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HIGH-FREEZING-POINT FUELS USED  
FOR AVIATION TURBINE ENGINES

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## HIGH-FREEZING-POINT FUELS USED FOR AVIATION TURBINE ENGINES

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### ABSTRACT

Broadened-specification aviation fuels could be produced from a greater fraction of crude source material with improvements in fuel supply and price. These fuels, particularly those with increased final boiling temperatures, would have higher freezing temperatures than current aviation turbine fuels. The higher-freezing-point fuels can be substituted in the majority of present commercial flights, since temperature data indicate that in-flight fuel temperatures are relatively mild. For the small but significant fraction of commercial flights where low fuel temperatures make higher freezing-point fuel use unacceptable, adaptations to the fuel or fuel system may be made to accommodate this fuel. Several techniques are discussed. Fuel heating is the most promising concept. One simple system design uses existing heat rejection from the fuel-lubricating oil cooler, another uses an engine-driven generator for electrical heating. Both systems offer advantages that outweigh the obvious penalties.

### INTRODUCTION

It is likely that aviation turbine fuels will continue to be conventional hydrocarbon types for a number of years (1).<sup>1</sup> The world-wide reserves of petroleum appear limited, demands for competing oil products are increasing, and of course prices have risen rapidly. Fuel costs are now an appreciable fracture of commercial airline operating costs. The supply, competition, and perhaps the cost situation can be eased if aviation turbine fuel specifications

are broadened to include petroleum fractions with a higher final boiling point and less compositional restrictions, giving producers wider flexibility in fuel refining (2). Relaxed specification jet fuels may also permit effective use of lower-grade crude sources, including shale oil, tar sands, and coal liquids with minimal refinery upgrading (3).

The optimization of future fuel characteristics requires an understanding of the relationship between airframe and engine requirements and fuel specifications. In this respect, fuel freezing point is a key property, affecting the fuel flow and pumpability at high-altitude, long-range cruise conditions. Incipient fuel freezing problems could certainly affect apparent engine performance. Fuel freezing-point specifications are sensitive to the final boiling point and blending composition of the fuel. In fact, nearly half the respondents in a recent refinery survey (4) stated that freezing point was the key, or limiting, property in their jet fuel production. Relaxed specification fuels with higher final boiling temperatures can be expected to show higher freezing points. For example, the same survey data indicated that increasing final boiling temperature by 13° C permits a 20 percent increase in jet fuel production, but at the expense of an 8° increase in freezing point.

It is recognized that broadened-specification fuels will introduce several important property changes affecting engine performance, efficiency, or durability. However, this paper is concerned only with freezing point and the practical application of higher-freezing-point aviation turbine fuels. The measurement and significance of freezing point is discussed first, since the low-temperature behavior of hydrocarbon fuels is not always uniquely described by a single laboratory characteristic. The temperature

<sup>1</sup>Numbers in parentheses designate references at end of paper.

environment of present commercial airplane missions is then defined from statistical and calculated data. Finally, methods of adapting higher-freezing-point fuels to the needs of current commercial airplanes are reviewed.

## MEASUREMENT OF JET FUEL FREEZING POINTS

### Specification Tests

Because aviation turbine fuels are complex mixtures of many compounds, freezing or crystallization does not occur at a definite temperature, but a phase change is exhibited over a range of temperatures. The higher molecular weight, straight-chain or normal paraffins (and certain symmetrical molecule hydrocarbons) crystallize first in the form of waxes. As temperatures are lowered a waxy matrix builds up, trapping other liquid constituents of the fuel until a nearly solid structure is formed (5). Several freezing point specification tests have been devised, based on the temperature at which wax crystals first appear, which in effect defines a conservative, maximum freezing temperature. These tests include wax appearance, cloud point, and wax disappearance methods (table I). Wax appearance is the observation of the temperature of the first appearance of the crystals in a chilled, stirred fuel sample. Cloud point is the temperature at which a solid suspension or "cloud" is observed near the bottom of an unstirred sample. Wax disappearance temperature is the temperature observed at the disappearance of crystals in a stirred fuel sample removed from a freezing bath and warmed after the first crystals are formed. In contrast, a minimum, solid phase, "freezing" temperature may be defined by the pour point, which is the lowest temperature at which the surface of a chilled fuel sample will move when turned vertically. Table I also lists approximate values of precision and accuracy for these test methods. For each specification, table I lists estimates for: (1) repeatability, the mean deviation between duplicate measurements by the same observer; (2) reproducibility, the mean deviation between comparison measurements by different observers, and (3) bias, the mean deviation of the specification with respect to wax disappearance specification D-2386-67, which is adopted as the present standard for aviation turbine fuels because of improved precision. The specifications (except for D-1477-65, which is now obsolete) are described in detail in the latest edition of the American Society for Testing and Materials (ASTM) Standards (6). Repeatability, reproducibility, and bias estimates are those published in this reference or reported at a December 1976 low-temperature symposium of the ASTM.

Freezing point measurements as a function of boiling point are illustrated in figure 1. The circular data points are freezing points of narrow boiling range ( $8^{\circ}$  to  $14^{\circ}$ )<sup>2</sup> fractions of a Diesel-type fuel, measured at the NASA Lewis Research Center. The difference between wax appearance and wax disappearance temperatures are represented by the shaded band, which ranges from  $0^{\circ}$  to  $4^{\circ}$ , being greatest at the lowest temperatures where the absolute accuracy of the measurements is lowest. (For acceptance testing, specification D-2386-67 requires that the difference between wax appearance and disappearance be no greater than  $3^{\circ}$  or the test must be repeated.) Data for wax disappearance tests of two other fuels are also shown in figure 1: a conventional petroleum-

derived aviation turbine fuel, and a similar fuel derived from shale oil (7). The three fuels shown in figure 1 represent a wide variation of composition. Freezing points vary as much as  $15^{\circ}$  at the same boiling temperature. In general, above a boiling temperature of  $230^{\circ}$ , the data show that freezing point increases with boiling temperature as expected, with an approximate slope of 0.6 degree per degree. Below  $230^{\circ}$ , the freezing point-boiling temperature relationship is not consistent; and over some temperature intervals, freezing point is seen to decrease with increasing boiling temperature.

Aviation turbine fuels are of course petroleum fractions with a range of boiling temperatures rather than a single boiling point. The higher boiling material is richest in the higher-molecular weight fractions, which tend to have higher freezing points, especially for the normal paraffins. Hence the maximum (final) boiling temperature is generally far more influential in characterizing the freezing point than the minimum (initial) boiling temperature. In addition, it is likely that broadened-specification aviation turbine fuels will have increased final boiling temperatures but unchanged initial boiling temperatures, with respect to present specifications, to avoid problems of decreased flash point and increased volatility (8). Future trends of freezing point may then be represented, as discussed in the INTRODUCTION, as a function of a single boiling temperature, the final boiling point (1,4). Figure 1 may also be interpreted as an illustration of the freezing point-final boiling temperature relationship.

### Performance Tests

Performance-oriented freezing-point measurements relate the low-temperature behavior of a fuel to a desired operating characteristic. These techniques may include measurement of viscosity-temperature relations, filter or pumping pressure drop, and flow rate through tubes or capillaries under pressure or vacuum. Most of the methods were devised for testing Diesel or fuel oils for winter service (9,10), but they may have eventual application to jet fuels.

At least two methods have particular interest for studies of low-temperature performance of aviation turbine fuels. A liquid-solid apparatus of Dimitroff (5) used a 100 kPa (one atm) pressure differential to force liquid through a filter in a cold, constant-temperature bath for two hours. The difference in fuel volume between the original sample and the liquid recovered through the filter is the fraction crystallized. A cold flow test developed by Shell Research, Ltd., measured the gravity flow discharge of chilled fuel between two chambers separated by a valve (11,12). The solid fuel retained in the upper chamber is recorded as a percent holdup. For both these performance tests, measurements can be taken at several temperatures to yield a plot of fraction of fuel frozen or held up as a function of temperature.

Large-scale flow tests simulating actual service conditions for aviation fuels were also conducted by Shell Research (12) in an apparatus consisting of rectangular or contoured aircraft fuel tanks mounted in a cold room. Fuel in the tanks was cooled for 32 to 72 hours to a uniform test temperature and then pumped out of the tanks to an external receiver. The fraction of fuel remaining in the tank that cannot be pumped was called the holdup, and several tests established a relation of holdup against temperature, analogous to the aforementioned smaller-scale test technique.

Example of results of performance tests, determining fraction of frozen fuel as a function of tem-

<sup>2</sup>Temperatures are reported in degrees Celsius ( $^{\circ}$ C) throughout this paper.

temperature, are shown in figure 2. Tests of three fuels by the Shell cold tank method (data from (13) and additional data from Dr. Peter Ford) and of a fourth fuel by the liquid-solid separator (5) are illustrated. Fuel A, a jet fuel with a high normal paraffin content, has a narrow range of freezing behavior, about  $1.5^{\circ}$  from liquid to completely solid. In contrast, fuel C with a low n-paraffin content, shows a wide range of freezing behavior; in fact, it is limited to only 10 percent solid by the  $-60^{\circ}$  low temperature capability of the apparatus. Fuel D is a wide boiling range oil, covering jet and Diesel specifications, also with a low n-paraffin content. The freezing behavior of this fuel was measured by the liquid-solid separator, yet the slope of the freezing curve for this fuel in figure 2 agrees well with that of fuel C measured by holdup tests. Finally, curve B illustrates results for an intermediate n-paraffin content fuel, with a range of freezing behavior covering about  $8^{\circ}$ . Laboratory studies of freezing behavior of mixtures of known composition confirm that normal paraffins crystallize most readily, and accordingly, the high n-paraffin fuel will form a complete crystalline matrix over a short temperature span. The low n-paraffin fuels, in contrast, exhibit a much slower buildup of the solid matrix extending over a larger range of temperatures. The zero holdup temperatures measured by the small scale cold flow tests (13) agree with the corresponding temperature measured in the full scale cold tank tests. On the other hand, the specification wax disappearance freezing point does not necessarily correlate with the zero cold tank holdup, nor does pour point correlate with the 100 percent holdup. These discrepancies are especially evident for higher boiling fuels above the jet fuel range.

## FUEL TEMPERATURES IN COMMERCIAL AIRPLANES

### In-Flight Fuel Temperatures

The fuel temperature in aircraft tanks varies with the rate of heat transfer to the surrounding environment. The heat flux, largely convective, is a function of the total air temperature, or more correctly the turbulent boundary layer recovery temperature.

$$T_R = (1 + 0.18M^2) T_S$$

where  $T_R$  is recovery temperature,  $T_S$  is static temperature, and  $M$  is Mach number. For a present day commercial aircraft cruising at a Mach number of 0.84, the recovery temperature at a static air temperature of  $-72^{\circ}$  is  $-46^{\circ}$ . The difference between recovery and total temperature is only  $2^{\circ}$  to  $3^{\circ}$  at these conditions and, therefore, no distinction will be made in this paper between recovery and total air temperatures.

In-flight measurements showing fuel and total air temperature for two commercial wide-bodied aircraft are presented in figure 3. The solid lines are fuel temperatures measured by a single thermocouple in the fuel tank. The broken lines are the corresponding total air temperatures measured by external thermocouples. The data for the 4400 km commercial flight, furnished by the Lockheed Company, indicate that the fuel cooled proportionately to the total air temperature, but fuel temperatures remained approximately  $10^{\circ}$  above the total air temperature throughout the flight. The very long range flight data were recorded by Pasion and Thomas (14) based on a Boeing Company delivery flight. The fuel temperatures closely approached the total air temperature during portions of the flight. When the airplane traversed zones of

rapidly changing total air temperature, however, the fuel temperatures responded much more slowly. Minimum altitude static temperature, not shown in figure 3, were reported as  $-67^{\circ}$ .

### Calculated Fuel Temperatures

The predictive calculation of fuel temperatures supplements the in-flight measurements and establishes parametric variations and extreme statistical probabilities. Fuel temperatures are calculated from a summation of time-related heat fluxes over an assumed schedule of total air temperatures for a flight period. Several computing programs of this type have been developed. A Boeing Company program (15), used for the calculations presented in this paper, includes the effects of external convective and radiative heat fluxes and internal heat transfer from the pump, hydraulics, and intertank fuel transfer. The major simplification of this calculation is the assumption of a uniform fuel temperature within the fuel tank. Overall gradients of  $10^{\circ}$  from top to bottom have been measured in aircraft fuel tanks and in simulated testing apparatus during cooldown. However, these gradients do not have a great effect on the accuracy of the computed bulk fuel temperature. A maximum discrepancy of  $2.5^{\circ}$  was reported for comparisons of computed temperatures with a variety of corresponding fuel temperature measurements (15).

Two examples are presented of calculated fuel temperature histories at extreme ambient conditions with a one-day-a-year (0.3%) probability (14). Figure 4 shows results for short range, 900 km flight, based on a  $-60.7^{\circ}$  static air temperature and a flight schedule of climb, cruise at a Mach number of 0.82, and descent. Two cases are shown: one for the fuel loaded at  $12^{\circ}$ , the other for fuel loaded at  $-21^{\circ}$ . For the colder initial fuel case, the fuel chilled continuously during flight, reaching  $-31.5^{\circ}$  at the end of the 92 minute flight. For the warmer case, the fuel cooled more rapidly, but the fuel temperature was still about  $10^{\circ}$  above that of the cold initial fuel case at the end of the flight. These histories resemble the measured data for the 4.7 hour Lockheed flight shown in figure 3. It is thus shown that, for short range flights, there is not enough time for the fuel temperature to cool to the total air temperature, and fuel temperatures throughout the flight retain the influence of the initial loading temperature.

Figure 5 shows results for a long range flight, 9100 km. The total air temperature schedule is based on a flight profile with cruise at a Mach number of 0.84 and an altitude static temperature variation that includes a portion of the flight at a minimum temperature of  $-72^{\circ}$ . Calculations for initial fuel temperatures of  $12^{\circ}$  and  $-21^{\circ}$  are shown. After about six hours of flight time, there is no longer an influence of initial temperature. The fuel temperature eventually approaches the total air temperature, and a minimum fuel temperature of  $-43^{\circ}$  is predicted. This type of fuel temperature history resembles the measured data for the long range Boeing flight shown in figure 3. For long range flights, fuel is exposed to low temperatures long enough that the fuel temperatures can approach the total air temperature, and the minimum fuel temperature is independent of the initial loading temperature. It should be noted that the minimum fuel temperature does not necessarily occur at the same time of flight as the minimum total air temperature because of the slow response of the fuel temperature to external temperature changes, during the coldest portions of the flight.

### Freezing Point Requirements for Commercial Flights

In-flight problems with freezing fuel have not been documented. Situations have occurred, however, where gage warning of low fuel temperatures have prompted flight crews to divert to warmer, low altitude air masses. Such diversions are costly in terms of operation at less than optimum altitude-speed combinations or increased path length. A tolerance of 3° to 5° above the specification freezing point is required as a minimum fuel temperature during flight. It has been pointed out that the sum of the reproducibility of the freezing point specification, the accuracy of the thermocouple and gaging system, and other factors can add up to uncertainties much greater than these tolerances, but experience has proved that even 3° is an adequate margin of safety.

It is interesting to note that for the calculated extreme case flight shown in figure 5, a fuel would be required with a maximum freezing point of -46° (-43° minimum temperature minus the 3° tolerance). Fuel meeting the aviation turbine fuel standard specification D-1655-77, type Jet A-1, has a maximum freezing point of -50°. Jet A-1, however, is no longer produced in the United States. The common domestic aviation turbine fuel, type Jet A, has a maximum specification freezing point of -40° although Department of Energy inspection statistics (16) report that the arithmetic average of the freezing point of Jet A samples in 1977 was -45°.

### ADAPTATIONS FOR USE OF HIGHER-FREEZING-POINT FUELS

#### Higher-Freezing-Point Fuels

As discussed earlier, fuels with increased freezing point specifications could make a greater proportion of jet fuel available in overall production, and these fuels may indeed be a necessity in the near future. Although a calculated extreme case shown in figure 5 indicates that there can be flights where a fuel with a freezing point of -46° or lower is necessary to meet specification tolerance limits, the majority of commercial flights have milder freezing point requirements. Pasion and Thomas (14) estimate that a fuel with a -29° freezing point would be acceptable for use in all flights up to 9100 km in length in summer, and in 94 percent of these flights in winter. The small fraction of remaining flights cannot be ignored, of course. These long-range flights, mostly international, could not use a higher-freezing-point fuel except with costly, low-altitude operation. The specification of several grades of jet fuel is an obvious suggestion, but this would be objectionable to both suppliers and users because of complications in production, distribution, and storage. The most promising approach for the future would be to specify a single grade of higher-freezing-point fuel, to be used for all commercial flights, with certain fuel or airframe adaptations made to meet the needs of the long-range flights. The most likely or practical modifications are discussed in this section.

#### Fuel Modifications

Preheating. For short-range flights, ground preheating of fuel can indeed keep the fuel warmer throughout the flight (fig. 4). Unfortunately, for the long-range flights where fuel temperatures are most critical, initial fuel temperatures have little or no influence in flight (fig. 5). Ground preheating of fuel prior to long-range flights may be helpful for storage and ground handling of very high-freezing-point fuels at extreme winter conditions (14).

Additives. It was previously pointed out that the freezing process of fuels generally involves a buildup of a waxy or crystalline matrix, which eventually traps even liquid constituents as gels (5,17). Certain polymeric compounds in small concentrations are effective in delaying the matrix buildup by dispersing the initially formed solid particles. These additives are pour point depressants, which improve the low-temperature flow properties of the fuel without affecting the crystal formation as observed by freezing or cloud point tests. The mechanism of this dispersion probably involves several physical actions altering crystal size, shape, and surface attractive forces (18). The flow-improving additives are often blended into lubricating or fuel oils for winter service, but they are not effective in modifying the low-temperature properties of jet fuels. The additives may be of interest, however, in the production of future broadened-specification jet fuels because the higher boiling fractions blended into these fuels may be quite sensitive to additives (19,20). In figure 6, an example of this behavior is shown. These data are taken from Shell cold tank tests (13), and the percent of frozen fuel held in the tank is plotted as a function of temperature. The base curve, shown as a solid line, is the freezing behavior of fuel B in figure 2. The freezing results of a wider-boiling-range fuel are shown by the broken curve in figure 6. This fuel was a mixture of the base jet fuel plus 20 percent of a heavier, higher-final-boiling point fraction from the same source material. The low temperature performance of the wider-boiling blend is poorer than that of the base fuel as evidenced by greater holdup, or less flowability, at the same temperature. The second broken curve shows the performance of the same blend with the addition of 300 ppm of a flow improver. In this case, the holdup of the wide-boiling fuel has improved to the extent that it surpasses that of the base fuel.

Greater utilization of additives awaits specification standards based on low temperature flow characteristics, rather than wax disappearance freezing points insensitive to flow improvers.

#### Aircraft Fuel System Modifications

Insulation. Fuel heat losses to the surrounding environment are reduced by insulating the fuel tank. Pasion and Thomas (14) calculated the effect of a realistic system of insulation that could be added externally to the wing surface of a wide-bodied airplane. A 2.5 cm thickness of an epoxy filled glass microballoon layer was shown to reduce fuel heat losses by about 20 percent. The calculated fuel temperature history for a long-range flight with insulated fuel tanks is shown in figure 7, compared to the reference uninsulated case from figure 5. The insulated fuel is about 6° warmer than the uninsulated fuel during most of the long-range flight, but the difference in minimum temperature is about 4.5°. The insulated fuel does not reach the minimum temperature until after 9 hours, at the end of the flight. Fuel tank insulation, however, adds serious structural problems and severe weight penalties even for simple systems. It is, moreover, a constant penalty in contrast to heating systems which can be turned off when not used.

Fuel heating systems. Existing airframe and engine heat rejection sources offer the most promising method of maintaining fuel above minimum temperatures in flight. Calculated fuel temperature histories for heated fuel (14) are shown in figure 8, which in-

cludes, for comparison, the reference calculated long-range temperatures (fig. 5) for unheated, uninsulated fuel tanks. The middle solid curve shows the result of computations which assume that 79 kW of heat per engine is added continuously during flight. These calculations are based on a four-engined wide-bodied airplane, in which each engine is fed by the equivalent of a single fuel tank. The heating rate of 79 kW is equivalent to the energy released by the combustion of 6.5 kg of fuel per hour, which is a negligible fraction of a typical, efficient engine cruise fuel consumption of about 2000 kg/hr. This constant fuel heating rate will maintain the minimum fuel temperature above  $-25^{\circ}$ . Continuous heating is not necessary. The heating system could be turned on when the fuel is  $5^{\circ}$  above the desired minimum temperature, for instance, and heating would still be effective, since fuel cooldown rates are relatively slow during the portion of the mission where temperatures are lowest. If the fuel tank were insulated with the previously assumed 2.5 cm thick material, fuel temperature would rise slowly throughout the flight with this rate of fuel heating, as indicated by the highest solid curve in figure 8. Combined fuel heating and insulation may be used to reduce the heat requirements. The minimum temperature of  $-25^{\circ}$  can be maintained by 20 kW of heating if the fuel tank is insulated, as shown by the broken curve in figure 8.

Pasion and Thomas (14) also evaluated methods and designs for heating fuel in flight. Figure 9 is a sketch of a simple system using the existing heat rejection of the engine by the addition of a second lubricating oil heat exchanger in series with the existing lubricating oil cooler. In the ordinary mode of operation, the fuel control relieves excess fuel to the engine fuel pump. For fuel heating, a three-way valve diverts the excess fuel through the added heat exchanger into the fuel tank to warm the bulk fuel. The heating system does not affect the operation of the fuel control or engine fuel system, whether in the normal or fuel heating modes of operation.

The calculated fuel temperature for a long-range flight with the lubricating oil-fuel heating system is shown in figure 10. The heating rate schedule, calculated by the engine manufacturer, includes the heat available from the lubricating oil and the small amount of heat rejection from the pump and fuel control. Although heating rates vary, particularly over the first climb phase of the flight, they are reasonably constant at about 50 kW throughout most of the cruise portion of the flight. The minimum fuel temperature is about  $-31^{\circ}$ , which shows that this simple system will permit use of a broadened-specification fuel with a  $-34^{\circ}$  freezing point (including the  $3^{\circ}$  operating tolerance). Weight, performance, and modification cost penalties of the added system are small. On the basis of preliminary calculations (14), even small fuel cost reductions through the use of broad-specification fuels can readily offset these penalties. The heating of the fuel tank by engine heat rejection is not only a promising concept for heating high-freezing-point fuels, but it may also prove advantageous for engine designs with problems of excessive heat rejection, such as those with reduction gearing (21).

A second approach to in-flight fuel heating is through the use of modifications that divert a small portion of the engine energy to fuel heating, in contrast to the use of existing heat rejection. A promising example is an engine-driven electrical generator to heat fuel electrically, using a secondary heat transfer loop for control and safety (14). There are

present day military aircraft with functional engine-driven auxiliary generators, although the installations are for electronic demands rather than for fuel heating. The advantages of engine-driven electrical heating are that it is simple and efficient; it can be diverted for ground heating or other uses; and it can generate practically any amount of constant heating power desired. The disadvantages of this system over the use of existing heat rejection, the lubricating oil cooler for example, are in the greater mechanical complexity of the engine-driven system; the small but appreciable engine thrust penalty; and the greater installation and operating costs.

#### CONCLUDING REMARKS

If aviation turbine fuels were specified with less compositional restrictions and higher final boiling temperatures, they could be produced from a greater fraction of the crude oil sources with obvious advantages of efficient utilization of raw material, reduced refinery complexity and energy consumption, and perhaps lower product cost. The broadened-specification fuels would most likely have several property changes of serious concern to engine and airframe technologists, but this paper concentrates on freezing point, which generally increases as boiling temperature increases.

This paper has reviewed the freezing behavior of present and broadened-specification jet fuels. Performance and flow tests indicate that, in many cases, fuels have a usable flow or pumpability at temperatures lower than the standard freezing point defined by a wax disappearance test. Higher boiling-point fuels are also sensitive to flow-improving additives which can extend the range of low temperature flowability. As yet, no standard low temperature flow specification has been accepted that defines this usable low-temperature flow.

In recent years, airlines have compiled extensive data on in-flight fuel temperatures. For most missions, the fuel temperature environment is mild, and present freezing-point specifications of  $-40^{\circ}$  C maximum could be relaxed. For example, data show that a  $-29^{\circ}$  C freezing point jet fuel may be used in all flights up to a range of 9100 km in summer and in 94 percent of these flights in winter. Moreover, this broad specification fuel may be used for all flights under any weather conditions if certain adaptations can be made. Heating the fuel tanks in flight appears to be the most practical approach for general use of higher-freezing-point fuels. Two promising systems use engine lubricating oil heat for low power, small penalty fuel heating, or engine-driven electrical heat for high-power heating at greater penalties. These concepts are still in an early state of development.

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TABLE I. - AMERICAN STANDARD FREEZING POINT SPECIFICATIONS

Test no.	Title	Type	Repeatability <sup>a</sup> ±°C	Repeatability <sup>b</sup> ±°C	Bias <sup>c</sup> °C
D-2386-67	Freezing point of aviation fuels	Wax disappearance	0.7	2.6	---
D-3117-72	Wax appearance point of distillate fuels	Wax appearance	0.8	2.2	-2
D-1477-65	Freezing point of aviation fuels (obsolete)	Wax appearance	0.8	3.1	-2
D-2500-66	Cloud point of petroleum oils	Wax appearance	2	4	-3
D97-66	Pour point of petroleum oils	Wax matrix	3	6	d-8

<sup>a</sup>Difference between repeat measurements by same observer (6).

<sup>b</sup>Difference between measurements by different observers (6).

<sup>c</sup>Approximate difference of method minus D-2386-67 as reference (as reported by

W. G. Dukek at the ASTM Symposium of Jet Fuel Low Temperature Requirements, Dec. 1976).

<sup>d</sup>Extreme bias values may range between 0° and -17° or greater (5,10).



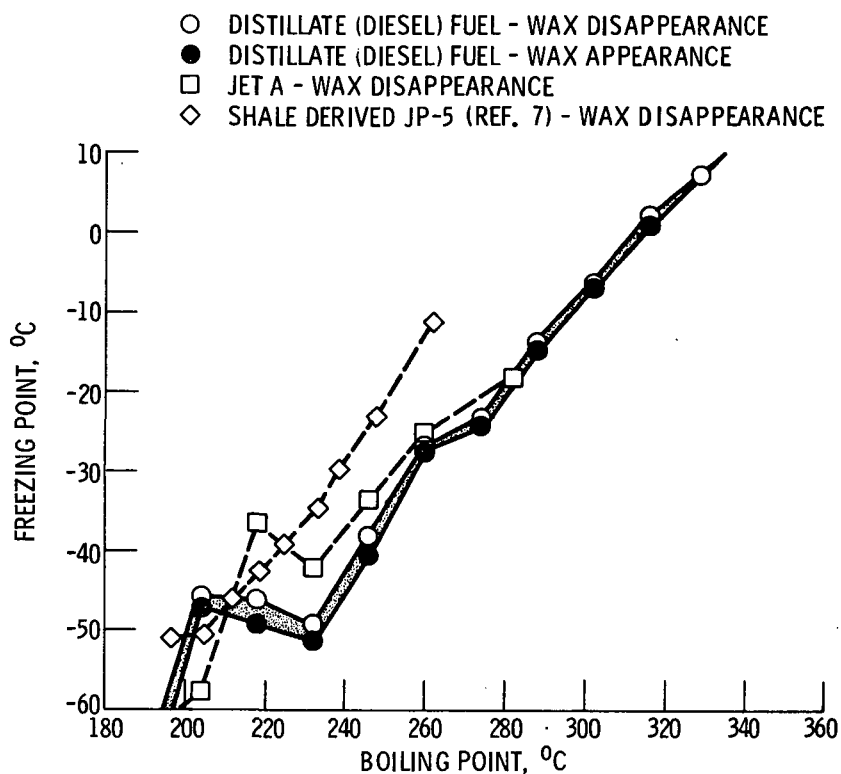


Figure 1. - Freezing points of narrow boiling range samples of fuels.

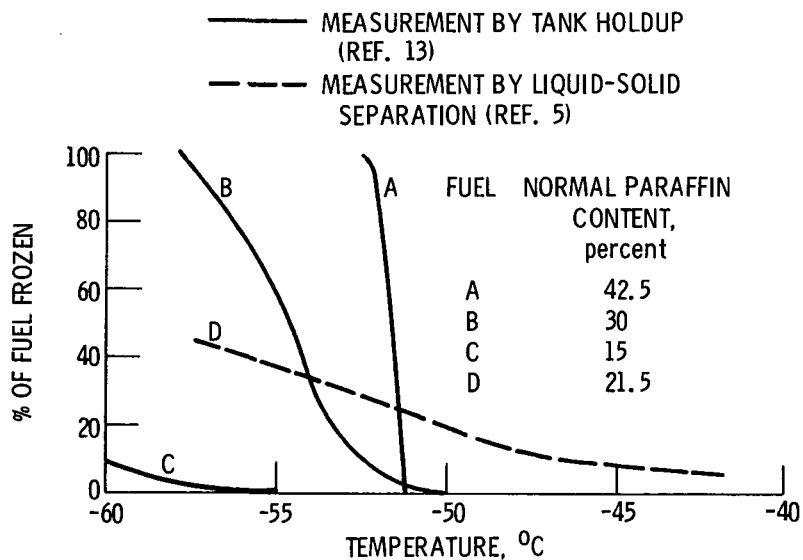


Figure 2. - Fuel freezing behavior.

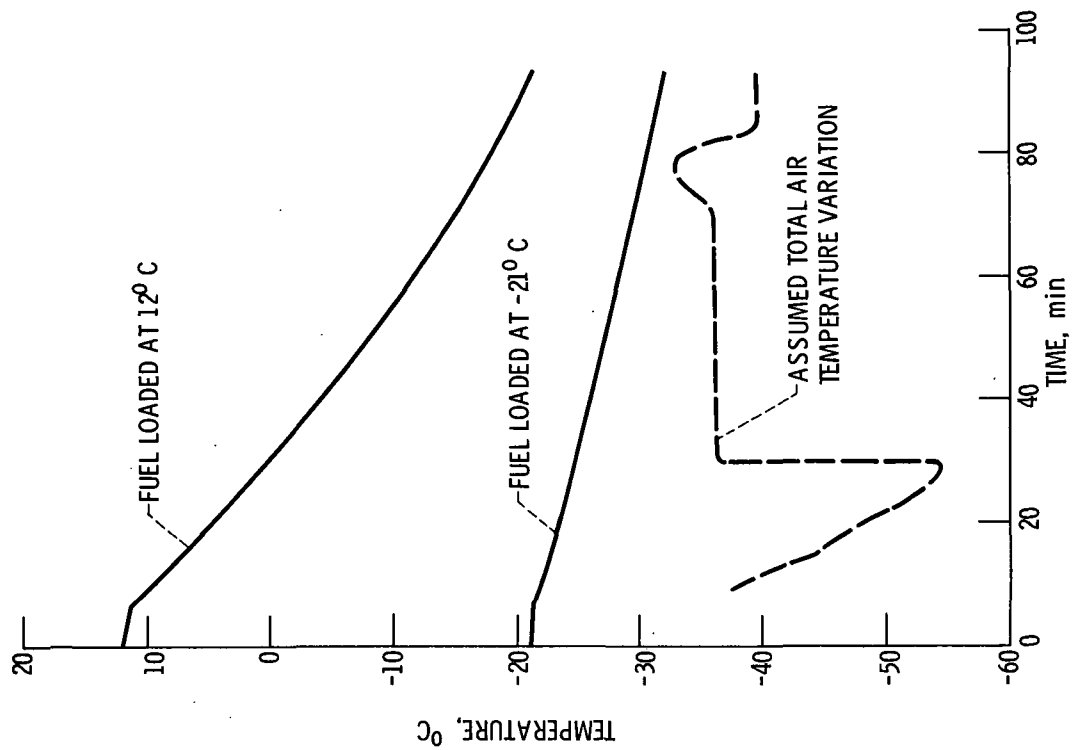


Figure 4. - Predicted fuel temperature for a short-range (900 km) commercial aircraft mission, based on minimum static air temperature of  $-72^{\circ}\text{C}$ .

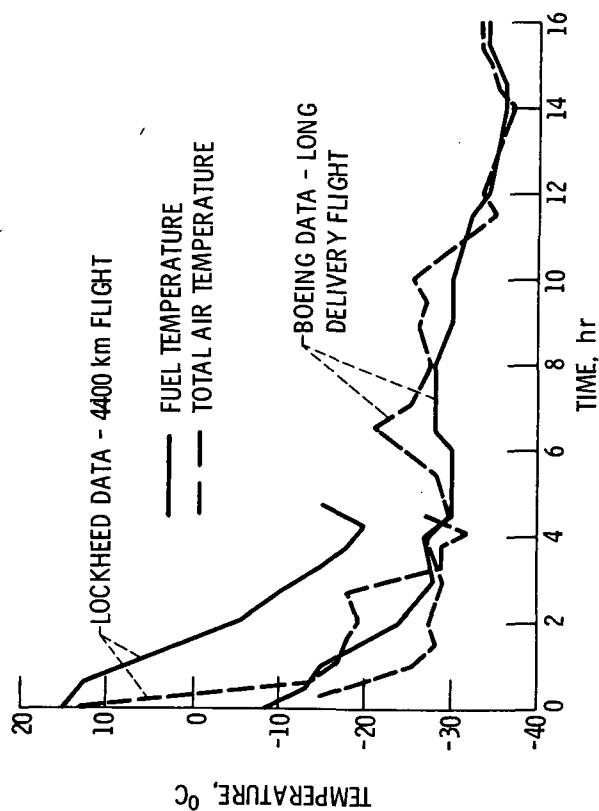


Figure 3. - In-flight measurements of fuel tank temperatures for two present-day wide-bodied aircraft.

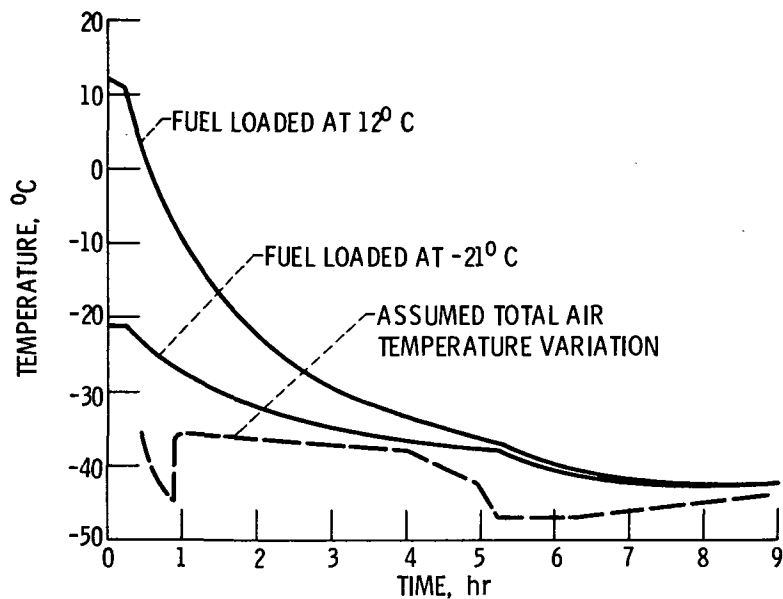


Figure 5. - Predicted fuel temperature for a long-range (9100 km) commercial aircraft mission, based on a minimum static air temperature of  $-72^{\circ}\text{C}$ .

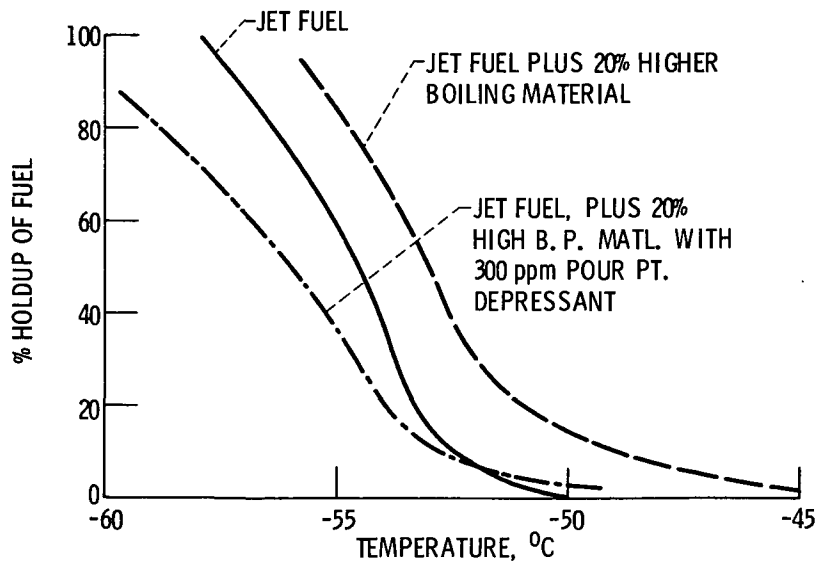


Figure 6. - Fuel freezing behavior curves, comparing higher-boiling-point fuel blends with and without additive.

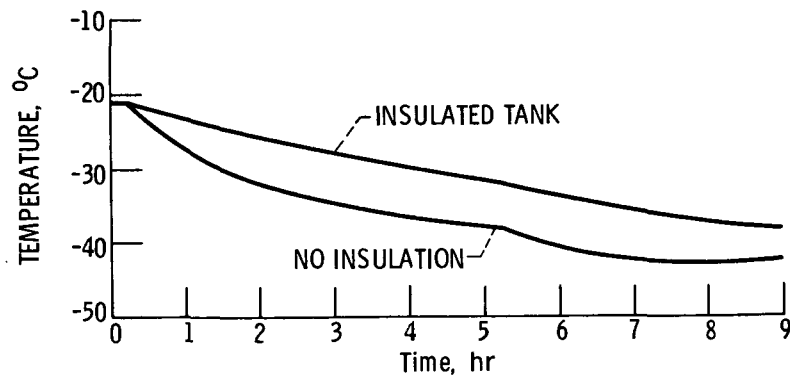


Figure 7. - Predicted fuel temperature for a 9100 km commercial aircraft mission, with 2.5 cm-thick fuel tank insulation,  $k = 0.65 \text{ W/(m}\cdot\text{K)}$ .

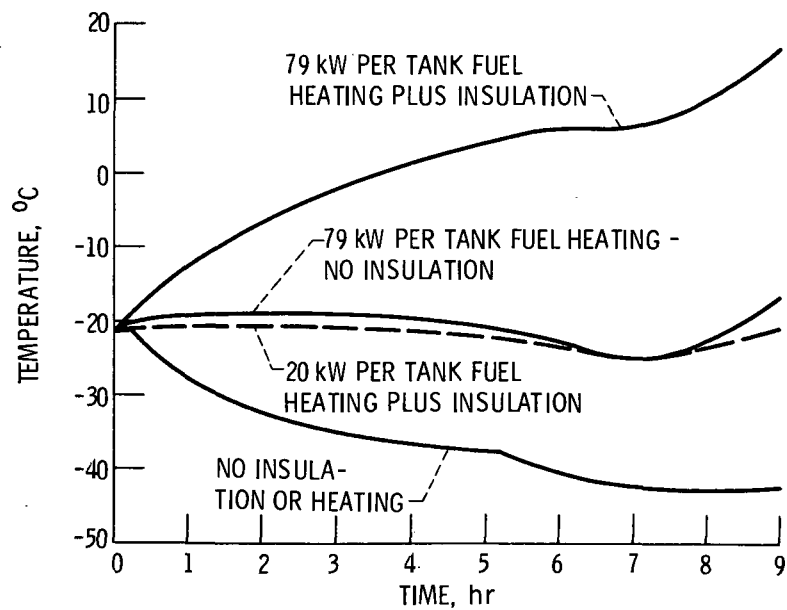


Figure 8. - Predicted fuel temperature for a 9100 km commercial aircraft mission, with heated and insulated fuel tank.

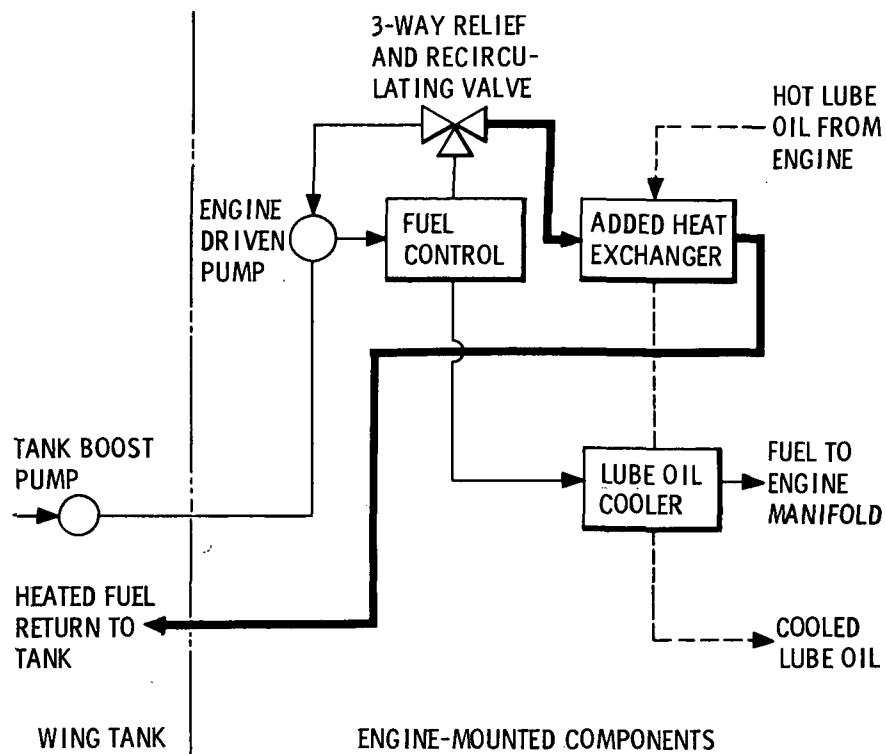


Figure 9. - Schematic of fuel heating system, using lubricating oil heat exchanger.

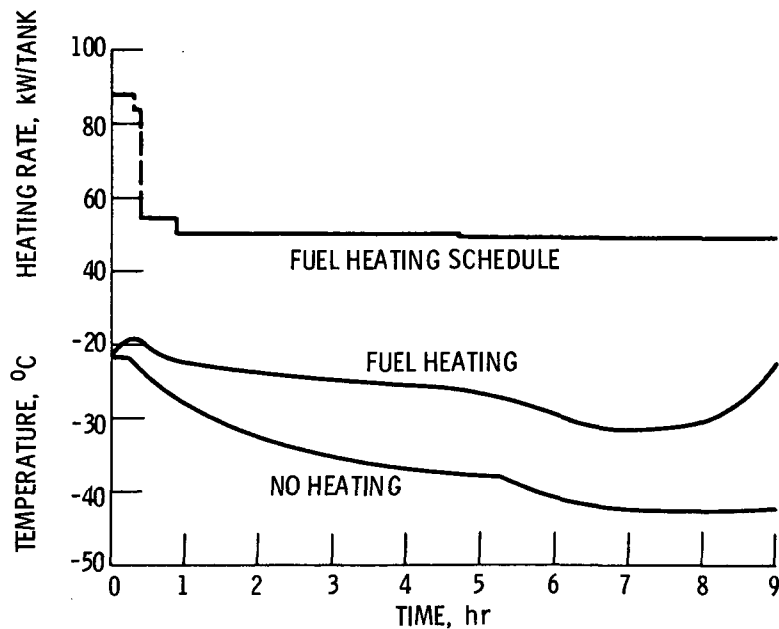


Figure 10. - Predicted fuel temperature for a 9100 km commercial aircraft mission, with fuel heated by lubricating oil heat rejection.

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16. Abstract <p>Broadened-specification aviation fuels could be produced from a greater fraction of crude source material with improvements in fuel supply and price. These fuels, particularly those with increased final boiling temperatures, would have higher freezing temperatures than current aviation turbine fuels. The higher-freezing-point fuels can be substituted in the majority of present commercial flights, since temperature data indicate that in-flight fuel temperatures are relatively mild. For the small but significant fraction of commercial flights where low fuel temperatures make higher freezing-point fuel use unacceptable, adaptations to the fuel or fuel system may be made to accommodate this fuel. Several techniques are discussed. Fuel heating is the most promising concept. One simple system design uses existing heat rejection from the fuel-lubricating oil cooler, another uses an engine-driven generator for electrical heating. Both systems offer advantages that outweigh the obvious penalties.</p>			
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