HIGH-FREEZING-POINT FUEL STUDIES

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Proposals to use heavier hydrocarbons as a means of obtaining more abundant and less costly aviation turbine fuel raise a number of concerns, among them being low temperature flowability. Long duration high altitude flights expose airplanes to static air temperatures in ranges as low as -72 C on a one time/year basis (fig. 1); for typical subsonic jet airplanes (M 0.84), aerodynamic heating increases the potential cold soak temperature for the fuel system to the vicinity of -47 C. Existing specifications aimed at insuring jet fuel flowability at such low temperature stipulate a maximum allowable freeze point. Even so, infrequent but costly instances of fuel temperature difficulties do occur which interfere with large range flight operations. It can be anticipated that the frequency of these instances would increase with higher freeze point fuels.

A few background observations on the nature of low temperature fuel systems behavior provide perspective on the problem. Fuels consist of a mixture of paraffinic, naphthenic, and aromatic hydrocarbons with a variety of crystallization temperatures as pure compounds (fig. 2); on dropping the temperature of a mixture of these compounds, the high freezing point materials which would solidify if pure tend to be soluble in the lower freezing fuel constituents. As a result, the first appearance of solids in a mixture is deferred; however, as temperature is further decreased, a solid phase consisting of isolated crystals of long chain paraffins begins to appear. At still lower temperatures, the crystals merge into a spongelike matrix which eventually traps the remaining liquid phase. At this point the semi-solid may resist flow to the fuel tank outlet. Agitation or the use of flow improvers interferes with matrix formation and maintains the flowable two phase slurry. The stages of conversion from liquid to solid as a function of airplane altitude are depicted in figure 3, and properties of interest are defined in figure 4. It is of interest that fuel is a very good thermal insulator (akin to rubber) with relatively high heat capacity (about half that of water). As fuel temperature drops below the freeze point, the transition from a flowable to a non-flowable fuel often occurs over a range of a few degrees of temperature. A device known as the Shell-Thornton tester has been used to study holdup (amount of non-flowable fuel) as a function of temperature, with results for a typical commercial fuel as shown in figure 5.

Military JP-4 fuel has such a low freeze point that flowability problems have never developed in service. However, other fuels (commercial Jet A and Jet A-1, and military JP-5 and JP-8) and certainly fuels with relaxed restrictions on freeze point can experience operational difficulties. In recognition of this fact, many commercial airplanes already incorporate fuel tank thermocouples; in the case of the 747, when the sensed fuel temperature is within 3 C of the specification freeze point, the airplane flight manual requires that the flight profile be altered to increase skin temperature by changing altitude, Mach number or route. For the 747, the fuel consumption penalty for an 1850 KM (1000 NMI) deviation was assessed for a 9260 KM (5000 NMI) flight; data shown on figure 6 translate into added cost and reduced range for either descent to a lower altitude, or a Mach number increase. In order to avoid these penalties, airline operators along polar routes may be forced to use Jet A-1, the higher cost lower freeze point alternative to Jet A, during severe low temperature operations.

Concern about safe operation limits with existing fuels, as well as the question of the acceptability of higher freeze point alternative fuels indicated the need for detailed studies of the flowability problem. These studies initially focused on understanding freezing phenomena as a function of temperature along a flight trajectory, using a combination of

- o in-flight measurements
- o ground simulation
- o analysis

More recently, additional effort has been expended on devising techniques to mitigate low temperature flowability problems by adding heat to fuel.

In-flight observations of 707 fuel tank temperatures showed significant vertical variations in fuel temperature (fig. 7), attributable to the very low thermal conductivity of fuel, and limited mixing. However, the study of actual freezing phenomena could not be carried out in flight for reasons of safety and practicality. Accordingly, a fuel tank simulator representing a section of a 747 outboard wing tank (fig. 8) was constructed, containing typical wing tank structures and plumbing in which controlled experiments could be conducted. The simulator (figs. 9 and 10) has been mounted on a slosh/vibration table to represent airplane motions. Slosh was modeled in one test as shown in figure 11. Upper and lower simulator skin temperature can be closely controlled in the range of -72 C to 35 C as a function of time. A central array of thermocouples gives continuous temperature data.

The simulator was recently used for CRC/USAF (ref. 1) sponsored experiments on five fuels, with the objective of measuring unavailable (holdup) fuel using severe thermal exposure. Fuel characteristics are listed in figure 12. The mission which was simulated was launch of airplanes from an Artic base to airborne alert status, calling for low speed flight in a holding pattern in Artic air masses. The experimental procedure called for pre-chilling the fuel to a temperature 10 to 20 C above the freeze point, and then rapidly dropping the skin temperature to 10 C below the freeze point. The temperatures in the tank were monitored to establish the shape of the thermal profile in the tank (fig. 13). The experiment was stopped when a thermocouple mounted 2.5 cm above the lower skin sensed a "target" temperature, at which time a holdup measurement was made by weighing the liquid fuel which could be drained from the simulator. The target temperatures used were +2.8, 0.0, -2.8 and -5.6 C with respect to the measured freeze point of the fuel.

Only limited interpretation of the data is reported here (a detailed report will be published by the CRC in the near future). For example, holdup data on one of the Jet A fuels indicates decreased holdup resulting from slosh/vibration agitation (fig. 14). It also appears from this test that slosh is more effective than vibration in reducing holdup. The thermal profile data is also useful in understanding the heat transfer mechanisms between the fuel and the tank walls. For full fuel tanks, the time variable thermal profiles (fig. 15) reveal three distinct regions:

- o at the lower skin, a steep gradient in a zone controlled by conductive heat transfer

- o at the upper skin, a very steep gradient in a zone where heat is transferred by free convection giving rise to downward movement of cold dense fuel

- o at the center, a zone of little or no gradient resulting from convectively driven mixing, with cold fuel descending and warm fuel rising; the cold fuel does not possess enough momentum to penetrate the lower zone controlled by conduction.

If fuel is withdrawn from the tank, the appearance of the thermal profile changes markedly. As the fuel loses contact with the upper surface, convection currents damp out, and the primary heat transfer is by conduction through the lower surface (fig. 16).

These insights have been translated into a computer technique for calculating fuel temperature profiles in full tanks; a comparison of calculation and experiment shows good agreement (fig. 17). The computer program is being extended to include the case of partially empty tanks. Ultimately, the completed package will be incorporated into Boeing's aircraft fuel tank thermal analyser (AFTTA) code to permit the designer to "fly" various thermal exposure patterns, study fuel temperatures versus time, and determine holdup.

If analysis shows holdup to be unacceptable, Boeing studies funded by NASA (ref. 2, 3) of fuel tank heating or skin insulation provide the basis for a designer to do trade studies of fuel properties versus airplane fuel tank complexity and operating costs. Two conceptual designs for fuel heating system appear feasible based on analysis conducted with the existing AFTTA code (which uses bulk mean fuel temperature rather than thermal profiles). The first design (fig. 18) uses heat rejected by hot engine lubricating oil, while the second (fig. 19) uses a dedicated electrical generator driven directly by the engine to heat the fuel electrically. A return on investment study (fig. 20) was made on each heating system to determine what incremental cost reduction in fuel price would be required to offset the cost of acquisition, installation, maintenance and loss of payload. As noted in the figure, engine oil heat was found to be insufficient to permit use of -18 C freeze point fuel. Offsetting fuel cost reductions are in the fractional cents/gallon for a 5500 kilometer (3000 NMI) range, but became as high as 17 cents/gallon at 9200 kilometer (5000 NMI) range.

The same AFTTA code was used to conduct a CRC/NASA sponsored study (to be published) of a new class of long range high altitude business jets (ref. 1). Two fuel loading temperatures and two thermal exposure profiles were used to assess the magnitude of the freezing problems that might be encountered. The study used actual fuel tank geometry, fuel withdrawal data and time variable thermal exposure to calculate bulk mean temperature. The results presented in figure 21 show that the fuel temperature at the end of five hours depend primarily on the lowest temperature of exposure, and little on loading temperature or on variations in the thermal exposure profile. An evaluation of the accuracy of the computations was made by comparing actual business jet inflight data and the results of computer analysis. A plot of the data (fig. 22) indicates good agreement.

In summary, the work reported demonstrates considerable progress in developing the experimental and analytical techniques that will be needed if it is necessary to design airplanes to accommodate fuels with less stringent low temperature specifications.

REFERENCES

1. CRC Contract No. CA-58-78, "Low Temperature Jet Fuel Study", 5 March 1979.

2. Pasion, A. J. and Thomas, I., "Preliminary Analysis of Aircraft Fuel Systems for Use with Broadened Specification Jet Fuels", NASA CR-135198, May 1977 (Contract NAS3-19783).

3. Pasion, A. J., "Design and Evaluation of Aircraft Heat Sources Systems for Use with High Freezing Point Fuels", NASA CR-159568, May 1979 (Contract NAS3-20815).

Figure 1. Inflight Altitude Ambient Temperature Profile

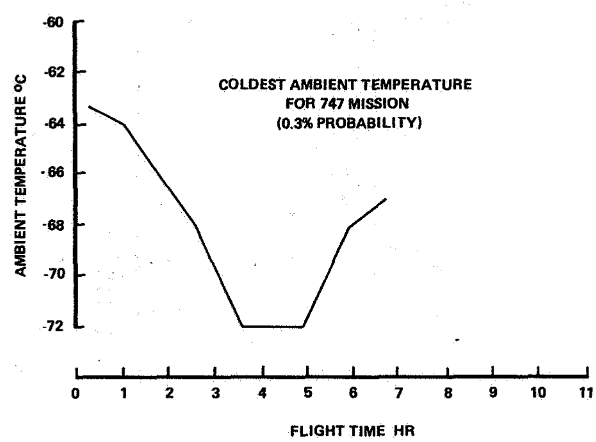

Figure 2. Variation in Crystallization Temperature for Various Single Compound Classes of Fuel Hydrocarbons

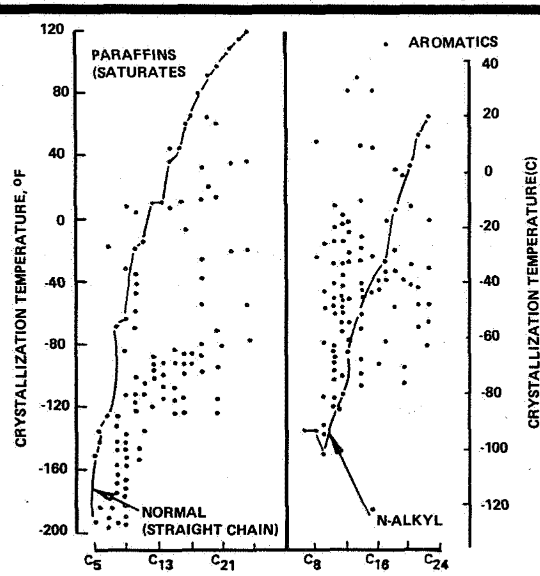

Figure 3. Low Temperature Behavior of Hydrocarbon Fuel

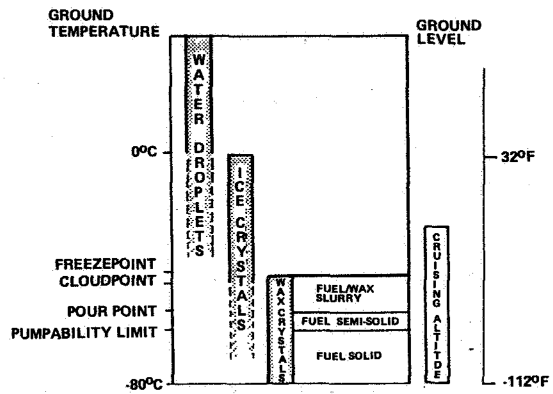

Figure 4. Low Temperature Properties

FREEZING POINT - THAT TEMPERATURE AT WHICH CRYSTALS OF HYDROCARBONS FORMED ON COOLING DISAPPEAR WHEN THE TEMPERATURE OF AN AGITATED FUEL IS ALLOWED TO SLOWLY RISE. ASTM D-2386

JET A	JET A-1	JP-4	JP-5	JP-8	BROAD SPEC FUEL
-40 C	-50 C*	-58 C	-48 C	-50 C	-34 C

* NOTE: ASTM HAS VOTED CHANGING TO -47 C

POUR POINT - RELATED TO THE LOWEST TEMPERATURE AT WHICH QUIESCENT FUEL WILL JUST POUR FROM A STANDARD GLASS CYLINDER OF 1-1/4" DIAMETER. THE POUR POINT IS 3°C ABOVE THAT FUEL TEMPERATURE WHERE NO FUEL MOVEMENT OCCURS WITH CYLINDER IN HORIZONTAL POSITION. ASTM D-97. (POUR POINT IS USUALLY FROM 3 TO 10 C LESS THAN FREEZE POINT)

HOLDUP - THAT FRACTIONAL AMOUNT OF FUEL WHICH WILL NOT FLOW BY GRAVITY FROM A CONTAINER BECAUSE OF PARTIAL FREEZING. IN THE SHELL-THORNTON TESTER, THE CONTAINER IS ESSENTIALLY ISOTHERMAL, AND 100% HOLDUP OCCURS BETWEEN FREEZE AND POUR POINT.

SPECIFIC HEAT (-40 C)	1.76 KJ/KG - C
THERMAL CONDUCTIVITY (-40 C)	0.143 W/M - C

Figure 5. Shell - Thornton Holdup Data - Paraffinic Jet A

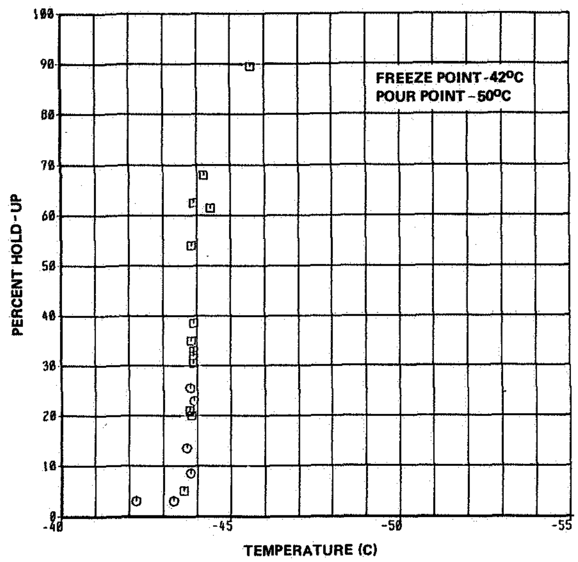

Figure 6. 747 Fuel Penalties for Flight in Cold Air Mass

BASELINE MISSION	
TRIP LENGTH	9,260 KM (5000 NM)
CRUISE MACH	.84
TRIP FUEL	117,930 KG (260,000 LB)
TRIP TIME	10.5 HRS
RESERVE FUEL	18,780 KG (41,400 LB)
ADDED FUEL FOR 1000 LOWER ALTITUDE	
-1220M (-4000 FT)	820 KG (1800 LB)
-2440M (-8000 FT)	2770 KG (6100 LB)
-3660M (-12000 FT)	5940 KG (13,000 LB)
ADDED FUEL FOR 1000 MILES AT INCREASED MACH NO.	
M = 0.87	1720 KG (3800 LB)
(TAT RISE +2.5°C)	

Figure 7. Stratification in an Airplane Fuel Tank (707 Outboard Reserve Tank)

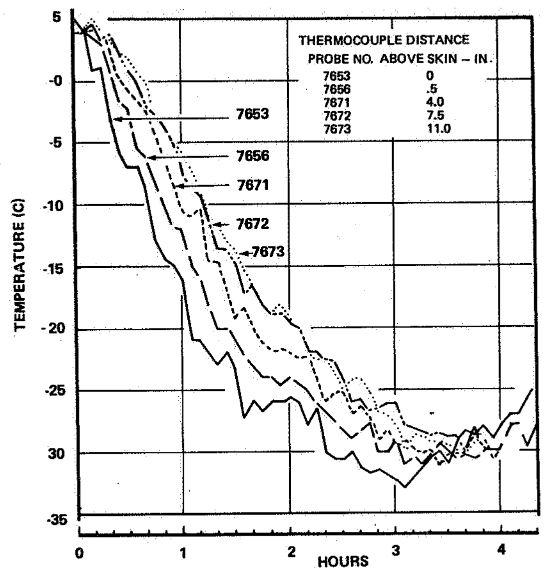

Figure 8. 747 Fuel Tank System

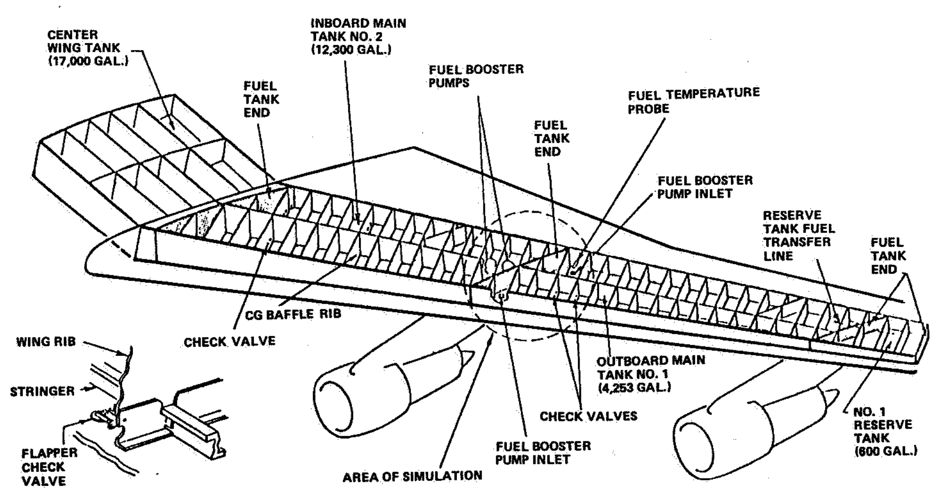

Figure 9. Fuel Tank, Thermal Simulator

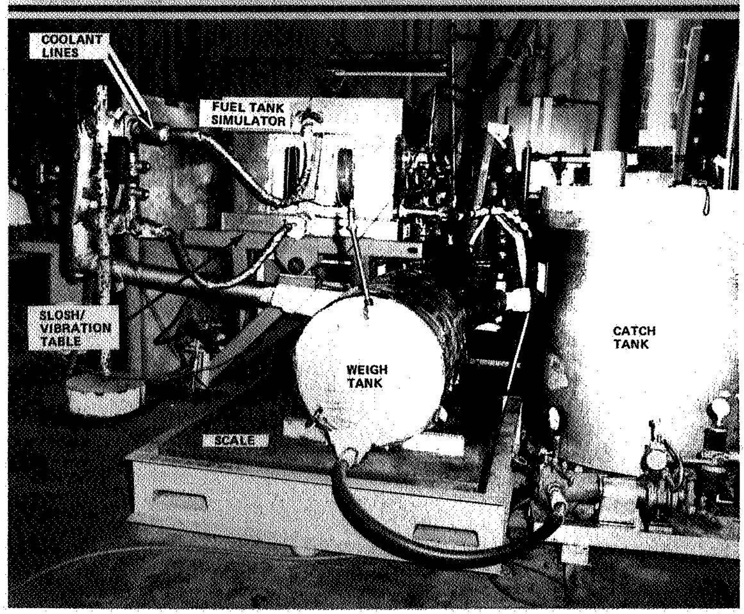

Figure 10. Interior of Fuel Tank Simulator

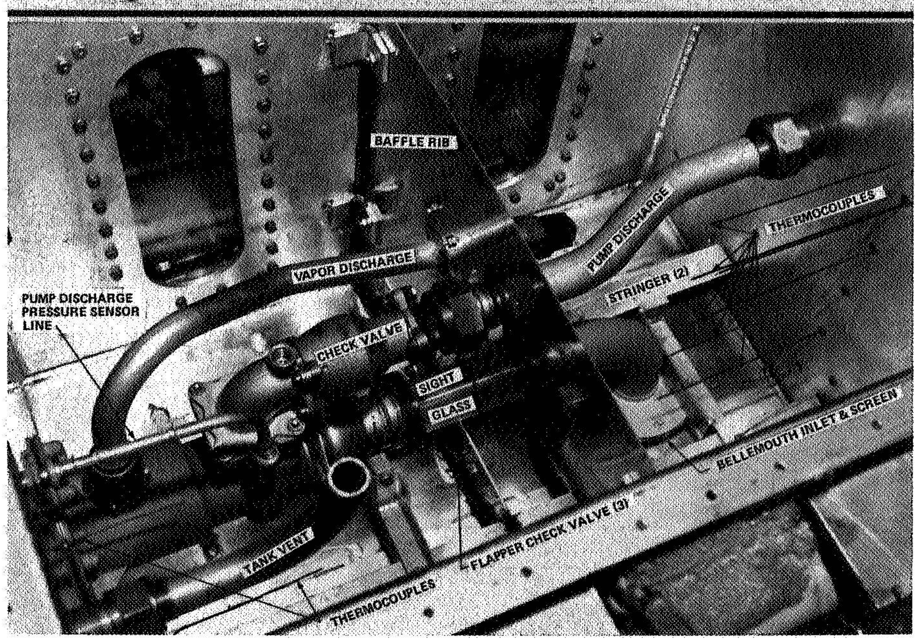

Figure 11. Simulated Gust and Maneuver (Slosh) Cycles

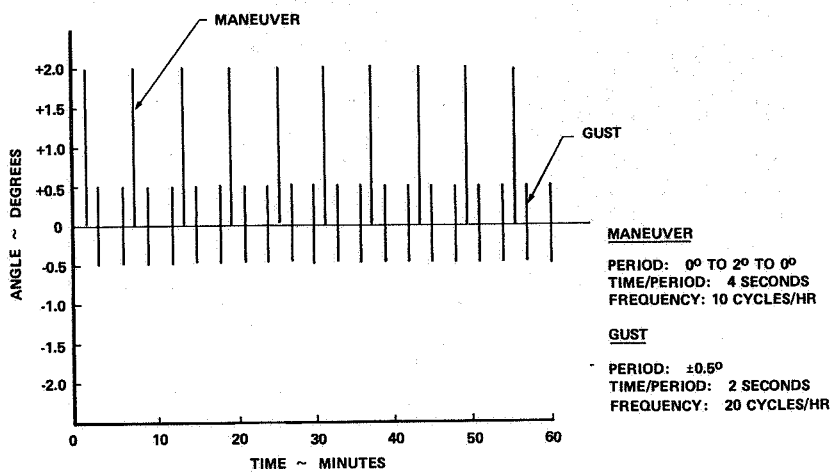

Figure 12. Test Fuel Characteristics

FUEL DESIGNATION	TYPE CRUDE	CRUDE SOURCE	FREEZE PT. °C	(°F)	POUR PT. °C	(°F)
JET A	PARAFFINIC	59% MINAS INDONEASIAN 41% MURBAN (ABU DHABI)	-42	(-43.6)	-50	(-58)
JET A	NAPHTHENIC	89% ALASKAN NO. SLOPE 9% CALIF. 2% MISC.	-51.1	(-60)	-52	(-61.6)
JP-8 (SHALE) MIL-T-83133	SHALE		-50	(-58)	-53.9	(-65)
JP-5 + 9% DFM MIL-T-83133			-25	(-13)	-51.1	(-60)
JP-8 (OUT OF SPEC)			-44	(-47)	-48	(-55)

Figure 13. Time Variation of Fuel Tank Temperature

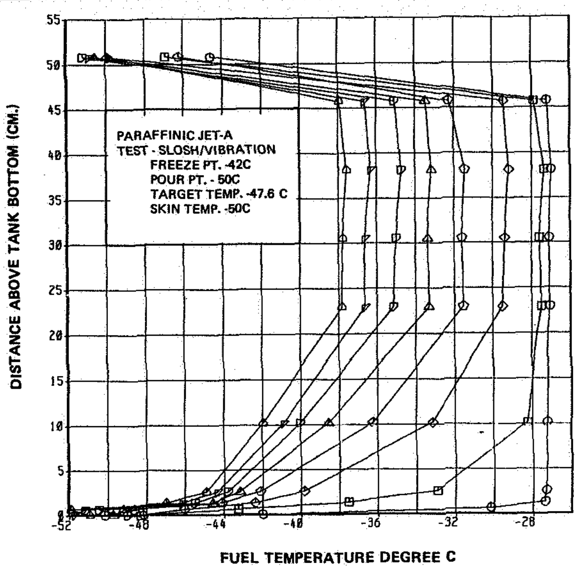

Figure 14. Effect of Tank Motion on Fuel Holdup

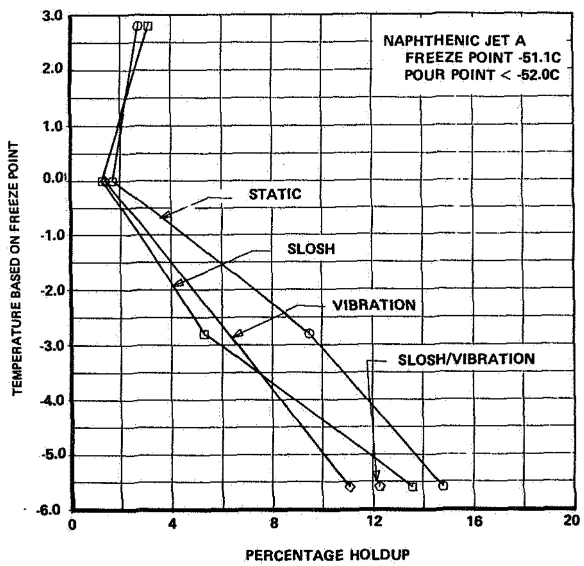

Figure 15. Temperature - Position Profiles for Jet A-1 Fuel and Wet Top Skin

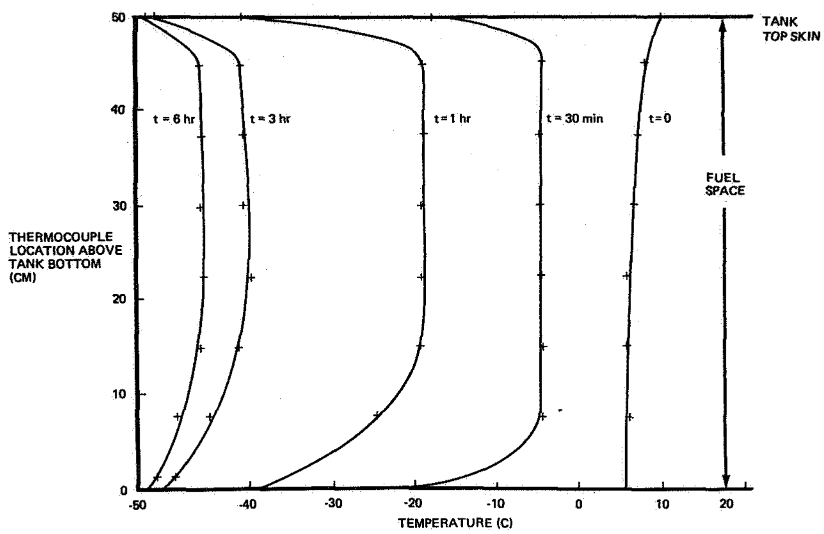

Figure 16. Temperature-Position Profiles for Jet A-1 and Dry Top Skin

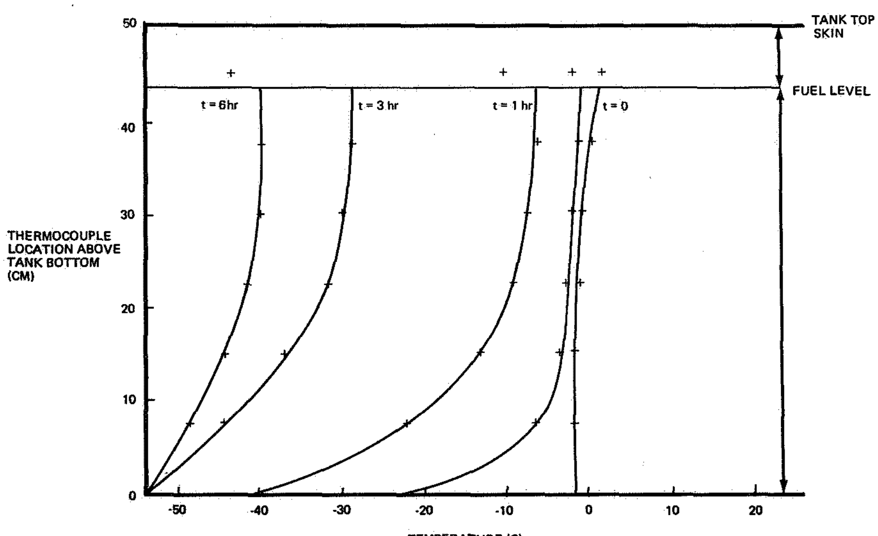

Figure 17. Comparison of Calculated and Experimental Fuel Tank Temperatures

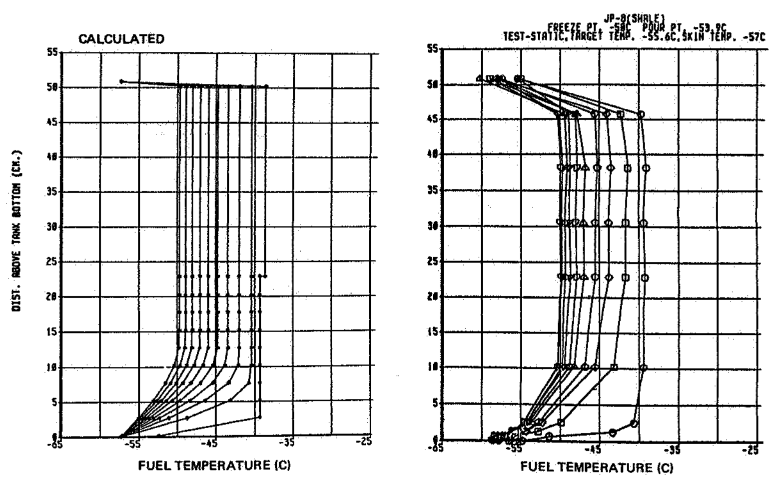

Figure 18. Fuel Heating with Engine Oil

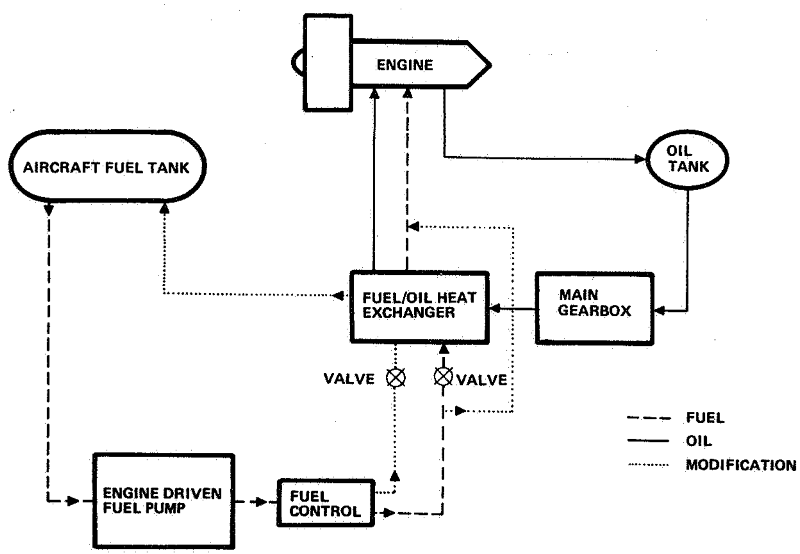

Figure 19. Fuel Heating with Electric Heaters

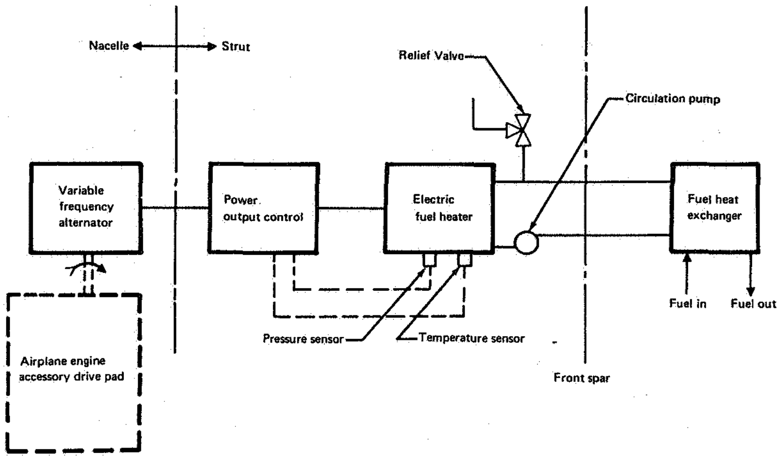

Figure 20. Return on Investment Study - 747 Airplane

FUEL PRICE INCREMENT REQUIRED TO BALANCE COST OF HEATING SYSTEM
FUEL PRICE BASIS: 45¢/GAL

3000 NMI FLIGHT	-18°C F.P. FUEL	-29°C F.P. FUEL
ENGINE OIL HEAT EXCHANGER SYSTEM	XXXX	-0.29¢/GAL
ELECTRICAL HEATING SYSTEM	-0.90¢/GAL	-0.77¢/GAL

5000 NMI FLIGHT		
ENGINE OIL HEAT EXCHANGER SYSTEM	XXXX	-2.6¢/GAL
ELECTRICAL HEATING SYSTEM	-17.0¢/GAL	-12.3¢/GAL

xxxx CANNOT MAINTAIN ACCEPTABLE FUEL TEMPERATURE

Figure 21. Calculated Business Jet In-Flight Fuel Temperature

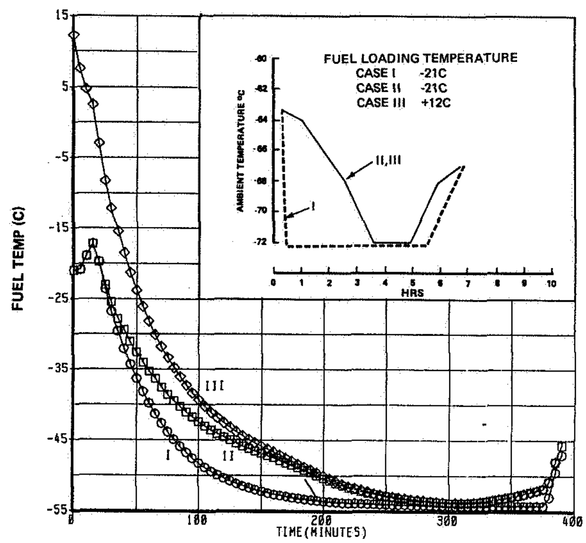

Figure 22. Business Jet, Wing Tank Fuel Temperature