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ALTERNATIVE AIRCRAFT FUELS TECHNOLOGY

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SUMMARY

NASA is studying the characteristics of future aircraft fuels produced from either petroleum or nonpetroleum sources such as oil shale or coal. These future hydrocarbon based fuels may have chemical and physical properties that are different from present aviation turbine fuels. This research is aimed at determining what those characteristics may be, how present aircraft and engine components and materials would be affected by fuel specification changes, and what changes in both aircraft and engine design would be required to utilize these future fuels without sacrificing performance, reliability, or safety. This fuels technology program has been organized to include both in-house and contract research on the synthesis and characterization of fuels, component evaluations of combustors, turbines, and fuel systems, and, eventually, full-scale engine demonstrations. The entire effort has been integrated with a similar program being conducted by the Air Force Aero Propulsion Laboratory (AFAPL) and is being coordinated with other government agencies within the DOD and ERDA. This paper is a review of the various elements of the program and presents significant results obtained so far.

INTRODUCTION

As shown in figure 1, the fuel consumption by commercial aviation has roughly tripled during the last 15 years (ref. 1). Most forecasts predict a reduced rate of growth in air transportation. Nevertheless, the rate of increase in demand for aviation turbine fuels is expected to exceed that for automotive gasoline. Forecasts of the growth rate in fuel consumption by U.S. airlines vary from about 4 to 7 percent. Even the conservative predictions indicate a doubling of the fuel required for air transportation by the year 2000.

Presently, jet aircraft are totally dependent on petroleum derived kerosene fuels. At some time in the future, it will be necessary to obtain aviation fuels from sources other than petroleum. Domestically, these alternative sources include oil shale and coal. The most likely aviation turbine fuel derived from these alternative sources will probably be a liquid hydrocarbon that is similar to petroleum derived turbine fuels.

The relative reserves of petroleum, oil shale, and coal are illustrated in figure 2 (ref. 2). Based on the current total energy use rate, the U.S. supply of petroleum will be depleted around the turn of the century. The U.S. must currently import about 35 percent of the oil that we consume. This figure could grow to over 50 percent by 1985. The reserves of oil shale and coal could supply our total energy needs for several hundred years. Both government and industry are conducting programs to exploit the conversion of oil shale and coal to a crude oil (refs. 3 and 4). These so-called "syncrudes" have properties somewhat similar to crude petroleum, with the exception that they contain a lower proportion of hydrogen to carbon and a higher concentration of undesirable impurities. Large capital expenditures will be required to launch the syncrude industry. Even with the support of government, initial production of syncrudes is not expected until about 1985, and this initial production will support only a small percentage of the total U.S. fuel demand.

The average distribution of finished products from a barrel of petroleum is shown in figure 3. The percent distribution of the various products are illustrated with the more volatile products at the top and less volatile products at the bottom of the barrel. Jet fuel, which takes most of the kerosene cut (or about 7% of the barrel), is obtained by a straight-run distillation of the crude plus a small degree of hydrotreating for sulfur removal. Distillation involves a relatively simple physical separation of the various components within the crude by a series of repeated stages of vaporization and condensation. Hydrotreating involves the chemical addition of hydrogen to unsaturated organic compounds to form saturated compounds or the removal of trace impurities such as sulfur by conversion to volatile compounds which may be more easily removed from the product. The cost of hydrotreating is directly related to the quantity of hydrogen required to process each barrel of crude. Until now, the kerosene portion of crude petroleum has been sufficient to supply the demand for aviation turbine fuels; however, as the demand for aviation turbine fuels grows faster than the demand for other petroleum products, it will become increasingly difficult to meet these demands from the kerosene cut of the barrel alone.

The alternatives to a shortened supply of aviation turbine fuel include (1) converting heavier cuts of the barrel to turbine fuel by hydroprocessing, which will result in increases in refinery cost and energy losses, (2) relaxing specifications for aviation turbine fuels, and (3) using shale oil and coal syncrudes as refinery feedstocks. Of course, another approach to alleviate the problem is fuel conservation by improving aircraft efficiency. The NASA has recently organized a program to evolve energy efficient propulsion and aerodynamic systems (ref. 2). However, this paper will concentrate on the technical problems related to the utilization of aviation turbine fuels with properties significantly different from current specification fuels.

AVIATION TURBINE FUELS TECHNOLOGY

The NASA fuels technology program is concerned with the evaluation of the potential characteristics of future jet fuels and the determination of the possible effects of these fuels on the performance and durability of engine components. The objective is to evolve any new technology required to use these fuels. The problems in using fuels with properties that are significantly different from specification aviation turbine fuels are emphasized. Research related to the effect of relaxed fuel specifications on combustors, turbines, fuel tanks, fuel system components, and materials is being conducted. The NASA effort is being conducted as part of a joint integrated fuels technology program with the Air Force Aero Propulsion Laboratory. The entire program is being coordinated with other government agencies that are involved with research on the use of shale oil and coal syncrudes.

Characteristics of Aviation Turbine Fuels

Commercial jet aircraft fuels have relatively tight specifications. As shown in figure 4, the initial boiling point of a typical commercial Jet A is generally greater than 440 K (330° F) in order to comply with the minimum specification value for a flash point of 310 K (100° F). The limiting value for flash point is set to minimize the probability of an accidental fire during fueling or following an emergency landing. The maximum final boiling point for Jet A may be as high as 570 K (570° F), but it is generally less than this value to comply with limits on freezing point.

Many of the important jet fuel properties are interrelated. An increase in final boiling point generally corresponds to an increase in both freezing point and aromatics concentration. The aromatic compounds found in petroleum products consist of a class of unsaturated cyclic hydrocarbons containing one or more benzene rings that have a wide range of boiling points. The volatility, which is related to the boiling range, must be a compromise between satisfactory combustion characteristics and an acceptable flash point. Low aromatic concentrations are desired to minimize smoke and flame radiation caused by smoke. Limits on the concentration of aromatics, olefins, and nitrogen compounds in the fuel are necessary to maintain chemical stability of the fuel so that gums, varnish, and carbon are not formed either during storage or within the heated parts of the fuel system. Olefins, which are a class of unsaturated organic compounds containing at least one double bond, are relatively reactive chemical compounds. Any nitrogen or sulfur in the fuel will be converted to undesirable oxide pollutants during combustion. Sulfur and trace metals such as vanadium, sodium, and potassium must be avoided to prevent the corrosion and oxidation of hot turbine blades. All of these elements are easily removed from petroleum derived fuels by hydrotreating.

However, the concentration of these elements in shale oil and coal syncrudes is much higher, and their removal, especially nitrogen from shale oil, is difficult (ref. 5). The freezing point and viscosity, which are generally controlled by limiting final boiling point, are important factors affecting fuel system design and reliability.

The Jet A fuel specification limits the maximum aromatic concentration to 20 percent by volume, which corresponds to a hydrogen content of about 13 to 14 percent by weight (fig. 5). As the aromatic concentration increases, the hydrogen content decreases and the tendency for smoke to be formed during combustion increases. A higher aromatic content is generally accompanied by increases in final boiling point, freezing point, and specific gravity. A higher specific gravity reduces the heat content of the fuel by weight but, correspondingly, increases heat content by volume.

Effects of Relaxed Fuel Specifications on Combustors

The effect of varying hydrogen content in a hydrocarbon fuel on the liner surface temperature of a conventional combustor is shown in figure 6 (ref. 6). The surface temperature increases with decreasing hydrogen content because the increased aromatics results in increased soot formation, which causes higher flame radiation due to increased flame emissivity. These experimental data for a single JT8D combustor can operating at simulated cruise conditions indicate that a 1-percent decrease in hydrogen leads to a 50 K (90° F) increase in liner wall temperature. Increasing liner surface temperature may reduce combustor operating life or at worst result in the gradual degradation of combustor components that could lead to further damage to the turbine.

Other data showing the effect of variations in hydrogen content on combustor performance were obtained from several experimental combustors designed to minimize exhaust pollutants (refs. 7 and 8). Two of the low-pollutant combustors being studied under a NASA contract designated as the "Experimental Clean Combustor Program" are shown in figure 7. The "Vorbix" combusor is being developed by Pratt & Whitney for the JT9D engine, and the double-annular combustor is being developed by General Electric for the CF6-50 engine. Both combustor designs consist of two combustion stages. A pilot stage burns a relatively rich fuel-air mixture at low power conditions such as idle in order to minimize hydrocarbon and carbon monoxide emissions. A main stage is used to burn a relatively lean mixture of fuel and air at high power conditions such as takeoff and cruise in order to minimize smoke and oxides of nitrogen.

Test results for these two experimental low-pollutant combustors are compared with the results for more conventional production combustors in figure 8. The maximum liner surface temperature minus the combustor inlet air temperature is shown plotted against the hydrogen content. Test data for the two conventional combustors follow a similar trend of increasing surface temperature with decreasing hydrogen content. However, the experimental two-stage combustors are relatively insensitive to the hydrogen content of the fuel over the limited range of hydrogen concentrations that were studied. This effect is attributed to the fact that the main stage of the low-pollutant combustors operates at relatively lean fuel-air ratios thus producing less soot and lower flame radiation. These results thus indicate that this design might permit the use of a fuel with a higher aromatic content without suffering smoke formation penalties. Other test data obtained with these low-pollutant combustors using No. 2 diesel fuel indicate a small loss in altitude relight capability and a small increase in carbon monoxide and total hydrocarbon pollutants at idle. The effects of using No. 2 diesel fuel on combustion efficiency and combustor exit temperature profile were negligible. Future test plans include studying the effects of broad specification fuels on combustor durability at elevated pressures to simulate takeoff operating conditions.

Effects of Relaxed Fuel Specifications on Fuel Systems

The typical spread in freezing point of a hydrocarbon fuel blend as a function of final boiling point is shown in figure 9. Freezing point is somewhat of a misnomer here since a jet fuel consists of many different organic compounds, and only a pure compound solidifies at a constant and definite temperature. For jet fuels the freezing point is defined by the initial presence of solid hydrocarbon crystals in the liquid phase. The wide spread in freezing point for a given final boiling point is probably due to the variations in the types and concentrations of organic compounds found in fuels refined from different crude sources. The only difference between the specifications for Jet A and Jet A-1 is the maximum allowable freezing point, which is 233 K (-40° F) and 223 K (-58° F), respectively. The freezing point for diesel No. 2 is considerably higher and varies from about 250 to 255 K (-10° to 0° F).

A representative variation in tank fuel temperature over a long distance flight is shown in figure 10 (ref. 9). As a safety margin for avoiding fuel line plugging, the FAA requires that the tank fuel temperature be maintained at least 3 K (5.4° F) above the freezing point of the fuel being used. For the example shown, the tank fuel temperature will fall below the safety margin for Jet A after flying about 3700 kilometers (2000 nm). This figure thus illustrates the necessity of using Jet A-1, which has a lower freezing point for long distance flights. It is interesting to observe that the effect of initial fuel temperature on tank fuel temperature becomes negligible for long flight times.

Several flight operational methods may be considered for maintaining a fuel above its freezing point. In the event that the measured tank fuel temperature approaches the safety margin, the tank fuel temperature may be increased by increasing flight Mach number, reducing flight altitude, or altering course to avoid cold air masses. All of these approaches penalize fuel consumption. Switching from outboard to inboard fuel tanks, which are at a slightly higher temperature, is relatively limited in effectiveness. As shown in the previous figure, preheating fuel on the ground has a negligible effect on the fuel tank temperature for a long flight. However, preheating fuel on the ground might be necessary during the winter in some regions just to transfer a broader-specification fuel such as diesel No. 2 to the aircraft.

The use of broader-specification fuel such as diesel No. 2 would require a major redesign of the airframe fuel system. Insulating the fuel tanks could provide a partial solution. However, heating the fuel in the tank during flight would probably be required to maintain the tank fuel temperature above the freezing point. Several approaches to heating the fuel during the flight could be considered. Fuel could be recirculated through the engine heat exchanger and returned to the fuel tank. This approach would probably require changes to the present design for the fuel pumps and engine heat exchanger. Another approach could be the addition of fuel tank heaters. Whatever method is used, high local fuel temperature must be avoided to prevent gumming of fuel passages due to degradation of the fuel. The problems in using a broader specification fuel with a higher freezing point are currently being studied analytically by Boeing under a NASA contract.

CONCLUDING REMARKS

Many areas of research and development will have to be explored if we are to use alternative fuels for jet aircraft. The research performed so far, in which the effects of higher aromatic content and lower volatility fuels on combustors were studied, must be extended to higher operating pressures to fully evaluate performance and durability problems. The initial low smoke and low liner temperature results obtained in experimental two-stage combustors look promising. Fuel system technology must be evolved to permit the use of fuels with higher freezing points and lower thermal stabilities. Additional fundamental data are needed to relate thermal stability to fuel composition. Data on the effects of alternative fuels on materials must be obtained, including their compatibility with both fuel system elastomers and turbine blade alloys and coatings. Any potential toxicity problems related to fuels derived from coal or oil shale must be studied, although undesirable toxic compounds will probably be removed at the refinery. Finally, extensive engine endurance testing will be required to establish the overall reliability of engines designed to use an alternative fuel.

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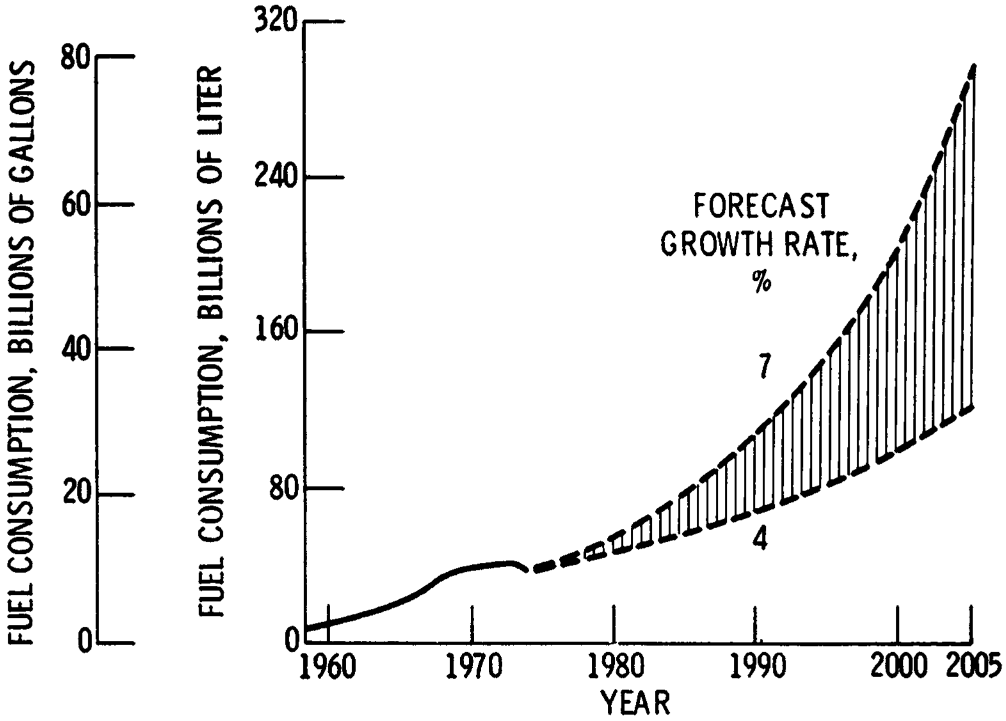


Figure 1.- U.S. air transportation fuel consumption estimates for certificated airlines.

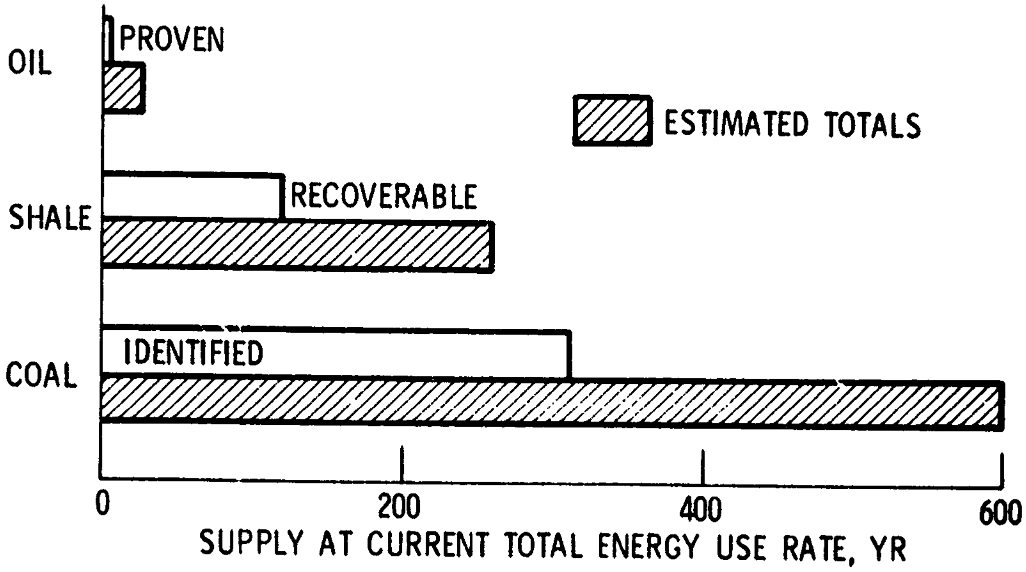


Figure 2.- Comparison of U.S. fuel resources.

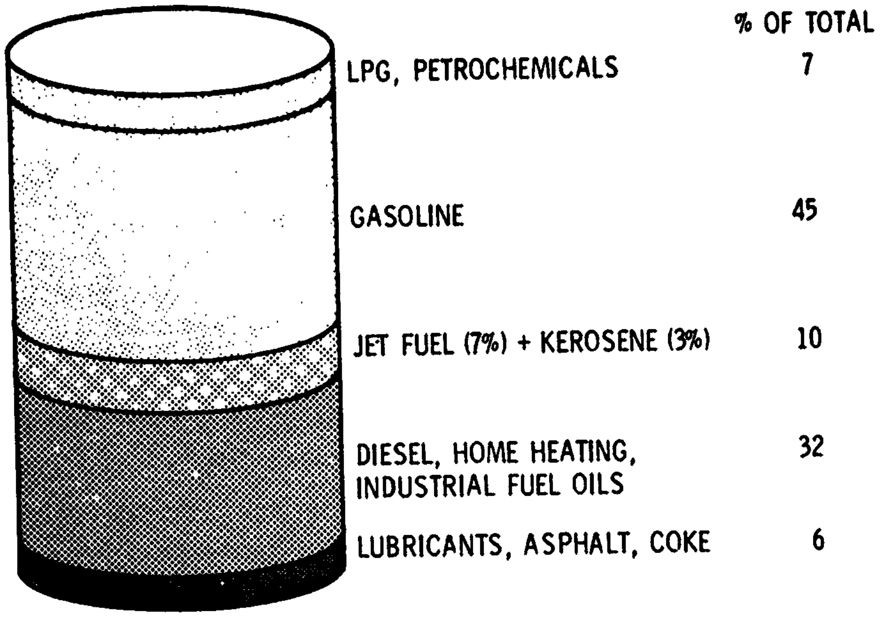


Figure 3.- Distribution of petroleum to finished products.

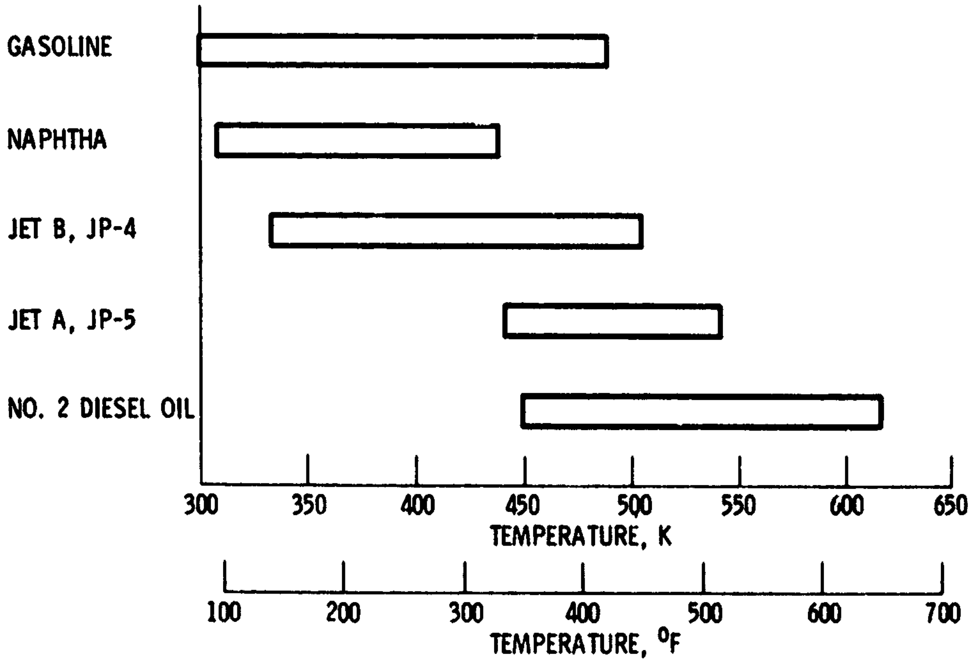


Figure 4.- Boiling range of various petroleum products.

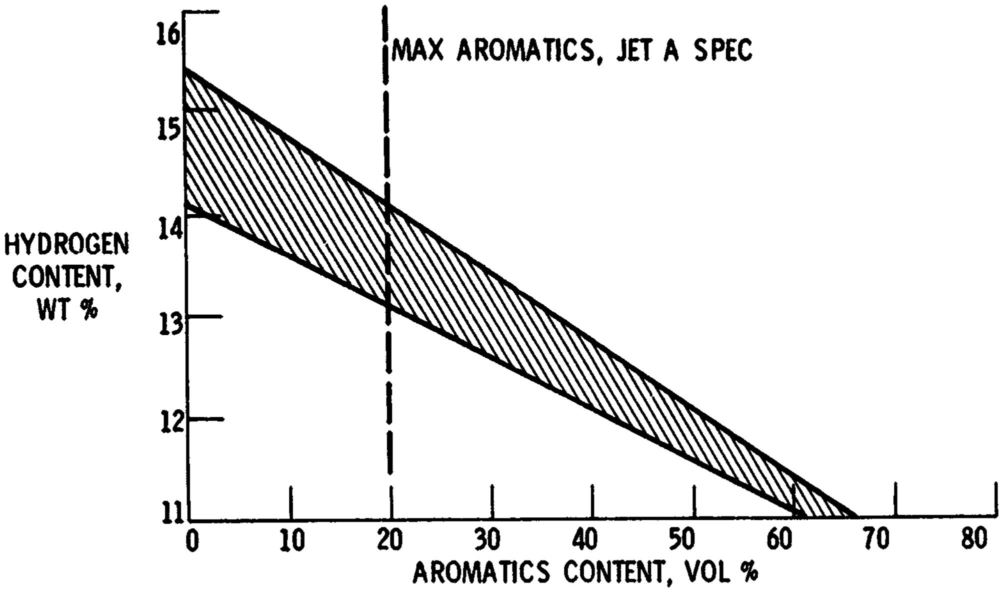


Figure 5.- Variation of hydrogen content with aromatics content.

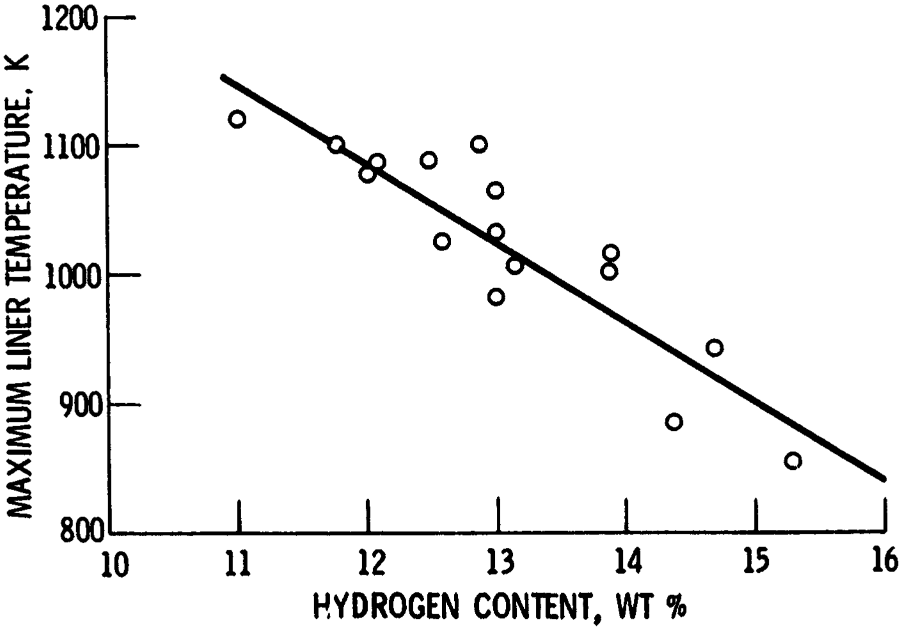
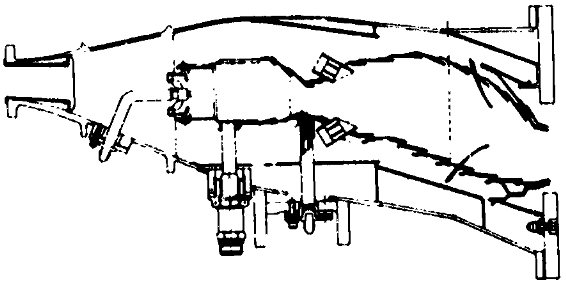
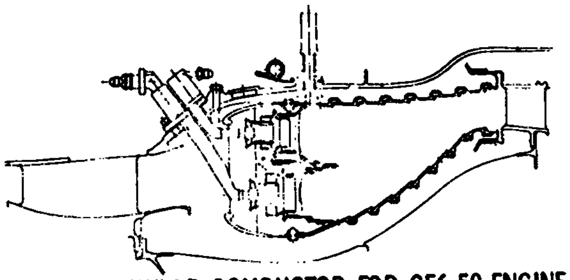


Figure 6.- Effect of hydrogen content of fuel on combustor liner surface temperature.



VORBIX COMBUSTOR FOR JT9D ENGINE



DOUBLE-ANNULAR COMBUSTOR FOR CF6-50 ENGINE

Figure 7.- Experimental clean combustor program.

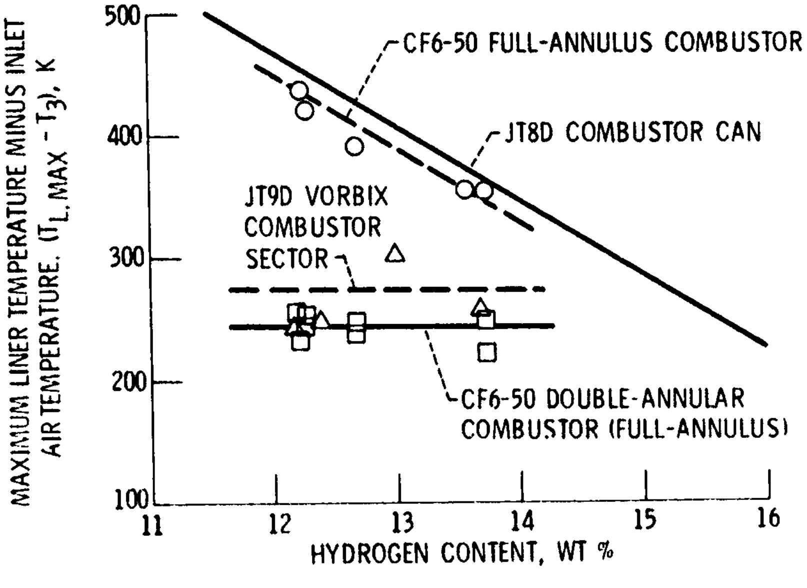


Figure 8.- Effect of hydrogen content of fuel on combustor liner surface temperature.

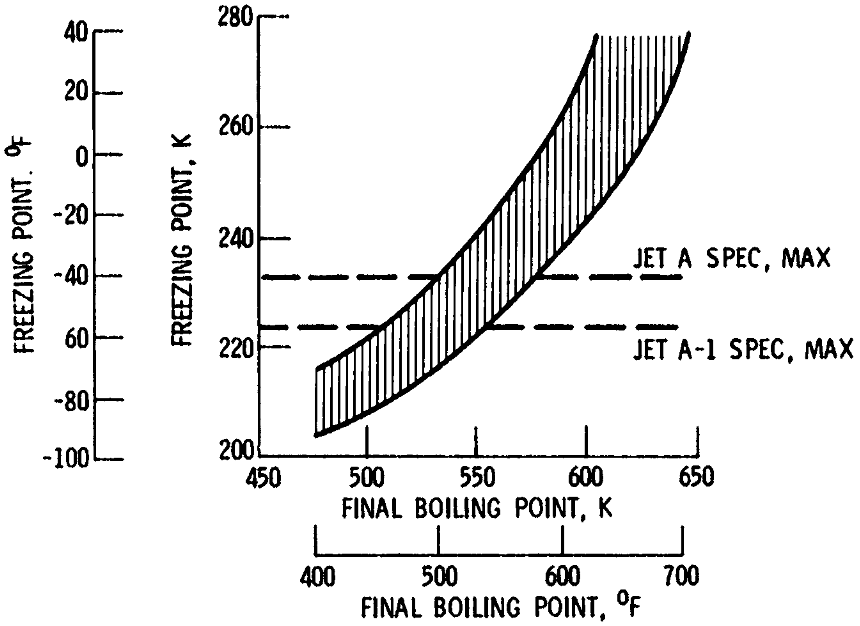


Figure 9.- Variation of freezing point with final boiling point.

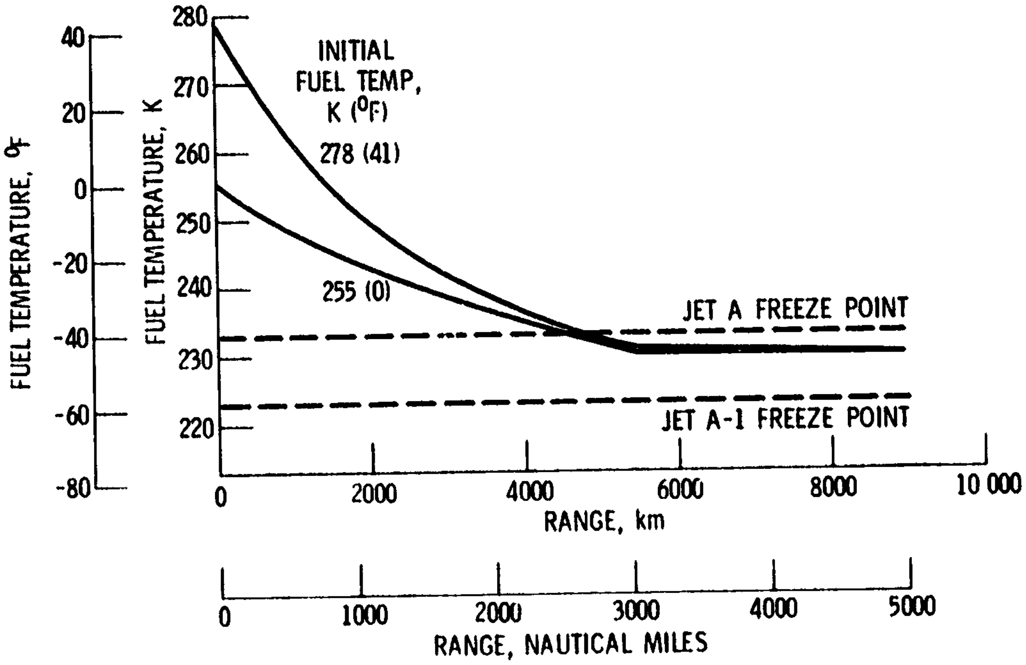


Figure 10.- Calculated minimum fuel temperature for Boeing 747 aircraft.