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EFFECT OF BROADENED-SPECIFICATION FUELS ON AIRCRAFT ENGINES AND FUEL SYSTEMS

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Abstract

A wide variety of studies on the potential effects of broadened-specification fuels on future aircraft engines and fuel systems are summarized. The compositions and characteristics of aircraft fuels that may be derived from current and future crude-oil sources are described, and the most critical properties that may affect aircraft engines and fuel systems are identified and discussed. The problems that are most likely to be encountered because of changes in selected fuel properties are described; and the related effects on engine performance, component durability and maintenance, and aircraft fuel-system performance are discussed. The ability of current technology to accept possible future fuel-specification changes is discussed, and selected technological advances that can reduce the severity of the potential problems are illustrated.

Introduction

Many studies are currently under way within the United States to predict the future availability and characteristics of crude oils.[1-4] Included in many of these studies is an analysis of the processing required to upgrade low-quality feedstocks, such as crude oils derived from oil shale and coal, to the current specifications for jet aircraft fuels. These studies conclude that severe economic and energy consumption penalties will be likely if these low-quality crudes must be refined to current specifications. Similarly, converting high-boiling-range petroleum fractions to current jet-fuel specifications, which may be necessary because of a shortened supply of middle distillates requires energy-intensive hydroprocessing.[5] An alternative to the additional processing approach would be to relax fuel specifications and thereby minimize the economic and energy consumption penalties. However, the relaxed-fuel-specification approach would require the development of a new level of engine and aircraft fuel-system technology.[6]

The main advantages and disadvantages of these two approaches are assessed in table I. The continued production of current-specification jet fuel certainly is the best approach from the aircraft airframe and engine manufacturers' point of view. But, as already mentioned, it could be prohibitive economically and in refining-energy consumption. Broadening the current jet-fuel specifications would obviously minimize the energy consumption and economic penalties but could require more complex component technology and adversely affect engine life. In the final analysis, the choice between maintaining current fuel specifications or establishing allowable variations in fuel properties and implementing advanced engine technology will be arrived at through an iterative process. Obviously, economics will play a key role, as will the availability of high-quality crude-oil feedstocks. Therefore, the criteria by which an optimum tradeoff can be made between future fuel specifications and advanced technological needs must be established. This is the principal objective of the Fuels Technology Program that is being conducted by the National Aeronautics and Space Administration (NASA) and from which a large part of the information presented in this paper was derived. Many other programs sponsored by both the U.S. Government and private industry are also under way, and they too have contributed information to this paper.

The results of a variety of investigations are summarized, and illustrations taken from these investigations are used to describe the relative effects of selected fuel properties on the behavior of engine components and aircraft fuel systems. The fuel properties used in these investigations are those that are most likely to be relaxed in future fuel specifications.[7] Illustrations are used to describe several technological advances that may be available for future engines and fuel systems that would use broadened-specification fuels. Finally, the areas of technology needing the most attention are described, and several activities that are under way to address these needs are briefly discussed.

Composition and Characteristics of Jet Fuel

Petroleum Crude Oil

The compositions of some typical petroleum crude oils obtained from various sources are shown in table II.[8] Selected data are included in the table for both the total crude and several middle-distillate fractions from which jet and diesel fuels are produced. The sulfur content of petroleum obtained from different sources varies considerably. The variability of the hydrogen content is significant in that many of the currently important U.S. sources of petroleum, such as the Alaskan crude from Prudhoe Bay, tend to have relatively high aromatic content. The nitrogen content of petroleum is generally quite low. The higher-boiling-range fractions have relatively higher sulfur and nitrogen contents and lower hydrogen contents than the lower-boiling-range fractions. (A lower hydrogen content is related to a higher aromatic content.)

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Synthetic Crude Oils

A similar set of data for "synthetic" crude oils derived from oil shale and coal are also shown in table II. The sulfur, nitrogen, and hydrogen contents of the coal-derived syncrude produced by the Synthoil process were all lower than those of shale oil. The higher-boiling-range fractions in the shale oil contain considerably more nitrogen (in the form of organic nitrogen compounds) than do the lower-boiling-range fractions. The hydrogen contents of both the shale oil and the coal syncrude are reduced significantly as the boiling point is increased. The low hydrogen content of the middle-distillate fractions in the coal syncrude is particularly significant because of the corresponding high aromatic content. (The composition of the Synthoil fractions can vary considerably depending on the properties of the coal feedstock and the process operating conditions, including the degree of hydrogenation.) In addition, other processes such as H-coal[9] would produce an oil with somewhat different properties from the same Kentucky coal feedstock.

Current-Specification Fuels

The American Society for Testing Materials (ASTM) specifications for jet fuels - including Jet B, Jet A, and Jet A-1 - are shown in table III.[10] The average properties of a current Jet A fuel are also shown for comparison. In general, the average properites of Jet A fuel fall well within the specification limits. Many of these properties are interrelated and can vary considerably with changing base-point conditions.

The boiling range of jet fuels extends from about 60° C for Jet B to about 270° C for Jet A and can overlap the boiling ranges of several other petroleum products. For example, the boiling range of Jet B fuel (JP-4) is comparable to the boiling range of gasoline (also naptha for petrochemicals) at the low end and is comparable to the boiling range of Jet A (JP-5), no. 2 diesel oil, and home heating oil at the high end. The boiling range of Jet A fuel is comparable to the high-boiling-range no. 2 diesel and home heating oils. This overlap of boiling range could have a significant effect on fuel specifications if they have to be broadened to improve jet-fuel availability.

One measure of fuel volatility, the initial boiling point, is determined by the allowable limits for flashpoint (Jet A) or Reid vapor pressure (Jet B) as shown in table III. Fuel volatility must be low enough to prevent the formation of flammable vapors at ambient conditions. Jet A is currently endorsed for commercial aircraft because of the lower probability of fire, due to its lower volatility, during emergency landings.[11] Although low volatility is preferred for safety, it adversely affects the ignition and altitude relight capabilities of the fuel. Another fuel property that is important in determining fuel ignition characteristics is fuel viscosity. The less volatile fuels are more likely to encounter ignition difficulties partly because of their higher viscosities. As with vapor pressure, the variation of viscosity with temperature is an exponential effect and becomes much more severe as temperature is reduced.

The preceding discussion was not meant to include all the characteristics of current specification fuels. It was intended only to point out some selected key fuel characteristics and to describe how they can vary within the listed specification limits.

Projected Changes in Fuel Properties

Perhaps one of the most significant trends in fuel properties over the last 15 years has been the steady increase in the average aromatic content of commercial Jet A fuel. This trend is illustrated in figure 1,[10] where it is compared with the current ASTM Jet A specification limit. During the fuel shortage of 1973-74, limited quantities of highly aromatic jet fuels were used, as illustrated in figure 7 by the 22-percent aromatic content of Jet A refined from a heavy Arabian crude. An estimate for Jet A refined from Alaskan crude indicates that the aromatic content may be as high as 25 percent. Because of these recent trends and projected occurrences, a waiver limit of 25-percent aromatic content has been set by the ASTM for Jet A fuel. The higher-aromatic-content petroleum crude sources will require additional hydroprocessing at the refinery to reduce the aromatic content to current specifications. Furthermore, future shortages of middle distillates may necessitate the conversion of higher-boiling-range petroleum cuts to middle-distillate fractions. These "cracked" fuels would have higher aromatic content and thus would require additional hydroprocessing to meet current specifications. Hydroprocessing techniques to improve fuel quality in terms of hydrogen and nitrogen content will also be needed if fuels refined from "synthetic" crude-oil feedstocks must meet current specifications. The increasing trend toward higher-aromatic-content fuels, regardless of the crude source, will result in straight-distillation fuels with lower hydrogen content. (Hydrogen content generally decreases in a linear manner with increasing aromatic content.)

Jet A fuel has a relatively narrow boiling range (table III[10]) Its final boiling point of approximately 270° C is necessary to comply with limits on the freezing point. (The freezing point of a fuel is generally defined as the temperature at which wax components in the fuel begin to solidify.) Freezing point is quite sensitive to variations in final boiling point, and any changes toward using higher-boiling-range fractions will correspondingly raise the fuel freezing point.[6]

As previously mentioned, potential increases in the aromatic content of petroleum crudes will result in lower fuel hydrogen content unless hydrotreating is done at the refinery. Additional hydrotreating will also be needed to reduce the nitrogen content and to increase the hydrogen content of future fuels refined from oil shale and coal syncrudes if they are to meet current specifications. Hydrocracking will be required to convert higher-boiling-range fractions to the boiling range and composition of current-specification jet fuels.

These projected needs for additional hydrotreating will surely increase the cost and energy consumption required to refine future fuels to current specifications. Therefore some broadening of current specifications may be needed to minimize adverse effects on cost and energy consumption at the refinery. Several of the major fuel properties that could be affected by such broadened specifications are shown in table IV.[10] The values in the table are levels that have been suggested[7] as being reasonable limits of a "broadened specification" fuel.

Engine Performance

Exhaust Emissions

The principal fuel properties that can affect engine exhaust emissions are volatility, hydrogen content, and fuel-bound-nitrogen content. These properties affect the exhaust emissions that have been designated as air pollutants and that are currently being regulated by the U.S. Environmental Protection Agency (EPA) (i.e., carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and smoke).

Fuel hydrogen content can affect all four pollutant emissions. Very dramatic increases in combustor smoke number with decreasing fuel hydrogen content have been obtained in experimental evaluations with conventional combustion chambers of current-technology aircraft engines. An example of this effect, for a conventional can-type combustor, is illustrated in figure 2.[12] At a simulated takeoff operating condition, the measured Society of Automotive Engineers (SAE) smoke number increased in a nearly linear manner as the percentage by weight of fuel hydrogen content was reduced. For the engine that uses this combustor an SAE smoke number of 25 is required at takeoff conditions in order to comply with the currently proposed U.S. EPA standards.

With this same can combustor operating at idle conditions, there was a slight increase in CO and HC emissions with decreasing fuel hydrogen content. The effect of fuel hydrogen content on CO and HC emissions is most prevalent at idle because of the much lower compressor discharge pressure and temperature at that condition. The effect of fuel hydrogen content on CO and HC emissions may not be significant in current and future high-pressure-ratio engines because the higher compressor discharge pressures and temperatures of these engines should minimize or eliminate this potential problem.

Increasing fuel-bound-nitrogen content is expected to affect only NO_x emissions. This effect for a low-pressure-ratio-engine combustor is illustrated in figure 3[13] for three simulated engine operating conditions. The NO_x emissions increased substantially at all operating conditions as fuel-bound-nitrogen content was increased. The increase in NO_x emissions would be even greater if all the fuel-bound nitrogen were converted to NO_x. A conversion efficiency of about 50 percent is quite typical in a combustion process and was realized from the results shown in figure 3. However, conversion efficiency can vary with combustor configuration and operating conditions. Conversion efficiencies from as high as 80 percent to as low as 40 or 50 percent have been realized.

In these illustrations (figs. 2 and 3) the fuel hydrogen and fuel-bound-nitrogen contents were varied by "doping" current specification fuels with such pure compounds as alkyl benzenes and pyridine. The range of hydrogen and nitrogen contents was purposely made large so that the effects could be evaluated parametrically. The lower and upper limits do not imply that these levels are expected in future fuels. Also most of the results were obtained in controlled combustor-test-rig experiments and thus may not be directly comparable to results obtained in operational engines. Nevertheless the trends in exhaust emissions illustrated are felt to represent what can be expected if fuels with properties similar to those of the test fuels are used.

Ignition and Relight Limits

The principal fuel properties that can affect the ignition and relight limits of an aircraft engine are volatility and viscosity. Fuel volatility and viscosity affect the atomization and vaporization characteristics of the fuel as it is sprayed into the combustion chamber. The effect of these properties on combustor ignition characteristics is illustrated in figure 4,[14] where time-to-start is plotted as a function of combustor primary-zone equivalence ratio for a JP-4 fuel and a Jet A fuel. Two effects are clearly shown in figure 4. The first effect is that for a given fuel (e.g., JP-4) the time-to-start increases dramatically with decreasing equivalence ratio after a critical minimum value is reached. This occurs because, for a fixed-orifice nozzle, reducing fuel-nozzle flow rate has an adverse effect on the atomization quality of the fuel spray. The second effect relates to fuel volatility and viscosity. Substituting a Jet A fuel for a JP-4 fuel, and thus changing both volatility and viscosity, made a higher primary-zone equivalence ratio necessary for successful ignition. The need to provide a higher primary-zone equivalence ratio for fuels with lower volatility and higher viscosity could make it difficult to obtain adequate ignition limits in a fixed-geometry conventional combustor. Volatility and viscosity can also affect the altitude relight envelope of an engine, as illustrated in figure 5.[14] This figure presents test-rig data of a conventional high-bypass-ratio jet engine combustor tested with both cold and heated JP-5 fuel. Reducing fuel volatility and increasing viscosity, as simulated by using the cold fuel, caused a noticeable loss in altitude relight capability, especially at the higher flight Mach numbers.

Technology Needs Related to Performance Problems

A variety of techniques can be considered to minimize potential ignition and relight problems. Heating the fuel to reduce its viscosity can be effective in improving fuel atomization. Primer or auxiliary fuel nozzles, designed for use during ignition and relight only, can improve fuel atomization at engine starting conditions. Torch ignitors have been very effective in many military applications for high-altitude relight. All these techniques add a degree of complexity to the engine and its fuel control. Therefore, simpler and more reliable techniques are surely going to be needed.

Several potential design techniques can be used to control the exhaust emissions that may be aggravated by broadened fuel specifications:

(1) Staged combustion
(2) Air-atomizing fuel injectors
(3) Intensive fuel-air mixing
(4) Lean combustion
(5) Fuel-air premixing
(6) Fuel prevaporization

In practice, a combination of several of the techniques could be used in any particular combustor concept. As an example, both the Vorbix and double-annular combustor concepts, which were evolved during the NASA Clean Combustor Program[15, 16] and are shown schematically in figure 6,[14] incorporate fuel staging, air-atomizing fuel injectors, and lean combustion. The Vorbix combustor concept also uses intensive fuel-air mixing. Both combustor concepts substantially reduced all the gaseous exhaust emissions below the levels of the conventional engine combustors that they were designed to replace. The use of one stage (pilot) to minimize CO and HC emissions during idle and a second stage (main) to minimize NO_x emissions during high-power operation proved to be very effective in test-rig and experimental engine tests. Staged-combustor concepts such as these may be needed to minimize the impact of decreasing fuel hydrogen content or increasing fuel-bound-nitrogen content on aircraft-engine exhaust emissions.

If more dramatic reductions in exhaust emissions are required (especially in NO_x), combining techniques such as prevaporizing the fuel and premixing the fuel and air may be needed. Prevaporizing-premixing techniques allow combustion to occur at extremely low fuel-air ratios and thus dramatically reduce flame temperatures and corresponding NO_x formation. Successful development of prevaporizing-premixing techniques could provide additional decreases in NO_x emissions, such as those discussed in reference 17.

Although most of the aforementioned concepts have been or are being evolved to respond to environmental constraints for engines using current-specification jet fuels, they should also be effective in future engines that would use broadened-specification fuels. Therefore continued investigation to define the capability of these concepts to control exhaust emissions when using fuels with broadened specifications is certainly going to be needed.

Engine Component Durability and Maintenance

Changes in future fuel characteristics will probably have a pronounced effect on engine component durability and maintenance. The increasing flame temperature and luminosity that can be expected as fuel hydrogen content is reduced can cause problems in cooling combustor liners and turbine vanes and blades. Changes in fuel volatility and chemical stability can be expected to increase carbon formation and deposition. And any increase in reactive trace constituents will certainly aggravate erosion and corrosion problems.

Flame Characteristics

The fuel property that has the largest effect on the characteristics of the flame within a gas-turbine combustor is hydrogen content. It affects soot formation, carbon deposition, flame temperature and total flame radiation. The effect of hydrogen content on soot formation is discussed in reference 18, wherein soot concentration is shown to increase markedly with decreasing hydrogen content. The soot formation rate can also be affected by the atomization quality and vaporization rate of the fuel being injected into the flame zone. Both volatility and viscosity can affect these processes. The calculated effect of fuel viscosity on the drop-size distribution of a typical fixed-orifice fuel nozzle is illustrated in figure 7.[19]

The effect of hydrogen content on flame radiation is shown in figure 8,[18] where total radiant energy is plotted as a function of combustion pressure and fuel hydrogen content. Two distinct characteristics are observable: (1) total radiant energy increases dramatically as the fuel hydrogen content is decreased at a constant combustion pressure; and (2) total radiant energy increases significantly as combustion pressure is increased at a constant fuel hydrogen content. Reducing hydrogen content or increasing pressure both increase soot concentration and thus increase flame luminosity.

Combustor Liner Temperature

The effective cooling of combustor liners is becoming more difficult because of the changing engine-cycle conditions associated with high-pressure-ratio engines. Increasing combustor-inlet temperature and pressure increases flame temperature and flame emissivity, both of which will cause higher liner-wall temperatures. The sensitivity of liner-wall temperatures to flame emissivity (luminosity) is also strongly affected by fuel hydrogen content. This effect is illustrated in figure 9,[12] where experimentally measured liner temperatures are plotted as a function of the hydrogen content in the fuel used for testing a can combustor at two simulated engine operating conditions. The steeper slope of the measured liner temperatures at the simulated cruise conditions suggests that the flame luminosity effect becomes more pronounced at cycle pressures associated with the cruise condition of the engine that uses this combustor. The effect of combustor pressure on soot formation, and hence flame luminosity, is discussed in detail in reference 20.

Carbon Deposition and Coking

Aircraft jet fuels must be thermally and chemically stable at all temperatures that they will encounter in the fuel system. No gums or deposits should occur on heated surfaces, such as heat-exchanger tubes, and no cracking of the fuel or particulate formation should occur that could clog small passages such as those in fuel nozzles. Laboratory tests have been developed to check on this particular fuel behavior. In the JFTOT procedure, a small tube is heated electrically to a designated test temperature. The fuel flows up through an annulus surrounding the heated surface and out through a test filter. During this procedure any tendency of the fuel to form particulates large enough to block the test filter can be noted by a buildup of pressure drop across the filter. At the same time, deposits such as those shown in figure 10[14] may also form on the heated tube. Any chemical changes, such as fuel-bound-nitrogen content, that could cause fuel instabilities should occur at an increased rate as the fuel temperature is increased. This is clearly shown in figure 10 by the lower temperature required to form deposits as fuel-bound-nitrogen content is increased. In general, either the pressure drop across the test filter increases at a faster rate or the deposits on the tube build up at a faster rate as the test temperature is increased. Thus one way of comparing the thermal stabilities of fuels is to determine the maximum temperature of the heated tube before the test exceeds certain specified limits of pressure drop or tube deposit buildup. This temperature is then referred to as the "breakpoint temperature."

Breakpoint temperatures determined for a number of oil-shale-derived fuels by the JFTOT procedure are shown in figure 11[10] as a function of fuel-bound-nitrogen content. For the cases shown in figure 11, the breakpoint temperatures were determined from tube deposit buildup, such as that shown in figure 10. Tube deposit buildup turned out to be the limiting factor. The variation in fuel-bound-nitrogen content in the test fuels was controlled by hydrotreating the fuels to different degrees of severity. The effect of the fuel-bound-nitrogen content is significant, and these data indicate that a nitrogen content above 0.01 percent by weight would reduce the breakpoint temperature to levels below the minimum allowable for current Jet A fuel (table I). Therefore, crude feedstocks with high fuel-bound-nitrogen content may require considerable hydrotreating in order to avoid deposition problems on heated surfaces in engine systems. Although it is known that fuel-bound-nitrogen is a major factor in fuel instability, it is not possible to determine if it is solely responsible for all the stability difference shown in figure 11.

Figure 12[10] shows the breakpoint temperature for some coal-derived fuels as a function of hydrogen content in weight percent. The fuel-bound-nitrogen content was 6 ppm or less in all the test fuels. For the cases shown in figure 12, the general trend was that breakpoint temperature increased as the hydrogen content increased. A 260° C breakpoint generally required at least a 13-percent hydrogen content in the fuel. Typical Jet A, which has a hydrogen content of about 13.5 to 14 percent, must have a breakpoint temperature greater than 260° C (table I).

Carbon deposition and coking within fuel nozzles can cause problems in fuel atomization, such as illustrated in figure 13.[14] The streaking effect that is shown in the spray pattern is probably caused by deposits (coking) in the small fuel-nozzle passages as a result of thermal stability problems in the fuel. Poor fuel atomization can cause carbon formation and deposition problems within a combustor and can also result in significant hot-streak and pattern-factor problems.

Erosion, Corrosion, and Deposition

Three factors can cause problems within the turbine area of an aircraft-engine hot section: (1) high combustion-exhaust-gas temperatures, (2) unburned combustion products and (3) impurities in both the fuel and the air. All these factors can combine to produce an environmental attack on turbine materials. Impurities such as sodium, chlorides, and sulfur can result in gaseous reactions, liquid deposition, and oxide fluxing--all of which can produce high-temperature oxidation and corrosion damage. Damage from liquid and solid deposits and fouling is caused by calcium, potassium, and magnesium impurities within the fuel. Erosion damage can be caused by liquid or solid particles (such as carbon, ash, or dirt particles) in the combustion gases. Corrosion is the most severe form of environmental attack, and the related long-term loss in specific weight can be disastrous. An example of material distress caused by erosion and corrosion is illustrated in figure 14.[14] If the allowable limits of fuel impurities such as sodium and sulfur and of fuel hydrogen content are relaxed in future fuels, erosion, corrosion, and deposition effects may become significant problems. A complete, detailed discussion of these effects is given in reference 21.

Technology Needs Related to Durability and Maintenance Problems

Several potential design approaches can improve component durability and reduce maintenance requirements:

(1) Lean-combustion techniques
(2) Advanced materials and coatings
(3) Advanced liner-cooling techniques
(4) Improved structures

Lean combustion can reduce the effect of fuel hydrogen content on flame luminosity and therefore reduce liner temperature, as shown in figure 15.[14] A maximum liner temperature more than 200° C lower than that of conventional combustors was realized when the two lean-burning combustor concepts previously shown in figure 6 were tested with a fuel having a hydrogen content of about 12.5 percent by weight. Another benefit of the lean-combustion approach that is indicated by the results shown in figure 15 is that the liner temperature appears to be insensitive to fuel hydrogen content. This insensitivity would be a significant advantage in future engines because fuels with different hydrogen contents could be used without compromising liner durability as a result of increasing liner temperatures. This then could allow a degree of flexibility in future fuel-hydrogen-content specifications.

Thermal-barrier coatings also offer the potential for lower liner temperatures. A conventional can combustor with a thermal-barrier coating is shown in figure 16.[22] A zirconia ceramic coating was applied to the liner inner wall. This combustor was tested over a range of conditions simulating engine takeoff and cruise, and the resultant effect of the ceramic coating on the maximum liner temperature is shown in figure 17.[22]

Significant reductions in maximum liner temperature from that of an uncoated liner were realized at both the cruise and takeoff conditions. Continued research and development of this and other advanced liner-cooling techniques is certainly warranted.

Solving the problems of erosion, corrosion, and deposition effects on engine hot-section life will require many of the design techniques already described. Reducing combustor soot and carbon formation and minimizing the effect of such trace constituents as sulfur, potassium, and manganese must be actively pursued. Corrosion-resistant materials are being developed, and the use of coatings to protect the parent metal is also being evaluated.[21] Continued investigation in this area is certainly warranted, as well as the continued development of advanced turbine blade and vane cooling schemes that are less susceptible to plugging by deposits.

Aircraft-Engine Fuel Systems

The fuel properties that are most likely to cause problems in aircraft-engine fuel systems are those that affect the thermal stability, flowability, pumpability, and material compatibility of the fuel. These factors are principally affected by the fuel-bound-nitrogen and hydrogen contents, the freezing point, and the aromatic content of the fuel. Another factor of concern in fuel systems is the effect of fuel volatility on safety. Since the forecasted trend in future fuels is toward a less volatile fuel, rather than toward a more volatile fuel that would present safety hazards, changes in potential safety problems are not expected and therefore are not discussed in this paper.

Deposition and Thermal Stability

Many factors are involved in the formation of fuel-system deposits. Several of the principal ones that have been identified are

(1) Fuel properties
(2) Engine-cycle pressure ratio
(3) Flight duration
(4) Fuel contamination
(5) Surface material
(6) Fuel oxygen content
(7) Fuel additives

Even though fuel properties (e.g., fuel hydrogen and fuel-bound-nitrogen contents) is only one of the many factors involved, it is the one factor that will most likely be affected by any broadening of fuel specifications for future aircraft engines.

Increasing fuel-bound-nitrogen content can result in a less thermally stable fuel. Reducing fuel hydrogen content can have a similar effect. The use of fuel as a heat sink in most aircraft fuel systems results in a rise in fuel temperature. If the fuel temperature becomes excessive, deposits can form in the heat-exchanger passages and a loss in heat-transfer effectiveness can occur. In the extreme these deposits can become severe enough to produce restrictions in the flow passages of the aircrafts fuel system.

Fuel Pumpability and Flowability

At the freezing point a fuel begins to enter a semisolid state and this can have an adverse effect on its pumpability and flowability. For example, a semisolid fuel can severely block a screen filter, as illustrated in figure 18.[14] Any blockage of this magnitude in an aircraft fuel system could have disastrous consequences. Also, as fuel is extracted from the aircraft tanks, the remaining fuel can form into a "slush" (figure 19) and this can severely decrease its pumpability. Hence maintaining fuel temperature at a safe margin above its freezing point is an absolute necessity. Therefore, any increases in fuel freezing point that could occur because of broadened specifications for future fuels must be carefully considered.

Many factors - such as flight routes, altitude, duration, and initial fuel temperature - must be considered in determining minimum expected fuel-tank temperatures in flight. An example of the calculated effect of both flight duration and initial fuel temperature on the fuel temperature for a long-range flight of 9300 kilometers is illustrated in figure 20.[14] The procedures involved in this calculation are described in reference 23. The calculations indicate that the fuel temperature would reach about -40° C, the current specified freezing point, after about 6 hours of flight, regardless of the initial temperature. A higher initial fuel temperature would allow a higher-freezing-point fuel to be used for short flights, but it would probably not provide any substantial benefit on typical long flights such as that illustrated in figure 20.

If a higher-freezing-point fuel - such as the broadened-specification fuel described in reference 7, which has a freezing point of about -29° C were to be used, some form of fuel heating would probably be required to prevent fuel pumpability and flowability problems for a long-range flight such as that illustrated in figure 21.[23]

A calculated projection of the percentage of commercial airline flights that would require fuel heating as a function of season, flight duration (mission),[23] and fuel freezing point is shown in table V.[23] The analysis used to arrive at the data shown in table V is discussed in detail in reference 23. From this analysis the need for fuel-tank heating would be very minimal for the -29° C-freezing-point fuel, but raising the freezing point to -19° C would require heating on all flights at all times of the year. From these freezing-point considerations only, it would appear that a fuel with a broadened fuel-freezing-point specification of -29° C (current value is -40° C) may be acceptable for aircraft use if fuel heating can be provided for selected flights.

Material Compatibility

The use of a broadened-specification fuel in an aircraft fuel system is also of concern because of the adverse effect that increasing aromatic content may have on the elasticity of elastomer compounds and sealants (reference 14). Many elastomer compounds can be and are tailored to specific fuel properties so that any adverse effects on elasticity could be minimized for a given fuel in a given application. However, for aircraft fuel systems that must use fuels with a wide range of aromatic contents, the material compatibility problems could become significant.

Technology Needs Related to Fuel-System Problems

Some of the technologies that must be developed to minimize or eliminate the fuel-system problems that have been described are discussed in this section. Some of the critical fuel-system areas where continued research and technology efforts will be needed are

(1) Fuel-tank heating
(2) Fuel-manifold and fuel-injection fouling
(3) Elastometers and sealants
(4) Ground handling

Although the need to improve ground-handling techniques for storing and loading higher-freezing-point fuels is recognized, it is not discussed because this paper principally addresses potential engine problems. The effects of fuel properties on fuel-manifold and injector fouling and on elastometers and sealants still need considerable evaluation before the technological needs can be clearly defined and pursued. Therefore, only those advances in technology that are needed to relieve the fuel pumpability and flowability problems that could occur when using fuels with freezing points higher than those currently specified are discussed.

The calculated effect of fuel-tank heating on fuel temperature as a function of flight time for a typical long-range, wide-bodied jet aircraft is shown in figure 21.[23] Two levels of constant heat input to the fuel were used in the computation. For the entire 9300-kilometer mission, a heat input of 3700 kilojoules per minute per fuel tank would be needed to maintain the fuel temperature above a freezing point of -29° C, and 6500 kilojoules per minute per fuel tank would be needed to maintain the fuel temperature above -18° C. Since the fuel temperature stays above the -29° C freezing point during the first several hours of the mission, no fuel heating would be needed during this portion of the mission for a fuel with this freezing point. Therefore, from an economic standpoint, it would seem reasonable to consider the use of selective heating, as required, rather than continuous heating. With selective fuel-tank heating,[10] less total heat input would be needed to heat the fuel during the entire mission. Another technique that could be used to reduce the total heat input needed for a mission would be to insulate the fuel tanks.

Some aircraft heat sources that could be used to provide the needed heat input to the fuel tanks are illustrated in figure 22.[14] Using the cabin air-conditioner and lubricating-oil heat exchangers would require only minor modifications to the aircraft and the fuel system and could be implemented with relatively low risk and cost. Using fuel boost-pump recirculation or an engine-driven electric heat exchanger would probably require minor-to-moderate modifications. Using compressor air bleed would require moderate modifications and development risks. And using a tailpipe heat exchanger would require the most difficult and highest risk modifications. The calculated increases in the weight of a typical wide-bodied jet aircraft and the resultant fuel penalties associated with using these fuel heat sources are given in table VI.[23] In the minor-to-moderate classes of modification, the lubricating-oil heat exchanger and the engine-driven electric heater appear to represent a reasonable approach from a combined heat-input and fuel-penalty consideration. Neither the air-conditioner heat exchanger nor fuel boost-pump recirculation would provide a satisfactory heat-input rate.[23] Compressor air bleed would result in a very high fuel penalty. And the tailpipe heat exchanger is not very attractive, because of its very high development risk, even though its successful application would result in the lowest fuel penalty for a given required heat-input rate (e.g., 6500 kJ/min).

Although research into all these heat-input techniques should and will be continued, the results of the present studies indicate that the engine-driven electric heater and the lubricating-oil heat exchanger may offer a reasonable trade-off between heat-input rate and fuel penalty. The electric heater technique (figure 23) may also have an additional advantage over the others because auxiliary ground power could be used for tank heating while the aircraft is on the ground with the engines off. This could be important for operations in extremely cold climates. A schematic of a lubricating-oil-heat-exchanger fuel heating system is shown in figure 24. This system is probably the simplest to use. However, very large fuel penalty associated with the weight of effective tank insulation certainly minimizes the attractiveness of this approach. The preceding results were based on calculations, and experimental verification is still needed. But they do help us to focus on the research and development to provide the technology that will be needed if fuel freezing-point specifications are relaxed.

Concluding Remarks

The critical properties of petroleum crude oil used to produce aircraft-engine jet fuel have been slowly changing because of changes in the available sources. Foremost among these changes is the slow average increase in the content of aromatic compounds and several rather large discrete increases in these compounds that have recently occurred or are projected to occur (e.g., in Alaskan crude oil). These large increases in aromatic content have led to considerable concern regarding decreases in the hydrogen content of jet fuels derived from these crude oils. Making up for possible future shortages of middle-distillate fractions by "cracking" higher-boiling-range petroleum fractions could also result in higher-aromatic-content jet fuels unless additional hydroprocessing is used to upgrade these fuels to current specifications. In addition, initial evaluations of the characteristics of jet fuels that could be refined from synthetic crude oils obtained from oil shale and coal have shown that considerable hydrotreating will be needed to upgrade the hydrogen content of these fuels to current specifications. Along with these concerns about hydrogen content, indications are that variations in fuel-bound-nitrogen content, thermal stability, boiling range, freezing point, and trace constituents may all be encountered in future jet aircraft fuels, especially in those derived from synthetic crude oils.

These potential fuel-property variations will probably adversely affect engine performance by changing ignition and relight limits and exhaust-gas emission levels. Counteracting these adverse effects will require such combustor technology advances as improved fuel atomizers, better fuel-air distribution and mixing, and lean-combustion techniques. Counteracting potential problems related to component durability and maintenance that may occur because of fuel-property changes will require such technological advances as improved fuel atomizers, lean-combustion techniques, thermal-barrier coatings, and new materials. Solving problems in aircraft fuel systems that may occur because of fuel-property changes will require fuel-tank heating techniques and "tailored" elastomer materials. Even though preliminary evaluations of technological advances in several of these areas have been encouraging, considerable research and development is still needed to make these advances acceptable in production engines and aircraft fuel systems. Furthermore, the ability to cope with problems related to potential variations in thermal stability and trace constituents has not been demonstrated to even an acceptable experimental level at the present time. The factors that contribute to variations in thermal and chemical stability are not well understood, and much more research is needed. Turbine erosion and corrosion problems may be somewhat relieved by using coatings, but considerable research is still needed to fully understand all the factors that contribute to these problems.

Although it is unlikely that future aircraft will have to operate with the wide variation in fuel properties discussed in this paper, a sound and complete technological data base must be developed if the jet aircraft community is to participate in setting acceptable variations in the specifications of future aircraft fuels, if and when such variations are needed. It is none too soon to start developing this data base since trade-offs will have to be made to determine the optimum choice between the cost and difficulty of developing advanced engine and fuel-system technology and the economic advantages to be gained by reducing the degree of refining needed to produce current-specification fuels from projected fuel feedstocks.

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TABLE I. - ASSESSMENT OF POTENTIAL ACTIONS

Action	Advantages	Disadvantages
Produce specification jet fuel	Optimized fuel properties Aircraft-engine retrofit not required	Increased refinery energy consumption Increased fuel cost
Relax jet-fuel specification	Conservation of energy Reduced fuel cost	More complex component technology required Adverse effect on engine life

TABLE II. - COMPOSITION OF TYPICAL CRUDE OILS (FROM REF. 8)

Crude source	Constituents	Total crude	Middle-distillate fractions		
			Boiling point, °C		
			120 - 205	205 - 275	275 - 345
			Content, wt %		
Nigeria (light)	Hydrogen Nitrogen Sulfur	13.0 .12 .14	13.4 .001 .02	13.1 .001 .09	12.8 .012 .17
Kuwait	Hydrogen Nitrogen Sulfur	12.7 .13 2.53	14.2 .001 .10	13.8 .004 .45	13.1 .010 1.52
Alaska (Prudhoe Bay)	Hydrogen Nitrogen Sulfur	12.3 .23 1.04	13.8 .001 .05	13.0 .009 .33	12.7 .028 .60
Shale oil (Paraho)	Hydrogen Nitrogen Sulfur	11.5 2.0 .71	12.5 .001 .90	12.2 1.01 .66	11.5 1.9 .69
Coal syncrude[a] (Synthoil)	Hydrogen Nitrogen Sulfur	9.2 .79 .22	11.0 .30 .10	10.8 .29 .09	10.4 .32 .14

[a]Kentucky coal.

TABLE III. - SPECIFICATIONS FOR AVIATION TURBINE FUEL (FROM REF. 10)

	ASTM D1655-77 standard specification for aviation turbine fuel		Average properties of Jet A (1976 ERDA)
	Jet B	Jet A, Jet A-1[b]	
Composition: maximum content of -			
Aromatics, vol%	20	20	17.0
Sulfur (total), wt%	0.3	0.3	0.06
Naphthalenes, wt%	-------------	[a]3	1.70
Olefins, vol%	-------------	[a]5	1.10
Volatility:			
Distillation temperature (max.), °C:			
Initial boiling point	-------------	-------------	171
10% recovered	-------------	204	188
20% recovered	143	-------------	195
50% recovered	188	[a]232	213
90% recovered	243	Report	246
Final boiling point	-------------	300	267
Flashpoint (min.), °C	-------------	37.8	53.7
Reid vapor pressure (max.), kPa	20.7	-------------	
Specific gravity (15° C/15° C)	0.751 - 0.802	0.775 - 0.840	
Fluidity:			
Freezing point (max.), °C	-50	[b]-40	-46
Viscosity at -34° C (max.), m^2/s (cS)	-------------	[c]15×10^{-6}	9.3×10^{-6}
Net heat of combustion (min.), kJ/kg	42 800	42 800	43 280
Thermal stability (JFTOT breakpoint temperature, °C)	260	260	--------

[a]Value is from earlier specifications; current specifications omit this.
[b]Jet A-1 freezing point is -50° C.
[c]Current viscosity specification is 8×10^{-6} m^2/s (cS) at -4° C.

TABLE IV. - MAJOR PROJECTED CHANGES IN

FUEL-PROPERTY SPECIFICATIONS

(FROM REF. 10)

	Current Jet A	Future broad-spec fuel
Aromatic content, vol%	17 - 25	30 - 35
Hydrogen content, wt%	14 - 13.5	13.0 - 12.5
Final boiling point, °C	260 - 280	290 - 330
Freezing point, °C	-45 - -40	-34 - -29
Thermal stability (JFTOT breakpoint temp, °C)	≥260	≥240

TABLE V. - UTILIZATION OF HEATING SYSTEMS (FROM REF. 23)

Mission length, km	Winter months		Summer months	
	-29° C fuel	-39° C fuel	-19° C fuel	-29° C fuel
	Flights predicted to use fuel heating systems, percent of total			
3700	53	0	45	0
5600	59	.1	50	|
9100	73	5.3	59	|
Combined utilization	62	1.8	52	|

TABLE VI. - COMPARISON OF POSSIBLE FUEL HEAT SOURCES (FROM REF. 23)

	Maximum heating rate per tank, kJ/min	Weight increase, kg	Fuel penalty, percent
Air conditioning system	2200	140	0
Lubricating-oil heat exchanger	4500	140	-.4
Fuel boost-pump recirculation	2100	140	-.4
Compressor air bleed	6500	300	3.9
Engine-drive electric heater	6500	450	.5
Tail-pipe heat exchanger	6500	250	.1
Insulation - 2.5 cm thick	----	5900	14.6
Equivalent heating by combustion	6500	----	.4

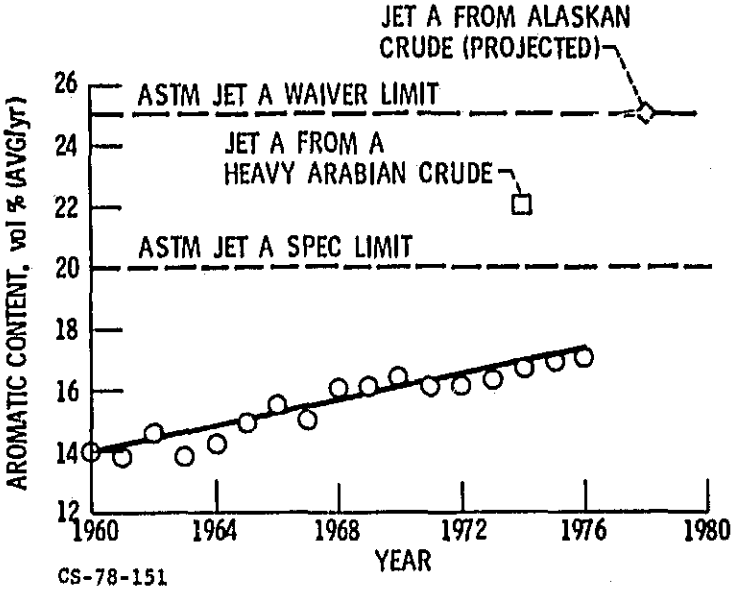


Figure 1. - Trend in aromatic content of commercial Jet A fuel.

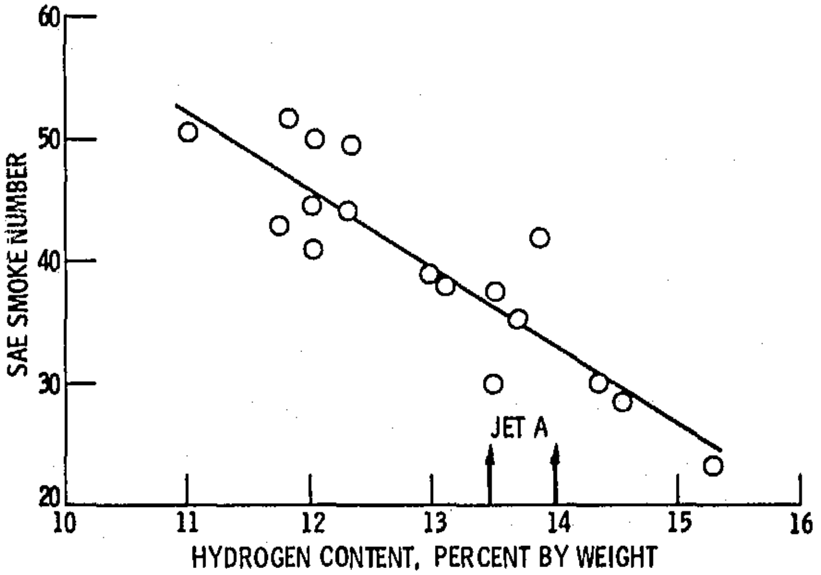


Figure 2. - Effect of fuel hydrogen content on smoke number at takeoff condition.

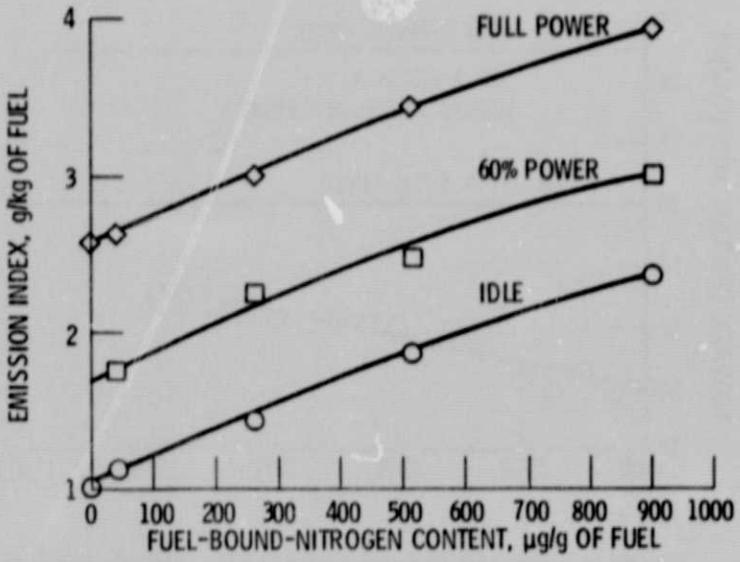


Figure 3. - Effect of fuel-bound-nitrogen content on total emissions of nitrogen oxides.

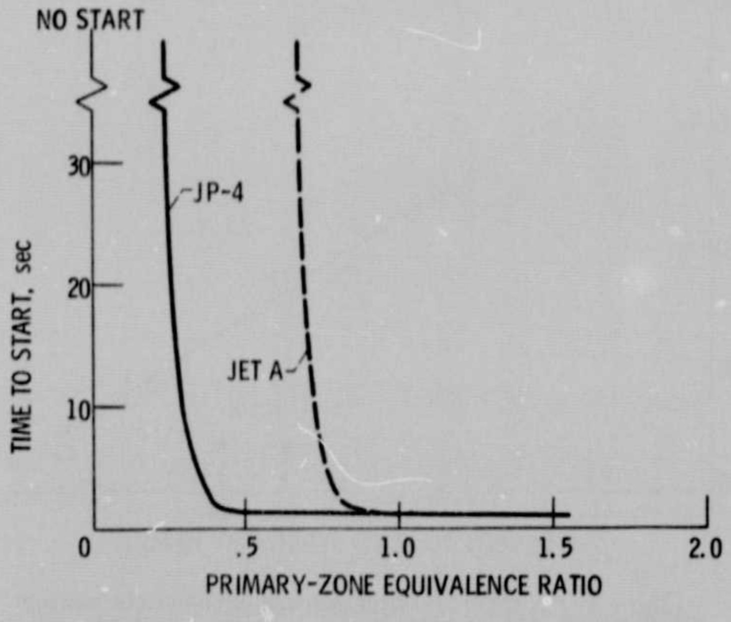


Figure 4. - Combustor ignition characteristics using different fuels.

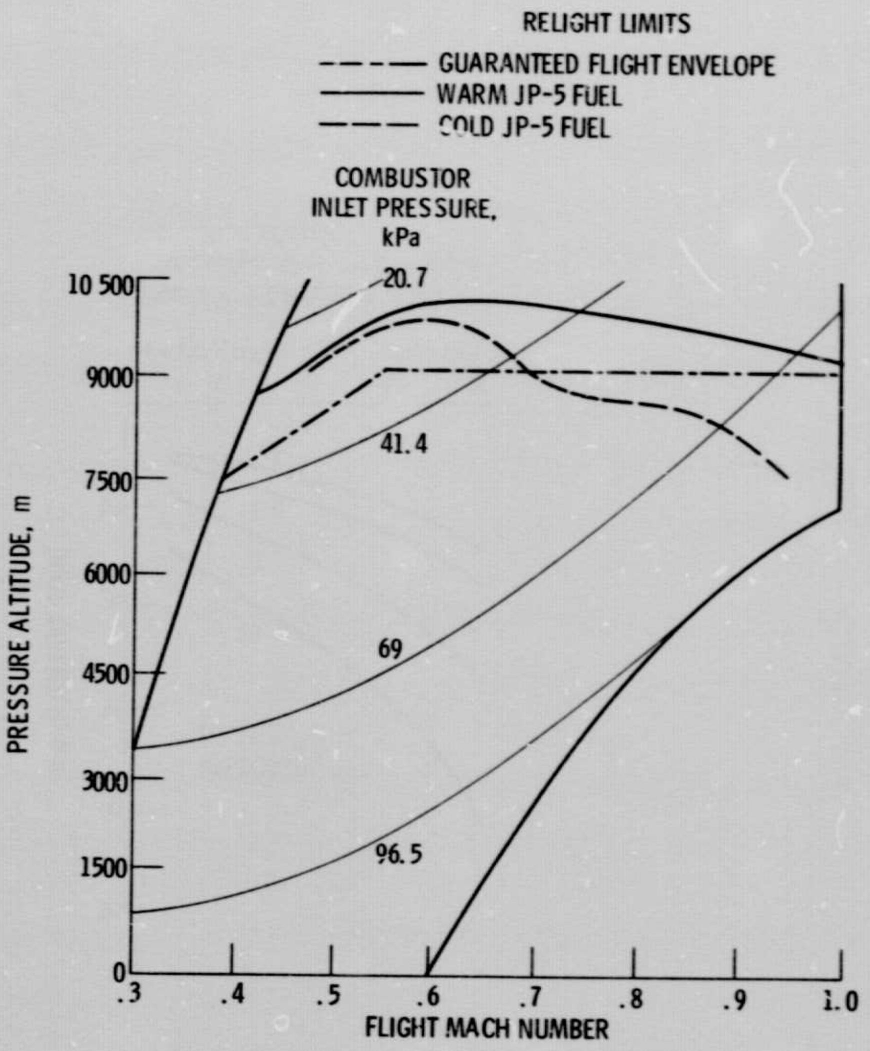
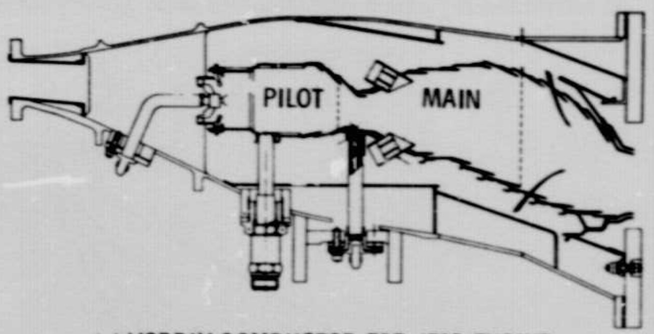
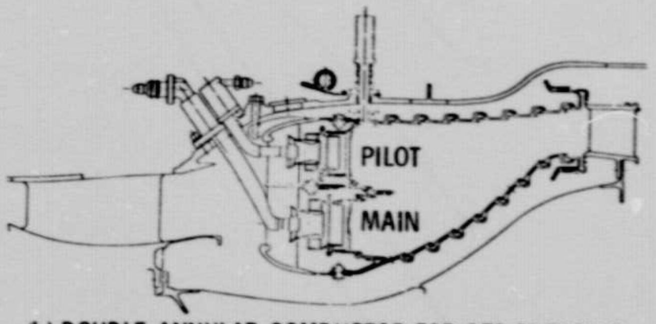


Figure 5. - Altitude relight limits of a conventional annular combustor.



(a) VORBIX COMBUSTOR FOR JT9D ENGINE.



(b) DOUBLE-ANNULAR COMBUSTOR FOR CF6-50 ENGINE.

Figure 6. - Combustor design concepts from NASA Experimental Clean Combustor Program.

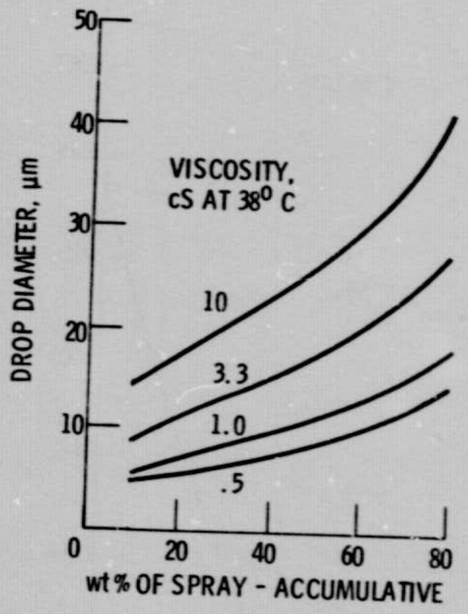


Figure 7. - Calculated effect of fuel viscosity on drop size distribution of sprays.

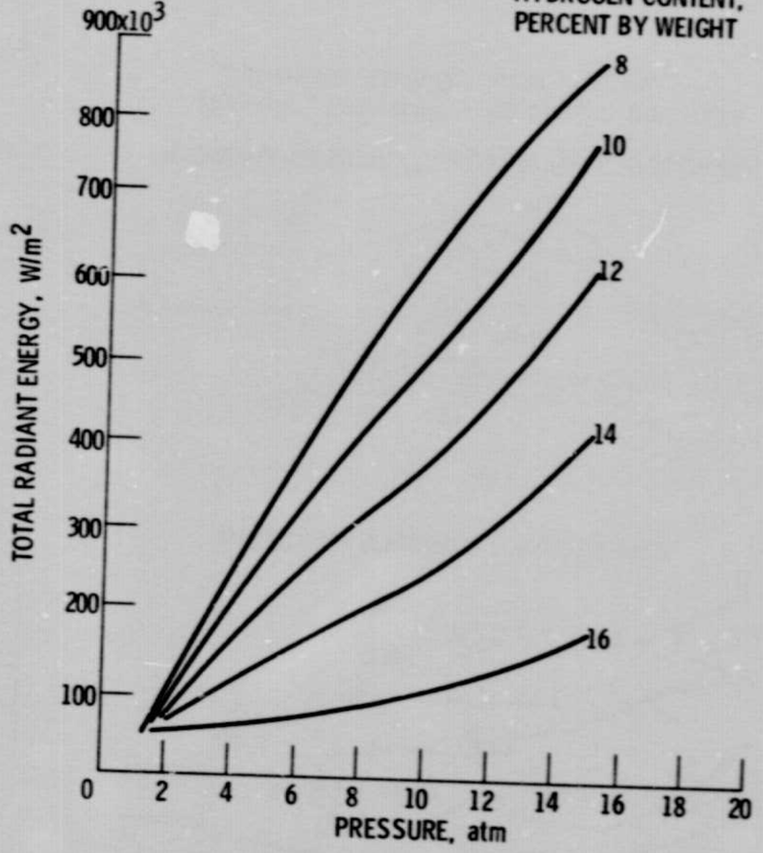


Figure 8. - Effect of fuel hydrogen content and pressure on flame radiation. Inlet-air temperature, 430° C.

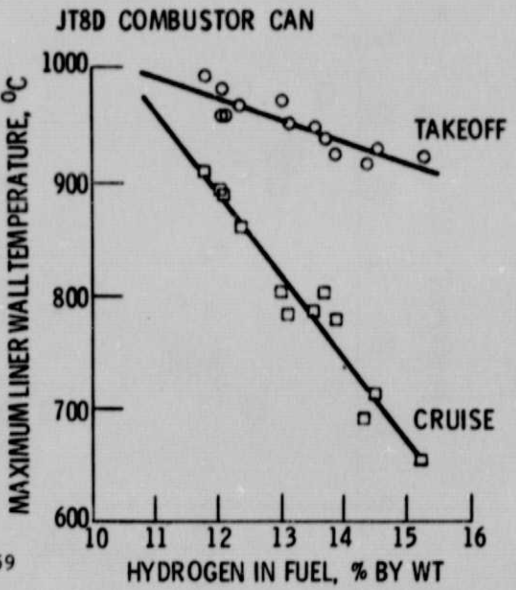


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Figure 9. - Effect of fuel hydrogen content on maximum combustor liner wall temperature.

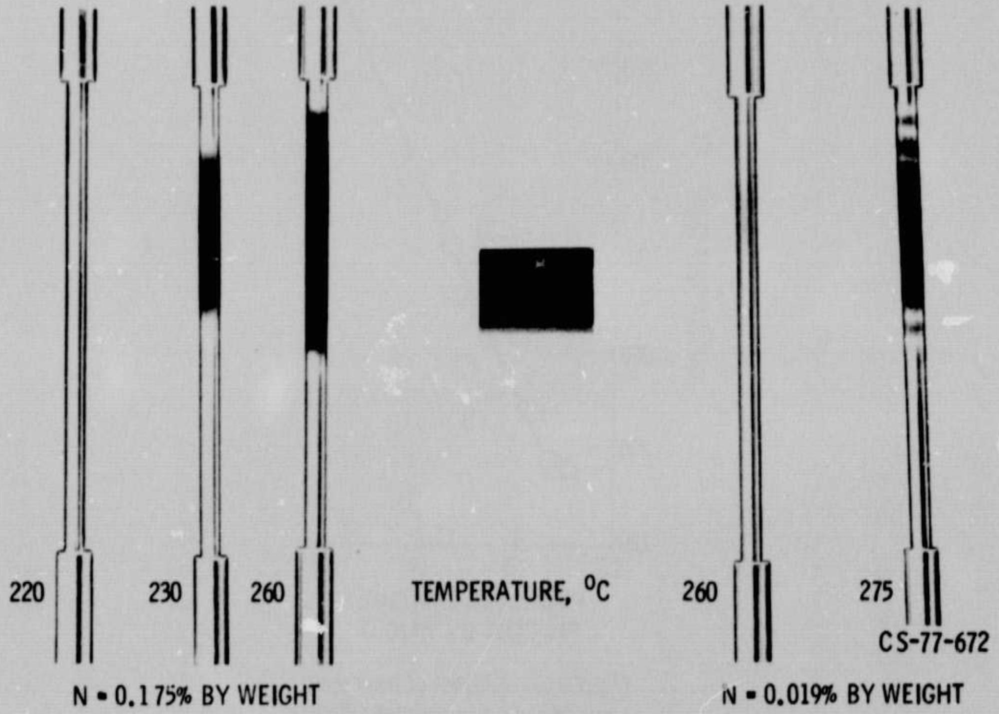
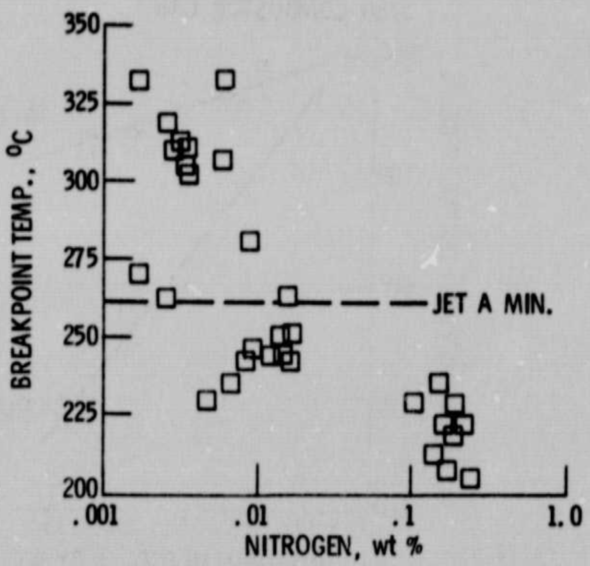


Figure 10. - Thermal stability of shale fuels.



CS-78-152

Figure 11. - Effect of nitrogen level in oil-shale-derived fuels on breakpoint temperature.

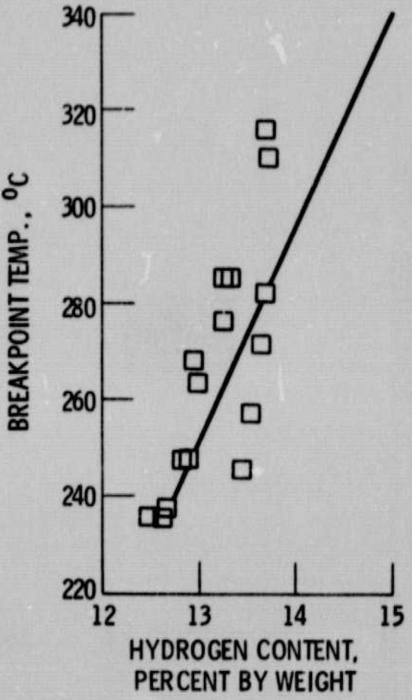
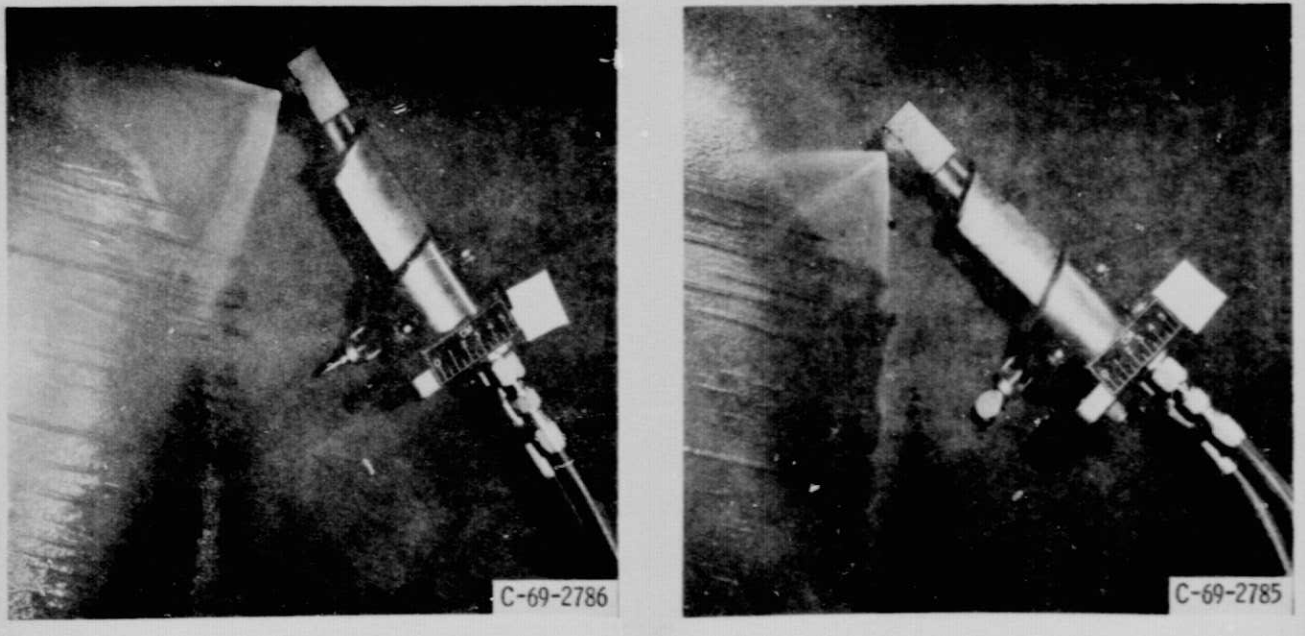


Figure 12. - Effect of hydrogen content in coal-derived fuels on breakpoint temperature.



(a) Zone 1 secondary nozzle flowing at 500 psi (33 atm) and showing essentially no streaking.

(b) Zone 1 nozzle demonstrating moderate amount of streaking.

Figure 13. - Fuel nozzle spray patterns.

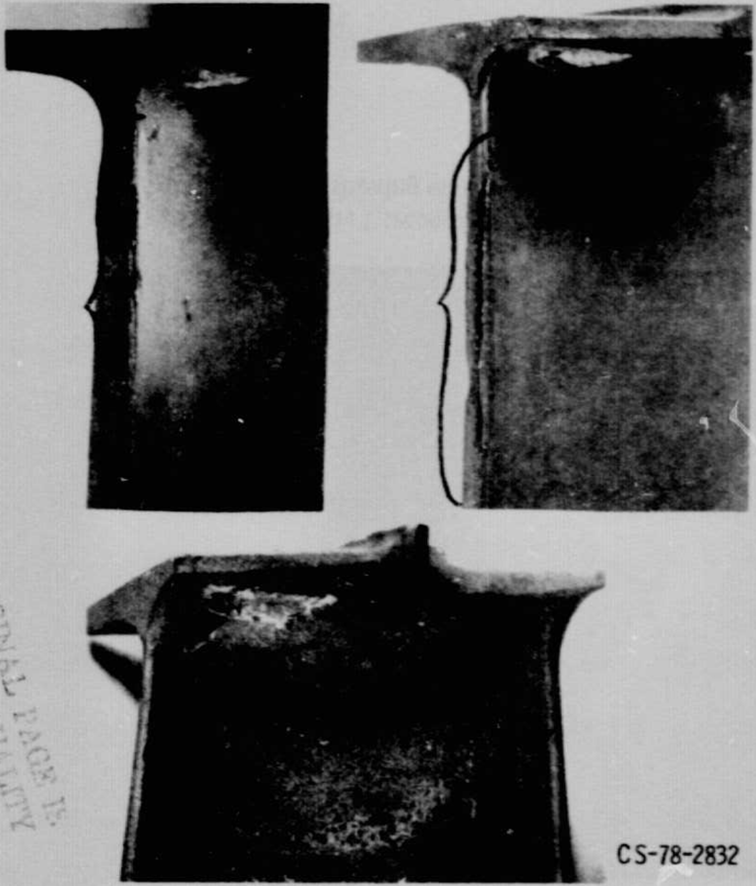

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Figure 14. - Examples of typical erosion and corrosion distress on turbine blade.

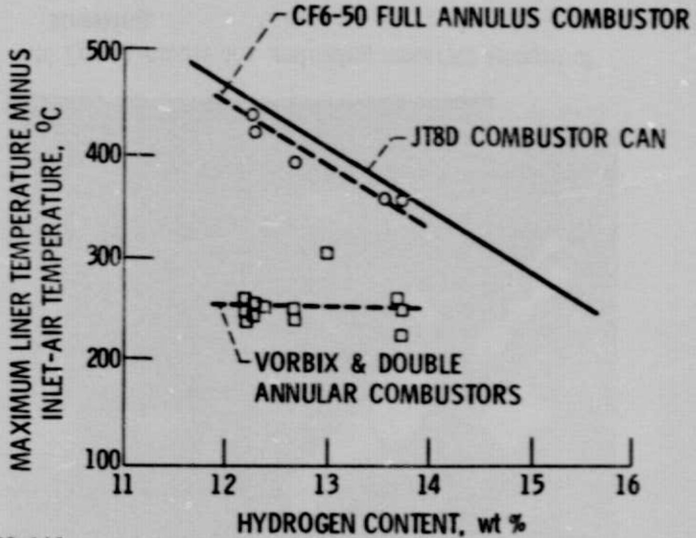

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Figure 15. - Effect of fuel hydrogen content on maximum combustor liner temperature.

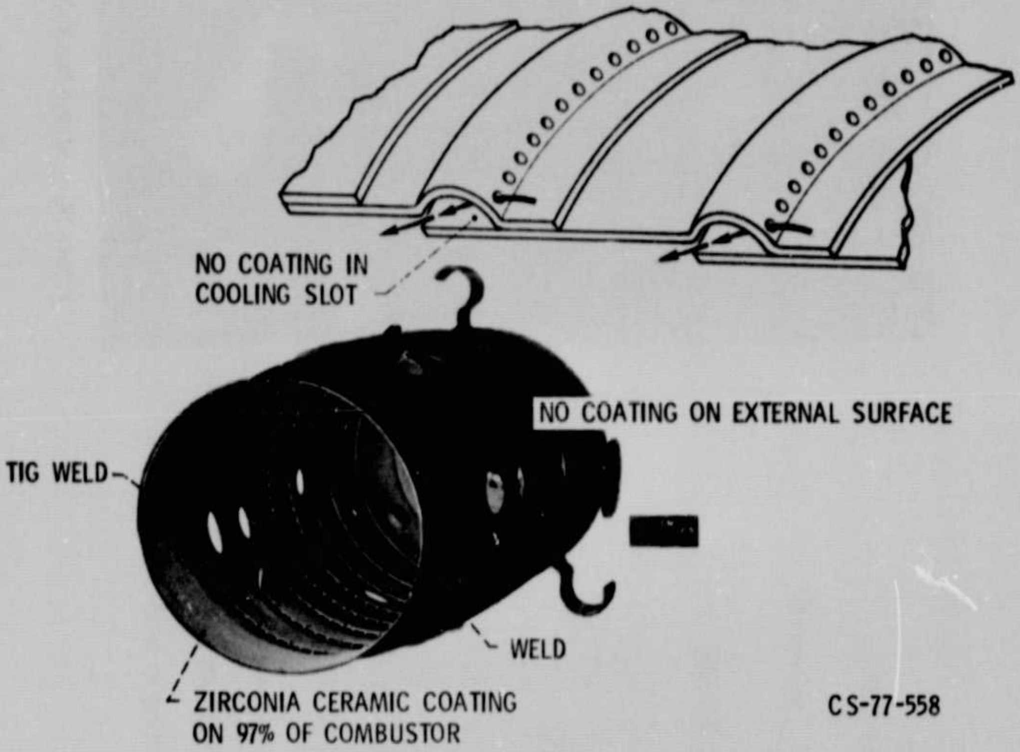

Figure 16. - Thermal-barrier-coated combustor.

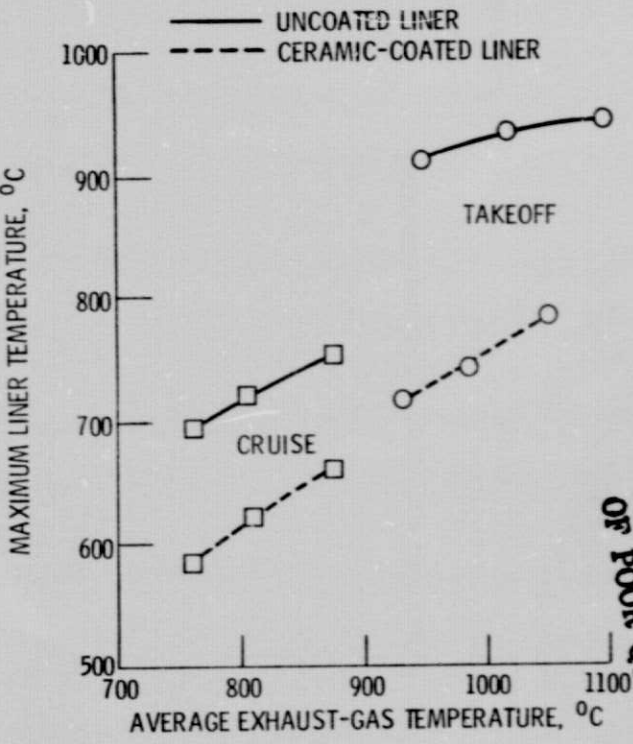

Figure 17. - Effect of ceramic coating on maximum liner temperature.

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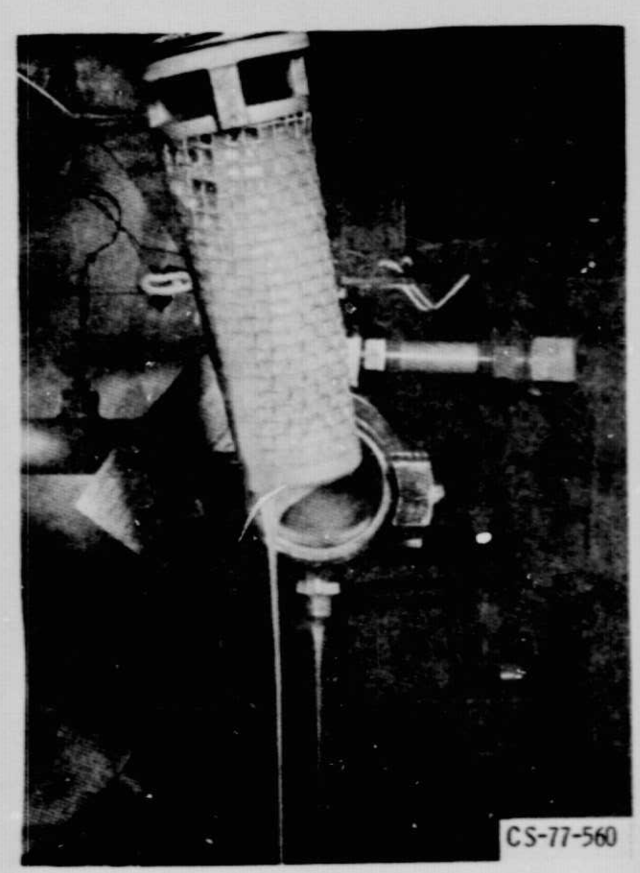
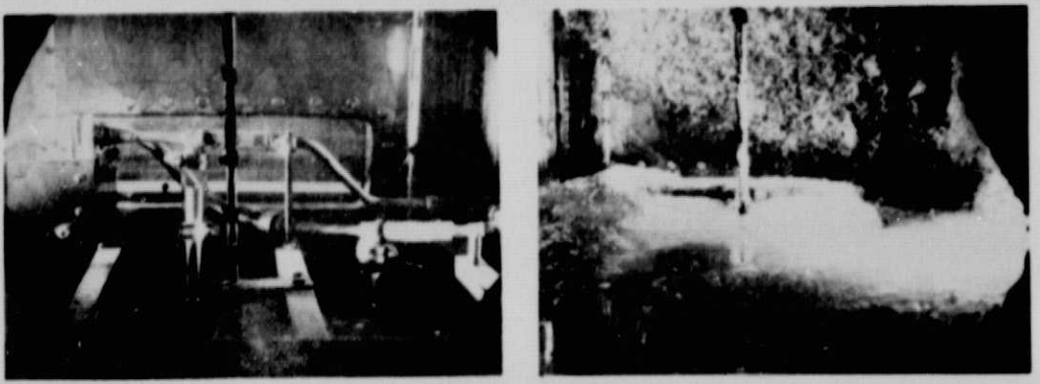


Figure 18. - Screen blockage by semisolid fuel.

OBJECTIVES:

- EXPERIMENTAL STUDY OF PUMPABILITY AND TWO-PHASE FLOW OF AVIATION FUELS AT LOW TEMPERATURES
- CORRELATION OF FUEL SYSTEM PUMPABILITY WITH LAB FREEZING POINT MEASUREMENT



INTERIOR OF FUEL TANK SIMULATOR FILLED WITH JET A (TYPICAL OF 1011 WING TANK SECTION).

END OF PUMPOUT TEST WITH JET A AFTER 7-HOUR COOLDOWN. FUEL SLUSH IS NOT PUMPABLE.

CD-12299-73

Figure 19. - Low temperature fuel system study (Lockheed).

E-9098

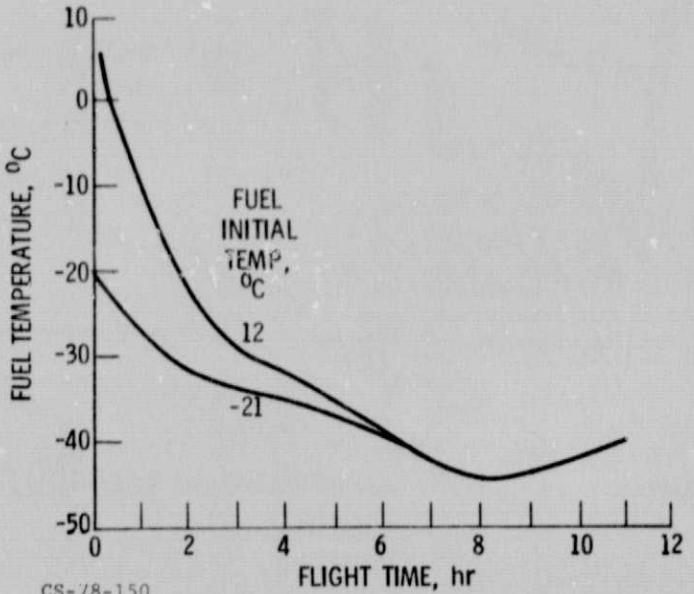


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Figure 20. - Fuel-tank temperatures for 9300-kilometer flight.

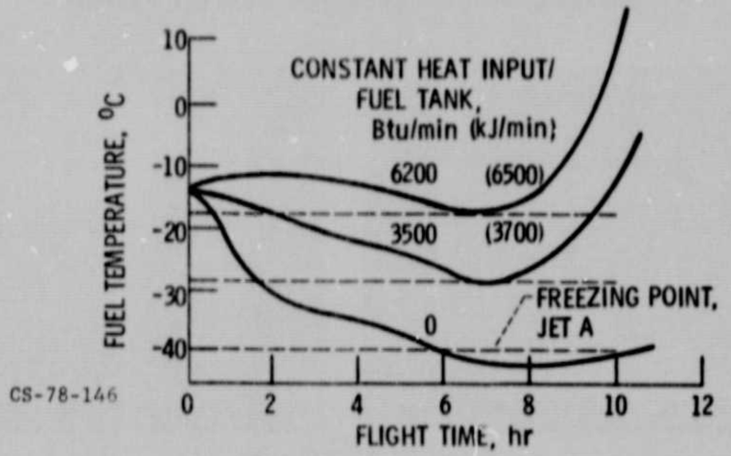

Figure 21. - Fuel-tank temperatures for a 9300-kilometer flight with heating.

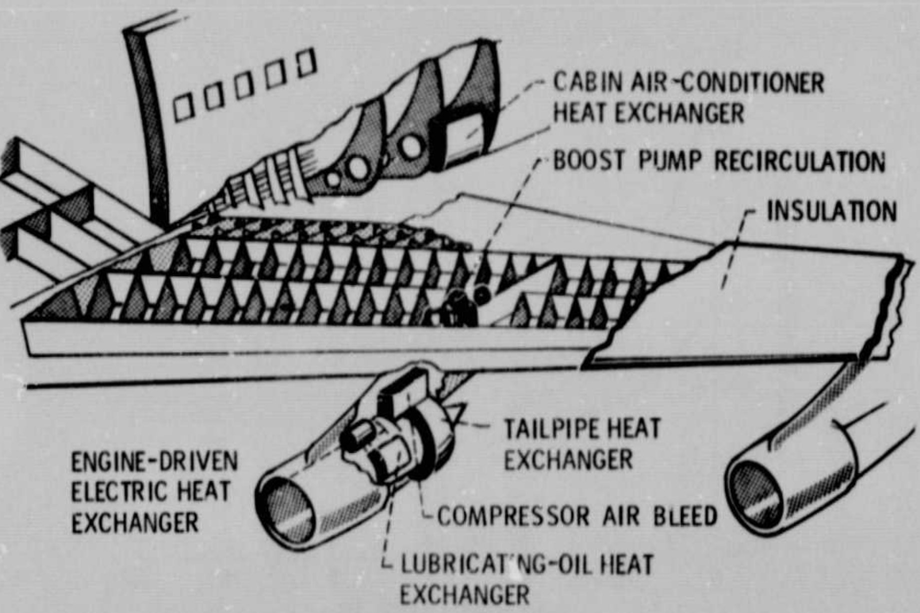

Figure 22. - Potential fuel-tank heating sources.

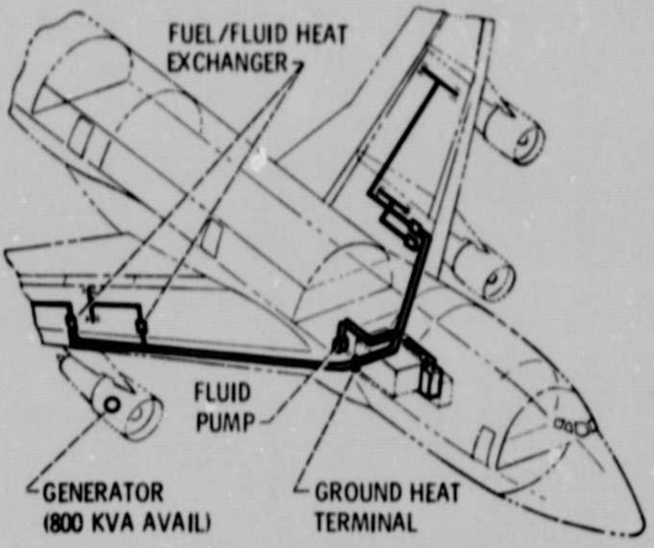

Figure 23. - Schematic of electrical fuel heating system on a wide-bodied jet aircraft.

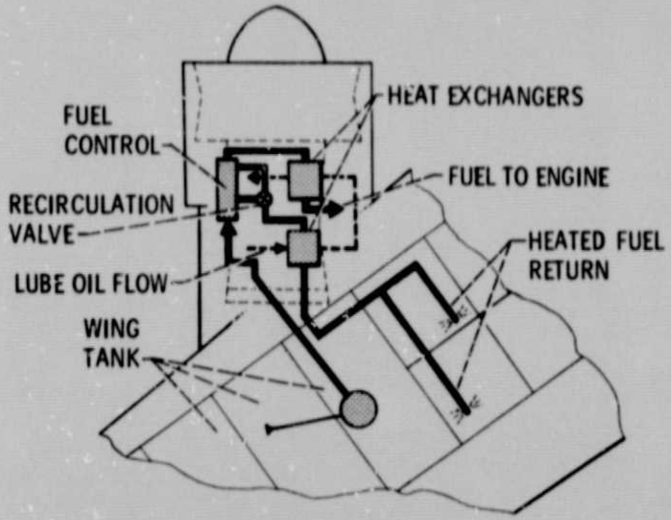

Figure 24. - Schematic of a lubricating-oil heat exchanger fuel heating system.