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ABSTRACT

The efficient utilization of fossil fuels by future jet aircraft may necessitate the broadening of current aviation turbine fuel specifications. The most significant changes in specifications would be an increased aromatics content and a higher final boiling point in order to minimize refinery energy consumption and costs. These changes would increase the freezing point and might lower the thermal stability of the fuel, and could cause increased pollutant emissions, increased combustor liner temperatures, and poorer ignition characteristics. This paper discusses the effects that broadened specification fuels may have on present-day jet aircraft and engine components and the technology required to use fuels with broadened specifications.

INTRODUCTION

While, on a worldwide basis, production of jet fuel can meet current requirements without difficulty, major price increases in recent years and the impending shortage of liquid fuels relative to basic demand is bringing about a serious examination of the possible changes in jet fuel composition that will result from future shifts in the usage of liquid fuels and in the raw materials used in their manufacture. Estimates of worldwide petroleum resources and of future economic growth are, of course, uncertain; however, there is a high probability that even without major disruptions or major output restrictions production of petroleum will go through a maximum in the 1990 to 2000 period while demand for energy will continue to grow [1].[†] Adjustment to the inability of world petroleum production to keep pace with basic world demand will force major substitution of other energy sources such as coal,

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[†]Numbers in brackets designate references at end of paper.

nuclear, gas and solar for liquid fuels and will require production of liquid fuels from resources such as coal, oil, shale and vegetable matter, where such materials are available.

Major substitution of other energy sources for liquid hydrocarbons is expected to occur in the electric power generation, industrial heat and commercial and residential heating sectors. In the United States substitution of oil for gas is currently resulting in a rapid short term increase in fuel oil use in the power generation and industrial sectors; however, subsequent displacement of fuel oil by coal and nuclear heat are expected with fuel oil use dropping off after 1985 to 1990. Changes in oil use for residential heating are expected to be slower with use decreasing somewhat before the end of the century.

The possibilities for displacement of liquid hydrocarbons for transportation fuel are quite limited during this century and growth in transportation fuel use is expected to the extent that supply will allow. Within the transportation sector growth of gasoline use is expected to be slow compared with the projected rapid growth of diesel fuel use and substantial but less rapid growth of aviation turbine fuel use. Both of these growing areas, at present, demand high quality paraffinic fuels. In addition the use of petroleum paraffins for petrochemical feedstock is expected to grow rapidly at 5 to 7 percent per year well into the next century with the result that this use is projected to be second only to transportation as a consumer of liquid hydrocarbons - much of which will be in the same boiling range as jet fuel, diesel fuel and heating oil (mid-distillates). The net result of these trends will be a decrease in gasoline/mid-distillate ratio from a current value of 1.5 to a value of about 1.2 in 1990 and quite possibly 1.0 in 2000. While production of an increased proportion of mid-distillate is quite feasible, the need to convert heavy fuel oil and gas oil to the mid-distillate boiling range and the increased use of heavy crude, tar and coal liquids will increase the aromatic content of the mid-distillate pool to the point where special processing would be required to produce the needed quantities of low-freezing-point, low-aromatic jet fuel called for by current specifications while also meeting diesel and other mid-distillate product demands.

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This view of the future has stimulated a re-examination of the optimum fuel specification/aircraft system. The bulk of the work related to this re-examination has been supported by the U.S. Air Force, the U.S. Navy, and by NASA with the goal of assessing the suitability of jet fuels made from oil shale and coal and of developing a data base which will allow optimization of future fuel characteristics taking energy efficiency of manufacture and the trade-offs in aircraft and engine design into account.

PROPERTIES OF FUTURE AVIATION FUELS

Jet fuel has traditionally been manufactured by distillation from petroleum crude followed by mild hydrogen treatment to control sulfur, corrosivity or thermal stability as needed. As the distillate fuels become a larger fraction of the total crude petroleum, a point is reached when an insufficient quantity of the proper boiling range is found in the crude and higher boiling materials must then be converted to the proper boiling range. These cracked products are, in general, higher in aromatic content than the naturally occurring fractions. The boiling range of the major "clean" fuels is shown in Fig. 1. Crude petroleum normally has a boiling range that extends to about 600° C and as jet fuel, diesel fuel, and No. 2 heating oil become a larger fraction of the total product, the need for conversion of fractions boiling above 300° C and the competition between these uses for the same material is clear. While in Europe there is no current difficulty in jet fuel production, in the U. S. , there are local situations where the total product demand forces importation of jet fuel from other areas and/or hydrogenation processing to meet current demand and specifications.

Note that in Fig. 1, commercial jet aircraft fuel, Jet A, has a relatively narrow boiling range specification. The initial boiling point, a minimum of about 170° C, is necessary to maintain 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 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, and Fig. 2 indicates that freezing point is quite sensitive to final boiling

point; however, an increased final boiling point would clearly allow increased flexibility in manufacturing the total mix of distillate products.

As mentioned earlier, the cracking of higher boiling materials to produce a product within the jet fuel boiling range, increases the aromatic content which is currently limited to a maximum value of 20 to 25 percent by volume. The aromatic content of jet fuel is also increased by extending the distillation range to a higher final boiling point. As shown in Fig. 3, increases in aromatic content reduce the hydrogen content of the fuel. Since a decrease in hydrogen content increases flame radiation, hence combustion liner heating and can also reduce fuel thermal stability, possible changes in this fuel property require careful study.

As shown in Fig. 4, coal and shale based hydrocarbons contain less hydrogen than petroleum and their use will further tend to reduce the hydrogen content of the fuel. Shale oils tend to be in the 10.5 to 11.0 percent range compared to about 14 percent hydrogen content in current jet fuels. Coal is very low and the hydrogen content of liquids produced from coal depends on the amount of hydrogen added. Coal syncrudes typically fall in the 9.5 to 11.0 percent range.

Another property problem introduced by shale oil and coal is a high organic nitrogen content, typically 1.4 to 2 percent for shale and up to 1 percent for coal liquids, whereas petroleum is normally less than 0.1 percent with occasional crudes having contents up to 0.2 percent. Organic nitrogen introduces fuel stability problems and also increases nitric oxide emissions formed during the combustion process.

PROPOSED SOLUTIONS TO PROBLEMS OF ALTERNATIVE FUELS

Refining Jet Fuel to Current Specifications

One obvious solution to the problems addressed in the preceding sections would be to pay the price for additional refining of alternative jet fuel to meet current specifications. Refining requirements will depend on the source of the crude and the yield required. Reduction of boiling range, increase in hydrogen content, nitrogen-removal and improved thermal stability can be accomplished by the hydrogenation and hydrocracking processes illustrated in Fig. 5. The hydrogen consumed in this

type of processing can be very large. Work done under U.S. Air Force and NASA contracts illustrates the extent of some of the hydroprocessing required in making jet fuels from syncrudes [2] to [4]. One of the considerations is the increased amount of hydrogen that will be required above that usually needed in petroleum processing. Two examples of specific cases are shown in Fig. 6. In the first, from shale oil processing, the hydrogen consumption is increased from 900 (160) to 1100 (200) standard $\text{ft}^3/\text{barrel}$ (m^3/m^3 oil) in reducing the nitrogen level from about 0.2 to 0.015 percent (2000 to 150 ppm). For coal syncrude processing, hydrogen content is the controlling factor and in this case, an increase in hydrogen consumption from 600 (110) to 1100 (200) standard $\text{ft}^3/\text{barrel}$ (m^3/m^3 oil) is needed to increase hydrogen content from 12.5 to 13.5 percent. Since hydrogen manufacture is of low thermal efficiency, 50 to 65 percent, and since hydrogen and the processes using it are very expensive, consideration of both cost and energy conservation encourage minimization of these types of refining.

Control of Fuel Thermal Stability

The upgrading of alternative fuels by improved refinery processing is one approach to solving the problem of reduced thermal stability. Changes in fuel system design is another approach. For an understanding of these solutions, it is helpful to look at some basic studies of fuel thermal stability [5].

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 deposits built up on heated surfaces such as heat exchanger tubes, or fuel manifold piping, and no cracking or particulate formation that might clog small passageways in the fuel system such as filters or fuel nozzles.

The laboratory tests that have been developed to check on this particular fuel behavior subject the fuel to a thermal stress in a test rig such as that shown schematically in Fig. 7. A small tube is heated electrically to the test temperature. The fuel flows up through an annulus surrounding this heated surface and out through a test filter. During this procedure, any tendency of the fuel to form particulates large enough to block this test filter can be noted by a build-up of a pressure drop

across the filter. At the same time, deposits may also form on the heated tube.

One would expect that any chemical changes bringing about the fuel instabilities would occur at an increased rate as the fuel temperature is increased. In general, either the pressure drop across this test filter builds up at a faster rate, or the indicated deposits on the tube build up at a faster rate, as the temperature of the test is increased. Thus, one way of comparing the thermal stabilities of fuels is to determine the maximum temperature that the fuel can be subjected to in this test before it fails to stay within certain specified limits of pressure drop or deposit level. This temperature is referred to as the "breakpoint temperature." Currently, Jet A is required to have a breakpoint temperature of 260° C or greater.

Breakpoint temperatures for a number of shale-and-coal-derived fuel samples were determined [5]. The shale fuels which were hydrotreated to remove nitrogen down to only 0.1 to 0.2 weight percent had breakpoint temperatures below 230° C. The fuels hydrotreated more severely, to nitrogen contents of about 0.01 to 0.02 weight percent (100 to 200 ppm) had breakpoints in the 230° to 260° C range. For breakpoints of 260° C or more it appears that the fuel will have to be hydrogenated to achieve nitrogen contents below about 0.01 percent (100 ppm). Although it is known that fuel-bound nitrogen is a factor contributing to instability of fuels, it is not possible to determine if it is solely responsible for the stability differences. In the preparation of these fuels, the nitrogen content of the product was monitored in establishing the severity of the hydrotreatment used.

More severe hydrotreatment conditions were required for the coal-derived fuels than for the shale fuels. The fuel-bound nitrogen in all these coal fuels was equal or less than 6 parts per million after hydrotreating. The variation of hydrogen content of the fuel was monitored as the indication of the severity of treatment. A general trend to higher breakpoint temperatures was observed as the weight percent of hydrogen was increased; a 260° C breakpoint generally requiring at least 13 percent hydrogen.

These results represent some of the early stability data available on turbine fuels from synthetic sources and indicate the general level of severity of refining processing

that would be required to produce synthetic fuels of comparable stability to current jet fuels. Hydrotreatment, of course, is not the only possible approach to solving the thermal stability problem. It may be that modifications can be made to the fuel system design so that the fuel does not reach as high a temperature level. This would permit the use of fuels of lower thermal stability.

Combustor Technology for Use of Broad Specification Fuels

Reducing hydrogen content of jet fuel has a pronounced effect on liner temperature and on smoke formation. Figures 8 and 9 illustrate this effect for laboratory studies of a single-can JT8D combustor for simulated takeoff and cruise conditions [6]. As hydrogen content is reduced below the currently typical value of 14 percent, there is a pronounced increase in liner temperatures caused by the formation of increased quantities of soot with a corresponding increase in flame emissivity.

A higher liner temperature markedly shortens liner life and increases maintenance costs. Increased liner and nozzle carbon deposits can cause turbine damage by changes in temperature distribution or by physical damage caused by flakes of carbon deposits passing through the turbine. Smoke in the exhaust is also increased. Since soot formation is a strong function of combustor design as well as fuel composition there is good reason to expect that advances in combustor design could allow satisfactory combustion of fuels containing less hydrogen.

Promising results have been obtained in combustors being studied in the NASA Experimental Clean Combustor Program [7] and [8]. Two of these, 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 Fig. 10. Both combustors feature staged combustion with a relative 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 Fig. 11. Since the various data were not all obtained at the same combustor-inlet conditions, the data are plotted as the difference between maximum liner temperature and combustor inlet temperature. The two top curves, representing data obtained with a production-model G. E. CF6-50 full-annular combustor and a single-can P&W 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. These data were obtained at combustor inlet pressures of 10 atmospheres or less. Further testing is required to evaluate their performance and durability at actual engine operating conditions.

Another method of reducing liner temperatures consists of coating the inside of the combustor liner with a thermal-barrier coating. Shown in Fig. 12 is a JT8D combustor liner which was coated with a thermal-barrier coating developed at the NASA Lewis Research Center for application to turbine blades. The coating consists of a bond coat of a nickel-chromium-aluminum-yttrium alloy covered with a ceramic layer of 12 percent by weight yttria-stabilized zirconia. To apply the coatings, it was necessary to cut the combustor lengthwise to accommodate the coating apparatus and then to reweld the parts. Care was taken not to cover the cooling slots and holes.

The results obtained with Jet A fuel [9] are shown in Fig. 13. Maximum liner temperatures are shown as a function of average exhaust-gas temperature. For both cruise and takeoff, substantial reductions in maximum liner temperatures were achieved. Although no endurance tests were made, no deterioration of the coating was observed after about 6 hours of cyclic operation including several startups and shutdowns.

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 System Technology for Use of High-Freezing-Point Fuels

Fuel system modifications, rather than combustor modifications, are the suggested solution for high-freezing-point problems. A preliminary study of the effect of high-freezing point fuels on the design of commercial aircraft fuel systems was recently carried out by Boeing under NASA Contract [10]. Figure 14 shows several predicted curves of fuel temperatures on board an aircraft during a long-range flight.

The bottom curve, labeled zero heat input, represents an extreme case, expected 1 day a year, with minimum fuel temperature of -43°C . The other two curves illustrate the fuel temperatures in flight with the fuel heated at the rates indicated. It can be noted that the minimum fuel temperatures in flight may be increased to -29°C by heating the fuel at a rate of 3500 Btu/min (3700 kJ/min) for each engine-fuel tank combination. This minimum fuel temperature can be raised to -18°C by a heat input of 6200 Btu/min (6500 kJ/min).

An analysis of potential fuel heating systems has been performed for the B-747 airplane [10]. Figure 15 is a cutaway drawing showing several possible heat source systems mounted on the wing fuel tanks and engines of the B-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 flow back to the wing tank. The excess fuel would be heated by the pump work or lubricating oil heat rejection to warm the bulk of the tank fuel. An additional three systems, each capable of higher heating rates, are also shown. These involve major modifications. These systems include a tailpipe heat exchanger, engine compressor air bleed heat exchanger, and an electrical heater, powered by an engine-drive generator. Most likely, these systems would heat the fuel indirectly through a second heat exchanger loop, using an inert fluid.

Data on these fuel heating systems are shown in Table I. The first three systems are minor modifications of existing aircraft components, using heat sources ranging from 2000 (2100) to 4300 (4500) Btu/min (kJ/min). These rates could be increased by use of combined systems at the risk of control complexity. Two columns in this table show predicted penalties for the heating systems in terms of increases in airplane weight and increases in fuel consumption, expressed as percent of cruise fuel flow. The penalties would be low for the minor modifications, because these systems, for the most part, use existing heat rejection in the airplane and powerplants.

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Table I 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 6200 Btu/min (6500 kJ/min), which can maintain fuel temperatures above -18°C for all of the flight profiles studied. Estimated weight increases per airplane for these systems are shown 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. Table I includes two other items. Insulation, which holds great promise toward reducing heat requirements, has a serious drawback in system weight and corresponding fuel consumption penalty. Reduction in heating requirements, as shown in Fig. 16, would not be sufficient to compensate for the insulation weight. Future designs, however, with composite wing material could incorporate lightweight insulation in basic design. Finally, Table I shows the equivalent fuel consumption representing 6200 Btu/min (6500 kJ/min) of combustion energy, about 40 kg/hr, or 0.4 percent of the cruise fuel flow. Systems which use 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.

CONCLUDING REMARKS

The advantages and disadvantages of the various solutions to the problems resulting from the use of alternative fuels are summarized in Table II. The first solution is to continue to develop the necessary technology at the refinery to produce specification jet fuels regardless of the crude source. 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. The sensitivity of fuel costs is illustrated by the fact that a likely increase in hydrotreating cost of producing specification jet fuel from alternative sources of 10 to 20 cents per gallon would cost the U.S. commercial

airlines an additional 1 to 2 billion dollars per year.

On the other hand, the second solution shown in Table II 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 the problems of increased pollutant emissions, increased combustor liner temperatures, poorer thermal stability, poorer ignition characteristics, and restricted fuel pumpability. Furthermore, the use of broadened-specification fuels may have adverse effects on engine life, thereby reducing the time between overhauls. Ultimately, the solution to these problems will involve the determination of the most energy efficient and cost effective path for optimizing the combined refinery-air transportation systems. The most practical solution will probably require a compromise between partially relaxing fuel specifications and a limited redesign of the aircraft and engine.

In order to carry out such an optimization program, it is helpful to have a target fuel for use in research programs on both fuel production and aircraft and engine design. A NASA sponsored workshop, June 1977, has recommended a fuel for experimental use with the following characteristics:

	<u>Jet A</u>	<u>Experimental fuel</u>
Hydrogen, wt %	~14	~13
Aromatics, vol. %	<25	~35
Flash point, °C	>40	>40
Freezing point, °C	-40	-29
Breakpoint temperature, °C	>260	>240

Such a fuel would allow use of cracked petroleum stocks, refined shale oil and limited amounts of coal liquids and also appears to represent a reasonable target for designing and developing new propulsion and aircraft systems. Efforts to reduce fuel costs must, of course, be integrated with other research efforts to reduce aircraft fuel consumption by means of improvements in aircraft energy efficiency such as the recently organized NASA program to minimize aircraft fuel usage by reducing specific fuel consumption, reducing engine weight, reducing aircraft weight, and improving aircraft aerodynamics [11].

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TABLE I. - COMPARISON OF POSSIBLE FUEL HEAT SOURCES

	Maximum heating rate per tank, Btu/min (kJ/min)	Weight increase, kg	Fuel penalty, %
Air condition system	2100 (2200)	140	0
Lube oil heat exchanger	4300 (4500)	140	~.4
Fuel boost pump recirculation	2000 (2100)	140	~.4
Compressor air bleed	6200 (6500)	300	3.9
Engine-drive electric heater	6200 (6500)	450	.5
Tailpipe heat exchanger	6200 (6500)	250	.1
Insulation -2.54 cm thick	-----	5900	14.6
Equivalent heating by combustion	6200 (6500)	----	.4

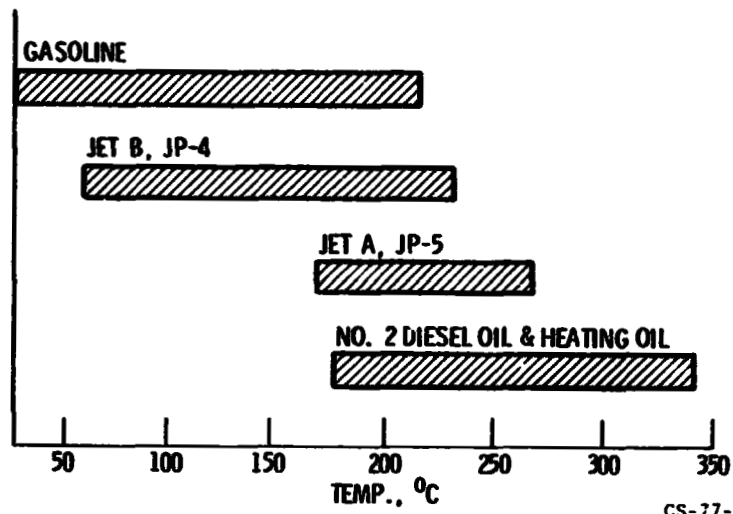
TABLE II. - ASSESSMENT OF POTENTIAL SOLUTIONS TO

JET FUEL PROBLEMS

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 com- ponent technology required Adverse effect on engine life

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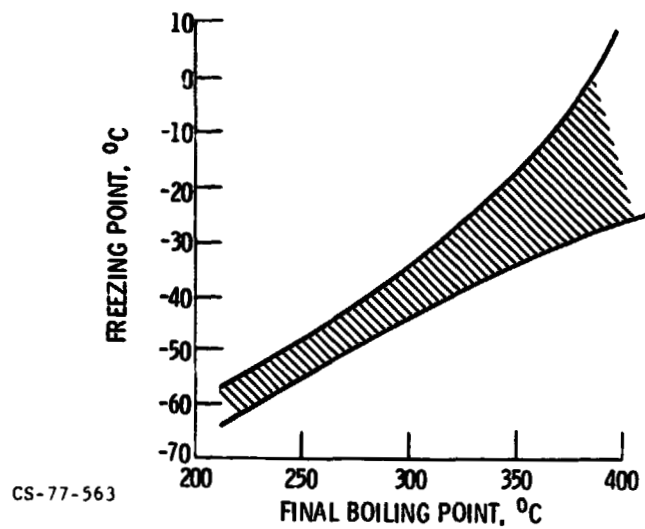
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Figure 1. - Boiling range of various petroleum products.

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Figure 2. - Typical fuel blend freezing points.

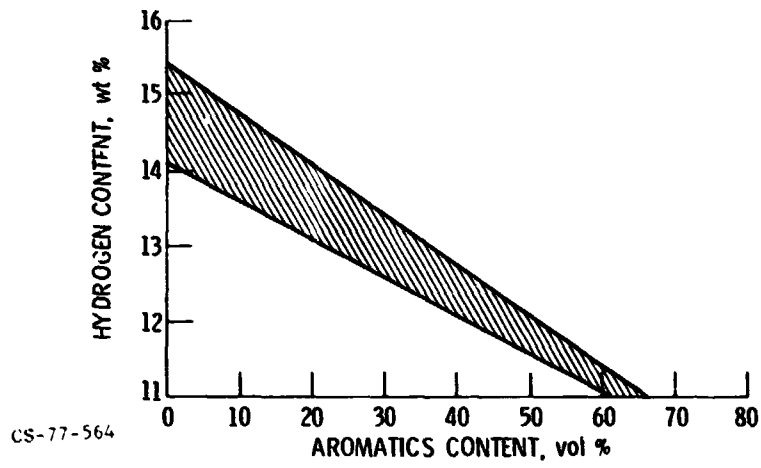


Figure 3. - Variation of hydrogen content with aromatics content.

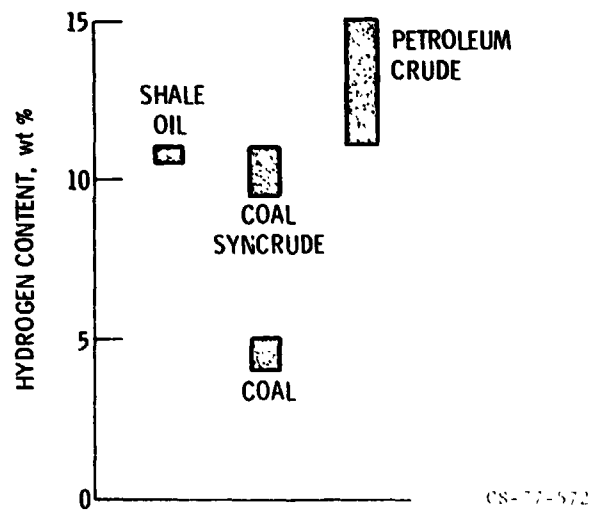


Figure 4. - Hydrogen content of alternative sources of jet fuel.

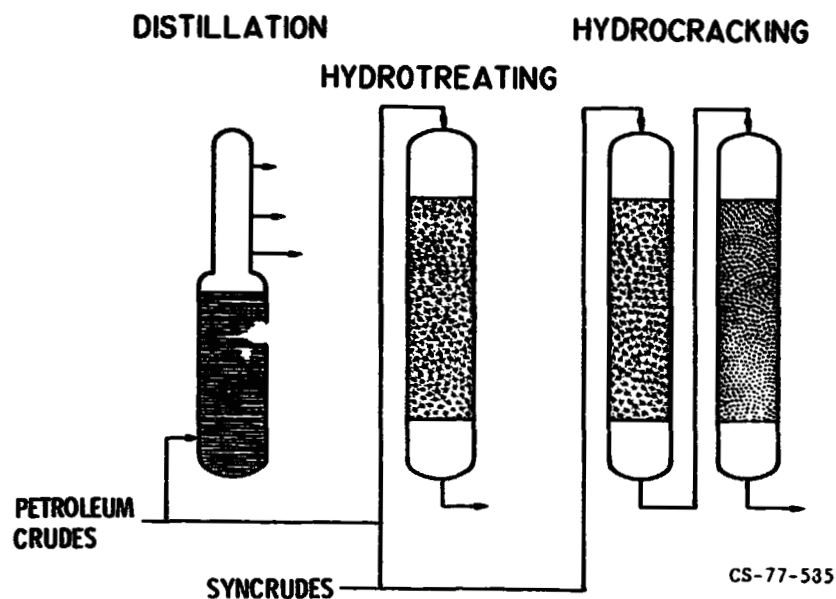


Figure 5. - Simplified refining sequence.

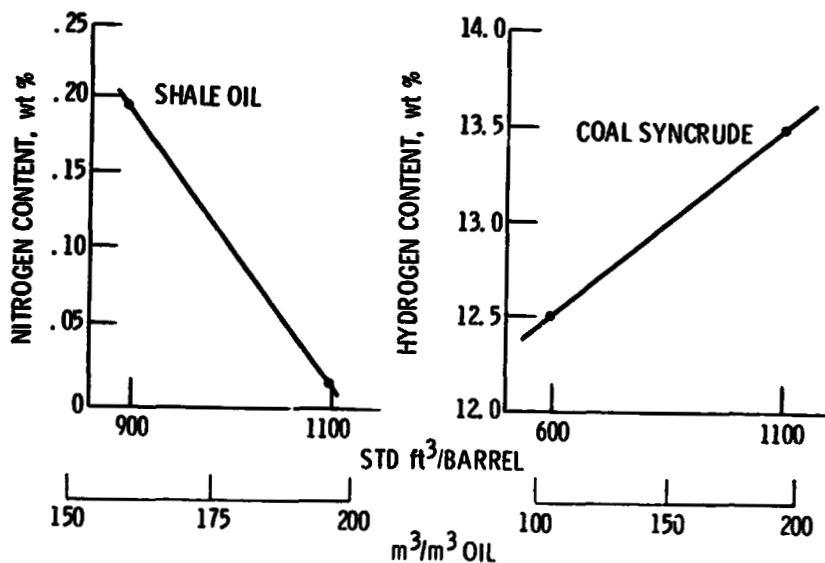


Figure 5. - Hydrogen consumption in processing.

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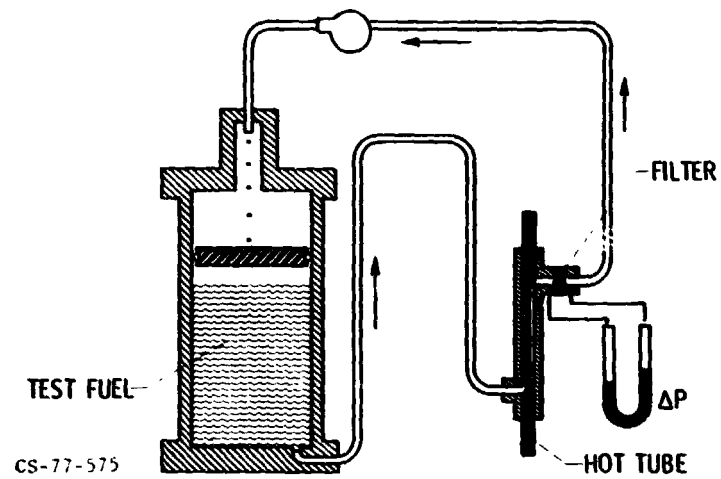


Figure 7. - Thermal stability test rig schematic.

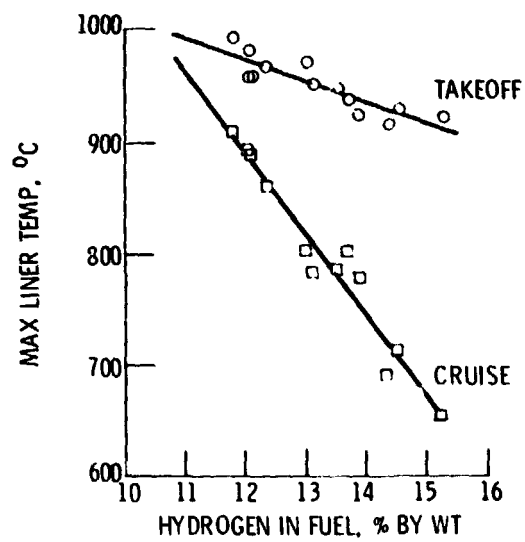


Figure 8. - Effect of hydrogen content of fuel on maximum combustor liner temperature.

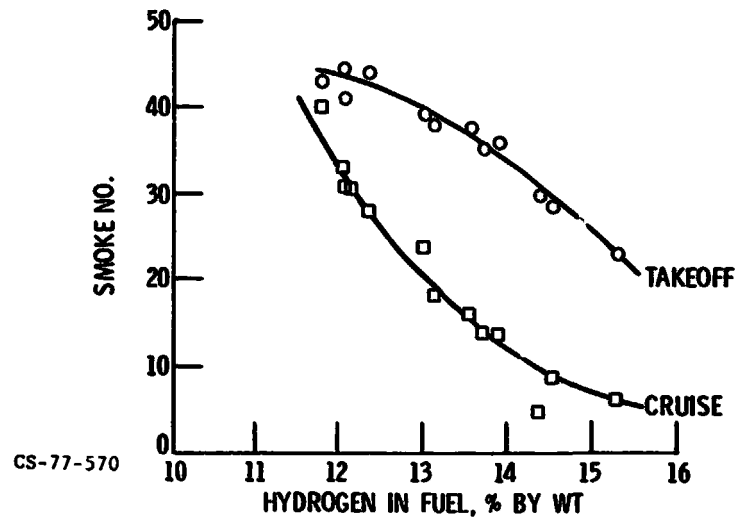
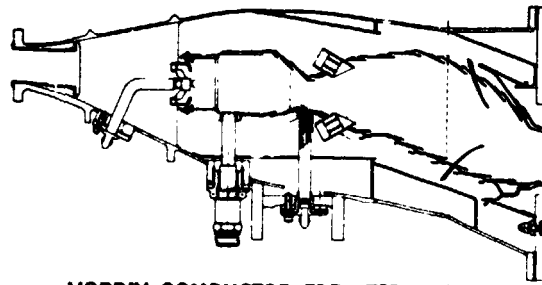
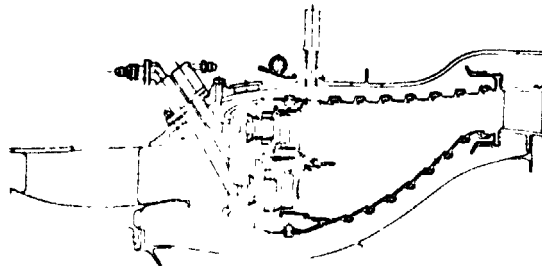


Figure 9. - Effect of hydrogen content of fuel on smoke number.



VORBIX COMBUSTOR FOR JT9D ENGINE



DOUBLE-ANNULAR COMBUSTOR FOR CF6-50 ENGINE

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Figure 10. - Combustor designs evaluated in NASA "Experimental Clean Combustor Program."

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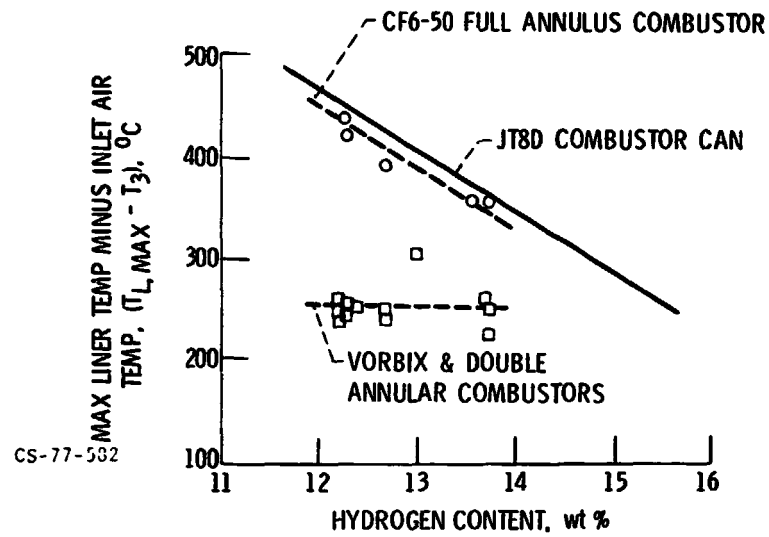


Figure 11. - Effect of hydrogen content of fuel on the maximum combustor liner temperature of several different combustor designs.

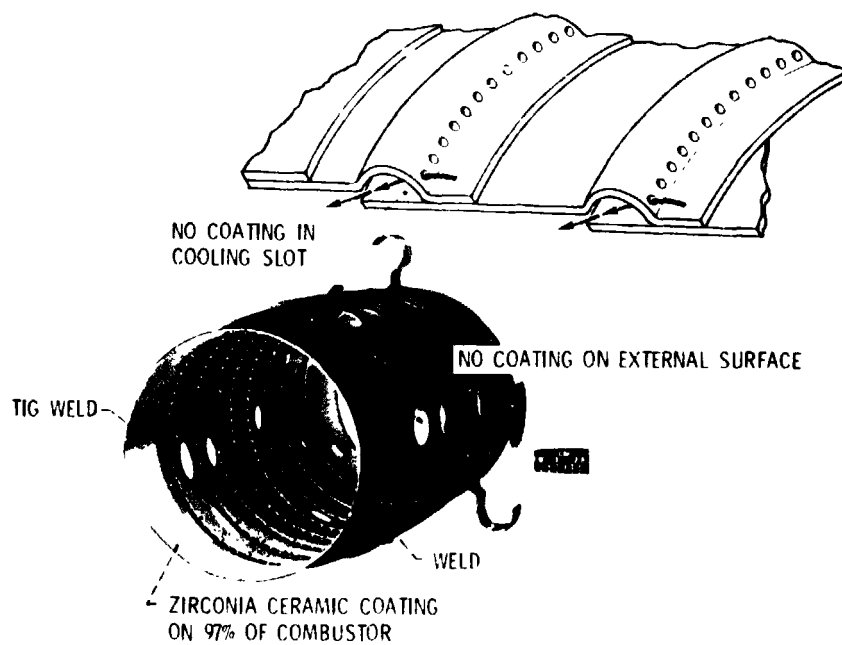


Figure 12. - Thermal barrier ceramic coated combustor.

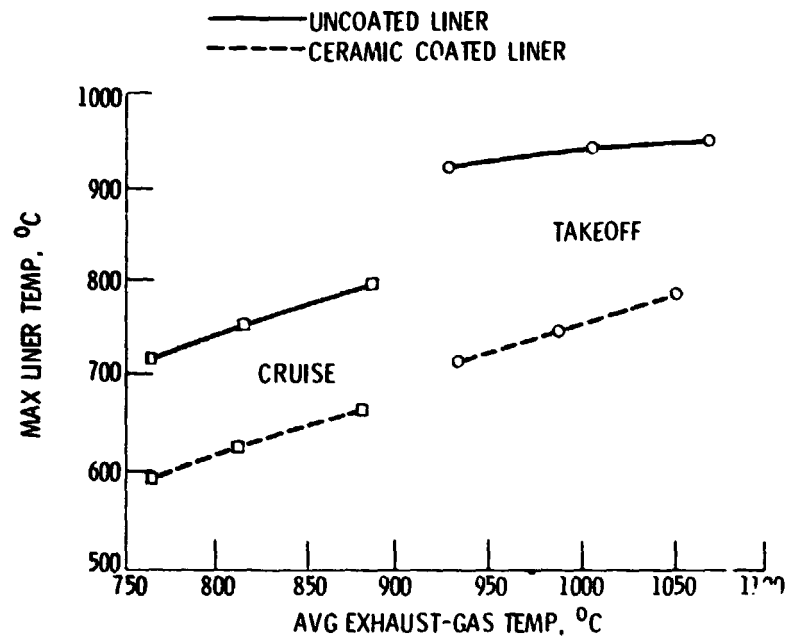


Figure 13. - Effect of ceramic coating on maximum combustor liner temperature.

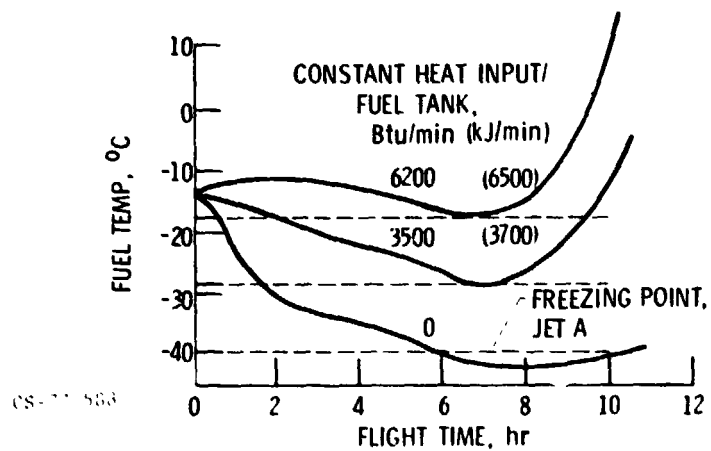


Figure 14. - Fuel tank temperatures for 5000 n.m. flight with heating.

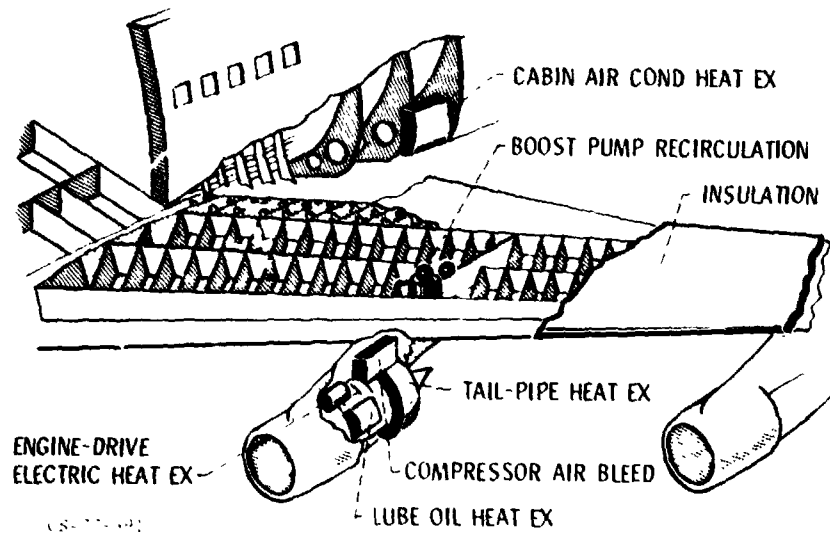


Figure 15. - Fuel tank heating sources.

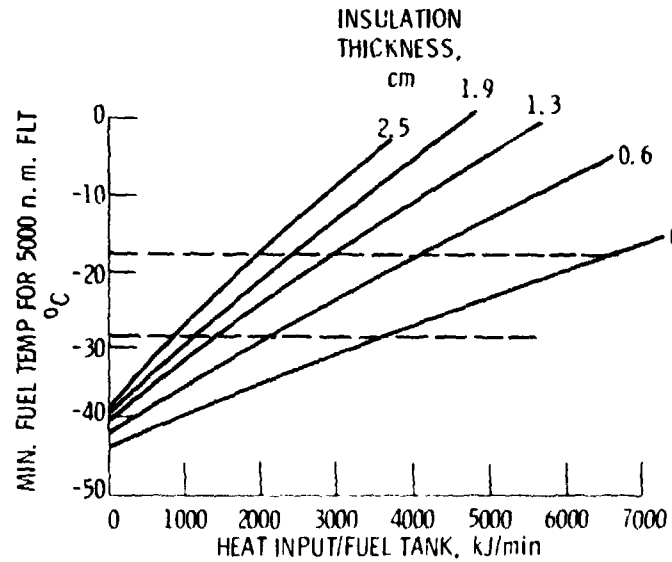


Figure 16. - Reduction of fuel heating requirements by tank insulation.