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Experiments on Fuel Heating for Commercial Aircraft

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EXPERIMENTS ON FUEL HEATING FOR COMMERCIAL AIRCRAFT

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Abstract

An experimental jet fuel with a -33° C freezing point was chilled in a wing tank simulator with superimposed fuel heating to improve low temperature flowability. Heating consisted of circulating a portion of the fuel to an external heat exchanger and returning the heated fuel to the tank. Flowability was determined by the mass percent of unpumpable fuel (holdup) left in the simulator upon withdrawal of fuel at the conclusion of testing. The study demonstrated that fuel heating is feasible and improves flowability as compared to that of baseline, unheated tests. Delayed heating, with initiation when the fuel reaches a prescribed low-temperature limit, showed promise of being more efficient than continuous heating. Regardless of the mode or rate of heating, complete flowability (zero holdup) could not be restored by fuel heating. The severe, extreme-day environment imposed by the test caused a very small amount of subfreezing fuel to be retained near the tank surfaces even at high rates of heating. Correlations of flowability established for unheated fuel tests also could be applied to the heated test results if based on boundary-layer temperature or a solid index (subfreezing point) characteristic of the fuel.

Introduction

Aviation turbine fuels with higher freezing points would have the advantage of meeting changing market demands for these fuels and competing distillate products by allowing their manufacture from poor-quality petroleum and syncrudes with minimal processing.[1-5] A small trend toward increasing average freezing point is already evident from statistics on inspection samples of jet fuels.[6] Higher-freezing-point fuels would be acceptable for commercial aviation use if adequate margins between flight storage temperatures and freezing points (or other flowability parameters) are assured. An obvious means of maintaining these temperature margins is by heating the fuel in the aircraft tank. There are several sources of heat rejected by the airframe-engine systems, which are potentially adaptable to fuel heating with minimal penalties.[7-10]

Experimental verification of the feasibility of fuel heating requires some understanding of the basic behavior of low-temperature fuel flow. Hydrocarbon fuels are complex mixtures. Phase change occurs over a range of temperatures, and the resulting two-phase mixture may retain most of its fluidity.[7,11] Isothermal fuel chilling tests have demonstrated that aviation turbine fuels are often partially or completely flowable at temperatures at or below the standard (ASTM D-2386) freezing point.[12,13] Fuel in an aircraft wing tank, however, is rarely isothermal. More recently, fuel chilling studies used aircraft wing tank simulators that maintained internal fuel temperature gradients believed representative of those encountered in airplane flights.[14-16] These studies demonstrated that flowability is often influenced by the minimum fuel temperatures near the simulator tank surfaces, temperatures considerably below the apparent fuel bulk temperatures.[15,17]

In the studies described in this paper, a wing tank simulator apparatus was operated with superimposed fuel heating. A portion of the fuel was withdrawn from the tank, heated in an external heat exchanger, and returned to the chilled tank. Tests employed two modes of heating: delayed heating where the heating flow started only when the fuel reached a prescribed minimum temperature, and continuous heating. Flowability was defined by holdup, the fraction of unpumpable fuel retained in the tank upon otherwise complete withdrawal at the end of a test.

This paper presents selected data from unheated and heated fuel tests, illustrating temperature histories and internal temperature gradients. The data are evaluated by a discussion of the quantitative effects of fuel heating and the general correlation of low-temperature flowability to various temperature parameters. Tests used an experimental jet fuel with a -33° C freezing point; some comparisons are made to previous data obtained with a reference Jet A fuel.

The experimental studies were conducted at the Lockheed-California Co., Rye Canyon Laboratories, Saugus, California under NASA Contract NAS 3-21977. A complete description of test conditions, covering the use of five experimental fuels, is given in a NASA contractor report.[18] The contributions of the test engineer, Mr. Ronald Deane, are gratefully acknowledged. Further acknowledgment is extended to the Coordinating Research Council, Inc., Atlanta, Georgia, and to Mr. J. A. Bert of Chevron Research Co., who devised a correlation presented in this paper.

Apparatus and Procedure

The experimental apparatus consisted of a wing tank simulator, discharge, chilling, and heating systems (Fig. 1). The tank was 51-cm high internally with a rectangular cross-section, 76 by 51 cm. Nominal tank volume was 0.193 m^3. The top and bottom surfaces of the tank were chilled through heat exchanger plates bonded to the outside of the stringer-reinforced skins. The side walls had viewing windows but were otherwise

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insulated. Fuel was withdrawn from the tank through an opening at a bottom corner surrounded by an open top "surge box." The discharge system consisted of a centrifugal pump mounted below the simulator tank, which pumped fuel to a weighing tank installed on a manual beam balance. The chilling system supplied cold methanol to the chilled tank surfaces, using a closed loop system with temperature and flow controls for programmed rates of chilling. For fuel heating a portion of the fuel could be pumped through an external heat exchanger. Heated fuel then returned to the simulator through a perforated recirculation distributor at the bottom of the tank. Lubricating oil heated by an electrical cartridge heater furnished the energy to the hot side of the fuel heat exchanger. Heating rates were usually controlled by the amount of heating of the lubricating oil, although the recirculating fuel flow could be varied as well.

This simple apparatus represented a portion of an outer wing tank of a wide-bodied commercial airplane. It provided the experimental conditions to simulate the expected environment during a long-range flight, where fuel is chilled through heat loss to the atmosphere through the upper and lower wing surfaces. The tank capacity and fuel heating rates were scaled about two orders of magnitude smaller than the reported airplane model.[7] This simulator has been used since 1978 for a variety of low-temperature flowability experiments.[15,18] A similar apparatus is in use at a Boeing Company laboratory,[16] but this apparatus at present lacks a fuel heating capability.

The series of tests incorporating fuel heating involved about 100 tests with 5 different experimental fuels. This paper will discuss interpretations of results not previously reported. For emphasis, reported tests concentrate on one experimental fuel, designated LFP-14. This fuel is a kerosine blend with a freezing point of -33° C and a pour point of -35° C, but it otherwise meets the specifications of commercial aviation turbine fuel, Jet A. The freezing point (ASTM D-2386) is the temperature at which wax or solid crystals are observed to disappear upon warming from a low temperature. The pour point (ASTM D-97) is the lowest temperature at which the fuel will flow when inverted in a standard cup apparatus. The flowability correlations presented in this paper also include test results with a reference Jet A fuel, LFP-11, which has a freezing point of -46° C and a pour point of -53° C.

Testing always began with a full fuel tank (155 to 160-kg load). Fuel loading temperatures varied with ambient conditions, but initially all the fuel in the tank was at a uniform temperature. A programmed rate of chilling reduced the fuel temperature as a function of test time, creating internal temperature gradients, since the fuel would chill more rapidly near the surfaces than at the center. During the test, internal and surface temperatures were measured and recorded. At the conclusion of a test, the discharge pump withdrew fuel to the weighing tank at a nominal rate of 0.010 m^3/min., requiring about 20 min. to evacuate the simulator. Flowability was defined by holdup, the ratio of the unpumpable solid or slush remaining in the simulator, determined by difference, to the original load. Completely flowable fuel has zero holdup, and at warm conditions all the fuel could be recovered from the simulator tank, within the precision of the weighing balance, about 0.1 kg. For tests with fuel heating, the recirculating fuel flow was maintained at a nominal rate of 0.003 m^3/min. (3L/min.). Heat input to the fuel was calculated from the recirculation flow rate and the temperature rise of the recirculating fuel.

Fuel Heating Test Results

Baseline, Unheated Tests

Figure 2 is a temperature history at selected locations in the simulator tank for a test where the experimental fuel, LFP-14, was chilled for nearly 7 hours, with no superimposed fuel heating. This test served as a reference baseline for comparison with fuel heating tests. The schedule of chilling the bottom surface of the simulator was based approximately on the environment expected for a long-range commercial flight on an extreme (0.3 percent probability) cold day, derived from Boeing analyses.[8,19] The baseline test is a shortened version of the modeled flight, omitting the final four hours at a warmer temperature environment, unnecessary for the test simulation. Some modifications in the rate of chilling for the first two hours were made to accommodate the requirements of the chilling system.[18]

Figure 2 shows temperatures measured at the inside surface of the bottom skin (0 cm) and at vertical heights within the tank at 0.6, 1.3, and 25.4 cm above the bottom surface, from a thermocouple rack located at the middle of the simulator tank. The 0.6 and 1.3-cm readings are those closest to the bottom surface; the 25.4-cm reading is at the vertical center of the tank. Figure 2 also includes the calculated average fuel temperature history.

The skin temperature schedule for the baseline test was a rapid chilling during the first hour, followed by slower but continued chilling thereafter. The bottom surface temperature reversal shown in Fig. 2 near 1 hr was caused by overshoot of the controller response, but this perturbation had no influence on subsequent temperature behavior. The temperatures near the bottom skin decreased almost in concert with the skin temperature decrease, but the center temperature responded much more slowly. The average fuel temperature decreased at the same rate as the center temperature, remaining within 3° C of the center temperature. Pumpout for the baseline and comparison heated tests started at 6.6 hr and was completed before 7-hr elapsed time.

Figure 3 is a crossplot showing the vertical temperature profile as measured at the 6.6-hr initiation of pumpout for the baseline test. The profile is typical of almost all measurements in the simulator tests.[17] The profile is distinguished by a uniform temperature over the central portion of the tank, about 70 percent of the volume. The temperature gradients to the chilled skins form a narrow boundary layer at the top and a wide boundary layer at the bottom, due to density differences. The average temperatures shown in Fig. 2 were calculated from a graphical integration of these profiles at various times during the tests.

The surge box surrounding the simulator tank outlet provided a head of fuel such that fuel withdrawal preferentially removed bulk temperature fuel before bottom boundary-layer fuel. At conditions where holdup was small (10 percent or less), the liquid fuel naturally decanted, which concentrated the solids and slush at the bottom of the tank.[17] For example, the baseline test illustrated in Figs. 2 and 3 produced a holdup of 8.8 mass percent. Since the center (-30.5° C) and average (-32.6° C) temperatures were above the LFP-14 fuel freezing point (-33° C), the unpumpable fuel solids originated in and were influenced by the cold boundary layers in the tank.

Tests with Heat Addition

Fuel Heating Modes. The tests with superimposed fuel heating were designed for comparison with the baseline, unheated temperature histories. The chilling system controller adjusted the coolant flows to maintain the desired cold-day schedule. Although some temperature-schedule variations occurred in the tests, they were never greater than 2° C.

There were two modes of heat addition, delayed and continuous (Fig. 4). Delayed heating tests had no fuel recirculation until the bulk fuel reached a predetermined temperature margin above the freezing point, at which time the recirculation flow valve was opened to provide fuel heating until the pumpout time. During the early part of the test, the lubricating oil heat transfer fluid was preheated to about 110 to 120° C. When the recirculating fuel flow initiated heat transfer, there was a rapid surge of thermal energy from the sensible heat of the heat transfer fluid. In Fig. 4, the delayed heating schedule shows a peak heating rate, or power, well over 3 kW at first, but the heating rate decreased rapidly to around 700-W as the heat transfer fluid reached equilibrium temperatures of 0 to 10° C. For the continuous heating tests, fuel recirculation and heating were initiated shortly (about 0.1 hr) after the start of the childown, and heating power was nearly constant until the pumpout time. The continuous heating schedule in Fig. 4 is typical for a low rate of fuel heating.

Temperature Histories. Figure 5 is a temperature history at selected locations in the simulator tank for a test where the LFP-14 fuel was heated by delayed heating while the surface temperature was maintained at the baseline temperature schedule. Heating was initiated when the thermocouple at the center of the tank reached -25° C (4.3 hr). The heating schedule was the delayed heating illustrated in Fig. 4. Temperature locations of Fig. 5 correspond to those of Fig. 2. The skin temperatures were slightly warmer than those of the baseline schedule due to inaccuracies of the chilling system controller. The vertical center temperature responded immediately and rapidly to the heating, increasing with time and reaching -16.5° C at 6.6 hr (pumpout). For the baseline test at the corresponding time this temperature was -30.5° C. The temperatures at the two stations nearest the bottom skin also increased when heating was superimposed but to a lesser degree than the center. At 0.6 cm, for example, heating increased the temperature at 6.6 hr to -40° C compared to a baseline value of -47° C. The delayed heating improved flowability, reducing holdup from a baseline 8.8 percent to 2.5 percent, but it did not restore complete flowability (zero holdup). This should be expected since the heated boundary layer temperatures remained below the -33° C freezing point.

Figure 6 is a temperature history at selected locations in the simulator tank for a test where the fuel was heated continuously. Again the test maintained a childown schedule of skin temperatures duplicating, as far as possible, the baseline test. This test incorporated the nominal 370-W heating rate schedule that was illustrated in Fig. 4. The effect of continuous heating on the fuel temperature is less apparent than that of delayed heating because temperatures decreased throughout the test. Nevertheless, a comparison with the baseline test temperatures shows that temperatures were increased appreciably with the continuous heating. At the 6.6-hr pumpout time, the vertical center temperature was -20.5° C compared to -30.5° C for the baseline test. At the same time, the 0.6-cm temperature was -41.5° C compared to -47° C for the baseline test. Flowability improved, with holdup reduced from the baseline 8.8 percent to 3.1 percent.

Figure 7 is a crossplot showing the vertical temperature profile as measured at 6.6 hr for the continuous heating test of Fig. 6. The profile overall resembles that of the baseline (Fig. 3), with a nearly uniform temperature over the bulk of the fuel. The profile shows the effective increase in the bulk temperature by heating, for there is about a 10° C greater difference between the center and skin temperatures than for the baseline example. More important is the smaller temperature increase in the subfreezing boundary layers, which improves but does not completely restore flowability. A test with the same average or bulk temperatures as Fig. 7 but with a profile that maintained skin temperatures at or above the -33° C freezing point would have complete flowability (zero holdup). Nevertheless, profiles similar to the Fig. 7 example are to be expected for all tests that maintained the representative cold skin temperatures, regardless of the mode or rate of heating.

Discussion of Results

Effect of Fuel Heating on Flowability

Test Summary. Table 1 is a summary of the results of selected tests, giving heating rates, average fuel temperatures at pumpout, and holdups. Tests are identified by the test numbers in the experimental program and illustrative figures, if applicable, in this paper. Heated tests include one delayed heating test and four continuous heating tests with a range of heating rates. Two unheated, baseline tests are also included. The cold day test (No. 212) is the baseline test described in this paper and used as a reference for all the heated tests. The other unheated test (No. 213) was a special warm day test with surface temperatures always above -33° C. Comparison of the holdup results of this test and the heated test No. 215 demonstrated that the heated test with cold boundaries could not achieve the zero holdup of the warm day test, even though average temperatures were about equal for the two tests.

The measured fuel heating rates are defined from the difference between the heated fuel enthalpies and those of the unheated, baseline test as a function of time. Enthalpies were computed from the temperature histories and estimated fuel transport properties: specific gravity from the fuel inspection data and specific heat from data for a typical jet fuel.[20] The calculations included latent heat of fusion as well as sensible heats. The former were estimated from an assessment of the volume occupied by subfreezing fuel shown by the temperature profiles and a nominal heat of fusion for appropriate molecular-weight n-paraffins. Table 1 lists the measured fuel heating rates as averages (enthalpy/time) over the entire 6.6-hr environmental simulation. The table also lists a second heating rate, the power supplied as calculated from the temperature rise of the recirculating fuel. For tests with a low rate of continuous heating (No. 215) or short duration delayed heating, the power supplied and measured fuel heating rates are nearly the same. The fuel heating is in fact slightly greater than the power supplied for test No. 212 only because of a small mismatch in the duplication of the baseline skin temperature schedule. At higher rates of fuel heating, however, the heat transfer to the simulator chilling system increased with respect to that of the unheated baseline. Hence a substantial portion of the heating power supplied was rejected to the chilling system and was unavailable for fuel heating. For example, to increase the fuel heating rate by 45 W (No. 217 compared to No. 216) required an increase of about 300 W of heating power. This decreasing effectiveness of higher-rate fuel heating under realistic heat transfer conditions is a factor to be considered in the determination of practical requirements for fuel heating systems.

Figure 8 is a graphical summary of the fuel heating and holdup relationships from Table 1. A curve is drawn through the baseline and three continuous heating test results, shown as circles. Figure 8 illustrates the diminishing improvement of flowability by increased heating, and it demonstrates that holdup may not be reduced much below 2 percent by even large rates of fuel heating. Two other test results from Table 1 are shown by different symbols in Fig. 8. The continuous heating test, No. 221, shown by a square, is one of several tests using variations of the heated fuel recirculation distributor designs.[18] A small improvement is indicated by the fact that the same fuel heating rate produced lower holdup than with the reference design for the tests shown by circles. However, this difference was small, and the effectiveness of distributor design and fuel mixing is not otherwise discussed in this paper. The other distinctive result in Fig. 8 is that of the delayed heating test, shown by a diamond. When calculated for the entire test period, delayed heating was more efficient in reducing holdup than the same rate of continuous heating, because continuous heating supplied heating power during early portions of the test where heating was unnecessary for maintaining fuel fluidity.

Practical Considerations. Since delayed heating was shown to be more efficient, supplying heating power only when required during a flight, it may have advantages in minimizing performance penalties for heating systems which require diversion of engine thrust, such as electrical heating. Delayed heating, however, may be difficult to program or control, whether manually or automatically. Continuous heating can be simple and easy to measure and control. It is best suited, however, for low-penalty heating systems such as engine waste heat rejection.

The results also show that fuel heating can greatly improve low-temperature fuel flowability but may not restore complete flowability. The "cold-day" flight environment maintains subfreezing surfaces and at least a small subfreezing boundary layer. Minimum holdup for heated fuel may never drop much below 2 percent. However, the surface temperature schedule used in the tests may be quite conservative and not entirely representative for even extreme-day heated fuel surface temperatures. Furthermore, previous work on long flight simulations with cruise and descent warming during the last portions of the test indicated that the small amounts of potential solid fuel accumulations will melt and all fuel is flowable by the end of the simulated flight.[17]

Correlations of Heated and Unheated Flowability

Introduction. In a previous paper, the authors discussed the relationships of low-temperature flowability by means of temperature correlations, which are very useful for prescribing test conditions or comparing results.[17] While these relationships are called correlations for convenience, they may not have universal application for prediction of behavior of a variety of fuels. Four separate correlations of holdup, for both unheated and heated fuel tests, are illustrated and discussed in this section. The test results used for the correlations are taken from a much broader set of low temperature tests than those included in Table 1. For the experimental fuel, LFP-14, results of 18 tests are plotted, including unheated tests and a broader range of heated test conditions. In addition, another group of 14 test results are also shown in the correlations, based on previous tests with a reference Jet A (LFP-11).[18]

Boundary-Layer Temperature. Almost all the tests in this simulator study, baseline or heated, produced temperature profiles after a period of time that had subfreezing temperatures near the chilled tank surfaces. Furthermore, the authors have observed that for low holdup conditions, under 10 mass percent, the warmer bulk liquid naturally decanted leaving a near-solid accumulation at the bottom of the tank.[17] A likely correlating parameter for flowability is thus the temperature at the lower boundary layer. Figure 9 presents the results of the collection of test data plotted as holdup as a function of the temperature measured at 0.6 cm above the bottom center of the simulator tank. This is the closest fluid temperature measurement to the bottom skin. The temperatures are as measured near the end of the pumpout period, or 6.9 hr. This is a departure from previously reported measurements of boundary-layer temperature, which were taken at the start of pumpout.[17] There was occasionally a small change in the boundary layer temperature during the 20 min. pumpout, and it was felt that the end of the pumpout period would yield temperatures more sensitive to the boundary-layer conditions.

Data shown in Fig. 9 include results of heated and unheated tests at low and high holdup conditions for both fuels, the experimental LFP-14, and the reference jet fuel LFP-11. The curves shown are the best fit to the unheated data points. Zero holdup is approached near the freezing points, -33° C for LFP-14 and -46° C for LFP-11. The heated test results have a very limited range of variation, but they are reasonably well represented by the curve fit to the unheated test results, implying that the principal effect of flowability improvement by heating lies in the increase of the boundary layer temperature.

Average Temperature. The authors have previously noted that where holdup is high, over 10 percent, subfreezing conditions prevail throughout the tank and average temperatures can characterize the flowability.[17] Figure 10 presents the results of the correlation of the test data as a plot of holdup as a function of average temperature. The average temperature was calculated by graphical integration of the temperature profile measured at the center of the tank at the start of the pumpout period.

Average temperatures at the freezing point produce holdups near 10 percent, and zero holdup is at average temperatures well above the freezing point. There is a good correlation of the unheated LFP-14 data and a fair correlation of the LFP-11 data. The heated fuel test results, however, do not correlate with the unheated test results. As a correlating parameter, average temperature may have significance only for conditions of nearly identical temperature profile shape. It has been shown (Table 1) that the "warm day" profile yields zero holdup at an average temperature of -22° C, instead of 5 percent as indicated by the Fig. 10 curve. Since fuel heating alters the temperature profile by raising the bulk temperature proportionately more than the boundary-layer temperature, the poor correlations of heated test results by average temperature are not surprising.

Fraction of Volume Below Solid Index. Earlier in this paper, typical simulator temperature profiles have been illustrated (Figs. 3 and 7). The boundary layer gradients in the profiles can define a height, and consequently a volume, of the simulator tank occupied by fuel below a temperature standard. A correlation can be based on the supposition that holdup originates from the precipitation in the low-temperature volume and is proportional to this volume. The standard freezing point is too high and conservative for this temperature standard. Pour point is probably too low. Instead, the mean of these two fuel characteristics, called the solid index, was used for the temperature criterion. For LFP-11, the solid index is -49° C. For LFP-14, the solid index is -34° C.

Figure 11 presents the results of the correlation of the test data as a plot of holdup as a function of the fraction of volume occupied by fuel with temperatures below the solid index. A single curve gives a reasonable fit to the data for both fuels, heated and unheated. As expected, holdup approaches zero for values of the correlating relating parameter near zero. This method, however, will fail for high holdup conditions. Where the bulk temperature of the fuel is at the solid index, the fraction of the volume below this criterion approaches 100 percent, yet holdup is no greater than 20 to 25 percent. The highest holdup points plotted in Fig. 10 are at this condition, although they are not included in Fig. 11. Furthermore, partially flowable conditions where all of the fuel is below the solid index are possible but cannot be defined by the correlation.

Coordinating Research Council Correlation. The problem of the use of the previous parameter at higher holdup conditions may be solved by including a measurement of the temperature profile as a normalizing factor. This technique has been developed by Mr. J. A. Bert of Chevron Research Co. and will be discussed in a future publication sponsored by the Coordinating Research Council, Inc. (CRC). The CRC method uses a nondimensional temperature ratio, $(T_I - T_S)/(T_M - T_S)$, where T_I is the solid index, T_S, the surface temperature, and T_M, the center temperature in the simulator tank.

Figure 12 presents the results of the correlation of the test data as a plot of holdup as a function of the CRC parameter. At a zero value of the parameter, the tank surface temperature is equal to the solid index. This corresponds to a zero volume fraction in Fig. 11, and for both correlations holdup approaches zero at this limit. For a CRC parameter value of 1, the center temperature is at the solid index and holdup is around 20 to 25 percent. Values of the parameter greater than 1 are feasible for cold, high-holdup conditions, although there are no such data points in the test series presented in this paper. A curve fit through the unheated test results in Fig. 12 shows a good representation of the data for both fuels by a single curve, although heated test results for LFP-14 show slightly lower values of holdup than predicted by the parameter.

The CRC parameter has the advantage of application over a wide range of fuel types and temperature conditions. It has been applied to correlate results for the ten different experimental fuels in the low-temperature, unheated tests conducted earlier using the wing tank simulator.[15] A revision of the parameter may be necessary to make it effective in relating to heated test results. The principal disadvantage may be in the normalizing factor based on center temperature, which shows the same insensitivity as the average temperature correlation to low holdup precipitates, which originate in the boundary layer. Furthermore, the small differences involving a solid index definition are dependent on the precision of this fuel characteristic, which is difficult to define within a degree or two.

Assessment of Correlations. The first two correlations discussed in this section are referenced to a single temperature parameter. The use of the boundary-layer temperature demonstrates the strong influence of this zone on holdup and provides a means of associating heated and unheated results. However the single parameter correlations yield relationships specific to each fuel and not useful for application to a variety of fuels in advance. The second two correlations include a fuel property, solid index. These correlations are universal relationships, which promise applications to any fuel characterized to the extent that freezing and pour points are known. For low holdup conditions, the solid fraction correlation shows that the solid index (the mean of freezing and pour points) defines a zone where about 70 percent of the fuel will be holdup. The CRC correlation appears to have wide application, and it is based on three readily measured values, the solid index and the bulk fuel and tank surface temperatures. Perhaps this correlation can be improved, for use with heated fuels in particular, by a more precisely determined fuel characteristic, such as a calorimetrically determined melting point.[21]

Concluding Remarks

Results of tests on an experimental jet fuel with a -33° C freezing point in a chilled aircraft wing tank simulator with superimposed fuel heating indicate that fuel heating is feasible and improves flowability. Delayed fuel heating, with initiation when the fuel reaches a prescribed low-temperature limit, can be more efficient than continuous heating. While the degree of flow improvement can be enhanced by greater heating rates, high heating rates become less effective because a greater portion of the heat supplied is rejected to the environment instead of increasing the enthalpy of the fuel. The cold surfaces of the simulator tank retain some subfreezing fuel in the boundary layer even under high-heating-rate conditions. Thus even the highest heating rates did not completely restore flowability, as measured by a zero holdup of fuel upon final withdrawal. The limiting fraction of unpumpable fuel, about 2 percent holdup, may be recoverable, however, under practical conditions during descent.

Heated test results can be correlated by some of the flowability correlations developed for unheated fuels. Promising relationships are based on boundary-layer temperatures, yielding specific curves for different fuels, or a general parameter including a subfreezing fuel characteristic as well as environmental temperatures.

Simulator fuel heating rates may be related to full-scale airplane requirements by an approximate two orders of magnitude scaling factor.

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TABLE 1. - SUMMARY OF SELECTED TEST RESULTS

Test identification	Type	Fuel heating rate, W		Average fuel temperature at pumpout, °C	Holdup, mass percent
		Measured (referenced to no. 210)	Power supplied		
210 (Figs. 2,3)	Baseline, cold day	----	0	-32.6	8.8
213	Baseline, warm day	(a)	0	-22.1	0
212 (Fig. 5)	Delayed heating	[b]325	305	-18.5	2.5
215 (Figs. 6,7)	Continuous heating	345	360	-22.6	3.1
221	Continuous heating	400	575	-16.9	2.4
216	Continuous heating	490	765	-17.0	2.3
217	Continuous heating	535	1070	-15.4	2.2

[a] Not applicable.

[b] Rates shown are averaged over the entire test period. During the actual 2.3-hr delayed-heating period, average fuel heating was 910 W.

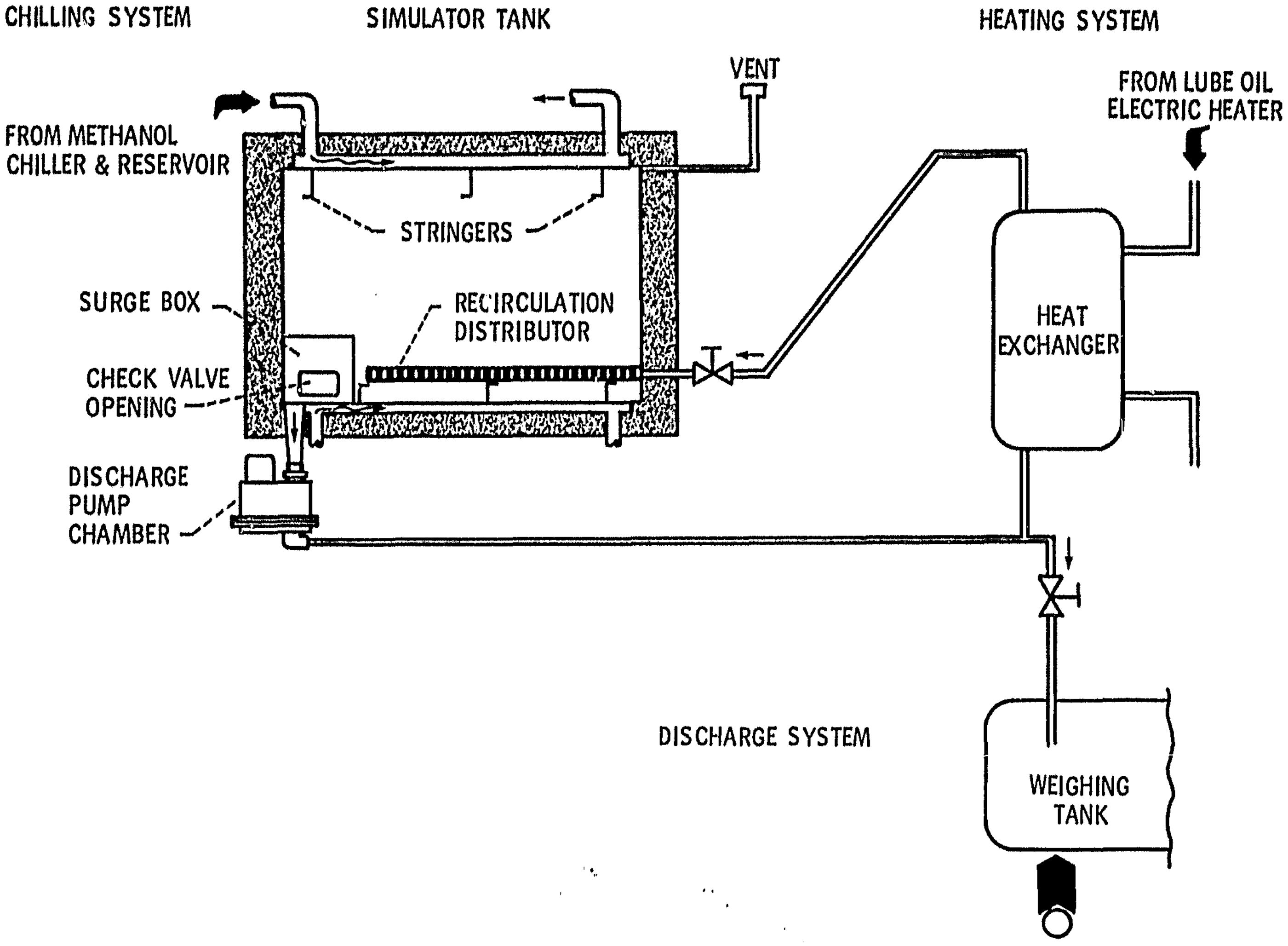

Figure 1. - Schematic of apparatus.

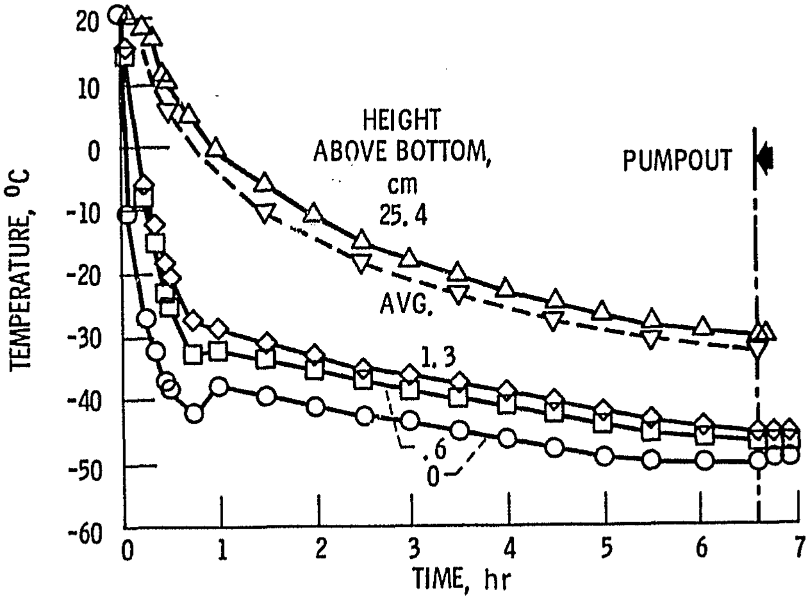

Figure 2. - Temperature histories in simulator tank for unheated, cold-day baseline test (No. 210).

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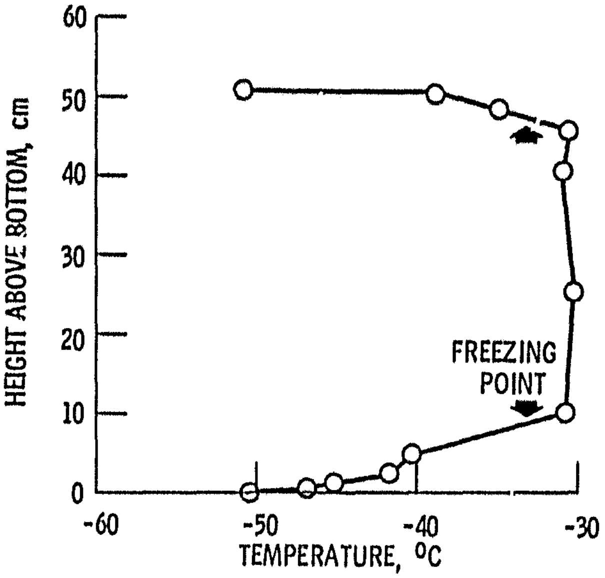

Figure 3. - Temperature profile at center of simulator tank at 6.6 hr for baseline test.

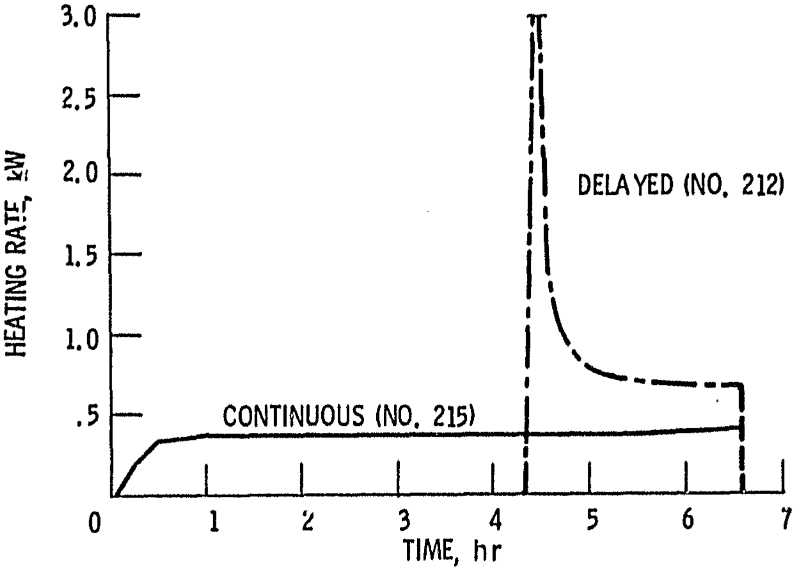

Figure 4. - Examples of fuel heating schedules.

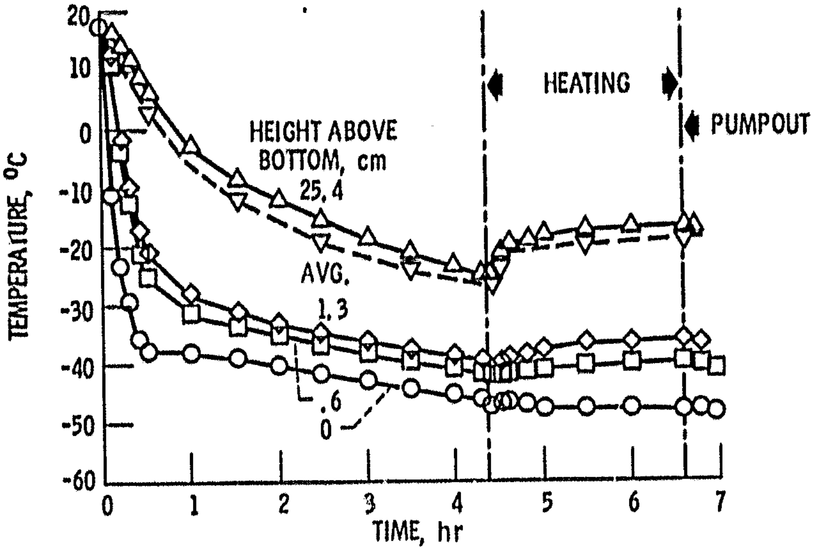

Figure 5. - Temperature histories in simulator tank for delayed heating test (No. 212).

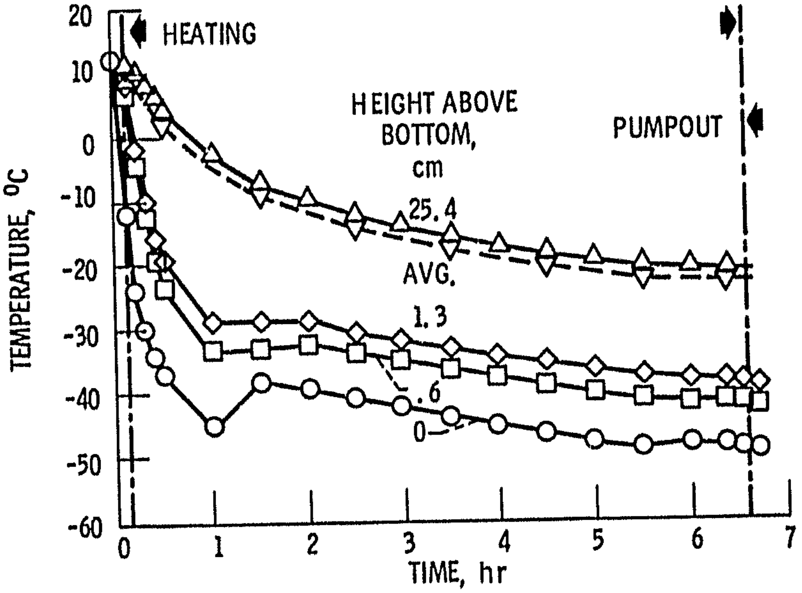

Figure 6. - Temperature histories in simulator tank for continuous heating test (No. 215).

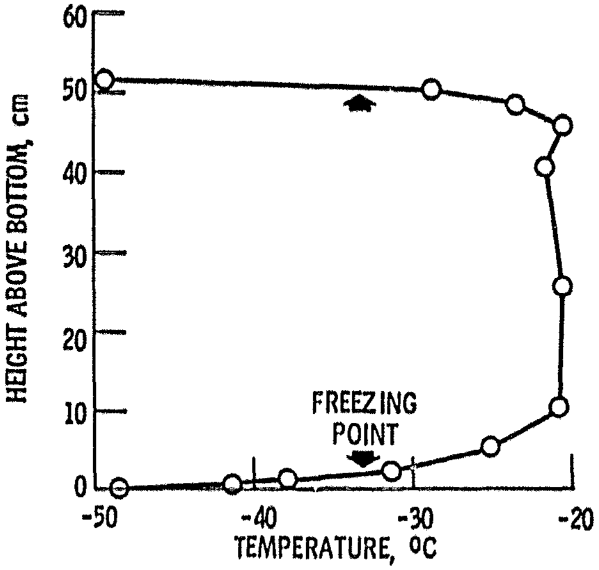

Figure 7. - Temperature profile at center of simulator tank at 6.6 hr for continuous heating test.

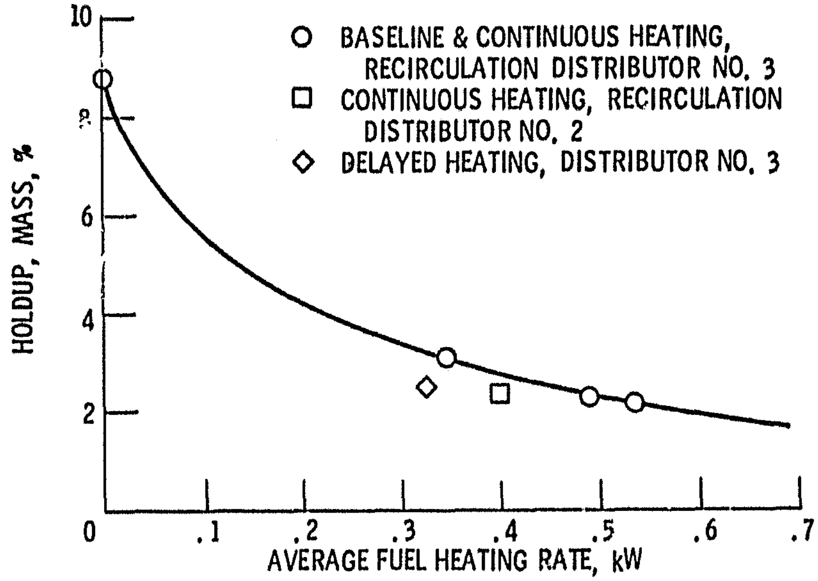

Figure 8. - Influence of average heating rate on fuel flowability, referenced to cold day baseline conditions.

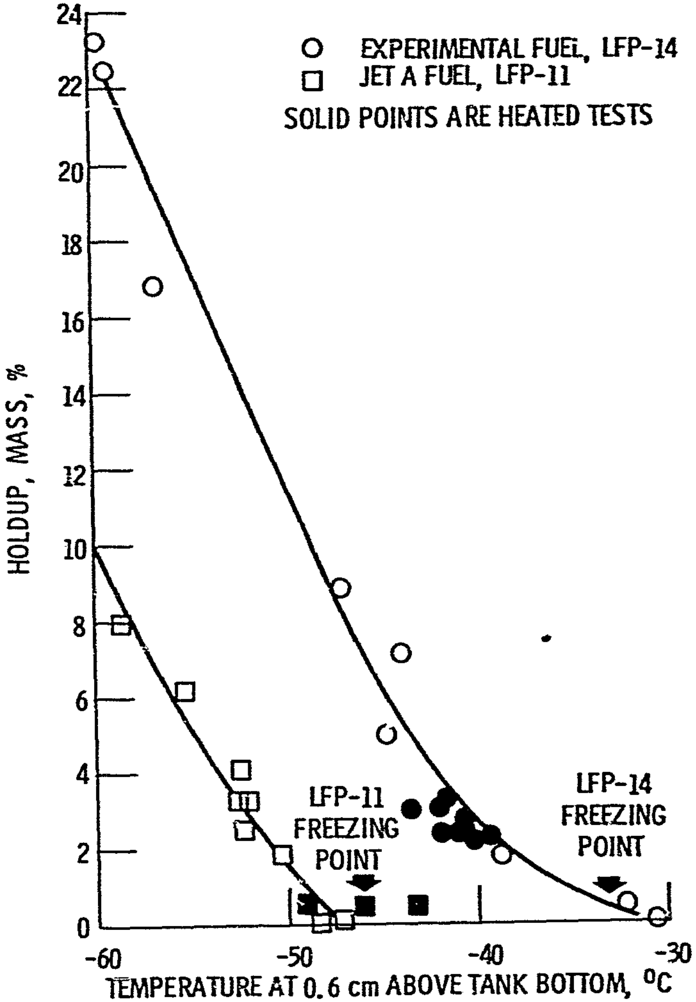

Figure 9. - Correlation of flowability by boundary-layer temperature.

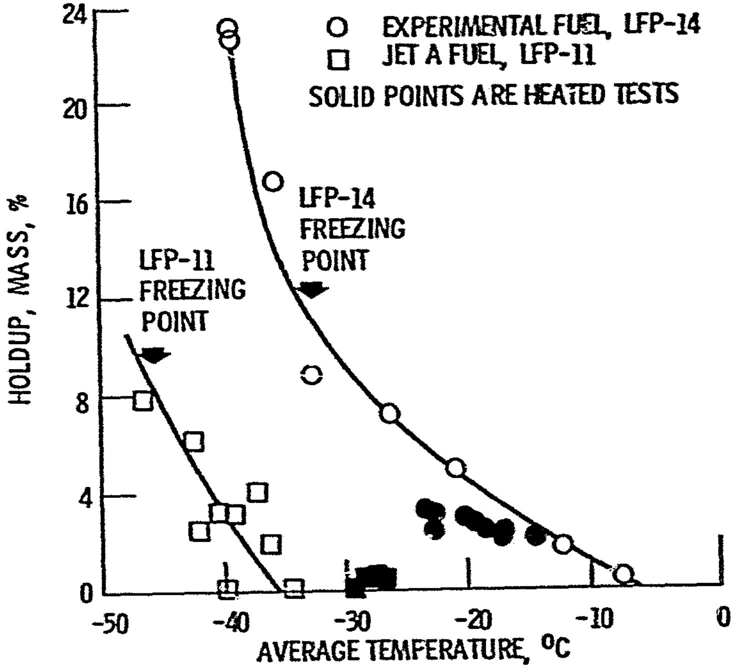

Figure 10. - Correlation of flowability by average temperature.

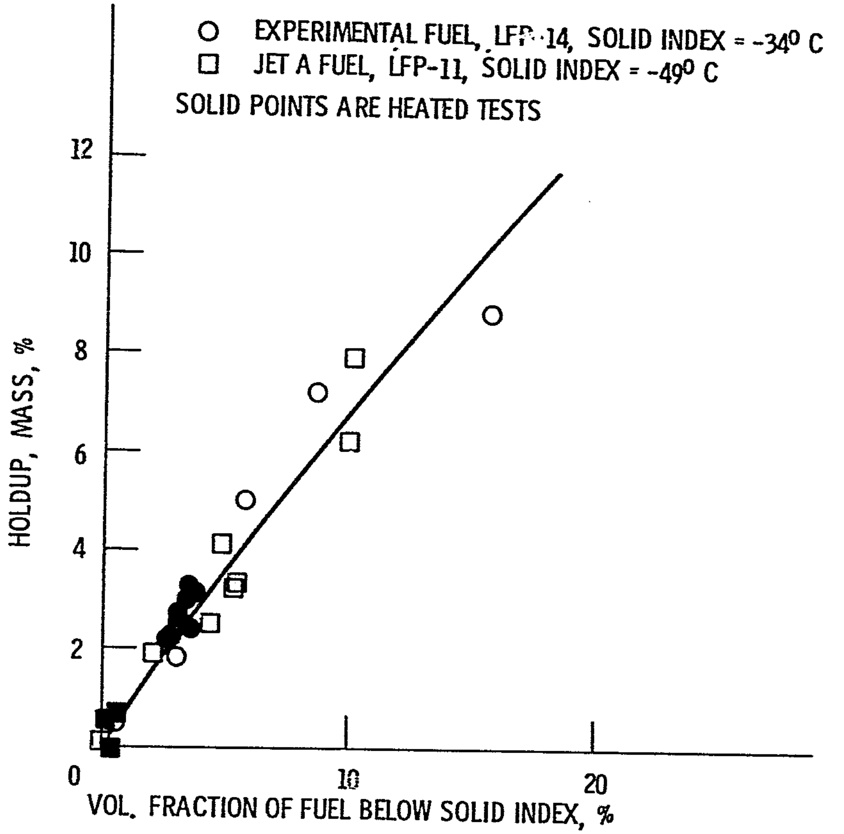

Figure 11. - Correlation of flowability by volume fraction of fuel at subfreezing conditions.

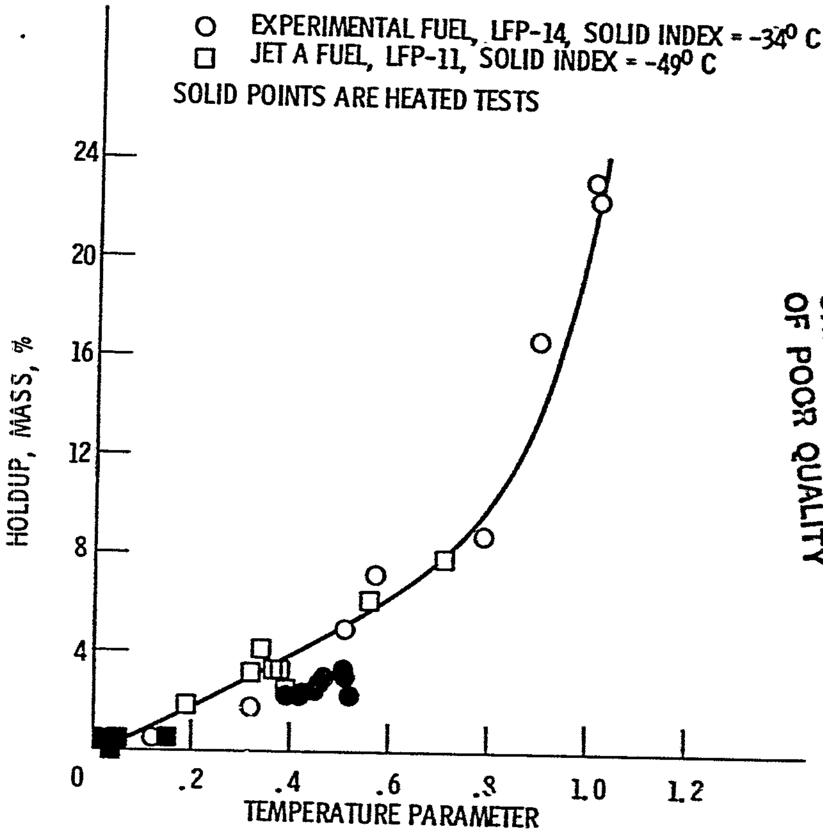

Figure 12. - Correlation of flowability by CRC temperature parameter, $(T_I - T_S)/(T_M - T_S)$, where T_I = solid index temperature, T_S = tank surface temperature, and T_M = center temperature of fuel.

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