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TEMPERATURE AND FLOW MEASUREMENTS ON NEAR-FREEZING AVIATION FUELS IN A WING-TANK MODEL

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INTRODUCTION

Shortages of liquid fuel relative to demand and increased refinery processing required by the introduction of heavier petroleum stocks and eventually oil shale and coal liquids have stimulated a reexamination of aviation turbine fuel specifications and their impact on aircraft and engine systems (1, 2).[1] Flexibility in the specification of the final boiling point, and consequently the freezing point, may be advantageous with respect to yield and market competition (3). Statistical compilations of in-flight fuel temperature data (4) indicate that a very small fraction of long-range commercial flights will encounter minimum fuel temperatures which approach the aviation turbine fuel freezing point specifications of -40°C (Jet A) or -50°C (Jet A-1).

Operating margins and temperature limitations on the use of present and higher freezing-point fuels are best determined from experimental studies of fuel pumpability at near-freezing conditions (5). The most practical studies have been those in large-scale apparatus, designed to represent airplane wing-tank sections (6-9). In these tests, fuel was withdrawn from the chilled tank, and the fraction remaining as unpumpable solids was reported as a function of temperature. It was observed that aviation fuels are pumpable at temperatures below the specification freezing point, the extent depending on the fuel boiling range and composition.

[1]Numbers in parentheses designate references at end of paper.

The previous studies of low-temperature fuel behavior have represented an idealized situation in the sense that the fuel was isothermal or temperature gradients, if present, were undefined. This paper presents the results of experimental investigations in an apparatus designed to simulate the internal temperature gradients encountered in an airplane fuel tank. Tests with seven different fuels are reported, including aviation turbine fuels and higher freezing-point fuels, all derived from known petroleum or alternative crude sources. The investigation included tests with a surface temperature schedule consisting of chilldown to a constant temperature and tests with a time-varying temperature schedule reproducing conditions of a long-range, winter commercial flight.

The experimental studies were conducted by the Lockheed-California Company at the Lockheed Rye Canyon Research Laboratories under NASA Contract NAS 3-20814. The test fuels were furnished as samples through the courtesy of members of the Coordinating Research Council, Inc., Group on Low Temperature Flow Performance of Aviation Turbine Fuels.

APPARATUS

The principal item of apparatus was an aluminum alloy, rectangular parallelepiped tank, 51 cm by 76 cm base by 51 cm high, about 190 liters capacity (Figure 1). The top and bottom horizontal surfaces were chilled; the remaining surfaces were insulated. The chilling system used methanol cooled by liquid carbon dioxide circulated through heat exchanger plates bonded to the tank surfaces. The test tank was operated at atmospheric pressure, having a vent tube equipped with a dessicator to remove atmospheric moisture. The test tank and associated equipment are described in more detail by Stockemer (10).

The test tank represented a section of an outboard wing tank of a wide-bodied commercial airplane (Figure 2). For a typical airplane, the wing thickness may vary from over a meter at the root to 30 cm

or less at the outboard end of the wing tank. The section represented by the test tank was full-scale with respect to thickness (tank height) at the outboard, or main, tank fuel outlet. The top and bottom surface construction of the tank was identical to that of the airplane wing, metal skins stiffened by chordwise channels, called stringers. The fuel outlet was through a tube opening at a corner of the bottom skin. Surrounding this opening within the tank was an open-top box formed of two sheet metal pieces, called a surge box, with a flapper check valve opening on one side. Two ejector tubes powered by the fuel discharge flow removed fuel from the bottom of the bays formed by the stringers, filling the surge box. The ejectors permitted the complete withdrawal of fuel from the bottom of the tank. In an airplane wing tank, however, the ejectors serve primarily to scavenge water accumulation from the bottom of the tank. These details of the tank are also shown in the photograph in Figure 3.

The fuel discharge tube led to a pump chamber, with an electrically-driven centrifugal pump surrounded by a 8-mesh screen. The discharge pump was an aircraft type but of reduced size compared to those used in wide-bodied airplanes. The pump was operated only when fuel was withdrawn from the tank; in contrast, airplane boost pumps operate continuously even when the discharge valves are closed.

Fuel temperature profiles within the tank were determined by copper-constantan thermocouples, arranged in 5 vertical racks of 7 or 12 thermocouples each. The center rack is seen in Figure 3. A second thermocouple rack extended from the surge box corner, and the other three racks were installed at the remaining corners of the tank. The thermocouples on each rack were spaced nonuniformly for better definition of temperature gradients near the top and bottom skins. Thermocouple outputs were digitized for on-line readout and storage of computed temperatures.

For visual and photographic observations, the sidewalls of the tank had double-paned glass windows, with vacuum purge between the panes to remove atmospheric condensation. Fuel discharge from the tank flowed to a clean drum mounted on a manual platform balance capable of 0.2 kg precision. Additional instrumentation measured wall temperatures, chilling system temperatures, pump discharge pressure difference and fuel flow rates.

FUELS

Some characteristics of the experimental fuels used in the tests described here are listed in Table 1. The identifying numbers are those used to designate the fuels in the test program (10). The two general types of fuels, according to distillation range, are the aviation turbine fuels, commercial Jet A or Navy JP-5, and the higher-boiling intermediate fuels. The latter are so named because they range between the aviation turbine fuels and common (No. 2) Diesel fuels. The experimental fuels were furnished as refinery samples and an identification such as Jet A does not imply that the fuel would necessarily meet all specifications of this class. The petroleum crude source of the fuels is described as paraffinic or naphthenic, where a paraffinic crude has a preponderance of saturated aliphatic hydrocarbon constituents and a naphthenic crude a preponderance of saturated cyclic hydrocarbon constituents. Table 1 also lists for each fuel the distillation range, specific gravity, freezing point (ASTM D-2386), pour point (ASTM D-97), and the Shell cold flow temperature. The freezing point is the temperature observed at the disappearance of solid crystals in a stirred fuel sample warmed after crystals are formed at a lower temperature. The pour point is the lowest temperature at which the surface of a chilled fuel sample will move when turned vertically. The cold flow temperature is the lowest temperature at which fuel will flow completely by gravity through a valved opening between two compartments (9, 11). Freezing and pour points for most of the fuels in Table 1 are mean values of 3 to 6 measurements taken by observers at different laboratories. Agreement was within 3°C or better. The data for Fuel No. 8 and LFP-8 are single values measured at the NASA Lewis Research Center.

Fuel No. 7 is the intermediate fuel LFP-5 modified by the addition of 0.1 percent of a proprietary flow-improving additive. Only the pour point is affected to any appreciable extent by this additive. Fuel No. 8 is the one shale-oil derived fuel, distilled to the nominal range of a military aviation turbine fuel, JP-5. This fuel is a sample from the fuel batch identified as "Shale-Paraho" in the paper by Solash (12).

PROCEDURE

Test procedures were based on a scheduled time variation of the temperature of the chilled surfaces of the tank. The surface temperature was defined by the skin temperature measured at the inside bottom center of the tank. This was the lowest skin temperature and least affected by end effects, and it differed from the measured temperatures near the corners or on the upper chilled surfaces by no more than 2°C. The tank was loaded with filtered fuel at ambient temperature and completely filled. The top and bottom surfaces were then chilled until a desired surface temperature (usually -50°C) was attained. The surfaces were maintained at this temperature for a further period of time while the fuel continued to chill by heat transfer to the cold surfaces.

At a desired fuel temperature, the discharge pump was started to withdraw fuel from the tank at a flow rate requiring 20 to 30 minutes for complete discharge. The internal ejectors operated during this pumpout. The discharged fuel was weighed, and the fraction of remaining unpumpable fuel determined by difference. The unpumpable fuel was subsequently permitted to melt and was added to the original withdrawn fuel batch to check the resulting weight against the original load. The mass ratio of unpumpable fuel is defined as the percent holdup. During the chilldown and pumpout, temperature profiles were recorded periodically, and the fuel condition was observed through the test tank windows. Total test times were a maximum of 8 hours.

An alternative test procedure had a time-varying surface temperature throughout the test. These tests were designed to reproduce wing skin temperatures experienced during a long-range, commercial flight at an extreme winter condition with a one-day-a-year probability. Skin temperature variations were calculated based on a constructed Mach number, altitude, and static temperature flight schedule traversing various isothermal regions, with the coldest at -72°C static temperature. The temperature history was similar to that calculated by Boeing (13, 14). The time-varying surface temperature tests were 11.3 hours long, and during the last three hours of the test, fuel was withdrawn from the tank. The rate of fuel discharge was ad-

justed to retain between 15 and 40 percent of the fuel in the tank at the end of the three-hour period. This procedure represented a typical management of fuel usage and reserve supply retention in a commercial airplane. At the end of the 11.3-hour test, the reserve fuel in the tank was withdrawn rapidly to determine holdup in a procedure identical to that for the constant surface temperature tests.

RESULTS

Observation of Low Temperature Behavior

Low Holdup. At mild temperatures, well above the freezing point, a "fog" or haziness was observed in the fuel, especially near the bottom surfaces. (Freezing point in this paper always refers to the average ASTM D-2386 value, as listed in Table 1.) Tests with water-dry fuels indicated that this phenomenon was fuel-related and distinguishable from water-release cloudiness appearing with some fuels near zero degrees C. Convection patterns of colder fuel descending from top to bottom could be distinguished. As fuel temperature was lowered, the fog concentrated in the lower section of the tank, and solid fuel crystals were observed on the lower surfaces, first on the skin only and then at lower temperatures along the vertical and horizontal surfaces of the bottom stringers (reinforcing channels). Pumpout of fuel at these conditions would withdraw all of the liquid fuel in the tank, including the "fog" of finely dispersed solid particles. The unpumpable solid fuel remained as a tightly adhering coating on the bottom surfaces. Figure 4 is a photograph showing the tank interior after pumpout for a test where 3.2 mass percent of the fuel remained as an unpumpable solid holdup, and Figure 5 is the measured vertical temperature profile at the center of the test tank for this test at the initiation of pumpout. This profile is typical for cases of little or no holdup. The bulk of the fuel in the center is at a nearly uniform temperature, with a wider gradient to the skin temperature at the bottom than at the top. The average temperature for the test illustrated is -38°C, seven degrees above the freezing point of -45°C, but the bottom 2.5 cm layer of fuel is at temperatures below the freezing point.

The phenomenon described here as a low-holdup condition prevails to low fuel temperatures producing holdups of about 10 percent. Figure 6 illustrates the unpumpable fuel remaining in the tank where the holdup is 8.8 percent. Frozen fuel is still largely confined to the bottom surfaces, but it now covers the ejector inlets and the surge box check valve. The solid residue after pumpout appears wet, as if some liquid is trapped in the solid matrix, but the cloudy bulk liquid in the tank was pumpable. The temperature profile for this test (Figure 7) retains the low-holdup shape characteristics, but some distortion is evident near the bottom surface. The average temperature is -26°C, only two degrees above the freezing point, and the bottom 8.5 cm layer of fuel is at temperatures below the freezing point.

High Holdup. For conditions where holdup is in excess of about 10 percent, the two-phase fuel behavior and pumpability change markedly. The high-holdup situation occurs when the average fuel temperature is at or below the freezing point. At these conditions, prior to pumpout, solid fuel accumulation is observed on the top surfaces and sidewalls, as well as on the bottom. The remaining liquid clearly contains solid particles, generally circulating downward according to the convective movements. Upon pumpout, a portion of the bulk liquid-solid fuel is easily withdrawn, flowing through the pump inlet screen. The withdrawal of fuel causes some of the upper surface solids to fall, creating dams or obstacles at the lower surface and the outlet surge box. Eventually pumpout ceases due to this inlet blockage, leaving the solid fuel and some trapped liquid in the tank. Figure 8 is a photograph showing the tank interior after pumpout for a test where 57.2 mass percent of the fuel remained in the tank as a holdup. Note the visible reflection of the thermocouple racks and solid fuel on the surface of liquid fuel in the lower third of the photograph. Two temperature profiles are presented in Figure 9 for two tests at different temperatures with the same fuel: one at temperatures which caused 16.6 percent holdup, the other at temperatures which caused 57.2 percent holdup (the test illustrated in the photograph in Figure 8). The fuel chilldown time for the smaller holdup test was long enough that bulk temperatures corresponded to the freezing point. The integrated average fuel temperature, however, was -45°C, four degrees below the freezing point. This temperature profile has much greater distortion and wider gradients toward the top and bottom surfaces than the typical low-holdup profiles shown in Figures 5 and 7. The greater holdup test illustrated by the second temperature profile in Figure 9 was conducted with a fuel chilldown time long enough that all the fuel was below the freezing point and the average temperature was -54°C. The temperature profile has lost its uniform center character and is almost parabolic. Even for the test at an average fuel temperature 13°C below the freezing point, it is interesting to note that nearly half the fuel could be pumped out of the tank. The temperature profiles illustrated in Figure 9 are for early tests, where the skin temperature was nearly -70°C and the tank was not completely filled but had a 2 percent vapor space at the top. The effect of these variations on comparative temperature profiles should be negligible.

Correlation of Holdup Measurements

On the basis of the foregoing observation that the low-temperature behavior of the fuels is different for low and high holdup situations, the holdup-temperature function was correlated separately for the low holdup situation, all the liquid fuel is withdrawn each regime.

Low Holdup. For this regime, it is evident that the degree of holdup varied with the temperature at or near the tank skin and not with the bulk or average fuel temperature. A convenient parameter for correlation of low holdups was found to be the temperature measured by the central thermocouple rack near the bottom skin. Figure 10 is a summary of the holdup results for the tests with the aviation turbine fuels, plotted as a function of the temperature measured 0.6 cm above the bottom skin. Figure 11 presents the same data for the intermediate fuels. The temperatures are based on actual thermocouple indications or on interpolations for some early tests with a different thermocouple placement on the central rack.

Separate curves are faired through the data for the aviation turbine fuels in Figure 10. The relative position of the curve of course reflects the

different freezing points of the fuels. The slope of the curves for each of the fuels is approximately the same except for that of Fuel No. 8, which is shale oil rather than petroleum-derived.

The data for the two intermediate fuels, LFP-5 and LFP-6, plotted in Figure 11, are close enough that a single curve is faired through the points. The two fuels do have the same freezing point, although the crude source and other properties are different (Table 1). The correlating slope for the intermediate fuels is lower than that of the aviation turbine fuels, showing a greater temperature variation for a given change in holdup, comparable to that the shale-oil-derived Fuel No. 8.

High Holdup. The correlations presented in Figures 10 and 11 are applicable up to a transition near 10 percent holdup. At higher holdup conditions, it is evident that the entire fluid bulk influences the freezing phenomenon rather than the fluid adjacent to the skin. Accordingly, holdup results are presented as a function of an average fuel temperature. Tests at high holdup, being of less practical interest, were limited to five of the fuels, and these holdup results are plotted in Figure 12. The average temperature is calculated from a graphical integration of the vertical temperature profile, and it represents in effect the temperature of the fuel if thoroughly mixed to a uniform temperature. The calculation was based on the straight-line segment profiles and ignored mass weighting of density differences, but a more precise computation would change the average very little even for the more distorted temperature profiles.

Curves are drawn in Figure 12 for the data for the aviation turbine fuel, LFP-1, and each intermediate fuel, LFP-5 and LFP-6. A small difference between LFP-5 and LFP-6 could be distinguished, in contrast to the low-holdup correlation in Figure 11. These three curves are similar in shape and slope to those for the low-holdup correlations. Holdup data down to values of 5 percent are included to show that the average temperature correlation can be extrapolated to some extent to holdup values clearly in the low-holdup regime. In addition, Figure 12 includes two data points each for the flow-improved Fuel No. 7 and for Fuel No. 8.

Flow-Improver Additive. Fuel No. 7 was prepared by the addition of 0.1 percent of a proprietary flow improver to the intermediate fuel, LFP-5. The flow improver is a polymeric agent which disperses the solid crystals or wax particles, preventing their agglomeration (15). Thus the flow improver is a pour point depressant, which in theory does not affect freezing point or any property of the base fuel. As actually measured, the mean freezing point was lowered by 3°C and the pour point by 17°C. (Compare the data for LFP-5 and Fuel No. 7 in Table 1.) Two tests were conducted with the additive-doped fuel. As shown in Figure 12, at an average fuel temperature of -35°C, the measured holdup was reduced from about 20 percent for LFP-5 to 10 percent for Fuel No. 7. At an average temperature of -42°C, the measured holdup for Fuel No. 7 was 17 percent. There was no corresponding test at that temperature with LFP-5, and in fact it can be seen by extrapolation that the holdup for LFP-5 would be nearly 100 percent. No effect of the flow-improving additive was observable in the temperature profiles; the profile for LFP-5 and Fuel No. 7 were nearly identical for the -35°C average temperature test except for minor differences near the top surface.

The dosage of flow improver was based on optimized concentrations from laboratory pour point tests (10). The same addition of flow improver to LFP-6 in the laboratory tests showed no improvement in pour point.

Time-Varying Surface Temperature Tests

Tests were conducted with time-varying surface temperatures to represent the temperature history of a long-range, commercial flight at an extreme winter condition. Results are presented here of tests with two of the fuels, an aviation turbine fuel and an intermediate fuel.

Aviation Turbine Fuel. Temperature-time measurements for the variable surface temperature test with LFP-9 are shown in Figure 13. The total test time was 11.3 hr. For the first 8.3 hr, the test tank was full; thereafter fuel was withdrawn for the next three hours until 20 mass percent remained in the tank. This remainder was then pumped out to determine holdup, which was zero for the test illustrated. Three temperature measurements at the center of the tank are presented in Figure 13, the bottom skin, 0.6 cm, and 10.2 cm above the bottom skin. The broken line drawn through the skin temperature points is the scheduled temperature variation, which conformed closely to the measured skin temperatures. The minimum bottom skin temperature of -49°C between 5.5 and 6.6 hr represents passage through a minimum static temperature isotherm of -72°C. The solid curve represents the average temperatures calculated from the vertical temperature profiles during the test. The average temperature history is almost identical to the 10.2 cm thermocouple measurement (20 percent of height above the bottom) throughout the test. The thermocouple rack at the surge box location (not shown in Figure 13) indicated that the pump inlet temperature is also the same as the average fuel temperature. The 10.2 cm location is where the fuel tank probe is located in the airplane model represented by the test tank. Hence during the simulated flight, the recorded temperatures in an airplane would also be as shown by the average, or 10.2 cm, indications in Figure 13. Minimum average fuel temperature is -38°C, compared to the -45°C freezing point of the LFP-9 fuel.

Vertical temperature profiles at three times during the test are shown in Figure 14. At 6.6 hr, when the 0.6 cm thermocouple indicated a minimum temperature of 47°C, the profile conforms to the normal low holdup profile (compare Figure 5) with the bottom one-cm of fuel below the freezing point. At 8.3 hr, with the warming of the skin, all the fuel is above the freezing point. At 11.3 hr, after the scheduled fuel withdrawal but before final pump-out, there is little change in bulk temperature, but the heat transfer to the warmed skin produces a temperature profile for the 20-percent full tank that is nearly uniform.

During the variable surface temperature test, a heavy "fog" was observed at the bottom of the tank during the time of coldest surface temperatures. It was not possible to determine if any solid deposition actually occurred at that time. Based on the correlation of holdup versus the 0.6-cm temperature for LFP-9 in Figure 10, however, it was estimated that frozen fuel equivalent to a holdup of at least 1.5 percent was present between 5 and 8 hr. After that time, the fuel adjacent to the skin was warm enough that no further freezing would take place. In fact, any solid accumulation melted before the end of the test, as evidenced by the final zero

holdup measurement.

Intermediate Fuel. Temperature-time measurements for the variable surface temperature test with LFP-5 are shown in Figure 15. The test procedure was identical to that discussed for LFP-9, except that the three-hour fuel withdrawal left 41 percent remaining in the tank. The following pumpout produced a holdup of 24.4 percent.

The intermediate fuel was clearly unsuitable for any practical use over the mission defined for the variable surface temperature tests. After 4.2 hr of chilldown, the calculated average fuel temperature reached the freezing point and then remained below this temperature for the remainder of the test, establishing the fuel behavior as within the high-holdup regime for the simulated flight. Vertical temperature profiles at three times during the test are shown in Figure 16. At 4.0 hr, the average temperature is slightly above the freezing point, and temperature profile maintains the low-holdup characteristic shape. At 6.6 hr, when the average fuel temperature is near a minimum, the profile is the distorted parabola high-holdup type. Visual observations confirmed that solids were accumulating on the upper, lower, and sidewall surfaces. The average fuel temperature remained nearly constant throughout the last 4 hr of the test, despite warming skin temperatures, most likely because of the insulation by the solid fuel layers. At 11.3 hr, prior to final pumpout, the temperature profile shows the effect of the warmed skin, but the profile is not as uniform as the final profile for the non-frozen fuel test (Figure 14).

DISCUSSION

The onset of each type of low-temperature behavior, low holdup or high holdup could be characterized by a temperature. For high holdups, the average temperature corresponding to 10 percent represents the minimum temperature for transition to the overall freezing or high-holdup regime. For the low-holdup regime, a temperature corresponding to zero holdup represents incipient solid formation. A zero-holdup temperature was difficult to determine with any precision by extrapolation of the results. Instead, the temperature 0.6 cm above the bottom skin where holdup measured 0.5 percent was arbitrarily selected as the low-holdup characterizing temperature. The temperature for 0.5 percent holdup measured 0.6 cm above the bottom skin corresponds approximately to the zero-holdup temperature measured at the bottom skin for the typical low-holdup profile.

The characterizing temperatures determined from this study and several other temperatures for each fuel are listed in Table 2. The high and low-holdup characterizing temperatures are nearly equal, since they are both defined as incipient freezing temperatures measured at the skin for low holdup or at bulk (average temperature) for high holdup. It is interesting to note also that, except for Fuel No. 7 and a small discrepancy with LFP-1, these characterizing temperatures are the same as the mean freezing point. A solid-liquid interface temperature is also listed in Table 2. This temperature was reported for the same fuels by Stockemer (10), who calculated an approximate height of the bottom solid layer for each test and noted the corresponding temperature at that height on the vertical temperature profile. The solid-liquid interface temperature for all fuels, except Fuel No. 7, is equal to or a few degrees lower than the holdup-derived characterizing temperatures. For Fuel No. 7, the flow-improved intermediate, the high-holdup characterizing temperature is 4°C below the freezing point, and the solid-liquid interface temperature is 14°C below the freezing point, near the pour point.

The time-varying surface temperature tests provided some insights into the temperature response of fuels during long-range flights. A bulk wing tank temperature probe, located 10.2 cm above the bottom for a representative airplane model, serves as an accurate indicator of average and pump inlet temperatures under almost all conditions. High-holdup situations would of course be avoidable because the bulk probe would indicate temperatures near the freezing point, and the incipient high holdup condition would be obvious. A low-holdup situation, however, is a rare but possible occurrence at extreme winter conditions. The bulk probe would not sense that the fuel temperatures near the skin are below minimum temperatures, since the average temperatures in these cases could be well above the freezing point. However, the tests showed that if holdup is small, freezing may be reversible. The frozen fuel melts and is recoverable as part of the reserve when skin temperature warms at the conclusion of the flight, a possibility suggested many years ago by Strawson (6).

To conserve test fuel supplies, fuel batches were reused. After each test, the frozen fuel remaining in the test tank was melted and flushed with the withdrawn fuel to reconstitute the fuel for subsequent testing. Laboratory tests showed no change in freezing point between new and reconstituted fuel. Comparison of holdup versus temperature data for the tank tests with new and reconstituted fuel also showed no differences; however, measurements are not sensitive enough to distinguish possible subtle changes in freezing behavior associated with the previous history of the fuel.

CONCLUDING REMARKS

Tests were conducted examining the low temperature behavior of seven aviation turbine and higher-freezing-point fuels in a test tank representing a section of a commercial airplane wing tank. The test tank was chilled to duplicate the internal temperature gradients encountered in the airplane wing tank. Two regimes of holdup behavior were recognized. In the low-holdup situation, all the liquid fuel can be withdrawn from the tank, leaving a solid residue dependent on the fuel temperature at the chilled skin. In the high-holdup situation, a general two-phase mixture is present in the tank dependent on the average fuel temperature, and pumping of fuel ceases due to pump inlet blockage. The transition between the two regimes is at an average fuel temperature at the freezing point, corresponding to approximately 10 percent holdup.

The high-holdup regime is comparable to the situation in an isothermal test where the increase of holdup with decreasing temperature is a separation of solid phase in the overall freezing mixture. The low-holdup regime, on the other hand, is a profile-sensitive phenomenon. The increase of holdup with decreasing temperature is largely a function of the growth of the boundary layer, or fuel exposed to the below-freezing zones near the chilled surfaces. The tests reported in this paper established temperature profiles by control of the heat transfer mechanism, intended to simulate those in a commercial airplane

wing tank. There are situations where the represented profiles are not applicable, such as those for appreciable internal fuel transfer and internal heating, and those with vibration and other mechanical effects.

It is possible to determine a characterizing temperatures for the onset of each regime of holdup. In general, this temperature is nearly identical to a standard freezing point temperature. In other words, while partial fuel pumpability is retained at temperatures lower than the freezing point, the freezing point still appears to be the most appropriate criterion for characterizing freezing behavior. A fuel treated with a flow improving additive is exceptional. Based on limited testing, it appears that the behavior of this fuel may be characterized with a temperature lower than the freezing point and close to the pour point.

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TABLE 1. - DESCRIPTION OF TEST FUELS

Fuel No.	Type	Crude Source	Approx. Distillation Range, °C	Density, kg/m^3	Temperature °C		
					Freezing Point	Pour Point	Shell Cold Flow
LFP-1	Jet A	Paraffinic	166 - 237	802	-41	-46	-43
LFP-5	Intermediate	Paraffinic	202 - 297	830	-28	-33	-30
LFP-6	Intermediate	Naphthenic	207 - 283	848	-28	-35	-30
LFP-8	Jet A	Naphthenic	165 - 238	827	-52	-53	-
LFP-9	Jet A	Paraffinic	182 - 238	800	-45	-48	-45
No. 7	Intermediate	Paraffinic[a]	203 - 294	829	-31	-48	-
No. 8	JP-5	Shale Oil	178 - 247	803	-34	-38	-

[a]LFP-5 with the addition of 0.10 percent by volume of a flow-improving additive

TABLE 2. - SUMMARY OF CHARACTERIZING TEMPERATURES

Fuel No.	Temperature, °C				
	Avg. at 10% High Holdup dup	Avg. at 0.5% Low Holdup	Avg. Solid-Liquid Interface[a]	Freezing Point	Pour Point
LFP-1	-42	-44	-44	-41	-46
LFP-5	-28	-28	-31	-28	-33
LFP-6	-28	-28	-32	-28	-35
LFP-8	-	-52	-54	-52	-53
LFP-9	-	-45	-46	-45	-48
No. 7	-35	-	-45	-31	-48
No. 8	-34	-33	-33	-34	-38

[a]From Reference (10)

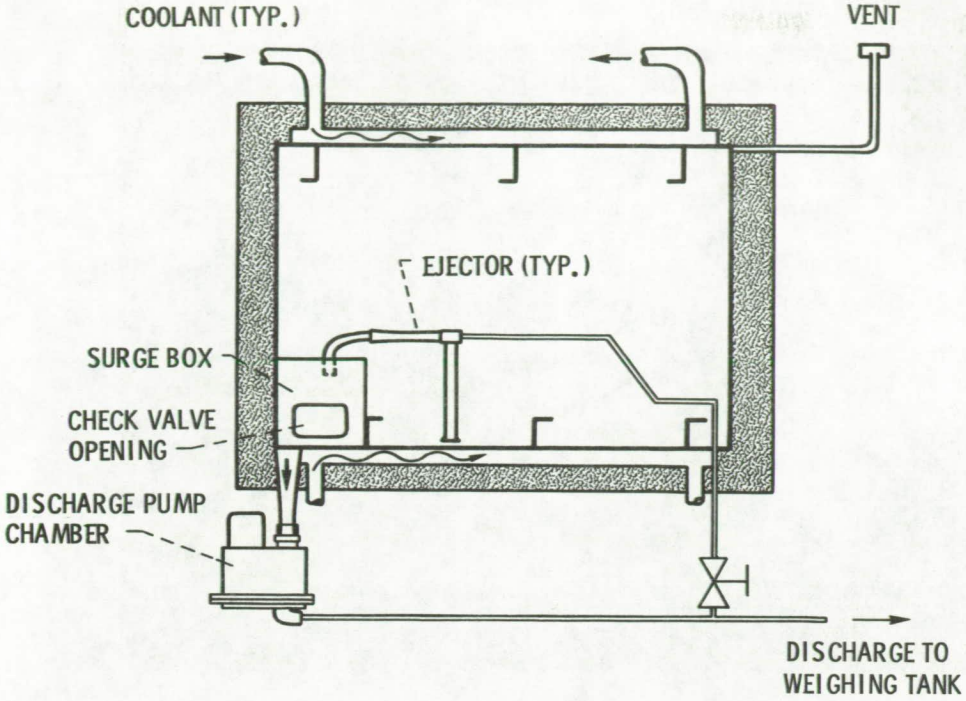

Figure 1. - Cross-section of apparatus.

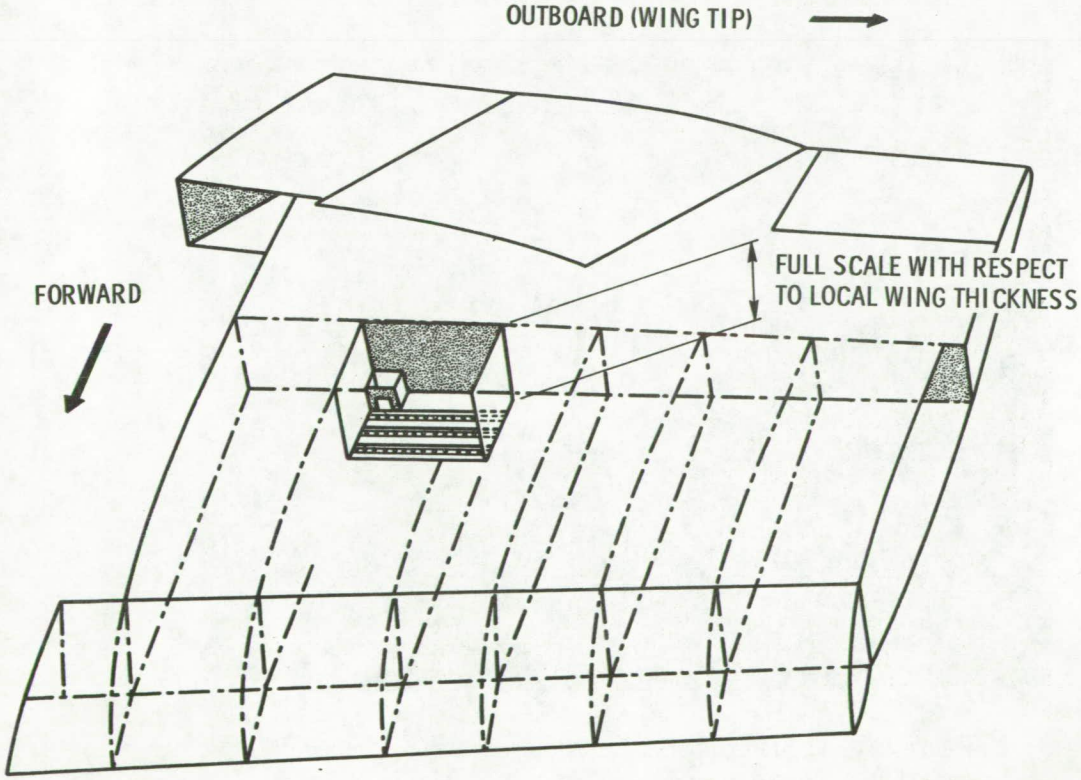

Figure 2. - Representation of test tank with respect to idealized wing fuel tank.

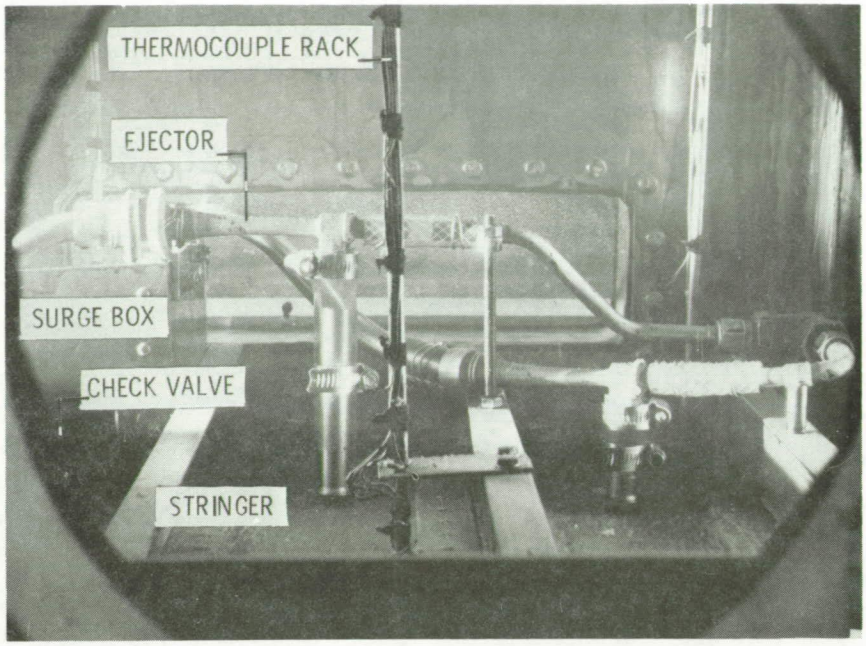

Figure 3. - Test tank interior view.

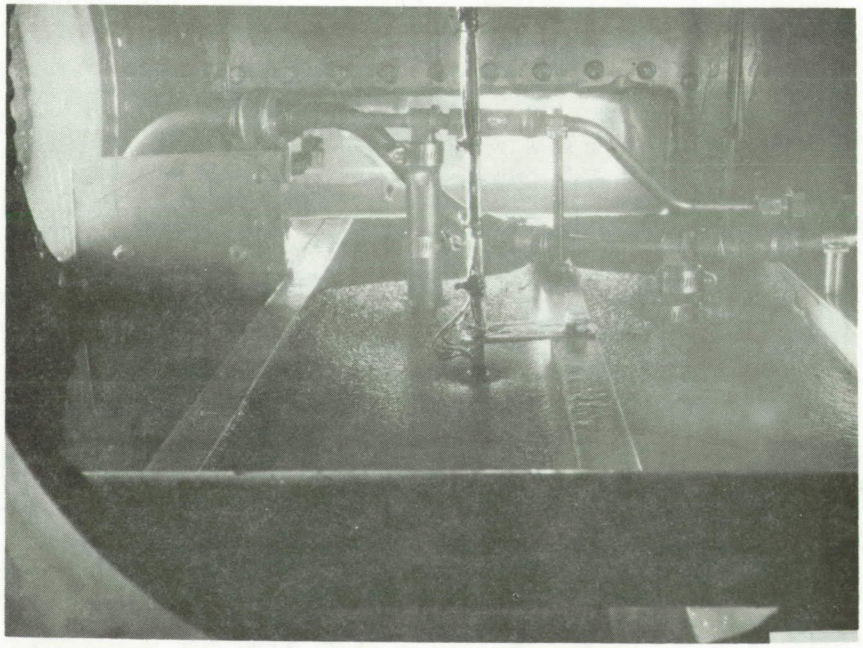

Figure 4. - Solid fuel remaining in tank at low holdup conditions; LFP-9 fuel; 3.2 mass percent holdup.

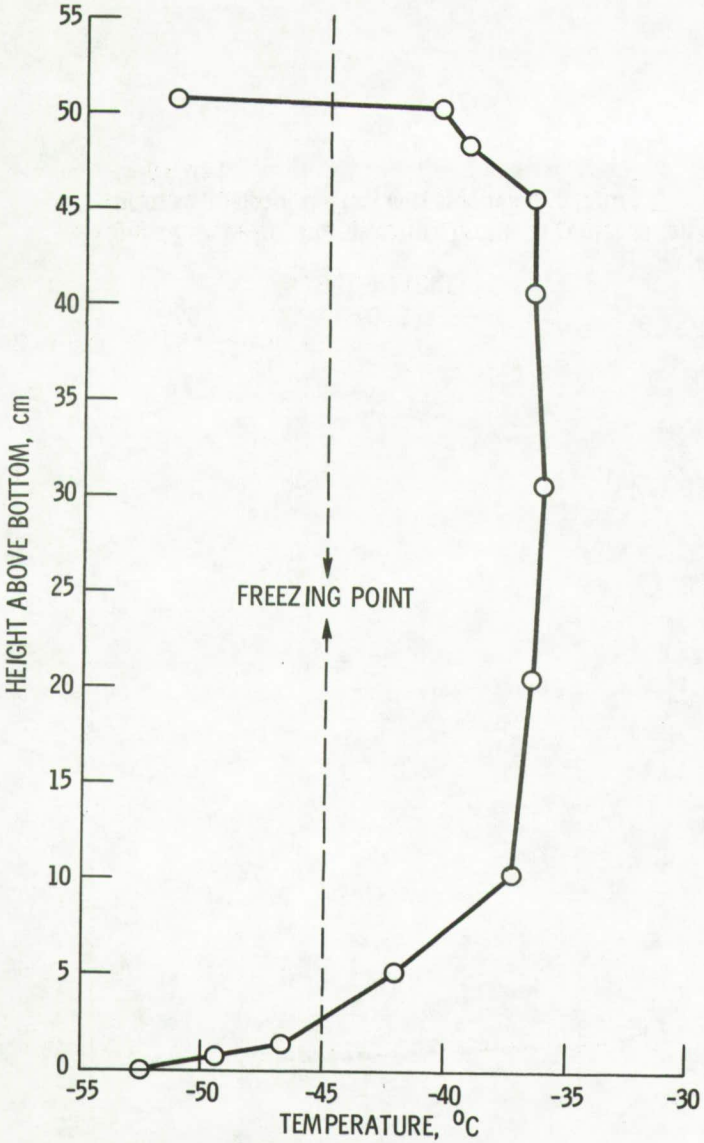

Figure 5. - Vertical temperature profile at center of tank prior to pumpout for test corresponding to figure 4; LFP-9 fuel.

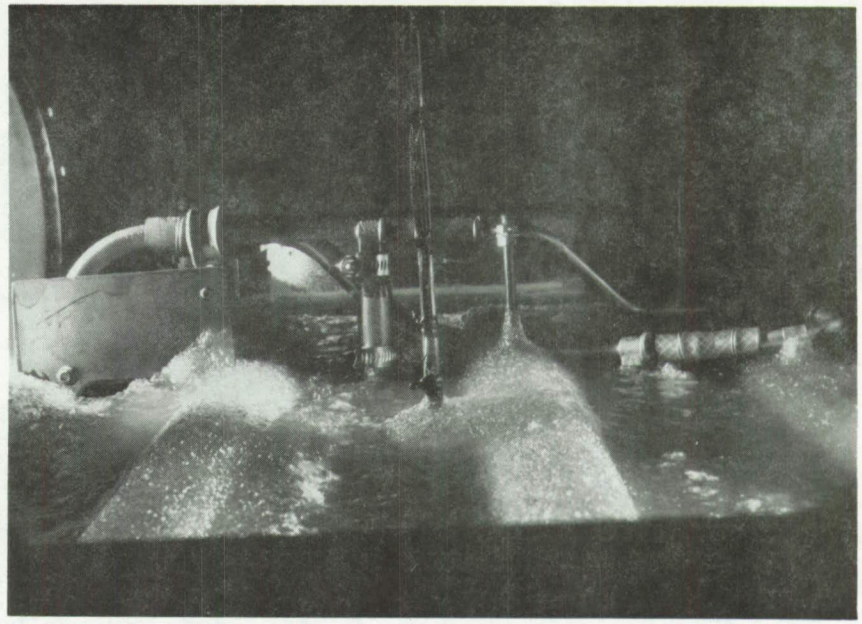

Figure 6. - Solid fuel remaining in tank at moderate holdup conditions; LFP-6 fuel; 8.8 mass percent holdup.

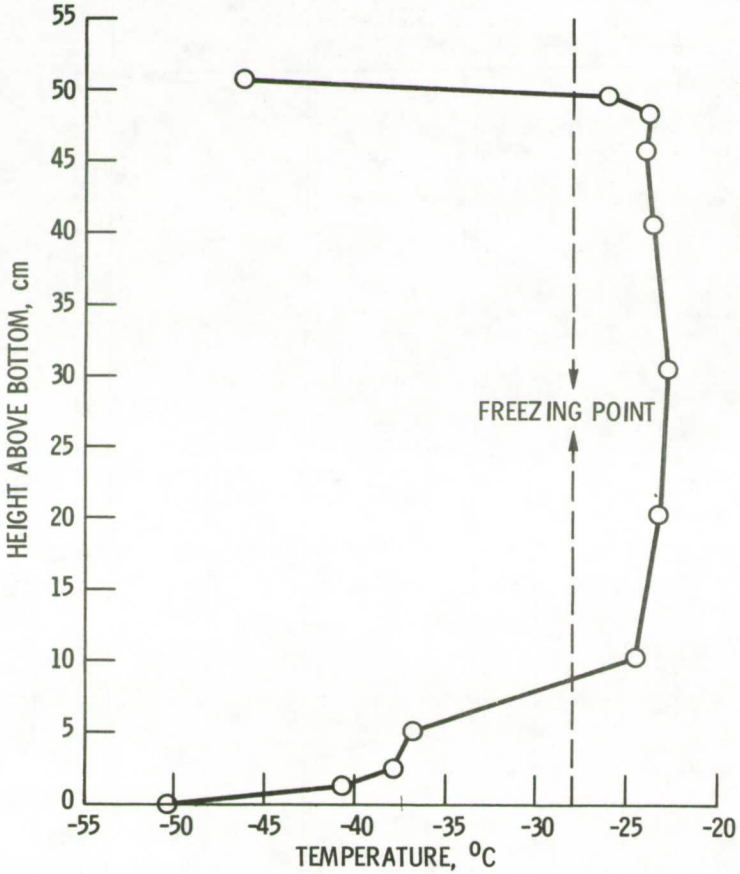

Figure 7. - Vertical temperature profile at center of tank prior to pumpout for test corresponding to figure 6; LFP-6 fuel.

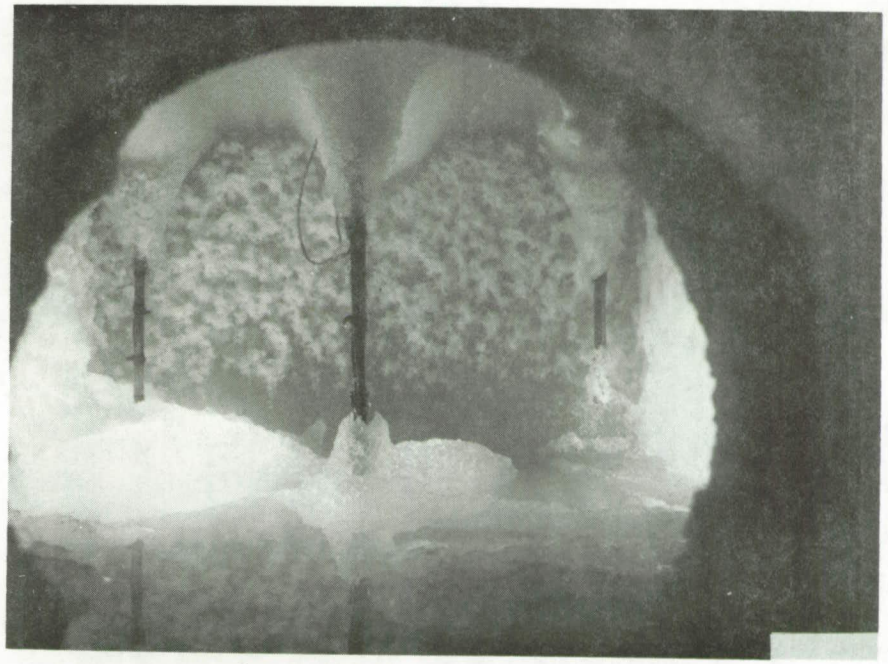

Figure 8. - Solid fuel remaining in tank at high holdup conditions; LFP-1 fuel; 57.2 mass percent holdup.

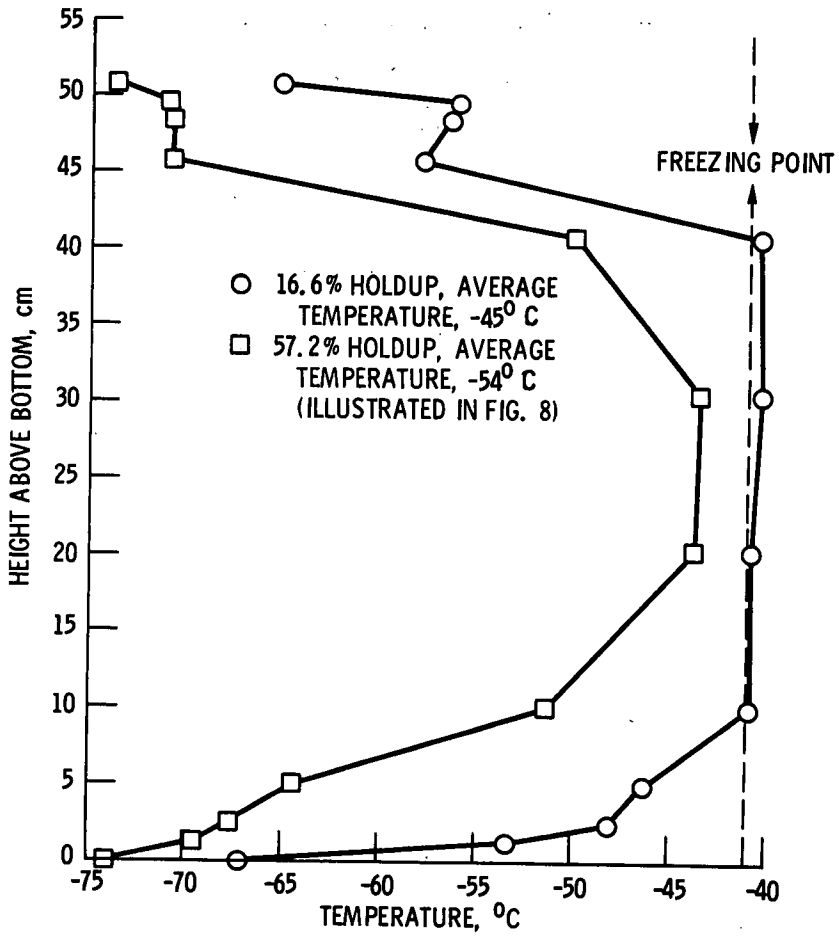

Figure 9. - Vertical temperature profiles at center of tank prior to pumpout for high holdup conditions; LFP-1 fuel.

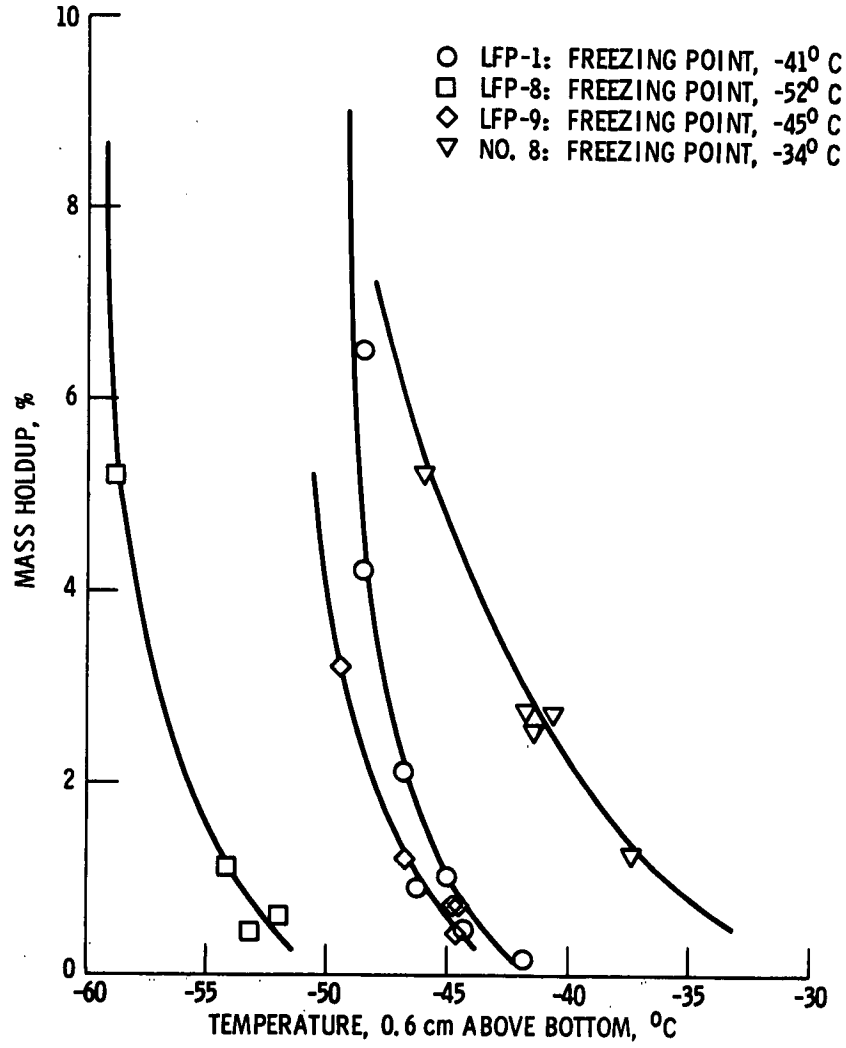

Figure 10. - Holdup summary for low holdup conditions; aviation turbine fuels.

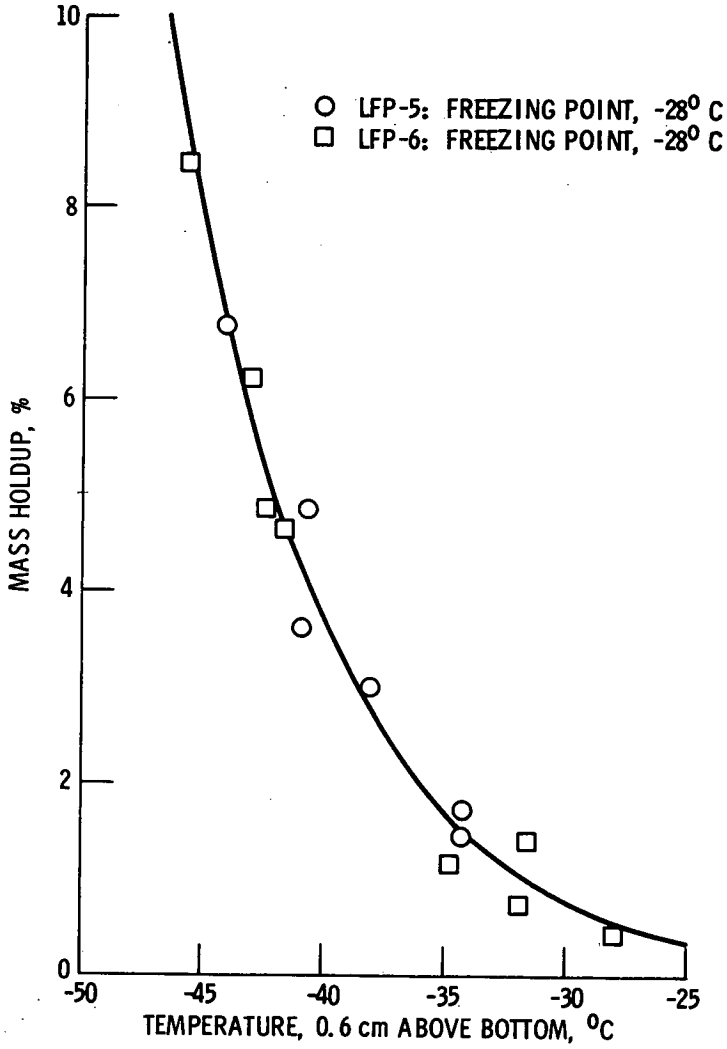

Figure 11. - Holdup summary for low holdup conditions; intermediate fuels.

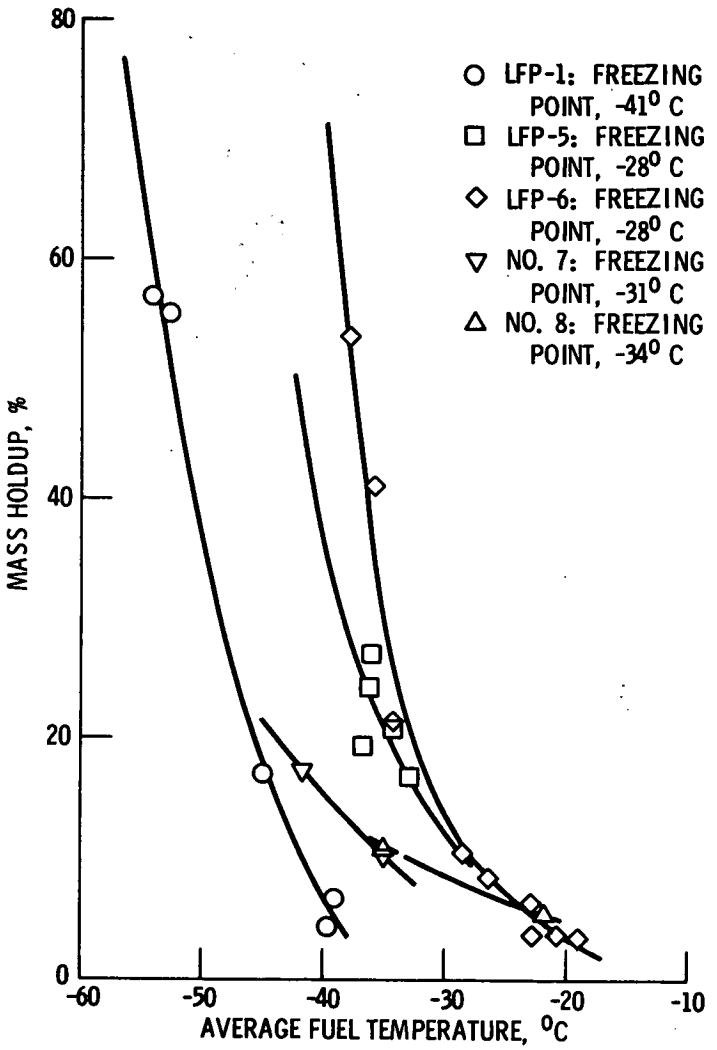

Figure 12. - Holdup summary for high holdup conditions.

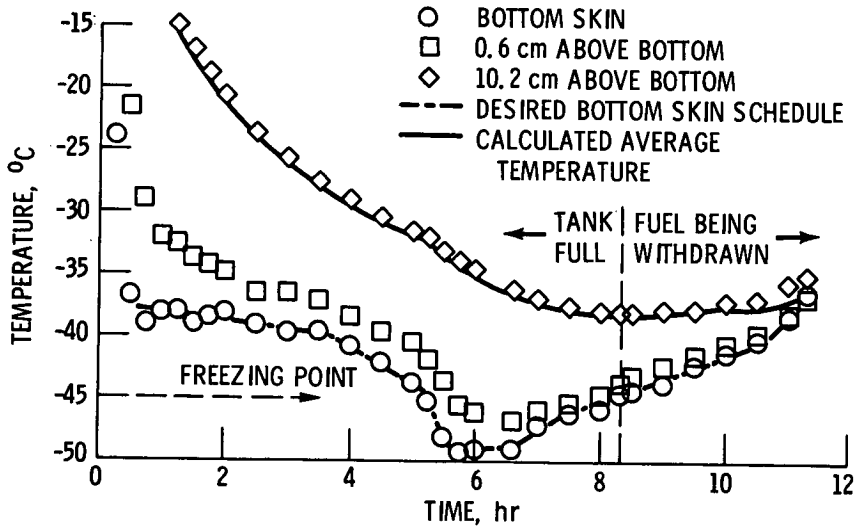

Figure 13. - Temperature history for time-varying surface temperature test with LFP-9 fuel.

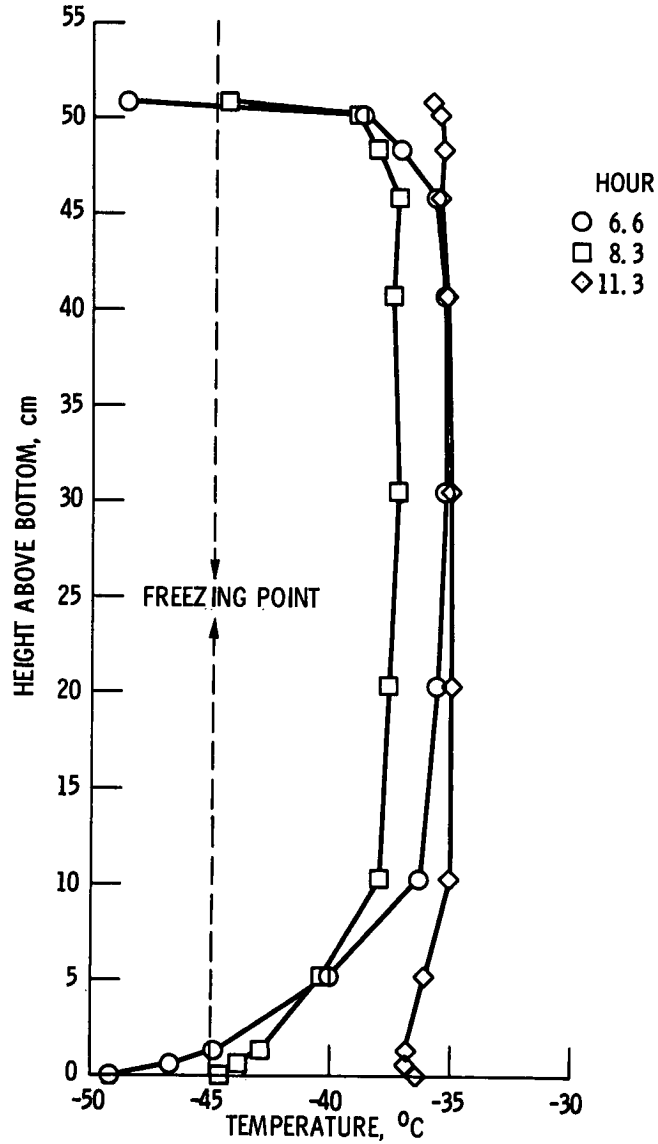

Figure 14. - Vertical temperature profiles at center of tank for time-varying surface temperature test; LFP-9 fuel.

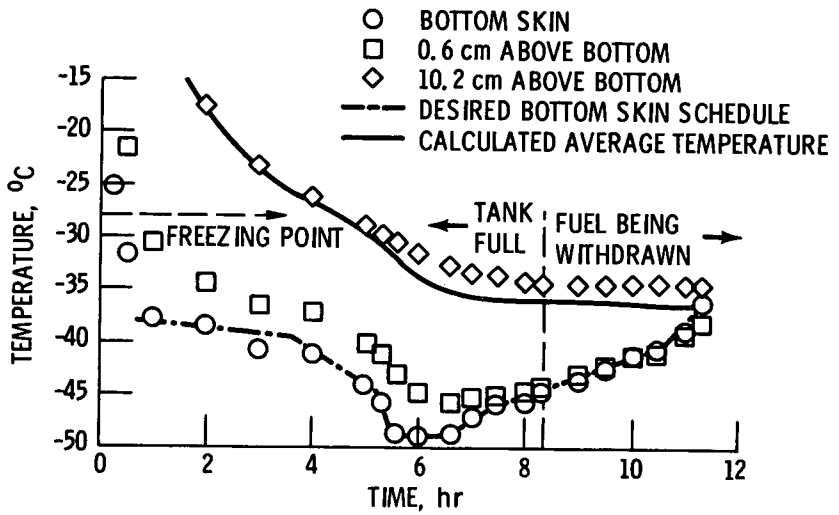

Figure 15. - Temperature history for time-varying surface temperature test with LFP-5 fuel.

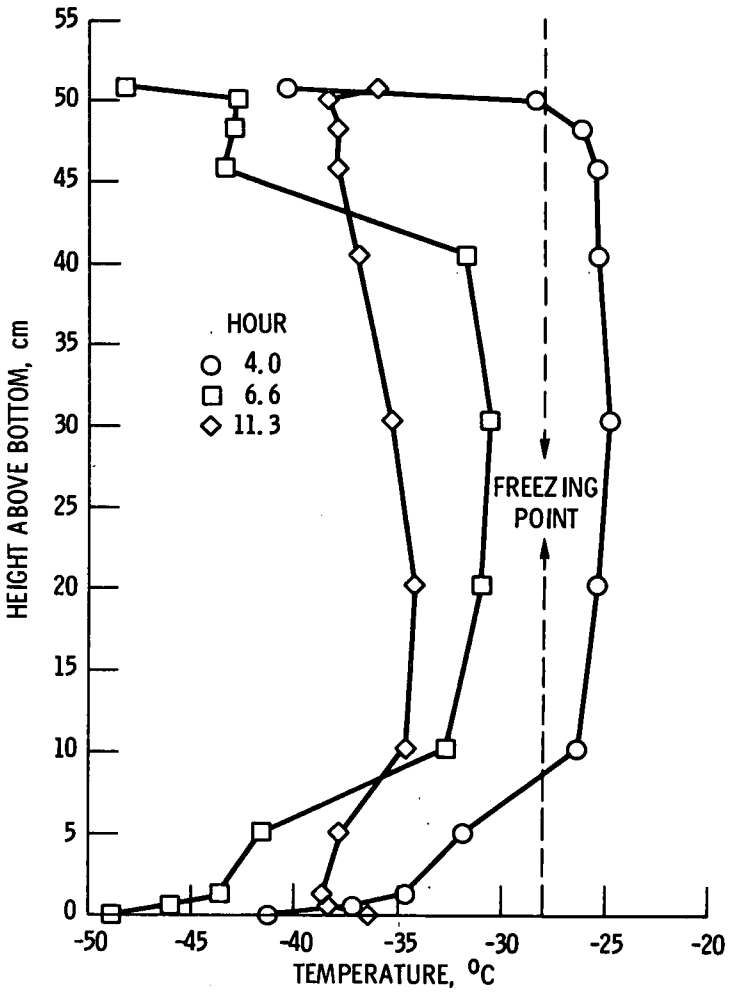

Figure 16. - Vertical temperature profiles at center of tank for time-varying surface temperature test; LFP-5 fuel.

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15. Supplementary Notes

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16. Abstract

Freezing behavior, pumpability, and temperature profiles for aviation turbine fuels were measured in a 190-liter tank, chilled to simulate internal temperature gradients encountered in commercial airplane wing tanks. Two low-temperature situations were observed. Where the bulk of the fuel is above the specification freezing point, pumpout of the fuel removes all fuel except a layer adhering to the bottom chilled surfaces, and the unpumpable fraction depends on the fuel temperature near these surfaces. Where the bulk of the fuel is at or below the freezing point, pumpout ceases when solids block the pump inlet, and the unpumpable fraction depends on the overall average temperature.

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