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**IMPACT OF FUTURE FUEL PROPERTIES ON AIRCRAFT  
ENGINES AND FUEL SYSTEMS**

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## IMPACT OF FUTURE FUEL PROPERTIES ON AIRCRAFT ENGINES AND FUEL SYSTEMS

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## SUMMARY

From current projections of the availability of high-quality petroleum crude oils, it is becoming increasingly apparent that the specifications for hydrocarbon jet fuels may have to be modified. The problems that are most likely to be encountered as a result of these modifications relate to engine performance, component durability and maintenance, and aircraft fuel-system performance. The effect on engine performance will be associated with changes in specific fuel consumption, ignition at relight limits, at exhaust emissions. Durability and maintenance will be affected by increases in combustor liner temperatures, carbon deposition, gum formation in fuel nozzles, and erosion and corrosion of turbine blades and vanes. Aircraft fuel-system performance will be affected by increased deposits in fuel-system heat exchangers and changes in the pumpability and flowability of the fuel. The severity of the potential problems is described in terms of the fuel characteristics most likely to change in the future. Recent data that evaluate the ability of current-technology aircraft to accept fuel specification changes are presented, and selected technological advances that can reduce the severity of the problems are described and discussed.

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## INTRODUCTION

This paper describes and discusses the propulsion-system problems that will most likely be encountered if the specifications of hydrocarbon-based jet fuels must undergo significant changes in the future and, correspondingly, the advances in technology that will be required to minimize the adverse impact of these problems.

Future jet aircraft fuels derived from petroleum or "synthetic" crude stocks such as oil shale or coal may have significantly different fuel properties than current jet fuels. The effect of these changes in fuel properties on selected combustion processes are described and discussed in reference 1. As pointed out in reference 1, significant changes in fuel properties may be encountered in the not-too-distant future; the most probable changes will be in the hydrogen-to-carbon ratio, the percentage of aromatic compounds, the percentage of nitrogen compounds, and the fuel boiling range. The relationship of these fuel property changes to potential propulsion-system problems is illustrated in Figure 1. A higher fuel boiling range will likely result in a less volatile, more viscous fuel, which will affect both ignition characteristics and idle emissions, and a higher freezing point, which will affect the pumpability and flowability of the fuel. Increases in aromatic compounds will result in increased smoke and flame radiation and poorer chemical stability. Increases in nitrogen compounds will result in increased nitric oxide emissions and, again, poorer chemical stability. These potential problems impose some very severe constraints on the ability of conventional aircraft-engine technology to accommodate fuels with variations in these properties. Several investigations have been recently made or are currently under way to evaluate the effects of some of these property changes on conventional aircraft-engine technology (2-7). The principal problem areas that have been identified to date are primarily associated with the engine combustor and turbine and with both the engine and the aircraft fuel system.

Although this paper describes potential problems and the ability of advanced technology to minimize or eliminate them, in the final analysis, the choice between establishing allowable variations in fuel properties and implementing advanced propulsion-system technology will be arrived at through an iterative process. Obviously, economics will play a key role, as will the availability of high-quality crude oil feedstocks. Therefore, the criteria by which to make an optimum trade-off between future fuel specifications and advanced technological needs must be established. This is the principal objective of the Fuels Technology Program that is being conducted by the National Aeronautics and Space Administration (NASA) and from which a large part of the information presented in this paper was derived. Many other programs sponsored by both the U.S. Government and private industry are also under way, and they too have contributed information to this paper.

Several investigations conducted are summarized. Illustrations are used to describe the relative effects of selected fuel properties on the behavior of propulsion-system components and fuel systems. The selected fuel properties are those that are most likely to be relaxed in future fuel specifications (1). Illustrations are also used to describe technological advances that may be needed in the future. Finally, the technological areas needing the most attention are described, and programs that are under way to address these needs are briefly discussed.

## ENGINE PERFORMANCE

Potential future fuel properties will generally affect engine performance by changing specific fuel consumption, ignition and relight limits, and exhaust emissions. Each of these factors is dealt with separately.

## Specific Fuel Consumption

In general, the specific fuel consumption (SFC) characteristics of aircraft engines go through a cyclic deterioration with time (Fig. 2): A short-term engine performance deterioration, or increase in SFC occurs during early operation within the fleet; long-term engine performance deterioration is modified in a cyclic manner by engine repair. The short-term deterioration ordinarily results from changes in running clearances and tolerances in what might be called the break-in period; it is not generally recoverable. The long-term trend can be modified by engine repair; for the newer high-pressure-ratio engines this generally means replacement or refurbishment of hot-section parts. Many hot-section problems are caused by temperature maldistribution and by erosion and corrosion. Without the repair of hot-section parts, the overall long-term engine performance deterioration would be much greater than that shown on Figure 2. Relaxed fuel specifications, especially in the percentage of aromatic compounds and trace species such as vanadium and sulphur, may considerably aggravate long-term deterioration. The problems that may be caused by changes in aromatic content and trace species are described in more detail in the section ENGINE COMPONENT DURABILITY AND MAINTENANCE.

## Ignition and Relight Limits

The principal fuel properties that affect the ignition and relight limits of an aircraft engine are volatility and viscosity. Fuel volatility and viscosity affect the atomization and vaporization characteristics of the fuel as it is sprayed into the combustion chamber. How these properties affect combustor ignition characteristics is illustrated in Figure 3 (taken from ref. 5), where time to start is plotted as a function of combustor primary-zone equivalence ratio for a JP4 fuel and a Jet A fuel. Two effects are clearly shown in Figure 3: For a given fuel (e.g., JP-4), the time to start increases dramatically with decreasing equivalence ratio after a critical minimum is reached. This is primarily due to the effect that reducing fuel-nozzle flow rate has on the atomization quality of the fuel spray. The second effect relates to fuel volatility and viscosity. Substituting a Jet A fuel for a JP-4 fuel, and thus varying volatility, made a higher primary-zone equivalence ratio necessary for successful ignition. The need to provide a richer primary-zone equivalence ratio could make it difficult to obtain adequate ignition limits for a fixed-geometry conventional combustor. Volatility and viscosity can also affect an engine's altitude relight envelope, as illustrated in Figure 4, for a modern high-bypass-ratio jet engine combustor using cold and heated JP-5 fuel. Reducing fuel volatility and increasing viscosity, as simulated by using the cold fuel, caused a noticeable loss in altitude relight capability, especially at the higher flight Mach numbers. Several techniques that can be used to improve relight are described later in this paper.

## Exhaust Emissions

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

**Effects of hydrogen content.** - Fuel hydrogen content can affect all four pollutant emissions. Very dramatic increases in combustor smoke number with decreasing fuel hydrogen content have been obtained in experimental evaluations using conventional combustion chambers from current-technology aircraft engines. An example of this effect, for a conventional can-type combustor, is illustrated in Figure 5 (taken from ref. 6). At a simulated takeoff operating condition (Fig. 5(a)) the measured Society of Automotive Engineers (SAE) smoke number increased in a nearly linear manner as the percentage by weight of fuel hydrogen was reduced. The relative impact, as indicated by the slope of the experimental data, was more severe at the cruise and idle operating conditions, as shown in Figures 5(b) and (c), respectively. For the engine that uses this combustor, an SAE smoke number of 25 is required at takeoff for compliance with the currently proposed U.S. EPA standards.

The carbon monoxide (CO) and unburned hydrocarbon (HC) emissions of this same can combustor operating at idle conditions are plotted as a function of fuel hydrogen content in Figure 6 (taken from ref. 6). Although a considerable amount of scatter is evident, a trend of slightly increasing CO and HC emissions is detectable with decreasing fuel hydrogen content. This effect of fuel hydrogen content on CO and HC emissions will be most prevalent at the idle condition, as illustrated in Figure 7 (taken from ref. 5), where the emission characteristics of a low-pressure-ratio engine combustor are plotted as a function of the percentage of engine rated power for a variety of fuel types. Because the number 2 diesel fuel (DF-2) has a significantly lower hydrogen content and lower volatility than

the jet fuels, it produces higher emissions. The larger relative effect on emissions at idle, as compared with the other operating conditions, is attributed to the much lower compressor discharge pressure and temperature at idle. The effect of fuel hydrogen content on CO and HC emissions, as illustrated in this example, may not be as significant in current and future modern high-pressure-ratio engines. The higher compressor discharge pressures and temperatures of these engines should minimize this problem.

The effect of fuel hydrogen content on oxides of nitrogen ( $\text{NO}_x$ ) emissions is illustrated in Figure 8 for the same can combustor used to obtain the results shown in Figures 5 and 6. For this combustor, the  $\text{NO}_x$  emission index increase was more pronounced at the takeoff condition than at the cruise condition. This increase in  $\text{NO}_x$  emissions was attributed to a possible increase in combustion flame temperature that could have occurred as the fuel hydrogen content was decreased. An example of such an increase in flame temperature is illustrated in Figure 9, where a computed maximum flame temperature (based on a homogeneous fuel-air mixture) is plotted as a function of fuel hydrogen content for the same cruise and takeoff test conditions used to obtain the experimental results shown in Figure 8. These theoretical temperature characteristics indicate that a trend toward increasing  $\text{NO}_x$  emissions with decreasing fuel hydrogen content should be expected.

Of all of these effects of fuel hydrogen content on exhaust emissions, the dramatic increases in smoke emission are felt to be the most severe and challenging problem.

Effects of fuel-bound-nitrogen content. - Increasing fuel-bound-nitrogen content is expected to have an effect only on  $\text{NO}_x$  emissions. This effect for a low-pressure-ratio engine combustor is illustrated in Figure 10 (taken from ref. 7) for three simulated engine operating conditions. The  $\text{NO}_x$  emissions increased substantially at all operating conditions as fuel-bound-nitrogen content was increased. The magnitude of the increase in  $\text{NO}_x$  emissions would be even more pronounced if all the nitrogen were converted into  $\text{NO}_x$ , but this was not the case, as shown in Figure 11. The conversion efficiency shown in Figure 11 is quite typical and comparable with many results currently being obtained in other experiments. In some studies, however, conversion efficiency has been shown to be a function of variations in combustor configuration and operating conditions. Conversion efficiencies from as high as 80 percent down to 40 or 50 percent have been realized.

In these experiments, fuel hydrogen and fuel-bound-nitrogen contents were varied by "doping" existing-specification fuels with such pure compounds as alkyl benzenes and pyridine. The range of hydrogen and nitrogen contents was purposely made large in order to evaluate the effects in a parametric manner. The lower and upper limits were not set to imply that any particular levels are expected in future fuels. Also, bear in mind that most of the results were obtained in controlled combustor test-rig experiments and thus may not be comparable to actual engine results. Nevertheless, the trends in exhaust emissions that were illustrated are felt to represent what can be expected if fuels having properties similar to the test fuels are used.

#### ENGINE COMPONENT DURABILITY AND MAINTENANCE

Changes in future fuel characteristics will likely have a pronounced effect on engine component durability and maintenance. The increasing flame temperature and luminosity that can be expected as fuel hydrogen content is reduced (1) can cause problems in cooling combustor liners and turbine vanes and blades. Changes in fuel volatility and chemical stability can be expected to increase carbon formation and deposition. And any increase in reactive trace constituents will certainly aggravate the erosion and corrosion problems. Each of these changes are considered in the following discussion.

##### Combustor Liner Temperature

The effective cooling of combustor liners is becoming more difficult because of the changing engine cycle conditions associated with high-pressure-ratio engines. The effect of increasing combustor inlet temperature on liner temperature is illustrated in Figure 12 (taken from ref. 8). The effect is almost linear and is probably caused by the increasing cooling-air temperature and the increasing flame temperature that would occur at a fixed primary-zone fuel-air ratio as inlet air temperature is increased. Another factor that can increase flame temperature and flame emissivity is combustor pressure. The effect of increasing combustor pressure on liner temperature is illustrated in Figure 13. Calculated liner temperatures are also shown in both Figures 12 and 13 and, in general, they are in reasonable agreement with both the shape and trend of the measured experimental temperature and pressure effects. However, the calculated absolute liner wall temperature levels are too high probably because total flame radiation cannot be accurately forecast. The sensitivity of liner wall temperatures to flame emissivity (luminosity) is strongly affected by the hydrogen-to-carbon ratio of the fuel (1). This effect is illustrated in Figure 14, where experimentally measured liner temperatures are plotted as a function of the hydrogen content in the fuel used for testing a can combustor (4) at two simulated engine operating conditions. The steeper slope of the measured liner temperatures at the cruise conditions suggests that the flame luminosity effect becomes more pronounced at the compressor discharge pressures associated with the cruise condition. The effect of combustor pressure on soot formation, and hence flame luminosity, is described in detail in reference 9.

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In summary, there are several factors that could affect combustor liner temperatures in future aircraft engines. Increases in cycle pressure ratio that are being sought to improve engine efficiency are certainly going to require additional attention to the liner cooling problem. It is also apparent that reductions in the hydrogen content of future fuels will surely aggravate any problems associated with liner cooling.

#### Carbon Formation and Deposition

The combination of the inability to effectively atomize the fuel that is injected into a combustion chamber and a reduction in fuel hydrogen content can cause some rather dramatic carbon formation and deposition problems, as illustrated in Figure 15. Figure 15 shows carbon deposition that occurred in an experimental annular combustor for a low-pressure-ratio engine. Carbon deposition this severe is not prevalent in today's high-pressure-ratio engines. However, carbon formation could once again become a problem if fuel volatility and hydrogen content are significantly modified. The effect of both volatility and hydrogen-carbon ratio on carbon deposition is illustrated in Figure 16 (taken from ref. 11). The use of fuels with higher boiling ranges (e.g., diesel oil) and lower hydrogen-carbon ratios (high aromatic content) would tend to increase carbon deposition. Because these effects are pressure and temperature dependent, the higher cycle temperature of most modern high-performance engines should reduce the probability that carbon formation and deposition as dramatic as that shown in Figure 15 would occur with the use of future fuels having low volatility and hydrogen content. However, some of the new low-pressure-ratio small engines used in remote-piloted vehicles (RPV's) could encounter rather serious problems when using fuels with relaxed volatility and hydrogen content specifications.

Carbon deposition and coking within fuel nozzles can cause problems in fuel atomization such as illustrated in Figure 17. The streaking effect that is shown in the spray pattern is most likely caused by deposits in the small fuel-nozzle passages that occurred due to thermal stability problems in the fuel. Poor fuel atomization can cause the carbon formation and deposition problems that were previously discussed and can also result in significant hot-streak and pattern-factor problems within the combustor.

#### Erosion, Corrosion, and Deposition

There are three principal factors that can cause problems within the hot section of an aircraft engine, particularly in the turbine: high combustion-exhaust-gas temperatures, unburned combustion products, and impurities in both the fuel and the air. All these factors can combine to produce an environmental attack on turbine materials (12), as shown schematically in Figure 18. Impurities such as sodium, chlorides, and sulphur can result in gaseous reactions, liquid deposition, and oxide fluxing, all of which can produce high-temperature oxidation and corrosion damage. Damage from liquid and solid deposits and fouling occurs because of calcium, potassium, and magnesium impurities within the fuel. Erosion damage can occur from the impact of liquid or solid particles such as carbon, ash, or dirt particles in the combustion gases.

The effect that the preceding damage forms can have on a turbine is illustrated schematically in Figure 19. Weight loss from erosion is estimated to occur in a nearly linear fashion with time as would the weight gain from deposition (fouling). Corrosion is the most severe form of environmental attack, and long-term loss in specific weight becomes disastrous. All of the factors illustrated in Figure 19 affect turbine life. Deposition and fouling can lessen the efficiency of turbine cooling by plugging film-cooling holes, as shown in Figure 20; and erosion and corrosion can cause material distress, as illustrated in Figure 21.

By combining the aforementioned "impurity"-related turbine life factors with the normal life-limiting factors of materials, a life-limiting picture of turbine components such as the one illustrated in Figure 22 can be constructed. This schematic representation illustrates how erosion and corrosion can drastically shorten turbine-component life beyond that which would normally be controlled by fatigue, creep, and material melting temperatures only. If the allowable limits of fuel impurities, such as sodium and sulfur, and of the fuel hydrogen content are relaxed in future fuels, the aforementioned effects may become significant problems.

#### ENGINE TECHNOLOGY NEEDS

The preceding sections of this paper describe several problems that may arise from the relaxing of fuel specifications for aircraft engines. The technology that will be needed to minimize or eliminate these problems is described in this section of the paper. Some critical research and development needs have been identified:

- Improved cooling techniques
- Reliable ignition and relight
- Reduced exhaust emissions
- Improved fuel injectors
- Prevention of carbon deposition
- Improved materials and coatings

Although it is not within the scope of this paper to discuss in detail the research and development needs in all these areas, technological advances currently being sought are presented and discussed.

#### Engine Performance

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

Several potential design concepts can be used to control exhaust emissions, a problem that may be aggravated by relaxed fuel specifications:

- Staged combustion
- Air-atomizing fuel injectors
- Intensive fuel-air mixing
- Lean combustion
- Fuel-air premixing
- Fuel prevaporization

In practice, a combination of many of these techniques could be used in any particular combustor concept. As an example, two recently evaluated advanced combustor concepts are shown by the cross-sectional schematics shown in Figure 23. Both the Vorbix and double-annular combustion concepts, which were evolved during the NASA Clean Combustor Program (13,14), incorporate fuel staging, air-atomizing fuel injectors, and lean combustion. The Vorbix combustor also uses intensive fuel-air mixing. Both combustor concepts substantially reduce all the gaseous exhaust emissions below the levels of the conventional engine combustors that they were designed to replace. The use of one stage (pilot) to reduce CO and HC emissions during idle and a second stage (main) to reduce these emissions during high-power operation proved to be very effective, as shown in Figure 24. Staged-combustor concepts such as these will be needed to minimize the impact of decreasing fuel hydrogen content or increasing fuel-bound-nitrogen content on aircraft engine exhaust emissions. Both concepts have gone through successful experimental engine testing and are strong candidates for future energy-conservative and environmentally acceptable engines.

If more dramatic reductions in exhaust emissions are required (e.g.,  $\text{NO}_x$ ) combining techniques such as prevaporizing the fuel and premixing the fuel and air will allow combustion to occur at extremely low fuel-air ratios and thus will dramatically reduce flame temperatures. Successful development of prevaporizing-premixing techniques could provide additional decreases in  $\text{NO}_x$  emissions, such as those discussed in reference 15 and shown in Figure 25.

A variety of minor combustor modifications can be used to reduce CO and HC emissions without the major changes in combustor design shown in Figure 23. These modifications would deal mainly with improving fuel atomization and the distribution of air and fuel in the primary zone.

Although most of the aforementioned concepts have been or are being evolved to respond to environmental problems with current-specification jet fuels, they can certainly apply to future engines that would use relaxed-specification fuels. Therefore, continued exploration to define the capability of these concepts to control exhaust emissions from fuels with relaxed specifications is certainly going to be needed.

#### Engine Component Durability and Maintenance

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

- Lean combustion techniques
- Advanced materials and coatings
- Advanced liner cooling techniques
- Improved structures

Lean combustion can reduce the effect of fuel hydrogen content on flame luminosity and therefore reduce liner temperature, as shown in Figure 26. A maximum liner temperature over  $200^\circ\text{C}$  lower than that of conventional combustors was realized when the two combustor concepts shown in Figure 23 were tested with a fuel having a hydrogen content of about 12 1/2 percent by weight. Another feature of the lean-combustion approach that is indicated by the results shown in Figure 26 is that the liner temperature appears to be insensitive to fuel hydrogen content. This insensitivity would be a significant advantage in future engines because a rather flexible fuel-hydrogen content specification could be used without compromising liner durability as affected by increasing liner temperatures.

Thermal-barrier coatings also offer the potential for reducing liner temperatures. A conventional can combustor with a thermal-barrier coating is shown in Figure 27 (taken from ref. 16). A zirconia ceramic coating was applied to the liner inner wall. The com-

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combustor was tested over a range of conditions simulating engine takeoff and cruise; the resultant effect of the ceramic coating on the maximum liner temperature is shown in Figure 28. Significant reductions in maximum liner temperature were realized at both the cruise and takeoff conditions. Research and development of this and other advanced liner-cooling techniques, such as those shown in Figure 29, is certainly warranted.

The continued development of all the aforementioned approaches will surely be needed to maintain acceptable durability and maintenance characteristics of future engines using relaxed-specification fuels.

#### Erosion, Corrosion, and Deposition

Solving the problems of erosion, corrosion, and deposition on engine hot-section life will require many of the design techniques already described. Reducing combustor soot and carbon formation and minimizing the effect of such trace constituents as sulphur, potassium, and manganese must be actively pursued. Corrosion-resistant materials are being developed, and the use of coatings to protect the parent metal is also being evaluated (17). One example of how materials and coatings can affect the impact of corrosion on specific weight change is shown in Figure 30. Continued exploration in this area is certainly warranted, as well as the development of advanced turbine blade and vane cooling schemes that are less susceptible to plugging by deposits.

Many of the aforementioned research and development needs are being addressed in the NASA Fuels Technology Program, as well as in other U.S. Government and industry-sponsored programs. Presently, the main emphasis in the NASA program is on evaluating combustion and durability problems. However, because of the importance of all the problem areas discussed in this paper, problem definition and response to technological needs must be continuously reviewed. A comprehensive data base will surely be needed if we are to optimize the trade-off between advanced technology development and fuel specification relaxation for future aircraft applications.

#### AIRCRAFT ENGINE FUEL SYSTEMS

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

#### Thermal Stability and Deposition

Increasing fuel-bound-nitrogen content can result in a less thermally stable fuel. A similar effect is also noted for reducing fuel hydrogen content. The use of fuel as a heat sink in most aircraft fuel systems results in a rise in fuel temperature. If the fuel temperature approaches or exceeds the "breakpoint" of the fuel, deposits may form in the heat-exchanger passages and a loss in heat-transfer effectiveness can occur. (Fuel breakpoint temperature is discussed in ref. 1.) In the extreme, these deposits can become severe enough to produce flow restrictions in the fuel passages, thereby increasing the pressure drop. Fuel nozzles are also susceptible to this potential problem. One test that is commonly used to measure the thermal stability of the fuel is the JFTOT technique (1). As an example, a fuel that was derived from shale oil and refined to two different fuel-bound-nitrogen content levels was exposed to this test and the results are shown in Figure 31. As illustrated, the deposits that were formed within the tube were much more severe for the fuel with high fuel-bound-nitrogen content when both fuels were heated to the same temperature (e.g., 260° C).

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

- Fuel properties
- Engine-cycle pressure ratio
- Flight duration
- Fuel contamination
- Surface material
- Fuel oxygen content
- Fuel additives

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



### Fuel Pumpability and Flowability

At the freeze point, a fuel begins to enter a semisolid state, which can have an adverse effect on its pumpability and flowability. For example, a semisolid fuel can severely block a screen filter, as illustrated in Figure 32. Any blockage of this magnitude in an aircraft fuel system could have disastrous consequences. Hence, maintaining fuel temperature at a safe margin above its freeze point is an absolute necessity. Therefore, any increases in fuel freeze point that could occur from relaxing the specifications of future fuels must be carefully considered.

Many factors must be considered in evaluating the minimum allowable fuel-tank temperature, such as flight routes, altitude, and duration and the initial fuel temperature. The effect that flight routes can have on fuel temperature is illustrated in Figure 33, where the average of the recorded in-flight fuel temperatures of a large number of aircraft is plotted as a function of the percentage of flight time that the fuel was above the minimum temperature recorded during the flight. The average fuel temperature data for each of three different routes, as documented by the International Air Transport Association, are shown. The North Atlantic and North Pole routes had fuel temperatures below  $-30^{\circ}\text{C}$  about 20 percent of the time, but the Europe-to-South-America route had fuel temperatures below  $-30^{\circ}\text{C}$  only about 2 percent of the time. An example of the calculated effect of both flight duration and initial fuel temperature on the fuel temperature for a long-range flight of 9300 km is illustrated in Figure 34. The procedures involved in this calculation are described in reference 18. After about 6 hours of flight, the calculations indicate that fuel temperature would reach about  $-40^{\circ}\text{C}$  regardless of the initial temperature. This effect of initial fuel temperature could allow a higher-freeze-point fuel to be used for short-duration flights, but it would probably not provide any substantial benefit on typical long-duration flights.

Since the "candidate" broad-specification fuel described in reference 1 has a freeze point of about  $-29^{\circ}\text{C}$ , some form of fuel heating will probably be required to prevent fuel pumpability and flowability problems in long-range aircraft using this fuel. A calculated projection of the percent of flights that would require fuel heating as a function of season, flight duration (mission), and fuel freeze point is shown in Table I. The analysis used to arrive at the data shown in Table I is discussed in detail in reference 19. Based on this analysis, the need for fuel-tank heating would be very minimal for the  $-29^{\circ}\text{C}$  freeze-point fuel, but increasing the freeze point to  $-19^{\circ}\text{C}$  would require heating on all flights at all times of the year. From these freeze-point considerations only, it would appear that a fuel with a relaxed fuel-freeze-point specification of  $-29^{\circ}\text{C}$  (current value,  $-40^{\circ}\text{C}$ ) may be acceptable for aircraft use if fuel heating can be provided for selected flights.

### Material Compatibility

One concern in aircraft fuel-system materials that could be affected by relaxing fuel specifications is the impact that increasing aromatic content may have on the elasticity of elastomer compound and sealants. This effect is shown in Figure 35. For an exposure time of 4 hours, the elasticity ratio  $f_e/f_0$  of a butadiene acrylonitrile rubber elastomer decreased from about 0.7 to 0.15 when the aromatic content of the fuel that it was immersed in was increased from 20 to 60 percent. The elasticity ratio  $f_e/f_0$  is described in reference 19 where  $f_e$  is defined as the measured stress relaxation after exposure and  $f_0$  before exposure. The loss in elasticity shown in Figure 35(a) may affect the ability of this elastomer material to be effective in applications such as O-ring seals. A similar, although not quite as pronounced, effect is shown in Figure 35(b) for a typical sealant material. It should be noted here that many elastomer compounds can be and are tailored to specific fuel properties so that these effects would be minimized for a given fuel in a given application. However, for aircraft fuel systems that must operate with fuels having a wide range in aromatic content, the material compatibility problems illustrated could become significant.

### AIRCRAFT FUEL-SYSTEM TECHNOLOGY NEEDS

The preceding section describes some of the fuel-system problems that can be anticipated from the relaxing of fuel specifications. The technologies that must be developed to minimize or eliminate these problems are discussed in this section. Some of the critical fuel-system areas where continued research and technology efforts are needed are:

- Fuel-tank heating
- Fuel manifold and fuel injection fouling
- Elastometers and sealants
- Ground handling

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



The calculated effect of fuel-tank heating on fuel temperature as a function of flight time for a typical long-range, wide-bodied jet aircraft is shown in Figure 36 (taken from ref. 19). Two levels of constant heat input to the fuel were used in the computation. For the entire 9300-km mission, a heat input of 3700 kJ/min per fuel tank would be needed to maintain the fuel temperature above a freeze point of  $-29^{\circ}\text{C}$ , and 6500 kJ/min per fuel tank would be needed to maintain the fuel temperature above  $-18^{\circ}\text{C}$  freeze point. Since the fuel temperature stays above the  $-29^{\circ}\text{C}$  freeze point during the first several hours of the mission, no fuel heating would be needed during this portion of the mission for a fuel having this relaxed freeze-point specification. Therefore, from an economic standpoint, it would seem reasonable to consider the use of selective heating as required rather than the continuous heating that was used to calculate the characteristics shown in Figure 36. The effectiveness of this approach is illustrated in Figure 37, where calculated fuel temperatures are plotted as a function of flight time for a 9300-km mission of a typical wide-bodied jet aircraft. The calculated characteristics shown for the various tank locations also indicate that it would probably not be necessary to apply heat during the early portion of the flight. Using selective fuel-tank heating would certainly reduce the total heat input needed to heat the fuel during the entire mission.

Another technique that could be used to reduce the total heat input needed for a mission would be to insulate the fuel tanks. An example of how tank insulation thickness could reduce heat input is shown in Figure 38 for a 9300-km mission of a typical wide-bodied jet aircraft. Increasing tank insulation from zero (value assumed in the Fig. 36 calculations) to a 2.5-cm thickness would result in a factor-of-4 reduction in the heat input needed to maintain the fuel above  $-29^{\circ}\text{C}$ . The application of this much insulation would produce an aircraft weight penalty that would have to be compared with the savings in heat input before such a technique could be considered.

An example of aircraft heat sources that could be used to provide the needed heat input to the fuel tank is illustrated in Figure 39. The use of the cabin air-conditioning and lubricating-oil heat exchangers would require minor modifications to the aircraft and fuel system and could be implemented with a relatively low risk. The use of fuel boost-pump recirculation and an engine-driven electric heat exchanger would probably require minor-to-moderate modifications. The use of compressor air bleed would require moderate modifications and developmental risks. And the use of a tailpipe heat exchanger would require the most difficult and highest risk modifications. The calculated increases in aircraft weight for a typical wide-bodied jet aircraft and the resultant fuel penalties associated with using these fuel heat sources are given in Table II. In the minor-to-moderate class of modification, the lubricating-oil heat exchanger and the engine-driven electric heater appear to represent a reasonable approach from a combined heat input and fuel penalty consideration. Neither the air-conditioning-system heat exchanger nor fuel boost-pump recirculation would provide a satisfactory heat input rate (Fig. 37). Compressor air bleed would result in a very high fuel penalty. And the tailpipe heat exchanger would have a very high development risk, which certainly reduces its attractiveness even though its successful application would result in the lowest fuel penalty for a given required heat input rate (e.g., 6500 kJ/min).

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

#### CONCLUDING REMARKS

The objective of this paper was not to discuss or debate the advisability of using relaxed fuel specifications for future aircraft applications. Rather, the intent was to point out and discuss some of the problems that could arise if these fuels must be used and to illustrate the advances in engine and fuel-system technology that may be needed for these fuels to be acceptable in future aircraft. In this context, then, it has been stated that the principal fuel properties of concern are those related to increased aromatic compounds (lower fuel hydrogen content), increased fuel-bound-nitrogen compounds, higher boiling points (reduce volatility), and higher freeze points. All these properties are associated with the relaxation in fuel specifications that may be needed to provide a larger supply of petroleum-derived jet aircraft fuels and to reduce the degree of refining needed to convert oil-shale- and coal-derived crude oils into acceptable jet aircraft fuels in the future. In addition to these fuel properties, increases in such trace constituents as vanadium and potassium may also be of concern. Techniques such as fuel heating may also be important.

Potential adverse fuel property effects on engine performance are related to probable changes in ignition and relight limits and in exhaust-gas emission levels. Counteracting both of these effects will require advanced combustor technology such as improved or auxiliary fuel atomizers, better fuel-air distribution, and mixing and lean combustion

techniques. Counteracting problems related to component durability and maintenance will require such advanced technology as improved fuel atomizers, lean combustion techniques, thermal-barrier coatings, and new materials. Solving problems in aircraft fuel systems will require fuel-tank heating techniques and "tailored" elastomer materials. Even though preliminary evaluations of several of these technological advances have been encouraging, considerable research and development is still needed to make them acceptable in production engines and aircraft fuel systems. Furthermore, the ability to cope with several other problems, such as those caused by variations in thermal stability and by trace constituents, has not been demonstrated to even an acceptable experimental level at the present time. The factors that contribute to variations in thermal and chemical stability are not well understood and much more research is needed. Turbine erosion and corrosion problems may be somewhat relieved by using coatings, but considerable research is needed to fully understand all the factors that contribute to these problems.

Because of the many unknowns that must still be explored and explained through research and development efforts, it is apparent that these efforts should proceed at an orderly and timely pace. Although it is unlikely that aircraft will have to operate with the wide variation in fuel properties discussed in this paper, a sound and complete technological data base must be developed as soon as possible if the aircraft industry is to have any impact on setting acceptable variations in the specifications of future aircraft fuels. It is none too soon to start developing this data base since trade-offs will have to be made to determine the optimum choice between the cost and difficulty of developing advanced engine and fuel-system technology and the economic advantages to be gained by reducing the degree of refining needed to produce current-specification fuels from projected future fuel feedstocks.

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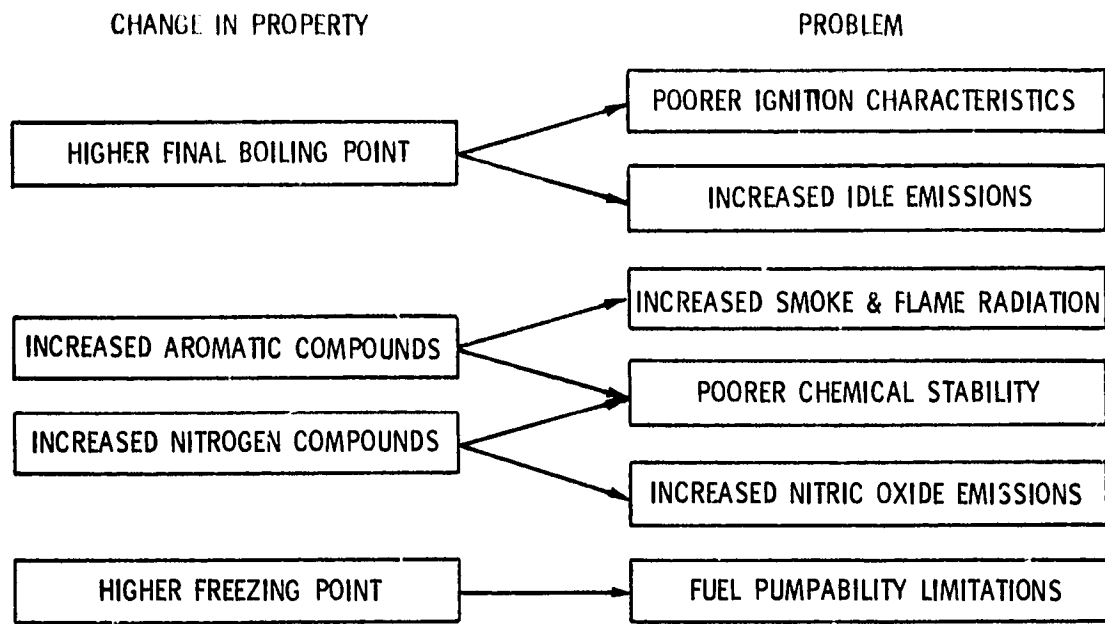
TABLE I. - UTILIZATION OF HEATING SYSTEMS (FROM REF. 19)

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

TABLE II. - COMPARISON OF POSSIBLE FUEL HEAT SOURCES

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

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Figure 1. - Potential problems from relaxing jet fuel specifications.

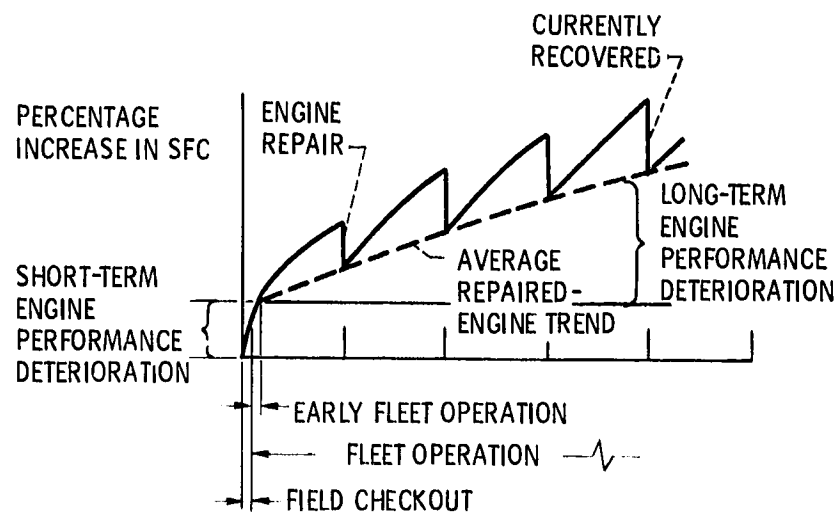


Figure 2. - Specific-fuel-consumption performance deterioration trends for typical engine. (From ref. 4.)

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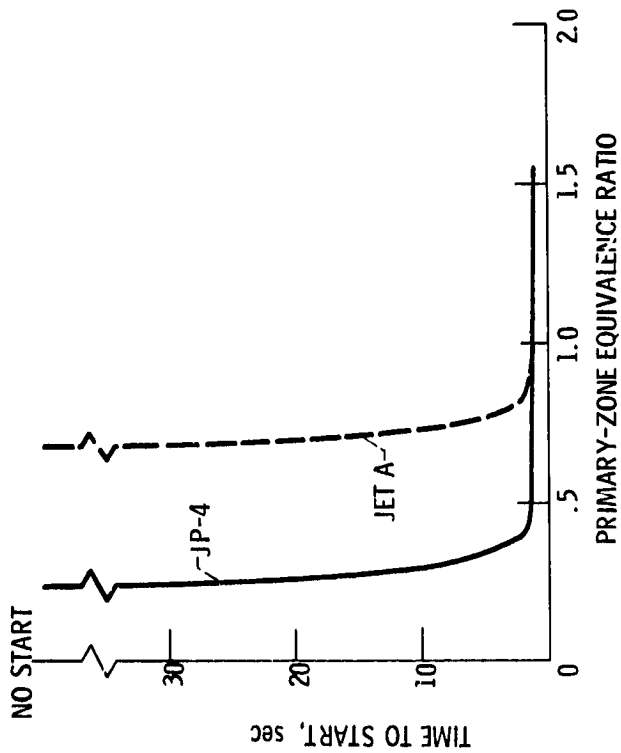


Figure 3. - Combustor ignition characteristics using different fuels. (From ref. 5.)

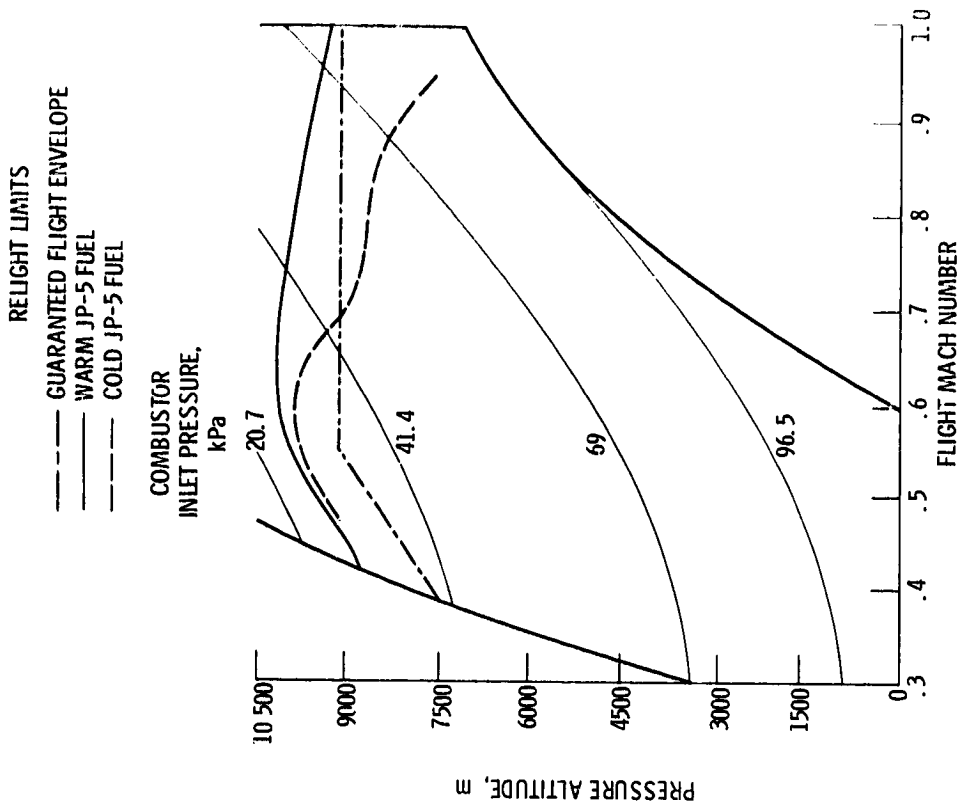


Figure 4. - Altitude relight limits of a conventional annular combustor.

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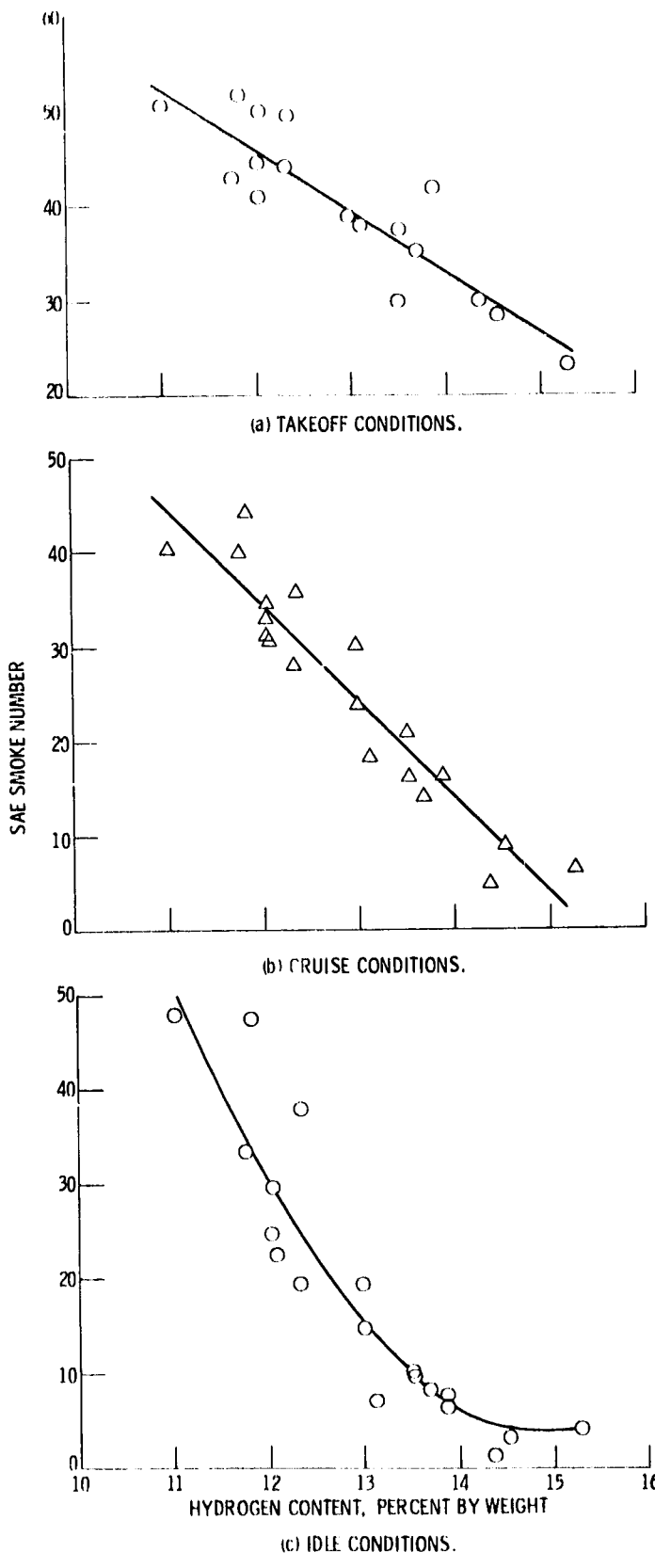


Figure 5. - Effect of fuel hydrogen content on smoke number. (From ref. 6.)

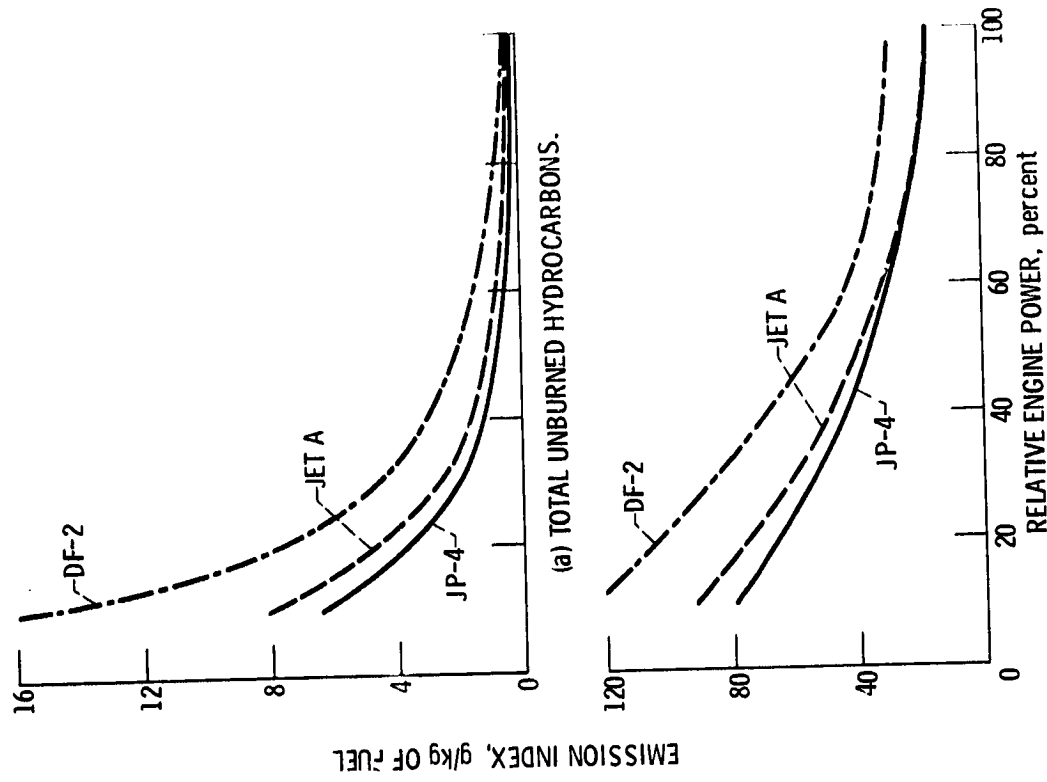


Figure 7. - Effect of engine power setting on exhaust emissions of total hydrocarbons and carbon monoxide. (From ref. 5.)

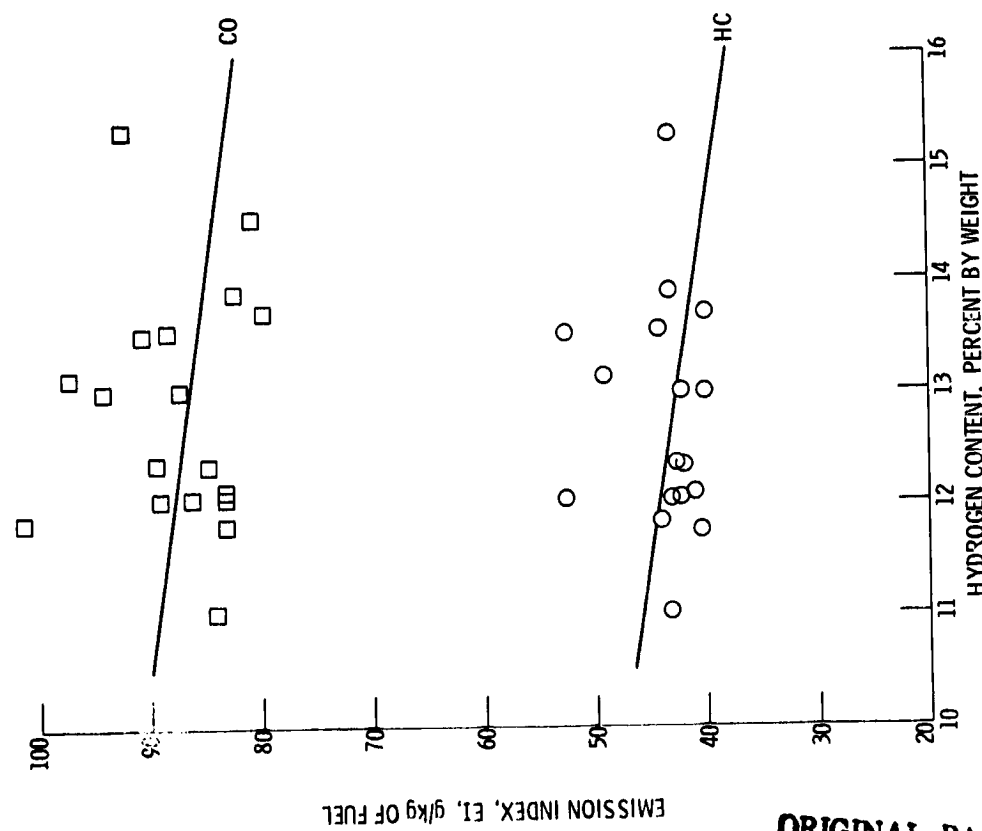


Figure 6. - Effect of fuel hydrogen content on emissions of carbon monoxide and unburned hydrocarbons at idle condition.

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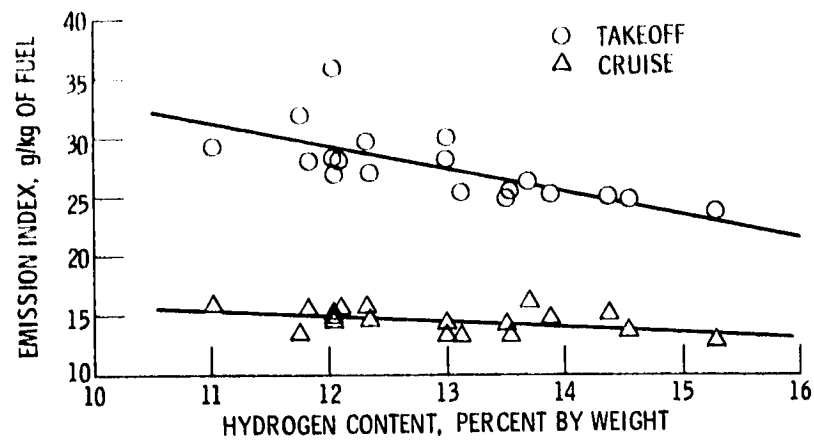


Figure 8. - Effect of fuel hydrogen content on emissions of nitrogen oxides at takeoff and cruise conditions. (From ref. 6.)

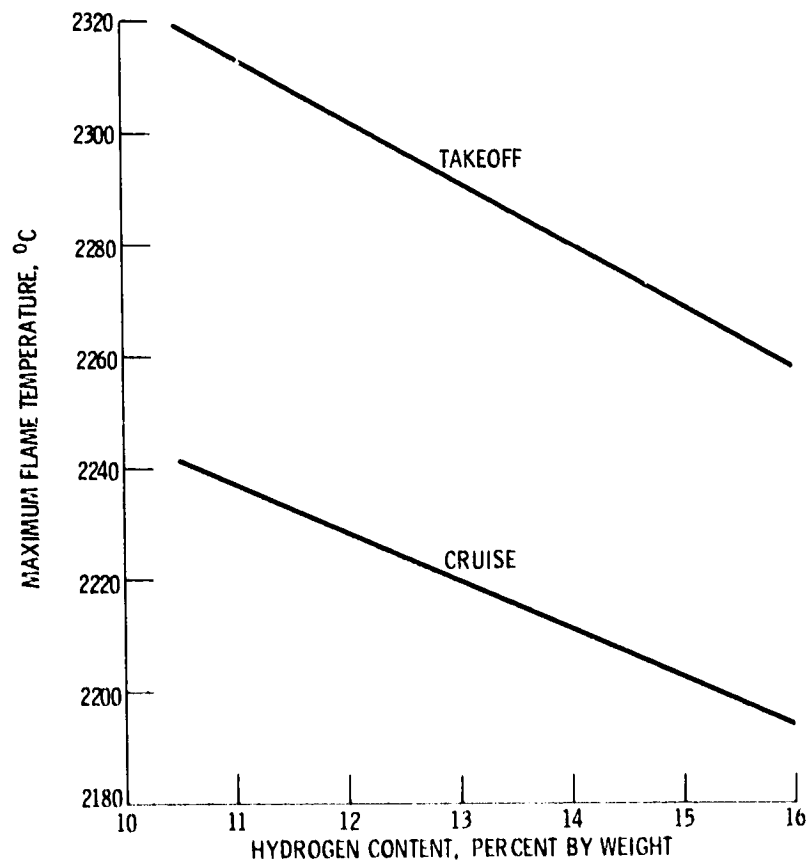


Figure 9. - Effect of fuel hydrogen content on maximum flame temperature.

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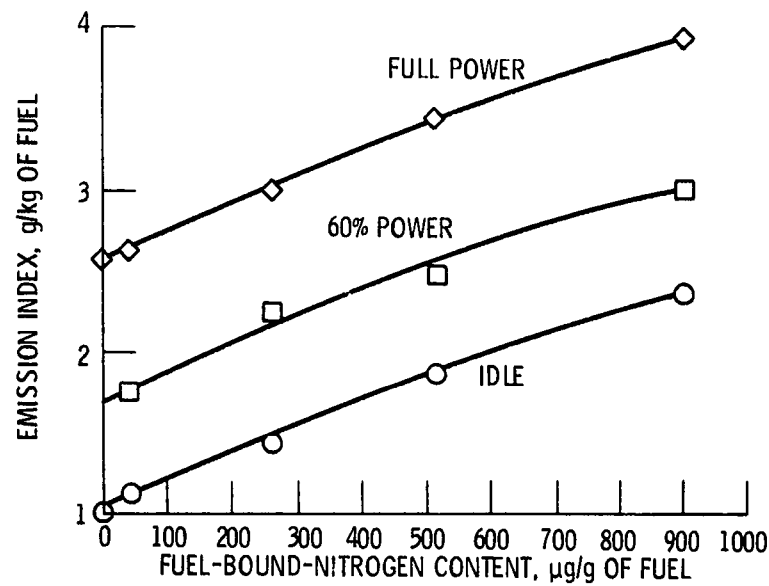


Figure 10. - Effect of fuel-bound-nitrogen content on total emissions of nitrogen oxides. (From ref. 7.)

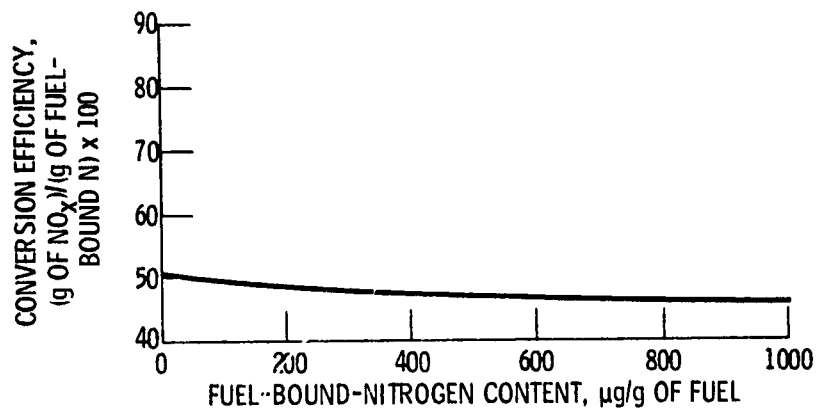


Figure 11. - Effect of fuel-bound-nitrogen conversion efficiency on total emissions of nitrogen oxides. (From ref. 7.)

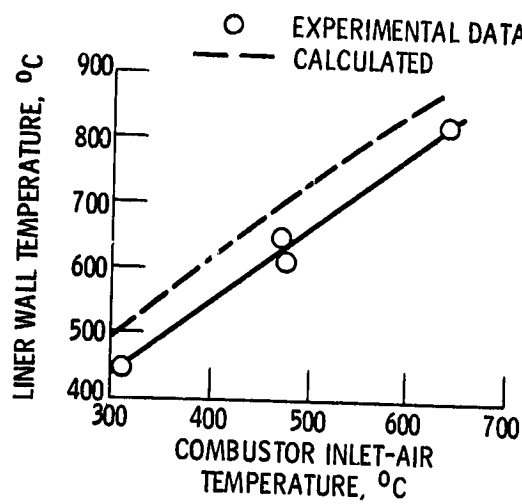


Figure 12. - Comparison of experimental and calculated liner wall temperatures over a range of inlet-air temperatures.

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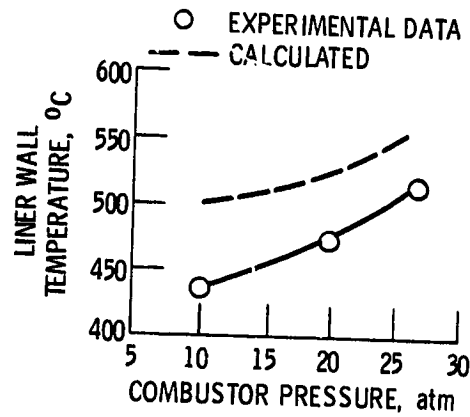


Figure 13. - Comparison of experimental and calculated liner wall temperatures over a range of inlet-air pressures.

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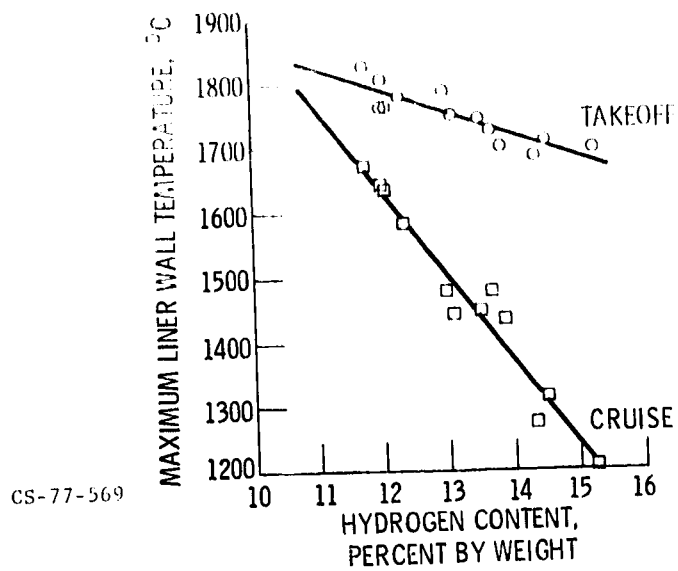


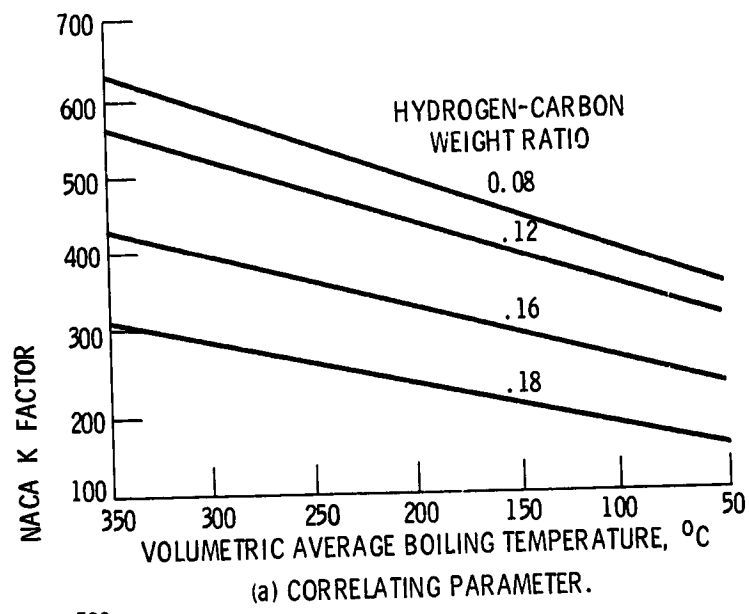
Figure 14. - Effect of fuel hydrogen content on maximum combustor liner wall temperature.



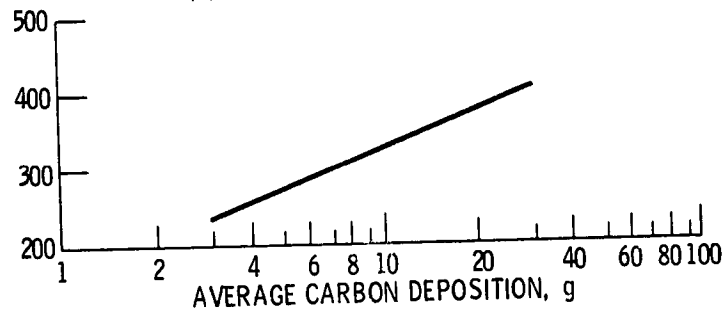
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Figure 15. - Example of carbon deposition in primary zone of experimental annular combustor.

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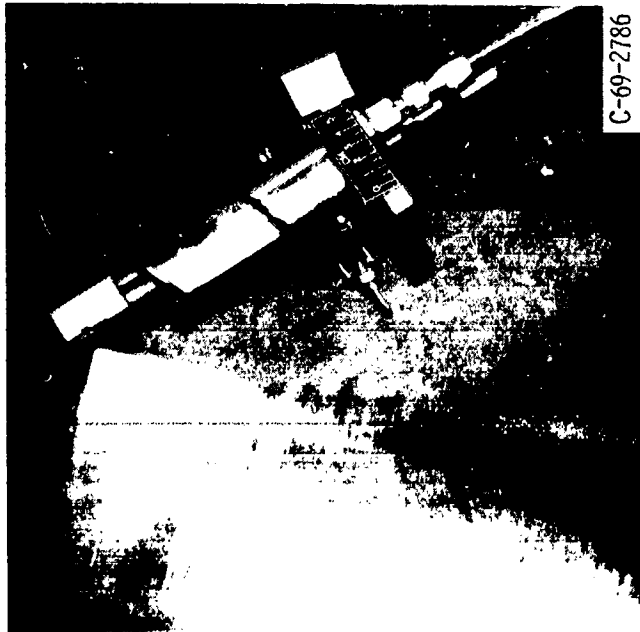


(a) CORRELATING PARAMETER.



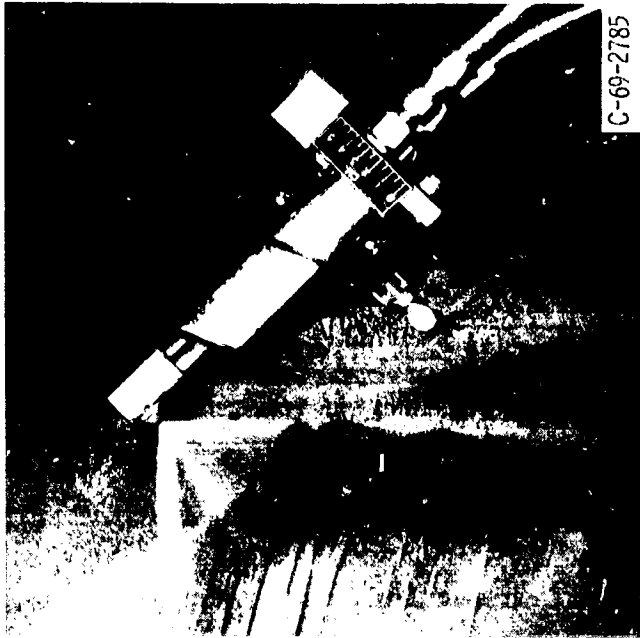
(b) CARBON DEPOSITION.

Figure 16. - Effect of fuel hydrogen content and volatility on carbon deposition.



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



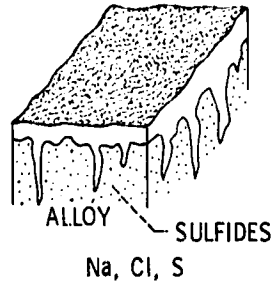
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(b) Zone 1 nozzle demonstrating moderate amount of streaking.

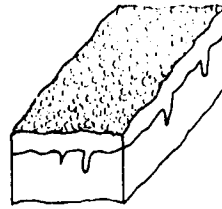
Figure 17. - Fuel nozzle spray patterns.

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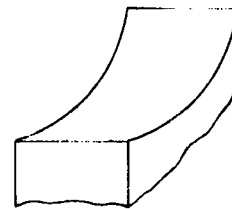
GASEOUS REACTION,  
LIQUID DEPOSITION,  
OXIDE FLUXING



LIQUID AND SOLID  
DEPOSITION & FOULING



LIQUID-OR-SOLID-  
IMPACT EROSION



CS-77-1301

Figure 18. - Schematic representations of environmental attack.

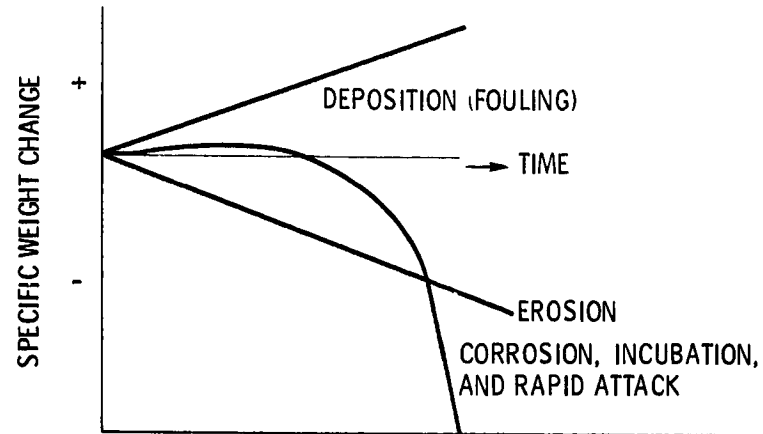
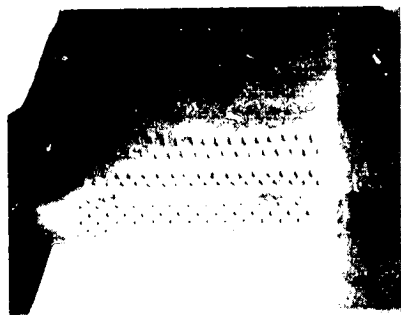
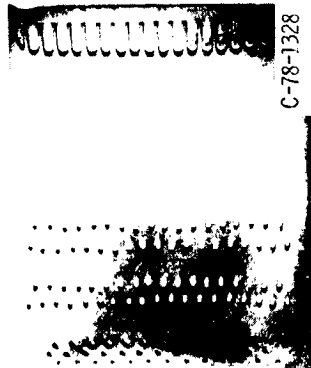


Figure 19. - Specific weight changes for three modes of "impurity" - associated environmental degradation.





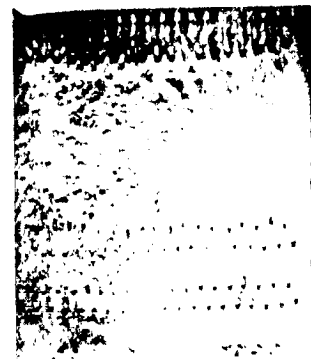
(b) LEADING EDGE, 2 ppm Fe; 27.6 HOURS.



(d) PRESSURE FACE, 2 ppm Fe; 27.6 HOURS; 30° C.



(a) LEADING EDGE, 2 ppm Fe, 1/2 Ca, 1 P; 28.7 HOURS.



(c) PRESSURE FACE, 2 ppm Fe, 1/2 Ca, 1 P; 28.7 HOURS; 200° C.

Figure 20. - Examples of deposits and cooling-hole plugging on turbine vane.



Figure 21. - Examples of typical erosion and corrosion distress on turbine blade.

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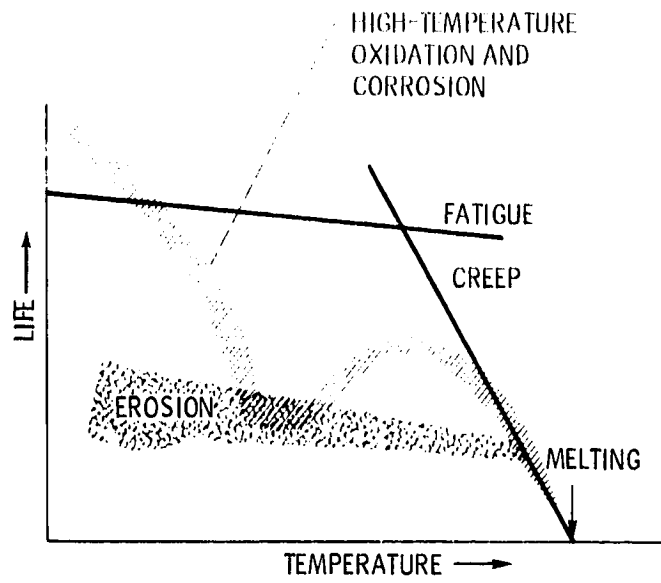
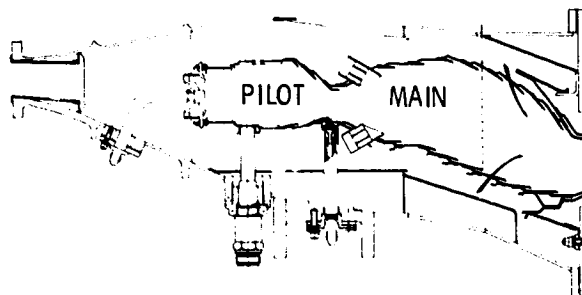


Figure 22. - Schematic representation of turbine-component life-limiting factors.

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(a) VORBIX COMBUSTOR FOR JT9D ENGINE.



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

Figure 23. - Combustor design concepts from NASA Experimental Clean Combustor Program.

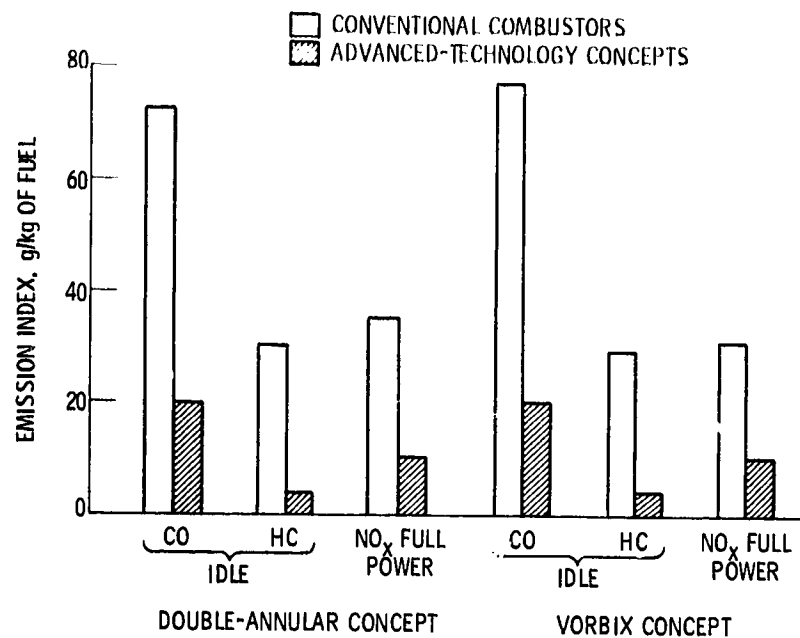


Figure 24. - Emission reduction capability of selected advanced-technology combustor concepts.

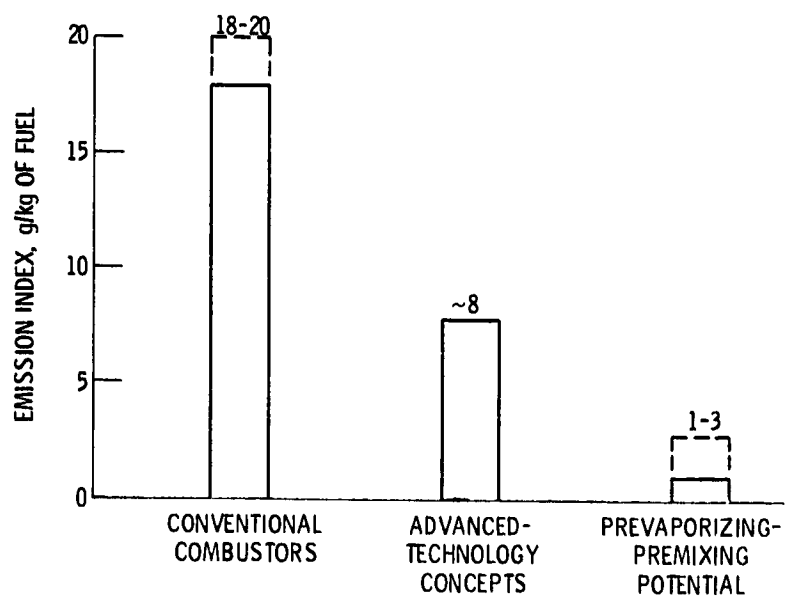


Figure 25. - Progress in high-altitude, subsonic-cruise NO<sub>x</sub> emission reduction.

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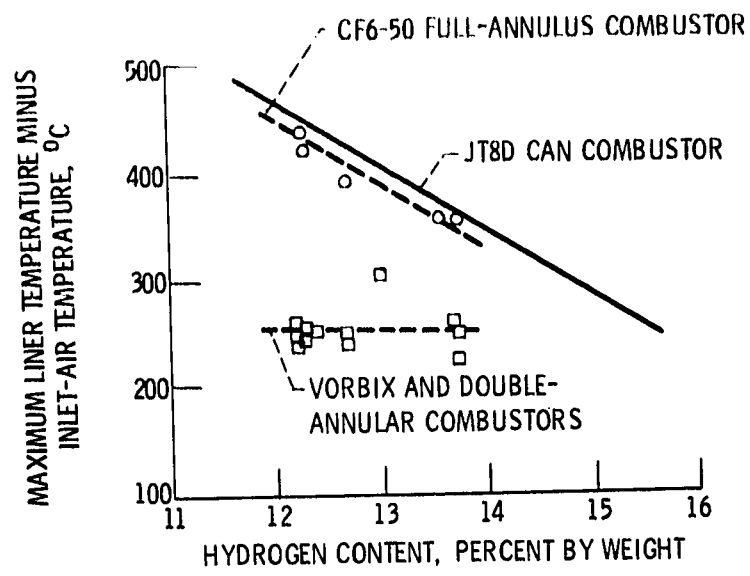
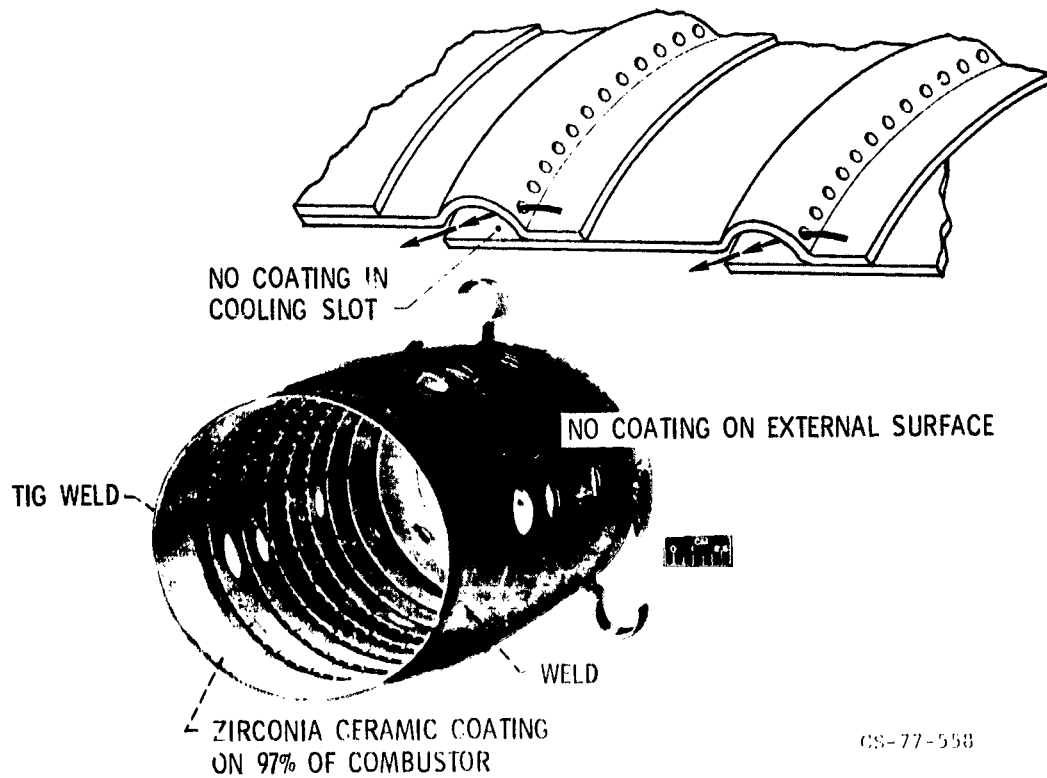


Figure 26. - Effect of fuel hydrogen content on maximum combustor liner temperature.



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Figure 27. - Thermal-barrier-coated combustor.

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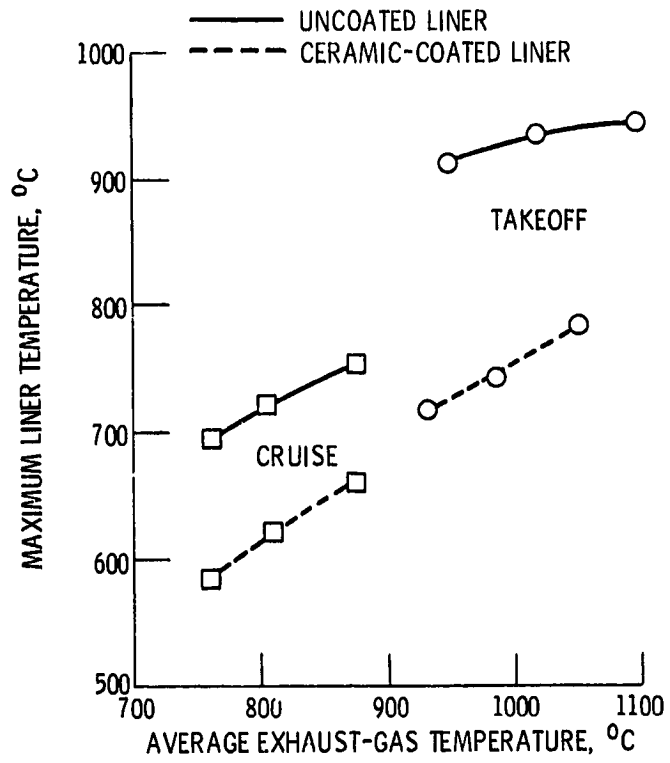


Figure 28. - Effect of ceramic coating on maximum liner temperature.

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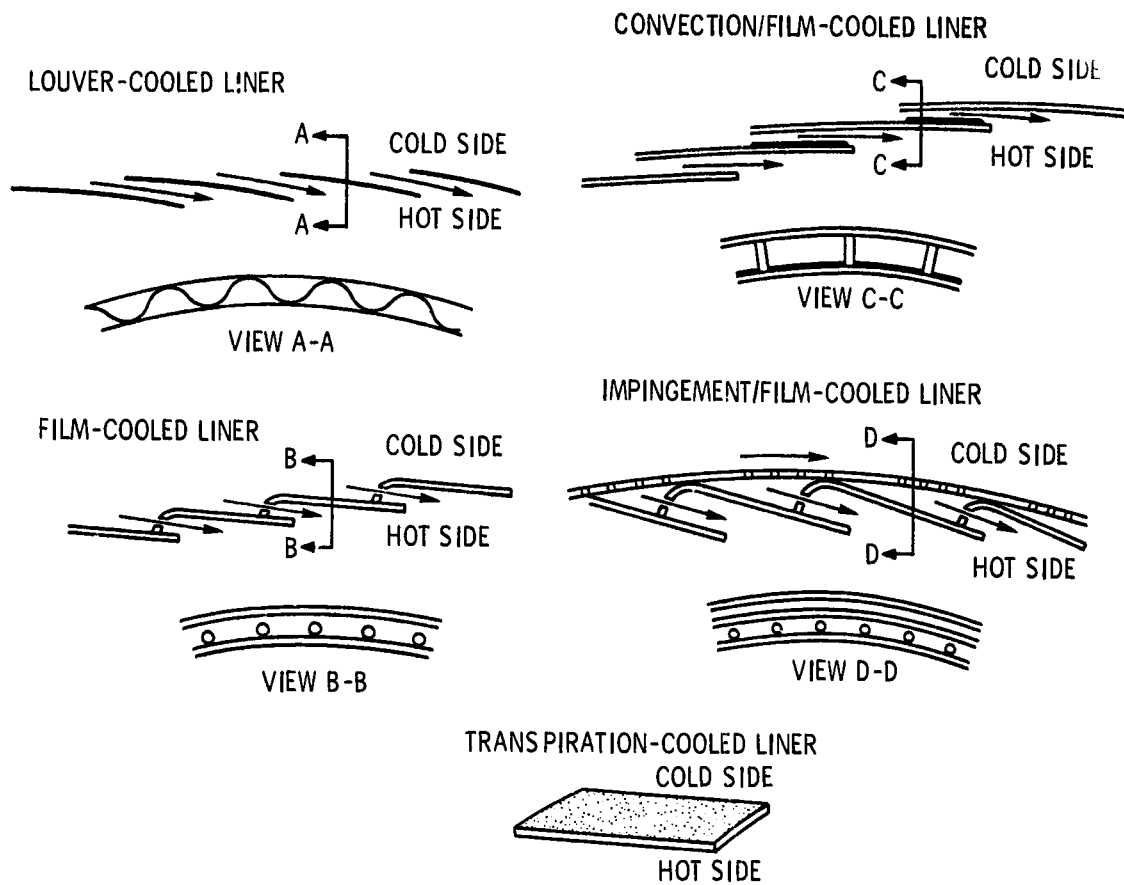


Figure 29. - Combustor cooling techniques.

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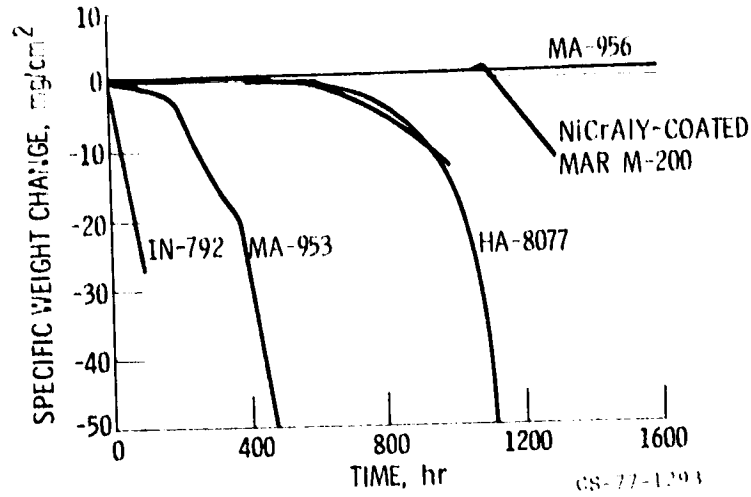


Figure 30. - Example of cyclic hot-corrosion results: 900° C metal temperature; 1 hour at temperature per cycle.

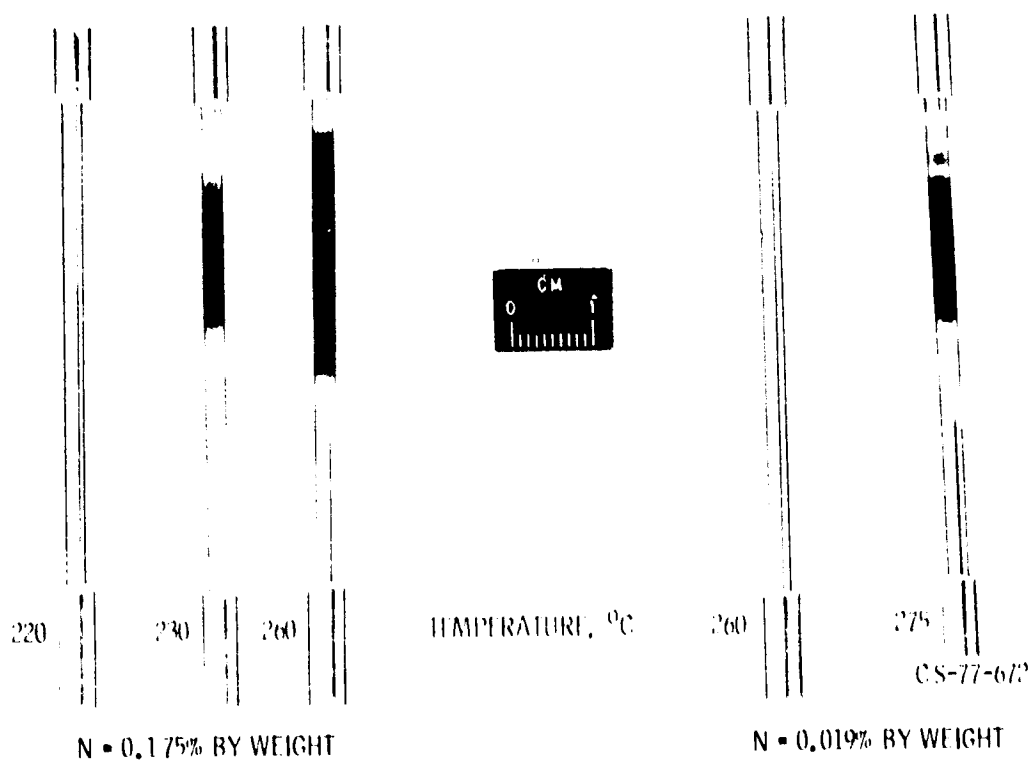


Figure 31. - Thermal stability of shale fuels.



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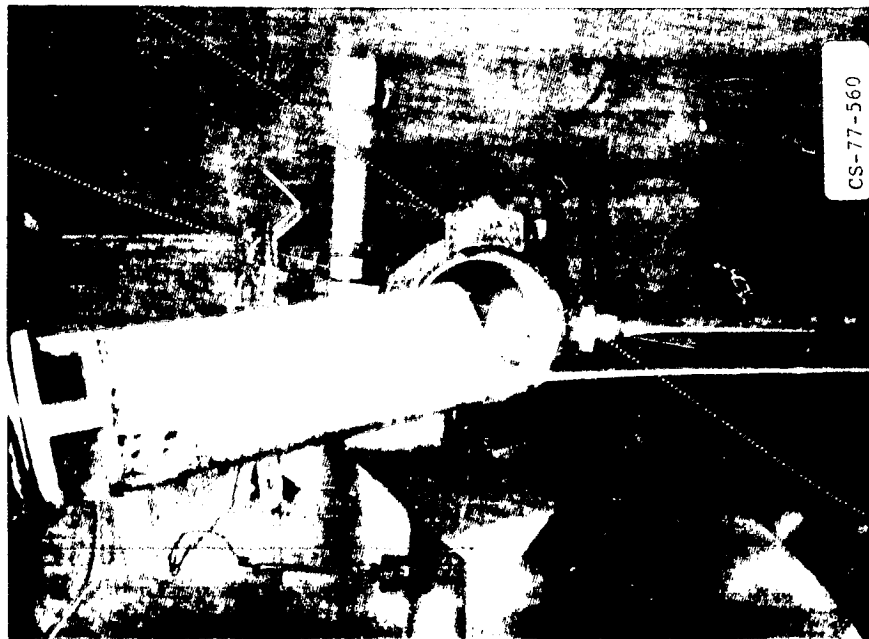


Figure 32. - Screen blockage by semisolid fuel.

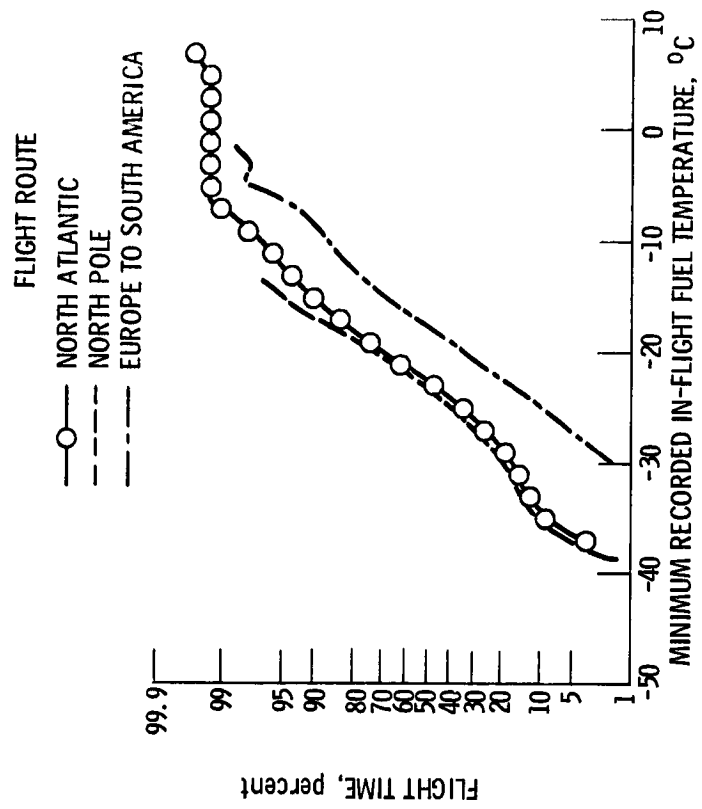


Figure 33. - Relationship between flight time and measured average fuel temperature for various flight routes. (From ref. 18.)

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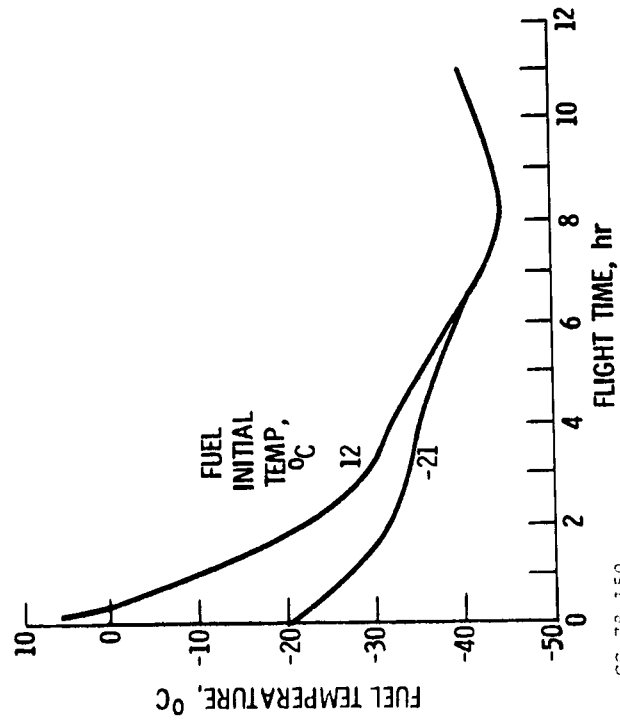


Figure 34. - Fuel-tank temperatures for 9300-kilometer flight.

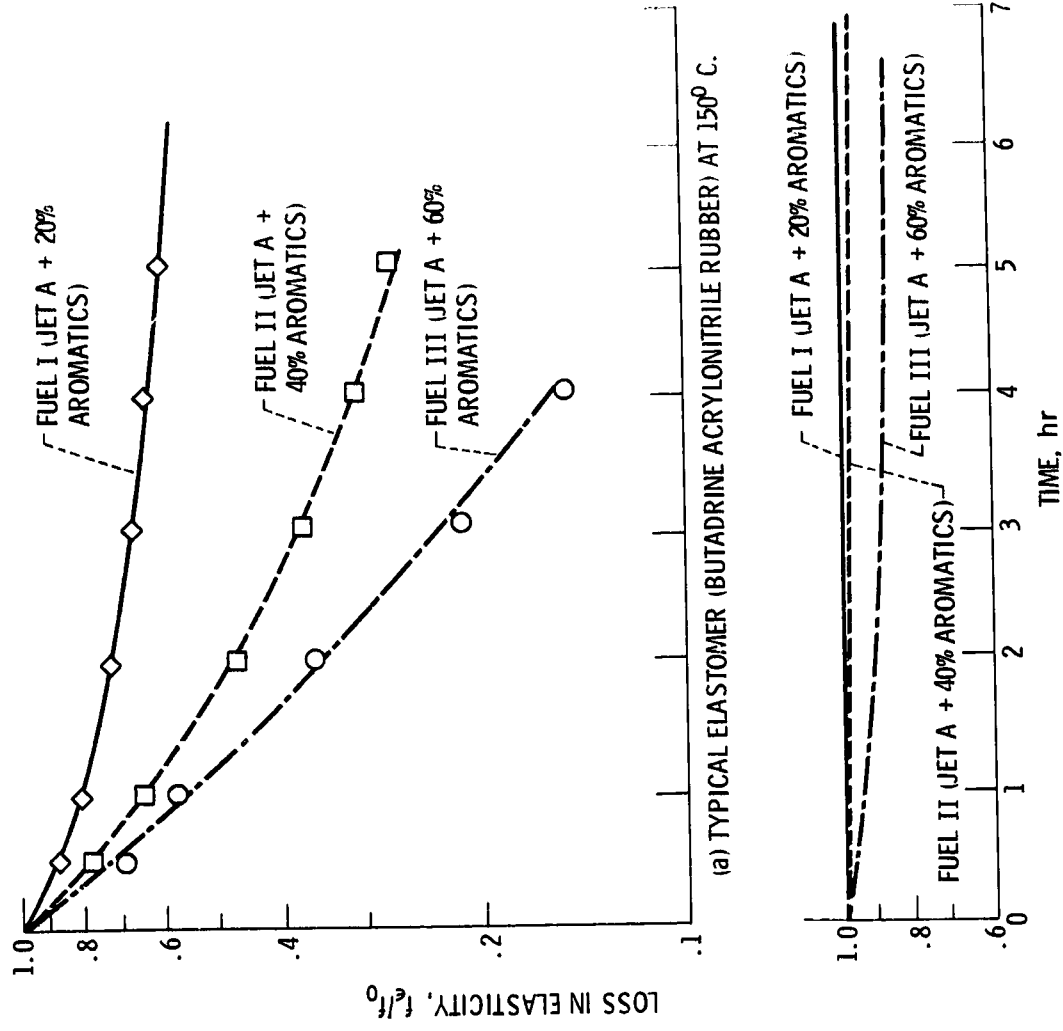


Figure 35. - Effect of various fuels on material elasticity. (From ref. 20.)

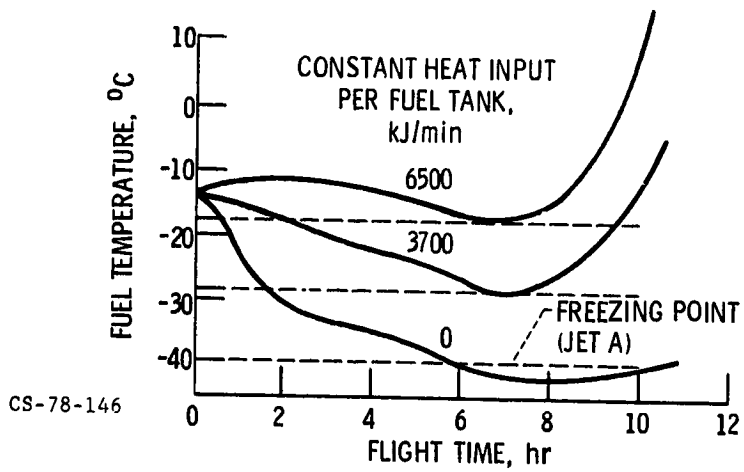


Figure 36. - Fuel-tank temperatures for a 9300-kilometer flight with heating

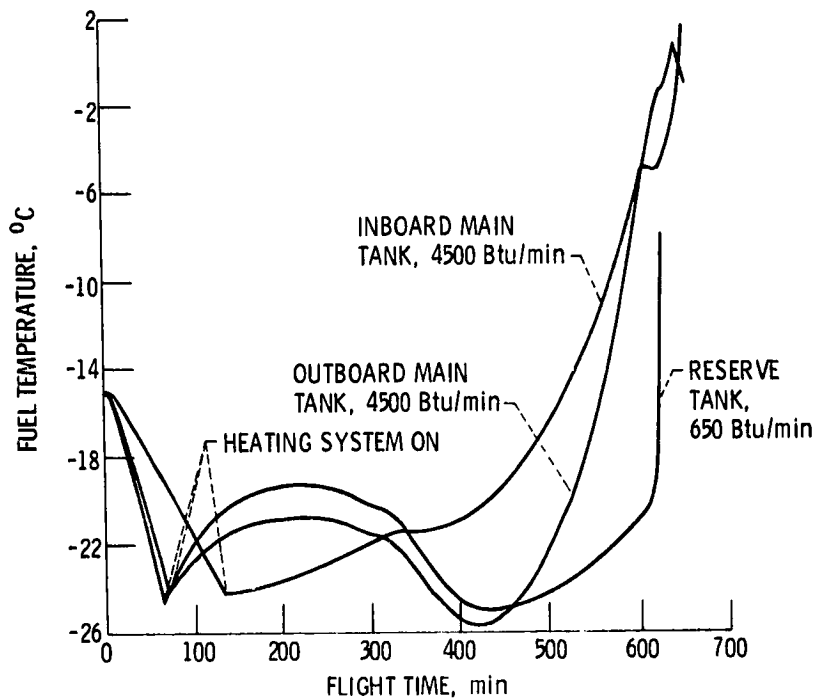


Figure 37. - Effect of intermittent heating on fuel tank temperature. Wide-body jet; 9300-kilometer mission. (From ref. 18.)

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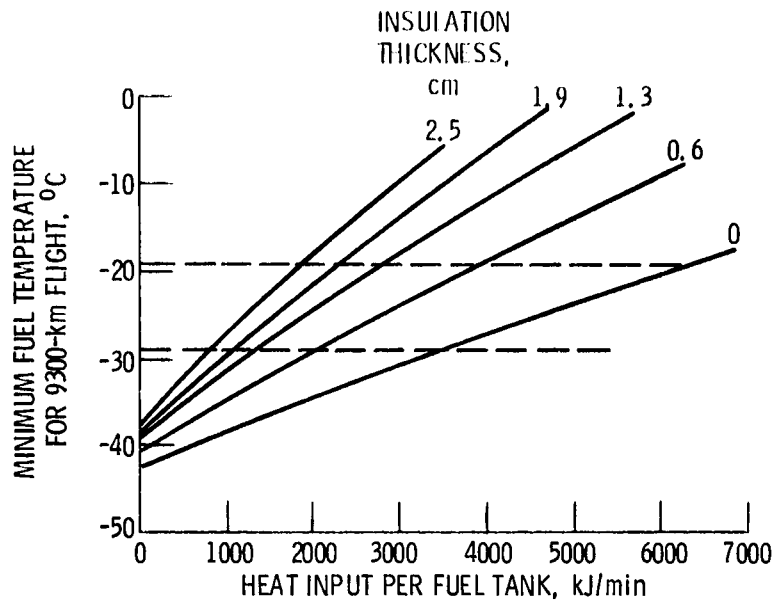
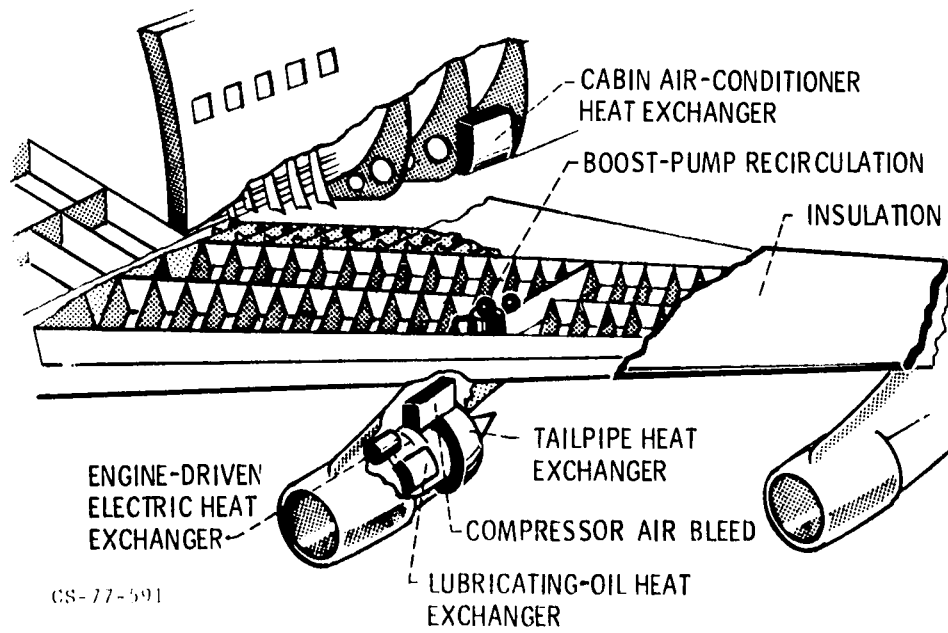


Figure 38. - Reduction of fuel heating requirements by tank insulation.



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Figure 39. - Potential fuel-tank heating sources.