IMPACT OF BROAD-SPECIFICATION FUELS ON FUTURE JET AIRCRAFT

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SUMMARY

The efficient use of fossil fuels by future jet aircraft may necessitate relaxing or broadening current aviation turbine fuel specifications. The most likely specification changes could be toward an increased aromatics content (increased carbon to hydrogen ratio) and a higher final boiling point. Permitting an increase in aromatics would minimize refinery energy consumption and costs for fuels derived from highly aromatic crudes or from nonpetroleum sources such as shale or coal. In addition, a higher aromatic content and final boiling point would allow greater jet fuel yields by simple distillation and low-cost refinery processes. A jet fuel with an increased aromatic content and higher final boiling point could cause increased gaseous pollutant emissions, increased smoke, increased carbon deposition, increased combustor liner temperatures, poorer thermal stability, poorer ignition characteristics, and potential fuel-tank pumpability problems due to increased fuel freezing point and viscosity. Broad-specification fuels could, therefore, reduce engine life and thereby increase maintenance costs. This paper discusses the effects that broad-specification fuels may have on present-day airframe and engine components, and it also describes the improvements in component technology that may be required to use broad-specification fuels without sacrificing performance, reliability, maintainability, or safety.

INTRODUCTION

Jet fuel price increases and projected jet fuel shortfalls due to shifts in future supply and demand have led to serious considerations of the actions necessary to prevent a constraint on the future growth of air transportation. These actions must be addressed to the overall conservation of energy in both the air transportation and petroleum refining industries. NASA, along with other government agencies and private industry, has been conducting a research and technology effort to establish the data base necessary to optimize future jet fuel characteristics in terms of refinery energy consumption and trade-offs in jet aircraft and engine design (ref. 1). Other research and technology efforts are being conducted by NASA to reduce jet fuel consumption by improving aircraft energy efficiency (ref. 2).

Broadening current jet fuel specifications would permit reductions in energy consumption at the refinery. A broad-specification fuel may be defined arbitrarily as a liquid hydrocarbon fuel with key properties or characteristics that substantially exceed current specification limits for aviation turbine fuels. Significant production of synthetic crude oil from shale or coal is not expected until about the turn of the century; therefore, petroleum will remain the only source of jet fuel for the foreseeable future. Although research is being conducted to evaluate the economic feasibility of using hydrogen as a jet aircraft fuel, conventional hydrocarbon fuels will, in all probability, continue to be used commercially well into the next century. This paper, therefore, emphasizes the problems related to broadening the specifications for conventional jet aircraft fuels produced from petroleum.

The probable characteristics of broad-specification fuels and the impact that these broad-specification fuels may have on future jet aircraft are discussed herein. (The topics covered include the properties of current commercial jet aircraft fuel, the projected future changes in jet fuel properties, the potential engine and airframe component problems that result from broadening fuel specifications, and the component technology improvements that are required to use broad-specification fuels without sacrificing performance, reliability, maintainability, or safety.

JET AIRCRAFT FUEL PROPERTIES

Jet fuel has traditionally been manufactured by distillation from petroleum crude followed by a mild hydrogen treatment to control sulfur, corrosivity, or thermal stability as needed. The boiling range of the major petroleum-derived fuels is shown in figure 1. Crude petroleum normally has a boiling range that extends to about 600° C. As the demand for jet fuel, diesel oil, and heating oil increases, a point will be reached where there is an insufficient quantity of material in the proper boiling range. It will then become necessary to convert fractions boiling above 300° C to these lower boiling products. These cracked products are, in general, higher in aromatic content (increased carbon to hydrogen ratio) than are the naturally occurring fractions. The processing required to produce current specification jet fuel from the higher boiling fractions consumes considerably more energy because of the process hydrogen requirements than does the conventional production of jet fuel by crude distillation.

The commercial jet aircraft fuel, Jet A, has a relatively narrow boiling range specification (fig. 1). The initial boiling point, a minimum of about 170° C, is necessary to keep the flash point above 40° C to reduce the probability of a fire during fueling or following an emergency landing. The final boiling point for Jet A is usually below 270° C to comply with limits on the freezing point. Figure 2 shows the increase in freezing point to be expected as the final boiling point is increased. The freezing point of a fuel blend is the temperature at which wax components in the fuel solidify. The specification for Jet A limits the freezing point to a maximum of -40° C. Figure 2 indicates that the freezing point is quite sensitive to the final boiling point; however, an increased final boiling point would clearly allow increased flexibility in the production of jet aircraft fuel.

Trends in the average aromatic content of commercial Jet A fuel between 1960 and 1976 are shown in figure 3. The average aromatic content has increased from 14 percent (by volume) in 1960 to about 17 percent in 1976. The ASTM Jet A specification for aromatic content is a maximum of 20 percent. During the emergency period of 1973-1974, the limit was temporarily raised to 25 percent; more recently, a waiver has permitted the limited use of Jet A with a maximum aromatic content of 25 percent. During the emergency period, the limited quantities of Jet A refined from heavy Arabian crude had aromatic contents as high as 22 percent. Projections indicate that Jet A refined from Alaskan crude may have aromatic contents as high as 25 percent. These increases in aromatic content may be attributed in part to the production of Jet A by distillation of crudes with relatively higher aromatic content. In addition, several other factors could cause the aromatic content of jet fuel to increase. As mentioned earlier, the cracking of higher boiling materials to produce a product within the jet fuel boiling range increases the fuel aromatic content. The aromatic content of jet fuel may also be increased by extending the distillation range to a higher final boiling point. As shown in figure 4, these increases in aromatic content result in a proportionate lowering of the hydrogen content of the fuel. Decreasing the hydrogen content can increase the soot and flame radiation levels within the combustor and thus can increase the combustion liner temperatures.

In the future, as the relative demand for jet fuel increases, it will be necessary for refineries to consume considerable quantities of hydrogen in order to meet the requirements for current specification aviation turbine fuel. Since the production of hydrogen requires significant energy consumption, and since hydrogen and the processes using it are very expensive, consideration of cost and energy conservation encourages minimizing these types of refining. Thus, there is a definite need to investigate the effects of broadening jet aircraft fuel specifications on jet engine performance and durability in order to develop a data base which will allow an optimization of future fuel characteristics that takes both refinery energy consumption and aircraft engine design trade-offs into account. In order to implement this optimization effort it is desirable to establish a target fuel for use in research programs on both fuel production and aircraft/engine design. An experimental fuel has been recommended with properties that approach those shown in table I (ref. 3). Comparing the representative values for the properties of the proposed future broad-specification fuel with those of current Jet A fuel indicates that the major changes to be expected would be (1) an increased aromatic content corresponding to a reduction in hydrogen content, (2) a higher final boiling point, (3) a higher freezing point, and (4) a lower thermal stability JFTOT (jet fuel thermal oxidation test) breakpoint temperature. The thermal stability breakpoint temperature is an empirical laboratory indication of the degree to which the fuel may be heated without incurring significant levels of fuel decomposition. The properties designated for the future broad-specification fuel tend to be similar to those of the current number 2 diesel fuels.

Effect of Hydrogen Content of Fuel on Turbine Engine Combustors

Increases in aromatic content or, conversely, decreases in hydrogen content of the fuel have a pronounced effect on smoke and on liner temperatures. Combustor tests have been conducted using prepared fuel blends with varying amounts of aromatics (ref. 4). At cruise and takeoff conditions strong increases in exhaust smoke were observed as the hydrogen content of the fuel decreased (fig. 5). The effect of hydrogen content on maximum liner temperatures is shown in figure 6. As the aromatic content of the fuel increases and hydrogen content decreases, the flame becomes more sooty and more luminous; hence, radiation to the liner increases. Sharp increases in maximum liner temperatures were observed as the hydrogen content of the fuel decreased. At cruise, liner temperatures observed with fuels in the Jet A range (13.5 to 14 percent) were 800° C or less for all fuels. However, with fuels having a lower hydrogen content, severe liner durability problems could arise. At takeoff, maximum combustor liner temperatures exceeded 900° C for all fuels. However, the time spent at takeoff and, hence, the exposure time of the liner to these high temperatures are quite short.

Advanced Combustor Technology

In the NASA Experimental Clean Combustor Program, experimental combustors have been developed which promise not only lower exhaust emissions but also reduced sensitivity to relaxed fuel specifications (refs. 5 and 6). Two of these combustors, the Vorbix combustor for the P&W JT9D engine and the Double-Annular combustor for the G.E. CF6-50 engine, are shown for reference in figure 7. Both combustors feature staged combustion with a relatively rich zone for idle operation and a leaned-out main combustion zone for high-power operation.

Some of the results obtained with these combustors are shown in figure 8. Since the various data were not all obtained at the same combustor-inlet conditions, the data are plotted as the difference between maximum liner temperatures and combustor-inlet temperature. The two top curves, representing data obtained with a production-model full-annular combustor and a single-can JT8D combustor, exhibit the strong dependency of maximum liner temperature on hydrogen content of the fuel. The bottom curve, representing data obtained with the experimental Vorbix and Double-Annular combustors, shows a relative insensitivity of maximum liner temperatures to the hydrogen content of the fuel. Similarly, since soot formation is a strong function of combustor design as well as fuel composition, there is good reason to expect that the advances in combustor design illustrated here could allow satisfactory combustion of fuels containing less hydrogen.

Another method of reducing liner temperatures is to coat the inside of the combustor liner with a thermal-barrier coating (ref. 7). A JT8D combustor liner was coated with a thermal-barrier coating developed at the Lewis Research Center for application to turbine blades. The coating consists of a bond of a nickel-chromium-aluminum-yttrium alloy covered with a ceramic layer of 12 percent (by weight) yttria-stabilized zirconia. The results obtained with Jet A fuel, for both cruise and takeoff, indicated that reductions in maximum liner temperatures were achieved.

While these findings represent limited laboratory tests and their practicality requires demonstration in a full development program, they do indicate that important advances may be feasible in the ability of aircraft gas turbine engines to use low hydrogen content fuels.

Fuel Tank Temperatures During Cruise

Fuel stored in aircraft tanks can reach very low temperatures during long flights. Figure 9 shows extreme fuel temperatures that may be encountered during long-range flight. These data were calculated to show fuel tank temperatures when the static temperature at altitude is as low as -72° C (ref. 8). This is an extreme case with a one-day-a-year probability. Two curves are shown, each with a widely different initial ground loading fuel temperature. The effect of the different initial temperatures on in-flight fuel temperatures decreases as the flight progresses. After a period of time, the in-flight fuel temperature is completely independent of the initial temperature. The fuel temperature eventually reaches a minimum of -43° C, which is approximately the stagnation temperature at a cruise Mach number of 0.84 for the ambient static temperature. The rise in temperature at the end of the flight occurs because of increased altitude ambient temperature at the latter portion of the flight.

Jet fuel is a mixture of chemical compounds and does not have a fixed freezing point. Instead, it undergoes a large increase in viscosity and a partial phase change over a range of temperatures. Even this semisolid fluid can threaten operating problems. Fuel freezing has always been avoided by in-flight monitoring of fuel tank temperatures and by using jet fuels with low, conservative freezing-point specifications.

Fuel System Technology for Use of High-Freezing-Point Fuels

Fuels with higher freezing points than those listed in current specifications might be used if the fuel is heated in flight. Figure 10 shows several curves of predicted fuel temperatures during a long-range flight. The zero-heat-input curve repeats the in-flight temperature calculations shown in figure 9, and it represents an extreme case expected one day a year with a minimum fuel temperature of -43° C. The other two curves illustrate the in-flight fuel temperatures with the fuel heated at the rates indicated. The minimum in-flight fuel temperature can be raised to -29° C by heating the fuel at a rate of 3700 kJ/min (3500 Btu/min) or can be raised to -18° C by heating the fuel at a rate of 6500 kJ/min.

The calculated heating requirements can be reduced by insulating the fuel tanks. Using insulation can result in a sizable decrease in heating requirements. For example, without insulation 6500 kJ/min are required to maintain the fuel above -18° C. With 1.3-cm-thick insulation, the same minimum temperature can be maintained with 3000 kJ/min; with 2.5-cm-thick insulation, only 2000 kJ/min are required.

The Boeing Company under NASA Contract (ref. 8) has completed a preliminary study of practical fuel heating systems based on the 747 airplane. Figure 11 is a cutaway drawing showing several possible heat source systems mounted on the wing fuel tanks and engines of the 747. Some existing components, with minor modifications, can be used as heat sources. Three examples are shown: the cabin air conditioning heat rejection, fuel recirculation from the fuel pump, and fuel recirculation from the engine lubricating oil heat exchanger. The latter two heating systems would be based on pumping fuel at a maximum rate at all times and then recirculating or returning the excess fuel back to the wing tank. The excess fuel would be heated by the pump or the lubricating oil heat rejection to warm the bulk of the tank fuel. Three additional systems, each capable of higher heating rates, are also shown. These systems, which involve major modifications, include a tailpipe heat exchanger, an engine compressor air bleed heat exchanger, and an electric heater powered by an engine-drive generator. Most likely, these systems would heat the fuel indirectly through a second heat exchanger loop by using an inert fluid. Wing tank insulation is also shown in figure 11.

Data on these fuel heating systems are compared in table II. The first three systems are minor modifications of existing aircraft components that use heat sources with 2100 to 4500 kJ/min ranges. These rates could be increased by combining systems at the risk of control complexity. Two columns in this table show predicted penalties for the heating systems in terms of airplane weight increase and fuel consumption, expressed as percent of cruise fuel flow. These calculations for the minor modifications indicate that the penalties would be low. These systems, for the most part, use existing heat rejection in the airplane and power plants.

Table II also compares the major modifications, which involve greater weight and performance penalties but which promise future use with very high-freezing-point fuels. These systems are sized for 6500 kJ/min and can maintain fuel temperatures above -18° C for all cases. Weight increases per airplane for these systems are estimated as 250 to 450 kg. Fuel consumption penalties for energy diverted to fuel heating are least for the tailpipe heat exchanger (0.1 percent of the cruise fuel flow rate) and greatest for compressor air bleed (3.9 percent). On the other hand, the tailpipe heat exchanger is perhaps the furthest from the state of the art in development feasibility.

Table II includes two other items. Insulation, which holds great promise for reducing heating requirements, has a serious drawback in system weight and corresponding fuel consumption penalty. Reducing the heating requirements, as discussed earlier, would not be sufficient to compensate for the insulation weight. Future designs, however, with composite wing material may incorporate lightweight insulation in the basic designs. Finally, table II shows the equivalent fuel consumption representing 6500 kJ/min of combustion energy, about 40 kg/hr, or 0.4 percent of the cruise fuel flow. Systems that use the heat rejection otherwise unavailable in the engine thermodynamic cycle, such as the tailpipe heat exchanger or some minor modifications, can have lower fuel consumption penalties than this combustion equivalent.

CRITICAL RESEARCH AND DEVELOPMENT NEEDS

Combustor Technology

The previous section discussed the potential of using either staged combustion or a thermal-barrier coating as a means of minimizing the combustion liner surface temperature when burning highly aromatic fuels. It is important to maintain acceptable liner surface temperatures without increasing the quantity of air used to cool the combustion liner. Any increase in liner cooling airflow requires an equivalent reduction in the dilution-mixing air that is used to cool the high-temperature combustion gases. The dilution mixing air controls the gas temperature distribution entering the turbine by cooling the high-temperature gases leaving the primary zone of the combustor. Reducing the dilution-mixing airflow would result in a more peaked combustor exit temperature distribution and would thereby place a lower limit on the turbine operating temperature and service life. This problem could be more critical in advanced engines with higher compressor pressure ratios and higher turbine inlet temperatures.

A staged combustor permits leaner combustion during takeoff and cruise and thus reduces flame radiation to the liner surface by reducing soot formation within the combustor. A thermal-barrier coating provides insulating and oxidation protective coverings over the surface of the liner. Another way to minimize liner cooling airflow requirements could be to use advanced cooling liners with increased cooling effectiveness. These as well as other approaches, such as advanced structural designs for combustion liners, could be investigated.

The formation of hard carbon particles or deposits within the combustion chamber must be avoided. Hard carbon particles may strike the turbine and cause erosion of the leading and trailing edges of the blades. Significant carbon deposition on either the fuel injectors or combustion liner may result in distorted fuel flows or cooling-air-hole blockages; either of these might cause local overheating or peaked temperature distributions at the turbine. Combustor testing with broad-specification fuel is needed to determine the effect of lowering fuel hydrogen content on carbon deposition. Research is needed to obtain a more fundamental understanding of the mechanisms of carbon formation within combustors.

More extensive combustor testing is needed to obtain parametric data on the effects of reduced fuel hydrogen content and reduced volatility on the exhaust emissions of different engines. The impact of broad-specification fuels on the emission levels of combustors designed to meet E.P.A. emission standards must be assessed. Smoke and nitric oxide emissions may increase during takeoff and cruise for some engines. Carbon monoxide and unburned hydrocarbons may increase during idle. Improvements in fuel atomization and fuel-air mixing may be required to cope with these problems.

Many of the aforementioned problems might be partially resolved by improvements in fuel injector design. Further research may be required to evolve more effective air atomizing fuel injection systems for handling more viscous and/or less volatile fuels. Ignition and relight of fuels with higher viscosity and/or lower volability could be another significant problem. On cold days fuel heaters may be needed at starting conditions with such fuels. In addition, special provisions such as a pilot burner may be needed to permit satisfactory ignition at altitude relight operating conditions.

Fuel System Technology

Possible approaches to fuel tank heating to enable using fuels with higher freezing points have been described herein. A more detailed analytical study has recently been initiated by Boeing under a NASA contract to design practical fuel heating systems for future jet aircraft. In addition, an experimental study has been initiated by Lockheed under another NASA contract to obtain a better understanding of the low-temperature pumpability limits of fuels with varying freezing points in a subscale fuel system simulator. These research efforts should eventually lead to the evaluation of broad-specification fuels in full-scale fuel system simulators.

Preventing fuel manifold and fuel injector fouling is another critical problem. Aircraft turbine fuels must be stable at the temperatures they will encounter in the fuel system. Practically, this means there must be no gum or deposit buildup on heated surfaces such as heat exchanger tubes or manifold piping, and there must be no cracking or particulate buildup to clog small passageways in the fuel system such as filters or fuel nozzles. Current jet aircraft fuels are marginally stable in present-day engines. The chemical changes that result in deposit formation occur at an increased rate as the fuel temperature is increased. Future engines with higher compressor pressure ratios will therefore be even more susceptible to deposition problems since the fuel manifold and fuel injectors may be exposed to higher compressor discharge air temperatures. Obviously, using broad-specification fuels with lower thermal stability will increase the severity of this problem. Modifications to the fuel system may, therefore, be required to limit the maximum temperature to which the fuel is exposed. Possible design approaches such as insulating or cooling the fuel manifold and fuel injector could be investigated. Fuel line purging during shutdown is another technique that could be evaluated. Fuel decomposition is known to be influenced by the oxygen dissolved in the fuel. Deoxygenation and fuel additives to control deposit formation rates should be investigated. In addition, more basic and applied research is needed to acquire a better understanding of the fuel system variables and fuel composition variables that affect deposit formation.

The compatibility of broad-specification fuels with sealants and elastomers used in the fuel tank and fuel system must be identified. Improved polymeric materials may be required to cope with higher aromatic contents. Finally, problems related to ground handling of broad-specification fuels must be examined. Ground heating of high-freezing point fuels might be required in northern hemisphere cities during the winter.

Obviously, the critical research and development needs emphasized herein have not covered all of the possible problems related to the use of broad-specification fuels. We are just beginning the task of determining the effects of broad-specification fuels on aircraft and engine components and of identifying the technology required to use broad-specification fuels.

CONCLUDING REMARKS

The advantages and disadvantages of several solutions to the problems associated with using broad-specification fuels are summarized in table III. The first solution is to continue developing the necessary technology at the refinery to produce specification jet fuels regardless of the feedstock that is used. By this approach, the fuel properties may be optimized or tailored to the needs of future jet aircraft. Furthermore, this would eliminate the serious cost penalty of retrofitting existing aircraft and engines. The disadvantage of this approach would be increased energy consumption at the refinery and thus increased fuel cost.

On the other hand, the second solution shown in table III is to minimize energy consumption at the refinery and keep fuel costs down by relaxing specifications. The disadvantage of this approach is that more complex component technology must be developed to cope with problems such as increased pollutant emissions, increased combustor liner temperatures, poorer thermal stability, poorer ignition characteristics, and restricted fuel pumpability. Furthermore, using broadened specification fuels may adversely affect engine life, thereby increasing aircraft maintenance costs. Ultimately, the solutions to these problems will involve determining the most energy efficient and cost effective path. The most practical solution will probably require a compromise between partially relaxing fuel specifications and a limited redesign of the aircraft and engine.

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TABLE I. - MAJOR PROJECTED CHANGES IN FUEL PROPERTIES

	Current Jet A fuel	Future broad-specification fuel
Aromatics, vol %	17 to 25	30 to 35
Hydrogen, wt %	14 to 13.5	13.0 to 12.5
Final boiling point, °C	260 to 280	290 to 330
Freezing point, °C	-46 to -40	-34 to -29
Thermal stability (JFTOT) breakpoint temperature, °C	≥260	≥240

TABLE II. - COMPARISON OF POSSIBLE FUEL HEAT SOURCES

	Maximum heating rate per tank, kJ/min	Weight increase, kg	Fuel penalty, %
Air conditioning system	2200	140	0
Lubrication 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, 2.54 cm thick	----	5900	14.6
Equivalent heating by combustion	6500	----	.4

TABLE III. - ASSESSMENT OF POTENTIAL SOLUTIONS TO JET FUEL PROBLEM

Solution	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

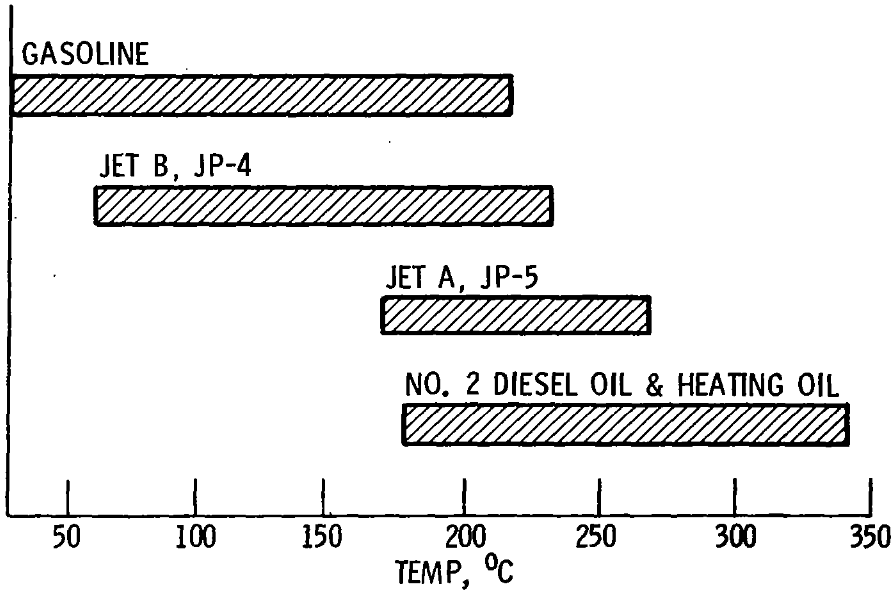


Figure 1.- Boiling range of various petroleum products.

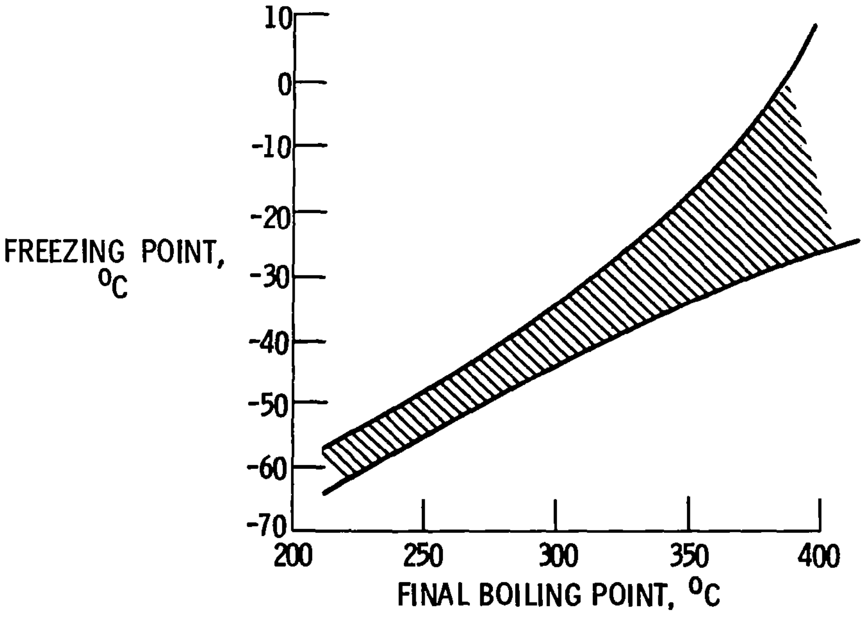


Figure 2.- Typical fuel blend freezing points.

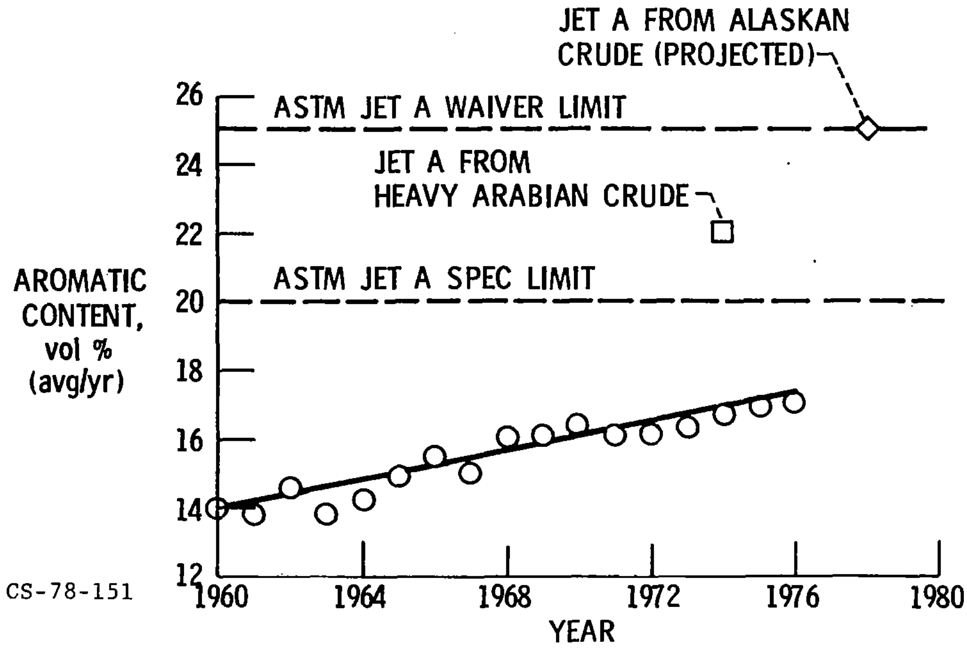


Figure 3.- Trends in aromatic content of commercial Jet A fuel.

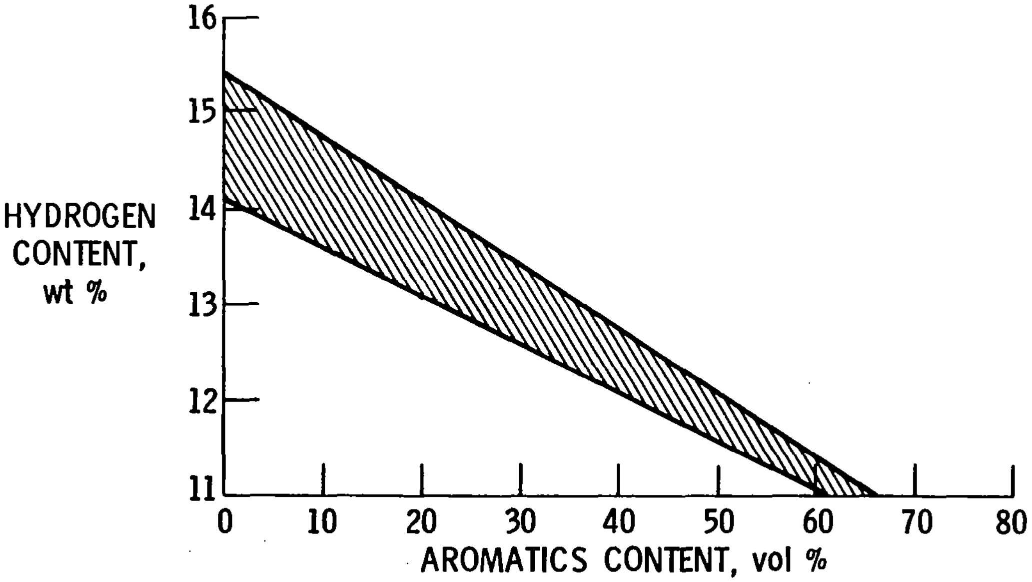


Figure 4.- Variation of hydrogen content with aromatics content.

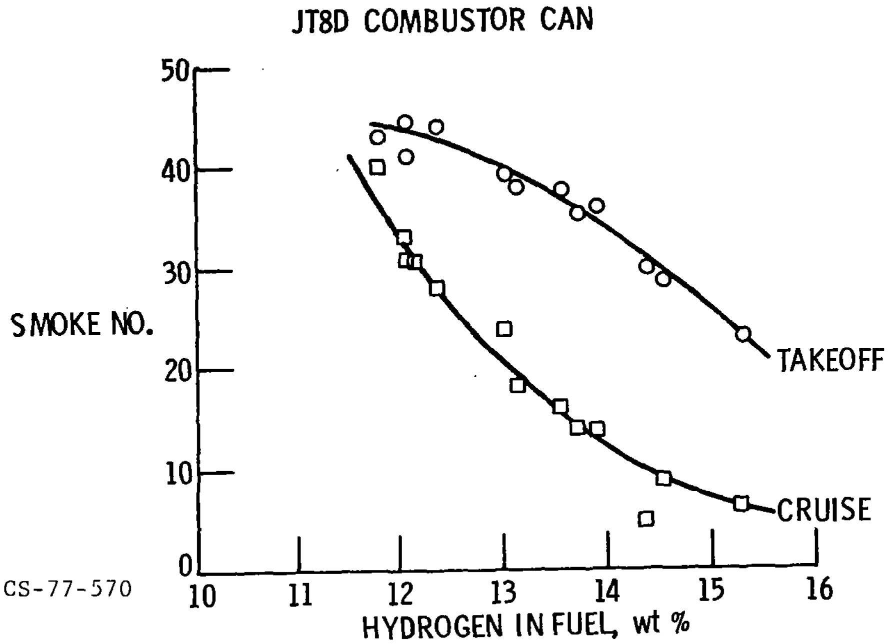


Figure 5.- Effect of hydrogen content of fuel on smoke number.

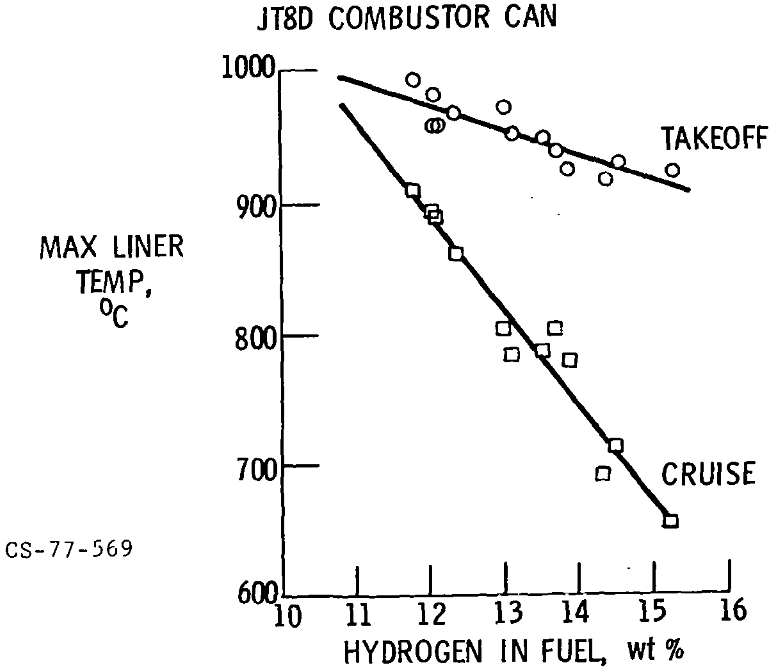
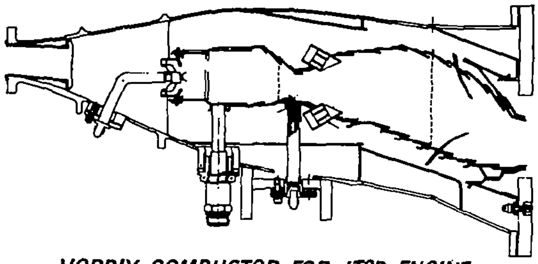
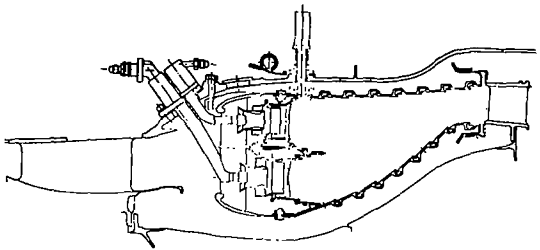


Figure 6.- Effect of hydrogen content of fuel on maximum combustor liner temperature.



VORBIX COMBUSTOR FOR JT9D ENGINE



DOUBLE-ANNULAR COMBUSTOR FOR CF6-50 ENGINE

Figure 7.- Combustor designs evaluated in NASA Experimental Clean Combustor Program.

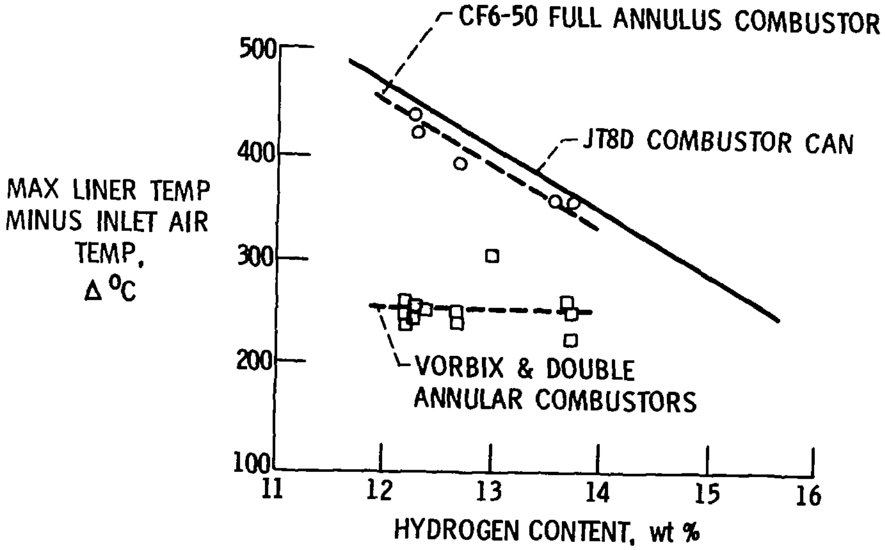


Figure 8.- Effect of hydrogen content of fuel on maximum combustor liner temperature of several different combustor designs.

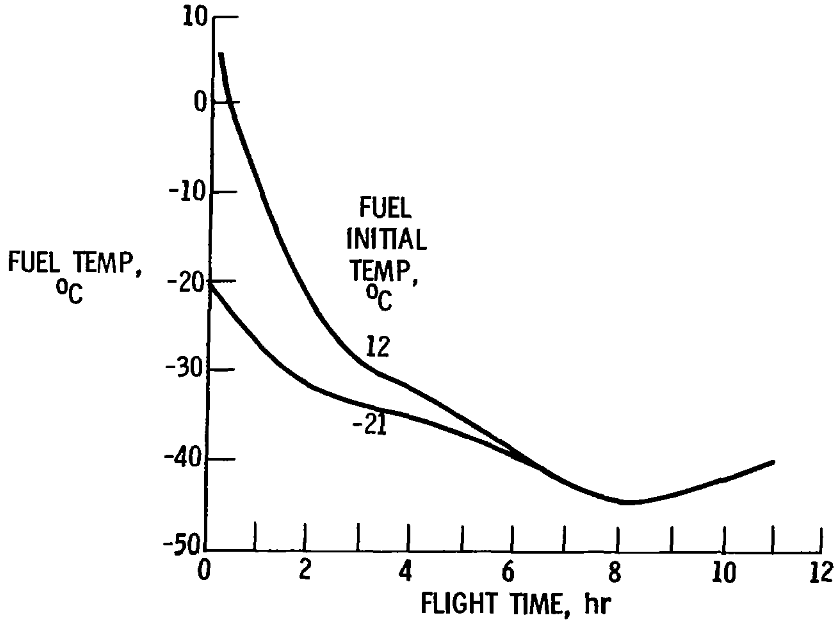


Figure 9.- Fuel tank temperatures for 5000 n. mi. flight.

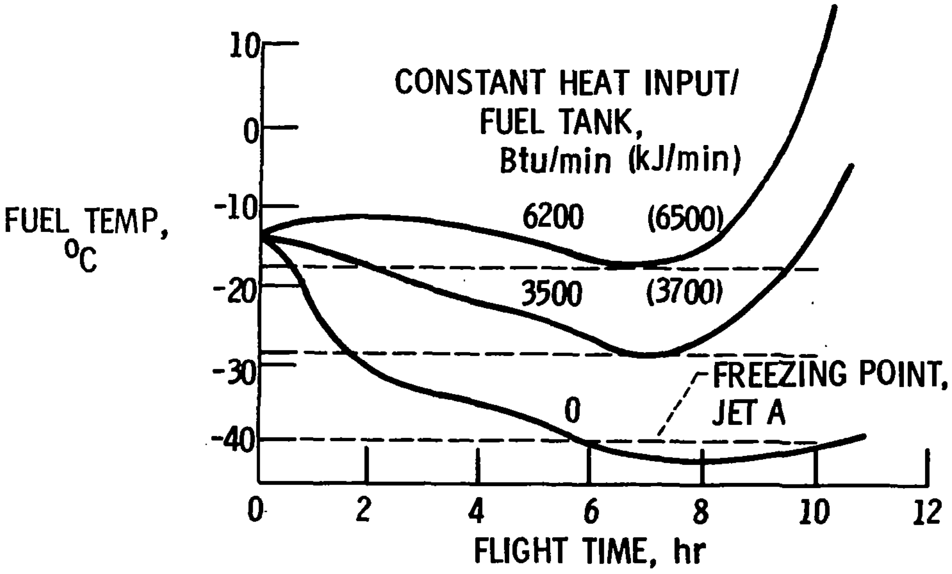


Figure 10.- Fuel tank temperatures for 5000 n. mi. flight with heating.

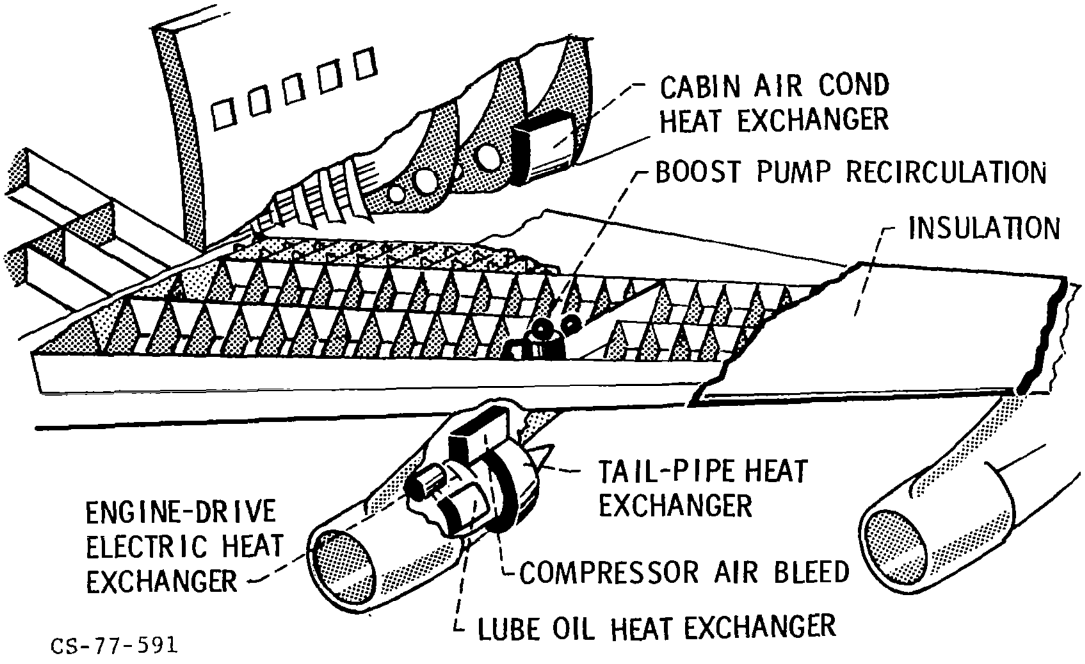


Figure 11.- Fuel tank heating sources.