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Design and Evaluation of Aircraft Heat Source Systems for Use With High-Freezing Point Fuels

Final Report

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16 Abstract

The efficient utilization of fossil fuels by future jet aircraft may necessitate the broadening of current aviation turbine fuel specifications. The objectives of this study are the design, performance and economic analyses of practical aircraft fuel heating systems that would permit the use of high freezing-point fuels on long-range aircraft. Two hypothetical hydrocarbon fuels with freezing points of -29° C and -18° C are used in this study to represent the variation from current day jet fuels

A Boeing 747-200 with JT9D-7/7A engines is used as the baseline aircraft. A 9300 Km mission was used as the mission length from which the heat requirements to maintain the fuel above its freezing point is based.

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1.0 SUMMARY

The objectives of this study are the design, performance and economic analyses of practical aircraft fuel heating systems that would permit the use of high-freezing-point fuels on long-range aircraft Two hypothetical hydrocarbon fuels with freezing points of -29° C and -18° C are used in this study to represent the variation from current day jet fuels

A Boeing 747-200 with JT9D-7/7A engine is used as the baseline aircraft A 9300 km mission is used as the mission length from which the heat requirements to maintain the fuel above its freezing point are based. The heat requirements for the extreme in-flight ambient temperature conditions are 127 kw/tank (7200 Btu/min/tank) for the -18° C freezing-point fuel and 79 kw/tank (4500 Btu/min/tank) for the -29° C freezing-point fuel

Several retrofit fuel heating systems are evaluated with the engine oil heat exchanger system and the electrical heating system picked for more detailed design The engine oil heat exchanger system has the advantage of its simplicity and relative ease of installation The disadvantage of this system is a limited heat input For the baseline airplane and engine, the system supplies only enough heat to permit use of a -34° C freezing-point fuel The electrical heating system is capable of maintaining -18° C freezing-point fuel above its freezing point This system has the disadvantage of being very complex The weight, installation costs, performance penalties, and maintenance costs are determined for both systems and the resulting penalty in direct operating costs established The penalty in direct operating costs and return on investment expressed as fuel cost decreases which are necessary to offset the increased economic costs is generally less than 1¢/L if allowances for limited utilization and realistic average route lengths are made

2.0 INTRODUCTION

This report presents the results of a study performed by The Boeing Commercial Airplane Company, under NASA Contract NAS3-20815, titled, *Design and Evaluation of Aircraft Heat Source Systems for Use with High-Freezing-Point Fuels* The objectives of this study are the design, performance, and economic analyses of practical aircraft fuel heating systems to permit use of broad specification, high-freezing-point jet fuels on long-range aircraft This study is a continuation of a previous study conducted by Boeing under NASA Contract NAS3-19783 and reported in reference 1

Jet fuels with a wider range of boiling point specifications will allow more flexible usage of scarce petroleum supplies or newer synthetic sources, such as coal or shale oil liquids The previous study, (ref 1), indicated that increasing the jet fuel boiling range toward the high final boiling points makes better use of resources and avoids aircraft safety hazards

Many characteristics of the fuel are unchanged by the higher boiling point The most obvious problems are higher freezing point and reduced thermal stability Some improvement in these properties can be made at the expense of greater fuel costs by additional refinery processing Alternatively, the aircraft fuel systems can be modified to accept the high-freezing-point fuels The previous study concluded that fuel heating systems using existing engine heat rejection or minor power diversion would be most promising for fuel system modification Several fuel heating systems were proposed to supply the maximum heat requirements of 110 kw (6200 Btu/min) for each engine-wing tank combination of the Boeing 747 Temperature predictions indicated a low frequency of usage for even a long-range aircraft and small economic penalties for the use of the heating systems

The present study continues the study of systems permitting the use of high-freezing-point jet fuels on long-range aircraft Fuel heating systems are designed for practical retrofit into a Boeing 747 aircraft

Of the various heating systems investigated, two heating systems are selected for a comprehensive level of design and evaluation This report presents preliminary details of plumbing layout, mechanical components, controls, mounting, and airframe and engine modifications for the selected heating systems. The two systems are evaluated in terms of weight, fuel consumption penalty, estimated direct operating costs, and return on investment penalties

Modifications for use of high freezing-point fuel incorporated into a future long-range aircraft of the 1990 period are discussed in an appendix. For future aircraft, wing tank insulation offers a low penalty alternative to the retrofit of fuel heating systems

3.0 BASELINE MISSION, TEMPERATURE, AND FUEL DATA

3.1 MISSION PROFILE

The baseline mission for which fuel temperatures and heating requirements are based is a 747-200, 9300 km (5000 nmi) flight The cruise Mach numbers, altitudes, and ambient temperatures established for the one-day-a-year worst case condition are used to determine the fuel tank cooling rates Figure 1 shows the altitude Mach number variation for this baseline mission and figure 2 is an example of the time history of fuel consumption for the 9300 km (5000 nmi) flight

3.2 TEMPERATURE BASELINE DATA

For these studies, the following sets of fuel loading and airport ambient temperatures are used to represent winter and summer days.

a	-15° C fuel temperature,	-29° C airport temperature
b	3° C fuel temperature,	-13° C airport temperature
c.	19° C fuel temperature,	27° C airport temperature
d	29° C fuel temperature,	38° C airport temperature

The in-flight altitude ambient temperatures corresponding to the winter and summer days were established in reference 1 and shown in figure 3 These temperature profiles represent the minimum and maximum 0.3 percent probability extremes and are not necessarily a representation of an individual flight

3.3 PROPERTIES OF HIGH-FREEZING-POINT FUELS

The properties of the high-freezing-point fuels used in this study are similar to those established in reference 1. The properties of these fuels are summarized in table 1 Properties of Jet A, ASTM D-1655 are typical rather than minimum specification values The typical values are taken from the 1977 sample surveys reported in reference 2 Although the thermal stability property of these fuels has not been determined, it is recognized that the thermal stability may be lower than current fuels. Thermal stability problems in the high-freezing-point fuel designs are avoided by specifying a maximum fuel temperature of 200° C

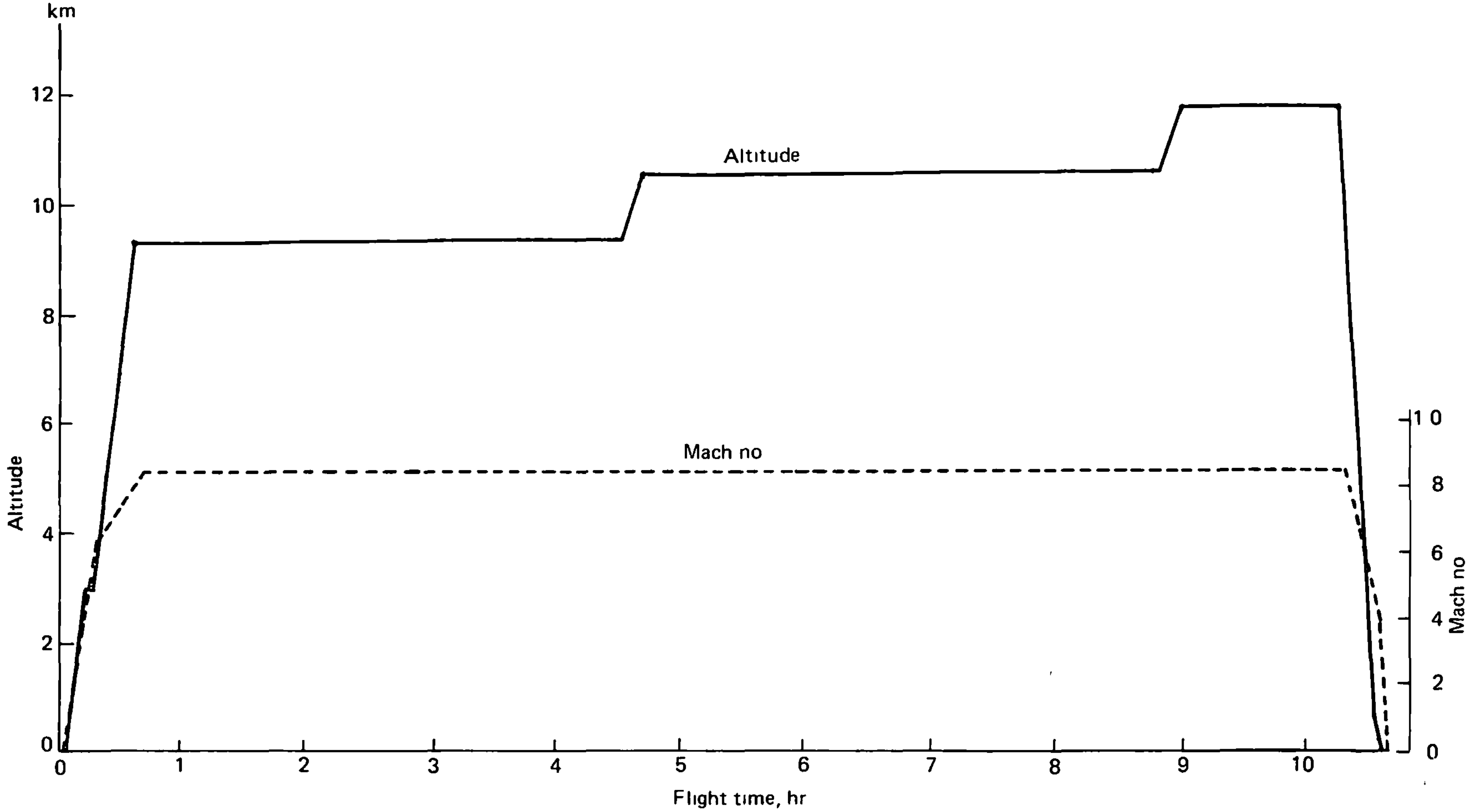

Figure 1.—Flight Profile for Boeing Model 747-200B with JT9D-7A Engines, 9300 km Mission

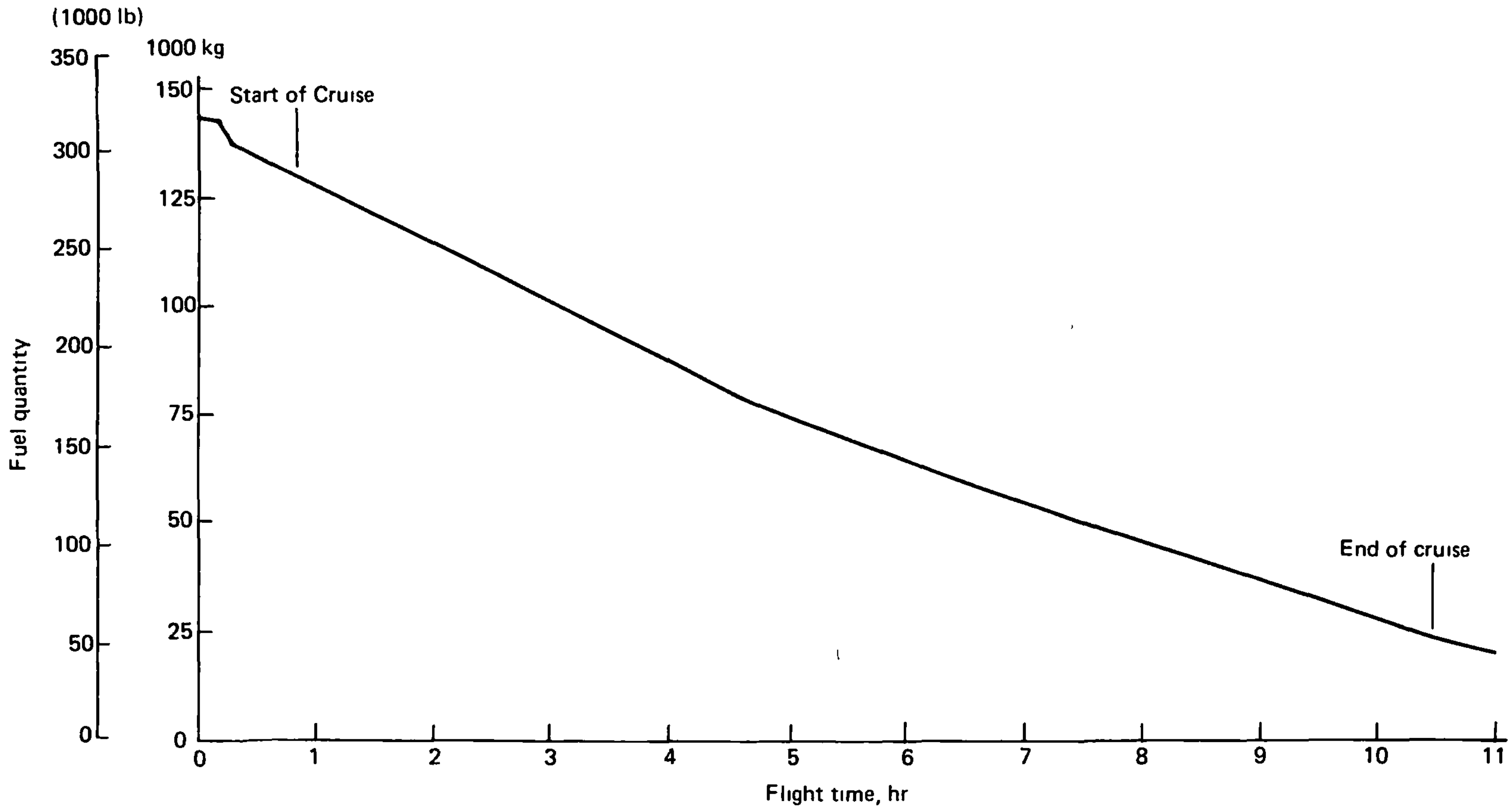

Figure 2.—Fuel Consumption History for Boeing Model 747-200B with JT9D-7A Engines, 9300 km Mission

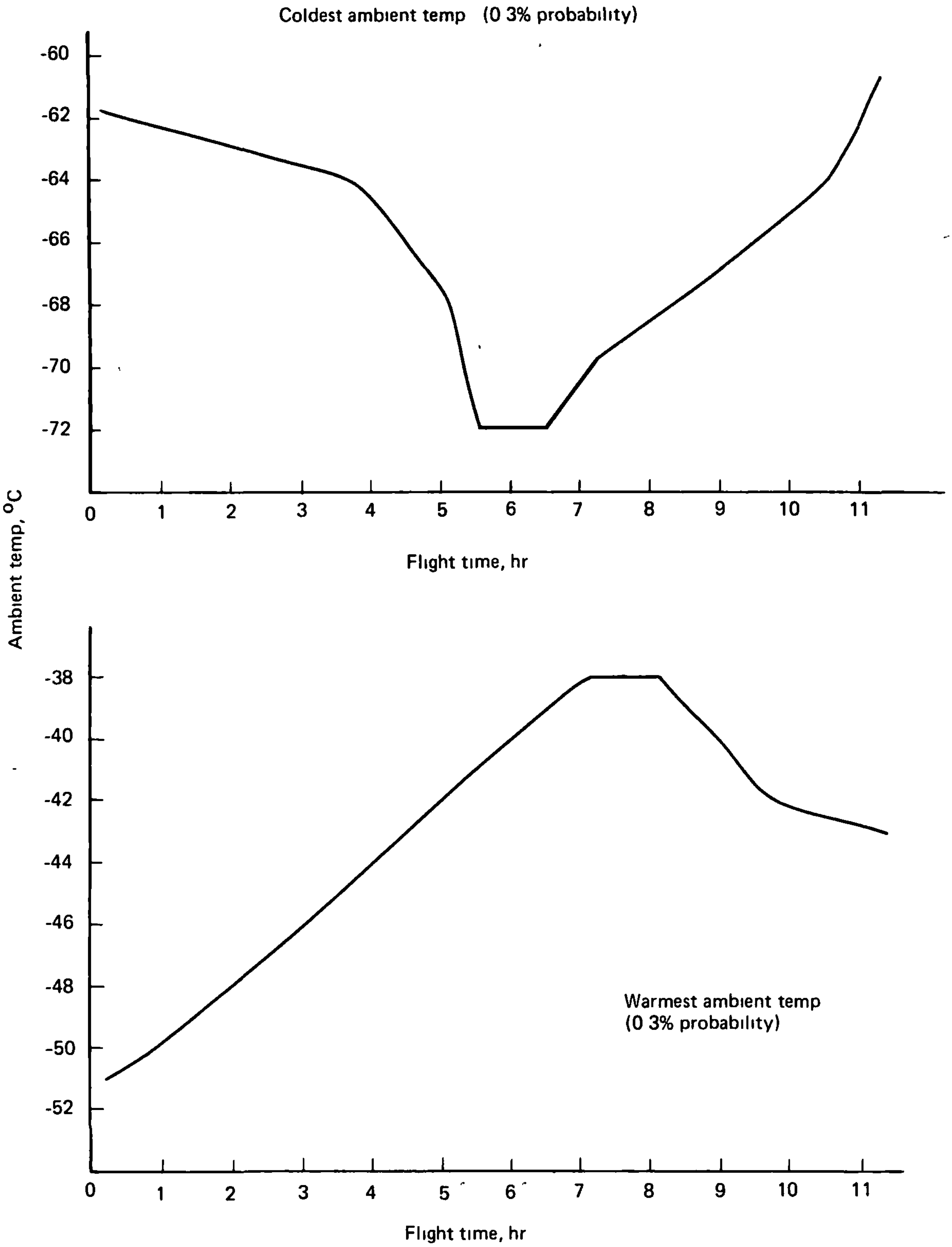

Figure 3.—Assumed Altitude Ambient Temperatures for 9300 km Boeing 747 Mission

Table 1.—Properties of Fuels

Property	Fuel type		
	Jet A, typical	High-freezing-point -20° F	0° F
Freezing point, °C	-46	-29	-18
°F	-51	-20	0
Distillation temp, °C			
volume recovery, 10%	188	210	252
20%	195	220	266
50%	213	238	288
70%	229	249	301
90%	246	266	322
final	267	288	357
10% to 90% slope, °C/%	0 73	0 70	0 88
Average volume boiling-point, °C	214	236	286
Specific gravity,			
60/60	810	832	858
°API	43 1	38 6	33 5
Net heat of combustion			
kJ/kg	43300	43000	42700
Btu/lb	18609	18470	18370
Viscosity at 50° C,			
cSt	1 4	1 6	2 8

4.0 ANALYSIS OF IN-FLIGHT FUEL TEMPERATURES

4 1 PREDICTION OF IN-FLIGHT FUEL TEMPERATURES

In-flight fuel temperatures were calculated for the 747-200, 9300 km mission at the winter-summer temperature combinations established in section 3 2 Boeing's aircraft fuel tank thermal analyzer (AFTTA) computer program described in reference 1 is used to calculate the in-flight fuel temperatures The calculations were based on the geometry and capacity of each tank on the 747-200 Examples of the in-flight fuel temperature calculation results are presented in figures 4 through 7

Figures 4 and 5 show the predicted fuel tank temperatures for the winter months based on the extreme minimum ambient temperatures illustrated in figure 3 Figures 6 and 7 show the predicted fuel tank temperatures for the summer months based on the extreme maximum ambient temperature illustrated in figure 3 Temperatures are shown for the inboard and outboard main tanks and the reserve tank located at the outer end of the outboard tank Fuel management techniques according to the schedule shown in figure 2 were assumed in the calculations The reserve tanks are not engine feed tanks, and they are kept full during most of the mission until the contents are transferred to the outboard main tanks These figures show that for coldest extreme conditions, the fuel temperature in the outboard main and reserve tanks is colder than the current specification freezing point of Jet A (-40° C) The use of higher freezing-point fuel of -29° C or -18° C would not be feasible without a fuel heating system An initial fuel temperature of -15° C is assumed for the extreme winter case of figure 4, hence, some ground heating may be necessary for the -18° C freezing-point fuel before loading Reference 1 discusses ground handling requirements for high-freezing-point fuels Since figure 4 depicts the coldest fuel tank temperatures, it is used to determine the heat requirement of each fuel tank to maintain the fuel temperatures above its freezing point

4 2 FUEL TANK HEATING REQUIREMENTS

Operationally the heating systems are designed to maintain the fuel temperature 3° C above the fuel freezing point This 3° C margin is identical to the margin which is currently FAA certified on Boeing aircraft Therefore, for the -29° C (-20° F) and -18° C (0° F) freezing-point fuels, the operational limits will be -26° C and -15° C respectively

The minimum heat input required to maintain the fuel tanks above the operational limits during the extreme ambient temperature condition (0 3% probability) was calculated by the Boeing AFTTA computer program The values are tabulated below

	Heat Required	
	-29° C Freezing Point	-18° C Freezing Point
Reserve Tank	11 kw (650 Btu/min)	18 kw (1000 Btu/min)
No 1 Main Tank-Outboard Tank	79 kw (4500 Btu/min)	127 kw (7200 Btu/min)
No 2 Main Tank-Inboard Tank	79 kw (4500 Btu/min)	127 kw (7200 Btu/min)

These heat requirements are the design goals for the evaluation of the proposed heating systems

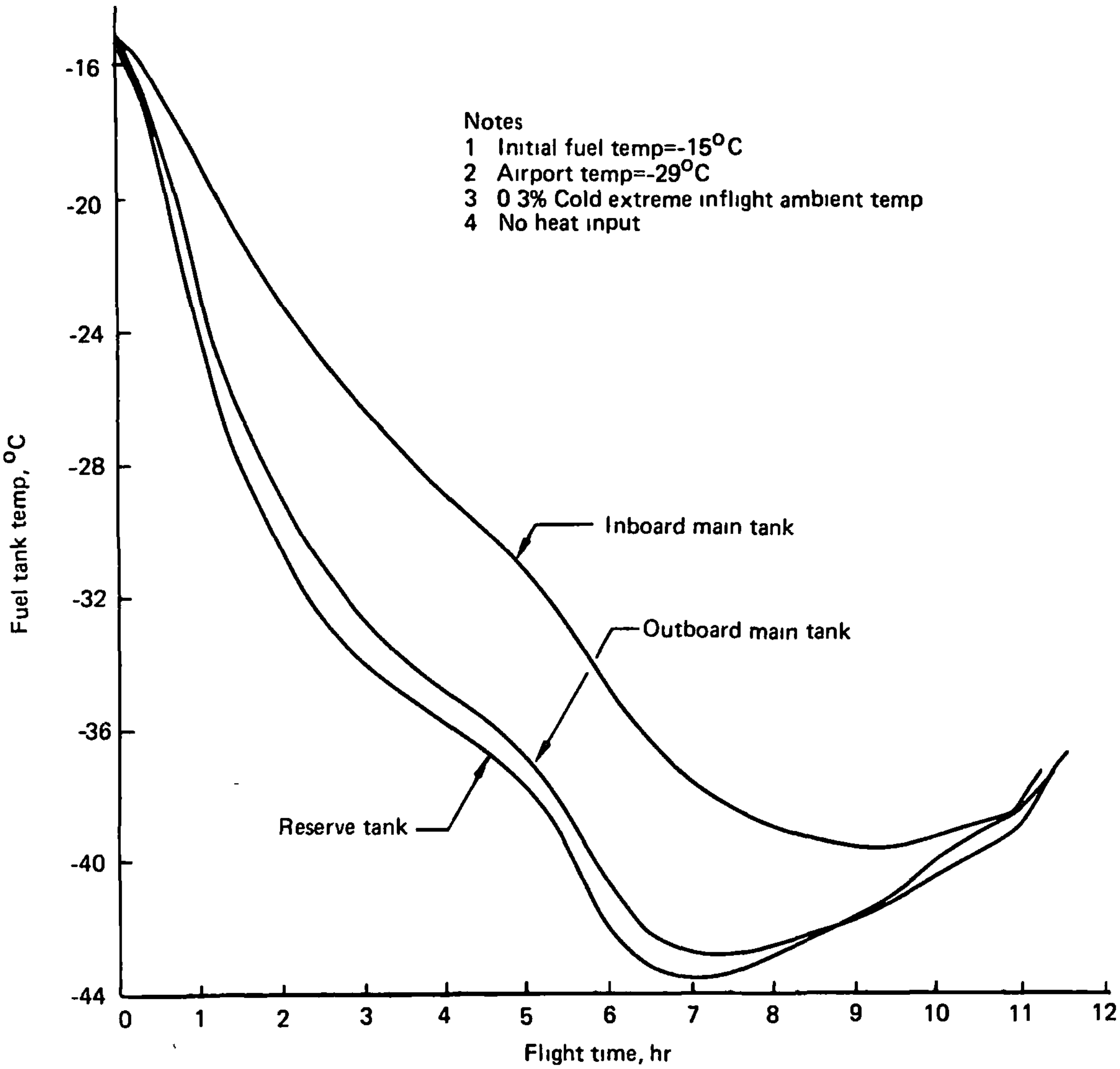

Figure 4 —Predicted Inflight Fuel Temperature for 9300 km, 747-200 Mission—Winter Months

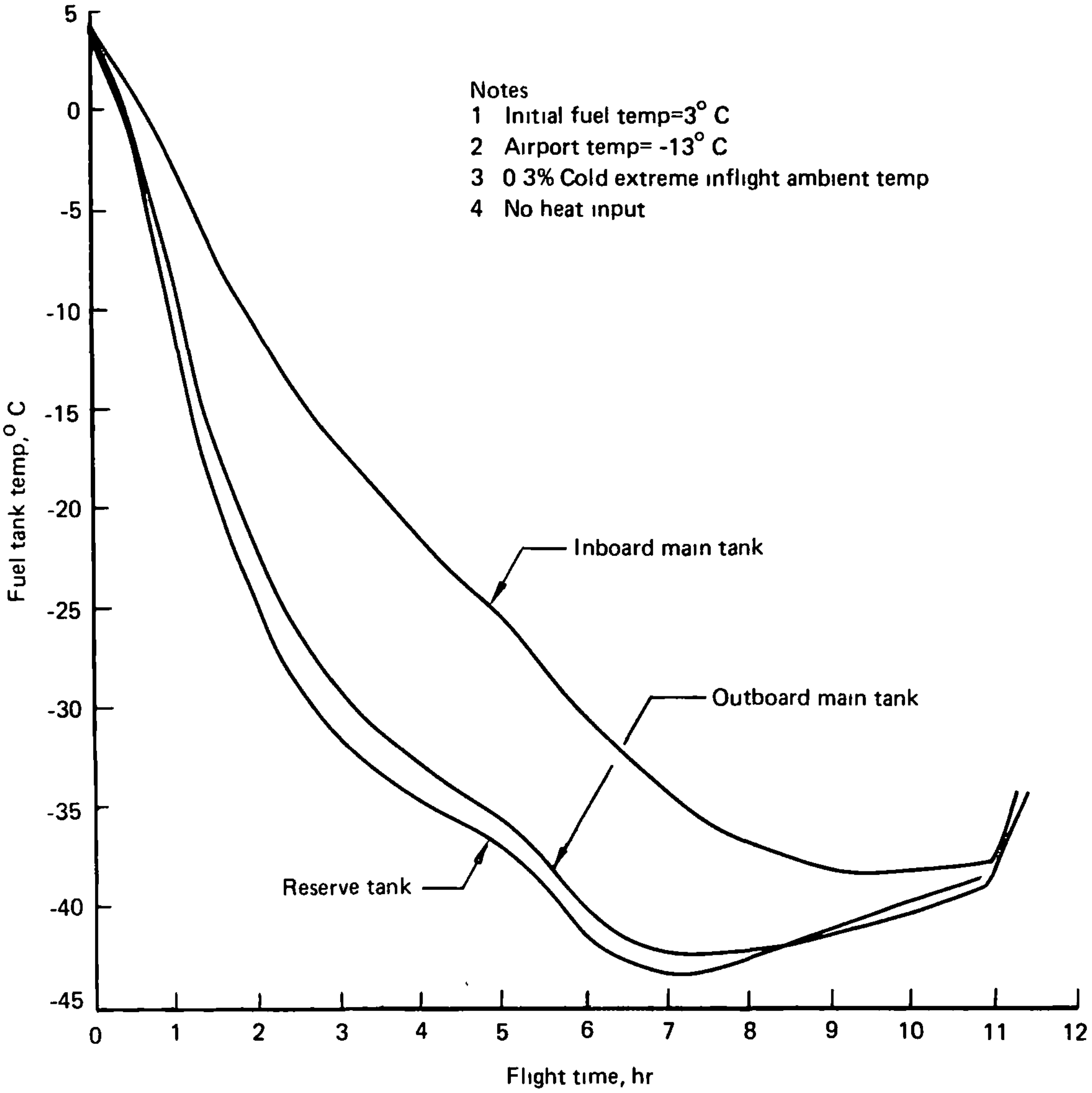

Figure 5 —Predicted Inflight Fuel Temperature for 9300 km, 747-200 Mission—Winter Months

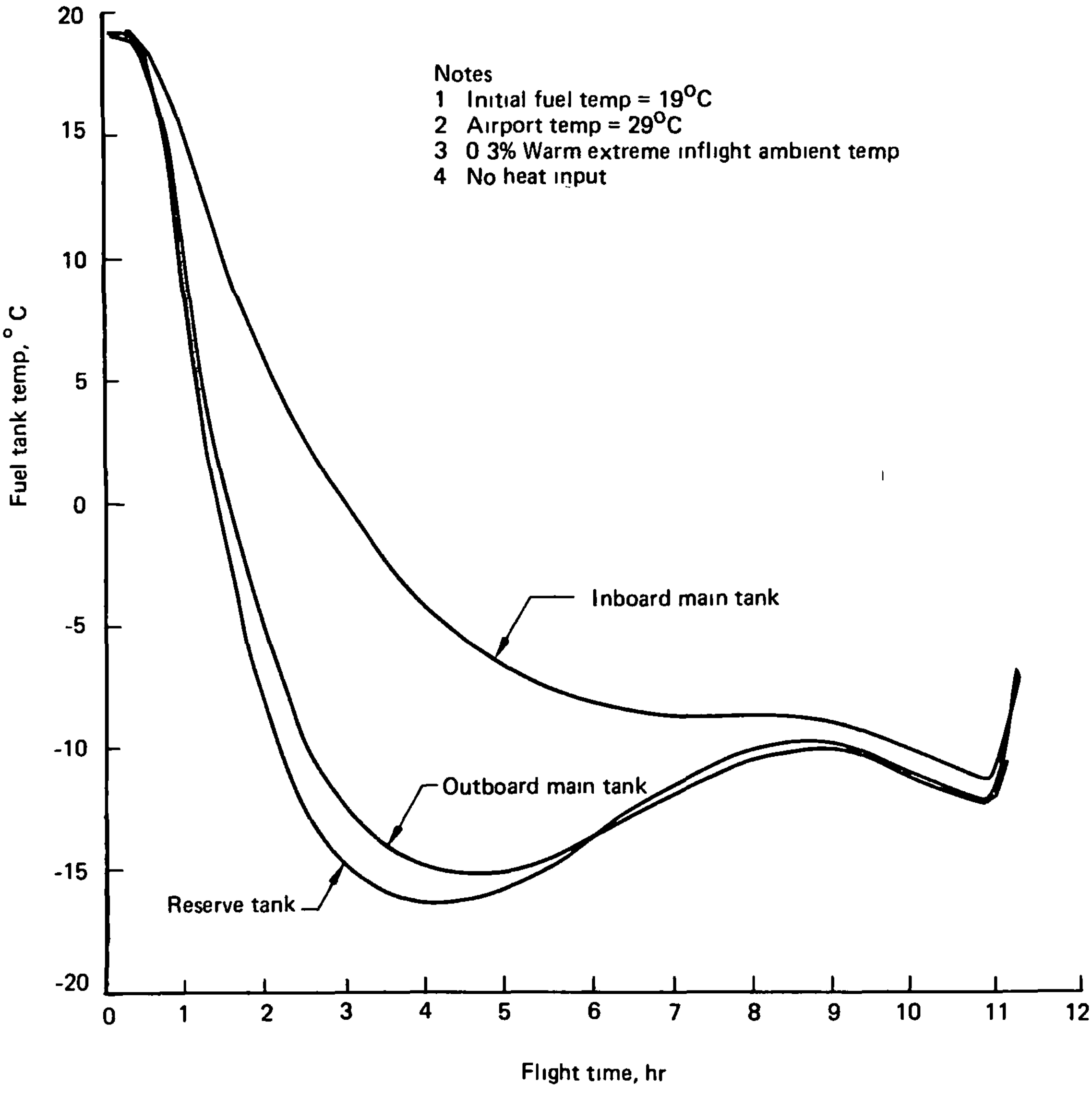

Figure 6.—Predicted Inflight Fuel Temperature for 9300 km, 747-200 Mission—Summer Months

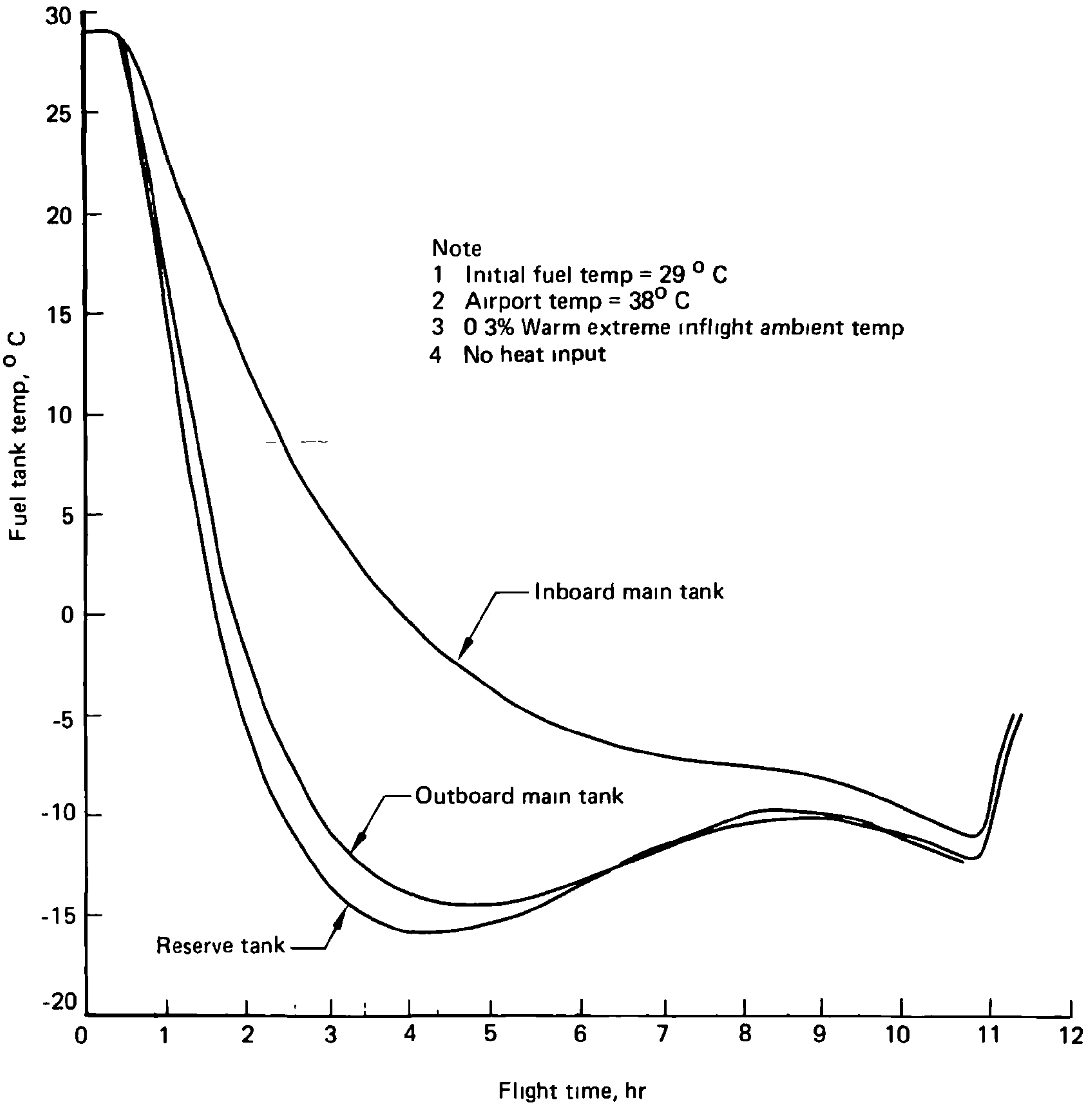

Figure 7 —Predicted Inflight Fuel Temperature for 9300 km, 747-200 Mission—Summer Months

4.3 EFFECT OF HEATING SYSTEM OPERATION ON FUEL TANK TEMPERATURE

The preliminary studies reported in reference 1 assumed a constant rate of heating superimposed on the calculated in-flight fuel temperature. Figure 8 is an example of these results. Curves for the outboard main tank temperature histories with 79 kw (4500 Btu/min) and 127 kw (7200 Btu/min) are shown. It is desirable, however, to operate a heating system in an on-off mode Figure 9 is the temperature history for heated fuel with the heating rate as required for the -29° C freezing-point fuel. The heating system is turned on when the fuel is within 2° C of the operational limit and turned off when the fuel temperature reaches 0° C The calculations assume an instantaneous heat addition when the heating system is turned on Thermal lags in the heating rate can be compensated by turning the heater on at higher temperatures above the operational limit Figure 10 is the temperature history for heated fuel with the heating required for the -18° C freezing-point fuel For this fuel, heating must be turned on at the beginning of the flight, but the turn-off limit of 0° C applies later in the flight The latter limit is arbitrary, based on the assumption that it is necessary to avoid the 200° C thermal stability limit in the fuel system. The procedure of turning the heating system on and off has little effect on the minimum heat requirements but it does reduce the mission heating time and associated flight penalties

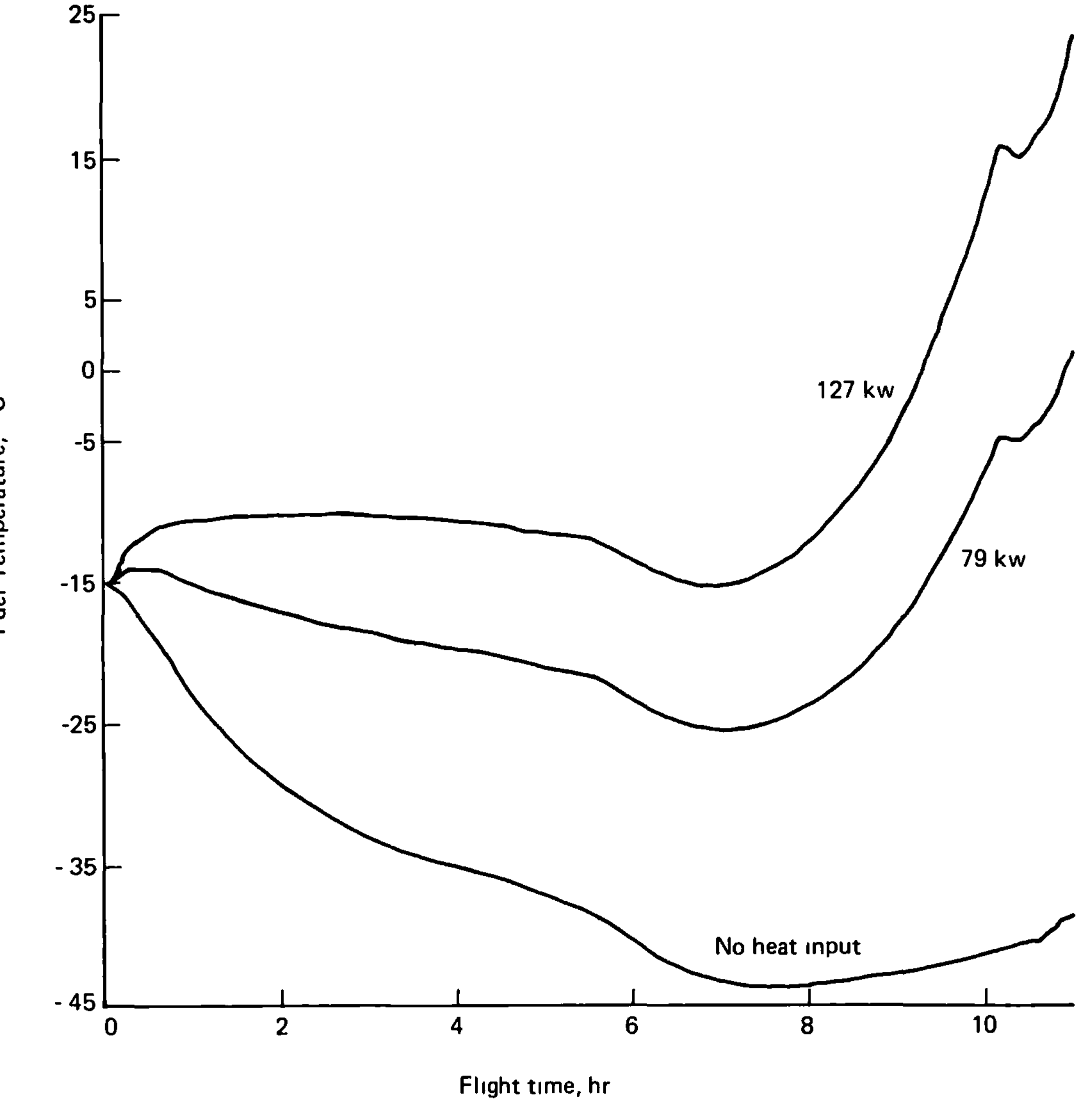

Figure 8 —Predicted Fuel Temperature With Constant Heat Input For 9300 km, 747-200 Mission—Outboard Main Tank

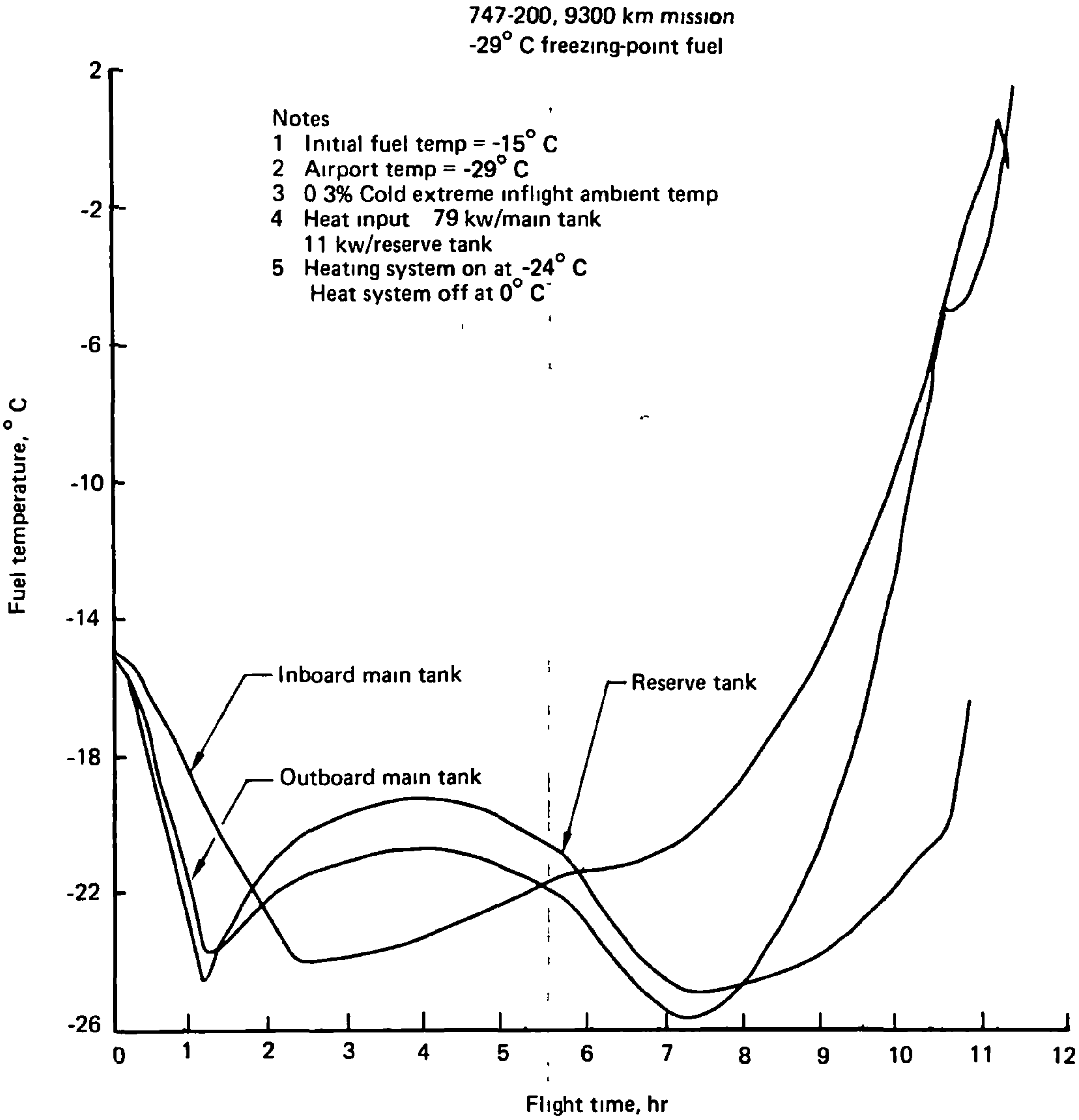

Figure 9.—Heating System Operation with -29° C Fuel

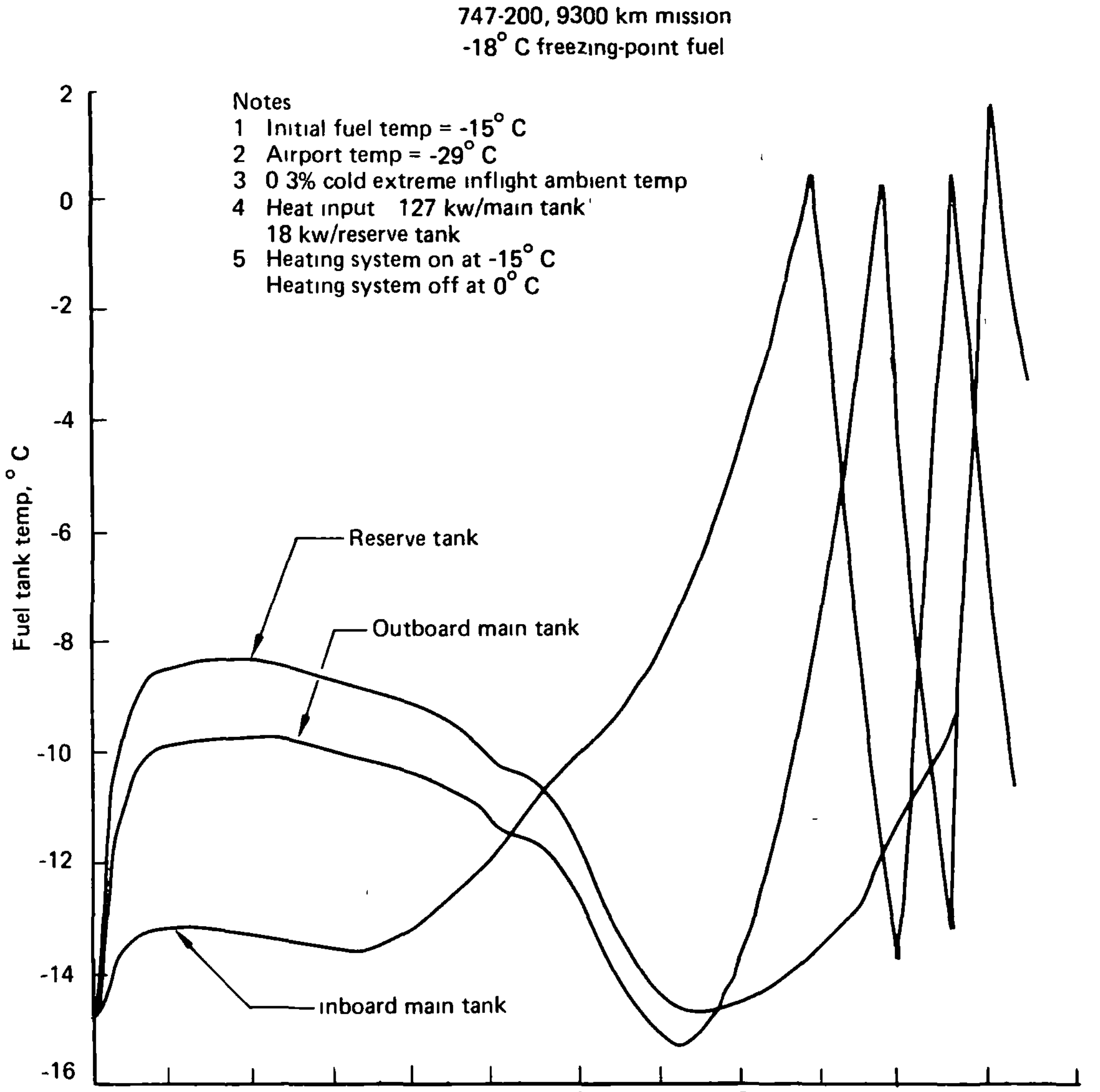

Figure 10.—Heating System Operation with -18° C Fuel

5.0 COMPARISON OF FUEL HEATING CONCEPTS FOR THE 747 AIRPLANE

5.1 INTRODUCTION AND DESIGN ASSUMPTIONS

The results of the predicted fuel tank temperatures 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 the flights. Thus the freezing point of the high-freezing-point fuels will be reached unless fuel, procedural, or aircraft system modifications are initiated

The present study concentrated on the design of five heating systems proposed in reference 1. The systems are

1 Cabin air-conditioning system heat exchanger

2 Engine oil heat exchanger system

3 Engine air bleed heating system

4. Electrical heating system

5 Primary tail pipe heating system

The electrical heating system and the primary tail pipe heating system are sized to maintain the -18° C freezing-point fuel at least 3° C above the freezing point under all conditions The other systems, with smaller heating capability, are sized for heating the -29° C freezing-point fuel 3° C above the freezing point as a minimum.

The basic design assumptions used for this study were

1. The heating systems are designed to be retrofitted on the 747-200 with JT9D-7/7A engines

2 The designs are certificable as determined by an FAA designated engineering representative (DER)

3 The heated fuel temperatures will not exceed 200° C to minimize thermal stability problems

5.2 DESCRIPTION OF FUEL HEATING SYSTEMS

This section of the report describes the heat sources investigated The design of these systems are based on the 747-200 aircraft with JT9D-7/7A engines flying a 9300 km mission Since the heat source for all these systems is the engine, the standard engine was used for specific design calculations However, it is likely modifications to the General Electric and

Rolls-Royce engines currently used on the 747-200 may be feasible.

5.2.1 CABIN AIR-CONDITIONING SYSTEM HEAT EXCHANGER

Air for the aircraft air-conditioning system is supplied by the engines during flight through the airbleed system Prior to entering the air-conditioning system the air is precooled to 177° C with a fan air precooler During flight when the air-conditioning and bleed air systems are operating at essentially a constant rate, the amount of heat rejected to the precooler is approximately 34 kw/engine (1950 Btu/min/engine) By replacing the fan precooler with an air/fuel heat exchanger, the rejected heat could be utilized to heat the fuel tanks

By modifying the air-conditioning system, temperature of the bleed air entering the air-conditioning system can be decreased from 177° C to 93° C to make more heat available This would increase the amount of heat available to 86 kw/engine (4875 Btu/min/engine) Figure 11 is a schematic drawing of the air-conditioning system used for fuel heating

5 2.2 ENGINE OIL HEAT EXCHANGER SYSTEM

The engine oil cooling system on the JT9D-7 engine is designed to maintain the engine oil temperature below 120° C 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 is also included for conditions where the heat rejection rate is high enough to depress the engine oil below 93° C (200° F)

Figure 12 shows a schematic of the proposed heating systems which would utilize the heat rejected to the fuel to heat the fuel tanks This system requires another oil/fuel cooler mounted in series with the present cooler and a three-way valve to control operation of the heating system During flight the heat available varies from 33 kw/engine to 70 kw/engine (1850 Btu/min/engine to 4000 Btu/min/engine)

5 2.3 ENGINE AIRBLEED HEATING SYSTEM

The engine airbleed system utilizes a separate bleed air source whose primary function is to heat the fuel To meet the pressure and airflow requirements, a combination of eighth and fifteenth stage bleed is required This combination makes the air temperature into the heat exchanger above 200° C (400° F) To minimize both the hazards involved and potential problems with thermal stability, an ethylene/glycol heat transfer fluid is required between the hot air source and the fuel A schematic of this system is shown in figure 13

5.2.4 ELECTRICAL HEATING SYSTEM

The fuel tank may be heated in-flight by electric immersion heaters in a reservoir To eliminate the hazards of directly heating fuel with electric heaters, an ethylene/glycol solution is used as a heat transfer medium To meet the requirements for the -18° C

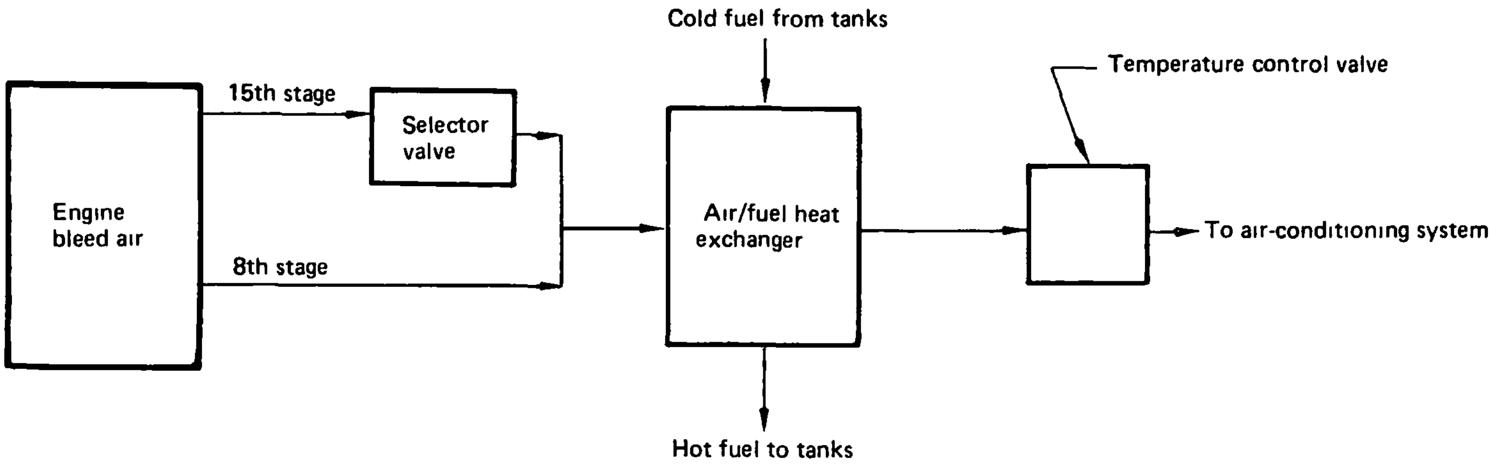

Figure 11.—Cabin Air-Conditioning System Heat Exchanger Schematic

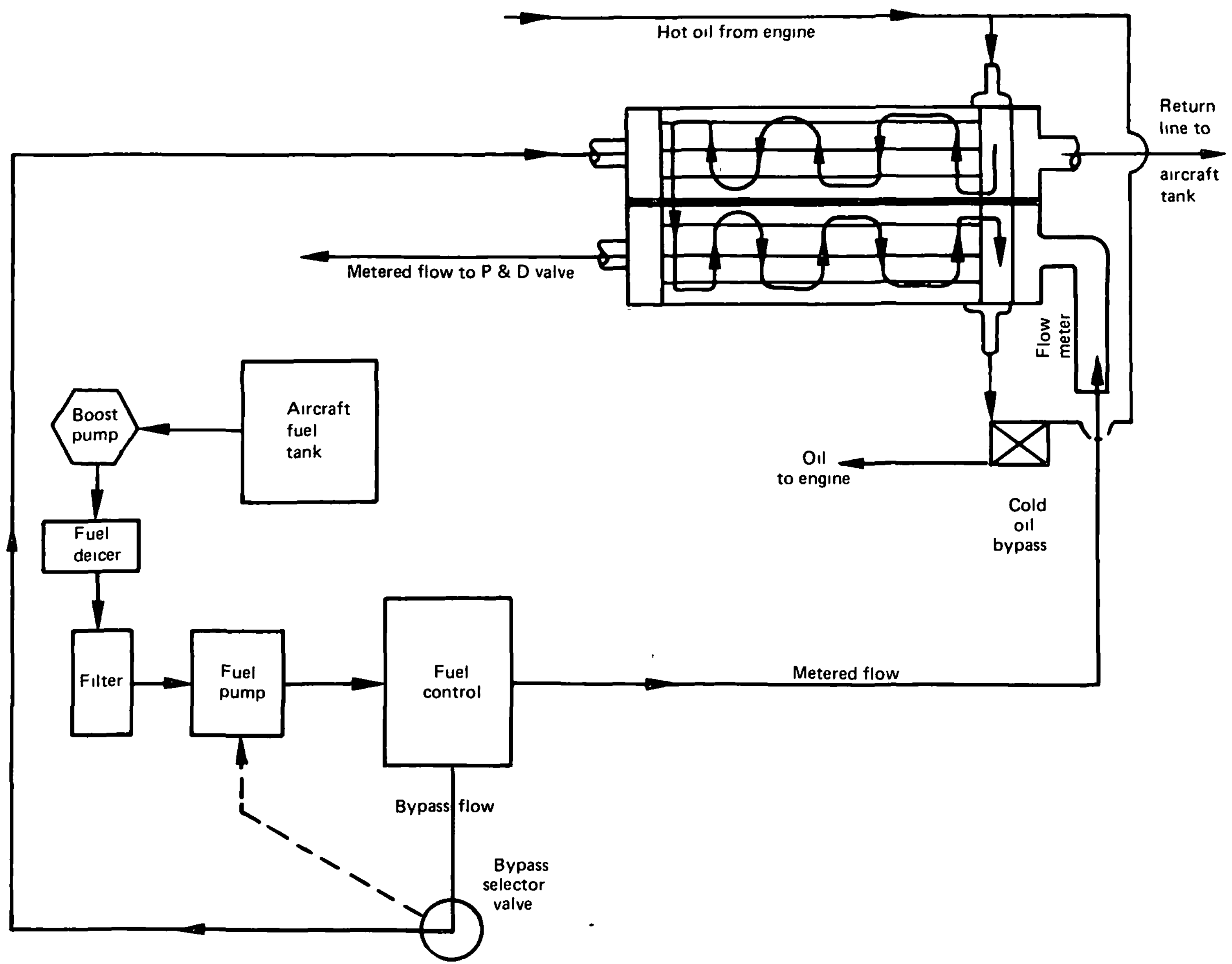

Figure 12 —Engine Oil Heat Exchanger System Schematic

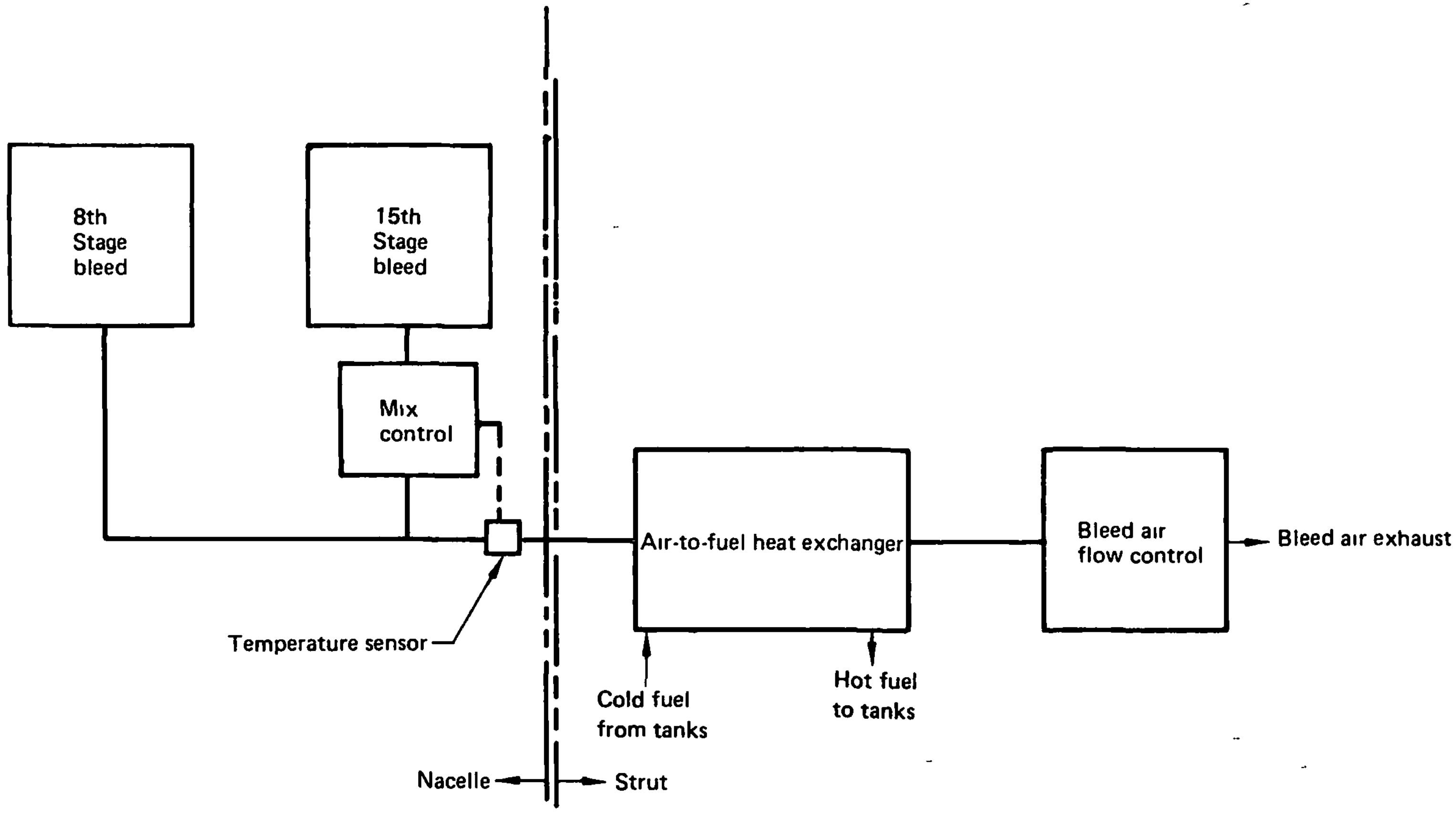

Figure 13.—Engine Airbleed Heat Exchanger System Schematic

freezing-point fuel, dual 150 kVA generators are installed on each engine for providing the electrical energy as required A schematic of this system is shown in figure 14

5.2.5 PRIMARY TAILPIPE HEAT EXCHANGER SYSTEM

The primary tailpipe heat exchanger system utilizes the heat available from the primary exhaust gases through a heat exchanger mounted in the primary tailpipe The present tailpipe is an Inconel honeycomb construction with perforations on the innerwalls for acoustic attenuation The heat exchanger will be wrapped around the tailpipe with baffles to prevent stagnant areas where localized heating may occur To meet the safety requirements a heat transport fluid is used between the fuel and the tailpipe heat exchanger A schematic of this system is shown in figure 15

5 3 DISCUSSION AND EVALUATION OF HEATING SYSTEMS

As mentioned, the five proposed heating system concepts are in two groups Three are sized to maintain the -29° C freezing-point fuel at least 3° C above the freezing point under all conditions, the other two are sized for the -18° C freezing-point fuel The systems in each group are ranked against each other The -29° C freezing-point fuel heating systems are considered as minor retrofit modifications with low complexity, cost and performance penalties as goals The -18° C freezing-point fuel heating systems are considered major modifications with feasibility as a goal at the expense of some complexity and performance penalties

Of the systems designed to meet the requirements for the -29° C freezing-point fuel, the system ranked highest from the standpoint of least risk, ease of installation, and minimum performance penalty is the engine oil heat exchanger system The cabin air-conditioning system heat exchanger is judged a high design risk since the air used in the heat exchanger is used in the air-conditioning system Extreme care must be taken to ensure that there is no fuel leakage into this air source. This would require a redundant system and a fuel leakage detection system Furthermore, during hot day operation when maximum cooling of the bleed air is required, there is a possibility the fuel temperatures within the heat exchangers could approach 200° C (400° F) From both a safety and thermal stability consideration, a secondary system is required for hot day situations

The engine airbleed heat exchanger system was judged difficult to install and has a high performance penalty when compared to the engine oil heat exchanger system For this system two additional heat exchangers would be required - an air/heat transfer fluid heat exchanger and a heat transfer fluid/fuel heat exchanger The air/heat transfer fluid heat exchanger could be mounted in the strut, however, a suitable location for the heat transfer fluid and reservoir, and its associated valves and pumps must be found Extensive rework of the fuel tanks and/or the area in the front spar would be required The increased fuel flow penalty associated with this system operating varies from 0 5% to 2% per engine depending on the airbleed required For comparison, the fuel flow penalty associated with the engine oil heat exchanger system is assessed to be negligible when this system is in operation

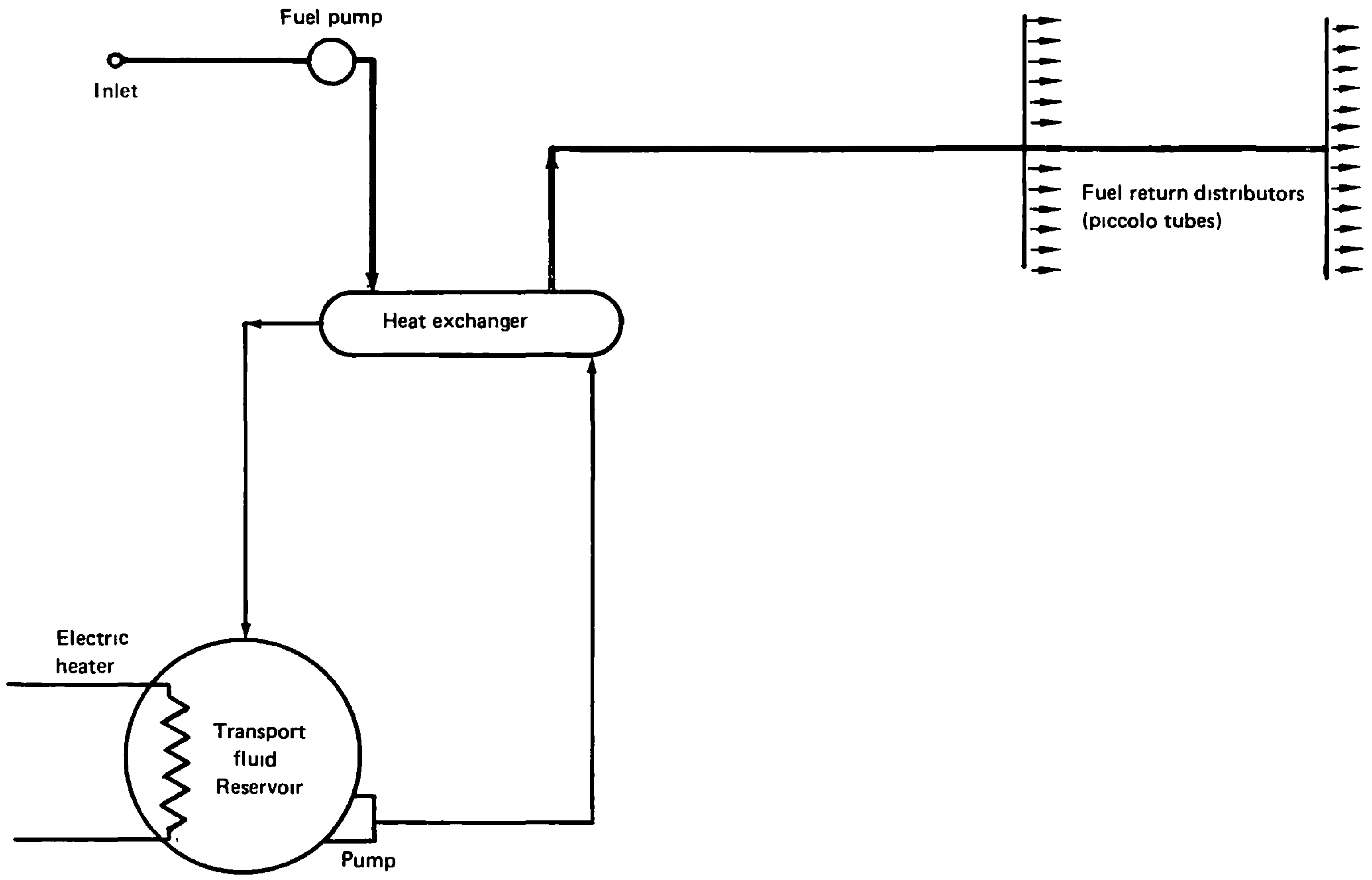

Figure 14.—Electrical Heating System Schematic

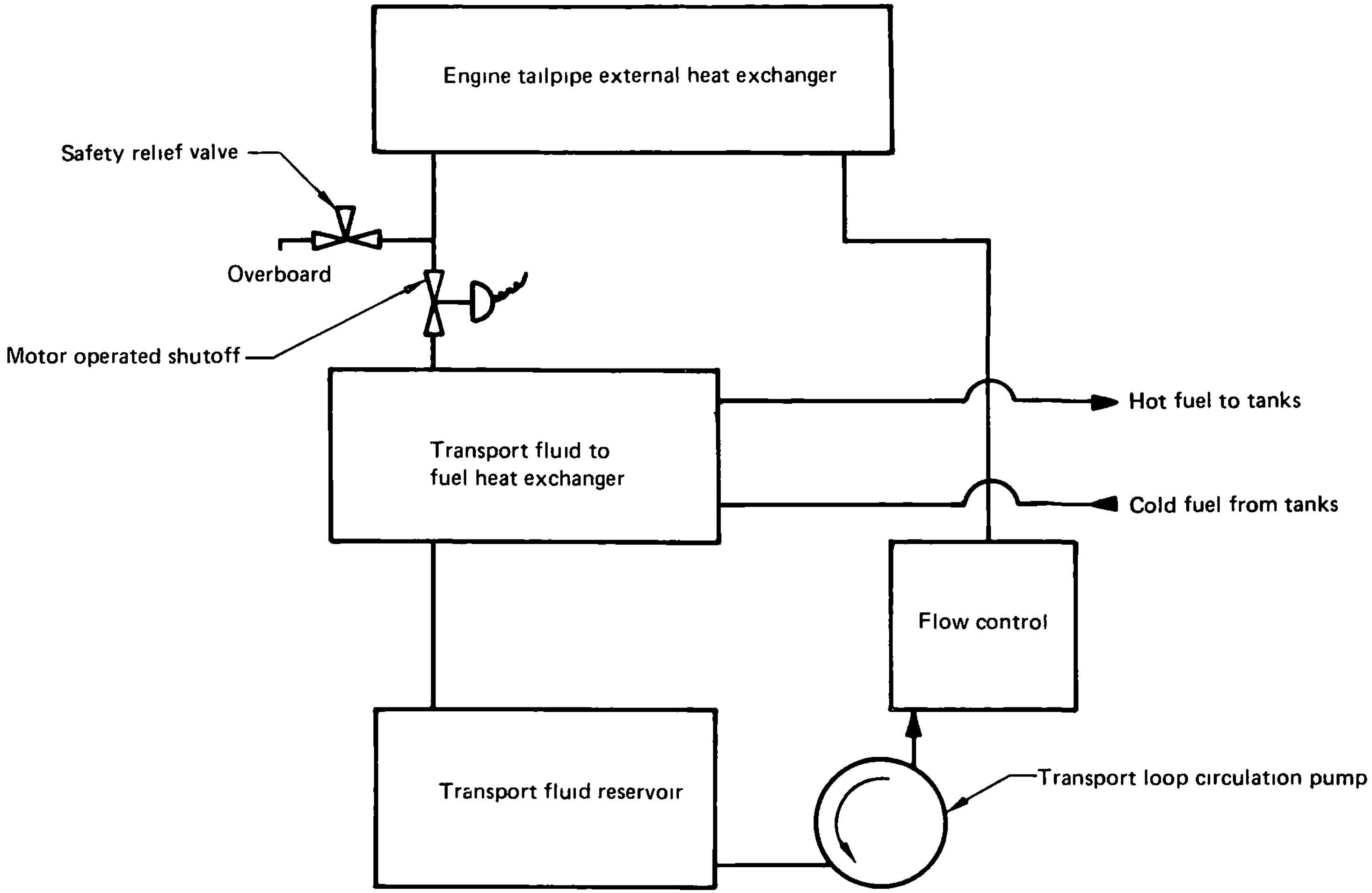

Figure 15.—Primary Tailpipe Heat Exchanger Schematic

It should be noted that the heat available for the engine oil heat exchanger system varies from 33 to 70 kw/engine which does not meet the requirements of 79 kw/engine for the -29° C freezing-point fuel. In fact, during the cruise portion of a long-range flight, the heat output for this system is nearly constant at about 50 kw/engine Figure 16 presents the calculated temperature history for the outboard main tank with heat addition by the engine oil heat exchanger system The maximum freezing point that this system will satisfy is -34° (-31° C + 3° C margin). Because of the clear superiority of this system in minimal weight and performance penalties, it merits consideration as the representative minor modification system

For the two systems designed to meet the requirements of the -18° C freezing-point fuel, the electrical heating system was ranked higher than the primary tailpipe heat exchanger system because of the high design risks associated with the primary tailpipe heat exchanger system The areas of concern with this system which may require redesign of the tailpipe installation to accomodate the heat exchanger are

1. Thermal stresses introduced into the inner honeycomb sleeve due to different temperature distributions with the system on or off

2. Design of the tailpipe heat exchanger to minimize additional stresses due to the thermal expansion of the tailpipe.

3. The effect of operating pressures of the heat exchanger system on the honeycomb structure

4. The stresses introduced on the rear engine by the heat exchanger weight of 86 kg (190 lbs) requires a redesign of the flange.

The design risks involved with the electrical heating system are minimized since the additional generators and accessory drive are modeled on an existing system designed and built for the Boeing 747-E4B Command Post This system is intended for electronics power, but the electrical power components are adaptable for the electrical heating system

In summary, the preliminary comparison of systems indicated that the engine oil heat exchanger system is the most promising minor modification for -29° C freezing-point fuel and the electrical heating system is the most promising major modification. The overall rankings of the heating systems evaluated are

1. Engine oil heat exchanger system

2. Electrical heating system

3. Engine airbleed heat exchanger system

4. Cabin air-conditioning system heat exchanger

5. Tailpipe heat exchanger

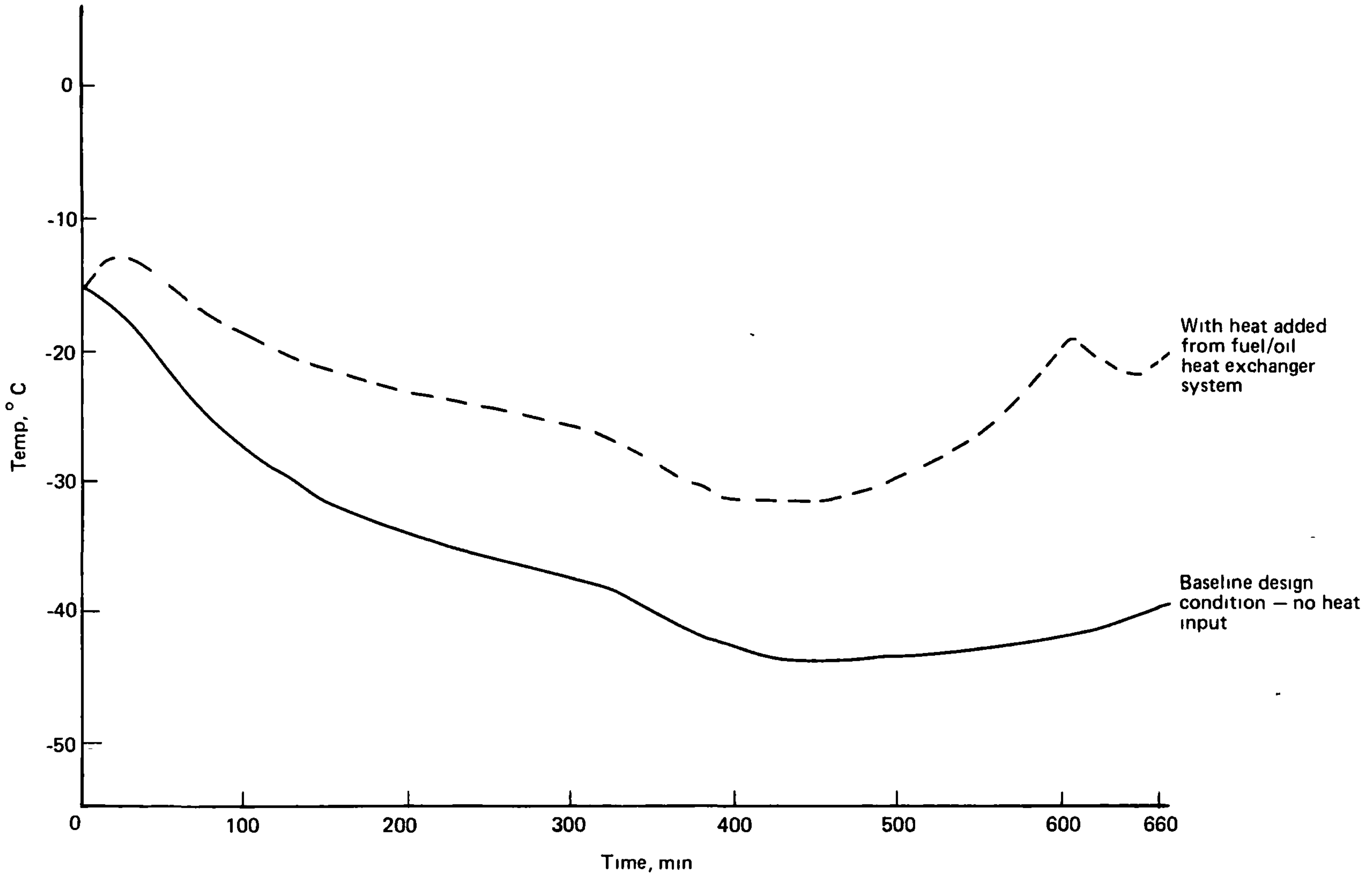

Figure 16.—747-200, 9300 km Mission, No 1 Main Tank Fuel Temperatures for Engine Oil Heating, P&WA JT9D-7A Engine

6.0 DESCRIPTION OF SELECTED FUEL HEATING SYSTEMS FOR THE 747 AIRPLANE

The engine oil heat exchanger system and the electrical heat system were selected for further detailed design so that a more precise estimate of weights, performance and costs is established.

6.1 ENGINE OIL HEAT EXCHANGER SYSTEM DESCRIPTION AND OPERATION

The engine oil heat exchanger system (fig 12) comprises an additional engine mounted oil/fuel heat exchanger, a three-way valve and fuel return lines from each engine to the tanks. The operation of this system is such that when heat is required, the three-way valve that is incorporated into the fuel bypass line is switched in the recirculation mode and directs the bypassed fuel to the new oil/fuel heat exchanger. The heated fuel is recirculated back to the tanks via the return lines When heat is not required the three-way valve is switched to the normal mode and the system operates normally

The modifications required for the wing tanks are sketched in figures 17 and 18. The fuel return lines include a shutoff valve at the front spar of each tank and perforated discharge or piccolo tubes at the discharge end These piccolo tubes are 3.8 cm (1½-inch) aluminum tubes that are capped on both ends with 1 cm (3/8-inch) holes along the length of the tube. The location of the piccolo tubes are such that the heated fuel would assure the flapper check valves will not be obstructed with frozen fuel and also achieve adequate mixing between the frozen and heated fuel

6 2 ELECTRICAL HEATING SYSTEM DESCRIPTION AND OPERATION

The electrical heating system is based on power supplied by additional engine accessory-drive generators, modeled after the existing 747-E4B Command Post design The 747-E4B Command Post requires approximately 700 kVA of electrical energy to power the aircraft To meet this power requirement Pratt & Whitney Aircraft (P&WA) proposed a JT9D-7 with a dual 150 kVA integrated drive generator (IDG) units/engine for a resultant power capability of 1200 kVA After considering loss of an engine and line losses, the total power available is approximately 800 kVA

For the design mission, the energy required for the -18° C and -29° C freezing-point fuels are 540 kVA and 340 kVA respectively The power available from the P&WA dual 150 kVA IDG units will meet the requirements for the -18° C freezing-point fuels

The engine changes required for the dual 150 kVA IDG/engine installation included gear box, housing, and oil tank modifications External fuel control, fuel, and oil plumbing changes are also required to accomodate the generator installation

The overall view of the airframe installation for the electrical heating system is shown in figure 19 The electrical energy generated by this system is used to heat four heat transfer fluid reservoirs located in the lower forward equipment bay, figure 20 The fluid in the reservoirs is heated with electric immersion heaters The heated fluid is pumped from the

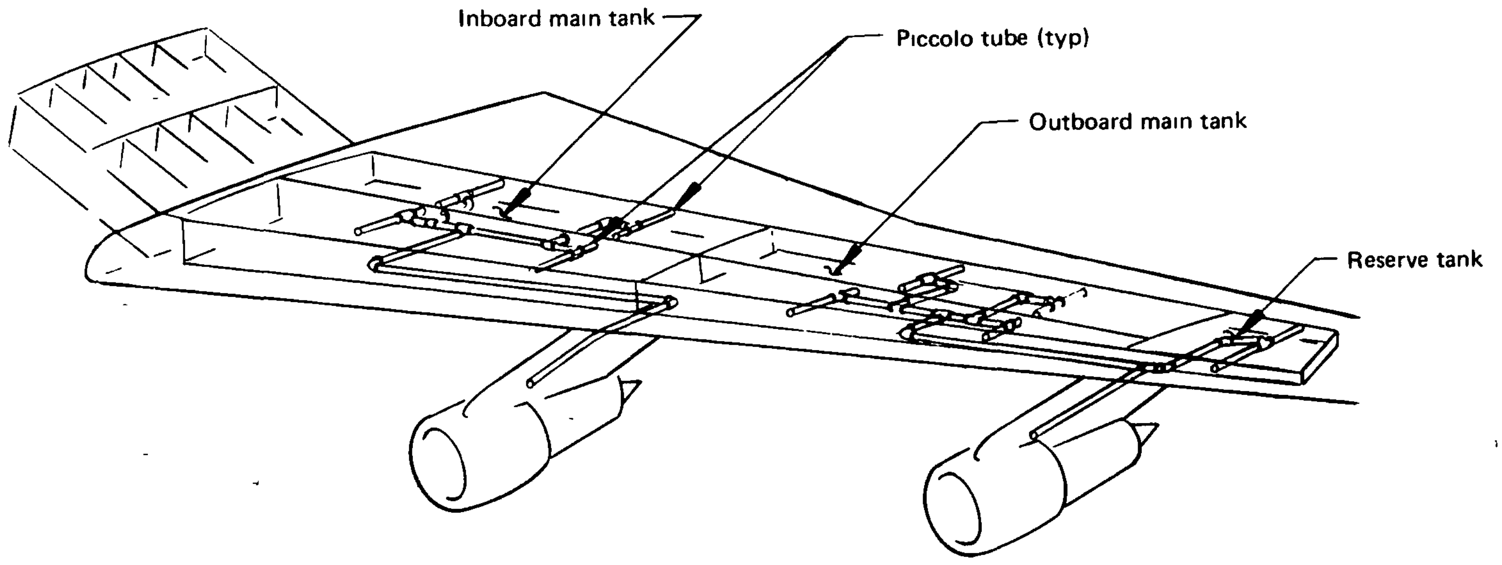

Figure 17.—Engine Oil Heat Exchanger System Airframe Installation—Perspective

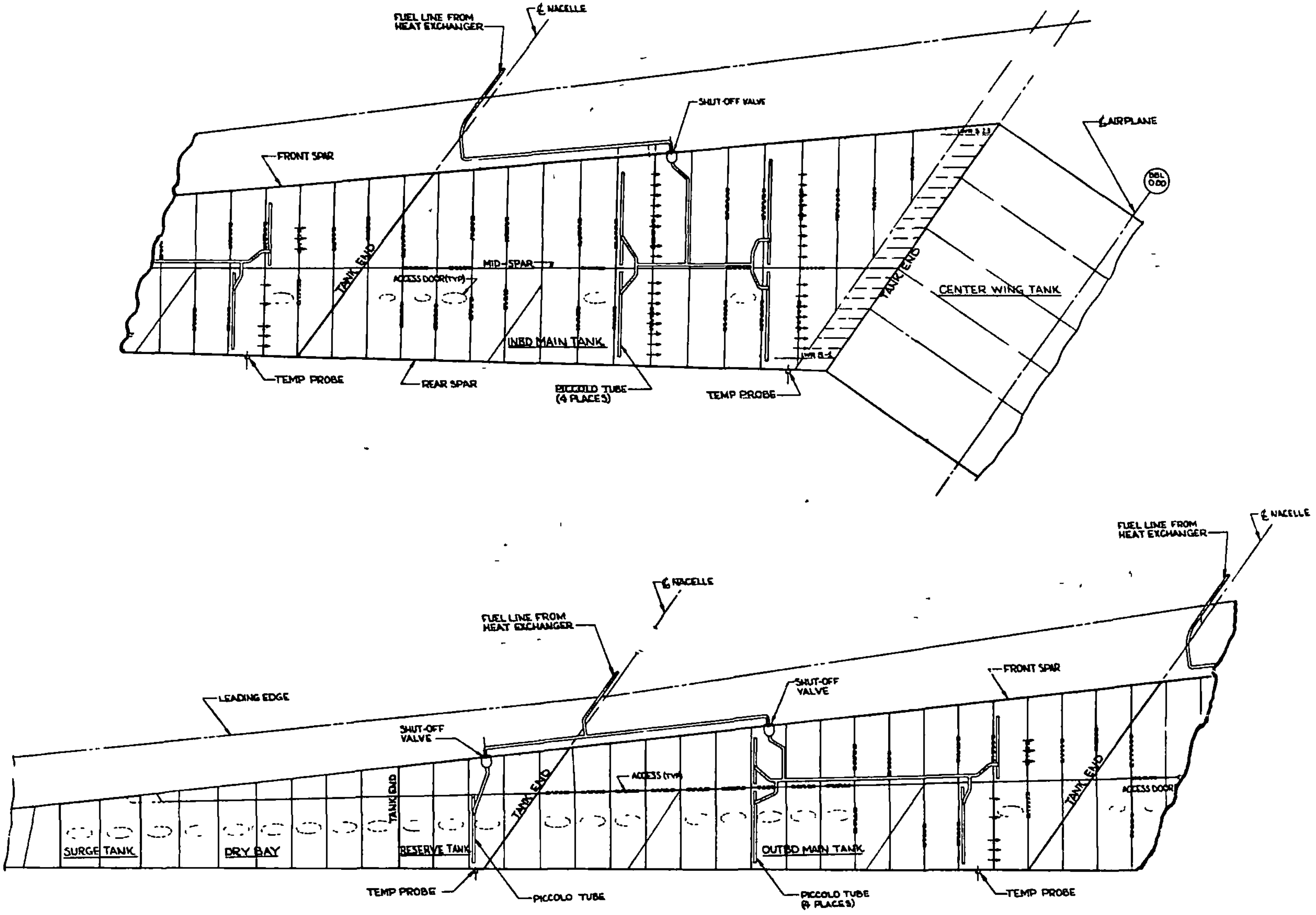

Figure 18.—Engine Oil Heat Exchanger System Fuel Return Lines—Plan View

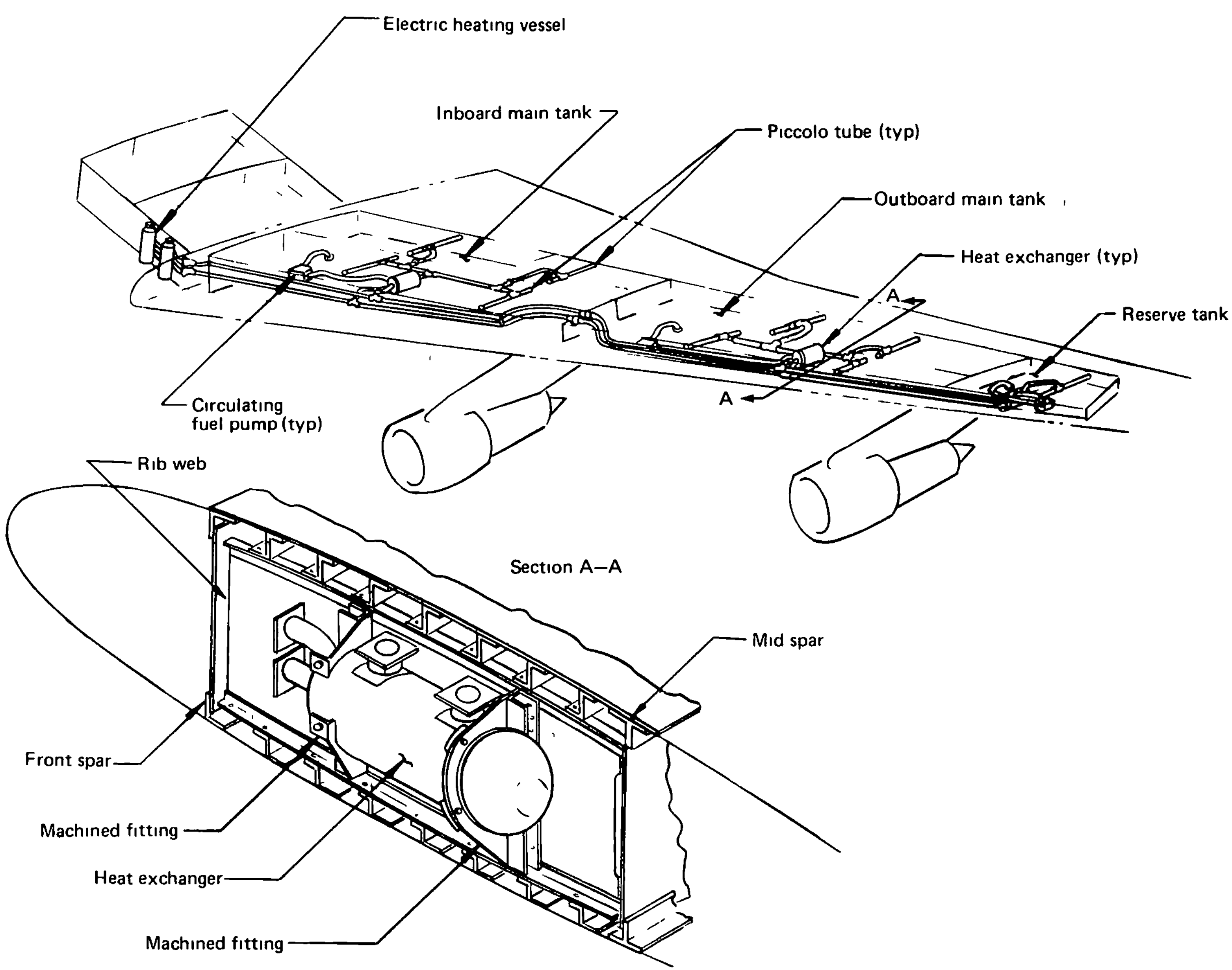

Figure 19 —Electrical Heating System Airframe Installation Perspective

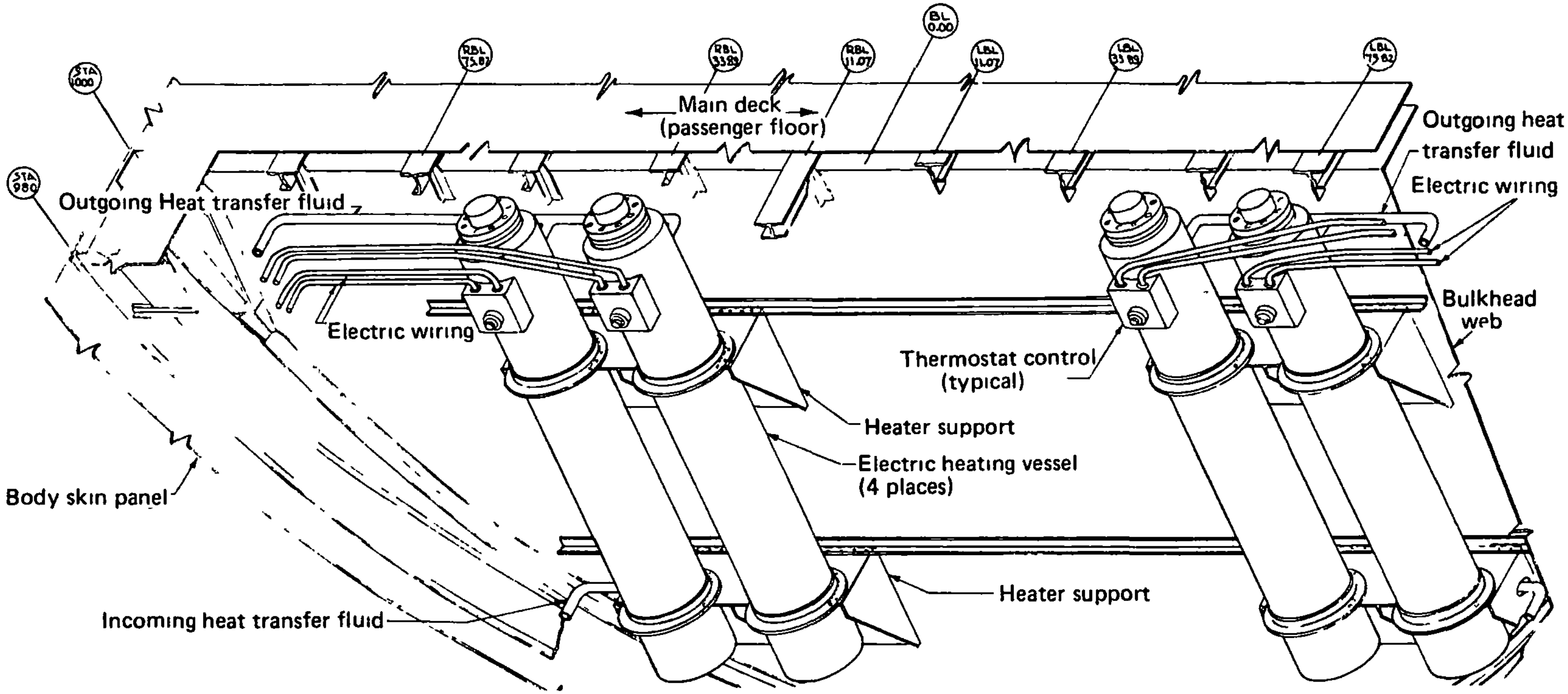

Figure 20.—Heat Transfer Fluid Reservoir

reservoir to the fuel/heat transfer fluid heat exchangers located in the fuel tanks Each reservoir is operated independently and is able to provide heat to any or all heat exchangers.

A ground service panel will be provided to allow fuel heating on the ground without engine power This system is similar to the liquid cooling system presently used on the E4B aircraft

The fuel heating lines are installed inside the fuel tanks and provide fuel recirculation for transferring the heat load from the heat transfer fluid to the fuel in the tanks, figures 19 and 21 Fuel from each of the wing fuel tanks is delivered to the corresponding heat exchangers and is mixed with the remaining fuel in the tanks through the piccolo tubes The fuel heating lines for each tank are an independent system that is not part of engine fuel feed system and does not transfer fuel from one tank to another Each fuel heating line consists of a fuel pump, shutoff valve, controls, and fuel recirculating plumbing

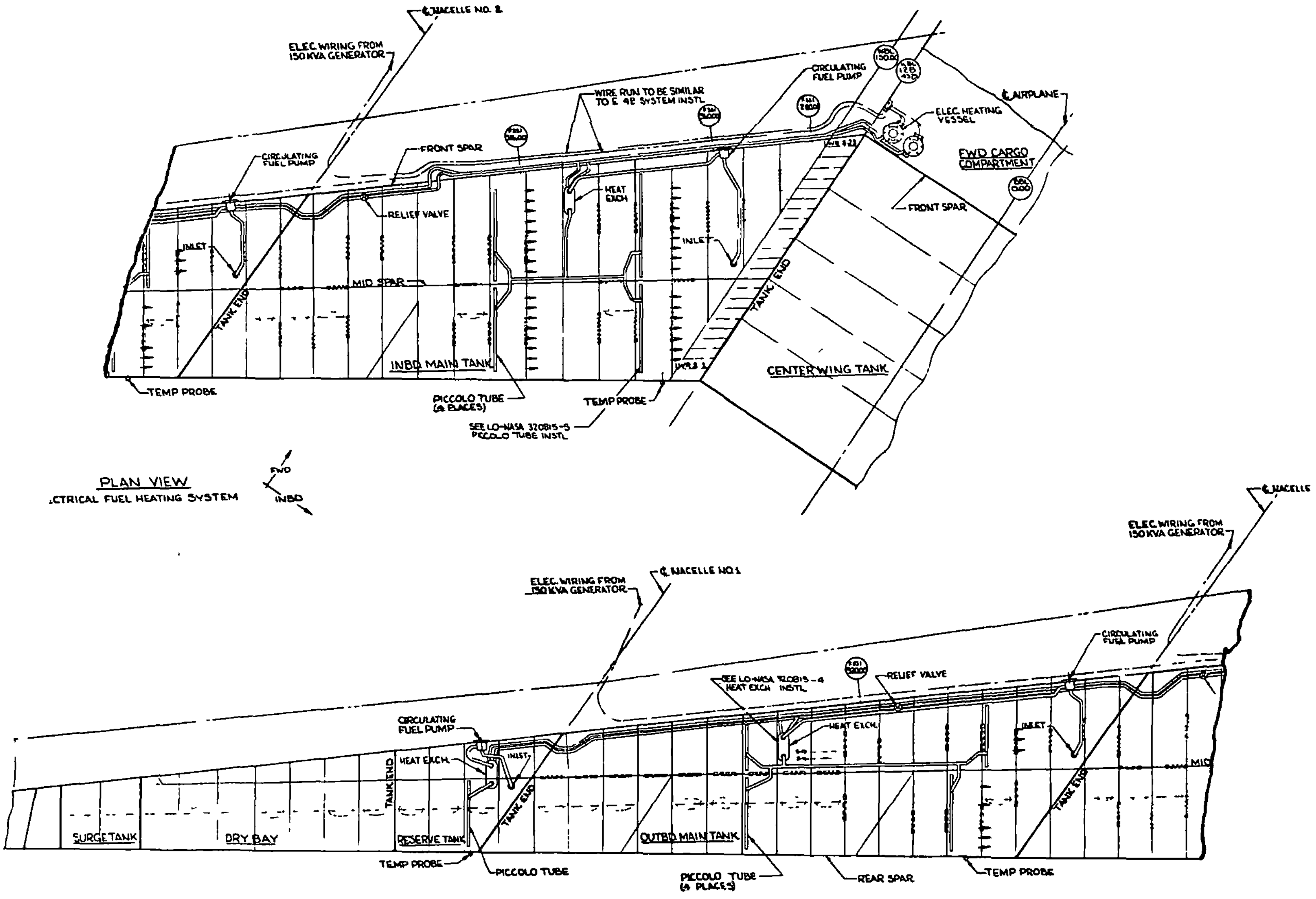

Figure 21.—Electrical Heating System Wing Installation—Plan View

7.0 PERFORMANCE AND ECONOMIC ANALYSIS OF SELECTED FUEL HEATING SYSTEMS

7.1 PERFORMANCE PENALTIES AND WEIGHTS

Performance penalties are calculated on the basis that a fuel flow change for the engine, due to the system operation, is calculated to maintain a constant net thrust at cruise This penalty is assessed as a fuel penalty for the mission and this increased fuel penalty is added to the weight of the heat source

7.1 1 ENGINE OIL HEAT EXCHANGER SYSTEM

The performance penalty of this system is regarded as negligible since the heat being utilized is only used to increase the fuel temperature prior to combustion The total weight of this system is 163 kg (360 lb)

7 1.2 ELECTRICAL HEATING SYSTEM

The performance penalty of this system is calculated as a percent change in thrust specific fuel consumption (TSFC) per engine for the requirements of the -29° C and -18° C freezing-poing fuels At a nominal thrust of 39kN (8800 lbs), the performance penalties are 0 43% and 0 67% TSFC/engine for the -29° C and -18° C freezing-point fuels respectively The total weight of this system is 1520 kg (3350 lbs)

7 2 PERFORMANCE PENALTIES BASED ON AVERAGE UTILIZATION

7 2 1 CALCULATION OF FLIGHT UTILIZATION

The penalties established in section 7 1 are based on a system sized to provide the required heating for an ambient temperature condition with a one-day-a-year probability Using these penalties assumes that the system is operated at 100% output on every flight

To obtain a realistic operating average fuel consumption penalty, the average utilization rate of the system based on flight frequency and average in-flight ambient temperature for both summer and winter months was determined This method was used in reference 1 and is equally applicable for this study The resulting utilization rates are summarized in table 2 for the 9300 km mission

Table 2.—Utilization of Heating Systems

	Percent of flights predicted to use system			
	Winter months		Summer months	
Mission	-18° C Fuel	-29° C Fuel	-18° C Fuel	-29° C Fuel
9300 km	73	5 3	59	0

7.2.2 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 3.

Table 3.—Average Fuel Consumption Penalty Based on Utilization Rates

Heating system	Percent fuel consumption penalty (100% utilization)		Percent average fuel consumption penalty using combined utilization rates			
			-18° C Fuel		-29° C Fuel	
	-18° C Fuel	-29° C Fuel	Winter	Summer	Winter	Summer
Engine oil heat exchanger system	—	0	—	—	0	0
Electrical heating system	2 68	1 72	1 96	1 58	0 09	0

It should be noted that the engine oil heat exchanger system is limited to a -34° C freezing-point fuel, but comparisons and analyses are labeled -29° C for simplicity.

7.3 ECONOMIC ANALYSIS

7.3.1 INSTALLATION COSTS

Price estimates for both systems included the following

1. Nonrecurring costs for each system, including detail design, staff and certification costs, lab tests and flight test

2. Manufacturing nonrecurring costs including planning, jig tooling, manufacturing development, and quality control.

3 Recurring costs developed from purchased equipment costs

Installation work statements are used to determine manufacturing costs for an assumed 300 airplane retrofit program The prices are based on a 300 airplane Boeing 747 fleet being retrofitted at a Boeing Modification Center using customary modification scheduling The baseline engine is the P&WA JT9D-7A The estimate does not include downtime penalty or receiving/delivery operations as it was assumed that this change would be incorporated into a routine maintenance period with other work

On these bases, the estimated initial cost for the oil heat exchanger system in 1978 dollars is about $200,000 per airplane The corresponding cost for the electrical heating system would be roughly three times greater

These costs are considerably higher than those estimated in reference 1. The higher costs are due to a more detailed estimate of retrofit and component costs

7.3.2 DIRECT OPERATING COSTS

Direct operating costs (DOC) are based on the Boeing Company revision to the basic ATA mission profile (ref 3) 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 4 The additional fuel, weight, and maintenance penalties are used in the program to obtain the incremental DOC increase

Table 4.—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 80% 1967 ATA
Cruise procedure	New minimum cost constant, M, step climb
Crew expense	Function of gross weight and speed
Fuel price	82¢/L (40¢/gal) U S domestic, 10 9¢/L (45¢/gal) U S intercontinental
Maintenance	Mature level maintenance based on detailed analysis Engine line maintenance labor is included in engine maintenance Labor rate = $10 50/manhour Burden = 200% of direct labor
Depreciation	New — 15 years to 10% on airplane and spares Used — 10 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 nonrevenue flying

Incremental decrease in fuel price required to affect the incremental increase in DOC is computed using a base price of 11 9¢/L (45¢ gal) Table 5 presents the resulting direct operating costs

Table 5.—DOC Analysis of Fuel Heating System — 9300 km Mission

Systems	-18° C Fuel			-29° C Fuel		
	Fuel price offset		ΔDOC	Fuel price offset		ΔDOC
	¢/liter	¢/gallon	%	¢/liter	¢/gallon	%
Engine oil heat exchanger system	—	—	—	-0 26	-1 0	2 2
Electrical heating system	-2 2	-8 3	10 4	-1 5	-5 7	7 4

7.3 3 RETURN ON INVESTMENT

Return on investment (ROI) estimates are calculated for the recovery of initial costs of the modifications Table 6 is a summary of the Boeing ROI criteria for amortization, depreciation and other cash recoveries The ROI calculations are made based on the utilization rates for both high-freezing-point fuels A summary of the ROI percentage decrease and the fuel price decrease which would offset the change in ROI is shown in table 7 This table is analogous to the DOC presentation in table 5

Table 6 —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 cost 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 7 —ROI Analysis of Fuel Heating Systems — 9300 km Mission

Systems	-18° C Fuel			-29° C Fuel		
	Fuel price offset		ΔROI	Fuel price offset		ΔROI
	¢/liter	¢/gallon	%	¢/liter	¢/gallon	%
Engine oil heat exchanger system	—	—	—	-0 67	-2 6	-0 61
Electrical heating system	-4 5	-17 0	-4 80	-3 2	-12 3	-3 40

7.3.4 EFFECT OF MISSION RANGE ON DOC AND ROI

The baseline mission for which the heating systems are designed is a 9300 km (5000 nmi) range The 747-200 with JT9D-7A engines will meet this mission requirement with a full fuel load and 423 passengers However, with the heating systems installed, this 9300 km trip cannot be accomplished without offloading of passengers which affects the ROI significantly because of the reduced revenue The number of passengers required to be offloaded are

Engine oil heat exchanger system	3 Passengers
Electrical heating system for -29° C fuel	21 Passengers
Electrical heating system for -18° C fuel	31 Passengers

The average mission of a 747-200 is 5600 km (3000 nmi) range. This mission can be accomplished with the heating systems installed without the offloading of passengers The DOC and ROI estimates for this mission are summarized in table 8

Table 8.—DOC and ROI Analysis for 5600 km (3000 nmi) Mission

	-18° C Fuel		-29° C Fuel	
	Fuel price offset		Fuel price offset	
Systems	DOC ¢/L	ROI ¢/L	DOC ¢/L	ROI ¢/L
Engine oil heating exchanger system	–	–	-0 11	-0 29
Electrical heating system	-0 45	-0 90	-0 34	-0 77

A comparison of table 8 with tables 5 and 7 shows a considerable economic penalty due to the offloading of passengers It should be noted that the 9300 km mission with full payload is a unique mission which comprises less than 1% of all 747 flights. Also the maximum trip that would not require offloading passengers is 8900 km Therefore, the fuel price offsets given in table 8 are closer to the actual economic penalties of the heating system

8.0 DISCUSSION

The predicted in-flight fuel temperatures for the mission and the extreme ambient temperature analyzed indicate that increasing the fuel freezing point beyond the current specification limit would require some modifications either to the flight procedures or to the aircraft This report focuses on selected heating systems studied in reference 1 These heating systems are regarded as the only acceptable means of maintaining fuel temperatures above the freezing points of fuels for long-range flights This study concentrated on these heating systems and evaluated two systems for more detailed analysis

Of the heating systems considered in this study, the engine oil heat exchanger system and the electrical heating system are the best methods of providing the required heat in today's long-range aircraft The engine heat exchanger system is not able to provide enough heat to meet the requirements of a -29° C freezing-point fuel The heat available from this system is adequate only for a -34° C freezing-point fuel However, this system is relatively simple for the function of fuel heating Retrofit considerations for the engine oil heat exchanger system would include the location and supports for the additional oil cooler and the associated engine plumbing

The electrical heating system is designed to meet the heating requirements of the -18° C freezing-point fuel This system is significantly more complex than the engine heat exchanger system and its complexity is of concern from the standpoint of system reliability, ease of retrofit, and maintenance costs The electrical system could be designed to meet the requirements of the -29° C fuel and thus eliminate two of the required four generators However, the complexity of the system would not be reduced significantly since the transport fluid subsystem with its associated controls would be unchanged

The installation costs, increased weight, increased maintenance costs, and increased fuel consumption are factors which determine the economic penalties imposed on the aircraft due to the modifications For the 9300 km study mission, these systems impose another penalty in that passengers are offloaded to meet the trip length The offloading of passengers significantly affects the return on investment because of reduced revenue With the heating systems installed, 8900 km is the maximum trip length for the 747-200 that would not require offloading passengers This is significantly higher than today's average 747-200 trip length of 6000 km

It is generally assumed that any changes to the current Jet A specification freezing point of -40° C would be gradual A freezing point change from -40° C to -29° C for the Jet A specification is very unlikely to occur in the next decade Incremental freezing point specification changes are a possibility, however, freezing point relaxation of a few degrees could increase jet fuel availability appreciably by introducing flexibility in fuel production, reference 4 For operation with these higher freezing-point fuels, the engine oil heat exchanger system is a promising heating concept that could be readily adapted to existing aircraft

It is unlikely that aircraft turbine fuel freezing point will be specified as high as -18° C Nevertheless, capability of operation with such a fuel may be desirable in the future, reference 5 For this high-freezing-point fuel, heating systems or other adaptations such as insulation, would be incorporated on a production basis

The engine oil heat exchanger system design is based on the current JT9D-7A engine heat rejection rates The growth of the JT9D engines indicate that the engine heat rejection rates are increased and thus more heat may be available for fuel heating

This study was conducted to design heating systems for a retrofit installation Significant installation cost reduction can be achieved if the heating systems are designed initially with the aircraft Under this design criteria, other modifications become feasible, including wing tank insulation

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 More theoretical and correlative work remains to be done on relating freezing point to boiling range and other properties Other properties of the hypothetical fuels are significant when designing a fuel heating system An accurate determination of the fuel's thermal stability qualities, density, and viscosity is required These properties greatly influence the size and complexity of any heating system

Although the results of this study indicate that the selected heating systems are feasible ways to heat the fuel, it is recommended that an experimental program be conducted to verify the concepts developed Specifically, the degree of fuel mixing required to efficiently heat the fuel in the tanks needs to be investigated

9.0 CONCLUSIONS

A design study has been conducted on the design, performance, and economic analyses of practical aircraft fuel heating systems to permit the use of broadened specification, high-freezing-point jet fuels on long-range aircraft Five heating systems suggested for further investigation from a previous study were evaluated Of these systems, two were selected for further study

A simple system, the engine oil heat exchanger system is considered an economically feasible retrofit system for providing the required heat for fuels with freezing points lower than -34° C The advantage of this system is its simplicity and relative ease of installation The disadvantage is a relatively small and uncontrollable limitation on heat energy

A more complex system, the electrical heating system is suitable for providing the required heat for fuels with freezing points up to -18° C The advantage of this system is its flexibility to provide the heat energy for any freezing-point fuel The disadvantages of this system are its complexity and economic penalties associated with a retrofit installation

The electrical heating system merits consideration only if jet fuel freezing-points are higher than -34° C The simpler engine oil heat exchanger system is adequate for fuels freezing below -34° C and the complexity of the electrical heating system would be the same for any fuel.

It is concluded that fuel heating systems are feasible and can be incorporated in present long-range aircraft Economics dictate that the most feasible combination of heating system and fuel freezing point is the engine oil heat exchanger system with a -34° C freezing-point fuel Further research is required to investigate the behavior of the mixing of hot fuel introduced into the fuel tanks and whether the assumed heat energies required to maintain the fuel above its freezing point are adequate.

APPENDIX

CONCEPTS FOR USE OF HIGH-FREEZING-POINT FUELS IN FUTURE AIRCRAFT

Examination of the possible 1990 market situation suggested that the future airline market place would be similar to the existing market place, i e., familiar size airplane flying familiar routes and schedules This prediction was based on the supposition that the air traveling community in the 1990's will be approximately the same percentage of the total population as today's air travelers, with a small annual incremental growth. The air cargo market should experience similar growth unless a large dedicated airfreighter is developed that might stimulate increased air cargo growth, reference 6.

Design and technology changes will be evolutionary and major changes cannot be expected until later than the 1990 period The principal emphasis of new technology is toward fuel and cost savings

The NASA Aircraft Energy Efficiency (ACEE) Program has the objective of improving the energy efficiency of future U S aircraft so that substantial savings in fuel can be achieved, reference 7 These advanced technology transports are projected to enter service in the 1990 time period

If the ACEE program is successful, the major technological advance that would have a direct effect on the freezing point of the fuel used is laminary flow control (LFC), reference 8 As defined by Boeing, the aircraft configuration is shown in figure 22 The feature of this configuration which would permit the use of a higher freezing-point fuel is the insulating property of the fiberglass cover used for the LFC surfaces This fiberglass cover is shown in figures 23 and 24 The thickness of the urethane in the fiberglass cover has not been optimized, however, it has been established to be between 2 0 to 3 0 cm (0 80 to 1 25 in) Figure 25 is a plot of heat required versus insulation thickness for the mission profile The insulating qualities of the fiberglass cover are more than adequate to allow the use of the -29° C freezing-point fuel and not quite adequate for the -18° C freezing-point fuel Depending on the insulation thickness, this aircraft can be operated on a -20 to -21° C freezing-point fuel allowing 3° C tolerance with no penalty of heating required Reference 1 reports insulation as a retrofit installation. However, the insulation conductivity assumed in reference 1 is higher due to the high thermal conductivity of the bonding material Comparisons cannot be made between this work and reference 1

Additional heat is available from the suction engines located at the wing-body interface These engines are used to drive the suction units which provide suction for the entire wing Since the suction engines are used for the suction requirements of the LFC aircraft only, the use of these engines as the heating source will have a minimal effect on the airplane performance A bleed air system or an engine oil/fuel system are also possible systems for providing heat to the fuel

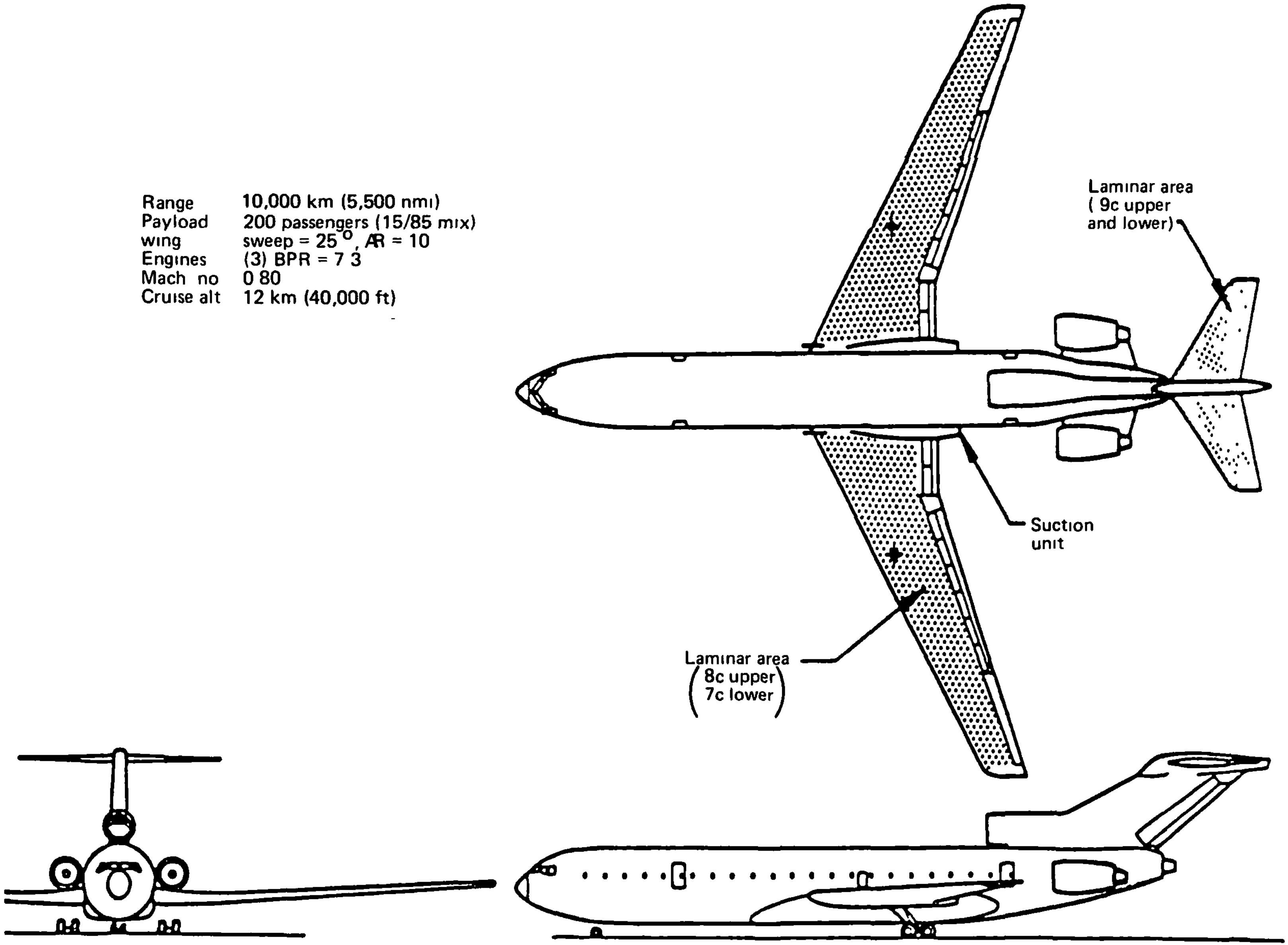

Figure 22.—Laminar Flow Control Aircraft Configuration

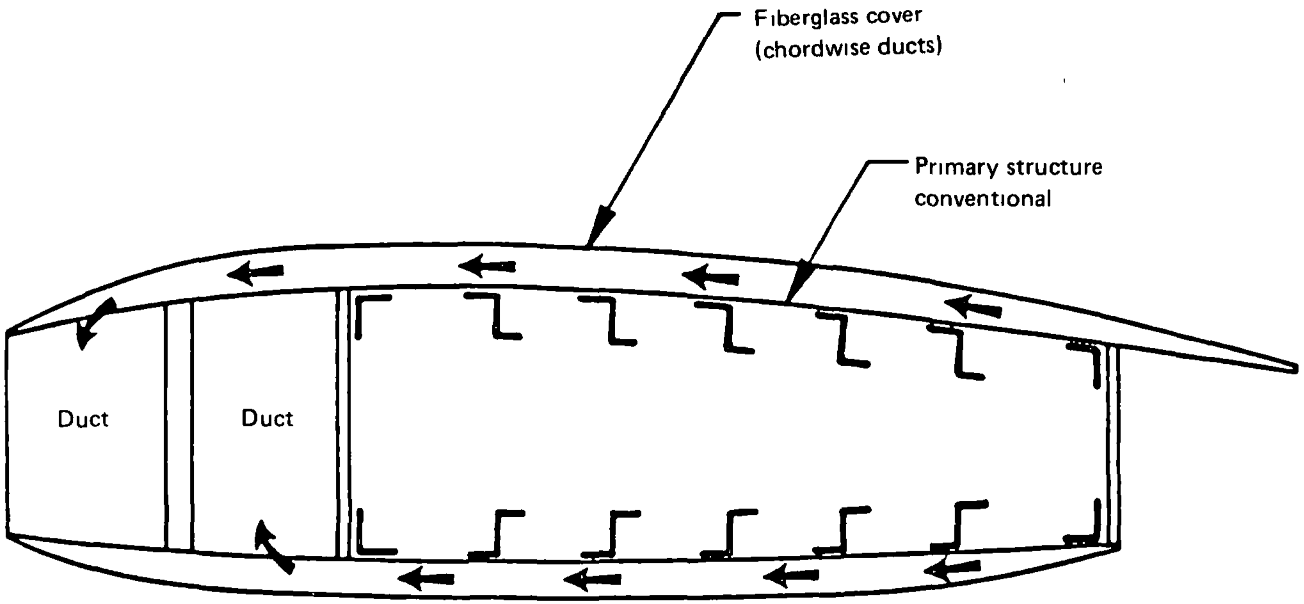

Figure 23.—Wing Structure with Fiberglass Cover

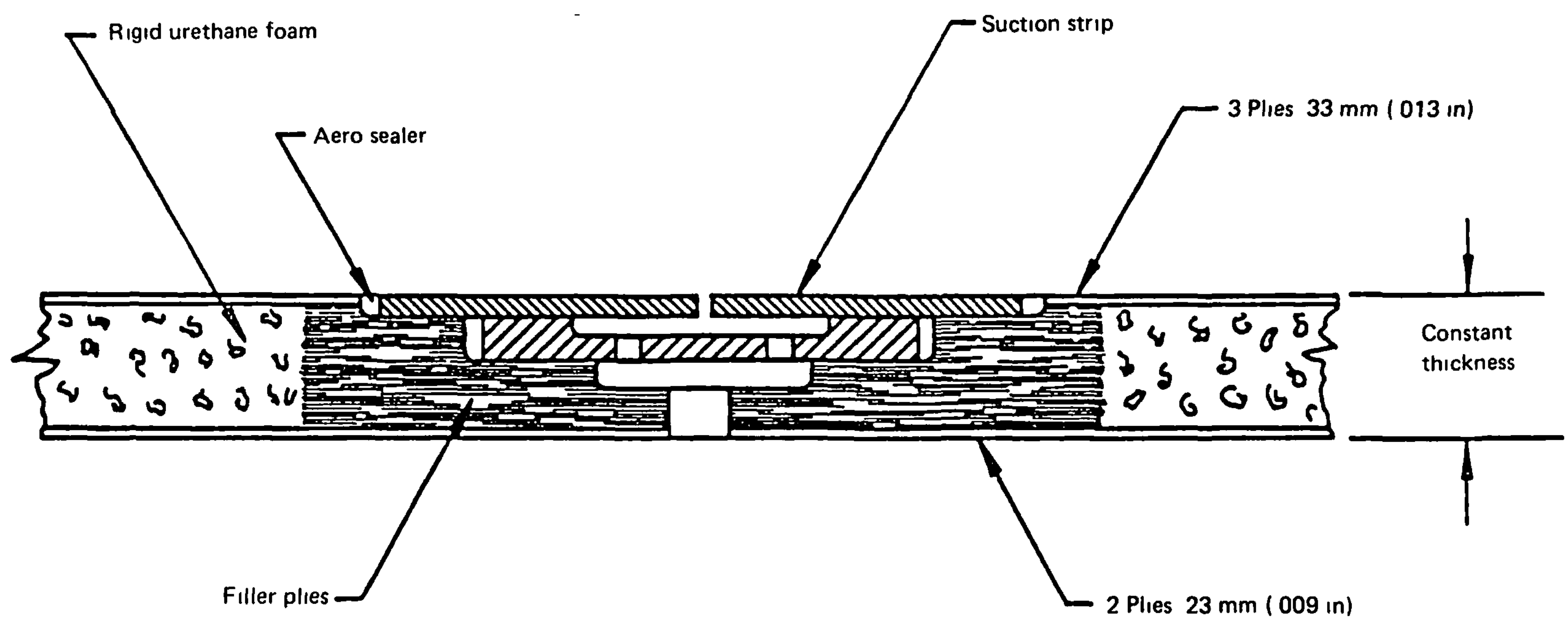

Figure 24.—Fiberglass Cover Detail

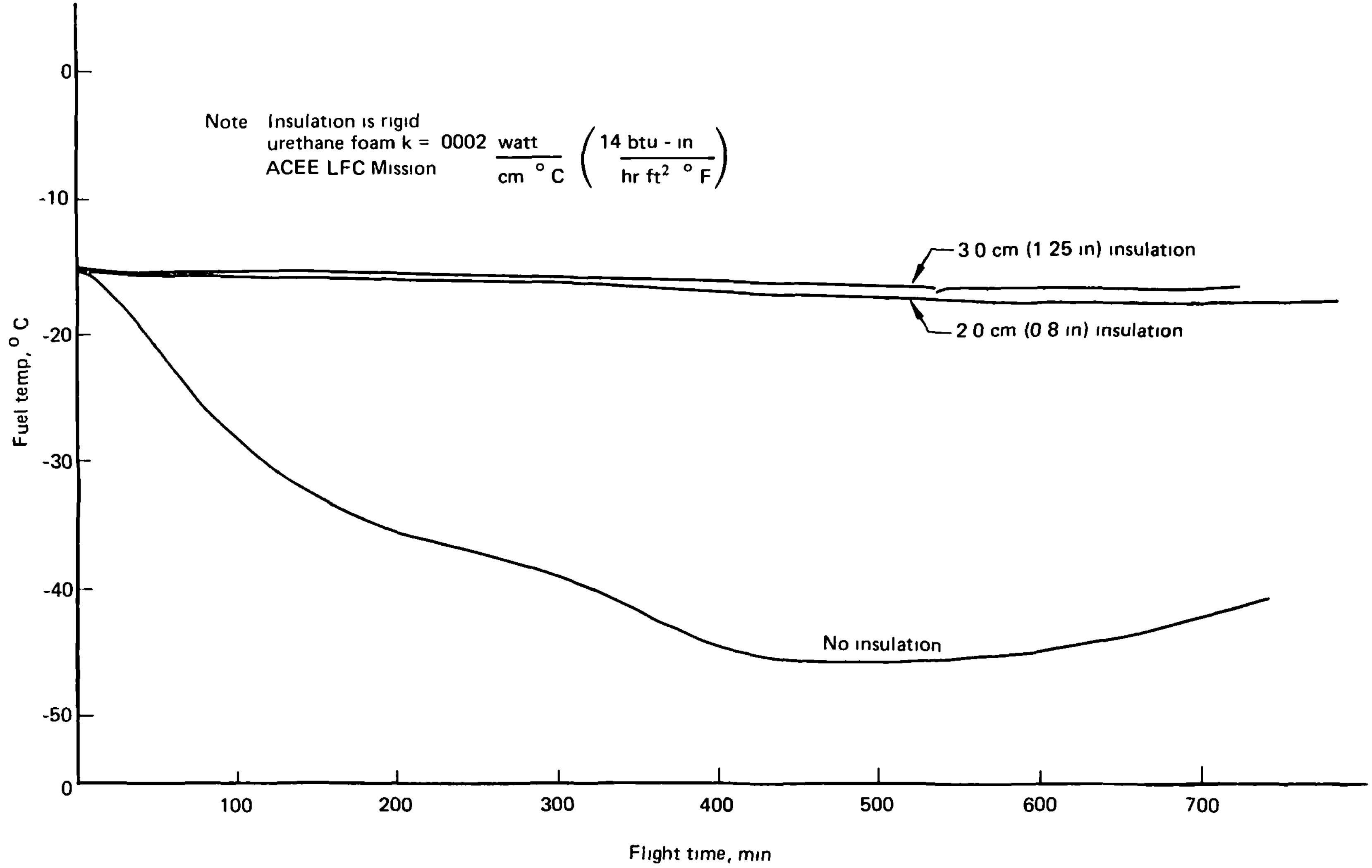

Figure 25 .—Laminar Flow Control Aircraft Predicted Fuel Tank Temperature

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