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PRELIMINARY ANALYSIS OF AIRCRAFT FUEL SYSTEMS FOR USE WITH BROADENED SPECIFICATION JET FUELS

Final Report

A. J. Pasion
I. Thomas

May 1976

Prepared under contract NAS 3-19783 by
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P.O. Box 3707
Seattle, Washington 98124

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16. Abstract

An analytical study has been conducted on the use of broadened specification hydrocarbon fuels in present day aircraft. A short range Boeing 727 mission and three long range Boeing 747 missions were used as basis of calculation for a one-day-per-year extreme values of fuel loading, airport ambient and altitude ambient temperatures with various seasonal and climatic conditions. Four hypothetical fuels were selected; two high-vapor-pressure fuels with 35 kPa and 70 kPa RVP and two high-freezing-point fuels with -29° C and -18°C freezing points. In-flight fuel temperatures were predicted by Boeing's Aircraft Fuel Tank Thermal Analyzer computer program. Boil-off rates were calculated for the high-vapor-pressure fuels and heating/insulation requirements for the high-freezing-point fuels were established. Possible minor and major heating system modifications were investigated with respect to heat output, performance and economic penalties for the high-freezing-point fuels.

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FOREWORD

This final report document describes work conducted by the Boeing Commercial Airplane Company and was prepared for NASA-Lewis Research Center in compliance with the requirements of contract NAS3-19783.

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1.0 SUMMARY

The objectives of this study are to calculate in-flight fuel temperatures, determine the effects of these temperatures on the use of broadened specification fuels in production aircraft, and to evaluate fuel system modifications for use of these fuels. Four hypothetical hydrocarbon fuels are used in this study to represent a wide variation from current jet fuels: two high-vapor-pressure, 35 kPa (5 psi Reid Vapor Pressure), 70 kPa (10 psi RVP); and two high-freezing-point fuels, -29°C (-20°F) and -18°C (0°F).

Four representative present day aircraft missions furnish the baseline data: a 900 km (500 n.mi.) Boeing 727 flight, and 3700 km (2000 n.mi.), 5600 km (300 n.mi.) and 9100 km (4900 n.mi.) Boeing 747 flights. Seasonal and climatic extreme values of fuel loading, airport ambient and in-flight ambient temperatures are established. These data are used in Boeing's Aircraft Fuel Tank Thermal Analyzer (AFTTA) computer program which is a theoretical model of an aircraft fuel system, to predict the in-flight fuel temperatures. Previous work has indicated excellent correlation of these predicted in-flight fuel temperatures with recorded data.

At conditions giving maximum-in-flight fuel temperatures, boil-off losses for the high-vapor-pressure fuels are calculated. These are a maximum of 3.3 percent for the 70 kPa vapor pressure fuel, with allowance for evaporative cooling. No modifications are investigated for the use of high-vapor-pressure fuel, but procedural changes are shown to be beneficial for long range missions.

At conditions giving minimum in-flight fuel temperatures, the predicted fuel temperatures are lower than the freezing-point of the study fuels. Consequently, methods of preventing the fuel from reaching its freezing point are investigated and the results indicate that the only feasible method is to provide heat into the fuel tanks. The heat requirements for the extreme minimum in-flight ambient temperature conditions are 6500 kJ/min/tank (6200 BTU/min/tank) for the -18°C (0°F) freezing-point fuels and 3700 kJ/min/tank (3500 BTU/min/tank) for the -29°C (-20°F) freezing-point fuel. Heating requirements can be reduced by insulating the fuel tanks, but insulation alone is insufficient to maintain fuel temperature above the freezing point in all cases.

Several modifications to existing aircraft systems are investigated, defined as minor modifications using existing heat rejected by the aircraft systems and major modifications which involve more extensive changes and sized for the use of the -18°C freezing point fuel. The modifications are evaluated as to their ability to provide the required heat and the complexity of their development and installation on current production aircraft.

A fuel consumption penalty is assessed for each modification operating at the design condition of an extreme minimum in-flight ambient temperature. Since it is unrealistic to assume that the aircraft will encounter the design condition on every flight, an average flight condition was established to determine the average utilization rate. The utilization rate is used to calculate the average fuel consumption penalty.

The results of this study indicate that minimum in-flight fuel temperatures on short range flights are influenced by fuel loading and airport ambient temperatures. Minimum in-flight fuel temperatures on long range flights are dependent only on altitude stagnation temperatures. The -29°C freezing point fuel can be used without modifications in short range flights. This fuel can be used under all conditions in long range flights through the use of modifications. The use of the -18°C freezing point fuel would require major modifications with greater economic penalties. Ground handling modifications are required with the use of -18°C fuel where ambient freezing may be a problem. These modifications involve a minimal cost per volume of fuel handled.

The penalty in increased direct operating costs (DOC) and return on investment (ROI) expressed as fuel cost decreases necessary to offset the increased economic costs, is generally less than 0.3 cents/liter (one cent/gallon). Changes in other fuel properties, e.g., heat of combustion, may have a several fold greater effect on costs.

2.0 INTRODUCTION

This report presents the results of a study performed by the Boeing Commercial Airplane Company, under NASA Contract NAS3-19783, titled, "Program to Study the Effect of Broadened Fuel Specifications on the Design and Performance of Aircraft Fuel Systems". The objectives of this study are to calculate in-flight fuel temperatures, to determine the effects of these temperatures on the use of broadened specification fuels in production aircraft and to evaluate fuel system modifications for use of these fuels.

The world production and reserve supply of petroleum crudes poses a continuing problem of maximizing fuel availability, in the face of increasing costs and limited choice of crude type. There is general agreement that permanent relaxation of jet fuel specifications will be required if fuel suppliers are to produce jet fuels in necessary quantities and at reasonable prices (Ref. 1).

Jet fuel is a blend of hydrocarbons which can be manufactured from any of the available fossil sources, including shale oil and coal liquids as well as petroleum. The fractional yield and cost of refining jet fuel from the crude sources are influenced by properties of the source and the specification limits of the fuel, particularly the boiling range. In addition to small changes in combustion and transport properties, the greatest effect of broadening the boiling range toward lower temperatures is increased vapor pressure. The greatest effect of broadening the boiling range toward the higher temperatures is increased freezing point. The relationship of jet fuel properties has been the subject of several reviews, including two recent books (Refs. 2 and 3). The problem associated with use of high-vapor-pressure fuels is altitude boil-off losses (Refs. 4, 5 and 6). The problem associated with high-freezing-point fuels is potential line blockage and poor pumpability (Refs. 2 and 6). Suggested methods for correcting freezing point problems have included fuel additives (Ref. 7), tank agitation (Ref. 7), insulation (Ref. 8), and heating fuel in flight by exhaust heaters (Ref. 8), combustion heaters (Ref. 8) and compressor bleed heaters (Ref. 7). The insulating effect of frozen fuel layers inside fuel tanks has also been calculated (Refs. 8 and 9).

In the present study, practical designs were sought for the use of the broadened specification fuels on short-range Boeing 727 and long-range Boeing 747 missions. In-flight fuel temperatures were calculated, using Boeing's Aircraft Fuel Tank Thermal Analyzer (AFTTA) computer program, to establish the maximum temperatures for high-vapor pressure fuel problems and the minimum temperatures for high-freezing-point fuel problems. Use of the Boeing AFTTA program has been described in Reference 10. Measured in-flight temperatures reported in References 5, 11 and 12 and various unpublished airline sources have been used to verify the AFTTA program. Baseline seasonal and climatic ambient airport and altitude temperatures and fuel loading temperatures were established in this study to represent a statistical one-day-a-year extreme case.

This report presents the boil-off calculations for the high-vapor pressure fuels. Procedural flight altitude changes are discussed but no structural modifications are evaluated for these fuels. The design studies concentrated on the high-freezing-point fuels. The scope of the investigation included several methods of in-flight heating, insulation and ground handling modifications. Heating systems include minor modifications using existing heat rejected by the aircraft and the major modifications were designed to maintain fuel above −18°C (0°F) at all conditions. The more promising designs are evaluated in terms of weight, fuel consumption penalty, estimated direct operating costs and return on investment penalties.

3.0 BASELINE MISSION, TEMPERATURE AND FUEL DATA

3.1 MISSION PROFILES

Four representative commercial airline missions were selected as the basis for the broadened specification fuel studies. For these missions, typical flight profiles were defined in terms of altitude, speed, fuel consumption, payload and gross weight. The four aircraft missions are:

(a) 900 km (500 n.mi.) flight of a Boeing 727-200 aircraft
(b) 3700 km (2000 n.mi.) flight of a Boeing 747-200 aircraft
(c) 5600 km (3000 n.mi.) flight of a Boeing 747-200 aircraft
(d) 9100 km (4900 n.mi.) flight of a Boeing 747-200 aircraft

The flight profiles were established as typical schedules based on standard atmospheric conditions. Although actual flight profiles would differ due to ambient conditions and aircraft traffic, these differences have a minimal effect on the resulting fuel temperatures. Therefore, the flight profiles for each of the four missions were the same regardless of the assumed climatic or seasonal conditions. The flight profiles are plotted on Figures 1 through 3. Figure 1 shows the altitude and Mach number variation for the short-range 727 mission. Figure 2 shows the altitude and Mach number variation for the long range 747 missions. Figure 3 is an example of the time history of fuel consumption for the 9100 km (4900 n.mi.) 747 mission. Similar data were obtained for all the other missions.

3.2 TEMPERATURES BASELINE DATA

For these studies, representative values were desired for the fuel loading, airport ambient and altitude ambient temperatures. Six seasonal-climatic conditions were selected, corresponding to summer and winter seasons at the tropical (±30° latitude), warm temperate (30° to 50° latitude) and cold temperate (50° to 65° latitude) zones. Extreme values of temperature were defined as those expected one-day-a-year, or a 0.3 percent probability.

The fuel loading temperatures were compiled from information from Shell Oil Co. and airline sources available to the Boeing Company. The data were analyzed for the airports in each climatic zone, and statistical distributions of expected fuel temperatures were calculated. An example of the range of fuel loading temperatures for the warm temperate zone is shown on Figure 4. From these plots for all the seasonal-climatic conditions, various fuel loading temperatures within the 0.3 percent probability were selected.

The airport ambient temperature data were compiled from the Boeing temperature data reported in Reference 13 for each of the airports from which fuel loading temperature data were obtained. Temperatures were selected to represent minimum and maximum 0.3 percent probability extremes and mean values for the six seasonal-climatic conditions.

In-flight altitude ambient temperatures for the 900 km (500 n.mi.) 727 mission were obtained from References 14 and 15, to correspond to each of the seasonal-climatic conditions. Uniform temperature gradients from the various airport ambients to the altitude ambient temperatures were assumed.

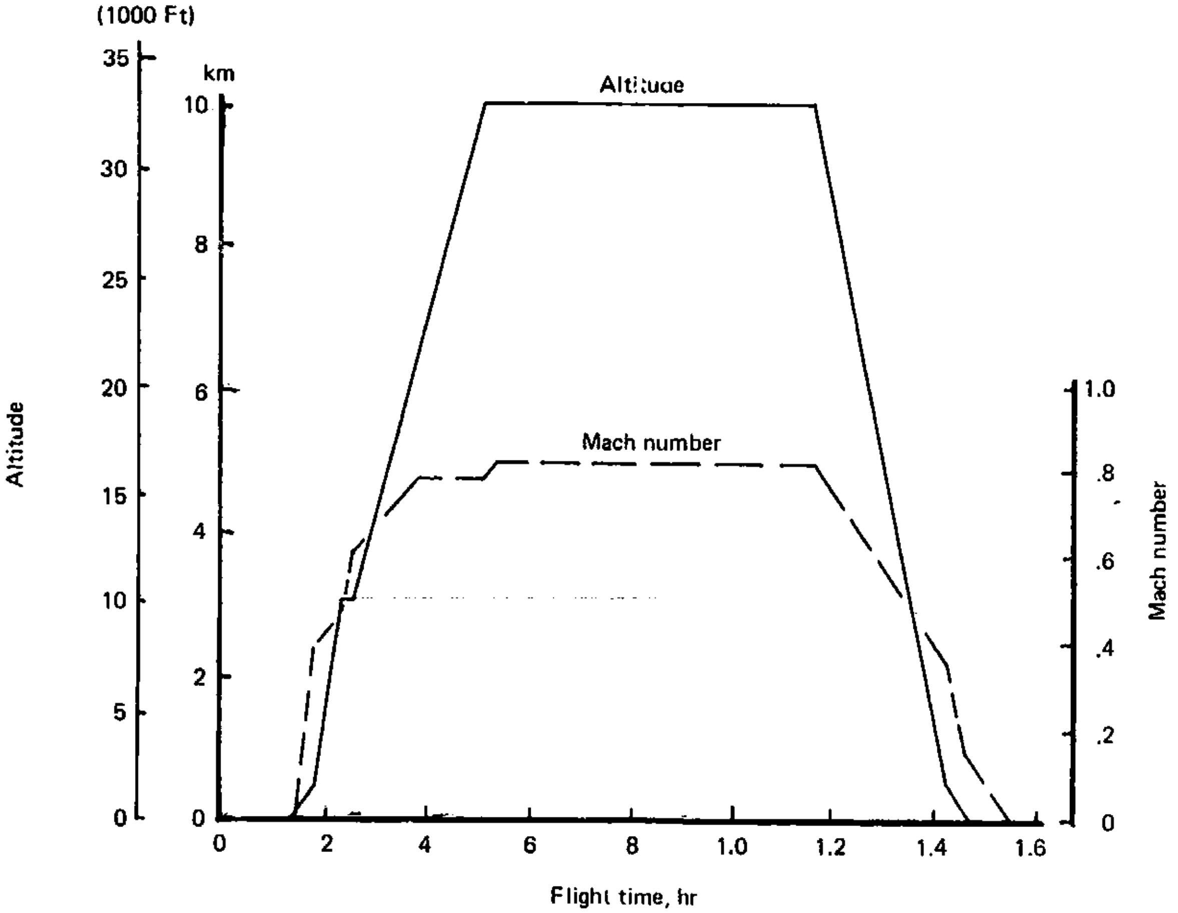

Figure 1.–Flight Profile for the Boeing Model 727-200, 900 km (500 nmi) Mission

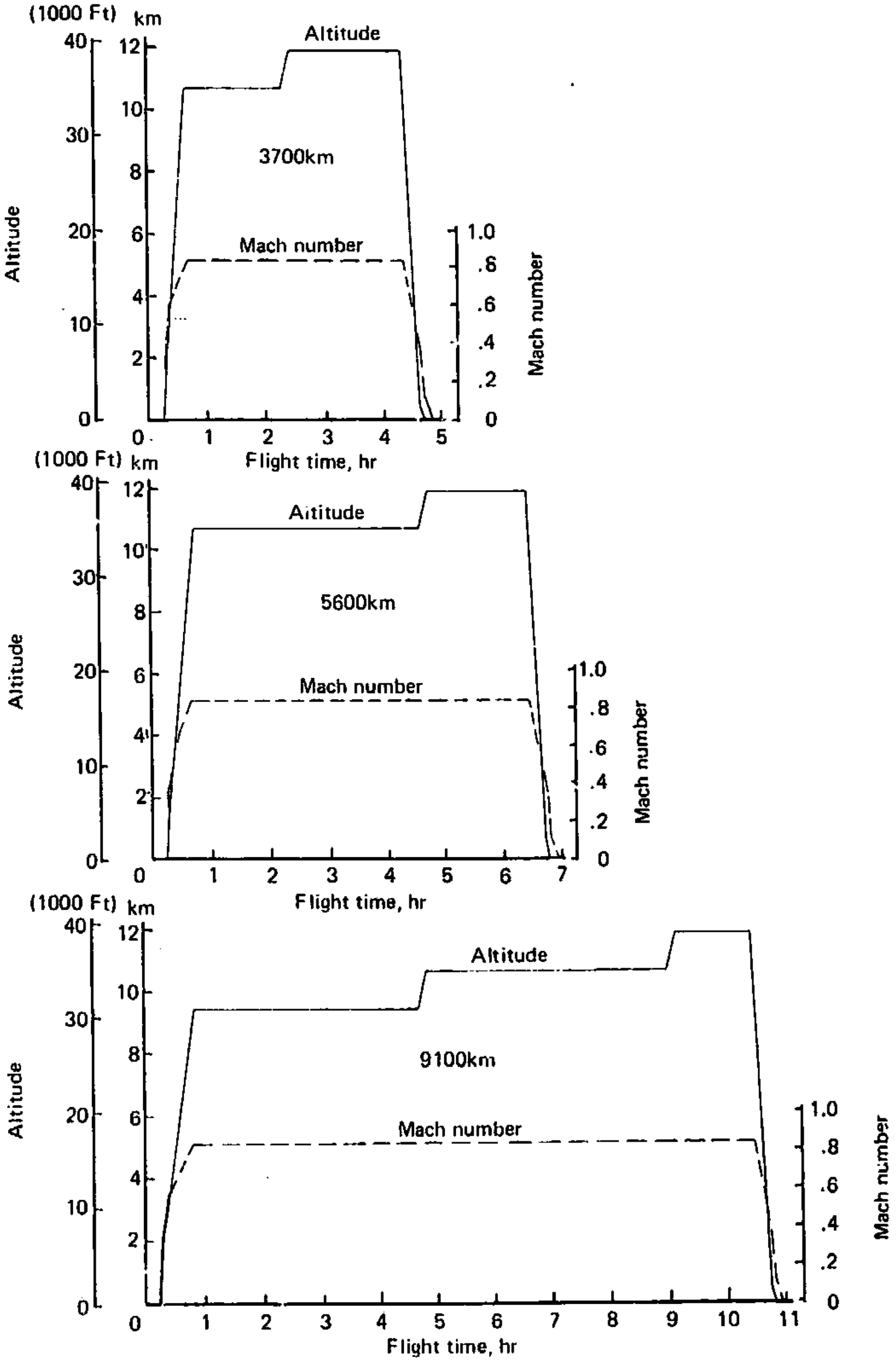

Figure 2.— Flight Profiles for the Boeing Model 747-200 Long-Range Missions

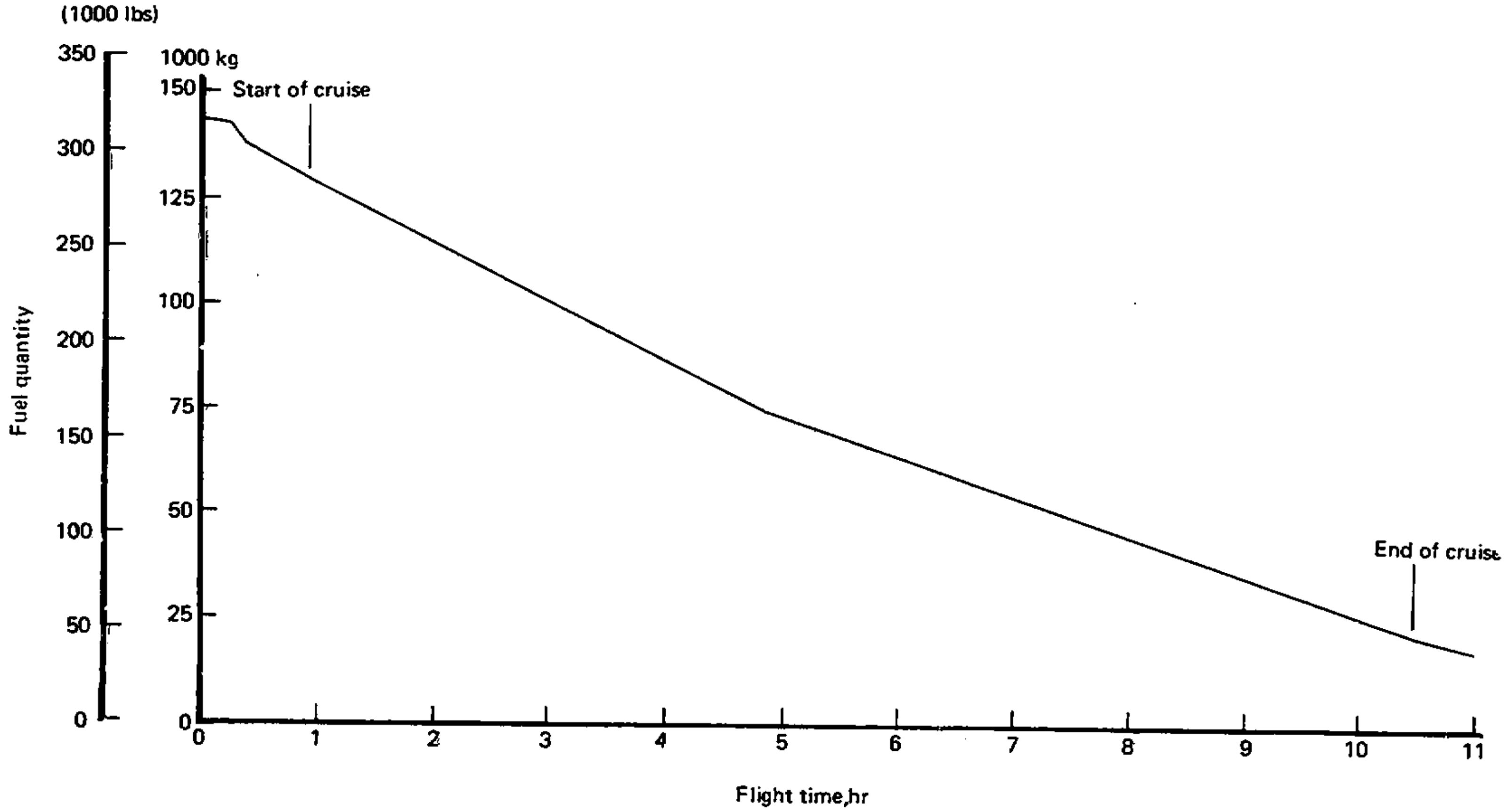

Figure 3–Fuel Quantity for the 9100 km (4900 nmi) 747-200 Mission

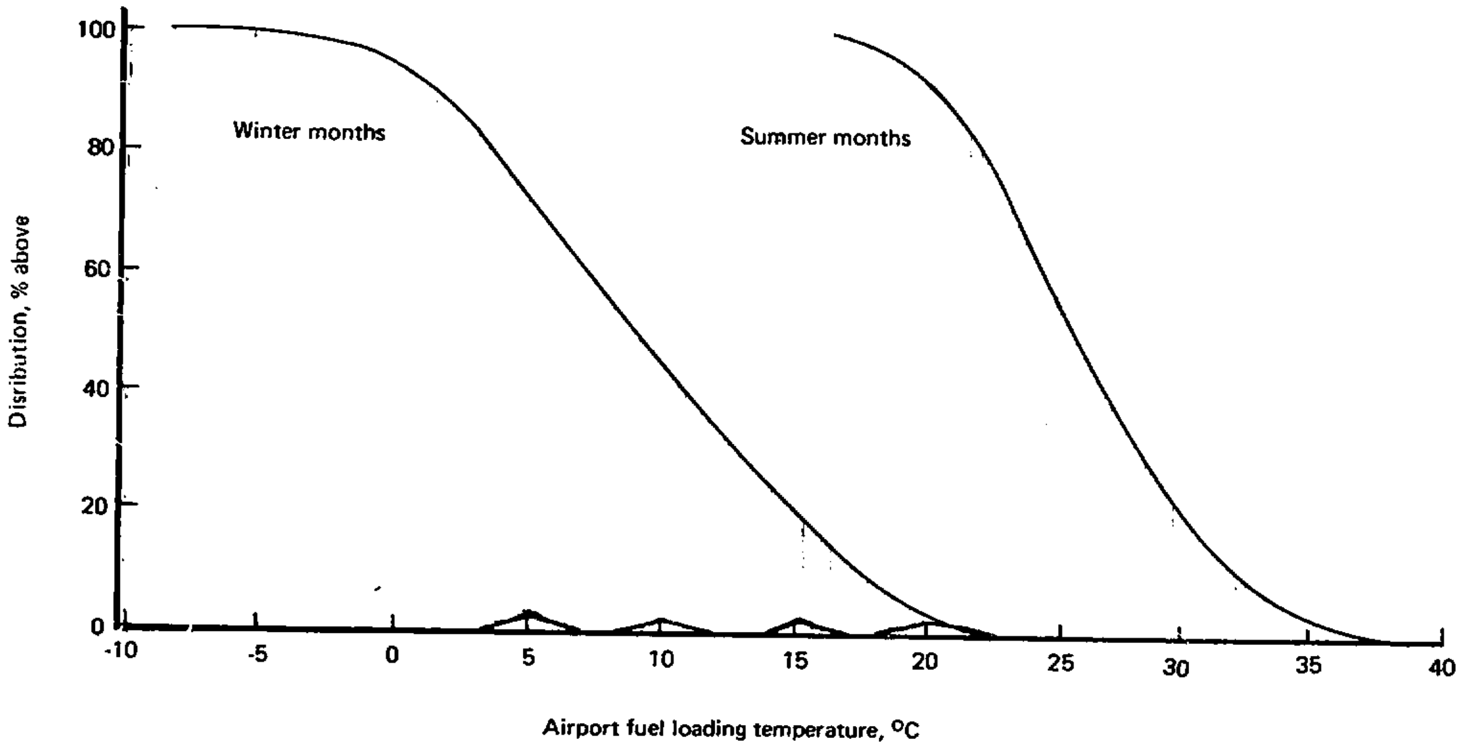

Figure 4.—Fuel Loading Temperature Distribution In Warm Temperate Zone

For the long-range 747 missions, in-flight altitude ambient temperatures were compiled from military standards and atlases as described in Reference 10. Scheduled airline routes were superimposed on polar temperature charts to establish representative temperature profiles. The resulting temperature-time plots shown on Figure 5 were established for each mission. These temperature profiles represent the minimum and maximum 0.3 percent probability extremes and are not necessarily a representation of an individual flight. The portion of the flight where the minimum altitude ambient temperature occurs corresponds to that portion of the flight which is over the Polar region. However, it has been determined that the minimum fuel tank temperatures during flight is not influenced by the minimum altitude ambient temperature or when it occurs, unless it occurred at the beginning of cruise. In this case, the minimum fuel tank temperature would not be as low as the case illustrated on Figure 5. Uniform temperature gradients from the various airport ambients to the altitude ambient temperatures were also assumed.

A summary of the extreme values of the fuel loading, airport ambient, and altitude ambient temperatures for the four missions and six seasonal-climatic cases are shown on Table 1.

3.3 PROPERTIES OF BROADENED SPECIFICATION FUELS

Four hypothetical fuels were selected as the basis for these studies. Two were defined as high-vapor-pressure fuels: 35 kPa (5 psi) Reid Vapor Pressure and 70kPa (10psi) RVP. The Reid Vapor Pressure (RVP), ASTMD-323, is a standard volatility characteristic defined nominally as the vapor pressure at 38°C with a 4 to 1 vapor-liquid volume ratio. Two fuels were defined as high-freezing-point fuels: -29°C (-20°F) and -18°C (0°F) freezing points.

Typical distillation curves were constructed for the hypothetical fuels. The high-vapor-pressure fuels had wide-cut distillation curves, similar in slope to those of wide-cut jet fuels such as ASTM Jet B. The distillation temperatures representing the desired RVP was calculated from charts in the CRC Aviation Handbook, cited in References 16 and 17. The high-freezing-point fuels had narrow temperature range distillation curves, similar in slope to those of ASTM Jet A. Correlations of distillation temperatures with freezing point is poorly defined, due to the variance of the chemical composition of the fuel. Representative data for establishing the distillation curves were taken from Reference 17. Comparison with typical diesel fuel and No. 2 fuel oil properties at similar distillation ranges showed freezing point agreement within 6°C.

The key properties of the hypothetical fuels are summarized in Table 2. Properties of Jet A, ASTM D-1655 are also included for comparison. The Jet A values are typical rather than minimum specification values. The typical values are taken from the 1976 sample surveys reported in Reference 18.

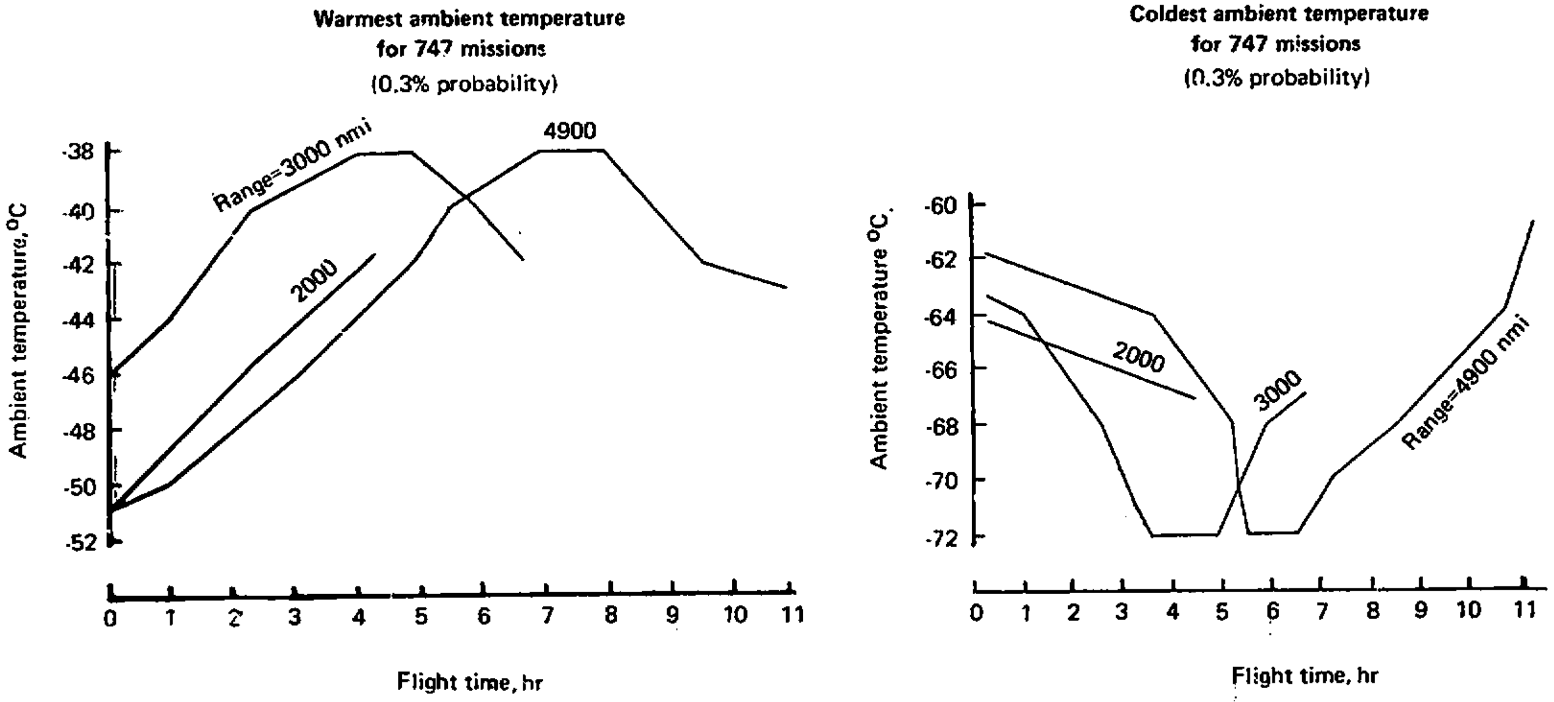

Figure 5.—Inflight Altitude Ambient Temperature Profiles for the Long-Range Missions

Table 1. —Temperatures for Baseline Studies

	Fuel loading temp °C, T_{fo}	Airport ambient temp °C, T_{am}	Ambient altitude temp °C, T_{alt} 727 missions	Ambient altitude temp °C, T_{alt} 747 missions
Tropical zone				
Winter months	32.8	30.8	-26.8	See profiles in figure 5 for maximum hot day extreme and minimum cold day extreme (one-day-per-year probability).
	7.8	-13.9	-52.7	
Summer months	38.2	38.9	-26.8	
	24.4	6.1	-39.2	
Warm temperate zone				
Winter months	22.2	32.8	-36.2	
	-10.0	-26.1	-58.3	
Summer months	37.8	47.2	-25.3	
	15.6	1.7	-44.7	
Cold temperate zone				
Winter months	12.2	16.1	-39.7	
	-21.1	-38.9	-60.7	
Summer months	21.1	35.0	-30.7	
	12.2	-0.6	-52.3	

Table 2. —Properties of Fuels

Property	Fuel type				
	Jet A typical (Ref 18)	High-freezing-point		High-vapor-pressure	
		-20° F	0° F	5 RVP	10 RVP
Freezing point, °C	-46	-29	-18	-	-
°F	-51	-20	0	-	-
Reid vapor pressure,					
kPa	-	-		35	70
(ASTM D-323) psi	-	-	-	5	10
Distillation temp, °C					
volume recovery, 10%	188	210	252	75	49
20%	195	220	226	100	74
50%	213	238	288	160	133
70%	229	249	301	200	171
90%	246	266	322	242	216
final	267	288	357	279	260
10% slope of curve, °C/%	-	-	-	2.6	2.4
10% to 90% slope, °C/%	0.73	0.70	0.88	2.09	2.09
Avg. volume boiling-point, °C	214	236	286	155	129
Characterization factor, Kc(ref. 17)	11.82	11.67	11.68	11.71	11.81
Specific gravity,					
60/60	.810	.832	.858	.783	.760
°API	43.1	38.6	33.5	49.2	54.3
Net heat of combustion					
kJ/kg	43300	43000	42700	43500	43800
Btu/lb	18609	18470	18370	18700	18820
Viscosity at 50° C,					
cSt	1.4	1.6	2.8	0.60	0.56

Table 2 shows several values from the constructed distillation curves, slopes, and average boiling points for the hypothetical fuels. The density and characterization factor for the −29°C freezing point fuel were selected from density-distillation data as found in References 17 and 19. The characterization factor (Ref. [illegible], page 81, for example) is a calculated index used to describe the general chemical classification of petroleums. The characterization factors and, in turn the densities of the other hypothetical fuels were calculated by the relationship of characterization factor and average boiling point from tables in Reference 19, assuming all fuels originate from the same crude base.

The net heat of combustion, viscosity and additional properties shown on Table 2, were estimated from correlations in References 17 and 19. In particular, it should be noted that the net heat of combustion of the -18°C freezing point fuel is slightly below the minimum specification for Jet A of 42800 kJ/kg (18400 Btu/lb).

4.0 ANALYSIS OF IN-FLIGHT FUEL TEMPERATURES

4.1 THEORETICAL MODEL OF FUEL TANK COOLING

Boeing's Aircraft Fuel Tank Thermal Analyzer (AFTTA) computer program was used to predict the in-flight fuel temperatures. This program utilizes a theoretical model which assumes that exchange of heat between the fuel and its surroundings is a time dependent phenomenon, but the properties involved generally change slowly enough to permit a quasi-steady state treatment over sufficiently small time intervals. Energy and mass balances are performed on the fuel system for a given time. The bulk mean fuel temperature in the tank is determined as a function of time by solving the steady state heat transfer equations for consecutive short time intervals.

The program takes into account heat flux from the fuel through the external boundary layer, heat input from pumps, hydraulic lines and radiation to the environment. The effect on the cooling rate of stringers within the fuel tank, the radiation from unwetted upper tank surfaces, and the change in wetted area of the tank as the fuel is withdrawn are included in the thermal calculations. This program also has the ability to determine the effects of fuel that is heated and recirculated back into the fuel tank and also fuel that is transferred from other fuel tanks.

The primary factors affecting fuel cooling rate are ambient temperature, airplane speed and fuel tank heat transfer characteristics. The secondary factors include fuel transfer procedure, initial fuel temperature and heat transfer characteristics of fuel pumps, and lines of heat exchangers. The principal uncertainty and major assumption in the theoretical model is that the fuel within the tank is uniformly at the same temperature everywhere at any given time. In the real system considerable stratification and gradients in fuel temperature will occur. Further, the real system fuel will be sloshed around depending on flight conditions. Neither of these factors are accountable at present and it is unclear without further testing what these effects will do to the resulting fuel temperature. Comparison with actual flight data as discussed in Section 4.3 suggests that fuel stratification is minimized by fuel sloshing and thus the effect on fuel temperature is small.

4.2 PREDICTION OF IN-FLIGHT FUEL TEMPERATURES

In-flight fuel temperatures were calculated for each of the missions and seasonal-climatic combinations listed in Table 1, using the Boeing AFTTA computer program. Calculations were based on the geometry and capacity of the outboard wing fuel tanks of the 727 and 747 aircraft. The fuel cooling rate in the outboard tanks is greater than the inboard tanks because of the smaller fuel capacity and the larger heat transfer surface per volume. The prediction of fuel temperatures for the 747 also included the small outboard wing reserve tank because fuel is transferred from these tanks to the outboard main tanks during flight.

Examples of some of the in-flight fuel temperature calculation results are presented in Figures 6 through 10. Figure 6 shows the predicted fuel tank temperatures for the 900 km (500 n.mi.), 727-200 airplane mission, based on the coldest airport and altitude ambient

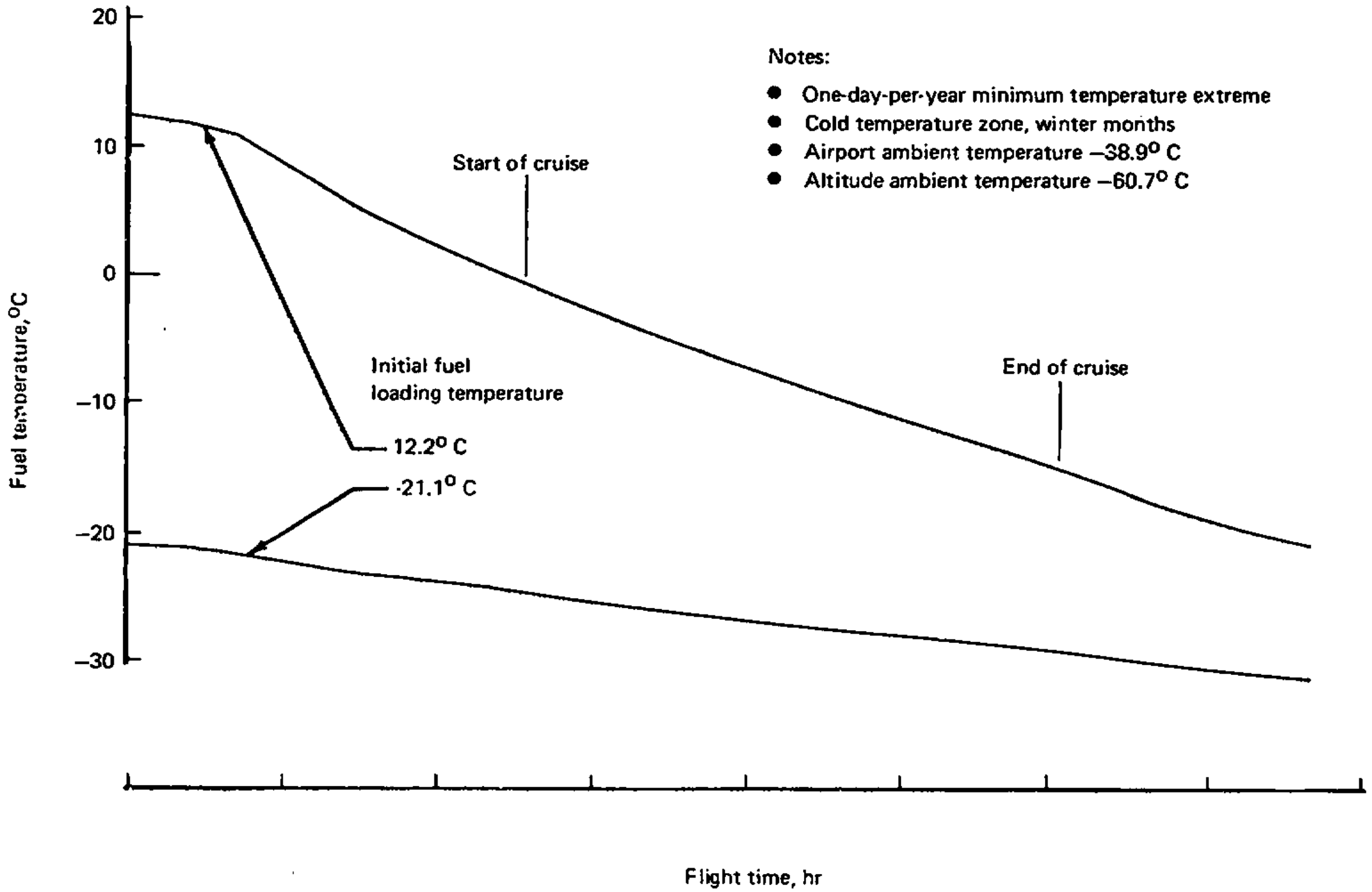

Figure 6.—Predicted Fuel Temperatures for 900 km (500 nmi) 727-200 Mission

temperatures. Two fuel loading temperatures of 12°C and -21°C are plotted. For the coldest fuel loading case, the minimum fuel temperature, attained at the end of the flight, is about -31°C. It is interesting to compare this temperature to the altitude boundary layer recovery temperature, T_R. For an 0.9 recovery factor, T_R is found by (Ref. 10).

$$T_R = (1 + .18\, M^2)\, T_{ALT} \qquad (1)$$

For a cruise Mach number, M, of 0.82 and an altitude ambient temperature, T_{ALT}, of 212K (-60.7°C), T_R is -35°C. Thus at the extreme case for the short-range mission, the in-flight fuel temperature will approach the altitude recovery temperature, T_R. Fuel loading temperature influences the in-flight fuel temperature, although its effect is somewhat diminished toward the end of the flight. Airport ambient temperature, not illustrated on this figure, has a similar affect.

Figure 7 shows the predicted fuel tank temperatures for the 900 km (500 n.mi.) 747-200 mission, based on the hotest airport and altitude temperature conditions. These conditions will occur in the summer, at the warm temperate zones in desert regions. (Two fuel loading temperatures are shown.) For the maximum temperature case, the airport ambient temperature influences the in-flight fuel temperature, altitude cooling is small.

Figures 8 through 10 are calculated in-flight fuel temperatures for the 3700 km (2000 n.mi.) 5600 km (3000 n.mi.) and 9100 km (4900 n.mi.), 747-200 missions at extreme minimum temperatures. Two fuel loading temperatures are shown on each plot. The altitude ambient temperature schedule for each mission has been illustrated on Figure 5. For the 3700 km (2000 n.mi.) mission, in Figure 8, the altitude recovery temperature is -40.8°C. The in-flight fuel temperature for the lowest fuel loading condition approaches the altitude recovery temperature at the end of the flight. The influence of initial fuel temperature is reduced during the course of the flight and is very small at the end of the flight. This effect is more pronounced for the longer missions shown on Figures 9 and 10. The effect of initial temperature is nil at the end of the 5600 km (3000 n.mi.) mission and at the last half of the 9100 (4900 n.mi.) km mission. For both these missions, the minimum in-flight fuel temperature approach the altitude recovery temperature of -44°C after about 5 hours of flight time. The final fuel temperature increase is a result of the altitude ambient temperature schedule shown on Figure 5.

Similar calculations were made predicting median and hottest day extremes for the long-range flights. For purposes of the broadened specification fuel used in this study, Figures 8 through 10 illustrate the coldest extreme conditions of interest.

In summary, it is noted that for short-range flights, in-flight fuel temperatures can be greatly influenced by fuel loading and airport ambient temperatures. Coldest fuel temperature occurs at the end of the flight and hottest fuel temperature, at the hottest initial condition occurs at the beginning of the flight. For long-range flights, minimum in-flight fuel temperatures are predicted during the flight approaching the altitude recovery temperature. After 5 hours of flight time (3700 km (2000 n.mi.) or longer), initial conditions have no influence on the resulting in-flight fuel temperatures.

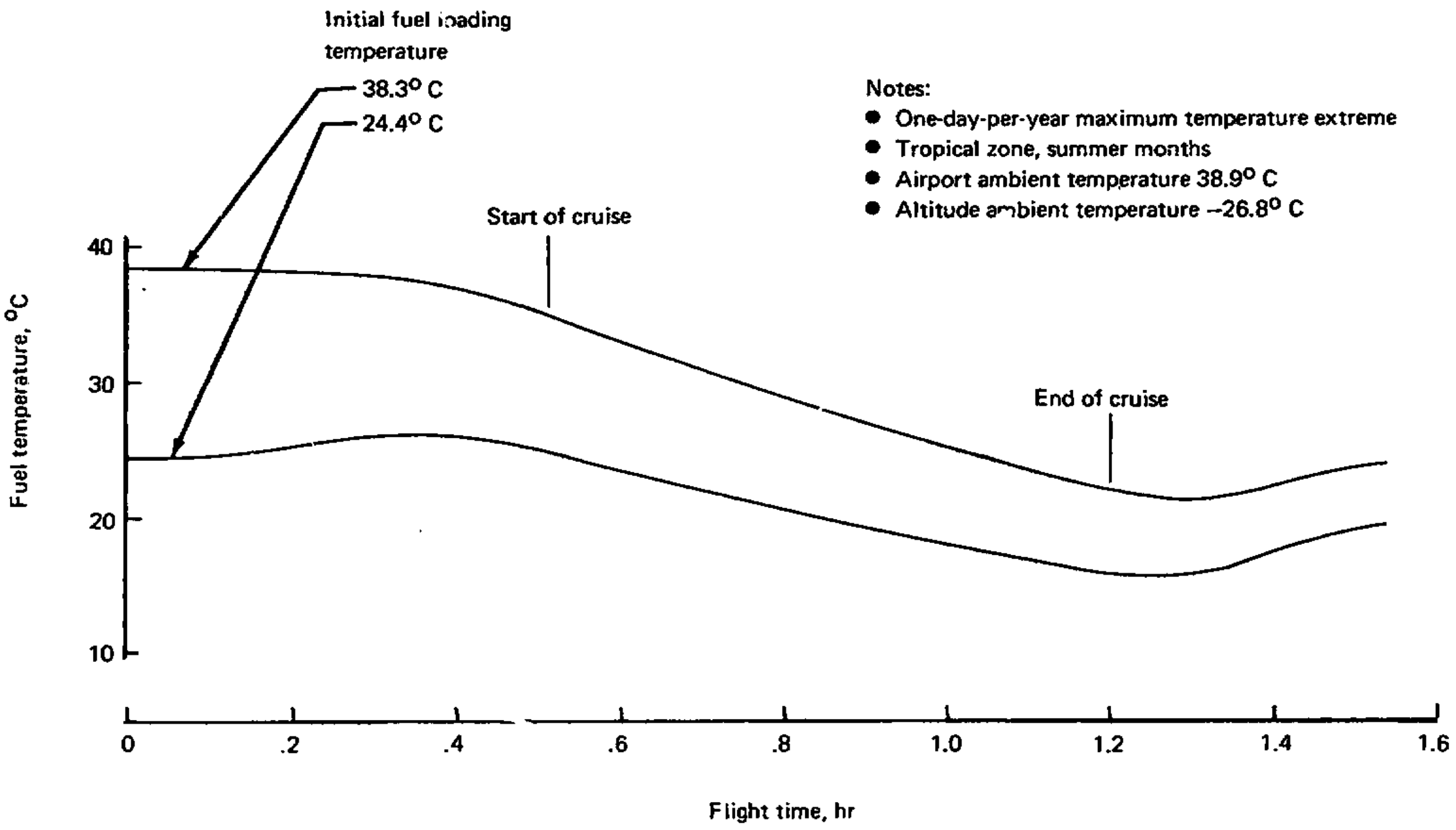

Figure 7.—Predicted Fuel Temperatures for 900 km (500 nmi) 727-200 Mission

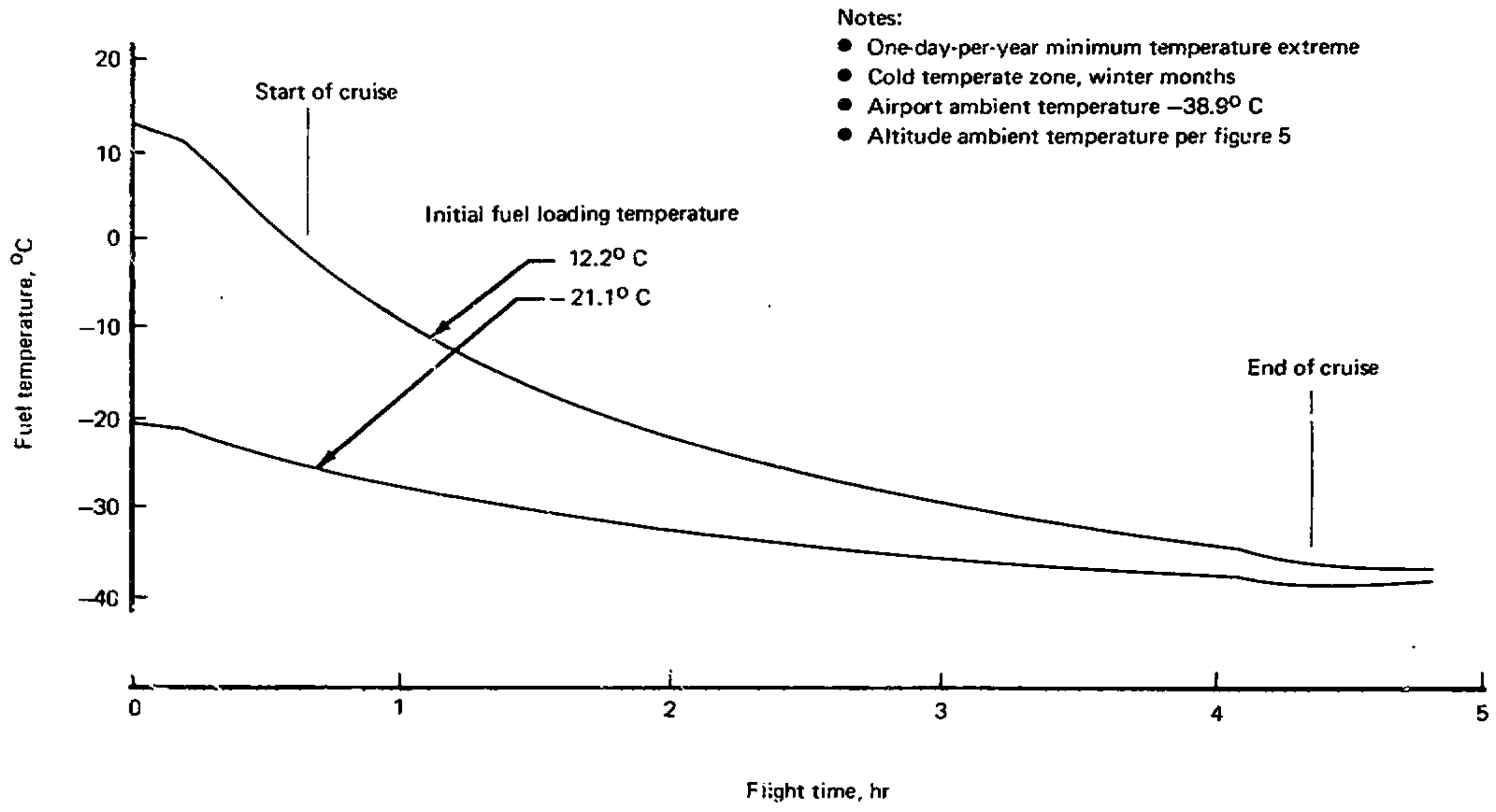

Figure 8.–Predicted Fuel Temperatures for 3700 km (2000 nmi) 747-200 Mission

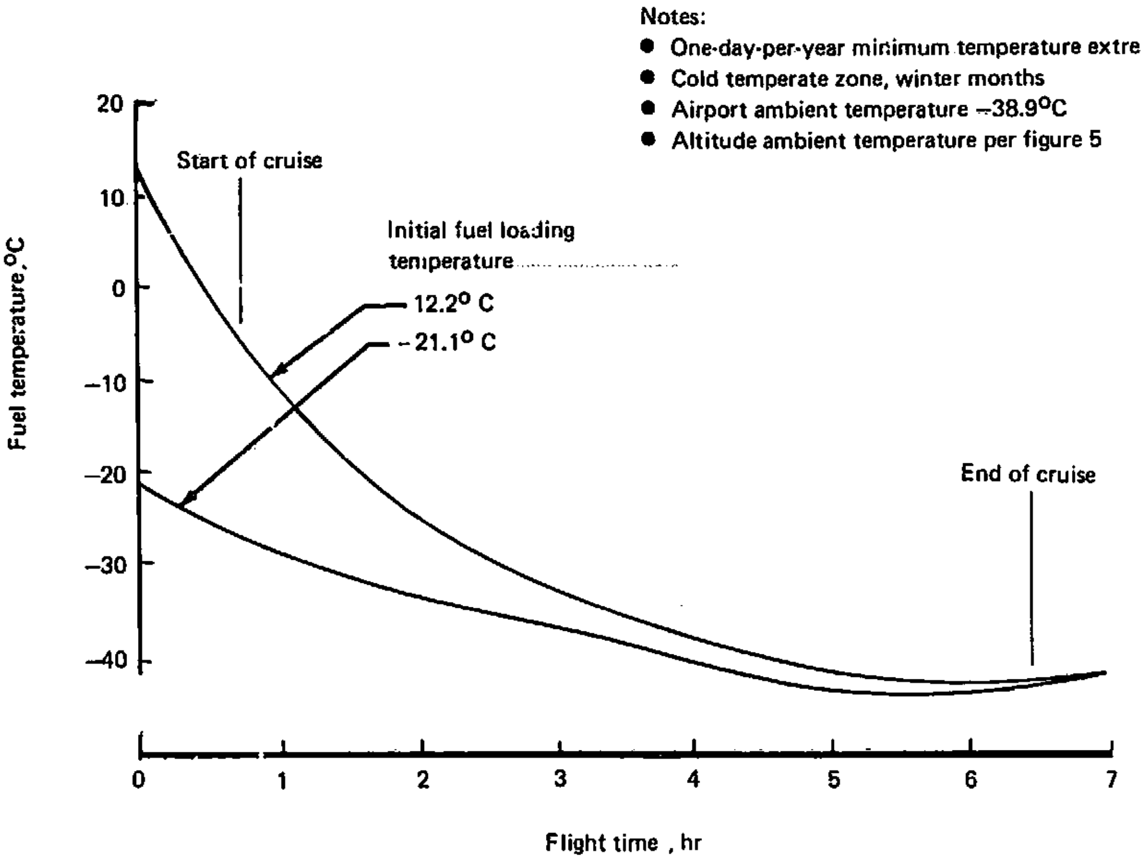

Figure 9.–Predicted Fuel Temperatures for 5600 km (3000 nmi) 747-200 Mission

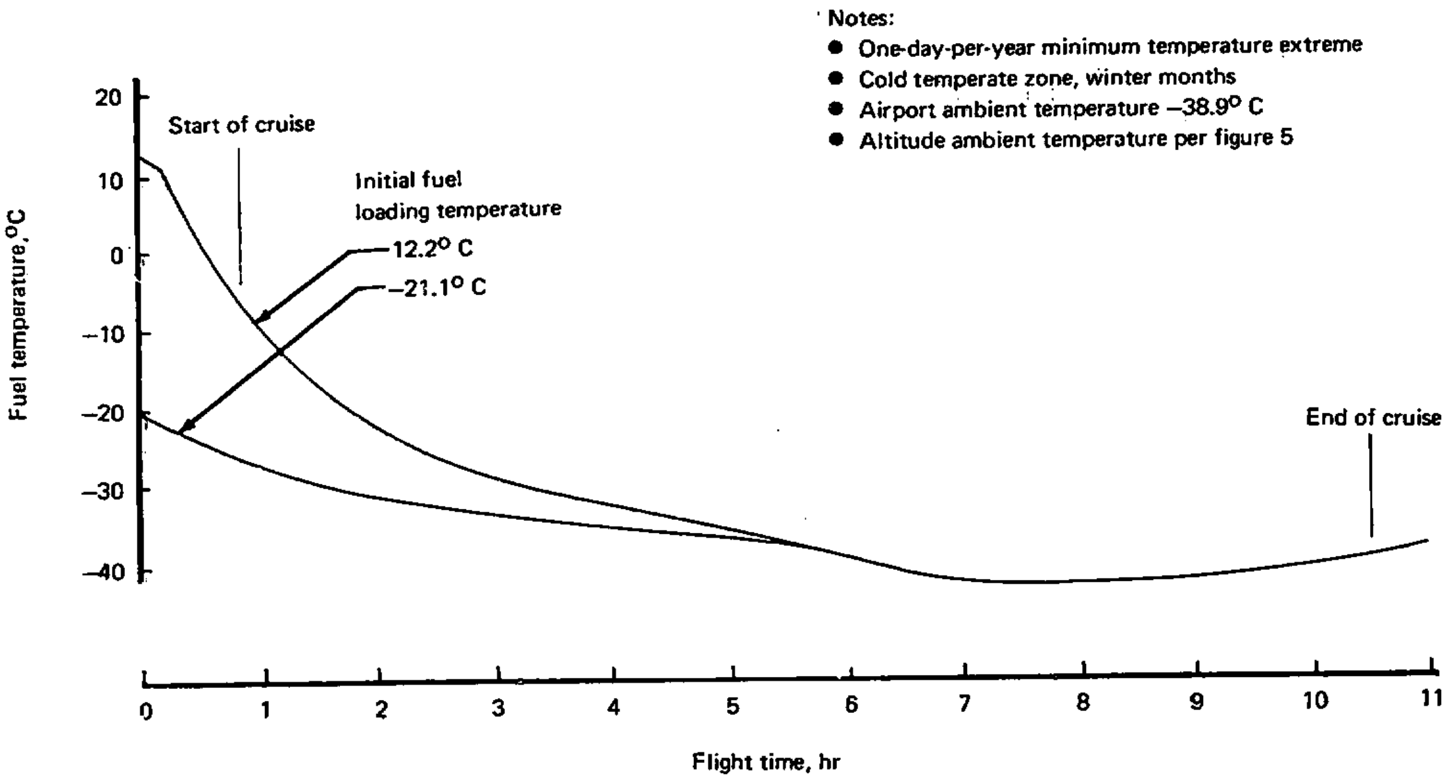

Figure 10.–Predicted Fuel Temperatures for 9100 km (4900 nmi) 747-200 Mission

4.3 COMPARISON OF PREDICTED FUEL TEMPERATURES WITH IN-FLIGHT DATA

A large number of transatlantic flight trip logs showing fuel cooling data were obtained from several airlines. The initial fuel temperatures, flight profiles, fuel quantities, tank characteristics and ambient conditions for these flights were used in the AFTTA program and the computed fuel tank temperature-time histories were then compared with the recorded data. The mean absolute deviation for all these comparisons was 2.5°C.

Reference 10 discusses the accuracy of the AFTTA program, its sensitivity to various parameters and possible sources of errors. A recent comparison of flight data and predicted fuel temperature is shown on Figure 11. For this very long-range flight, Mach number, stagnation temperature and fuel tank temperatures were recorded. These values together with the fuel usage and flight altitude were input into the AFTTA program to yield the predicted fuel temperatures. The predicted fuel temperatures agree within 2°C of the measured fuel tank temperatures.

The statistical extremes used in this report and shown on Table 1 and Figure 5 are regarded as reasonable representations. By comparison, early literature reports (Refs. 5, 11 and 12) indicate representative minimum altitude ambient temperatures of -66 to -70°C. Data furnished by British Airways indicate measured altitude ambient temperatures as low as -80°C with a very low probability. Consequently, the minimum value of -72°C used in this study is regarded as a reasonable extreme for the stated 0.3 percent probability and the derived in-flight fuel temperatures are reported with confidence.

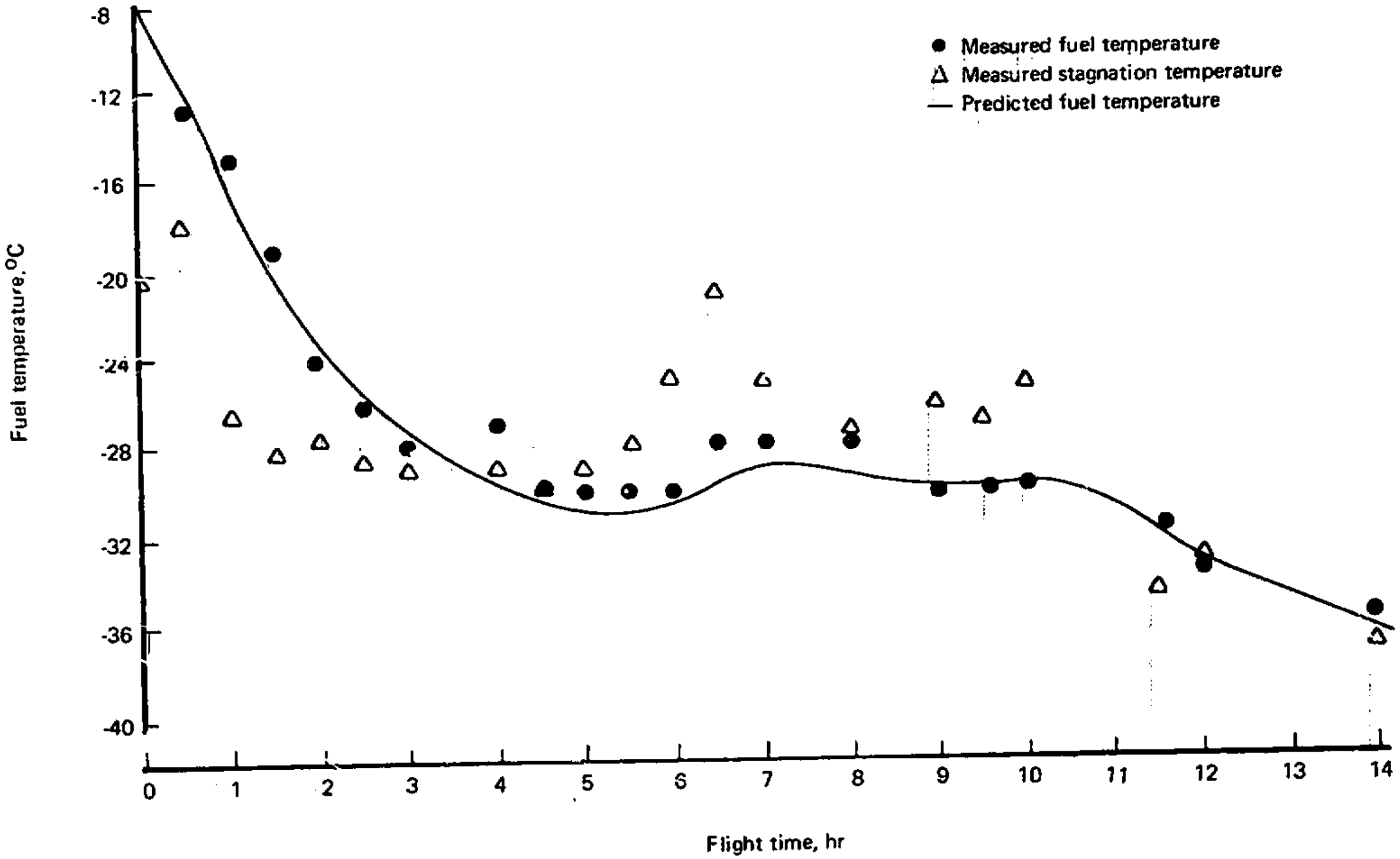

Figure 11.–Correlation Between Predicted and Measured Fuel Temperatures

5.0 ANALYSIS OF EFFECT OF HIGH-VAPOR-PRESSURE FUELS ON AIRCRAFT FUEL SYSTEMS

The use of high-vapor-pressure fuels in aircraft will be limited by maximum fuel temperatures, where boil-off losses may occur. Ground and crash safety and other high-volatility problems were outside the scope of this study. The fuel temperature prediction indicate that maximum fuel temperatures will occur at the initial climb portion of the flight (see Figure 7). Data for the hottest combination of temperatures shown on Table 1 were used for the calculations with the two hypothetical high-vapor-pressure fuels.

5.1 FUEL BOIL-OFF LOSSES

5.1.1 THEORETICAL CALCULATIONS

For the hypothetical high-vapor-pressure fuels, plots of vapor pressure as a function of temperature were constructed by relating the Reid Vapor Pressure (RVP) to the true vapor pressure (Refs. 20 and 21) and establishing true vapor pressure-temperature correlations (Ref. 19). From standard altitude-pressure charts, (Ref. 22) and the altitude ambient temperatures used in this study (Table 1), the altitude at which boiling begins was determined for each fuel and mission. At altitudes above which boiling begins, the weight percent of fuel lost was calculated by (Ref. 23):

$$W = X\,(h-h_b) \qquad (2)$$

where W is the weight percent of fuel vaporized at altitude, h,

hb is the altitude where boiling begins
$X = \frac{3.5907}{S+1.076}$ in S.I units
S = slope of distillation curve at 10% distilled point, °C/%.

From the fuel property table, Table 2, for the 70kPa (10 psi) RVP fuel S=2.4 and X=1.04. For the 35 kPa (5 psi) RVP fuel S=2.6 and X=0.98. The calculated values of W for the 70kPa RVP fuels are plotted on Figure 12 as parameters in a graph of altitude against fuel temperature. The maximum case of fuel temperature for the 900 km (500 n.mi.) 727-200 mission taken from Figure 7 is superimposed on this figure, indicating boil-off losses for this flight, based on the adiabatic vaporization calculation. Maximum boil-off loss is indicated as about 5.8 percent. Similar calculations were made for the other missions at the hottest temperature conditions.

5.1.2 CORRECTIONS TO CALCULATIONS

A realistic assessment of fuel boil-off losses should include the change in fuel temperature due to adiabatic latent heat evaporation, changes in fuel tank pressure due to fuel depletion and pressure losses in the vent systems, changes in fuel composition due to fractional vaporization, fuel loss through bumping or foaming, and fuel loss through evaluation of dissolved air at altitude. Only the first of these is treated quantitively here, but some remarks will be made concerning the other effects.

Notes:

- 900 km (500 nmi) 727-200 mission
- Tropical zone, summer months
- Fuel loading temperature 38.3° C
- Airport ambient temperature 38.9° C
- Altitude ambient temperature −26.8° C

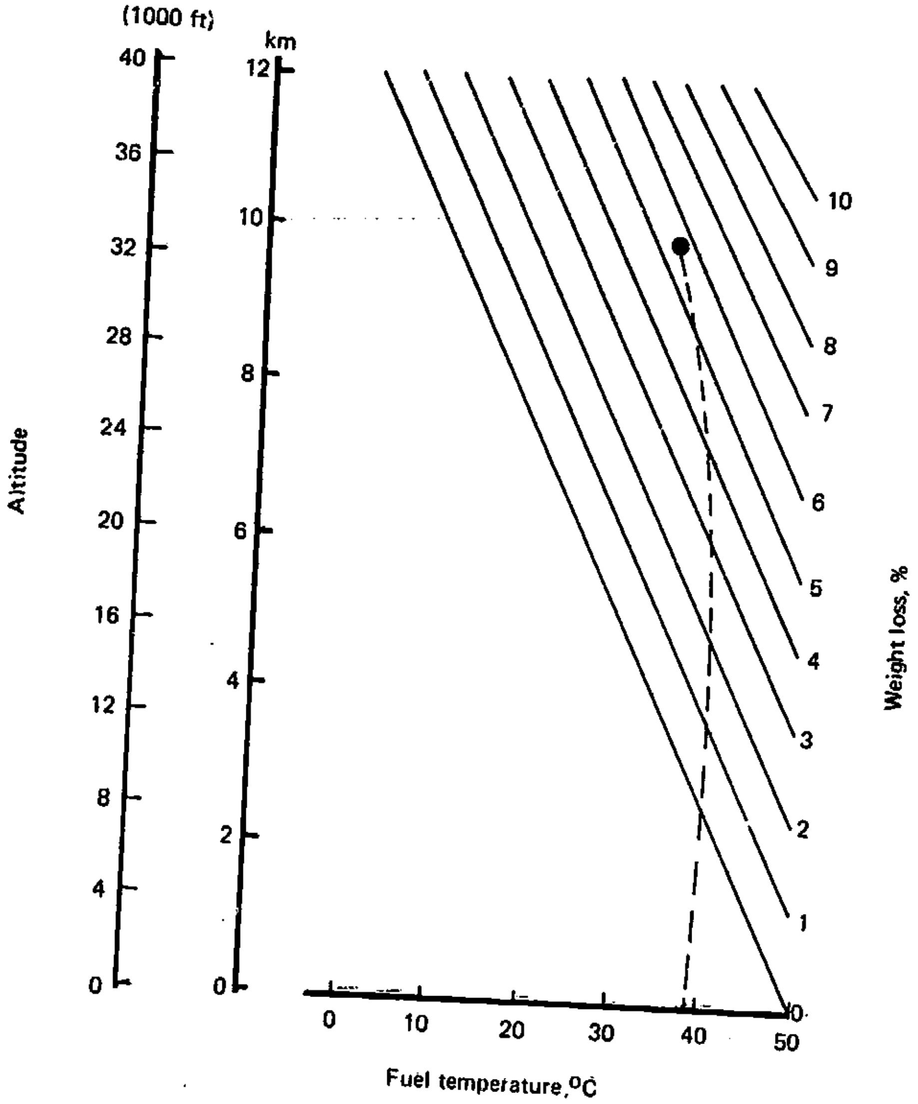

Figure 12.—Boil-Off Losses for 70 KPA (10 psi) RVP-Fuel

5.1.3 LATENT HEAT OF EVAPORATION EFFECTS

The bulk fuel temperature decrease, ΔT, in the aircraft fuel tank due to the latent heat of vaporiation is given by:

$$\Delta T = \frac{LW}{C_p\,(100\text{-}W)} \qquad (3)$$

where W = weight percent of fuel evaporated
L = latent heat of evaporation
C_p = specific heat of the fuel

For the high-vapor-pressure hypothetical fuels, ΔT is 1.8°C/% evaporated, a typical jet fuel value. The effect of latent heat cooling is to reduce the rate of evaporation. Table 3 is a summary of the maximum boil-off losses for the 70kPa RVP fuel for each mission at the hottest conditions, comparing boil-off losses without corrections and boil-off losses with latent heat of evaporation effects.

Table 3.—Boil-Off Losses for 70kPa RVP Fuel at Maximum Temperature Flight Conditions

Mission	Without cooling	With evaporative cooling	Temperature decrease
	W%	W%	ΔT, °C
900km (500 n.mi.) 727-200	5.8	3.3	10.4
3700km (2000 n.mi.) 747-200	5.1	3.0	9.2
5600km (3000 n.mi.) 747-200	5.4	3.2	9.7
9100km (4900 n.mi.) 747-200	3.3	2.0	5.9

Additional calculations for the 35kPa RVP fuel indicate maximum boil-off losses for the short-range mission are 1.2 percent with no cooling assumed, and 0.7 percent with the latent heat correction. There are no boil-off losses for the longer missions with this fuel.

5.1.4 OTHER BOIL-OFF EFFECTS

Several other factors influencing fuel boil-off have been noted. As a mixture of hydrocarbons, the equilibrium vapor composition of the fuel is richer in the lower boiling constituents. Hence, as the fuel is vaporized, it "weathers", changing in composition, such that the boiling point of the remaining liquid increases. This reduces the quantity evaporated after an appreciable percent boil-off.

In addition, "bumping" or foaming of the high-vapor-pressure fuels at altitude can occur. Evidence indicates that this behavior results from the supersaturation of the fuel with either vapor or air, or both. With the high-vapor-pressure fuels, instability when boiling is about to commence may lead to a very violent bump. This type of fuel is prone to foaming and boil-over at high rates of climb. Experimental results indicate that the severity of bumping is dependent on the rate of climb. Rates of climb greater than 1500 m/min (5000 ft/min) were required to produce bumping with sufficient vigor to project liquid fuel into the vent line (Ref. 23). The maximum rate of climb for the study missions of the 727 and 747 aircraft are 800 and 550 m/min (2500 and 1700 ft/min) respectively. Thus, it appears unlikely that bumping or foaming will be sufficient to cause significant fuel loss through the vents.

An inadequate fuel tank system can cause a pressure drop resulting in a higher tank pressure. This will decrease boil-off and cause tank pressurization which can be desirable, if controlled, as discussed in the following section.

5.2 SYSTEM AND FLIGHT MODIFICATIONS FOR USE OF HIGH-VAPOR-PRESSURE FUELS

5.2.1 TANK PRESSURIZATION

Pressurizing the fuel tanks is an obvious approach to allow use of high-vapor-pressure fuels at the extreme temperature conditions. On Table 4, fuel evaporation losses are compared for unpressurized systems and those with a nominal 14kPa gauge (2 psig) pressurization. Maximum pressurization required for no boil-off losses and conversely maximum initial temperature to prevent boil-off losses with no tank pressurization are also shown. For the case of the 727 aircraft mission, pressurization required for zero boil-off exceeds the structural limit of 24kPa gauge (3.5 psig).

Table 4.—Boil-Off Losses for Pressurized Systems
70kPa RVP Fuel

Mission	Weight % fuel loss for maximum temperature conditions		Pressurization required to prevent boil-off kPa, gauge (Psig)	Maximum initial fuel temperature to prevent boil-off °C
	Unpressurized	Pressurized to 14kPa (2 psig)		
900km (500 n.mi.) 727	5.8	3.2	40 (5.6)	7
3700km (2000 n.mi.) 747	5.1	2.5	32 (4.7)	7
5600km (3000 n.mi.) 747	5.4	2.7	33 (4.8)	7
9100km (4900 n.mi.) 747	3.3	1.0	20 (2.9)	7

5.2.2 ALTITUDE CHANGES

Since the amount of fuel boil-off is a function of tank pressure (airplane altitude), changing the flight profile by climbing to a lower initial cruise altitude will reduce fuel boil-off losses. On the other hand, fuel consumption will increase due to the lower cruise altitudes. Some preliminary calculations were made on these effects. A reduction in cruise altitude of 122m (400 ft) will reduce boil-off losses by approximately 1% for the 70 kPa RVP fuel. For long range 747 missions, the increased fuel consumption with this change of initial cruise altitude is small and a net savings of fuel is predicted. For the short range 727, fuel consumption penalty from the change of initial cruise altitude is greater than the savings in fuel boil-off.

5.3 EVALUATION OF HIGH-VAPOR-PRESSURE FUELS

The calculation and evaluation of the performance and economics of the system modifications for use of the high-vapor-pressure fuels were outside the scope of this study. The thermal analyses reported here indicate possible trends in the use of these fuels. It appears at this time that future broadening of jet fuel specification will be in the direction of high-boiling-point (high-freezing-point) fuels rather than towards the high-vapor-pressure fuels. The high-vapor-pressure fuels compete with the large motor gasoline market and introduce safety and flash point problems which were not considered in this study. Furthermore, the use of high-vapor-pressure fuels may require aircraft structural changes for increased pressurization in some missions which may involve substantial and costly modifications.

6.0 ANALYSIS OF EFFECT OF HIGH-FREEZING-POINT FUELS ON AIRCRAFT FUEL SYSTEMS

The use of high-freezing-point fuels is limited by the minimum fuel temperatures, where freezing of the fuel may occur. Freezing of the fuel, which is a mixture of hydrocarbons, is not a definite phase change at a fixed temperature. Nevertheless, freezing of jet fuels is to be avoided because the great increase in viscosity can affect the pumpability of the fuel or the presence of solid crystals of wax can block filters and other flow passages. The subject of fuel freezing and pumpability is reviewed in Reference 2.

6.1 MINIMUM PREDICTED FUEL TEMPERATURE

The predicted in-flight fuel temperatures calculated by the Boeing AFTTA program were used to establish operating limits for the high-freezing-point fuels by establishing minimum fuel temperatures. In practice, an additional in-flight margin of 3°C is required above the fuel freezing point to allow for temperature gradients, gauging inaccuracies, or fuel specification tolerances. For the purposes of this report, minimum temperature for use of the high-freezing-point fuel will be the defined freezing point.

For the short range mission, it was noted (Fig. 6) that the minimum fuel temperatures are largely dependent on the fuel loading or airport ambient temperatures rather than the altitude ambient temperature, because of the relatively short cruise time. For this short range mission, the following minimum in-flight fuel temperatures were calculated for all combinations of airport and altitude ambient temperatures:

Fuel loading temperature °C	Minimum in-flight fuel temperature °C
Minimum (-21.1)	-31
above -14	-29
above +4	-18

Thus the -29°C (-20°F) freezing-point fuel can be used for all short range flights where the fuel loading temperature is -14°C or higher and the -18°C freezing-point fuel can be used for flights where the fuel loading temperature is 4°C or higher.

For the longer range 747 missions, it was noted that the influence of fuel loading temperatures diminishes and becomes negligible for flights longer than 3700km (2000 n.mi.). Thus the minimum fuel temperature cannot be controlled by the fuel loading temperature, and for the extreme case, minimum in-flight fuel temperature is as low as -44°C. This study concentrated on reducing the cooling rate of the fuel tanks with insulation and heating the fuel tank with heat available from the aircraft systems.

6.2 FUEL TANK INSULATION

Prediction of in-flight fuel temperatures were calculated using a reduced heat transfer coefficient of 0.65 W/m-°K (0.375 Btu/Hr-Ft^2-°F/Ft) equivalent to a glass micro-balloon and epoxy insulation. The insulation, including coatings, supports and adhesives, was assumed

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to have an overall density of about 600 Kg/M^3 (specific gravity of 0.60). It was recognized that the practical installation of this insulation inside present production aircraft fuel tanks would be extremely difficult but an external coating might be possible. Examples of the in-flight fuel temperatures for insulated fuel tanks are presented in Figures 13 to 15. Figure 13 is a one-day-per-year extreme altitude ambient temperature condition with a -21°C fuel loading temperature for the 747-200, 3700km (2000 n.mi.) mission. The zero curve represents the baseline, no insulation case which was presented on Figure 8 and is included as a reference. The other curves show the effects of various thickness of insulation for the same flight conditions. A 2.5 cm (1 inch) thick insulation raises the minimum fuel temperature from -39°C to -32°C. Figures 14 and 15 present the corresponding insulated tank data for the 5600km (3000 n.mi.) and 9100km (4900 n.mi.) 747-200 missions respectively. For all three long range missions, a 2.5m insulation thickness which is considered a practical maximum, minimum fuel temperatures remain colder than -29°C. Thus insulating the fuel tank is not sufficient to prevent use of the high-freezing point-fuels in all cases.

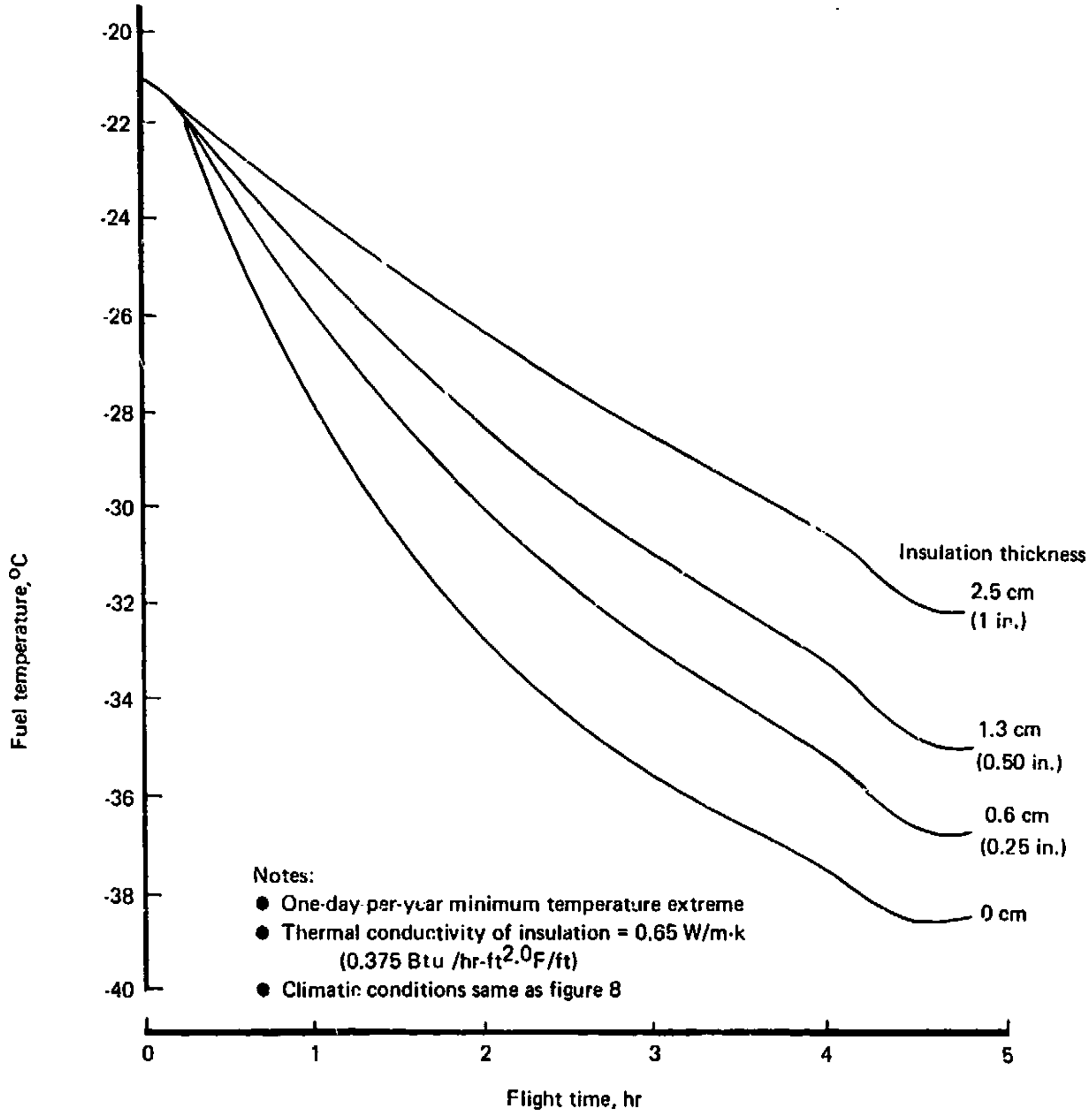
6.3 FUEL TANK HEATING

In-flight fuel temperatures were also calculated with constant heat input into the fuel tanks, representing sources of aircraft system heating. Representative results are plotted on Figures 16 to 18. Figure 16 is the predicted in-flight fuel temperature for the 3700km (2000 n.mi.), 747-200 mission at the one-day-per-year extreme, altitude ambient temperature conditions. Again the zero curve represents the baseline no-heat input condition previously presented on Figure 8 and included as a reference. The additional curves are the resulting fuel temperatures for the given heat inputs per tank. Figures 17 and 18 show the corresponding predicted in-flight fuel temperatures for the 5600km (3000 n.mi.) and 9100km (4900 n.mi.), 747-200 missions respectively.

Heat input increases fuel temperature during flight and raises the minimum fuel temperature. Thus rates of heat input can be selected to provide the desired minimum fuel temperature. The determination of heating rate for the use of high-freezing-point fuel is illustrated on Figure 19. This is a plot for the various amount of heating for the 9100km (4900 n.mi.) mission at the one-day-per-year extreme altitude ambient temperature condition. It indicates that to maintain the fuel above -29°C, 3700 kJ/min/tank (3500 Btu/min/tank) is required. To maintain the fuel above -18°C, 6500 kJ/min/tank (6200 Btu/min/tank) of heating is required. It should be noted that for this condition a fuel loading temperature of -21°C was assumed. The fuel loading temperature is colder than the freezing point of -18°C and means for ground heating must be provided. Ground heating requirements will be discussed later in this report.

6.4 COMBINED HEATING AND INSULATION

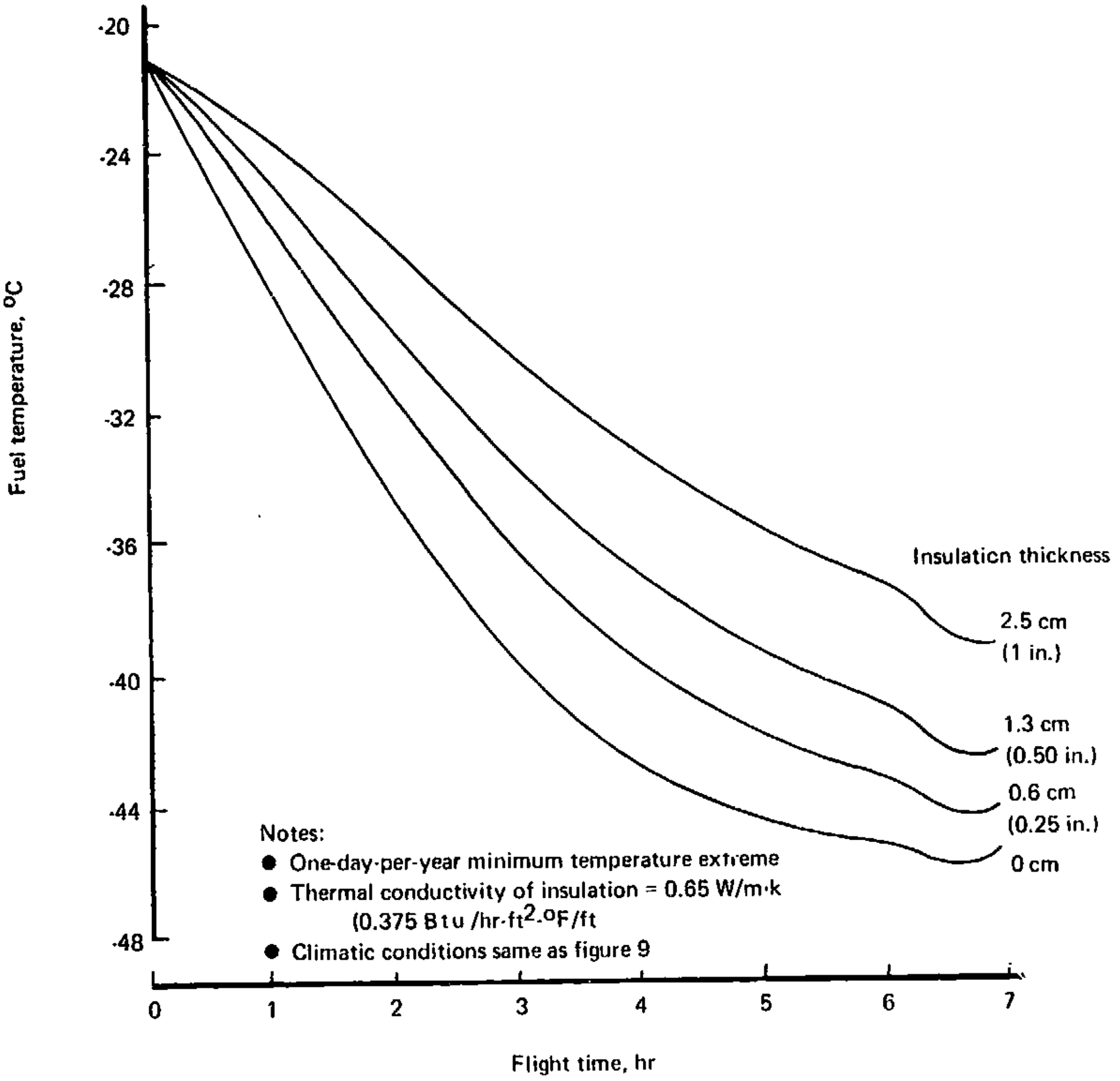
Although the calculations indicated that insulation alone was not sufficient for use of high-freezing-point fuels, insulation may be used to reduce the heat input required. Figure 20 shows the predicted in-flight fuel temperature for the 9100km (4900 n.mi.), 747-200 mission with 0.6cm (1/4 inch) thickness of insulation with various rates of heat inputs. Figure 21 shows the corresponding data for a 2.5cm (1 inch) thick insulation. The zero curve represents the baseline condition of no-insulation and no-heat input previously presented on Figure 10 and is included as a reference. Figure 22 is a cross-plot based on the previous figures which illustrates the combination of heating and insulation required to maintain a minimum fuel temperature for the 9100km (4900 n.mi.) mission. Lines are shown across the figure corresponding to the freezing-point of the two hypothetical fuels at -29°C and -18°C. For use of the highest freezing point fuel, it can be seen that the heating requirement of 6500 kJ/min/tank for non-insulated tanks is reduced to 4100 kJ/min/tank with 2.5cm of insulation.



Notes:

- One-day-per-year minimum temperature extreme
- Thermal conductivity of insulation = 0.65 W/m·k (0.375 Btu /hr-ft^{2}·°F/ft)
- Climatic conditions same as figure 8

Figure 13.–Predicted Fuel Temperatures With Insulation for 3700 km (2000 nmi) 747-200 Mission



Notes:

- One-day-per-year minimum temperature extreme
- Thermal conductivity of insulation = 0.65 W/m·k (0.375 Btu/hr-ft^2-°F/ft
- Climatic conditions same as figure 9

Figure 14.--Predicted Fuel Temperatures With Insulation for 5600 km (3000 nmi) 747-200 Mission

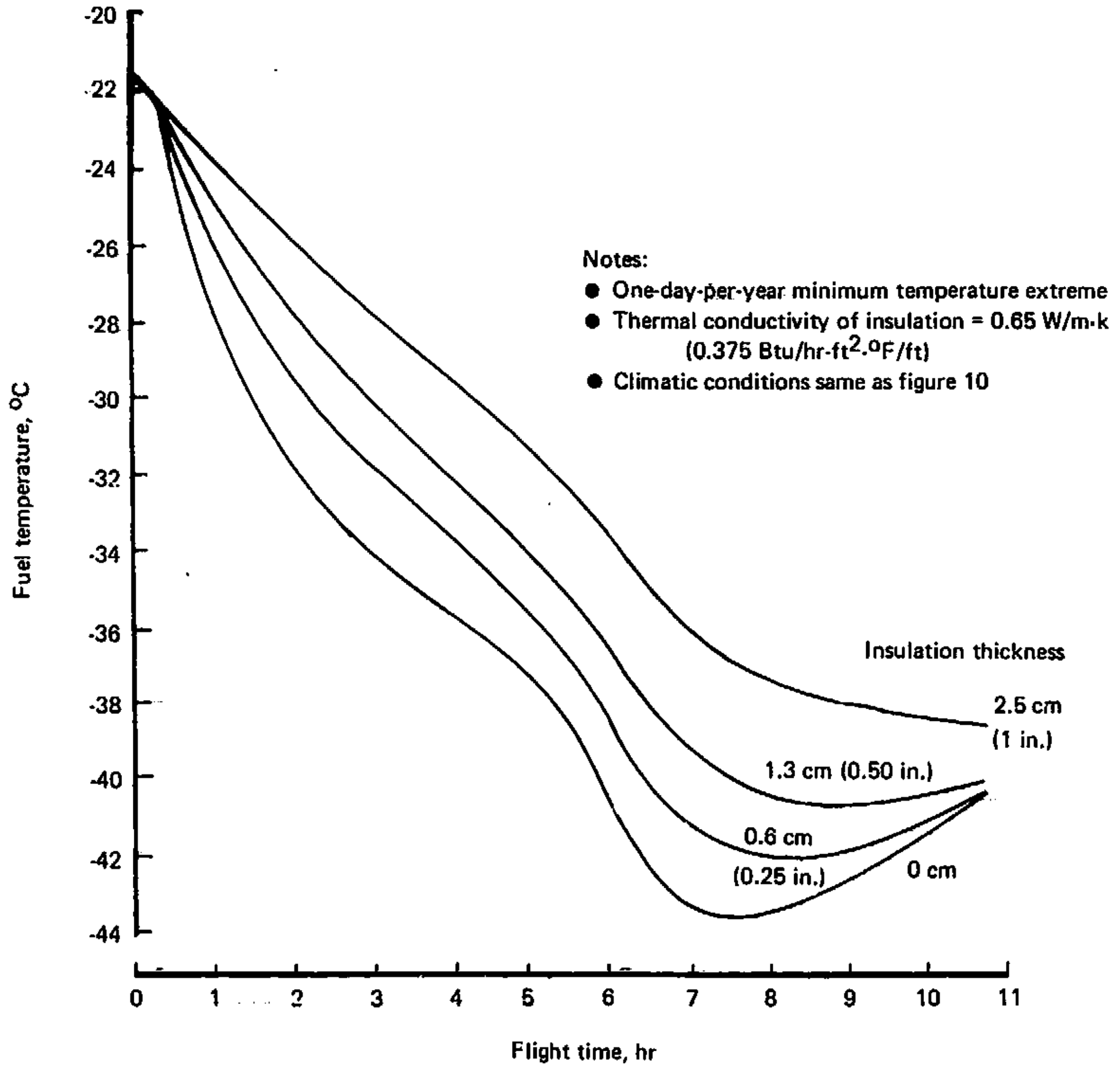


Figure 15.–Predicted Fuel Temperatures With Insulation for 9100 km (4900 nmi) 747-200 Mission

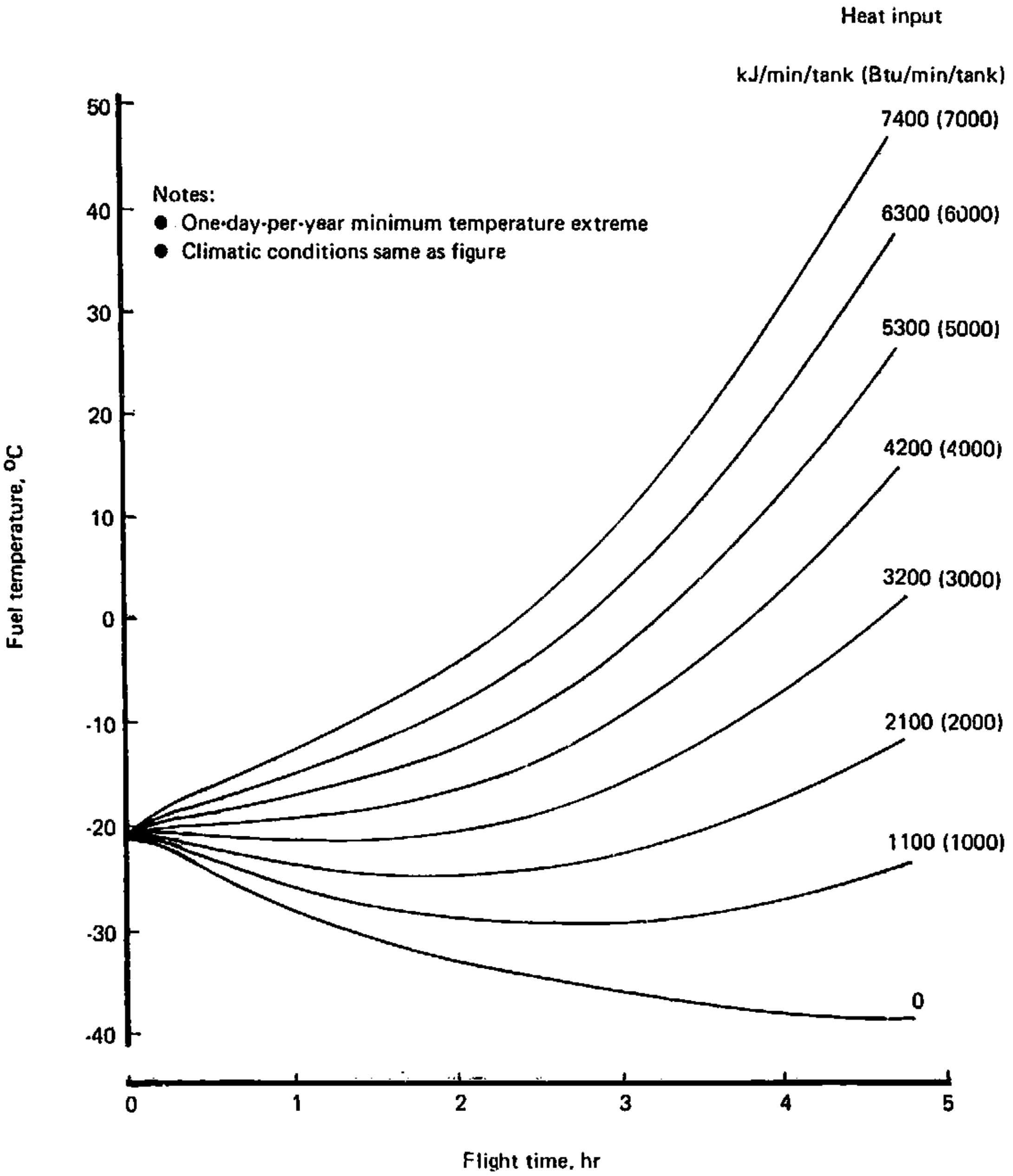
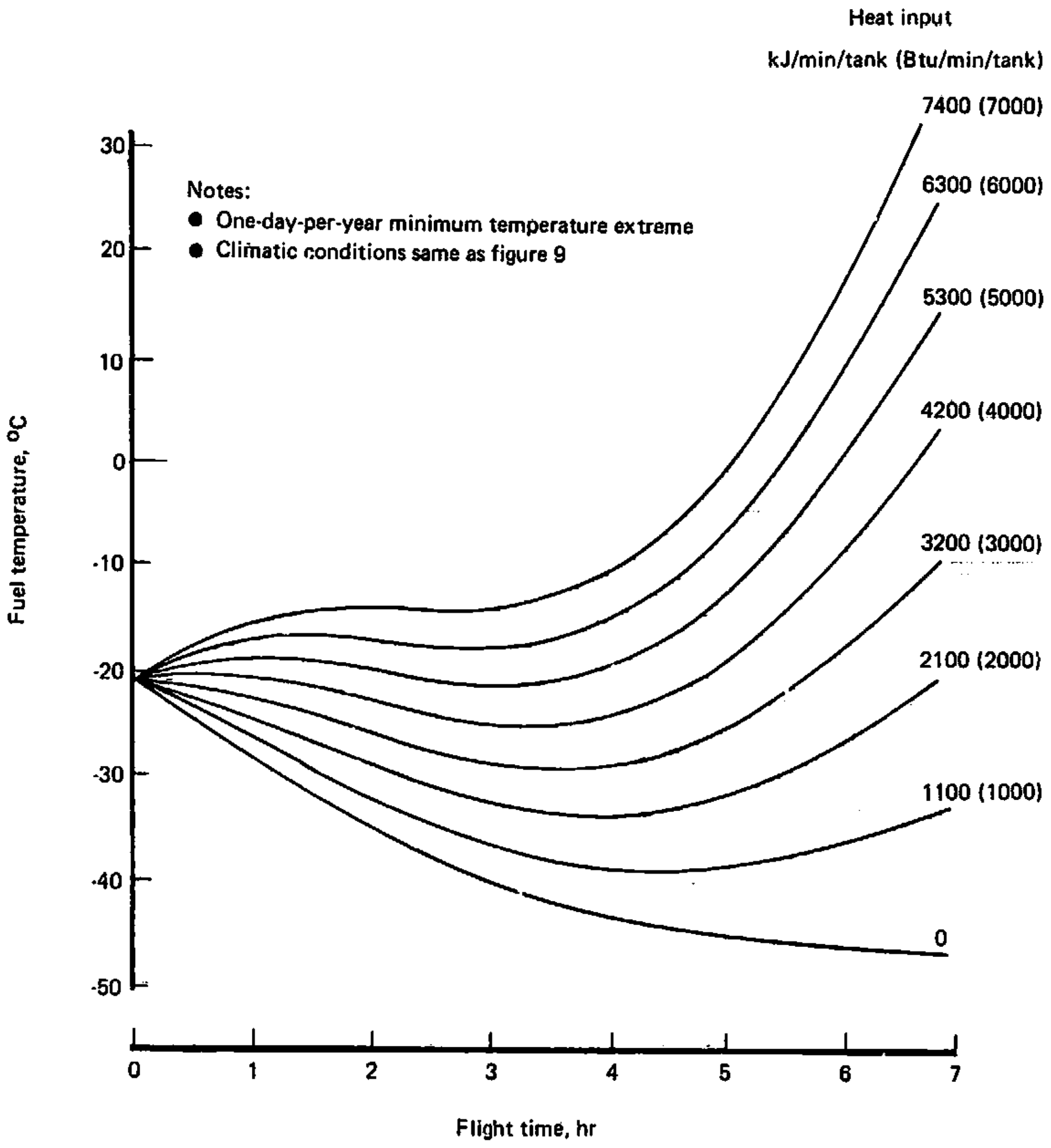


Figure 16.–Predicted Fuel Temperatures With Constant Heat Inputs for 3700 km (2000 nmi) 747-200 Mission



Notes:
- One-day-per-year minimum temperature extreme
- Climatic conditions same as figure 9

Figure 17.–Predicted Fuel Temperatures With Constant Heat Inputs for 5600 km (3000 nmi) 747-200 Mission

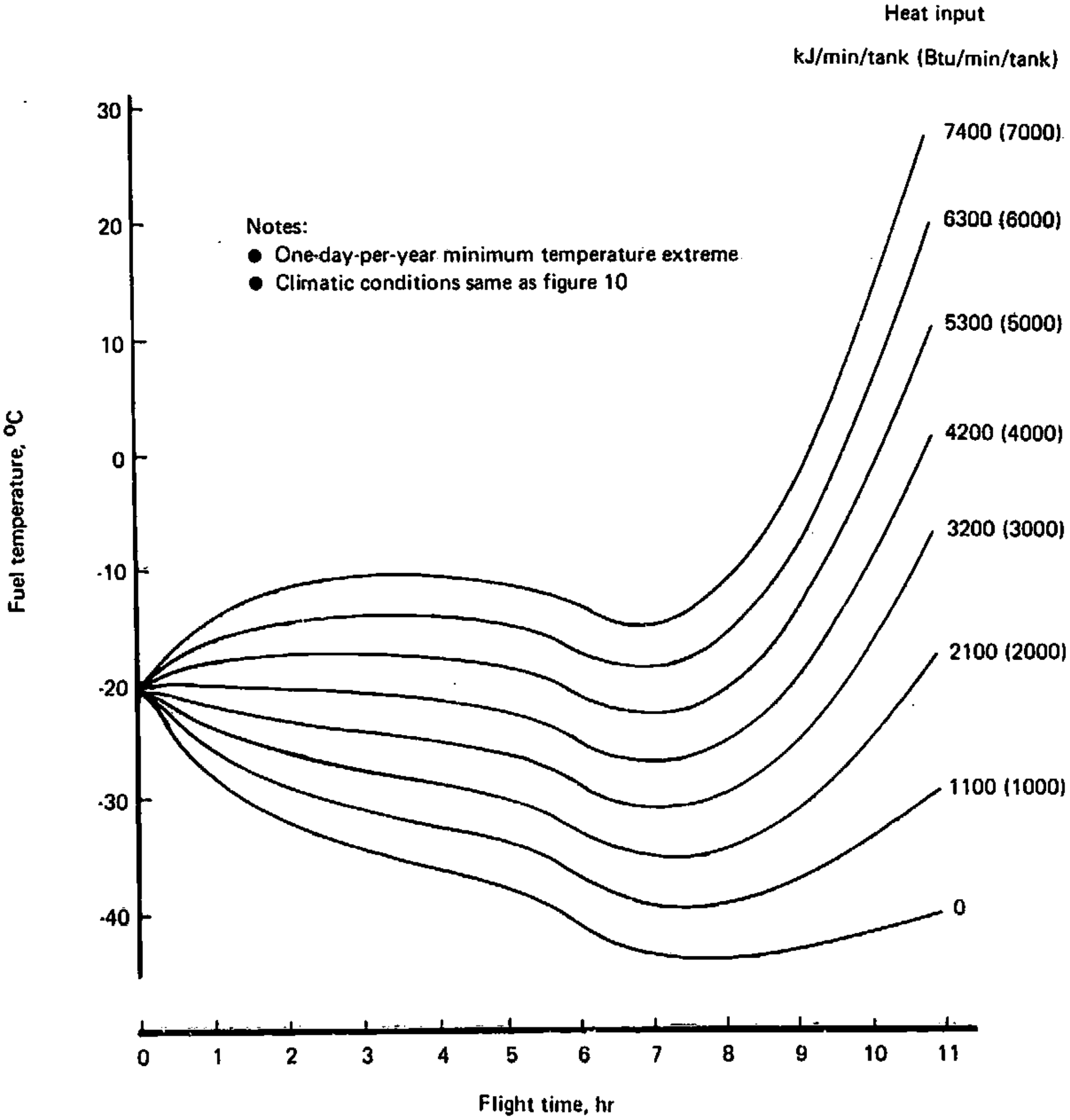


Figure 18.–Predicted Fuel Temperatures With Constant Heat Inputs for 9100 km (4900 nmi) 747-200 Mission

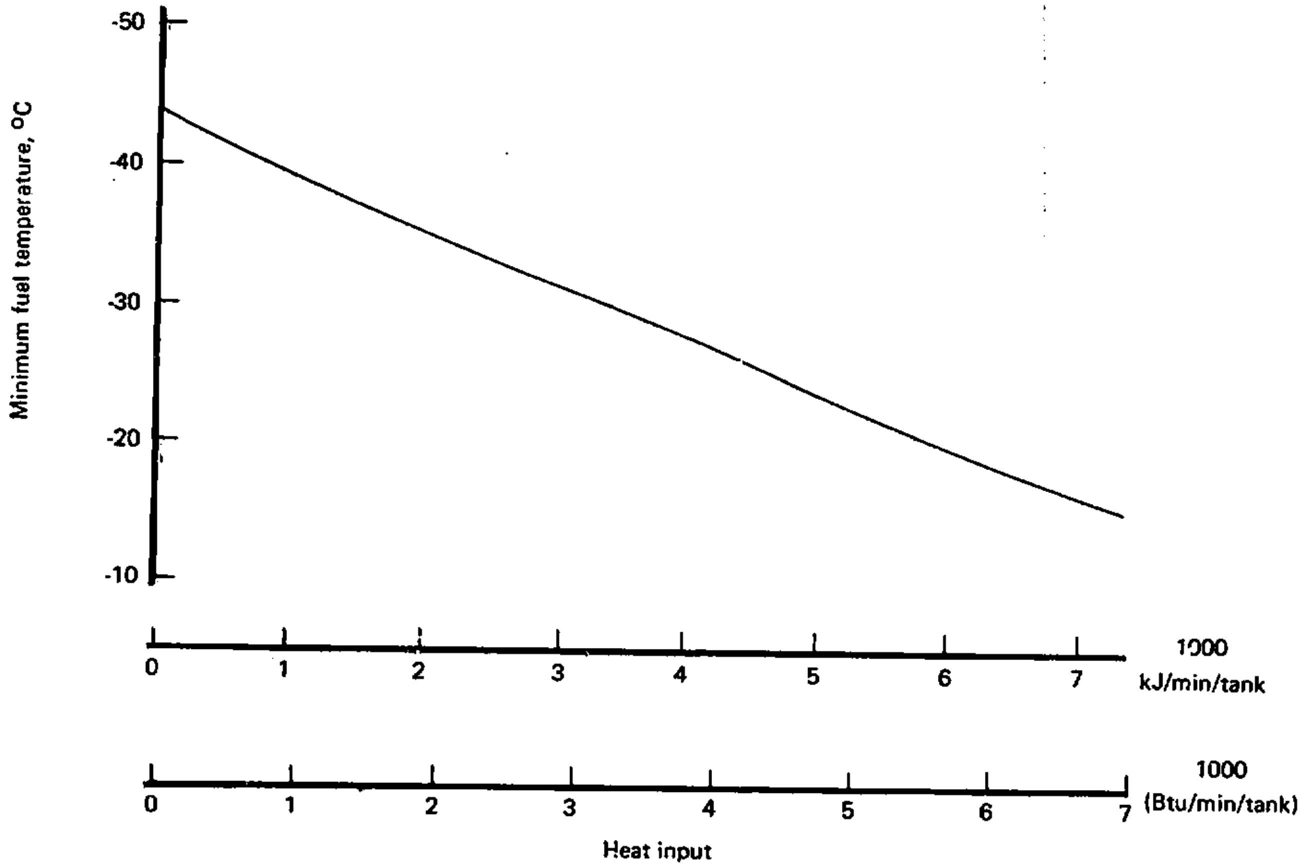


Figure 19–Heating Rates Necessary To Provide the Desired Minimum Fuel Temperature for the 9100 km (4900 nmi) 747-200 Mission

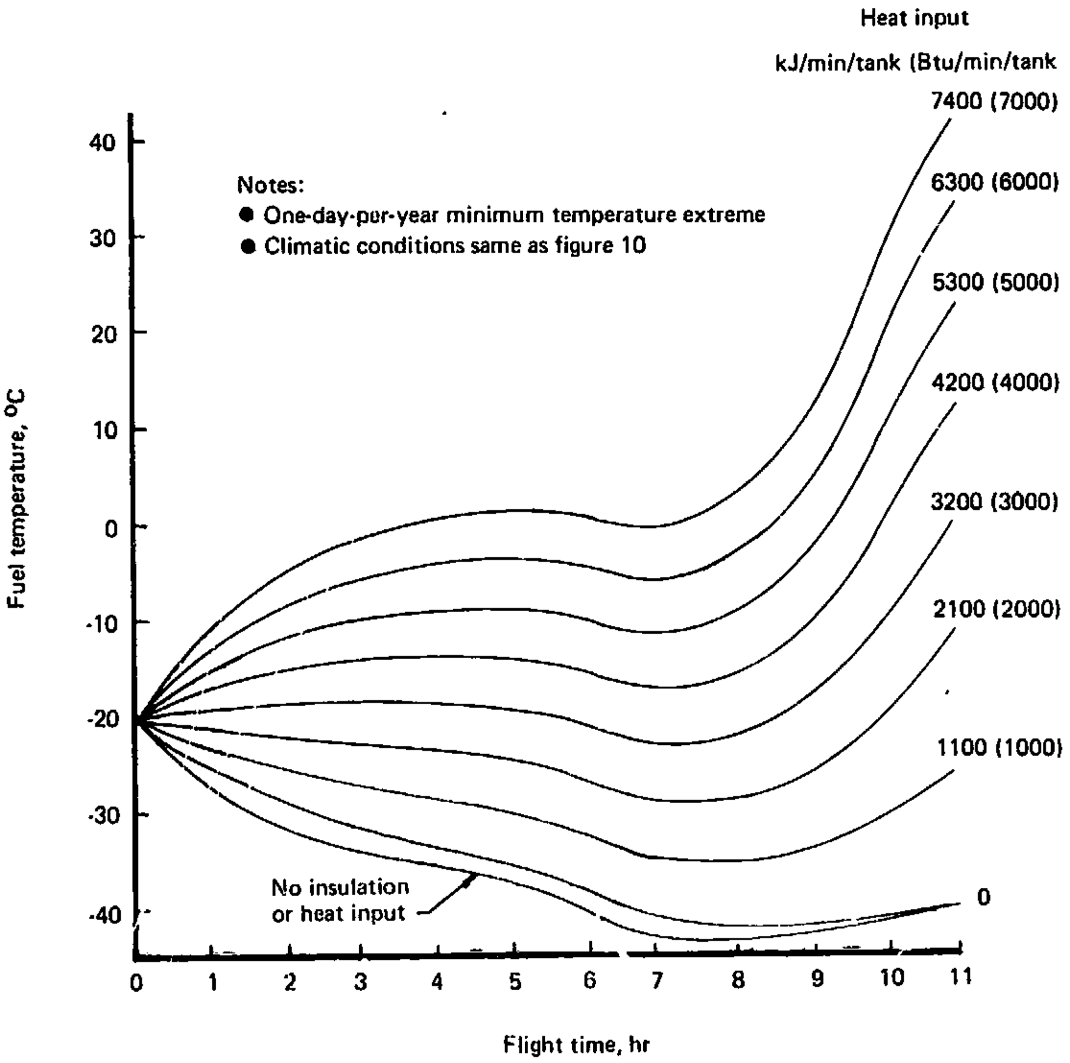


Figure 20.— Predicted Fuel Temperatures for Insulated Tanks With Constant Heat Input for 9100 km (4900 n mi) 747-200 Mission -0.6 cm Insulation Thickness

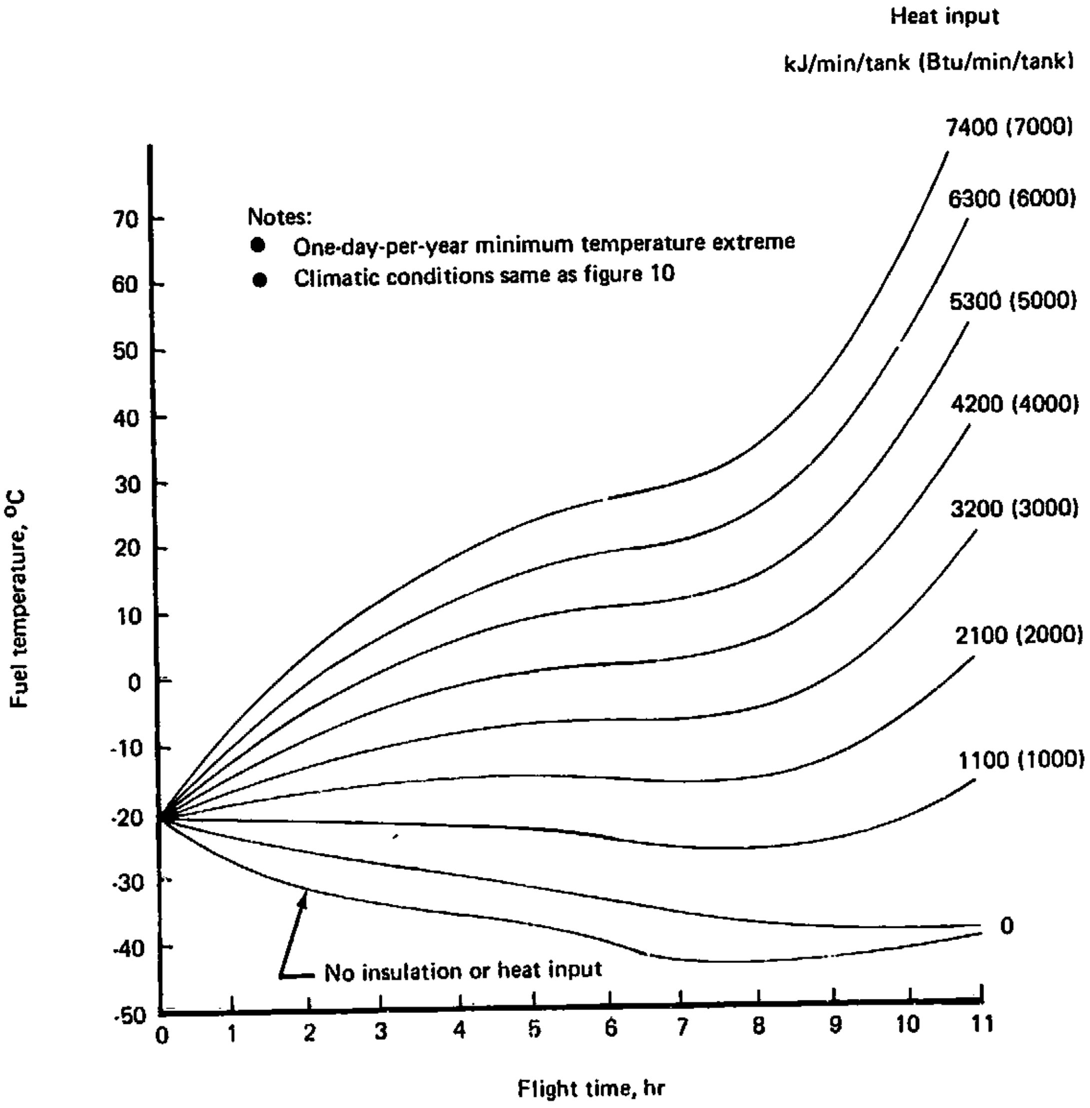
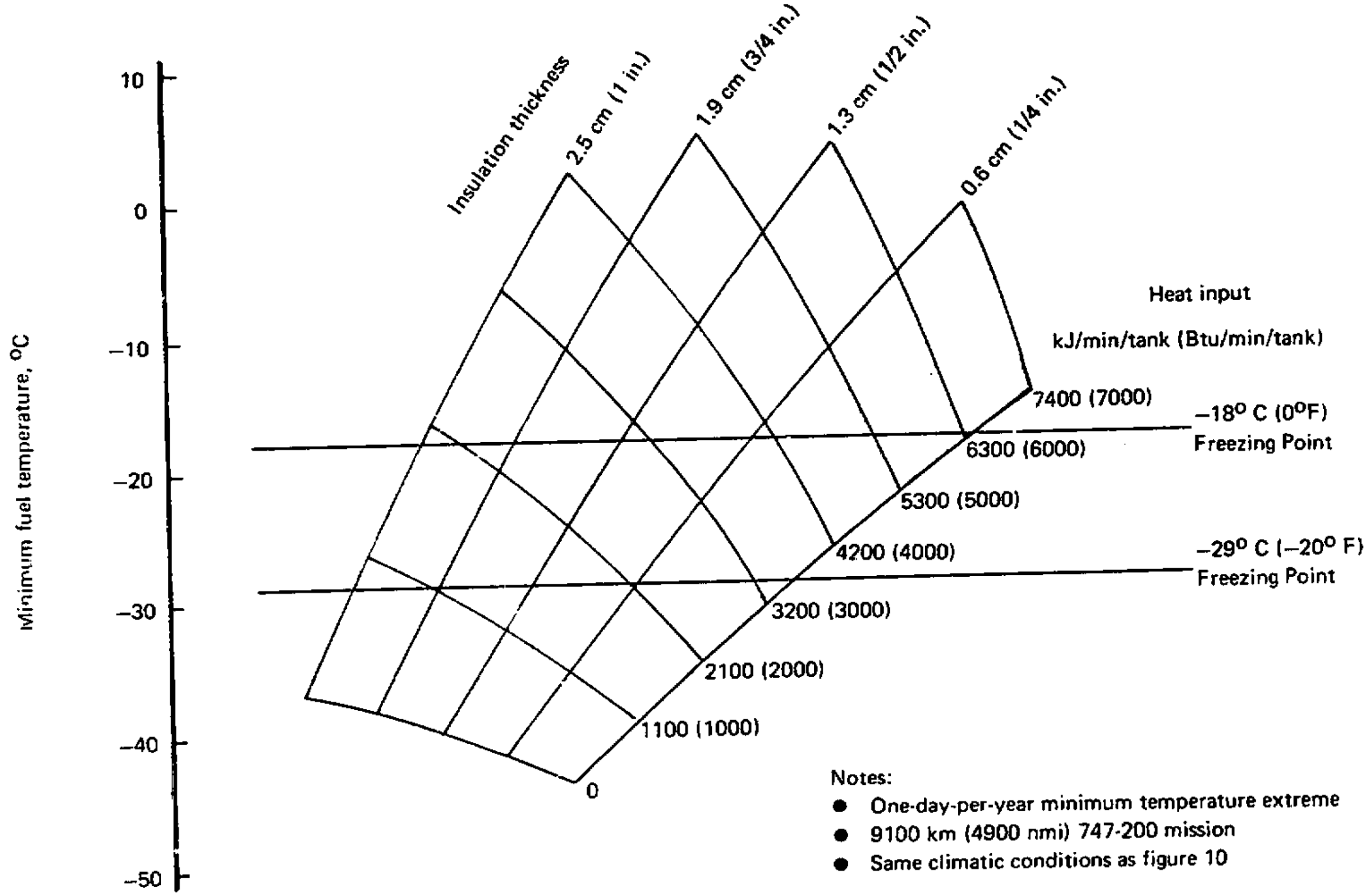


Figure 21.— Predicted Fuel Temperatures for Insulated Tanks With Constant Heat Input for 9100 km (4900 n mi) 747-200 Mission -2.5 cm Insulation Thickness



Notes:
- One-day-per-year minimum temperature extreme
- 9100 km (4900 nmi) 747-200 mission
- Same climatic conditions as figure 10

Figure 22.— Insulation and Heat Input Combination for Maintaining Minimum Fuel Temperatures

7.0 MINOR MODIFICATIONS OF EXISTING AIRCRAFT SYSTEMS FOR USE OF HIGH-FREEZING-POINT FUELS

7.1 INTRODUCTION AND DESCRIPTION

The results of predicted fuel tank temperatures, examples of which are shown on Figures 6 through 10, indicate that minimum in-flight fuel temperatures may be as low as -44°C. Fuel temperatures lower than -29°C are predicted for a portion of long range flights in winter. Fuel temperatures lower than -18°C are predicted for a greater portion of short and long range flights. Thus the freezing point of the two high-freezing-point fuels will be reached unless fuel, procedural, or aircraft system modifications are initiated.

Several possible approaches to allow the use of high-freezing-point fuels are feasible but were considered outside the scope of this study. These include additives, or other alteration of standard hydrocarbon fuel properties, aircraft flight altitude and procedural changes (see discussion in Ref. 10) and minor effects such as fuel agitation (Ref. 8). Intertank transfer between the warmer inboard and colder outboard tanks was considered and the results showed only a small fuel temperature difference between the tanks, 5°C maximum. This fuel temperature difference diminishes toward the end of the flight. This technique is not covered in this report. Insulation has been included in the thermal analyses but evaluation of insulated tanks or systems will be shown to involve extreme weight penalties as a modification to present aircraft, and no details of insulation systems are included.

This study therefore concentrated on minor and major modifications to the aircraft fuel systems to permit the use of high-freezing-point fuels. Minor modifications are defined as the use of existing heat rejection sources by system changes readily incorporated in production aircraft. These heat inputs were assumed to be provided to the fuel throughout the length of the flight. Each heat source system was considered individually for simplicity. Combined heat sources would add operating complexity and possible safety hazards.

7.2 DESCRIPTION OF MINOR MODIFICATIONS

This section of the report describes the heat sources investigated for the minor modifications. These modifications are based on the 747-200 aircraft with the JT9D engines because the previous calculations have indicated fuel freezing problems are most likely to be encountered on long range 747-200 missions. However, similar systems and modifications can be proposed for the 727 aircraft.

7.2.1 AIRCONDITIONING SYSTEM BLEED AIR

During flight each engine provides bleed air for the air conditioning system. Prior to the air entering the air conditioning system, it is precooled to 177°C (350°F) via a fan air precooler. During cruise when the bleed air and air conditioning system are operating at essentially a constant rate, the amount of heat rejected through the precooler is approximately 2210 kJ/min/engine (2100 Btu/min/engine) which would be the amount potentially available to each tank.

By modifying the air conditioning system more heat may be made available by decreasing the temperature of bleed air entering the air conditioning system from 177°C (350°F) to 93°C (200°F). This would increase the amount of heat potentially available to 5540 kJ/min/tank (5250 Btu/min/tank). Figure 23 is a schematic drawing of the air conditioning system bleed air used for fuel heating.

7.2.2 ELECTRICAL GENERATOR AND CSD COOLER

Each engine has an electrical generator driven through a Constant Speed Drive (CSD) and gear box. The generator is cooled by the engine fan air and the CSD is oil cooled. The CSD oil cooler is also cooled by engine fan air. The amount of heat rejected to the engine fan air during cruise with normal electrical loads is 1780 kJ/min/aircraft (1680 Btu/min/aircraft). If the fan air coolers were replaced by a fuel heat exchanger, the amount of heat potentially available to each tank is 440 kJ/min/tank (420 Btu/min/tank). Figure 24 is a schematic drawing of electrical generator and CSD cooler modifications used for fuel heating.

7.2.3 FUEL RECIRCULATION

Figure 25 is a schematic drawing of the engine fuel recirculation modification used for fuel heating. Fuel is supplied from the fuel tanks through the necessary aircraft fuel system to the engine pump. From here it is pumped to the fuel control unit where it is metered to the quantities required by the engine. The JT9D engines use fuel pumps which consist of a centrifugal boost stage and two gear stages. The main gear stage provides fuel to the fuel control with a maximum flow capacity of 210 kg/min (470 lb/min) and a maximum pressure rise of 7600kPa (1100 psia).

The fuel control meters the required fuel for the engine and excess fuel is returned downstream of the boost stage.

The proposed engine recirculation system would utilize the excess fuel returned from the fuel control. The fuel will be recirculated back to the aircraft fuel tank utilizing the heat gained by the fuel as it travels through the engine pumps and the fuel control.

For the JT9D engine at cruise power, the recirculation rate of fuel flow per engine is approximately 90 kg/min (200 lb/min); the estimated heat gained from the recirculation flow is 2200 kJ/min/engine (2050 Btu/min/engine).

7.2.4 ENGINE OIL-FUEL COOLER

The engine oil cooling system on the JT9D-7 engine is designed to maintain the engine oil temperature below 120°C (250°F) for continuous operation. The oil is cooled by a heat exchanger with fuel used as the cooling medium. The oil/fuel cooler is a full-flow type with a pressure bypass feature to ensure continued oil flow to the bearings in the event excessive pressure drop occurs across the cooler. A thermal bypass valve is also included for conditions where the heat rejection rate is high enough to depress the engine oil below 77°C (170°F).

A schematic of the engine oil system is shown on Figure 26. Oil from the engine oil tank is supplied to the inlet of the main gearbox, directed through the main filters, through the

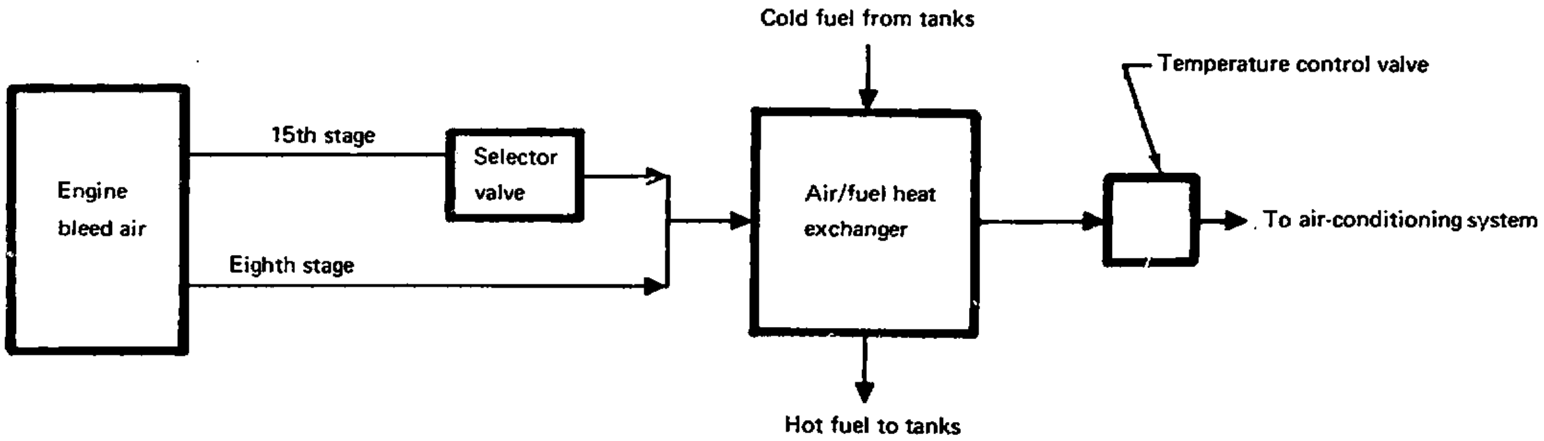


Figure 23.— Modified Air-Conditioning Bleed Air With Fuel Heat Exchanger

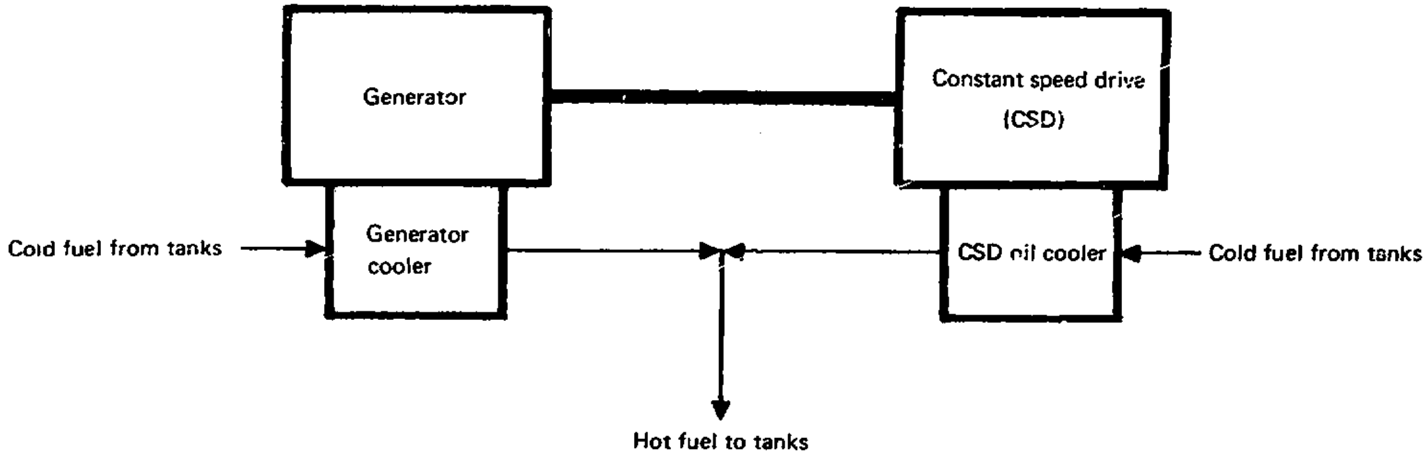


Figure 24.— Electrical Generator and Constant Speed Drive (CSD) Cooler Modification

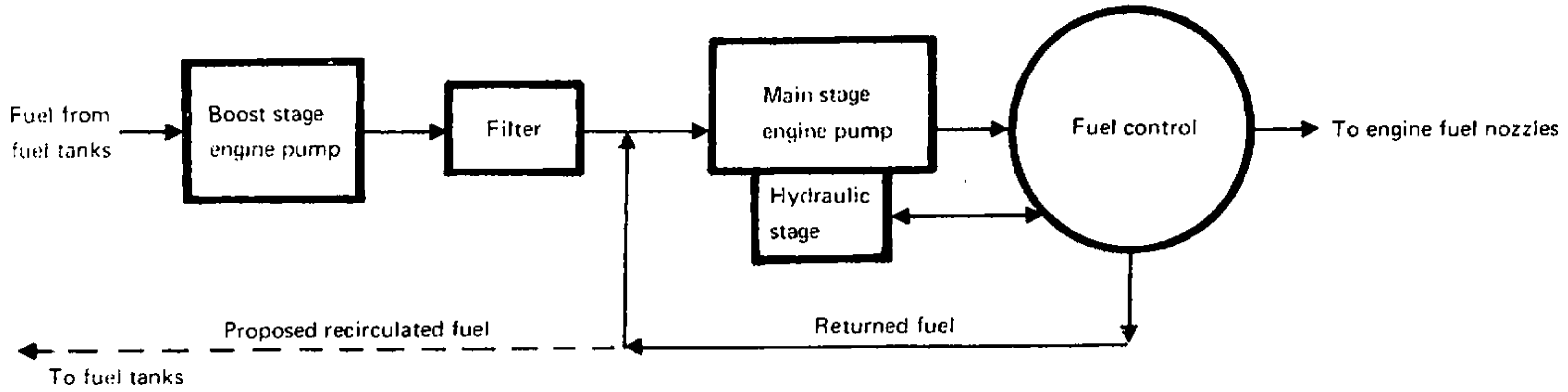


Figure 25.— Engine Fuel Recirculation Modification Schmatic

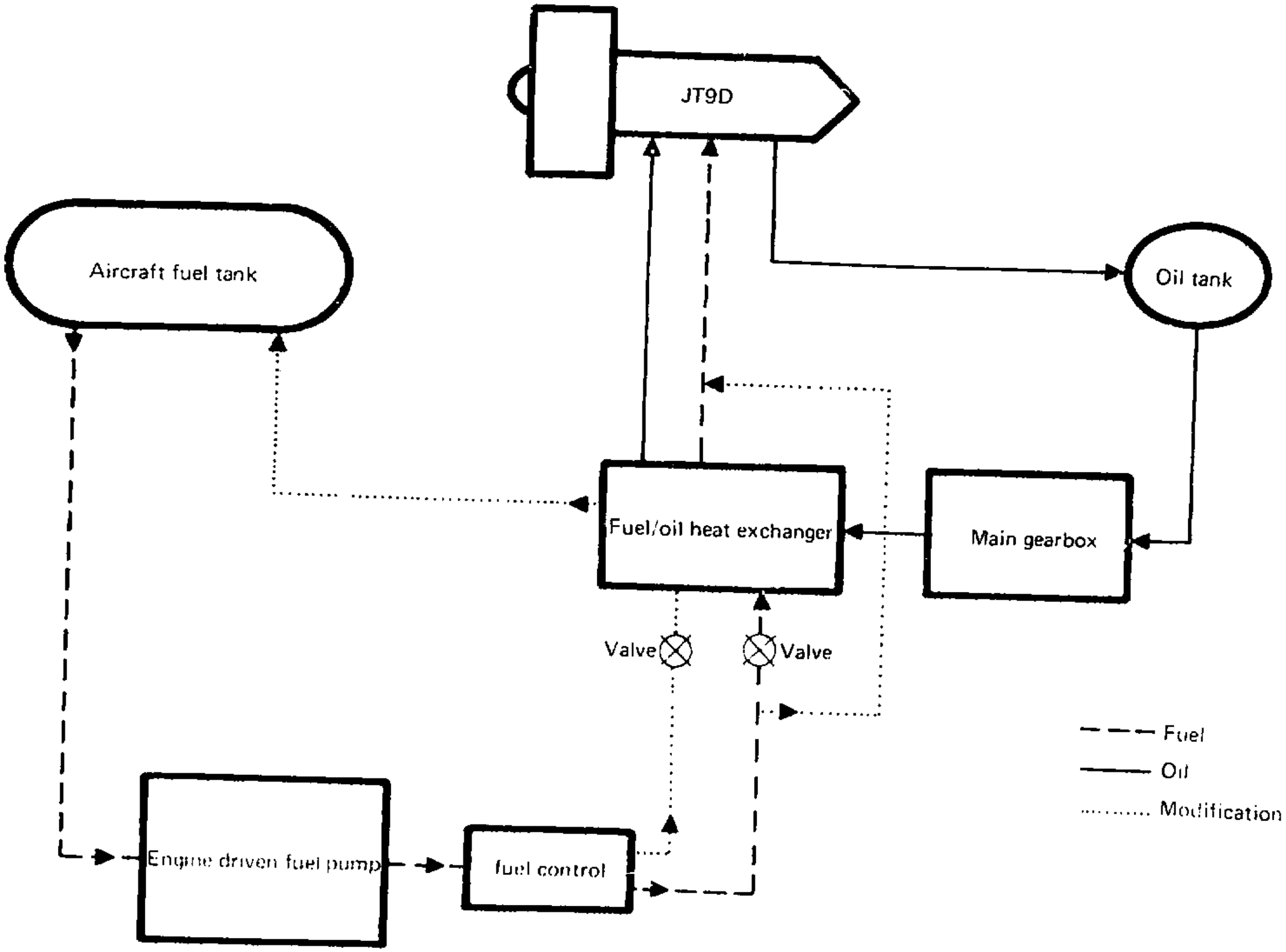


Figure 26. – JT9D Engine Oil and Fuel System Modification

oil/fuel cooler and to the engine bearings. The oil is then returned through the oil/fuel cooler and to the engine bearings. The oil is then returned through the scavenge system to the oil tank. The fuel side of the cooler receives metered fuel from the fuel control, which after absorbing heat transferred to it from the engine oil, continues to the fuel nozzles.

During cruise the heat rejected to the oil and therefore potentially available to the fuel varies from 3600 kJ/min/engine (3400 Btu/min/engine) a 4500 kJ/min/engine (4300 Btu/min/engine) depending on engine thrust. A modification to the oil/fuel cooler would provide heated fuel to the fuel tanks instead of to the fuel-nozzles.

7.2.5 GROUND HANDLING FUEL HEATING

Although heating of the fuel for ground handling systems is not an aircraft system modification, ground handling heating may be necessary for the use of the high-freezing-point fuels.

Ground heating may furnish all the heating required for the use of high-freezing-point fuels for short range flights. For long range flights, even where in-flight heating systems are incorporated on the aircraft, ground heating of the fuel may be required at severe conditions. The matrix of climatic conditions used in this study includes fuel loading temperatures below the freezing point of the -18°C hypothetical fuel.

Existing fuel handling systems at Chicago's O'Hare, Minneapolis, Seattle and Anchorage Airports were evaluated with respect to potential problems with use of high-freezing-point fuels. Climatological design conditions were investigated particularly for O'Hare and Minneapolis based on an amalgamation of data from several sources and patterned after the profile given in Reference 24.

No system modifications would be required for the use of the -29°C freezing-point fuel. For the -18°C freezing point fuel, it was concluded that transfer pumps and exposed fuel piping and small satellite tanks would be sheltered and hydrant carts and refueling tankers would have canopy or cable heaters. Estimated cost penalties are discussed in the economics penalty section of this report. No calculations were made on the additional preheating of fuel for short range flights at severe temperatures but the procedures and heating required should be similar to those required to protect the fuels from freezing prior to long range flights.

7.3 EVALUATION OF HEAT AVAILABLE FROM MINOR MODIFICATIONS

Table 5 summarizes the heat available from minor modifications of existing aircraft systems as discussed in this section. As shown on Figure 19, 3600 kJ/min/tank is the minimum heating rate required for use of the -29°C freezing point fuel at the most severe conditions; 6500 kJ/min is the minimum required for the -18°C freezing point fuel. Only two systems, the modified air conditioning system and the engine oil-fuel cooler are capable of individually supplying enough heat for use with the -29°C freezing point fuel. Of course, combinations of systems, use of insulation, plus the heating systems and selected seasonal use would make all these modifications promising. However, for purposes of comparison, combined use of modifications was not evaluated.

A number of other existing aircraft heat sources could be suggested, but each would supply less than 400 kJ/min/tank of the smallest heat available shown on Table 5. The minor modifications have the advantage that they use heat already rejected to the fan air, fuel or other sources and thus the performance penalties would be minimal if not negligible. Since these system modifications are small, weight and cost increases should be correspondingly small.

Table 5.—Available Heat from Minor Modifications

Source	Heat available per tank	
	kJ/min	BTU/min
Air conditioning system bleed air	2200	2100
Modified air conditioning system	5500	5200
Electrical generator and CSD cooler	440	420
Fuel recirculation	2200	2000
Engine oil-fuel cooler	4500	4300

8.0 MAJOR MODIFICATIONS OF EXISTING AIRCRAFT SYSTEMS FOR USE OF HIGH-FREEZING-POINT FUELS

8.1 DESIGN CRITERIA

Major modifications are system changes to supply heating for use of high-freezing-point fuels which require more extensive redesign than the minor modification. The criteria used for design of the proposed major modification heat sources are: (1) modification will provide adequate heat for the −18°C (0°F) freezing point fuel, that is, 6500 kJ/min/tank (6200 Btu/min/tank), (2) modification will be a single heat source system rather than a combination of different heat sources and (3) system will not affect current aircraft procedures.

8.2 DESCRIPTION OF MAJOR MODIFICATIONS

8.2.1 CATALYTIC REACTOR HEATING

Heating the fuel by combustion energy is possible by using a gas generator system with a catalytic reactor as a heat source. Ambient air is compressed and passes through the catalytic combustor, the exhaust drives the first turbine which drives the compressor. Air is bled from the compressor which is used to cool the catalytic reactor. After cooling the reactor the air drives the second turbine and then heats the fuel in a heat exchanger. A schematic of the proposed system is shown in Figure 27. Approximately two thirds of the airflow passes through the fuel heat exchanger and the remainder exhausts from the hot turbine. The catalytic combustor has the advantage of very lean, relatively cool combustion. It is still an experimental concept although recent studies have shown good performance (Ref. 25).

8.2.2 ENGINE AIRBLEED

Hot air bled from the engine compressors can be used to heat fuel during flight through a heat exchanger. At cruise power, the engine airbleed air temperature is nominally 200°C (400°F). Eighth (low pressure) and 15th (high-pressure) stage bleed air is mixed to maintain the required temperature and airflow. The amount of air mixed is a function of engine power and required airflow. A schematic of the system is shown on Figure 28. Fuel is pumped from the tanks to the heat exchanger located in the engine strut and recirculated back to the outboard portion of the tanks. The amount of heat transferred to the fuel will depend on the amount of bleed air that can be extracted from the engine. It should be noted that as the amount of bleed air used is increased the engine fuel consumption must also be increased to maintain the same engine thrust.

8.2.3 ELECTRICAL HEATING

The fuel can be heated in flight by an electrical heater, driven by the engine. Currently some Boeing 747 airplanes are equipped with engines with dual drive pads to accommodate two generators per engine. Each generator delivers 142.5 KVA. This study assumes dual drive pads on each engine in which four of the eight generators would be used for fuel heating. The total amount of energy available from each generator is approximately 8400 kJ/min (7960 Btu/min) which is more than adequate for the −18°C freezing point fuel.

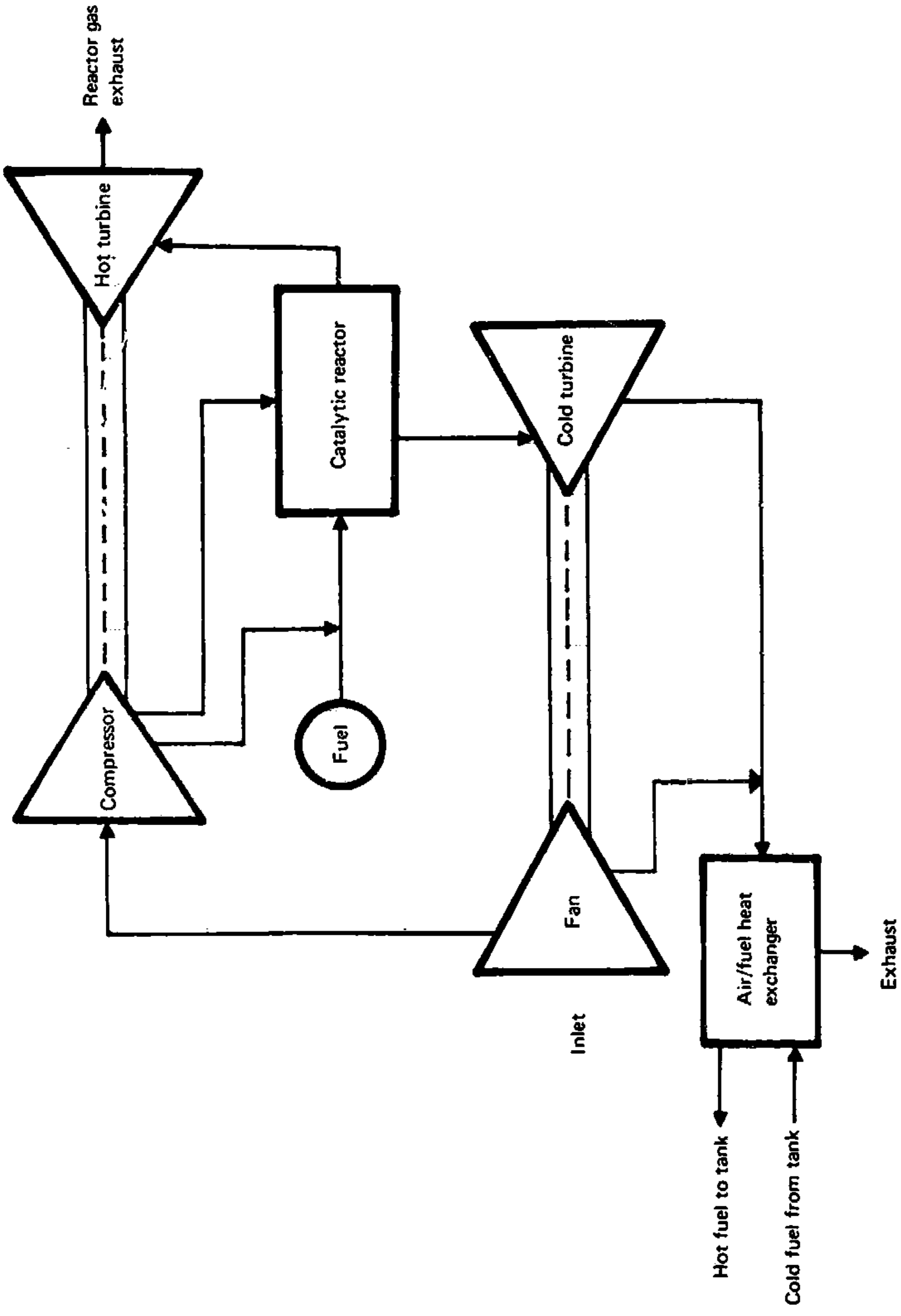


Figure 27.— Schematic of the Catalytic Reactor Heating Modification

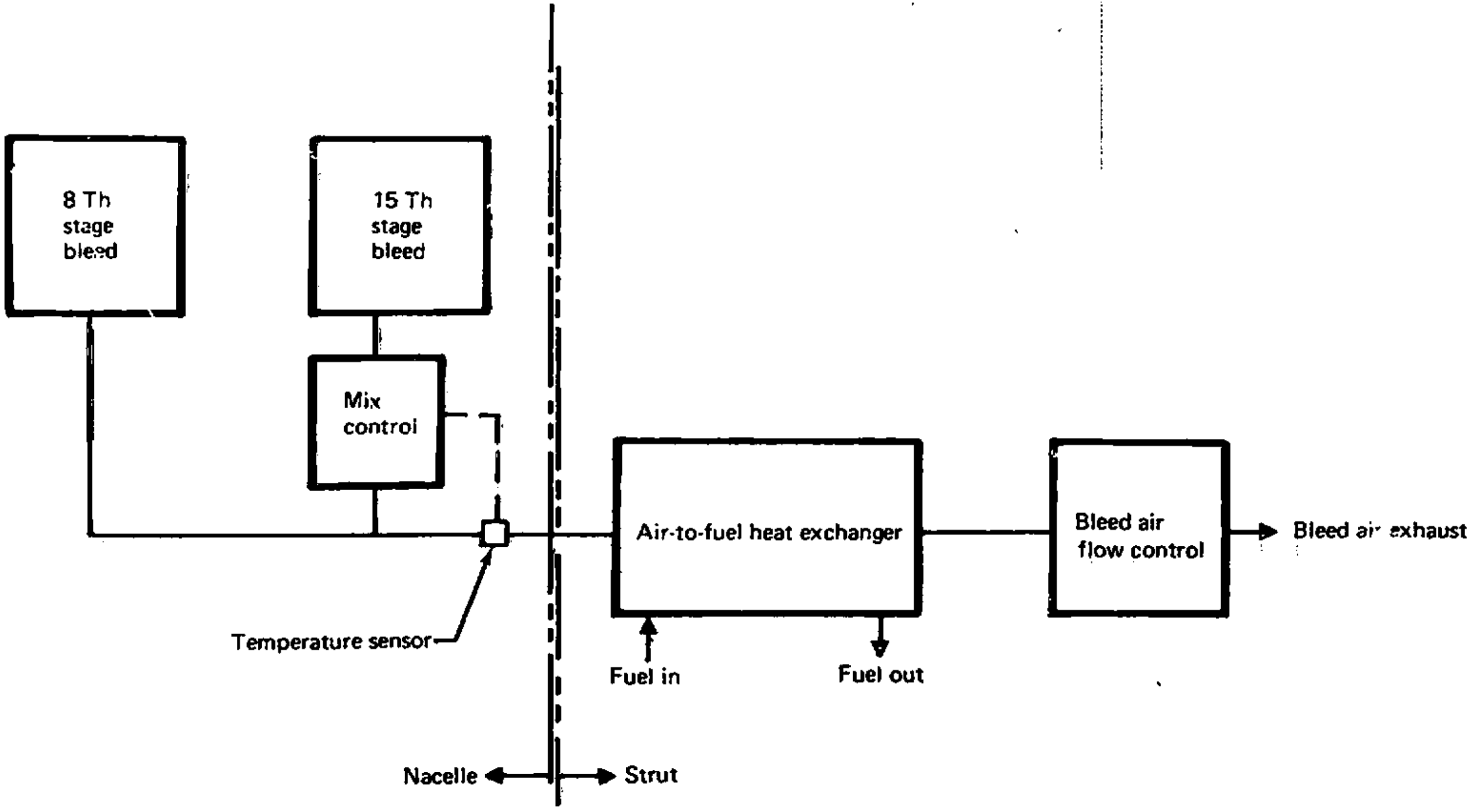


Figure 28.— Schematic of the Engine Airbleed Modification

Since the electrical energy will only be used for heating, the need for a Constant Speed Drive (CSD) could be eliminated thus reducing cost and weight of the system. To meet safety requirements, a heat transport loop has been assumed. A schematic of this system is shown on Figure 29.

8.2.4 TAILPIPE HEAT EXCHANGER

Another method of heating fuel in flight is by transfer of heat energy from the engine. Calculations were run on a computer simulation of a JT9D-7 engine on Boeing's General System Analyzer (GSA) Program, which simulates various power extractions and bleed modes, with output close to actual performance data. The location that provided the least penalty for heat extraction was the primary jet exhaust. To meet safety requirements a heat transport loop would be required and a second heat exchanger for the fuel would be required. A schematic of this modification is shown in Figure 30.

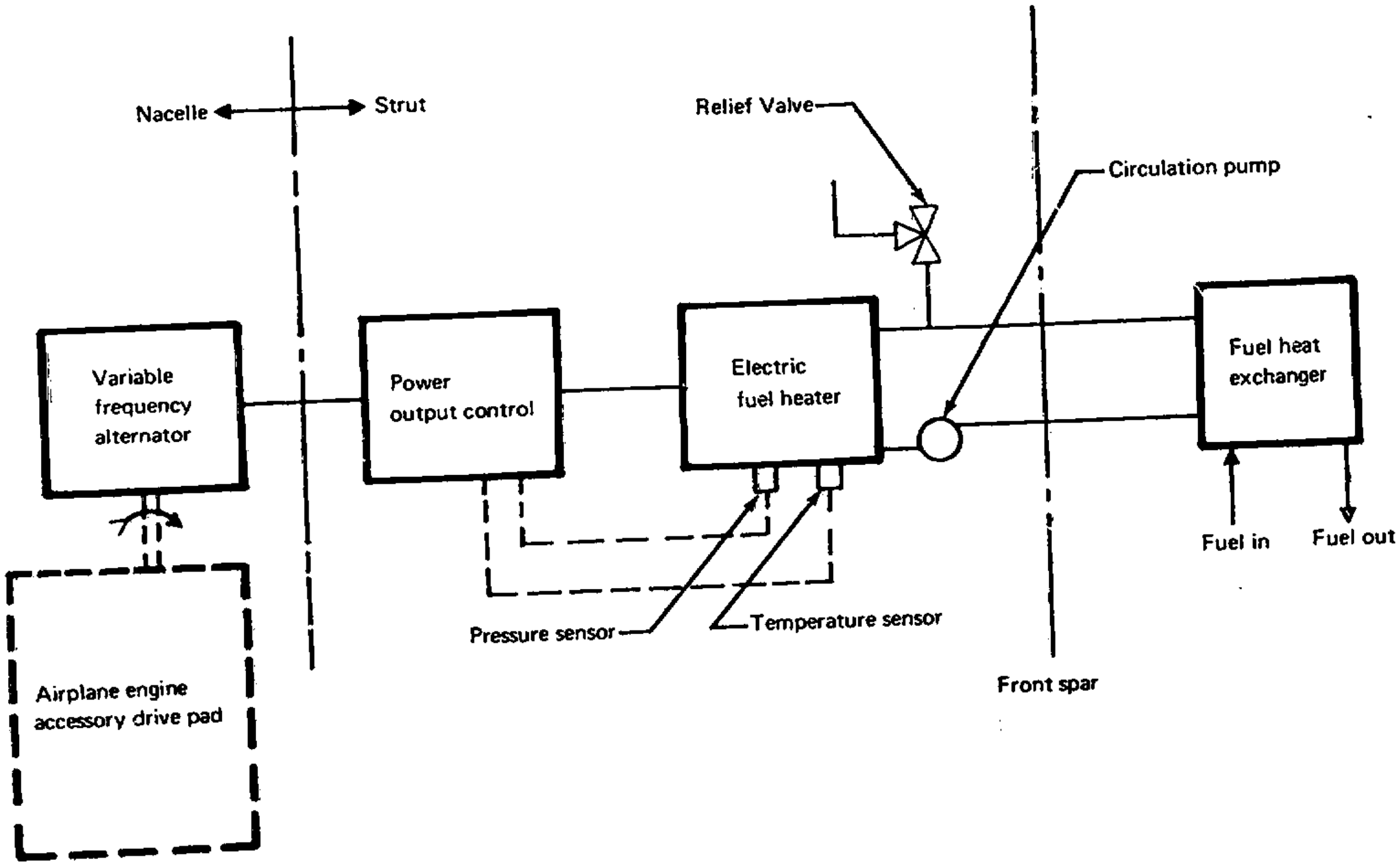


Figure 29.— Schematic of the Electrical Heating Modification

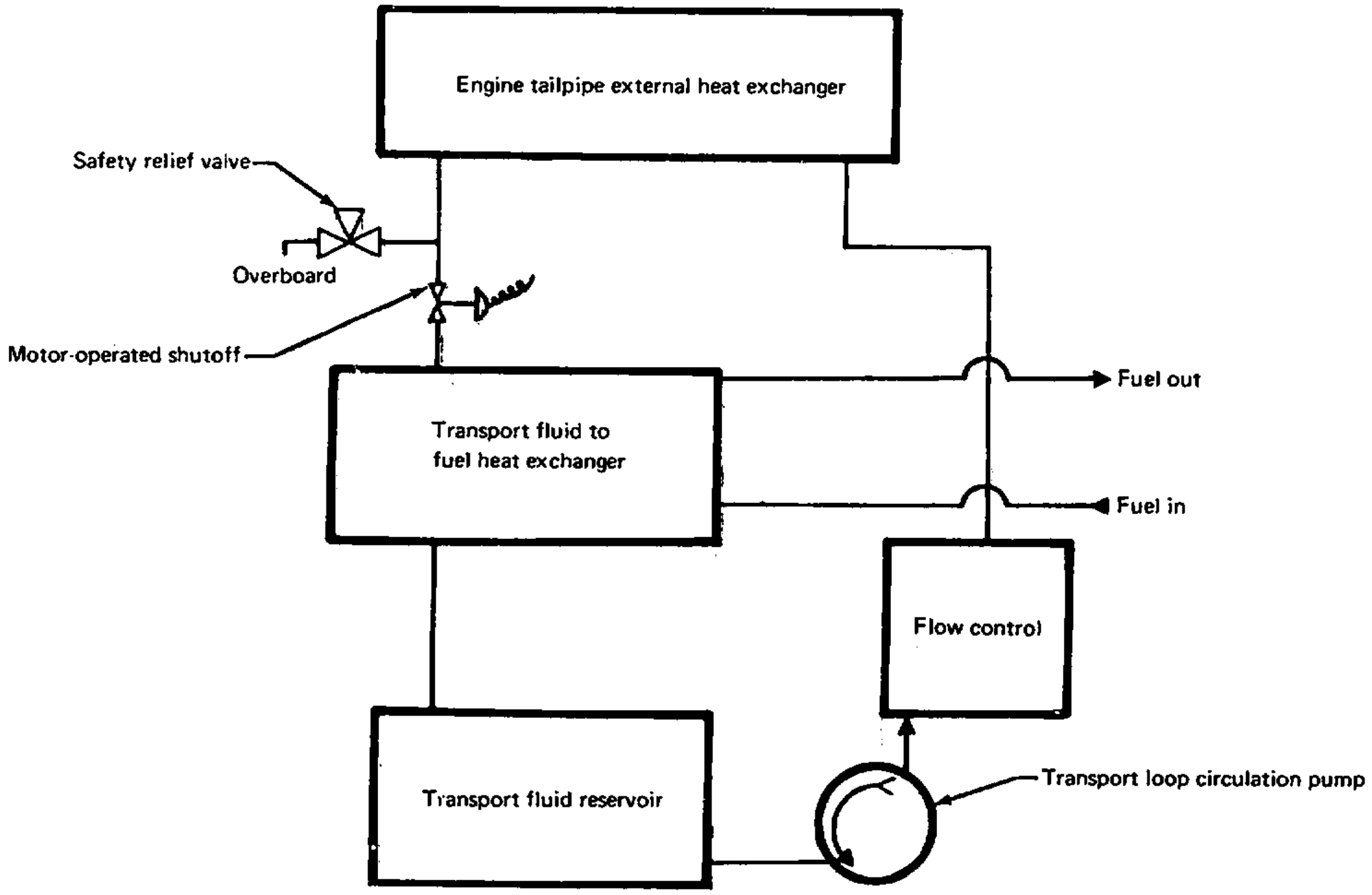


Figure 30.— Schematic of the Tailpipe Heat Exchanger Modification

9.0 PERFORMANCE AND ECONOMIC EVALUATION OF HEATING SYSTEMS

9.1 PERFORMANCE PENALTIES OF MINOR MODIFICATIONS

The performance penalties associated with the minor modifications would theoretically be small since the heat energy supplied by these systems is heat already rejected to the ambient or the fuel. In practice there would be some inefficiencies due to heat exchanger and fuel pressure drops. The increase in weight due to additional plumbing, valves, controls and accessories is estimated to be approximately 140 kg (300 lbs) for the minor modifications.

9.2 PERFORMANCE PENALTIES AND WEIGHTS OF MAJOR MODIFICATIONS

The performance penalties for use of the major modifications were calculated on the basis of the following guidelines:

a. A fuel flow change for the engine, due to the system operation, was calculated to maintain a constant net thrust at cruise. This penalty was then assessed as a fuel penalty for the mission and as an added weight of the heat source.

b. A requirement of 6500 kJ/min/tank (6200 Btu/min/tank) was assigned to each source to cover the extreme fuel heat requirement.

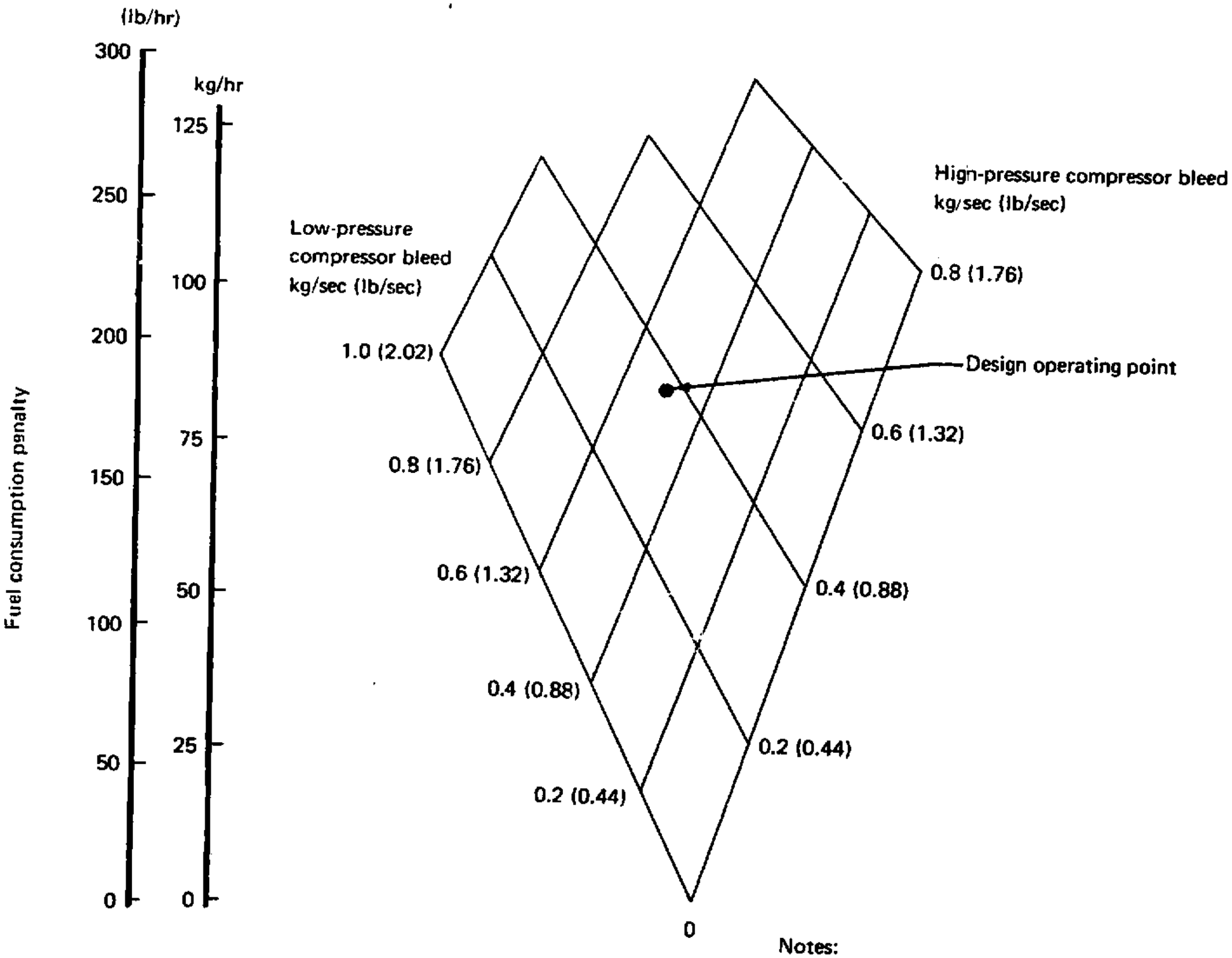
c. Where the system involved ram drag, this penalty was assessed as a main engine fuel flow increment to offset the ram drag. This penalty was then assessed to the system.

9.2.1 CATALYTIC REACTOR HEATING

The catalytic reactor heating system was designed for two units installed on the 747 aircraft with each unit serving a pair of engine-fuel tank combinations. For the requirement of 6500 kJ/min for each tank, or 13000 kJ/min for each catalytic reactor unit, it was calculated that a fuel flow of 45 kg/hr (100 lb/hr) and an airflow of 1.4 kg/sec (3 lb/sec) per unit would be required. Heated air to the heat exchanger unit would be at 230°C (440°F). The fuel flow penalty would be 45 kg/hr per catalytic reactor or 90 kg/hr (200 lb/hr) per airplane. A weight of 225 kg (500 lb) per unit or 450 kg (1000 lb) per airplane was estimated for this modification.

9.2.2 ENGINE AIRBLEED

The performance of the engine airbleed heating system was calculated using the Boeing GSA program for the JT9D-7 simulation mentioned in section 8. Various combinations of low pressure (8th stage) and high pressure (15th stage) bleed air extraction could be used. Figure 31 is a composite plot showing the penalties in terms of fuel consumption for various combinations of low-pressure and high-pressure air bleed. Penalties for extraction of low-pressure air are less than those for high pressure air bleed. A reasonable estimate of bleed air required for 6500 kJ/min, if available at 230°C with an air temperature drop of 110°C, is 0.9 kg/sec (2 lb/sec). This quantity cannot be supplied in total by low pressure bleed.



Notes:

- One-day-per-year minimum temperature extreme
- Climatic conditions same as figure 10

Figure 31.—Fuel Penalty for Airbleed Extraction

Instead, the best combination is a maximum of 0.51 kg/sec low pressure bleed and 0.39 kg/sec high pressure bleed. The resulting fuel penalty (see Figure 31) is 83 kg/hr (184lb/hr) per engine or 332 kg/hr per airplane.

The estimated weight of this airbleed system is 75 kg (165 lb) per engine or 300 kg (660 lb) per airplane.

9.2.3 ELECTRICAL HEATING

The performance penalty of the electrical heating system was calculated assuming an 80% efficiency in transmission. To provide 6500 kJ/min/engine each engine would be required to generate 130 kW. The fuel penalty associated with this required power is approximately 11 kg/hr (24 lb/hr) per engine or 44 Kg/hr per airplane. The estimated weight of the electrical heating system is 110 kg (250 lb) per engine or 450 kg (1000 lb) per airplane.

9.2.4 TAILPIPE HEAT EXCHANGER

The JT9D-7 simulation program GSA, computed performance penalties for heat extraction from the engine air stream at various locations. Penalties for heat extraction at several compressor and turbine stations are approximately equal to the fuel flow for combustion energy equivalent to the desired 6500 kJ/min or 9 kg/hr. At the tailpipe, the fuel flow penalty was calculated to be 2.7 kg/hr (6 lb/hr) per engine, a fraction of the fuel flow equivalent to the combustion energy.

The weight of this system, based on a heat exchanger using the 530°C tailpipe temperature was estimated as 63 kg (140 lb) per engine or 250 kg (550 lb) per airplane.

9.2.5 INSULATION

Weights were estimated for using tank insulation, although insulation would be effective only in connection with additional minor or major modification heating sources. For an assumed insulation weight of 600 kg/m^3, and approximately 390 m^2 of wing tank surface, the weight of 0.6 cm (1/4-inch) thick insulation is 1500 kg (3300 lbs), and the weight of 2.5 cm (1-inch) thick insulation is 5900 kg (13000 lbs). Thrust or fuel flow penalties were not estimated for insulation. It should be noted that the assumed weight of 2.5 cm of insulation is 15% of the 747-200 payload for the 9100 km mission.

9.2.6 SUMMARY OF PERFORMANCE PENALTIES FOR MAJOR MODIFICATIONS

Table 6 lists the performance penalties of the major modification discussed and sized for 6500 kJ/min/tank heating. Total airplane fuel consumption increase required to maintain engine thrust and weight increases are shown also. The fuel consumption increase is stated as the percent of an average cruise fuel flow of 8600 kg/hr/airplane. For comparison the equivalent fuel consumption based on 43000 kJ/kg heating value, to produce 6500 kJ/min/tank is listed. This represents any concept using a fuel fired heat exchanger, although no practical system of this type was discussed in this section.

Table 6.—Performance Penalties for Major Modifications

One-day-per-year probability and use of -18°C Freezing Point Fuel	Fuel consumption increase		Weight increase kg/airplane
	Kg/hr/airplane	% of cruise fuel flow	
Catalytic reactor heating	90	1.1	450
Engine airbleed	332	3.9	300
Electrical heater	44	0.5	450
Tailpipe heat exchanger	11	0.1	250
Insulation 0.6 cm thick	Not applicable		1500
2.5 cm thick	Not applicable		5900
Combustion heating	36	0.4	For reference only

9.3 PERFORMANCE PENALTIES BASED ON AVERAGE UTILIZATION

9.3.1 CALCULATION OF FLIGHT UTILIZATION

The penalties calculated in section 8 expressed as fuel consumption are based on systems sized to provide the required fuel heating for an extreme ambient temperature condition with a one-day-a-year probability. This assumes that the system will be operated at 100% output on every flight.

To obtain a realistic operating average fuel consumption penalty, the average utilization rate of the systems based on flight frequency and average in-flight ambient temperature for both summer and winter months was determined. The 747 routes and flight frequencies were compiled from a Boeing program that uses current commercial flight data published in Reference 26. Long-range flights were divided into categories corresponding to the three long-range missions established for this study as shown on Table 7.

Table 7.—747 Flight Frequencies

Route distance range km	Corresponding mission km	Representative frequency flights/week	
		Winter	Summer
2800 to 4600	3700	845	957
4600 to 6500	5600	684	1034
Greater than 6500	9100	361	510

For each of the flight routes an average in-flight altitude ambient temperature was obtained using References 14 and 15. These data were used to calculate the percentage of flights that would require the heating system for use of the hypothetical high-freezing point fuels. Data similar to the AFTTA output of Figures 6 through 10 were used to determine those average in-flight altitude ambient temperatures that were low enough to require any amount of heating for the particular fuel and mission. Thus the utilization rate was determined by using the number of flights that required a heating system and the amount of heat necessary to maintain the fuel above its freezing point during the flight. This method gives a conservative prediction of utilization rates summarized in Table 8. It indicates that for use of -18°C freezing-point fuel, heating systems would have to be used in the majority of the flights. In the use of -29°C freezing-point fuel, heating systems would not be used in summer and only on a small percentage of the longest range winter flights.

Table 8.—Utilization of Heating Systems

Mission	Percent of flights predicted to use systems			
	Winter months		Summer months	
	-18°C fuel	-29°C fuel	-18°C fuel	-29°C fuel
3700	53	0	45	0
5600	59	0.1	50	0
9100	73	5.3	59	0
Combined utilization	62	1.8	52	0

9.3.2 FUEL CONSUMPTION WITH UTILIZATION RATES

The previously determined utilization rates were used to modify the fuel consumption penalties derived assuming 100% utilization of the heating systems. The fuel consumption penalties are shown in Table 9.

Included in this table are calculations for the -29°C fuel which requires 3700 kJ/min/tank, and the -18°C fuel which requires 6200 kJ/min/tank. The reference combustion heating figure, discussed in Table 6, is also included.

Table 9.—Average Fuel Consumption Penalty Based on Utilization Rates

Heating system	% fuel consumption penalty 100% utilization		% average fuel consumption penalty using combined utilization rates			
	-18°C fuel	-29°C fuel	-18°C fuel		-29°C fuel	
			Winter	Summer	Winter	Summer
Catalytic reactor heating	1.1	0.62	0.70	0.59	0.012	0.0
Engine airbleed	3.9	2.20	2.50	2.10	0.042	0.0
Electrical heating	0.5	0.28	0.32	0.27	0.005	0.0
Tailpipe heat exchanger	0.1	0.06	0.06	0.05	0.001	0.0
Combustion heating	0.4	0.23	0.25	0.21	0.004	0.0

9.4 ECONOMIC ANALYSIS

9.4.1 INSTALLATION COSTS

Preliminary price estimates were made on all four major modifications and on the engine oil-fuel heat exchanger representing a typical minor modification.

This procedure involved establishing:

a. Non-recurring costs for each system, including detail design, staff and certification costs, lab test and flight tests.

b. Manufacturing non-recurring costs including planning, jig tooling, manufacturing development and quality control.

Recurring costs were developed from purchase equipment costs and installation work statements which were used to estimate manufacturing costs for an assumed 300 airplane production run. For the purposes of this study, in-line production only was assumed.

Ground handling modifications discussed in Section 7.2.5 were also priced based on the use of the −18°C freezing-point fuel at O'Hare Airport. The average initial cost of each system per airplane (except for ground handling) is shown below:

Catalytic reactor heating	$290,000	
Engine airbleed	80,000	
Electrical heating	140,000	
Tailpipe heat exchanger	150,000	
Engine oil-fuel heat exchanger	80,000	
Ground handling modifications	$350,000	Total

9.4.2 DIRECT OPERATING COSTS

Direct operating costs (D.O.C.) were based on the Boeing Company revision to the basic ATA mission profile (Ref. 27). Changes have been made in ground and air maneuver time and distance factors to correspond closely to actual flight operations. Basic characteristics of the Boeing program are listed in Table 10. The additional fuel, weight and maintenance penalties were used in the program to obtain the incremental D.O.C. increase. Figures 32 through 35 are examples of the data output from the D.O.C. program. Figure 32 shows the data for no initial cost for the systems. The percent D.O.C. is shown as a function of percent fuel penalty for several values of total weight increase. Figure 33 presents the same information but plotted as a fuel price offset, that is, the fuel price decrease of the high-freezing-point fuel that would offset the D.O.C. penalty. Fuel prices were computed using a base price of 10.9¢/liter (41¢/gal). Figure 34 shows the fuel penalty and D.O.C. penalty for a system initially priced at $200,000. Figure 35 is the corresponding fuel price offset.

Table 11 was constructed from data similar to those of Figures 32 through 35 utilizing the calculated fuel penalties, weights and initial costs. One minor modification, the engine oil-fuel heat exchanger is also included although the heat available from this system is not sufficient for use with the -18°C fuel. For reference the modification costs ground handling the high-freezing-point fuels at O'Hare Airport are included. The cost of the ground handling modification per liter of fuel "through-put" with the costs spread over five years is minimal.

The data in Table 11 indicate that the system ranking with -29°C fuel almost entirely on the basis of weight since yearly utilization is low. With the -18°C fuel, however, relative ranking changes because utilization time is greatly increased. Systems with large fuel consumption penalties show increased D.O.C. penalties with the -18°C fuel.

9.4.3 RETURN ON INVESTMENT

Return on investment (R.O.I.) estimates were also calculated for the recovery of initial costs of the modifications. Table 12 is a summary of the Boeing R.O.I. criteria for amortization, depreciation and other cash recoveries. The R.O.I. calculations were made based on the utilization rates for both high freezing point fuels. A summary of the R.O.I. percentage decreases and the fuel price decrease which would offset the change in R.O.I. are shown on Table 13. This table is analogous to the D.O.C. presentation of Table 11.

Table 10.—Basic Characteristics of Boeing 1976 Direct Operating Costs (DOC) Coefficients

Applicability	New and used airplanes Domestic trunk, U.S. intercontinental and local service
Mission Profile	1967 ATA with revised taxi, air maneuver, and airway distance factors
Utilization	New—approximately 95% 1967 ATA Used—approximately 30% 1967 ATA
Cruise procedure	New minimum cost constant, M, step climb
Crew expense	Function of gross weight and speed
Fuel price	82¢/liter (31¢/gal.) U.S. domestic, 10.9¢/liter (41¢/gal.) U.S. intercontinental
Maintenance	Mature level maintenance based on detailed analysis Engine line maintenance labor is included in engine maintenance Labor rate = $9.00/manhour Burden = 200% of direct labor
Depreciation	New— 15 years to 10% on airplane and spares Used— 7 years to 10% on airplane and spares
Insurance	1%/year based on fly-away price
Spares	6% airframe price 30% engine price
Non-revenue factor	2% added to fuel and maintenance for non-revenue flying

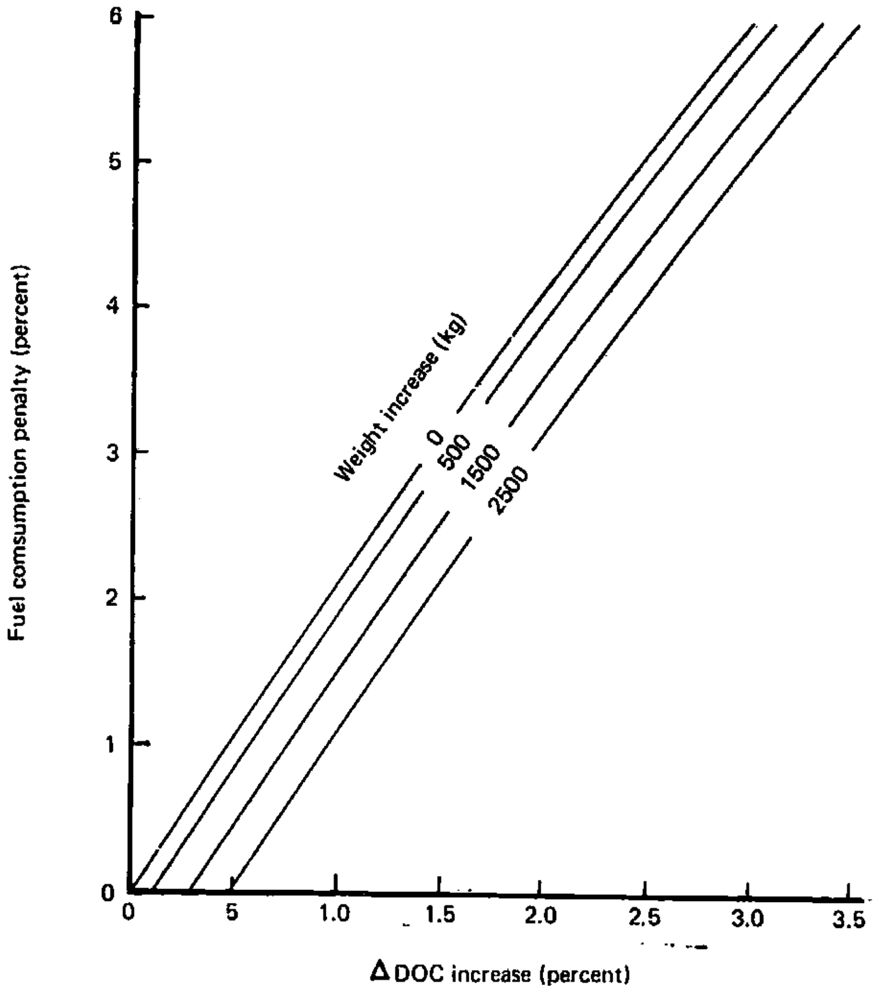


Figure 32.— Direct Operating Cost (DOC) Increase for Fuel Heating System (0 Cost)

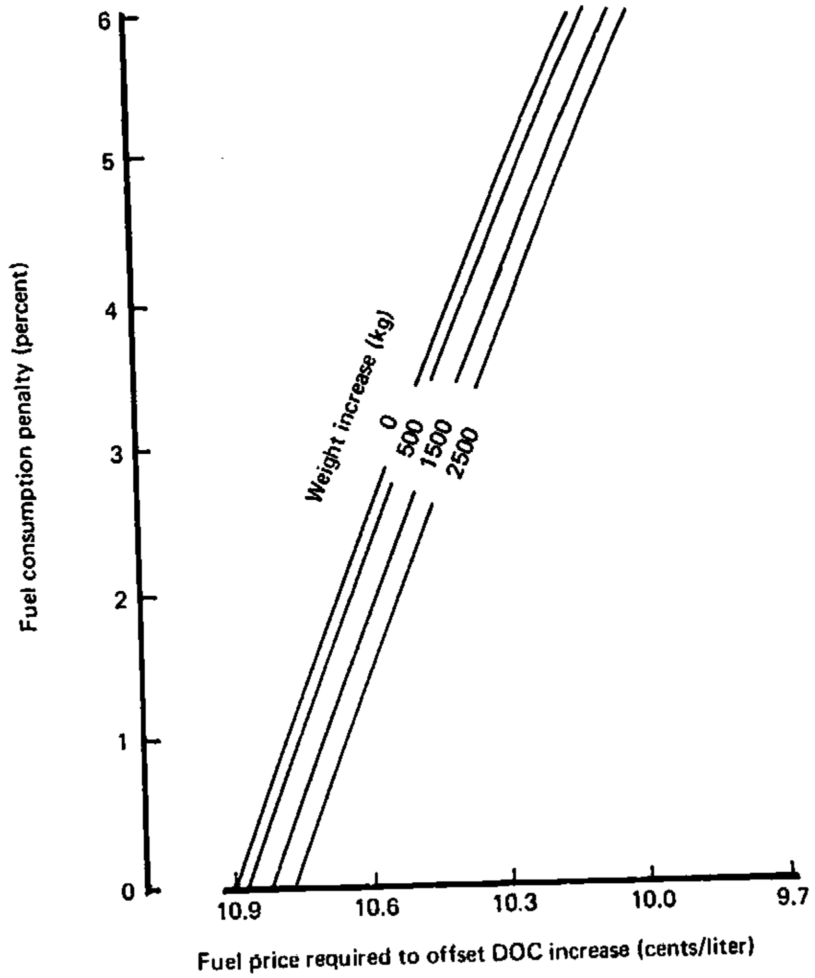


Figure 33.—Fuel Price Decrease Required to Offset DOC Increase (0 Cost)

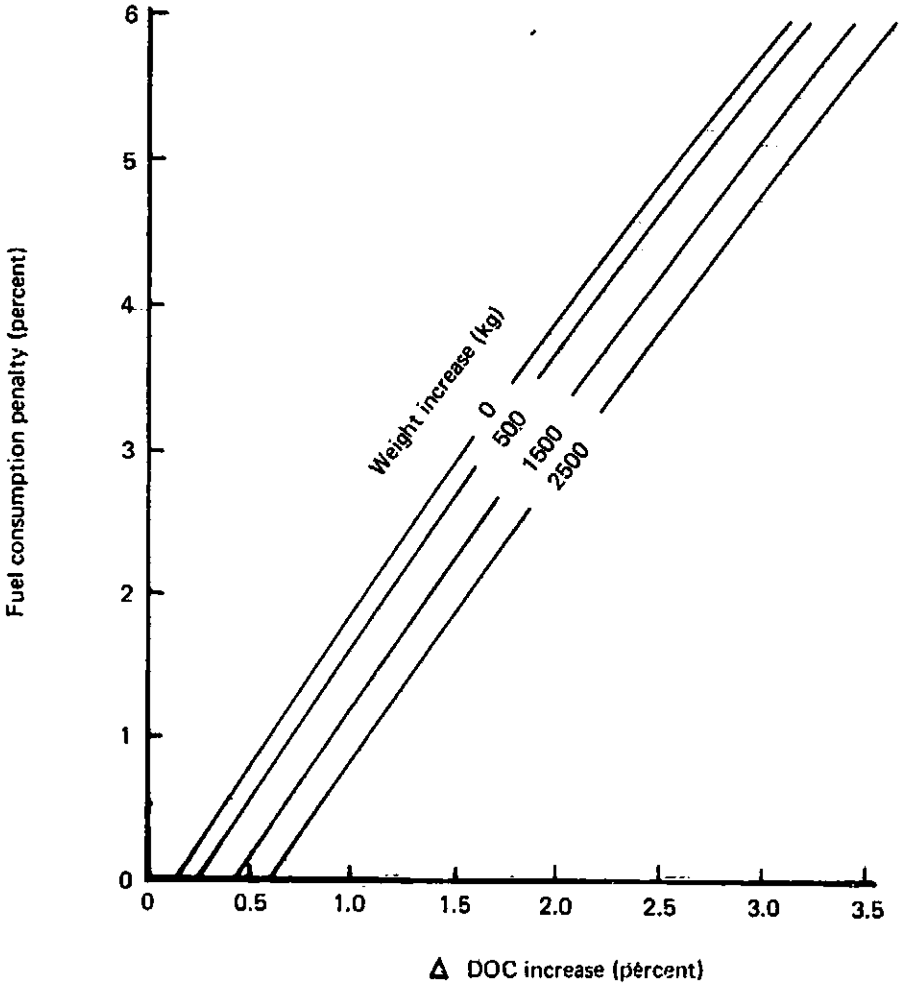


Figure 34.— DOC Increase for Fuel Heating Systems ($200K Cost)

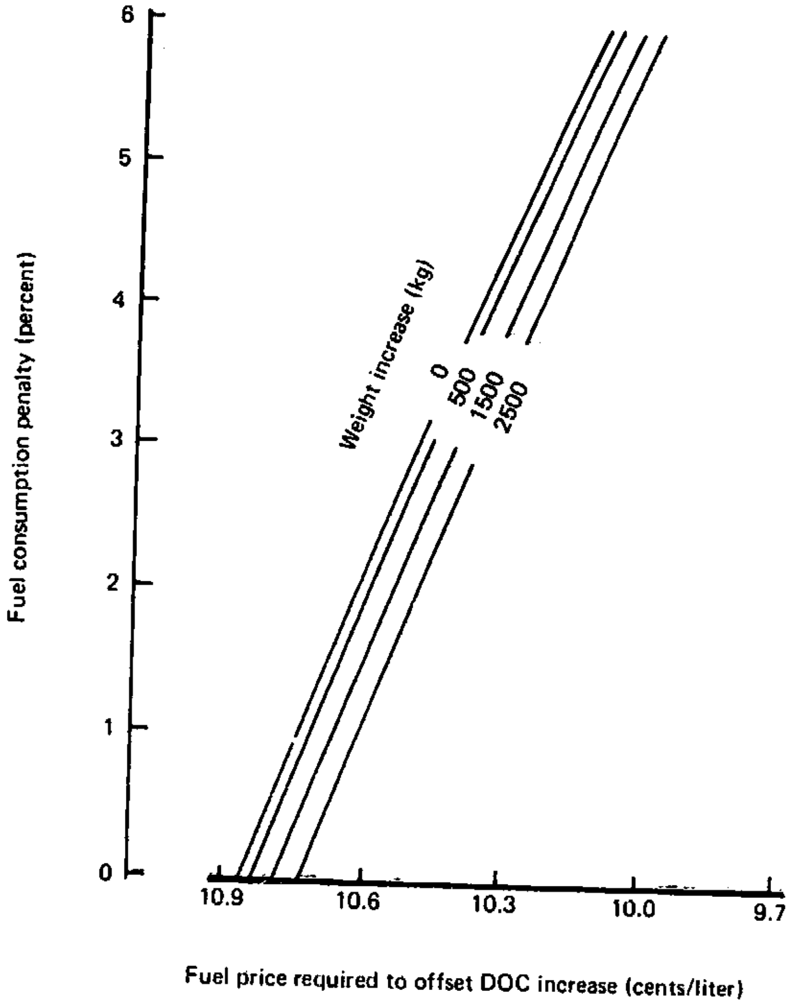


Figure 35.— Fuel Price Decrease Required to Offset DOC Increase ($200K Cost)

Table 11.—DOC Analysis of Fuel Heating Systems

Systems	-18°C freezing point fuel			-29°C freezing point fuel		
	ΔDOC %	Fuel price offset		ΔDOC %	Fuel price offset	
		¢/liter	¢/gallon		¢/liter	¢/gallon
Catalytic reactor heating	0.55	-0.13	-0.51	0.285	-0.067	-0.26
Engine airbleed	1.07	-0.28	-1.05	0.125	-0.030	-0.12
Electrical heating	0.33	-0.08	-0.29	0.20	-0.046	-0.18
Tailpipe heat exchanger	0.183	-0.04	-0.15	0.16	-0.035	-0.13
Engine oil/fuel heat exchanger	--	--	--	0.075	-0.018	-0.07
Ground handling modification (O'Hare)	--	-0.002	-0.009	--	--	--

Table 12.—Boeing Return on Investment (ROI) Method

- ROI is the rate that makes the present value of future net annual cash in-flows equal to the out-flow at the time of equipment acquisition
- Cash flows and their timing are considered as follows:
  - Standard prepayment schedule for new airplanes

Time prior to delivery	Percent of price paid
15 months	20
12 months	5
9 months	5
6 months	5
0 (delivery)	65% + spares

  - No prepayments for used airplanes
  - Investment tax credit of 10% spread over the first three years of operation
  - Annual operating costs and revenue at stated missions and load factors
    - Accelerated depreciation for tax purposes (sum of years digits for 10 years)
    - Income taxes at 48%
  - Airplane life (new) is 15 years and residual value is 10% of price + spares
  - Airplane life (old) is 7 years and residual value is 10% of price + spares

Table 13.—ROI Analysis of Fuel Heating Systems

Systems	-18°C freezing point fuel			-29°C freezing point fuel		
	ΔROI %	Fuel price offset		ΔDOC %	Fuel price offset	
		¢/liter	¢/gallon		¢/liter	¢/gallon
Catalytic reactor heating	0.24	-0.32	-1.20	0.17	-0.22	-0.83
Engine airbleed	0.20	-0.28	-1.05	0.05	-0.07	-0.25
Electrical heating	0.12	-0.16	-0.60	0.09	-0.12	-0.44
Tailpipe heat exchanger	0.11	-0.13	-0.50	0.09	-0.11	-0.43
Engine oil/fuel heat exchanger	---	---	0.04	-0.05	-0.20	

9.4.4 EFFECT OF FUEL HEATING VALUE ON COSTS

The fuel property values for the hypothetical fuels that were used throughout this study have been presented on Table 2. Most of the properties and their possible variations would have no effect on costs. The fuel's net heating value per mass, however, is shown to offset cost penalties seriously. The economic calculations used a value for Jet A per ASTM D-1655. The values in Table 2 indicate that a representative average value for Jet A is 43300 kJ/kg. For the two hypothetical high freezing point fuels, standard property correlations gave a heating value of 43000 kJ/kg of the –29°C freezing point fuel which meets the ASTM D-1655 specification minimum and 42700 kJ/kg for the –18°C fuel which is slightly below the minimum. The DOC and ROI were determined for both hypothetical fuels using a 2% decrease in net heating value of 41900 kJ/kg (18000 Btu/lb). Results are summarized on Table 14. Comparison with the previous tables shows that the reduction in net heating value per mass substantially increases the DOC and ROI penalties.

Table 14.—DOC and ROI Penalties for Fuel Systems Using 41900 kJ/kg Net Heating Value Fuels

Systems	-18°C freezing point fuel		-29°C freezing point fuel	
	ΔDOC %	ΔROI %	ΔDOC %	ΔROI %
Catalytic reactor heating	1.82	0.47	1.46	0.41
Engine airbleed	2.07	0.43	1.29	0.29
Electrical heating	1.54	0.35	1.39	0.33
Tailpipe heat exchanger	1.47	0.34	1.36	0.33
Engine oil/fuel heat exchanger	---	---	1.27	0.25

It should be noted that the penalties associated with the net heating value should also be evaluated based on the method by which the fuel is purchased. That is, if fuel is purchased by volume, the increased density of the two hypothetical fuels may result in a higher heating value based on volume and offset the reduction in heating value based on mass. If fuel is purchased to obtain a specific quantity of energy, i.e., ¢/kJ, the DOC and ROI penalties will be affected.

10.0 DISCUSSION AND EVALUATION OF SYSTEMS FOR USE OF HIGH-FREEZING-POINT FUELS

10.1 FUEL TANK TEMPERATURE

The predicted in-flight fuel temperatures for the mission and the extreme minimum ambient temperature analyzed indicated that increasing the fuel freezing point beyond the current specification limit would require some modification either to flight procedures or to the aircraft itself.

For short range flights, initial fuel loading and airport ambient temperatures influence the minimum in-flight fuel temperature. The use of -29°C and even -18°C freezing-point fuels is possible without modification under most seasonal conditions. Ground heating systems will permit use of these fuels under most winter conditions.

For long range flights, greater than 3700 km (2000 n mi.) in-flight fuel temperatures will approach the ambient altitude stagnation temperature. For these flights, the minimum in-flight fuel temperatures are independent of fuel loading and airport ambient temperature but are solely dependent on altitude ambient temperature and aircraft Mach number. Procedural changes to avoid temperatures below the freezing point of the hypothetical fuels are considered unacceptable due to the frequency these procedural changes would have to be used. Fuel heating systems are regarded as the only acceptable means of maintaining fuel temperatures above the freezing points of these fuels on long range flights.

10.2 MINOR MODIFICATIONS

Of the minor modifications investigated the two which were considered most feasible from the amount of heat available were: (1) engine oil/fuel heat exchanger and (2) modified air conditioning heat rejection system. Both systems would provide enough heat to maintain the fuel above the freezing-point of the -29°C fuel. Between these systems, the engine oil/fuel heat exchanger system was considered superior because it could be designed to be independent of any of the current aircraft systems. This can be done by designing a by-pass on the existing engine oil cooler such that the fuel would be cooled by fuel from the tanks rather than fuel from the fuel control. In this way the system may be turned off when heat to the tanks is not required and engine oil would again be cooled by fuel from the fuel control.

The modified air conditioning heat rejection system was considered less promising because it would require extensive modifications and because using fuel to cool the air conditioning bleed air would demand the use of the fuel heating system on all flights. During hot days, the fuel heating system is unnecessary and the heat rejected to the fuel may overheat the fuel.

The recirculation of fuel from the fuel control and boost pumps back to the tank to warm the fuel has also been discussed as a minor modification. Maximum heating rate is estimated as 2200 kJ/min/tank. This modification as well as electrical generator cooling and other heat sources are systems that promise simple installation and small cost and weight penalties. However, in this study only systems that were capable of use with at least the -29°C freezing-point fuel (a minimum of 3700 kJ/min/tank heat supply) were considered. Systems such as fuel recirculation can offer near term promise for use of a relaxed specification Jet A with freezing points between the present day specification and that of the -29°C fuel. Furthermore, combinations of minor modifications can be useful. For example, engine oil/fuel heat exchanger flow combined with the pump-fuel control recirculation could produce about 6500 kJ/min heating sufficient for use of the -18°C fuel. The design criteria for this study excluded combination heating systems for two reasons: (1) to provide a basic comparison study of systems alone and (2) on a practical operational basis, use of two or more systems to provide required heating may add complexity and system failure conditions that may make certification of the systems difficult. It is recognized however, that further study of minor modifications, their variations and combinations would be worthwhile.

10.3 MAJOR MODIFICATIONS

The major modifications were designed to provide the required heat to each tank to maintain fuel temperature above the -18°C freezing point. These modifications are independent of any of the existing aircraft systems and are designed to operate only when required. Of the modifications investigated, electrical heating and engine airbleed systems would require the least developmental effort. The tailpipe heat exchanger would require a greater effort and the catalytic reactor would require considerable advances in the state-of-the-art.

The major modifications were sized for use with the more extreme freezing point fuel, -18°C. For use strictly with the -29°C freezing point fuel, it would be advantageous to use a minor modification such as the engine oil/fuel heat exchanger. However, the major modifications could be operated or scaled down for use with the -29°C freezing point fuel. In this respect, for the engine mounted modifications, only two of the four units could be mounted or used. For example, there could be a two generator electrical heating system, instead of a four generator system. The catalytic reactor heating system does not adapt well to a scaled-down version.

Insulation has been excluded as a competitive modification due to excessive weight penalties and installation difficulties. For future designs, where insulation can be incorporated as an integral component of wing tank design, insulation may offer a trade-off of initial weight versus fuel consumption penalties of heating systems. Insulation weight, nevertheless, is a fixed penalty that cannot be turned "on" and "off" in contrast to the heating systems.

For reference, performance of a system supplying heat by combustion has also been calculated based simply on the amount of heat supplied by a fuel with an average heat of combustion of 43000 kJ/kg. This is included in the table of fuel consumption penalties on Table 6. An operating system of this type was not designed directly, the catalytic reactor is the closest concept of direct combustion heating. It is noted that the fuel consumption of the catalytic reactor is 2.5 times that of the direct combustion because of the ram drag penalty. On the other hand, such systems as a tailpipe heat exchanger uses less than one-fourth of the fuel consumption for direct combustion. Energy extracted at the primary exhaust nozzle reduces the jet velocity and thrust only fractionally.

10.4 ECONOMIC AND PERFORMANCE PENALTIES

The installation costs, increased weight, increased maintenance costs and increased fuel consumption are the factors which determine the economic penalties imposed on the aircraft due to the modifications. The fuel consumption penalty is directly related to the utilization rate of the heating system. Thus, if the system utilization time is low enough as in the case for the -29°C freezing point fuel, the fuel consumption penalty has a negligible effect on the economic penalty. Only system weight and installation costs influence the economic penalty. This would indicate that for a -29°C fuel, a light weight, low cost system would be most economical even if it is associated with high fuel consumption penalties while in use.

When the utilization time is greatly increased as in the case for -18°C fuel, fuel consumption strongly influences the economic penalties. For example, compare the D.O.C. changes for the airbleed heating system and the electrical heating system shown on Table 11. With the -29°C fuel, the high priced electrical heating system shows the greater economic penalty. With the -18°C fuel, the less-fuel-efficient airbleed system shows the greater penalty. Therefore, if a heating system will be used regularly, a system with low operating fuel consumption would be most economical.

The influence of heat of combustion on performance penalties was also noted. Reduction of heat of combustion by only 2% imposes several times the economic penalties as the most costly modification for fuel heating. This may be offset by the method used to purchase the fuel, i.e., price/volume or price/kJ.

10.5 RECOMMENDATIONS

This study relied on hypothetical fuels with constructed properties. It was assumed that a fuel with a given boiling range would have a predictable freezing point. Much theoretical and correlative work remains to be done on relating freezing point to boiling range and other properties in defining a useful freezing point for aviation use and in relating freezing point to fuel system behavior and pumpability.

Other properties of the hypothetical study fuels are of significance. The strong effect of heating value on performance has been noted; probable changes of net heating value with boiling ranges or freezing point should be predicted accurately. Thermal stability of jet fuels used as heat sinks, such as for supersonic transport, is of great concern (Ref. 28). Heating the high-freezing point fuels may introduce similar problems. Thus, local temperatures of the fuel heat exchangers should be accurately determined to avoid overheating and possible fuel coking.

The most promising modifications appear worthy of more detailed study. In particular, the engine oil/fuel heat exchanger system is a low penalty system and readily adapted to existing aircraft. A study of the engine oil system may show additional capability to increase the heat output of this concept. An early work reported in Reference 29, indicates that 5100 kJ/min can be removed from the oil at a maximum oil temperature of 160°C. It appears that the system may be upgraded even further to supply 6500 kJ/min for use with the -18°C freezing-point fuel.

11.0 CONCLUSIONS

An analytical study has been conducted on the use of broadened specification hydrocarbon fuels in present day aircraft. A short range 727 mission and three long range 747 missions were used as basis of calculations at a one-day-a-year extreme values of seasonal and climatic fuel loading, airport ambient and altitude ambient temperatures. Four hypothetical fuels were selected; two high-vapor-pressure, with 35 kPa (5 psi Reid Vapor Pressure) and 70kPa (10 psi RVP) and two high-freezing-point, -29°C (-20°F) and -18°C (0°F). In-flight fuel temperatures were predicted by an established computer program. Boil-off rates were calculated for the high-vapor-pressure fuels, heating and insulation requirements for the high-freezing-point fuels. In addition for the high-freezing-point fuels, possible minor and major heating system modifications were investigated with respect to heat output, performance and ecomonic penalties.

The following conclusions are based on the results of this study.

1. For long range flights, high-vapor-pressure fuels may be usable with small boil-off losses if procedural changes in initial cruise altitude are acceptable. Fuel boil-off penalties with use of high-vapor-pressure fuels in short range flights of 900 km (500 n.mi.) or less appear unacceptable.

2. Predicted in flight temperatures for the 900 km (500 n.mi.) missions are such that fuels with up to -29°C freezing point may be used with a very small probability of fuel temperature below the freezing point.

3. Fuels with freezing-points up to -18°C can be used under all seasonal and climatic conditions for the short range missions, if the fuel were preheated at ground loading. Modifications to airport ground handling equipment and procedure are necessary for storage and use of the -18°C fuels at some temperate zone airports in winter. The costs of these modifications at major airports are minimal based on the quantity of fuel handled.

4. For long range flights, 3700 km (2000 n.mi.) or longer it appears economically feasible to use a -29°C fuel on present production aircraft with a heating system installed. The weight and installation cost of the heating system will have the greatest effect on the economic penalty on the airplane.

5. The use of -18°C fuel on long range flights is also economically feasible although the economic penalties are greater than those associated with the -29°C fuel. The increased fuel consumption of the heating system will have the greatest effect on the economic penalty on the airplane.

6. Two systems appear feasible as minor modifications as heat sources for use of the -29°C freezing point fuel. For use of the -18°C fuel major modifications are necessary and several possible systems show promise.

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P. O. Box 3707, Mail Stop 8K-54
Seattle, Washington 98124, U.S.A.
Attention: Manager - Customer Support, Materials & Services

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