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NASA Technical Memorandum 81492

(NASA-TM-81492) THE IMPACT OF FUELS ON  
AIRCRAFT TECHNOLOGY THROUGH THE YEAR 2000

(NASA) 26 p HC A03/MF A01

CSCL 21D

N80-23472

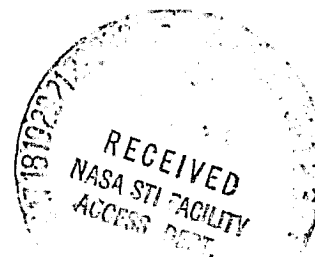
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THE IMPACT OF FUELS ON AIRCRAFT  
TECHNOLOGY THROUGH THE YEAR 2000

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Prepared for the  
International Meeting and Technical Display: Global Technology 2000  
sponsored by the American Institute of Aeronautics and Astronautics  
Baltimore, Maryland, May 5-11, 1980



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THROUGH THE YEAR 2000

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ABSTRACT

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Many uncertain factors could influence the supply, quality and cost of aviation turbine fuels through the year 2000. In the future, it may be necessary to use jet fuels with a broader range of properties in order to insure a more flexible and reliable supply and to minimize energy consumption and processing costs at the refinery. Broadening fuel properties could penalize the performance, durability, and reliability of the propulsion system unless actions are taken to develop the technology required to use broader property fuels. This paper describes research being conducted to (1) determine the potential range of properties for future jet fuels, (2) establish a data base of fuel property effects on propulsion system components, (3) evolve and evaluate advanced component technology that would permit the use of broader property fuels and (4) identify technical and economic trade-offs within the overall fuel production-air transportation system associated with variations in fuel properties.

INTRODUCTION

The purpose of this report is to assess the impact that the supply, quality and processing costs of future fuels may have on aircraft technology. Concern about the availability of good quality and reasonably priced aircraft jet fuels has been mounting since the early seventies and many papers have addressed the subject (1-5)<sup>1</sup>. Despite uncertainties regarding total worldwide petroleum reserves, the production of petroleum is expected to reach a peak between 1990 to 2000 (6). The future imbalance between petroleum supply and demand may be corrected by using approaches such as substituting coal or nuclear power in the power generation industry and by producing liquid hydrocarbon fuels from oil shale or coal. Many research studies have examined the suitability of cryogenic fuels such as hydrogen and methane as jet aircraft fuels. The production

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1. Numbers in parentheses designate References at end of paper.

of either of these cryogenic fuels from coal does not currently appear attractive economically (7). Even should a technological breakthrough occur that would permit major improvements in production economics and efficiency, major technological advancements would be required in the storage and pumping of cryogenic fuels both at the airport and onboard the aircraft. These technological advancements could not be implemented until far beyond the turn of the century. Methyl or ethyl alcohols are not considered to be an attractive alternative fuel for aircraft because of their low heats of combustion. Thus, it would appear that jet aircraft will continue to use liquid hydrocarbon fuels exclusively in the foreseeable future; and up to the turn of the century, these fuels will be produced primarily from petroleum (8) and the availability, quality and cost of aircraft jet fuels will be predominately influenced by the supply and demand for petroleum.

Jet fuel price increases and potential jet fuel shortages 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 also consider 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 tradeoffs in jet aircraft and engine design (9). Other research and technology efforts are being conducted by NASA to reduce jet fuel consumption by improving aircraft energy efficiency (10).

This report will discuss recent estimates of the supply and quality trends of jet aircraft fuels through the year 2000, and will describe the potential benefits that could be obtained by broadening fuel properties. The effects of varying fuel properties on the performance and durability of aircraft and engine components will also be considered. Finally, the report will describe the advanced component technology required to use broader property fuels and the economic and technical tradeoffs that must be considered.

## FUEL SUPPLY AND QUALITY THROUGH THE YEAR 2000

### Current Conditions

Currently, jet fuel is produced principally by distillation of a specified boiling-range fraction from petroleum followed by a mild finishing process to remove sulfur. This simple distillation does not alter the hydrocarbon composition of the fuel with respect to aromatic compounds, which are organic rings deficient in hydrogen. The aromatics have undesirable

combustion characteristics in jet fuels. The average aromatic content has increased steadily over the past several years (figure 1). This increase is due to the increased proportion of high-aromatic crude oils being used to produce jet fuel (11). The aromatic content is limited to a maximum of 20 percent by the current ASTM Jet A fuel specification; however, Jet A produced from some of the available sources of crude oil exceeds this limit as shown by the symbols for typical heavy Arabian and Alaskan crudes in figure 1. This trend is further illustrated by the histogram shown in figure 2 (11), representing the aromatics content of kerosene fractions from 420 worldwide crudes. Approximately 20% of the world's crudes cannot be used to produce jet fuel limited to 20 percent aromatics by conventional distillation and finishing processes, and this proportion appears to be increasing with current conditions.

A waiver currently in effect permits the limited use of jet fuels with aromatic contents as high as 25 percent. United Airlines has maintained records over the past years on the purchases of Jet A fuel that meet specifications only through the use of this waiver (unpublished ASTM bulletin). Figure 3 illustrates the trends for recent years by plotting percent of "waivered" fuels to total fuels purchased. While there has been a random variation in the percentage of "waivered" fuels received over the past several years, the value for the peak percentages has tended to get higher with time. The peak experienced in the last quarter of 1977 was attributed to the introduction and use of Alaskan North Slope crude. No specific information is available to explain the random nature of the data other than the obvious inferences that it is due to shifts in the availability of low and high aromatic crudes at the refinery or variations in blending procedures used during the preparation of the refinery product mix. As U.S. refineries are modified to permit the use of high-sulfur feedstocks, the percentage of "waivered" fuels could increase because crudes containing high sulfur content may also contain a higher aromatics content.

The price of jet fuel has escalated so rapidly since 1973 (figure 4) (12) that it has become nearly impossible to make rational price projections for the future. The effect of these price increases has been to make fuel cost the dominant influence on airline direct operating cost (DOC) (figure 5) (13). The estimates shown in figure 5 for 1979 and 1980 are based on average fuel prices of 56 and 73 cents per gallon respectively with an annual inflation rate of 12% in the remaining direct operating cost elements. In addition to the fuel price problem, a fuel supply shortage of about 10 percent in 1979 caused airlines to either curtail some flight service or to purchase fuel on the spot market at prices about 30¢/gallon higher than from conventional suppliers.

## Projected Trends

A forecast of U.S. demands for various petroleum products through the year 2000 based on projected changes in relative demand between gasoline and middle distillates (8) is illustrated in figure 6. The middle distillates share of the market is predicted to increase from a current value of about 25 percent to a value between 40 and 50 percent by the year 2000. Middle distillates represent the boiling fraction that includes jet fuel, No. 2 diesel oil, and No. 2 heating oil. A major uncertainty in these projections (indicated by the deviation between the continuous and dashed curves) is the future growth of the diesel automobile.

As the demand for middle distillates increases, the refineries will be unable to produce all of the middle distillate products needed by conventional distillation and finishing processes. The refineries will thus be required to makeup the middle distillate shortfall by cracking higher boiling-heavy gas oils. The heavy gas oils contain a larger aromatics content than the middle distillates in the crudes, therefore, middle distillates produced by cracking these heavy gas oils will contain a larger concentration of aromatics than those obtained by conventional distillation of the crude. It would thus be necessary for the refinery to employ very energy intensive hydrocracking (a catalytic process combining cracking and hydrogen addition) to produce Jet A within current specifications for aromatics content. These processes also require a considerable amount of expensive hydrogen. Hydrogen is currently produced as a by-product in refineries that employ reforming, a process that upgrades gasoline octane number by hydrogen removal. However, as the refinery product mix shifts to more middle distillates and less gasoline, insufficient by-product hydrogen will be available from the reforming process and the refinery will be required to manufacture more hydrogen for hydrocracking processes (14). Current specification Jet A produced by hydrocracking heavy gas oil will consume about 4-5 times the processing energy required in producing Jet A from conventional distillation and finishing processes.

A summary of future trends in jet fuel production is illustrated in figure 7. As the supply of natural petroleum diminishes, the next likely domestic source of fossil fuel would be shale oil. The production of jet fuel from shale oil requires relatively severe hydrotreating (catalytic hydrogen addition) to remove undesirable impurities. For shale oil, nitrogen removal is particularly important because these crudes contain a relatively large quantity of organic nitrogen compared to those in petroleum. Nitrogen is undesirable because it reduces the chemical stability of the fuel and because it may be converted to the pollutant oxides of nitrogen (NOx) during combus-

tion. Ultimately the Nation's large reserves of coal could be used as a source of jet fuel. The use of coal syncrudes, which have very high concentrations of aromatics, would require even more severe hydrogenation for the production of jet fuel. The cost of producing jet fuel to current specifications will certainly rise as less desirable feedstocks and more-energy-intensive refining processes are used. Rising production costs will be an increasing incentive to broaden jet fuel specifications in order to minimize refinery energy consumption and reduce total fuel costs.

Initially, small quantities of shale oil could be blended with other petroleum feedstocks, but significant commercial quantities of jet fuel will probably not be produced from shale oil until after the year 2000. As already discussed, the severe treatment necessary for coal-derived liquids make them less attractive as jet fuel feedstocks, although they would be suitable for producing gasoline or heavy fuel oils. In any event, the commercial production of jet fuel from coal will probably lag behind the commercialization of jet fuel from shale oil. Another alternative source for producing jet fuels is tar sands. The U.S. does not have extensive tar sand reserves, however, tar sands represent a significant future source of refinery feedstocks in Canada. Canadian forecasts predict that tar sand plus heavy oil will represent about 13 percent of total Canadian crude production in 1980, 40 percent by 1990, and about 67 percent by the year 2000 (unpublished data by Dr. R. B. Whyte, NRC of Canada). The aromatics content of the kerosene fraction produced from oil extracted from tar sands is typically intermediate between that for high-aromatics-content petroleum and coal syncrudes. Thus, as the year 2000 approaches, unless refineries incorporate the energy-intensive processes required to upgrade the hydrogen content of the fuel, jet fuels may have higher aromatic content because of (1) changes in available feedstock properties and (2) increases in fuel production by cracking of higher-aromatics content, high-boiling fractions. Increasing amounts of "waivered" fuels could appear in the market and more frequent shortages in jet fuel could occur as a result of increasing competition with other middle distillate fuel users. Airlines might eventually be subjected to the choice of curtailing flights or using broader property fuels.

Obviously, the aircraft industry must consider and assess all potential alternatives regarding the future availability of jet fuel. If jet fuels that meet current specifications could be produced at the refinery, jet aircraft could continue to use fuels with the most desirable properties for performance and durability of current aircraft and engine components. Of course, this approach could possibly result in fuel shortages, increases in refinery energy consumption, and higher aircraft

operating costs. Conversely, allowing variations in jet fuel properties beyond current specification and waiver limits could provide a more flexible, reliable fuel supply, and could minimize refinery energy consumption and aircraft operating costs. The disadvantage of following this approach could be possible adverse effects on aircraft and engine life, performance, and exhaust emission characteristics. A comprehensive research and technology effort is required to assemble the data base required by the aircraft industry to make rational and acceptable decisions regarding the economic and technical tradeoffs between future fuel specifications measured against refinery, airframe, engine, and airline operating technologies. The subsequent sections of this report will describe preliminary activities that have been initiated to establish this needed data base.

#### POTENTIAL CHANGES IN FUEL CHARACTERISTICS

A range of hypothetical characteristics for future broad-property jet fuels are compared to current properties in Table I, based on recommendations which evolved from a NASA workshop held in 1977 (8). 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 less acceptable thermal stability. Thermal stability is a measure of the fuel's chemical stability and relates to the degree to which the fuel may be heated without incurring significant levels of fuel decomposition and deposit formation. The properties designated for the future broad-property fuel tend to be similar to those of the current number 2 diesel fuels.

The inverse relationship of aromatics content to hydrogen content is illustrated by the data shown in figure 8 (15). The importance of hydrogen content on combustor performance will be discussed in a following section.

The boiling range of selected petroleum products is illustrated in figure 9. Jet A has a relatively narrow boiling range compared to other petroleum products. The initial boiling point, a minimum of about 170°C, is necessary to keep the flash point above 40°C to reduce fueling fire hazards and altitude boil-off losses. The final boiling point for Jet A is usually below 270°C to comply with limits on the freezing point. 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. Freezing point increases as the final boiling point is increased, and an increased final boiling point would clear-



ly allow increased flexibility in the production of jet aircraft fuel. The increase in maximum theoretical yield of Navy jet fuel JP-5 produced from North Slope Alaskan Crude with increasing freeze point and/or decreasing flash point is shown in figure 10 (16). JP-5 represents a narrower petroleum cut than Jet A, hence the gains in theoretical yield for JP-5 shown in figure 10 are not necessarily identical to what might be expected for Jet A but the trends should be similar.

Many of the characteristics of jet fuel are interrelated. For example, heat of combustion (by mass) decreases linearly with decreasing hydrogen content. Viscosity increases with increasing fuel density which is inversely proportional to hydrogen content. Thermal stability is decreased as the concentration of certain chemically reactive species increases which generally occurs as the aromatics content and/or final boiling point is increased.

## FUEL PROPERTY EFFECTS ON COMPONENT TECHNOLOGY

### Combustion Characteristics

Decreases in hydrogen content have a pronounced effect on exhaust smoke and liner temperatures in a conventional combustor (figs. 11 and 12). Combustor tests were conducted using prepared fuel blends with various hydrogen contents (17). Simulated cruise and takeoff conditions revealed significant increases in exhaust smoke, shown as arbitrary smoke number units, as the hydrogen content of the fuel decreases. Lowering the hydrogen content makes the flame more sooty and more luminous, thus increasing the heat radiated to the liner walls and increasing their temperature. Higher liner temperatures reduce liner life due to accelerated metal fatigue and oxidation. Combustor liner life predictions for a J79 engine using fuels with varying fuel hydrogen content are shown in figure 13 (18). The relative combustor liner life is predicted to decrease about 33 percent when fuel hydrogen content is decreased from 14 to 13 percent. These specific predictions are for the J79 engine combustor which contains tubular liners. Analyses reported in (19) estimate decreases in liner life as high as 40 percent for the same reduction in hydrogen content in an annular combustor. Other combustor performance and durability criteria that could be adversely affected by reduced hydrogen content, lower volatility, and higher viscosity include ignition and relight, gaseous exhaust emissions, and carbon deposition.

### Fuel Thermal Stability

Fuel system deposits may occur with jet fuels that are not thermally stable at the temperatures they will encounter on

their way through the system to the combustor (20). These deposits result from the auto-oxidation of reactive constituents, particularly nitrogen and oxygen, and the rate of deposition increases with temperature as well as the concentration of reactive species. Deposit buildup in a fuel injector may cause nonuniform fuel sprays. These can cause local hot spots on the liner or non-uniformities in the exit temperature profile.

#### Fuel Pumpability at Low Temperature

Fuel stored in aircraft tanks can reach very low temperatures during long flights. Figure 14 shows a correlation of in-flight minimum fuel temperatures for Boeing 707 and 747 aircraft flying polar route missions (21). Data were obtained from about 1100 missions, each greater than 4000 nautical miles. The probability that the temperature of fuel in the tank will fall below a given minimum value is plotted against minimum fuel temperature. The minimum temperature that the fuel may reach during flight is lower than  $-26^{\circ}\text{C}$  for half of these missions. The differences in temperature between the two types of aircraft are mainly attributed to differences in flight Mach number or flight envelope. For a probability of 1 day per year, the minimum fuel temperature is as low as about  $-42^{\circ}$  to  $-47^{\circ}\text{C}$ . An experimental study was conducted to determine the flow behavior of fuels cooled below their freezing points in a scalemodel fuel tank (22). Cooling was provided at the top and bottom of an insulated tank to simulate the in-flight cooling of the upper and lower surfaces of a section of the wing. After being cooled, fuel was discharged from the tank by the boost pump. Conditions in the tank were observed through viewing ports on each side of the tank. The effects of cooling a fuel below its freezing point are illustrated in figure 15 which shows the frozen and liquid fuel remaining in the tank after pumpdown. During the initial part of the pumpdown, the two-phase mixture of wax and liquid fuel may be removed by the boost pump, but eventually the pump inlet becomes plugged by this slushy mixture, and the remaining fuel cannot be pumped from the tank. Airlines have always avoided potential fuel freezing problems by using fuels with low freezing points and when necessary, altering flight conditions.

### AIRCRAFT TECHNOLOGY FOR FUTURE FUELS

#### Engine Combustor Technology

The higher liner temperatures associated with the use of fuels with higher aromatic content could be reduced or tolerated by the use of advanced alloys and coatings, improved

cooling effectiveness, and new mixing or burning concepts. Improved liner cooling by increasing the proportion of coolant airflow might not be an acceptable approach because this would reduce the amount of air available for control of the exit temperature profile. Increasing coolant airflow might also increase carbon monoxide and unburned hydrocarbon emissions by quenching the combustion reactions near the combustor liner wall.

Approaches such as lean burning or improved fuel atomization that have been explored to control exhaust emissions may also be effective in reducing liner temperature by minimizing luminous-flame radiation. These approaches could also help prevent carbon deposition and reduce exhaust smoke. The use of multi-zone combustion or variable geometry, in addition to controlling emissions at both high and low power levels, could also be used to insure reliable ignition and relight. Several multi-zone designs have been evaluated with fuels of various hydrogen content (23-25). Figure 16 compares the liner temperatures measured in tests of these experimental multizone combustors using a fuel-lean main stage with those of several conventional single-zone combustors. The conventional combustors exhibit a strong dependency of maximum liner temperature on hydrogen content of the fuel. The multi-zone combustors show an insensitivity of maximum liner temperature to hydrogen content.

NASA has recently initiated a technical program to evaluate promising combustor concepts that would permit the use of broader property fuels (26). This program which is entitled The NASA BroadSpecification Fuels Combustion Technology Program is a contracted effort to evolve and evaluate the technology required to utilize broad-property fuels in current-and-next-generation commercial Conventional Takeoff and Landing (CTOL) aircraft engines, and to verify this technology in full-scale engine tests. The program consists of three phases: Combustor Concept Screening, Combustor Optimization Testing, and Engine Verification Testing. Phase I contracts have been awarded to the General Electric Company and the Pratt & Whitney Aircraft Group of the United Technologies Corporation to evolve and screen combustion system designs for the CF6-80 engine and the JT9D-7 engine, respectively, in high-pressure sector test rigs. Combustor design concepts to be evaluated by each contractor are illustrated in figures 17 and 18. One concept having the least technical risk involved relatively minor modifications to the production engine combustion system (figs. 17a and 18a). The purpose of testing this concept is to determine the feasibility of modifying in-service engine combustion systems to make them capable of using broad-property fuels while meeting and maintaining the performance and durability characteristics of the production combustion systems. The combustor concepts illustrated in figures 17b, 17c, 18b and 18c represent advanced

designs incorporating the means for controlling reaction zone stoichiometry by the use of either multi-zone combustion or variable geometry. These designs might permit future aircraft to use fuels with an even broader range of properties, but they are inherently more complex and more difficult to develop than conventional combustors.

### Fuel Systems Technology

Many approaches to prevent fuel-system fouling are already in use. For example, designers attempt to limit the maximum fuel temperature by insulating the parts of the fuel manifold exposed to high temperature; and suppliers attempt to control reactive constituents in the fuel by adding antioxidants during the final stages of refining. Further design improvements must be sought, however, to limit fuel exposure temperature. Research is currently underway to obtain a better understanding of the effects of constituents in the fuel on fuel degradation. The dissolved oxygen in the fuel plays an important part in these reactions. Removal of this oxygen may prove impractical, but more efficient antioxidant additives may be developed, and removal of certain reactive or catalytic impurities may help. Fuel-system purging could be investigated as a means of minimizing fuel deposits in multi-zone combustors.

Modifications to aircraft fuel systems that might be necessary to permit the use of higher-freezing-point fuel are also being investigated (27-29). A number of fuel-tank heating concepts as well as tank insulation were evaluated as approaches to maintaining the fuel in the tanks above the freezing point. Insulation of the fuel tanks is not practical in present aircraft because it entails a large weight penalty; but future aircraft wing designs may permit the use of effective lightweight insulation. Analytical studies indicated that the two most promising approaches for providing fuel tank heating were a lubricating-oil heat exchanger and an electric heat exchanger powered by an engine-driven generator (fig. 19). Fuels with freezing points up to  $-34^{\circ}\text{C}$  could be used for long range flights by using a modified lubrication-oil heat exchanger system. The existing lube-oil heat exchanger system would be modified by adding a second heat exchanger to heat excess fuel flow to be returned to the wing tank. The recirculation system could be shut off when fuel-tank heating was not required. This system has the advantage of using existing components, being low in cost, having a low cycle penalty, and being a simple system, requiring only a relatively minor modification of the existing lube-oil heat rejection system.

The electrical fuel-heating concept could provide much higher heating rates to permit the use of fuels with freezing points up to about  $-18^{\circ}\text{C}$ . Heater control would be independent

of engine operating point, and this system would be adaptable to layover heating by means of auxiliary ground power. In-flight power would be obtained by installing a generator on each engine. An inert fluid would be heated by an electric-resistance heater. The heated fluid would then be pumped to another heat exchanger to reject heat to the fuel tank. This system has the disadvantage of involving major modifications and additions to the engines and aircraft. Furthermore, it introduces significant weight and cycle penalties. The judgment to use such a fuel-heating system will partially depend on savings from using a broad-property fuel compared to system installation and operating costs.

#### CONCLUDING REMARKS

It is difficult to make an accurate prediction regarding the degree to which jet fuel properties might actually change by the year 2000 and beyond. This report has discussed the factors that could affect the supply and cost of future fuels and the potential benefits that might be realized by broadening fuel properties. It has also described potential approaches to counteract the adverse effects of variations in jet fuel properties by means of advancements in aircraft and engine components technology. Some of the research activities currently in progress that are attempting to establish a technological data base for future fuels were also described. The research activities described herein are not meant to be a complete survey of all of the fuel related efforts being conducted by government and industry but they merely illustrate some of the more significant problem areas that must be addressed to permit the use of future broad-property fuels. The overall effort required to assess the feasibility of using broad property fuels in both in-service and future aircraft fuel systems and engines will be considerable. Not only performance but also durability over the extended service life of the aircraft must be evaluated to insure component and system reliability, maintainability, safety, and environmental acceptability with the use of these fuels. Furthermore, it will be necessary to conduct extensive economic and engineering tradeoff studies to evaluate the effects of broadening fuel properties on the overall fuel production and air transportation system. These tradeoff studies must consider the effects of fuel property changes on (1) projected jet fuel supply and relative cost, (2) refinery energy consumption and processing requirements, (3) airline investment and operating costs for both current and future aircraft and (4) general aviation aircraft investment and operating costs. For current in-service aircraft, it is important to establish the degree to which fuel properties may be varied without resorting to prohibitive equipment modifications or

significant reductions in service life. The overall time required, first, to evolve and evaluate new technology for a fuel with different properties and, then, for industry to perform the required development and certification could be from 10 to 20 years depending on the technological changes to be implemented. Obviously, with this long a lead time, it is imperative to begin the effort to establish the necessary technological data base long before a new fuel becomes available.

Finally, it must be recognized that broadening jet fuel properties will not necessarily insure an increase in jet fuel availability. Minimizing processing energy consumed in the production of jet fuel may permit some increase in total product yield from a barrel of crude, but the jet fuel users must still compete with the other fuel consumers for their share of the total supply. Nevertheless, the ability to use a jet fuel with less stringent specifications would provide the aircraft industry with the flexibility of using fuels that might otherwise not be acceptable.

## REFERENCES

1. Pinkel, I. I., "Future Fuels for Aviation," Advisory Group for Aerospace Research and Development, Paris, AGARD-AR-93, Jan. 1976.
2. Stewart, W. L., Nored, D. L., Grobman, J. S., Feiler, C. E., Petrash, D. A., "Preparing Aircraft Propulsion for a New ERA in Energy and the Environment," Astronautics & Aeronautics, Vol. 18, Jan. 1980, pp. 18-31, 37.
3. Longwell, J. P. and Grobman, J., "Alternative Aircraft Fuels," Journal of Engineering for Power, Vol. 101, January, 1979, pp. 155-161.
4. Blazowski, W. S. and Jackson, T. A., "Evaluation of Future Jet Fuel Combustion Characteristics," Air Force Aeropropulsion Lab., AFAPL-TR-77-93, July, 1978.
5. Rudey, R. A., "Effect of Broadened-Specification Fuels on Aircraft Engines and Fuel Systems," NASA TM-79086, 1979.
6. Energy: Global Prospects 1985-2000, McGraw-Hill, New York, 1977.
7. Witcofski, R. D., "Comparison of Alternate Fuels for Aircraft," NASA TM-80155, 1979.
8. Longwell, J. P., ed., "Jet Aircraft Hydrocarbon Fuels Technology", NASA CP 2033, 1978.
9. Grobman, J., "Alternative Jet Aircraft Fuels," Aeropropulsion 1979, NASA CP-2092, 1979, pp. 129-148.
10. Nored, D. L., Dugan, J. F., Saunders, N. T. and Ziemianski, J. A., "Aircraft Energy Efficiency (ACEE) Status Report," Aeropropulsion 1979, NASA CP-2092, 1979, pp. 1-58.
11. Dukek, W. G. and Longwell, J. P., "Alternative Hydrocarbon Fuels for Aviation," Exxon Air World, Vol. 29, No. 4, 1977, pp. 92-96.
12. "Fuel Cost and Consumption, Monthly Reports," Civil Aeronautics Board.
13. "Trends in Airline Cost Elements," Second ed., Civil Aeronautics Board, July 1977 plus Supplement, Jan. 3, 1979; and "Trends in Airline Unit Costs," Fourth ed., Civil Aeronautics Board, February, 1979.

14. Posey, L. G., Kelly, P. E., and Cobb, C. B., "Analysis Shows U.S. Refiners to Need More Hydrogen by 1990," The Oil and Gas Journal, Vol. 76, Oct. 23, 1978, pp. 131-136.
15. Shayeson, M. W., "Jet Fuel Quality Considerations," Shell Aviation News, No. 440, 1977, pp. 26-31.
16. Lieberman, M. and Taylor, W. F., "Effect of Refining Variables on the Properties and Composition of JP-5," Exxon Research and Engineering Co., Linden, NJ, Interim Technical Report Set. 1978 - July 1979, Jan. 1980. (NAPC Report RL.1PE.80).
17. Butze, H. F. and Ehlers, R. C., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor," NASA TMX-71789, 1975.
18. Gleason, C. C., Oller, T. L., Shayeson, M. W., and Bahr, D. W., "Evaluation of Fuel Character Effects of J-79 Engine Combustion System," General Electric Co., Cincinnati, OH, R79AEGe21, June 1979. (AFAPL-TR-79-2015, CEEDO-TR-79-06)
19. Lohmann, R. P., Szetela, E. J., and Vranos, A., "Analytical Evaluation of the Impact of Broad Specification Fuels on High Bypass Turbofan Engine Combustors," Pratt and Whitney Aircraft Group, East Hartford, Conn., PWA-5565-15, Dec. 1978. (NASA CR-159454)
20. Taylor, W. F., ed., "Jet Fuel Thermal Stability," NASA TM-79231, 1979.
21. Pasion, A. J., "In-Flight Fuel Tank Temperature Survey Data," Boeing Commercial Airplane Company, Seattle, Wash., D6-48611, May 1979. (NASA CR-159569)
22. Stockemer, F. J., "Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a Wing Tank Model," Lockheed-California Company, Burbank, Calif., 1979. (NASA CR-159615)
23. Gleason, C. C. and Bahr, D. W., "Experimental Clean Combustor Program, Alternate Fuels Addendum, Phase II," General Electric Company, Evendale, Ohio, R76AEG268, Jan. 1976. (NASA CR-134972)
24. Roberts, R.; Peduzzi, A.; Vitti, G. E., "Experimental Clean Combustor Program, Phase II, Alternate Fuels Addendum," Pratt & Whitney Aircraft, East Hartford, Conn., PWA-5370, July 1976. (NASA CR-134970)



25. Gleason, C. C. and Bahr, D. W., "Experimental Clean Combustor Program - Diesel No. 2 Fuel Addendum, Phase III," General Electric Company, Evendale, Ohio, R79AEG367, May 1979. (NASA CR-135413)
26. Fear, J. S., "NASA Broad-Specification Fuels Combustion Technology Program - Status and Description," NASA TM-79315, 1979.
27. Pasion, A. J. and Thomas, I., "Preliminary Analysis of Aircraft Fuel Systems for Use with Broadened Specification Jet Fuels," Boeing Commercial Airplane Company, Seattle, Wash., D6-44538, June 1977. (NASA CR-135198)
28. Friedman, Robert, "High-Freezing-Point Fuels Used for Aviation Turbine Engines," NASA TM-79015, 1979.
29. Pasion, A. J., "Design and Evaluation of Aircraft Heat Source Systems for Use with High-Freezing-Point Fuels," Boeing Commercial Airplane Company, Seattle, Wash., D6-48097, May 1979. (NASA CR-159568)

TABLE I. - POTENTIAL CHANGES IN FUEL PROPERTIES

Property	Current Jet A	Potential broad-property fuel
Aromatics, vol. %	17 → 25	30 → 35
Hydrogen, wt. %	14 → 13.5	13.0 → 12.5
Final boiling point, °C	260 → 280	290 → 330
Freezing point, °C	-46 → -40	-34 → -29
Thermal stability	Acceptable	Marginal

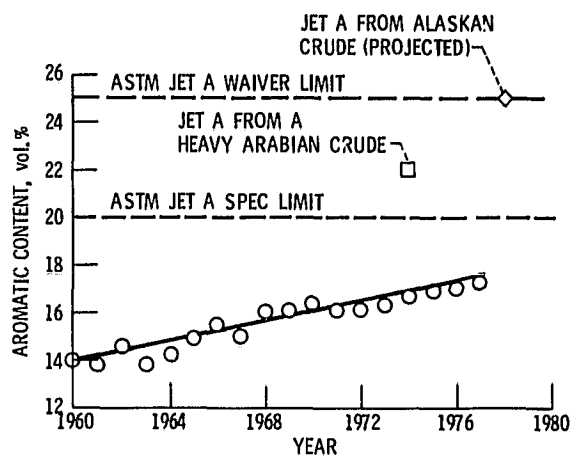


Figure 1. - Average aromatic content of commercial Jet A fuel.

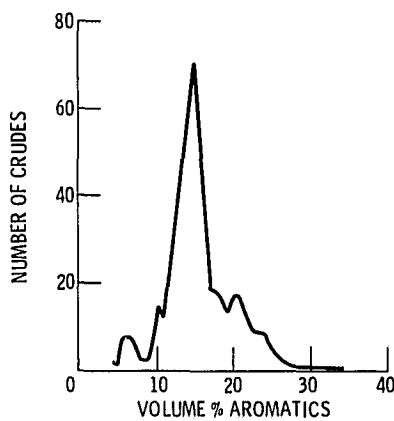


Figure 2. - Distribution of aromatic content in kerosene fraction of 420 crudes (ref. 11).

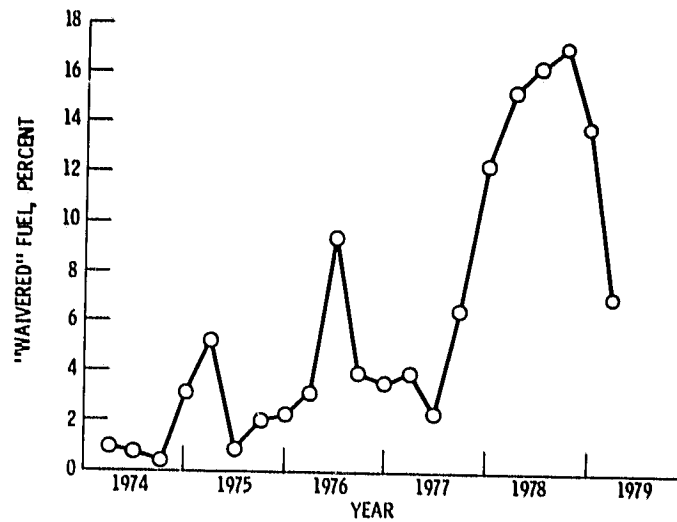


Figure 3. - Statistical trends in quantity of "waivered" jet A fuel purchased by United Airlines.

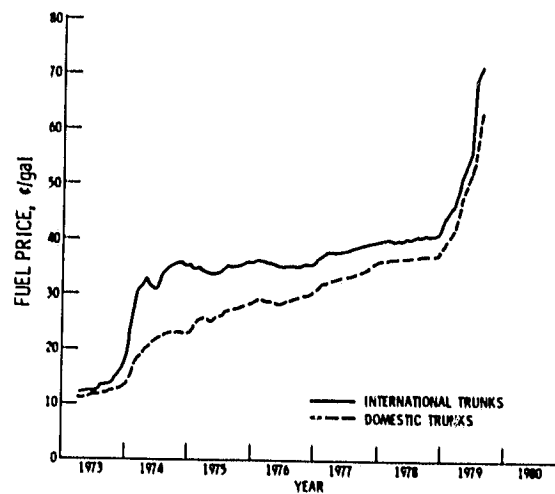


Figure 4. - U. S. airline jet fuel price, monthly averages.

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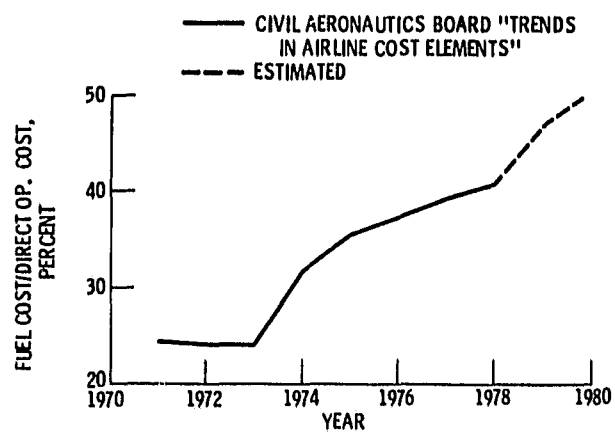


Figure 5. - Trend in fuel cost as an element of airline direct operating cost (domestic operations of domestic trunk airlines).

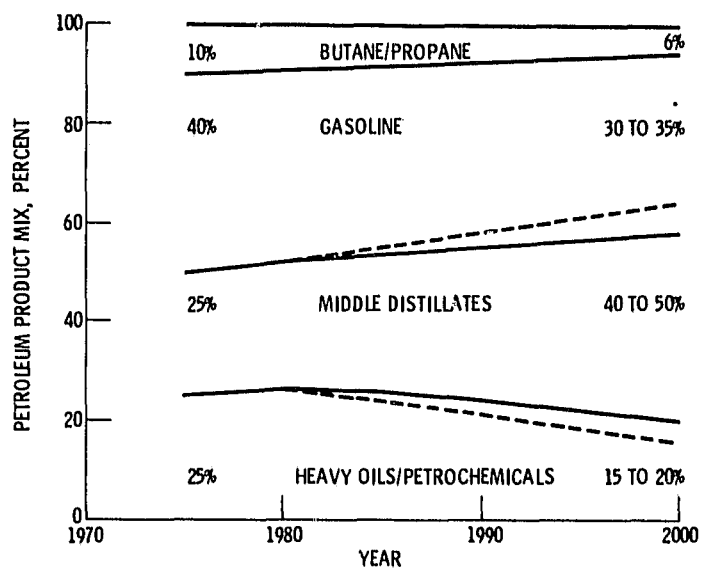


Figure 6. - U. S. petroleum product distribution forecast.

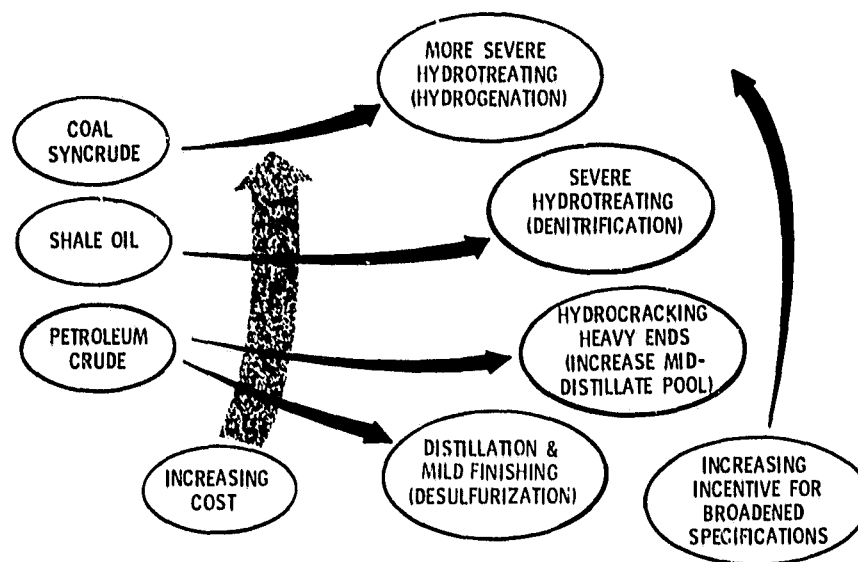


Figure 7. - Jet fuel production alternatives.

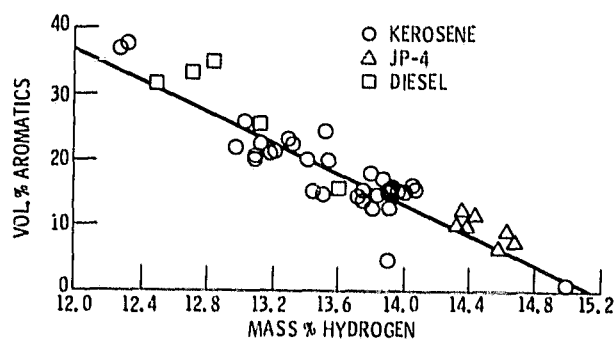


Figure 8. - Correlation of aromatics and hydrogen content of 50 fuels (15).

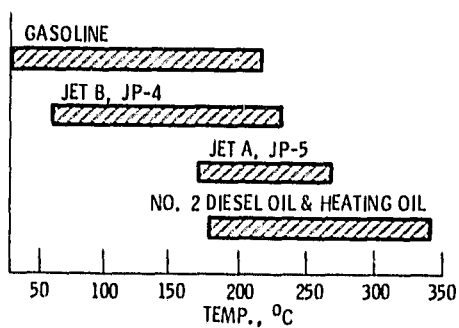


Figure 9. - Boiling range of selected petroleum products.

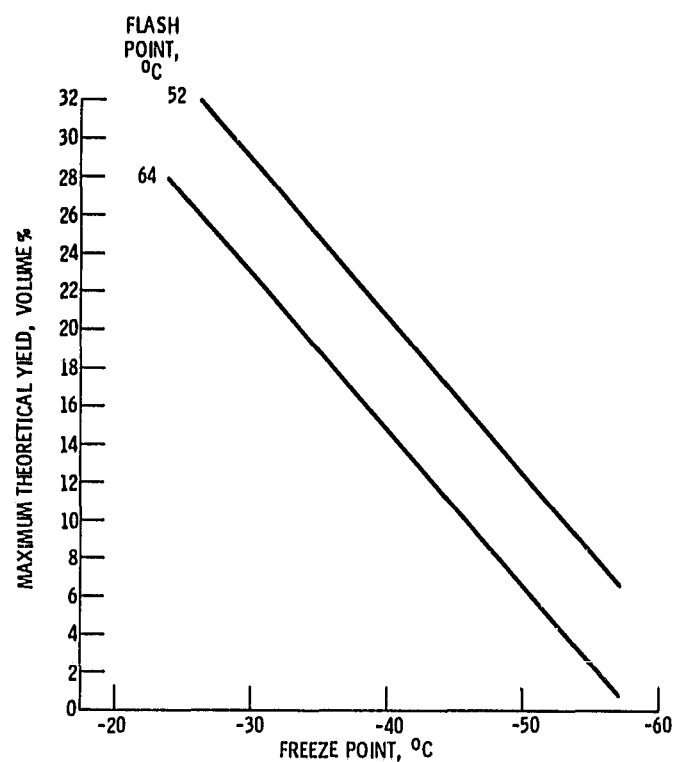


Figure 10. - Effect of relaxation of freeze/flash points on maximum theoretical yield of JP-5, north slope Alaskan crude (16).

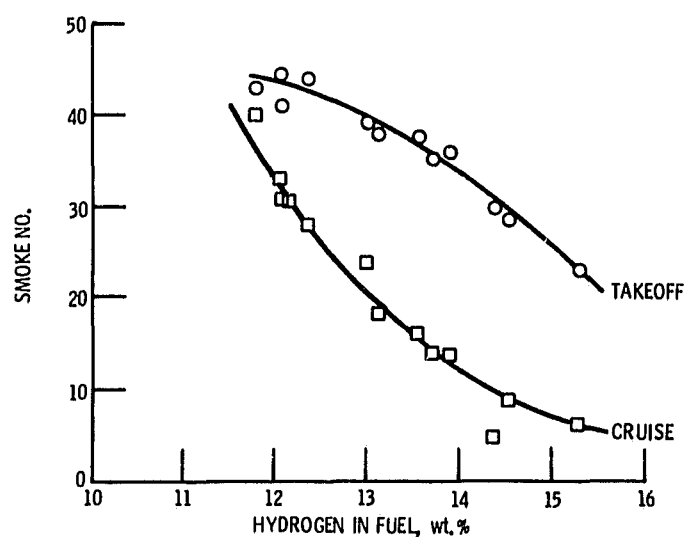


Figure 11. - Effect of hydrogen content of fuel on smoke number.

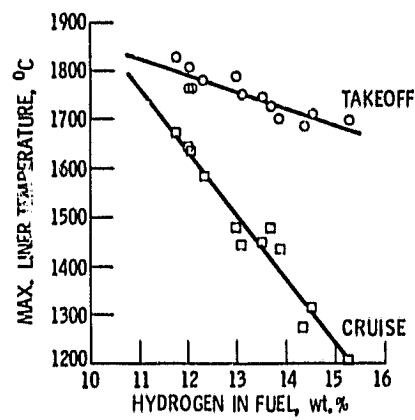


Figure 12. - Effect of hydrogen content of fuel on maximum combustor liner temperature.

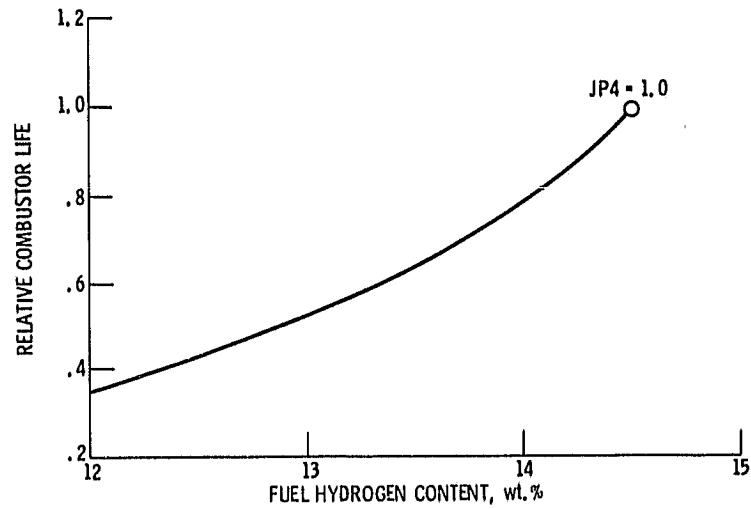


Figure 13. - Predicted effect of fuel hydrogen content on combustor life (Ref. 18).

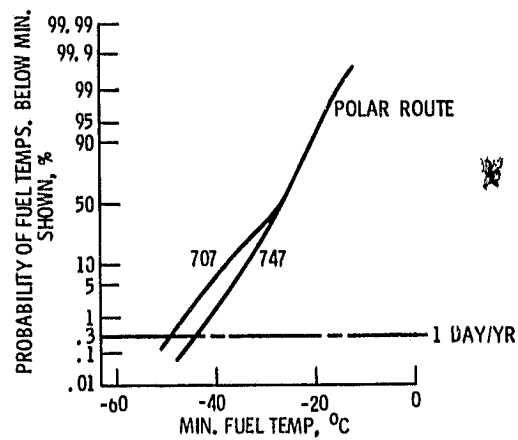


Figure 14. - Summary of in-flight minimum fuel temperatures.

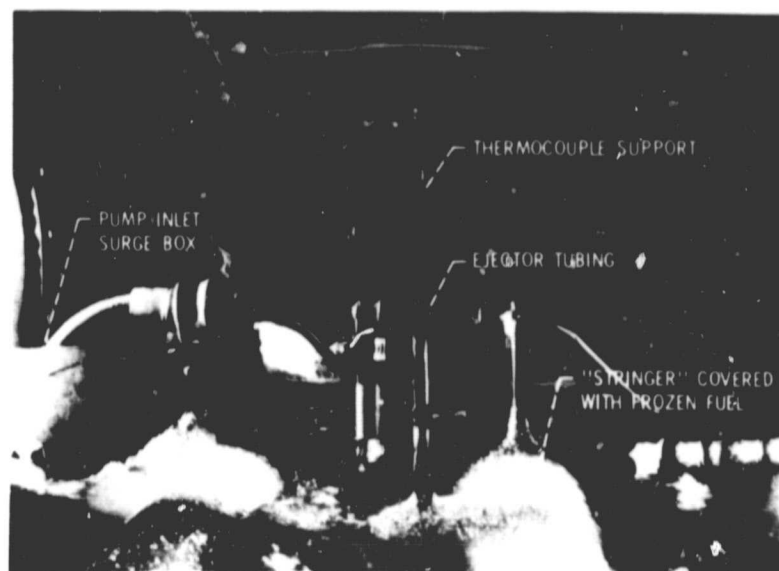


Figure 15. - Interior view of fuel tank simulator. Fuel cooled down below freezing point.

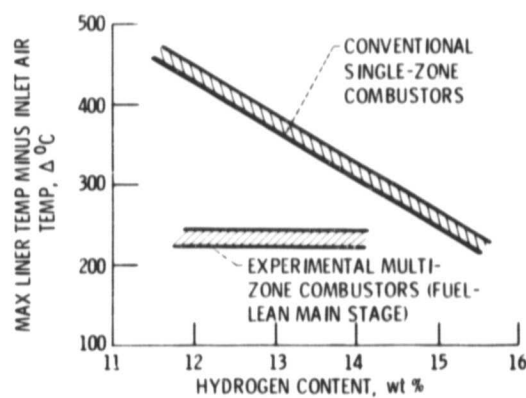
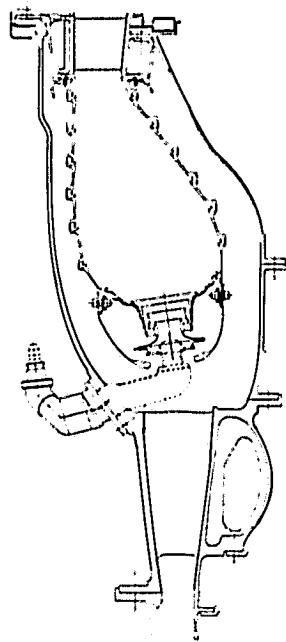


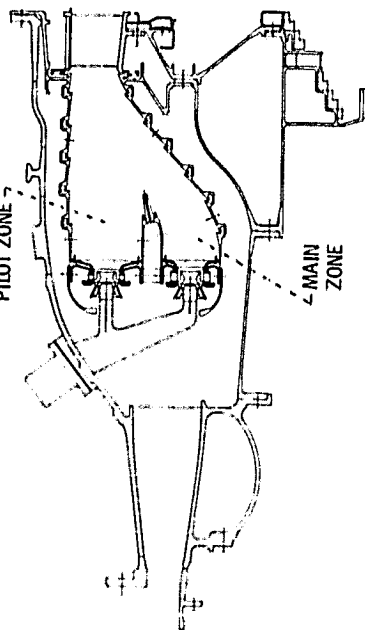
Figure 16. - Effect of hydrogen content of fuel on liner temperature for different combustors.

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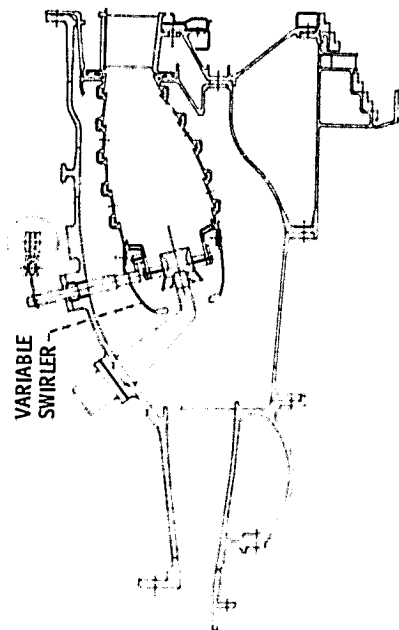




(a) CF6-80 COMBUSTION SYSTEM.

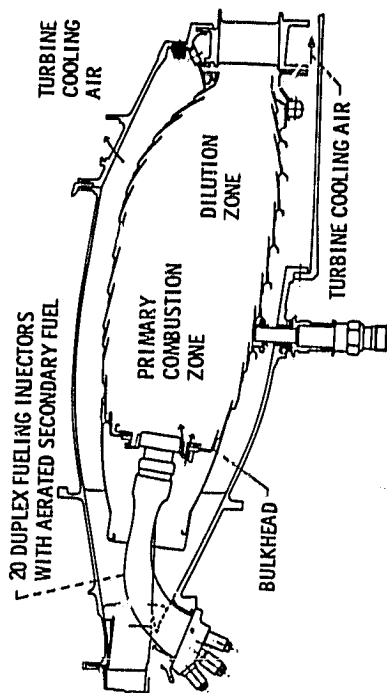


(b) DOUBLE-ANNULAR COMBUSTOR CONCEPT.

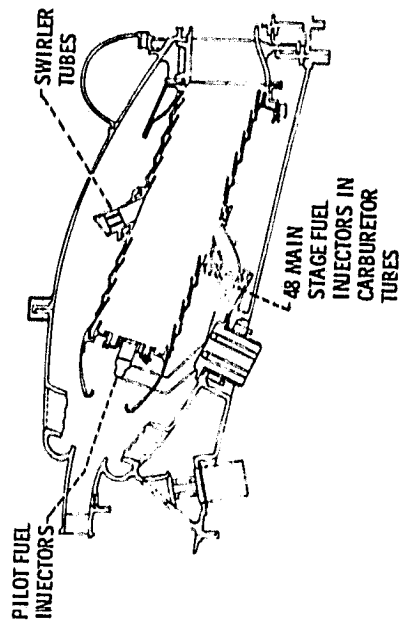


(c) SHORT SINGLE-ANNULAR COMBUSTOR CONCEPT WITH VARIABLE GEOMETRY.

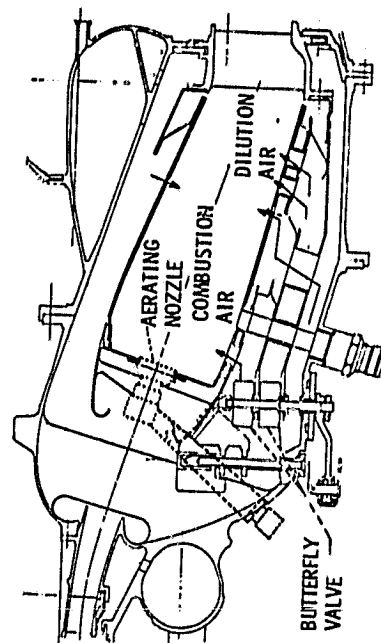
Figure 17. - Combustor design concepts for the General Electric CF6-80 engine.



(a) ADVANCED BULKHEAD COMBUSTOR CONCEPT.

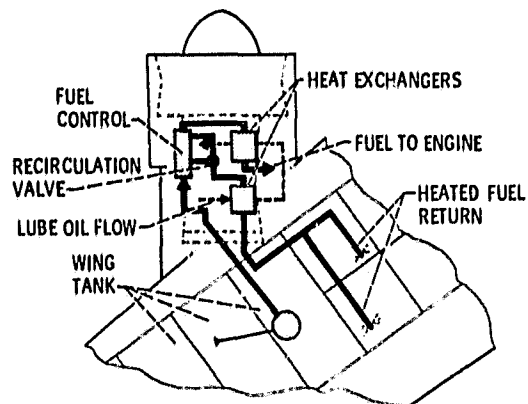


(b) "VORBITX" COMBUSTOR DESIGNED FOR NASA-P&WA ENERGY EFFICIENT ENGINE PROGRAM.

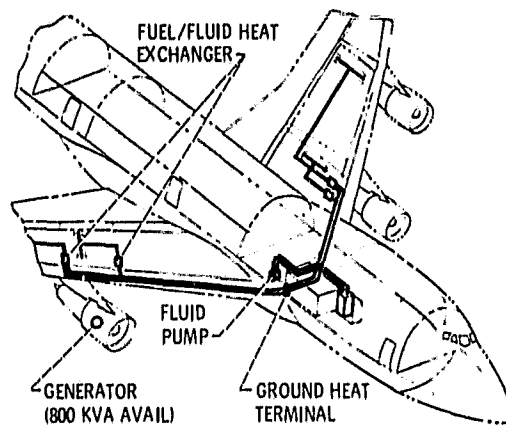


(c) VARIABLE GEOMETRY COMBUSTOR CONCEPT.

Figure 18. - Combustor design concepts for the Pratt & Whitney Aircraft JT9D-7 engine.



(a) SCHEMATIC OF A LUBRICATING-OIL HEAT EXCHANGER FUEL HEATING SYSTEM.



(b) SCHEMATIC OF ELECTRICAL FUEL HEATING SYSTEM ON A WIDE-BODIED JET AIRCRAFT.

Figure 19.