total (max.), wgt. %	0.3
Sulfur, mercaptan (max.), wgt. %	0.003
THERMAL STABILITY (min. JPTOT breakpoint temp., °C)	260

^aJet A-1 freezing point is -50°C max.

^bA waiver permits delivery of fuels with 20-25 vol. % aromatics

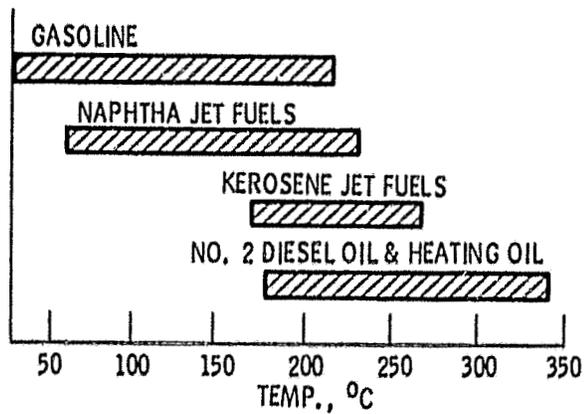
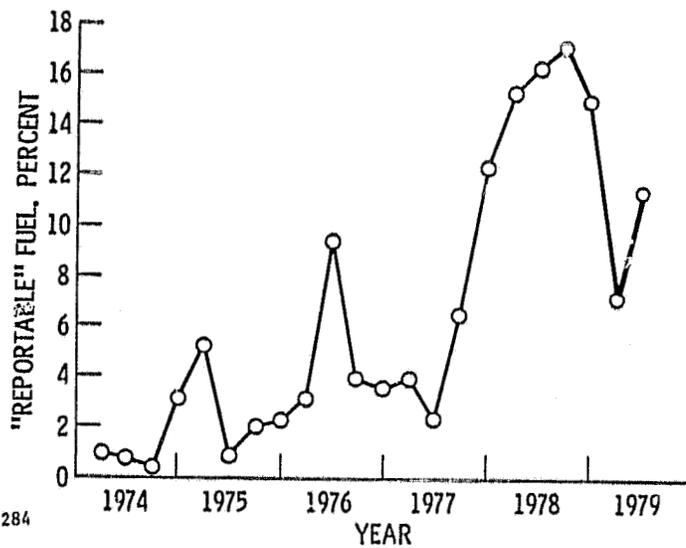


Figure 1. - Boiling range of selected petroleum products.



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Figure 2. - Statistical trends in quantity of "reportable" Jet A fuel purchased by United Airlines.

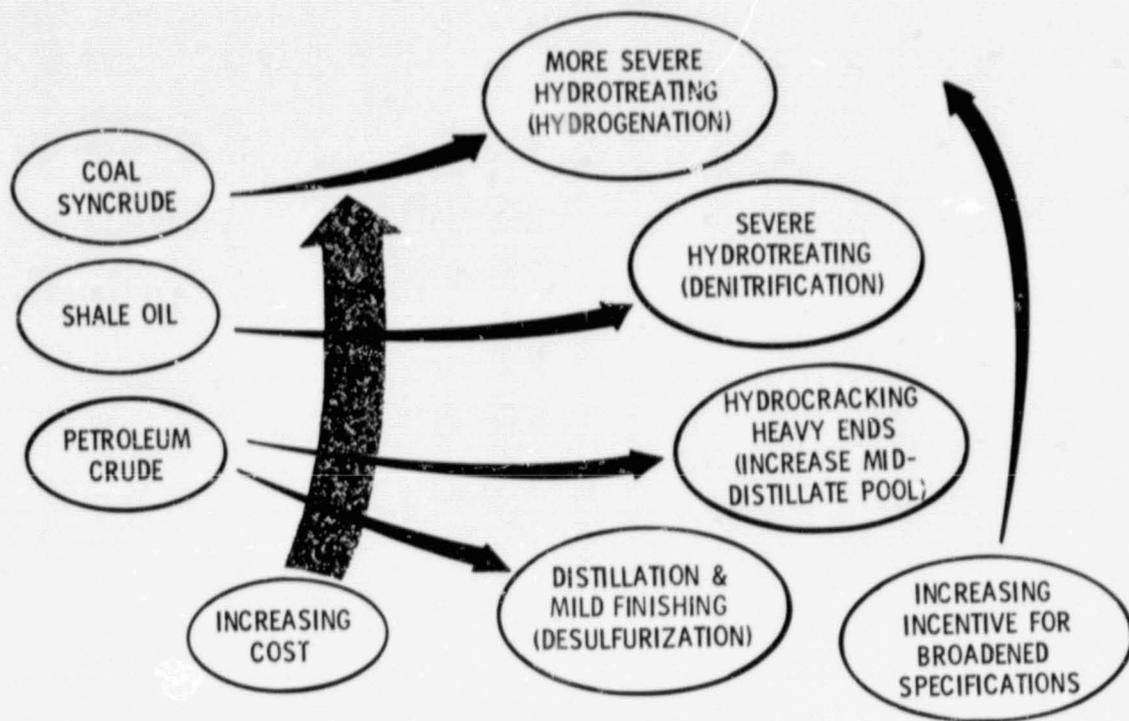


Figure 3. - Jet fuel production alternatives.

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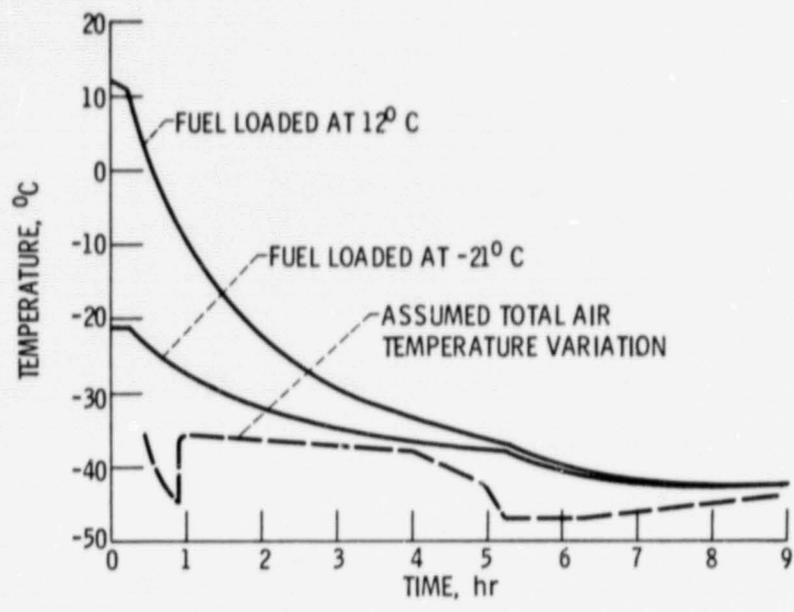


Figure 4. - Predicted fuel temperature for a long-range (9100 km) commercial aircraft mission, based on a minimum static air temperature of -72°C .

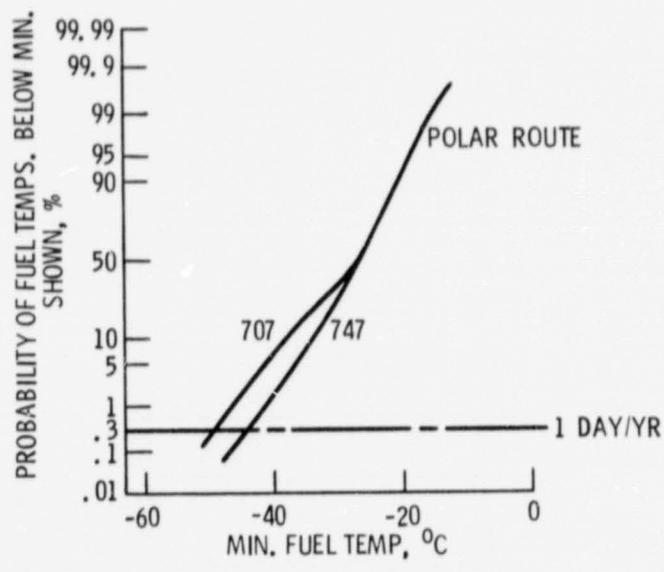
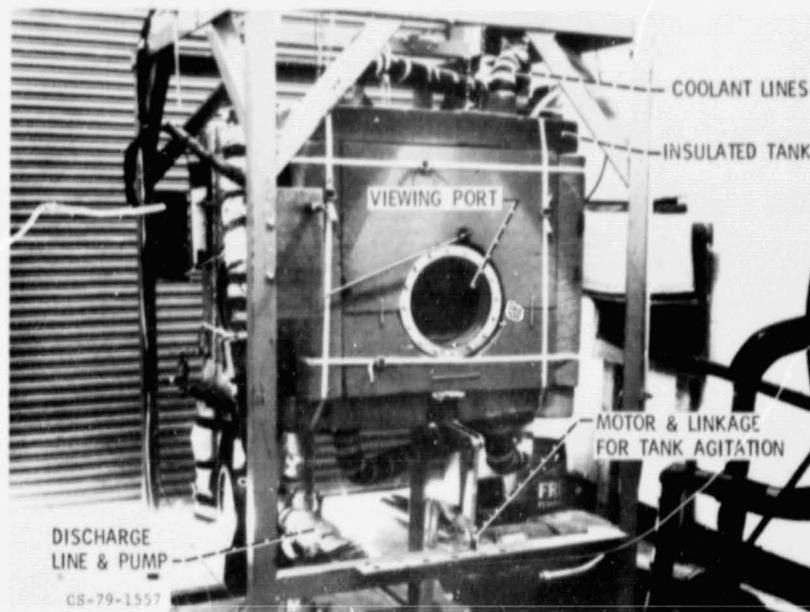
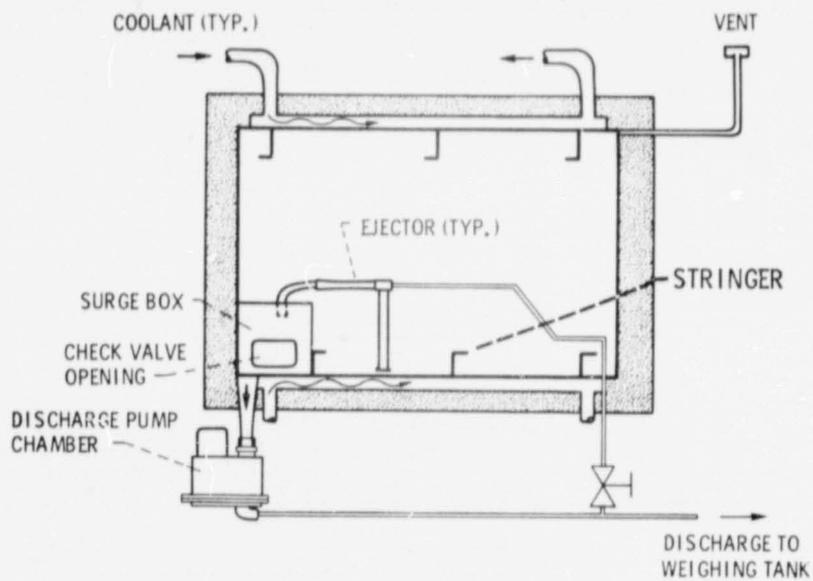


Figure 5. - Summary of in-flight minimum fuel temperature measurements.

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(a) PHOTO OF APPARATUS.



(b) CROSS-SECTION OF APPARATUS.

Figure 6. - Apparatus used to simulate low temperature environment of aircraft fuel tank.

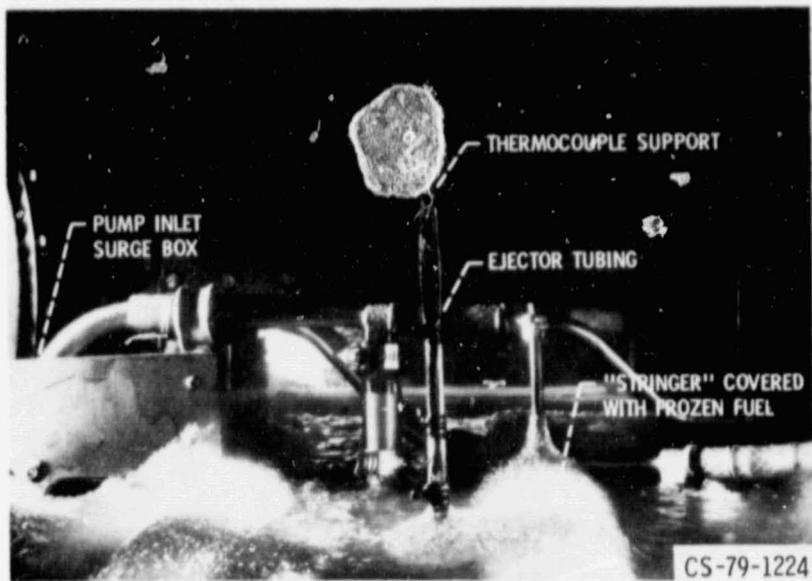


Figure 7. - Interior view of fuel tank simulator apparatus after completion of test with approximately 8.8 percent fuel holdup.

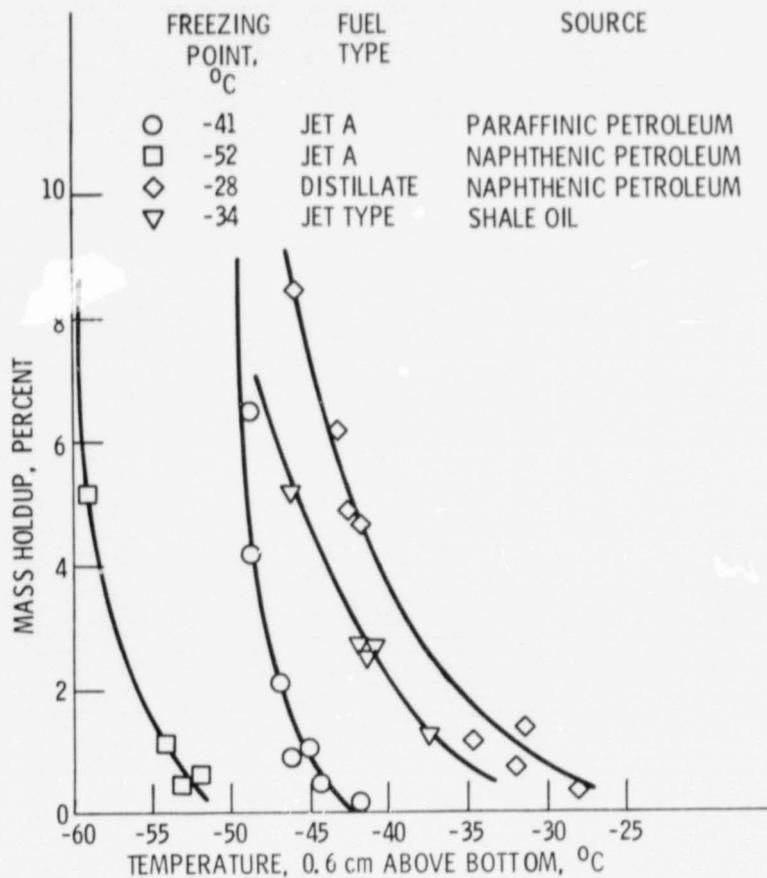


Figure 8. - Results of fuel tank simulator tests with low holdup conditions.

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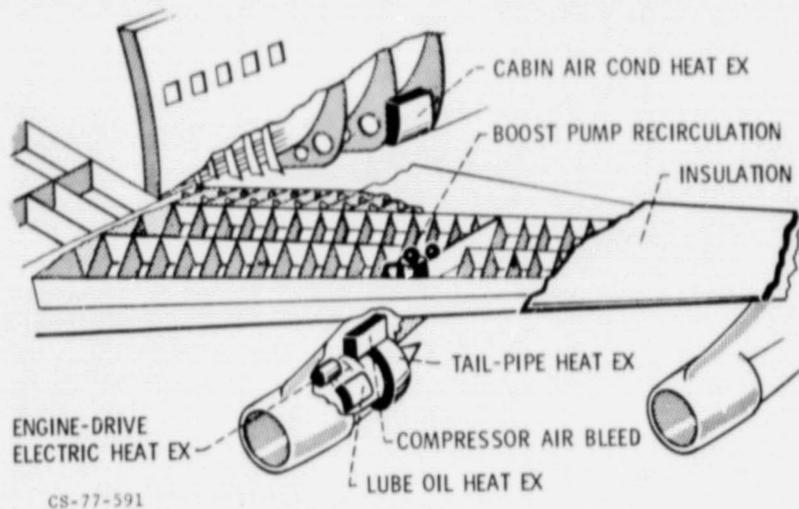


Figure 9. - Potential fuel tank heating sources.

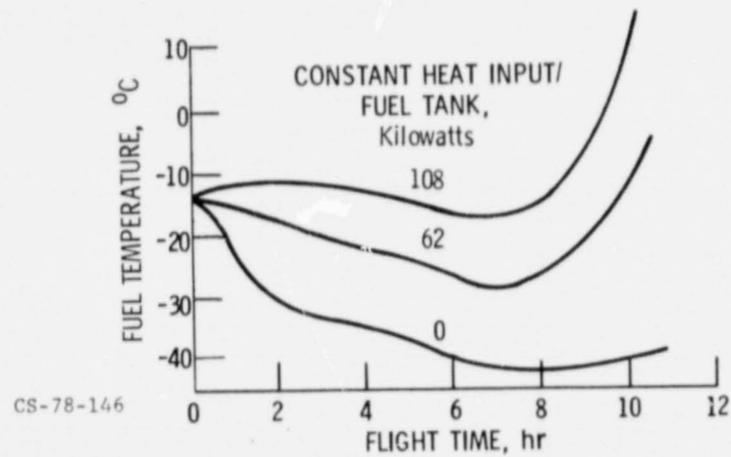


Figure 10. - Fuel-tank temperatures for a 9100-kilometer flight with heating.

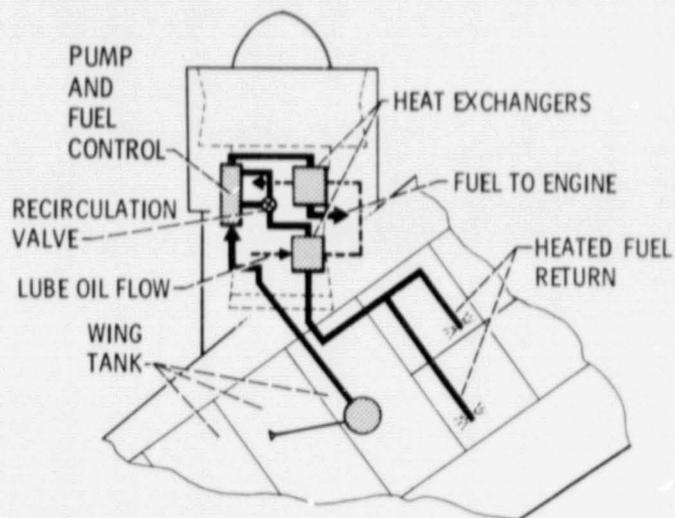


Figure 11. - Schematic of a lubricating-oil heat exchanger fuel heating system.

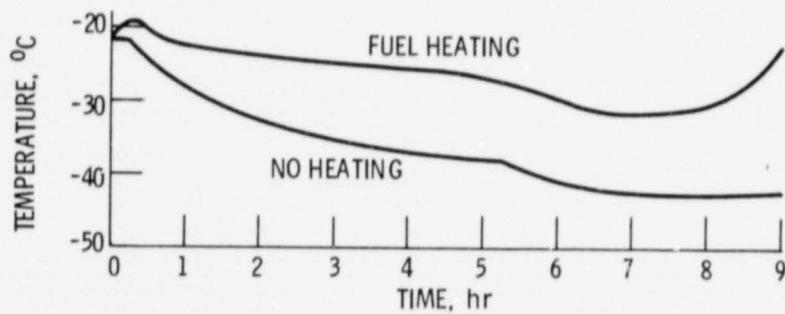


Figure 12. - Predicted fuel temperature for a 9100 km commercial aircraft mission, with fuel heated by lubricating oil heat rejection.

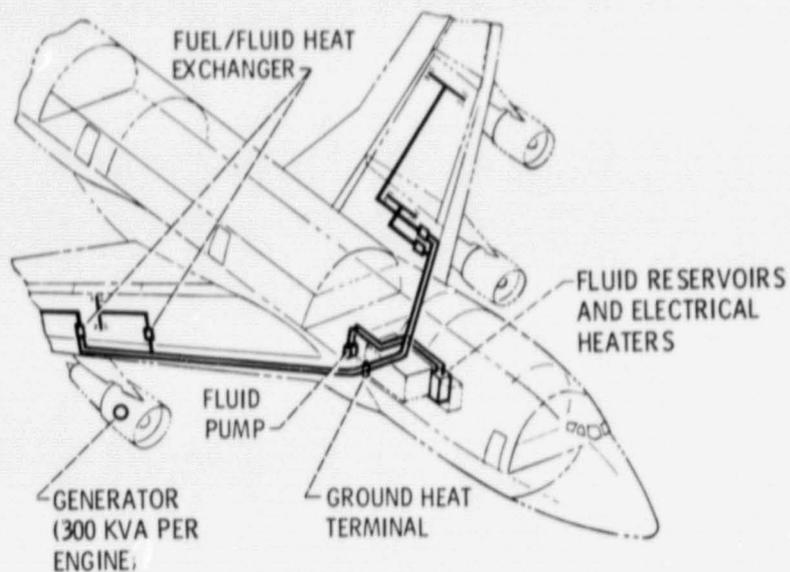


Figure 13. - Schematic of electrical fuel heating system on a wide-bodied jet aircraft.

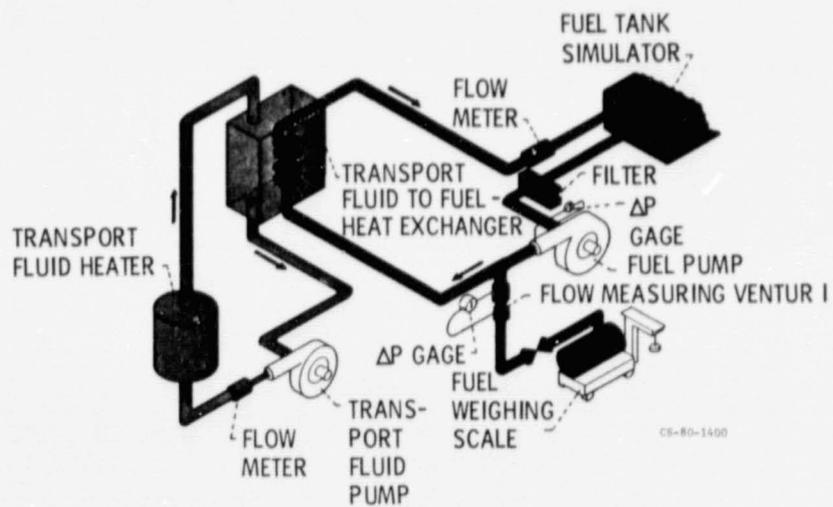


Figure 14. - Sketch of fuel heating system simulator.

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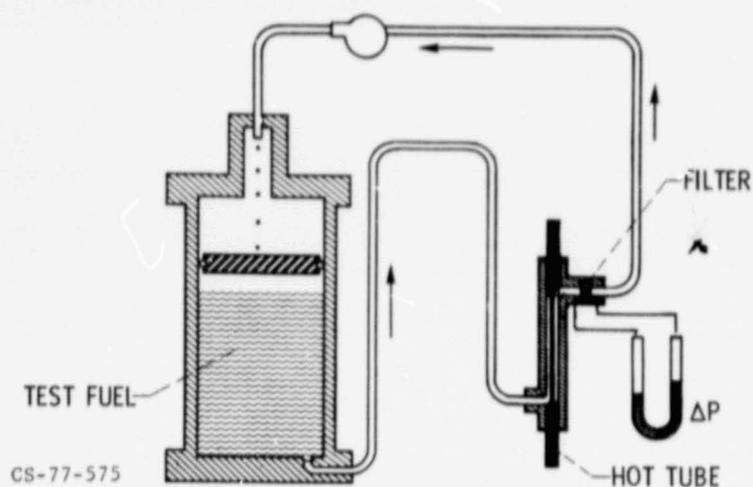


Figure 15. - Schematic of jet fuel thermal oxidation tester.

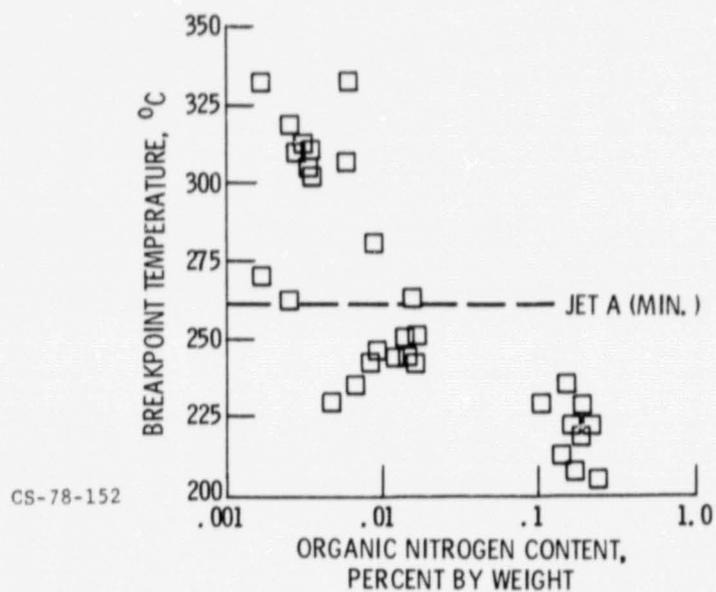


Figure 16. - Effect of nitrogen content in oil-shale-derived fuels on JFTOT breakpoint temperature.

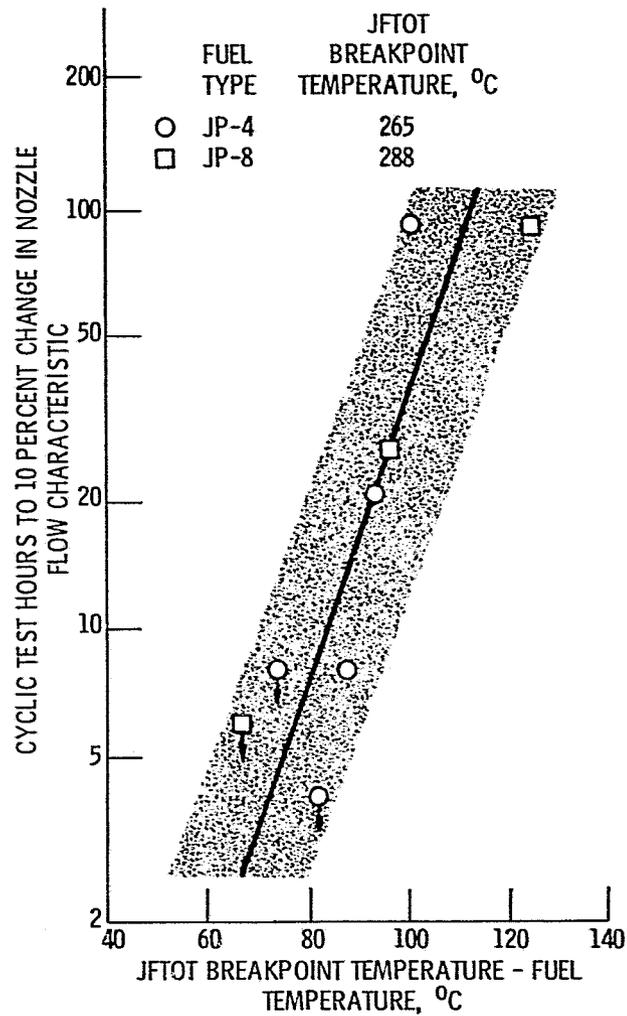


Figure 17. - Effect of fuel temperature on F101 fuel nozzle performance with two fuels in accelerated fuel system simulator tests.

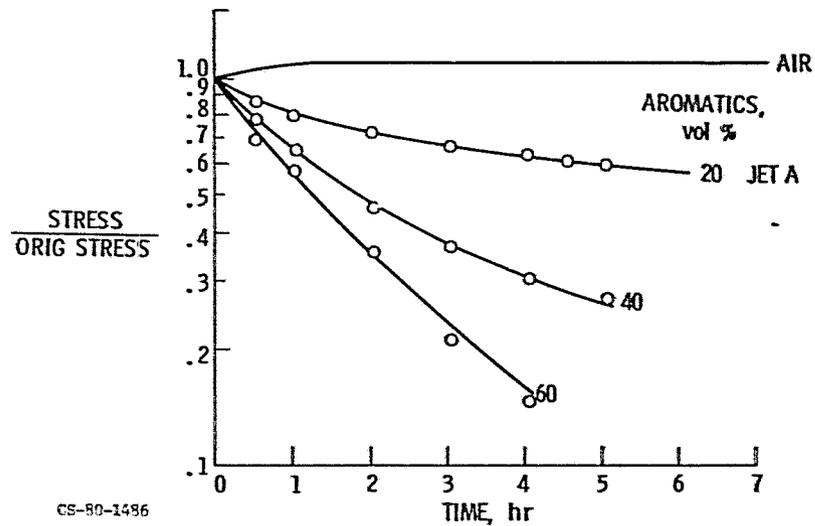


Figure 18. - Stress relaxation of butadiene-acrylonitrile rubber exposed to Jet A with varying aromatics content at 150°C.

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16. Abstract Consideration of a number of uncertain factors which may influence the future availability of high quality, reasonably priced aviation fuels suggests that the effect of potential changes in aircraft fuels be examined. In view of possible future crude sources and characteristics some changes in fuel properties may be desirable to provide a more flexible and reliable fuel supply as well as minimizing fuel processing in the refinery. However, before any change can be considered, the impact on the entire air transportation industry including the costs of developing and operating new technology must be carefully assessed and compared with perceived benefits related to fuel supplies. This paper identifies some possible changes in fuel properties based on current trends and projections, examines the effect of those changes with respect to the aircraft fuel system and describes some technological approaches to utilizing those fuels. Fuel system research activities are also described which are being conducted to establish a data base for broadened property fuels that can be used in future technical and economic tradeoff studies.			
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