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Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a Wing Tank Model

Final Report

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1.0 SUMMARY

An experimental investigation was performed under NASA Contract NAS 3-20814 to study aircraft fuels at low temperatures near the freezing point. The principal objective was an improved understanding of the flowability and pumpability of the fuels in a facility that simulated the heat transfer and temperature profiles encountered during flight in long range commercial wing tanks.

A test tank simulating a section of an outer wing integral fuel tank approximately full scale in height, was designed and fabricated. Internal tank construction included stringers, scavenging ejectors, pump inlet surge box, and other details corresponding to an airplane wing tank construction. The test tank was chilled through heat exchange plates on the upper and lower level horizontal surfaces. Other surfaces were insulated. A viewing port was installed in each vertical panel.

Fuels used during the program included commercially obtained Jet A and Diesel D-2, a special JP-5 type derived from oil shale, paraffinic and naphthenic Jet A, Diesel D-2, and intermediate freeze point fuels, and the paraffinic intermediate treated with a pour point depressant. The pour point depressant and most of the fuels were furnished through the Coordinating Research Council.

Tests were generally conducted by chilling the tank skins to a nearly constant temperature. Fuel was withdrawn from the tank by gravity flow after the fuel reached a desired temperature with time. Suspensions of solid fuel particles were readily withdrawn and presented no obstacles to flow. The accumulation of solid particles at the bottom of the tank, remaining after the liquid was withdrawn, was defined as gravity holdup. For cases where 10% or less of the fuel was held up, the holdup was essentially a solid deposition. At greater holdups, entrapment of liquid fuel within the matrix of solids was discernible. Solid buildup commenced on the bottom of the tank, spread over the lower stringers, then began to form on the upper surfaces and vertical panels. At large holdups, accretions on the walls and upper surfaces sometimes fell and could obstruct gravity flow.

Temperatures measured at the approximate location of the commercial fuel temperature probe provided a good measurement of bulk temperature, but ignored lower temperatures near the chilled walls. Tests were also conducted at a varying wall temperature schedule, with fuel withdrawal over a 3-hour period to represent an extreme condition, long range flight. With specification Jet A fuels, all fuel could be withdrawn, but there was evidence of some solid formation at the time of minimum temperatures, and subsequent melting of the solid material.

Sloshing, recirculation, and use of ejectors tended to decrease the temperature difference between the chilled walls and the bulk fuel and indirectly affected the holdup by altering the temperature profiles. Tests with an internal baffle or with dehydrated fuel showed no change from comparable baseline tests.

Tests with an intermediate distillate fuel, with the addition of a suitable pour point depressant, provided a significant reduction in gravity holdup, compared to that of the undoped fuel. Tank results agreed with laboratory data.

This experimental investigation provided considerable insight into the behavior of fuel at low temperatures representative of flight conditions. A rather large quantity of test data was obtained which could furnish material for further analysis.

2.0 INTRODUCTION

This report presents the results of a study performed by the Lockheed-California Company under NASA Contract NAS 3-20814, titled "Experimental Study of Aircraft Jet Fuels at Low Temperatures Near the Freezing Point".

This experimental study was designed to examine the near-freezing-point behavior of aviation turbine engine fuels in a test facility representative of a section of a commercial aircraft fuel tank. The principal objective was an improved understanding of the practical flowability and pumpability of the fuels utilized in the test program. This understanding would be applied to evaluation of various specification tests related to the freezing point of the fuel and the formation of solids within the fuel. Correlation of all these factors would establish a set of reproducible flowability/pumpability criteria (Ref. 1, 2, 3, 4, 5). These criteria should be suitable for existing jet fuels and for future fuels such as might be produced from raw materials other than crude oil; examples of such potential raw materials are oil shale and coal.

Jet fuel is a complex mixture of a large number of hydrocarbon compounds (Ref. 6). In general, the number and types of compounds are controlled by the crude stocks available at each given refinery, and by the various specification requirements. Reduced availability of crude oil from which jet fuel can be manufactured with a minimum of refinery processes may instigate proposals to broaden the boiling range and compositional specifications of jet fuel to increase the yield of jet fuel product. These changes very likely may raise the freezing point of the jet fuel (Ref. 2, 4, 7). Although the individual compounds have repeatable freeze points, the freeze point of the mixture cannot be determined by calculation. The ASTM D 2386 Freezing Point of Aviation Fuels test determines a temperature at which solids disappear, while the ASTM D-97 Pour Point of Petroleum Oils test determines a temperature at which the fuel does not flow when the test apparatus is positioned horizontally (Ref 8). The principal point of interest is the lowest temperature at which the fuel will flow by gravity, leaving no solid residue. This temperature is between the temperature determined by the two tests. Fortunately for aircraft operations, the freeze point test assures some conservatism relative to the temperature at which some of the fuel becomes unavailable due to solidification.

The pumpability and low temperature behavior of jet fuels have been studied in tank environments previously (Ref. 6, 9, 10). These tests involved the slow chilling of fuel over a period of many hours to maintain a uniform temperature within the tank. The fuel was then discharged from the tank to determine the fraction of holdup, or frozen, unpumpable fuel. Repeat tests at several temperatures established a relationship of holdup as a function of temperature. The tests reported herein were intended to model an aircraft wing tank environment rather than an idealized situation. Internal temperature profiles, cooling rates, and test times simulated extreme cold day commercial aircraft missions. The tank construction was based on a scale model of a wide-bodied airplane wing tank.

The general scope of this investigation covered the following:

- Design and fabricate a sub-scale tankage system representative of commercial jet aircraft practice, and capable of simulating in-flight temperature histories.
- Procure test fuels and characterize them in terms of established test methods.
- For a range of test fuels, define the fluidity and pumpability temperature limits in quiescent and agitated states.
- Determine the effects, if any, of sloshing, baffles, fuel recirculation, and other factors on the low-temperature fluidity.
- Record temperature profiles and time histories for a matrix of fuel and test conditions and obtain photographic records of important phenomena.
- Recommend future research, standards, or practical applications resulting from this study.

This report includes a description of the test apparatus and procedures, and selected temperature and photographic data. The significance and trends of the results are discussed. Appendices A and B present results of various property and characterization tests performed on the fuels used in this investigation. The fuels and fuel characterizations were furnished through the courtesy of the Coordinating Research Council (C.R.C.) Group on Low Temperature Flow Performance of Aviation Turbine Fuels.

3.0 APPARATUS

This section of the report describes the test locale, test tank configuration, including the structure and associated plumbing, access, and observation ..., as well as data acquisition capabilities.

3.1 TEST CELL

Experiments with the test tank were performed at the Rye Canyon Research Center of the Lockheed-California Company's Engineering Laboratories. The test cell, located at the east end of Building 209, measures approximately 3.35 meters (11 feet) by 4.57 meters (15 feet). A large window permits observers to view the test cell from the main building; a self-closing door permits easy access. At the outer end of the test cell is a wide retractable metal door, which was normally open during testing. Both ends contained penetrations through the walls for service and instrumentation. On the floor a low temporary barrier was erected to contain any spillage which might occur.

3.2 TANK SHELL

Configuration of the test tank was designed to simulate a portion of an outer wing fuel tank of a modern commercial jet aircraft. Interior dimensions of the tank are 50.8 centimeters (20 inches) high, 50.8 centimeters (20 inches) wide, and 76.2 centimeters (30 inches) long. This latter dimension is parallel to the upper and lower stringers, and would be spanwise relative to an aircraft wing.

Figure 1 is a sketch of the test tank in plan view, showing the recirculation path and other features.

Figure 2 is a cross-section of the test tank, looking toward the removable panel.

Figure 3 is a photograph of the partially finished test tank showing the internal construction, and rods for thermocouple supports.

Panels for the upper and lower surfaces were fabricated from 6061-T6 aluminum alloy sheet 3.18 millimeters (0.125 inch) thick. Panels for the vertical walls were fabricated from 6061-T6 aluminum alloy sheet 4.83 millmeters (0.190 inch) thick.

Lower stringers were modified I-sections made of aluminum alloy extrusion 57.2 millimeters (2.40 inches) high, and 25.4 millimeters (1.00 inch) across the upper half-flange; thickness of the section was 6.4 millimeters (0.25 inch). The three stringers were located to form four bays with interior widths of approximately 69.8 millimeters (2.75 inches), 146.0 millimeters (5.75 inches), 146.0 millimeters (5.75 inches), 127 millimeters (5.0 inches).

Upper stringers were made from 6061-T6 aluminum alloy sheet formed into a Z section 25.4 millimeters (1.00 inch) wide at the attaching flange,

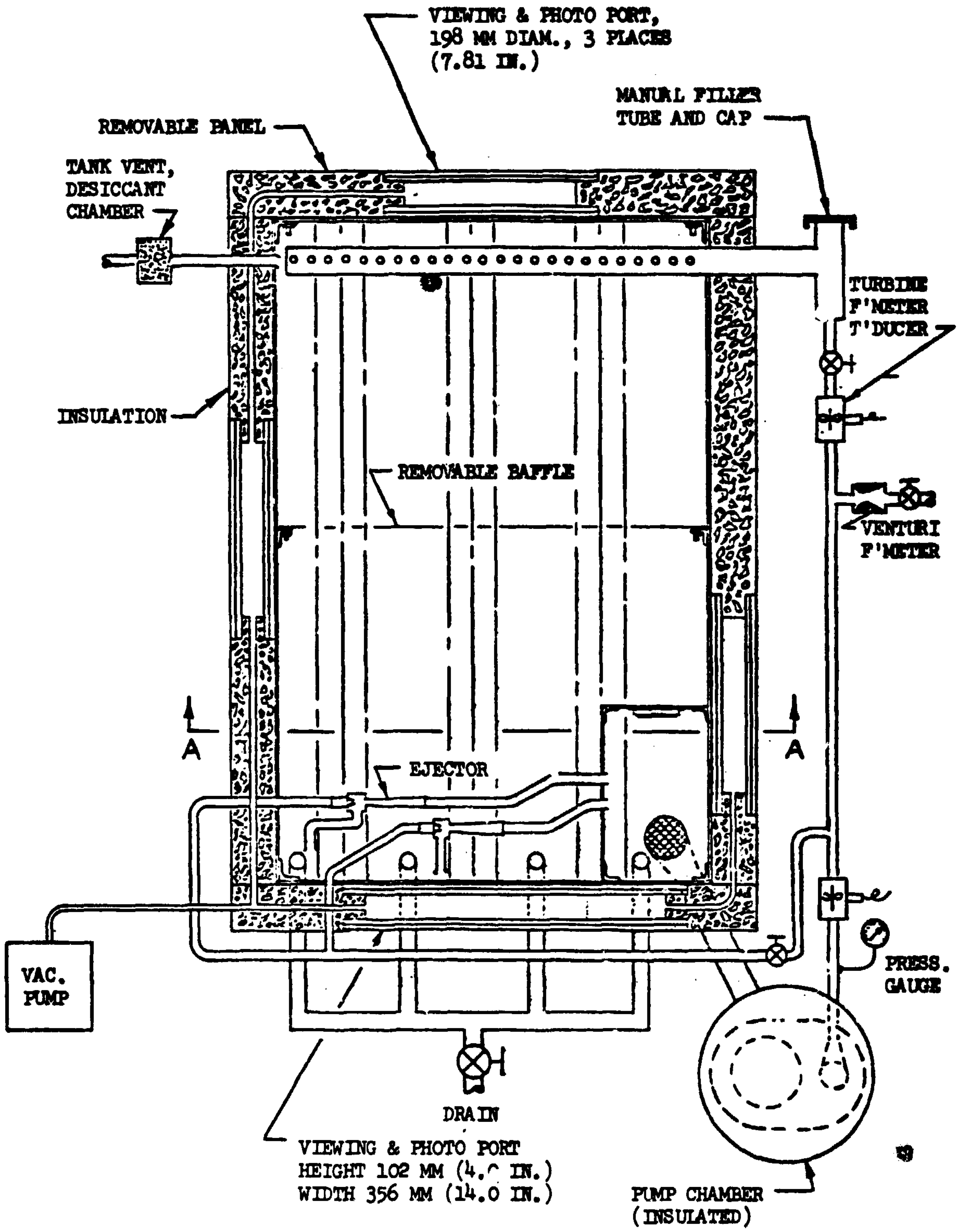
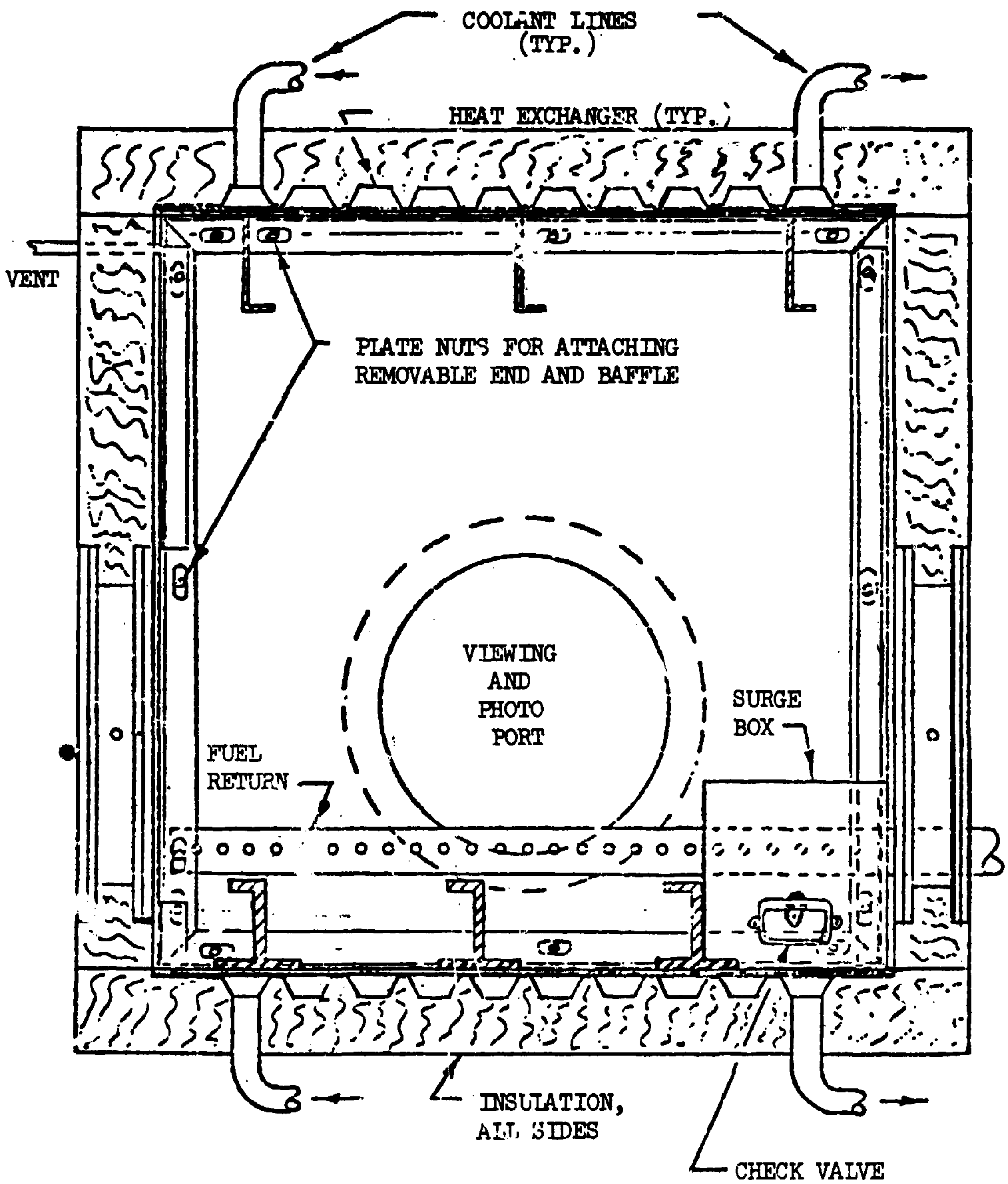


Figure -1. Plan View Sketch of Fuel Test Tank



(EJECTORS & FUEL OUTLET OMITTED FOR CLARITY)

Figure - 2. Cross Section of Fuel Test Tank
(View A-A in Figure 1)

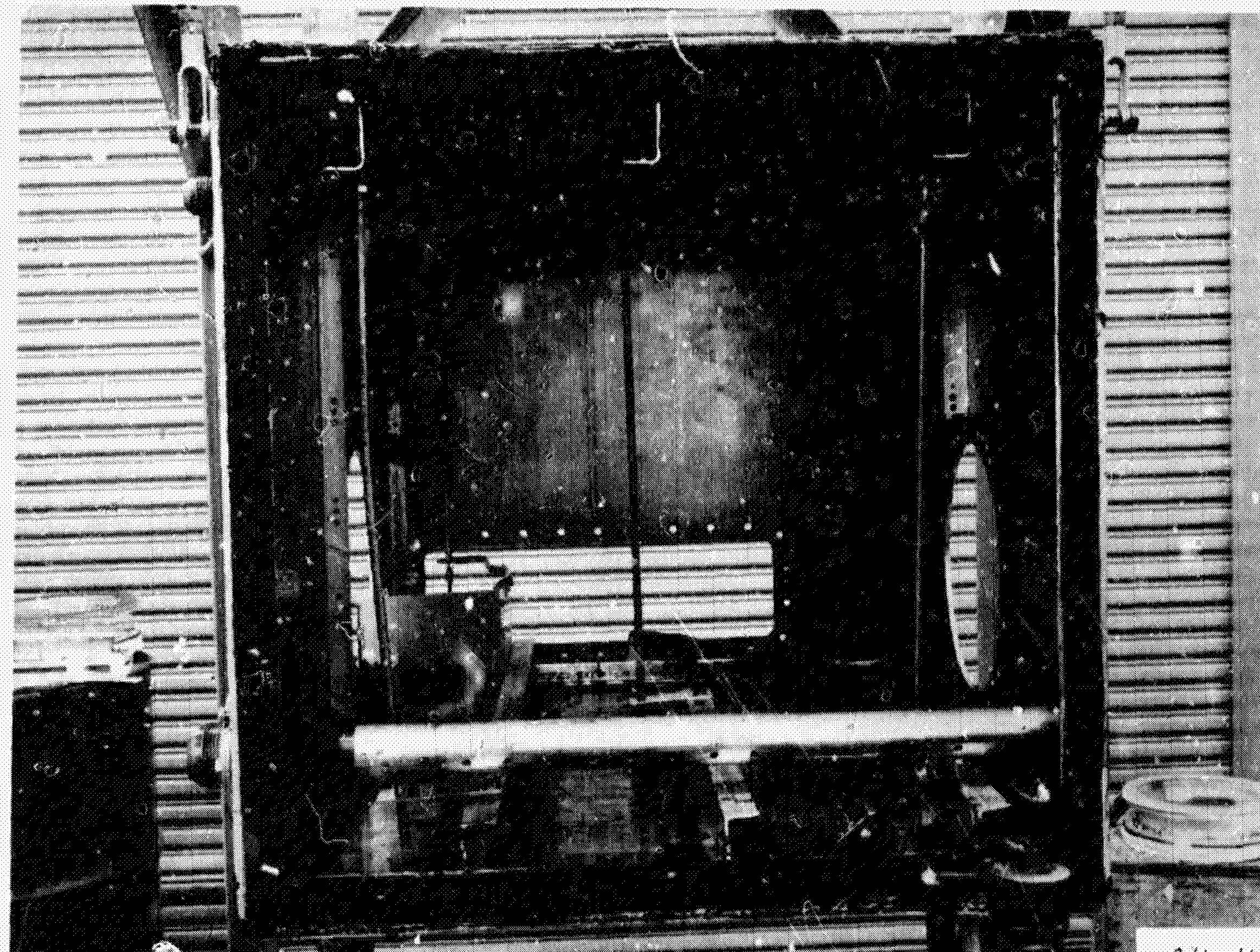


Figure - 3. Test Tank During Final Assembly, End Panel Removed.

71.1 millimeters (2.80 inches) deep, and 20.3 millimeters (0.80 inch) wide at the other flange; material thickness was 3.2 millimeters (0.12 inch). Three stringers formed four bays with interior widths of 60.4 millimeters (2.38 inches), 187.4 millimeters (7.38 inches), 187.4 millimeters (7.38 inches), and 63.5 millimeters (2.50 inches).

At one corner of the tank, two small panels were erected to form a "surge box" between a vertical wall and a bottom stringer, surrounding the fuel exit. Dimensions of this enclosure were 127.0 millimeters (5.00 inches) high, 127.0 millimeters (5.00 inches) wide, and 203.2 millimeters (8.00 inches) long. A small free-swinging "flapper" check valve was installed in the end of the surge box to permit fuel to flow into it from the stringer bay.

Prior to assembly, various cutouts were made in the panels to accommodate viewing ports in all vertical walls, as well as the required plumbing penetrations. Angle clips were attached to the two longer vertical panels to permit installation and removal of a sheet metal divider panel simulating a fuel tank baffle. Cut-outs were made in the divider to accommodate the envelope dimensions of the stringers and allow generous passage for liquid fuel.

Assembly of the tank was accomplished primarily by riveting. Top, bottom, and three of the side panels were attached to angles at the junctions of the panels, while the 50.8 centimeter (20 inch) square panel at one end of the tank was removable. The angles to which this panel attached were provided with sealed plate nuts to facilitate removal and installation of the end panel. The tank was sealed with fuel tank sealant, and the interior was painted with a urethane anti-corrosion coating as used on the L-1011 airplane.

3.3 COOLING PANELS

Since the test tank simulated a portion of an aircraft fuel tank, the upper and lower surfaces represented wing skins and were provided with cooling panels to simulate in-flight heat transfer to the atmosphere. Each panel consisted of a flat stainless steel plate 50.8 centimeters (20 inches) by 76.2 centimeters (30 inches) to which was spot-welded another stainless steel plate which had been embossed to provide a serpentine passage for the coolant flow. On the lower panel, one convolution of the embossed panel was shortened slightly to accommodate the fuel exit tube. The panels were bonded to the tank shell with a special thermally-conductive cement.

Figure 4 shows the upper cooling panel bonded to the test tank.

3.4 VIEWING PORTS

Because visual observation was considered an important feature, viewing ports were installed in all four vertical panels. Three of the ports were circular, with a view diameter of 198.4 millimeters (7.81 inches). One was centered opposite the interior end of the surge box, one was centered opposite the location of the divider panel and the other was located in the removable panel. At the surge box end of the tank was a rectangular port 101.6 millimeters

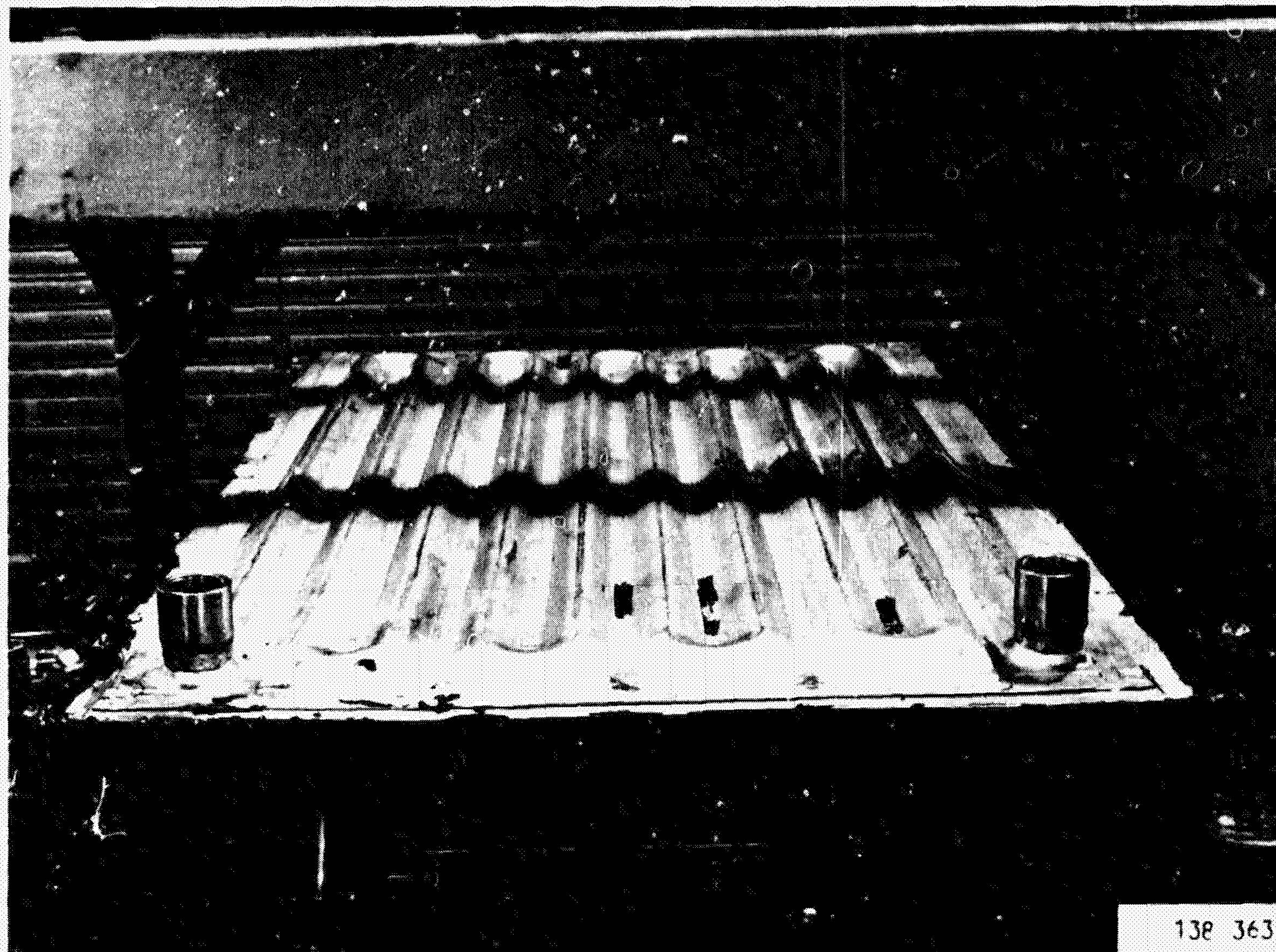


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Figure - 4. Cooling Panel Bonded to Top of Test Tank.

(4.00 inches) high by 355.6 millimeters (14.00 inches) wide, designed to provide a broad view of the bottom of the tank. Figure 2 illustrates the locations of the three circular ports while Figure 3 shows the rectangular port and two of the circular ports prior to installation of the transparencies and spacers. Viewing at each port was provided through two panes of 9.6 millimeter (0.38 inch) thick Plexiglas, separated by a flanged aluminum spacer 47.8 millimeters (1.88 inches) thick. Each spacer was provided with a small fitting so that the space between the panes could be evacuated during test to prevent moisture condensation and to improve insulation properties.

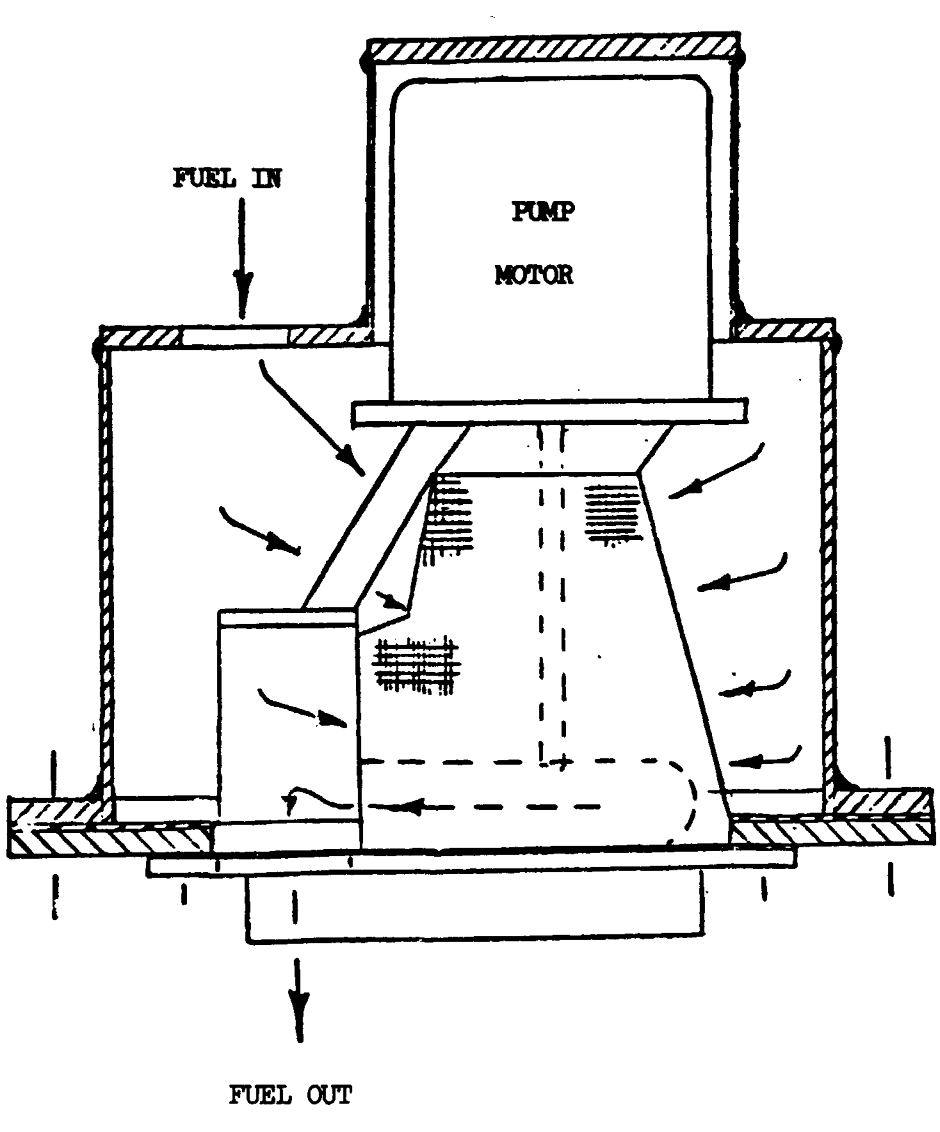
3.5 FUEL DISCHARGE AND RECIRCULATION PROVISIONS

Fuel exited from the tank through a 48.3 millimeter (1.90 inch) diameter opening in the bottom of the tank at the corner of the surge box (Figure 1). Over this opening was an aluminum disc perforated with 6.4 millimeter (0.25 inch) diameter holes. An aluminum tube, tapering from 50.8 millimeters (2.00 inches) outside diameter at the tank to 31.8 millimeters (1.25 inches) diameter, connected the test tank to a small chamber housing an aircraft-type 24 volt direct current boost pump. This is a centrifugal pump used on early jet fighters and was selected for its relatively small power requirements of approximately 360 watts, thereby minimizing heat rejection to the fuel. (By comparison, one L-1011 fuel boost pump consumes over 10 times that power.) The pump assembly incorporated a large area 8-mesh screen surrounding the impeller inlet. The boost pump installation is sketched in Figure 5. The dome around the pump motor inhibits fuel circulation and minimizes heat rejection to the fuel. The pump discharged into a line of 12.7 millimeters (0.50 inch) outside diameter and through a turbine flowmeter transmitter. Downstream of the flowmeter the line branched in one direction to supply motive flow through a control valve to two small ejectors, or jet pumps, which could suck fuel from two of the bays formed by the bottom stringers. These ejectors discharged into the surge box. A branch and shutoff valve in the other direction would permit fuel to be pumped either into or out of the tank. Another turbine flowmeter transmitter was installed downstream, after which the line size was increased to 31.8 millimeters (1.25 inches) outside diameter. A tee in this line allowed fuel to recirculate into the tank through a perforated tube extending across the tank, and was also connected to a standpipe which served as a dipstick well, or as a manual filler; it was capped during testing.

3.6 FILL, VENT, AND DRAIN PROVISIONS

Filling of the test tank usually was accomplished by pumping fuel through the perforated recirculation return tube in the tank. An alternate method was to fill through the standpipe mentioned in the previous section.

Venting of the tank was accomplished through a 12.7 millimeter (0.50 inch) tube pentrating the test tank vertical wall as high as possible near the removable end panel. A short bent-up elbow was connected to a transparent tube which in turn was connected to a desiccant chamber and then to the top of the coolant reservoir. This arrangement prevented moisture from entering the test tank through the vent system.



(FITTINGS OMITTED FOR CLARITY)

Figure - 5. Cross Section of Boost Pump Installation

In each stringer bay, on the bottom of the test tank, a 9.5 millimeter (0.38 inch) tube was installed to provide tank drainage. The tubes were manifolded together and terminated in a shutoff valve and exit tube. In addition, removal of virtually all liquid fuel could be accomplished by means of the boost pump and ejectors. Drainage of small quantities of remaining fuel, or tank flushing, could be accomplished through the gravity drain manifold.

Figure 6 is a photograph showing the drain manifold, as well as the tapered fuel exit tube for connection to the boost pump chamber, and the variable speed drive used for sloshing the tank, described in the following section.

3.7 SLOSHING PROVISIONS

The tank had the capability of sloshing oscillations over a range of 50.8 millimeters (2.0 inches) each side of the neutral position. An explosion-proof variable speed drive rotated a stud located eccentrically on a disc attached to the output shaft (Figure 6). From the stud, a pair of push-rods actuated a bellcrank whose other arm actuated push-rods attached to a bracket attached to the removable panel of the test tank.

In order to provide freedom of movement during tests requiring sloshing, the test tank was suspended by cables attached to the four upper corners (Figure 7). Each cable passed over a pulley and was attached through a turnbuckle to the support frame. This arrangement allowed the tank to be positioned at an angle simulating wing dihedral, with the fuel exit at the low end. The push rod between the test tank and the sloshing bell crank could be disconnected readily to permit the tank to swing on its cables by manual force if desired.

3.8 INSULATION

Insulation was provided for the test tank to assure that heat transfer was confined to the top and bottom chilling surfaces. Fiberglass batting was used to fill small voids, such as the spacing between cooling panel duct embossments, the space between flanges on the viewing port spacers, and to fill in as required. Over the entire tank blocks of solid urethane foam 76.2 millimeters (3.00 inches) thick were positioned. These blocks were held in place by a combination of wire clips and strapping tape, to permit easy removal whenever required. The insulated tank is illustrated by the photograph in Figure 8. All external lines, and the boost pump chamber, were insulated by appropriate combinations of fiberglass batting, urethane foam and pre-formed foam rubber tubing jackets. During testing, the tank had an additional covering of a light blanket of insulating paper bonded to flexible aluminum foil which acted as a vapor barrier to inhibit condensation of atmospheric moisture. Cutouts in the blanket permitted observation through the viewing ports.

3.9 COOLANT SYSTEM

The coolant system consisted of a reservoir of methanol which was chilled by liquid carbon dioxide. In turn, the methanol was circulated to the heat

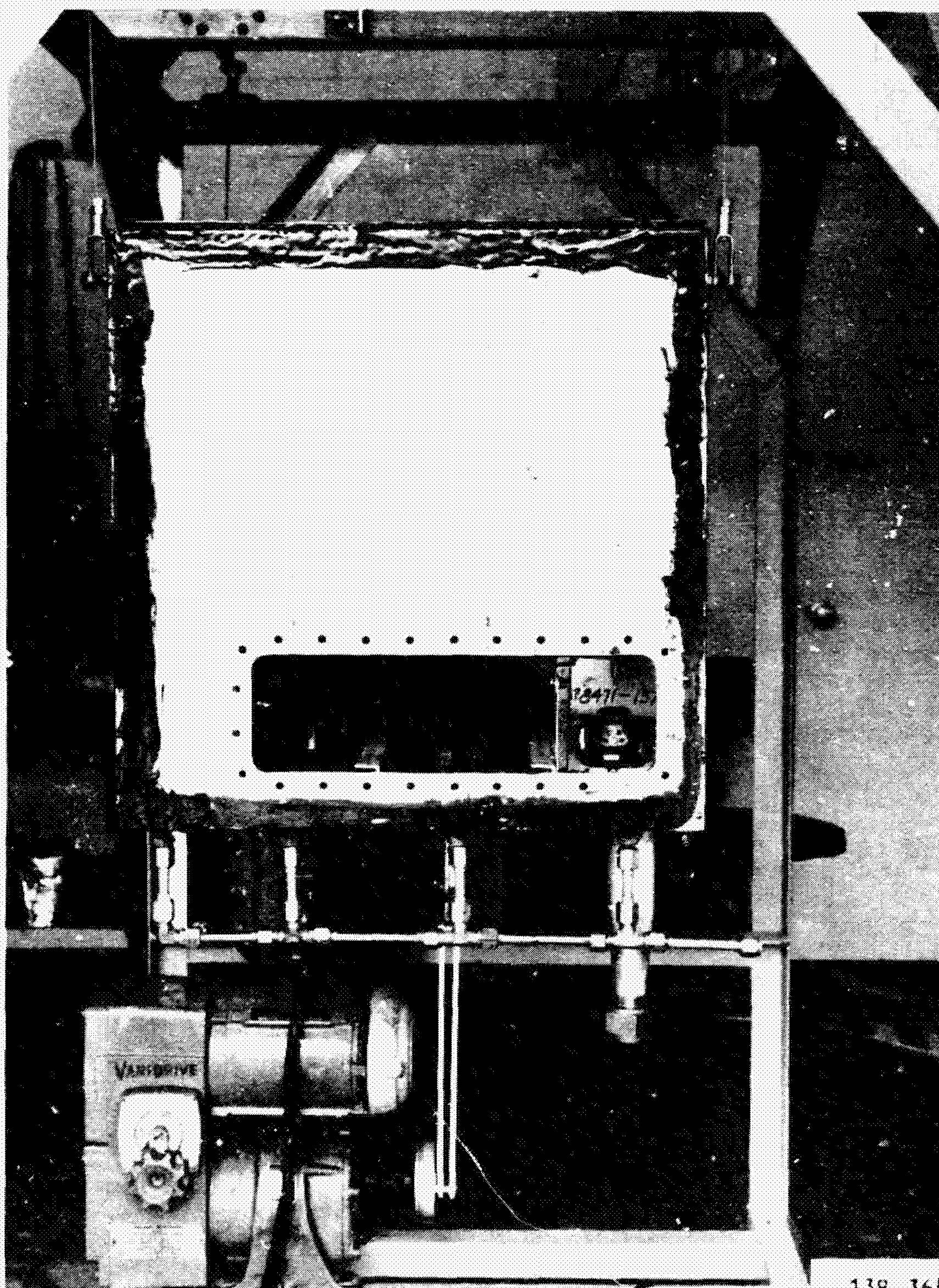


Figure - 6. Test Tank During Final Assembly.

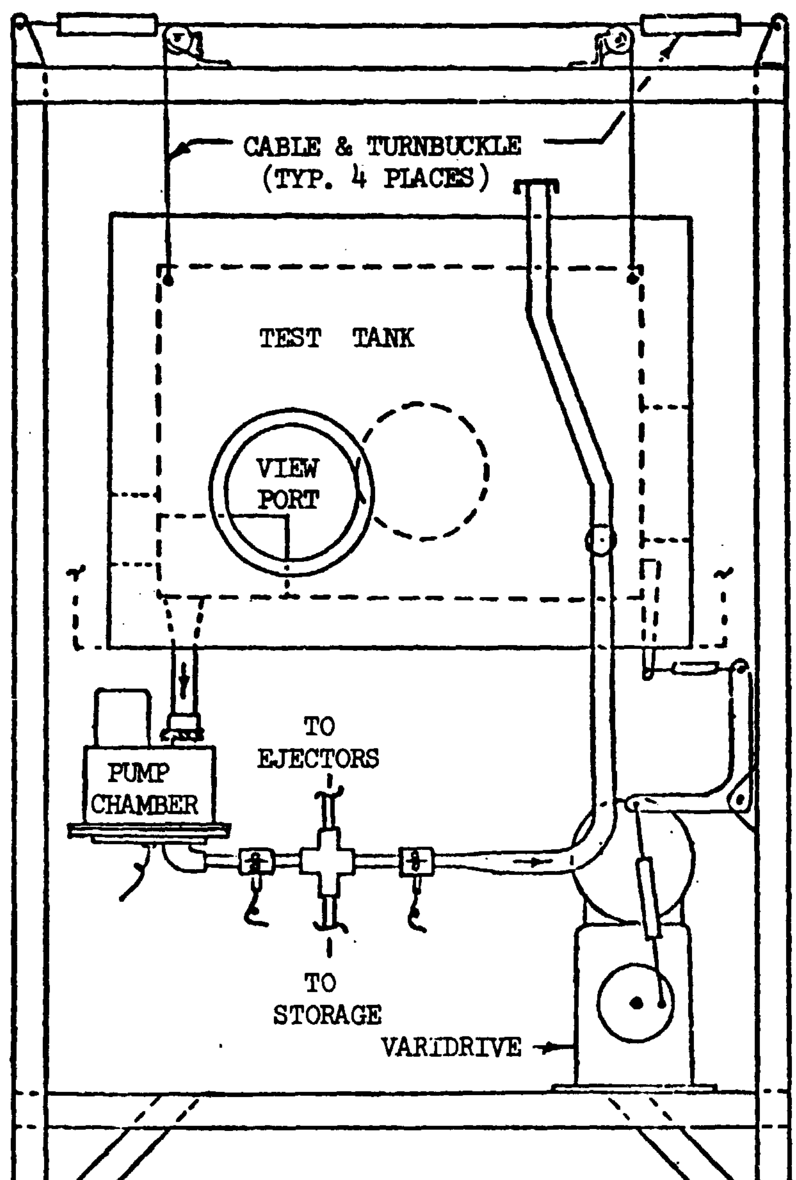


Figure - 7. Test Tank Installation

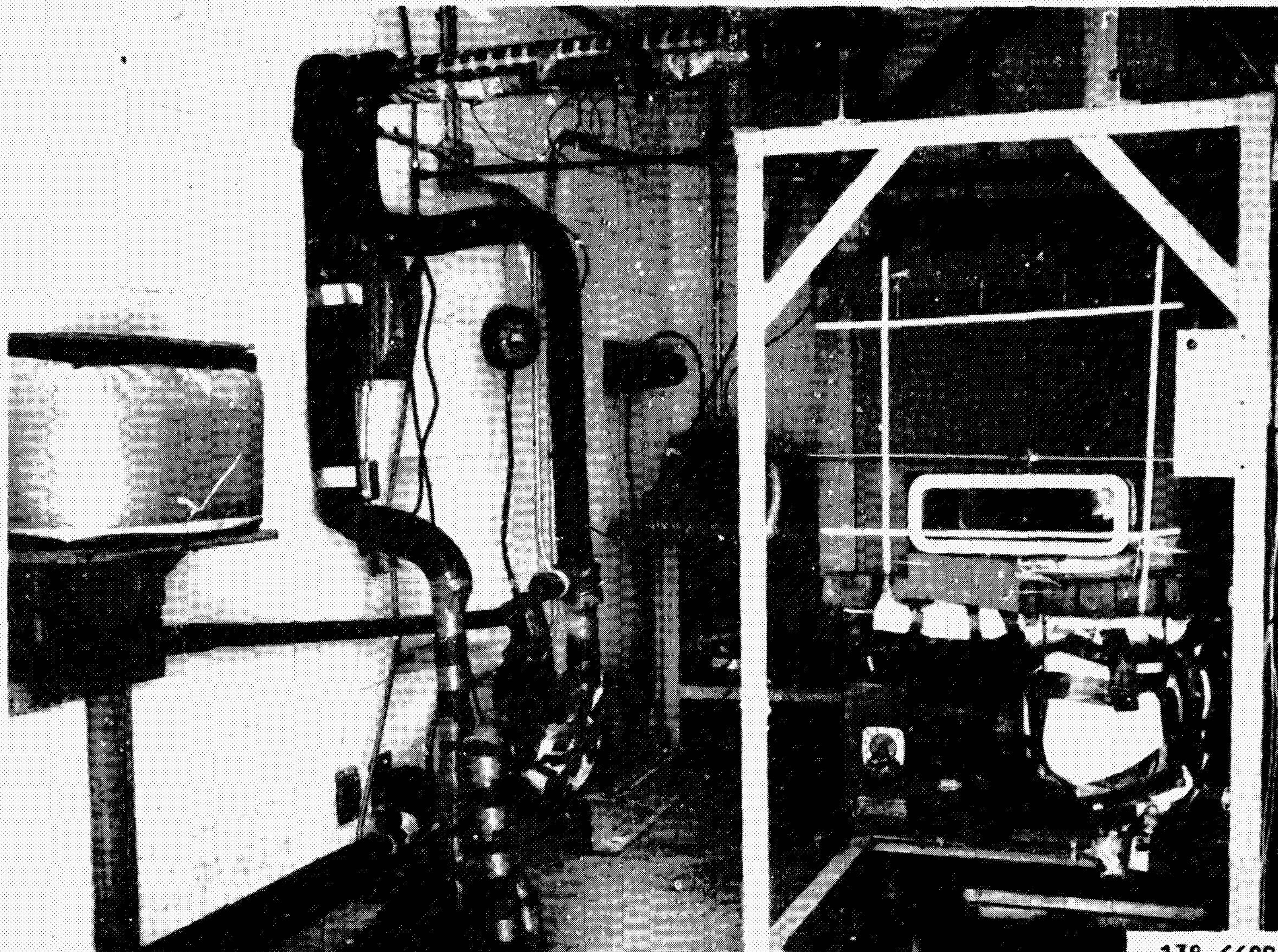


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Figure - 8. Insulated Test Tank Apparatus, Vapor Barrier Covering Removed exchange panels by a centrifugal pump. The flow of refrigerated methanol was divided just outside the test tank to supply the upper and lower cooling panels simultaneously through lines of equal length. Return lines from the cooling panels teed into a common line before returning to the reservoir. Figure 9 is a schematic diagram of the coolant system. The overflow tank for level control, the pump, and some of the insulated plumbing are visible in Figure 8, along the left hand wall. Flexible couplings were installed in both common lines to accommodate angular and axial movement during sloshing.

Valving was installed to provide throttling of the coolant flow and to alter the distribution as required to achieve approximately equal temperatures on the upper and lower surfaces.

3.10 TEMPERATURE SENSING

An array of 55 thermocouples was used to sense temperatures inside the test tank. Thermocouples were fabricated from copper-constantan wire, and attached to five vertical rod supports inside the test tank. The beads of the thermocouples projected approximately 12.7 millimeters (0.50 inch) from the rods. Wire bundles from the tops of the rods were gathered to pass through a common penetration near the top of the test tank, after which a sealant was applied at the penetration to prevent fuel leakage.

Figure 10 illustrates the arrangement of these thermocouples inside the test tank. As shown, there were three thermocouple racks with 12 thermocouples each, two with 7 thermocouples each, and five additional skin thermocouples. The identification and location of each thermocouple is listed in Table 1. Note that for Tests 58 and following, thermocouples in Racks 2 and 3 were relocated for improved definition of temperature gradients near the cooling surfaces.

3.11 FLOW RATE SENSING

Two turbine flowmeters were used to measure flow rates in the recirculation/ejector system, installed in 12.7 millimeter (0.50 inch) outside diameter tubing. One transmitter was installed upstream of the branch to the ejectors and the other downstream (Figure 1). Determination of ejector motive flow as the difference between readings of the two instruments was unreliable. Ejector flow rate was estimated by comparison of recirculation flow rates with and without ejector use. For the scheduled withdrawal tests, a small venturi was installed as shown in Figure 1 to measure the withdrawn fuel flow rate.

3.12 AUTOMATIC DATA RECORDING SYSTEM

An automatic data recording system was available to acquire temperature and flow rate data. This system was compatible with the central data system at the Rye Canyon Research Center, so that temperature tabulations and time histories of temperatures could be produced by computer.

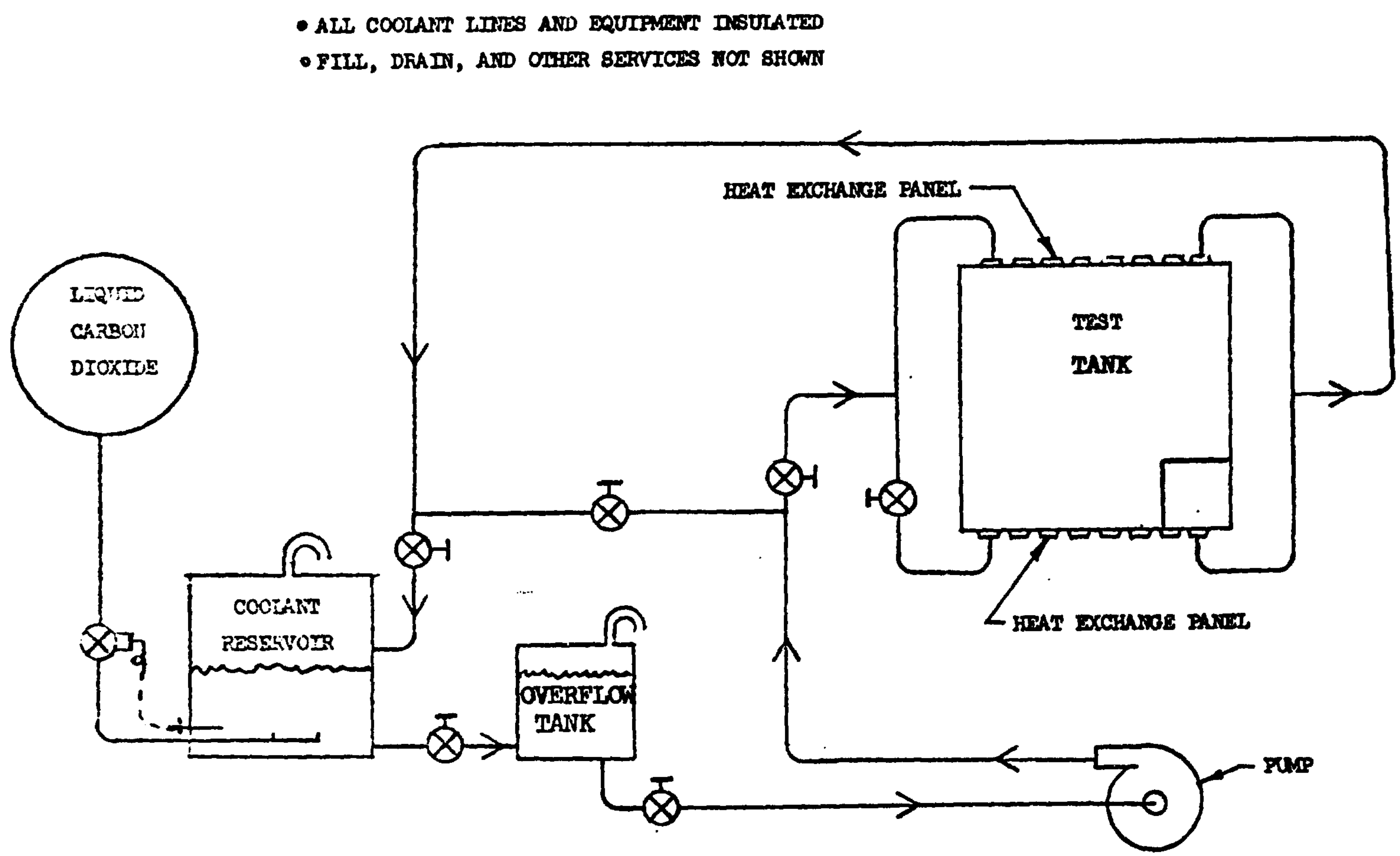

Figure - 9. Schematic Diagram - Coolant System

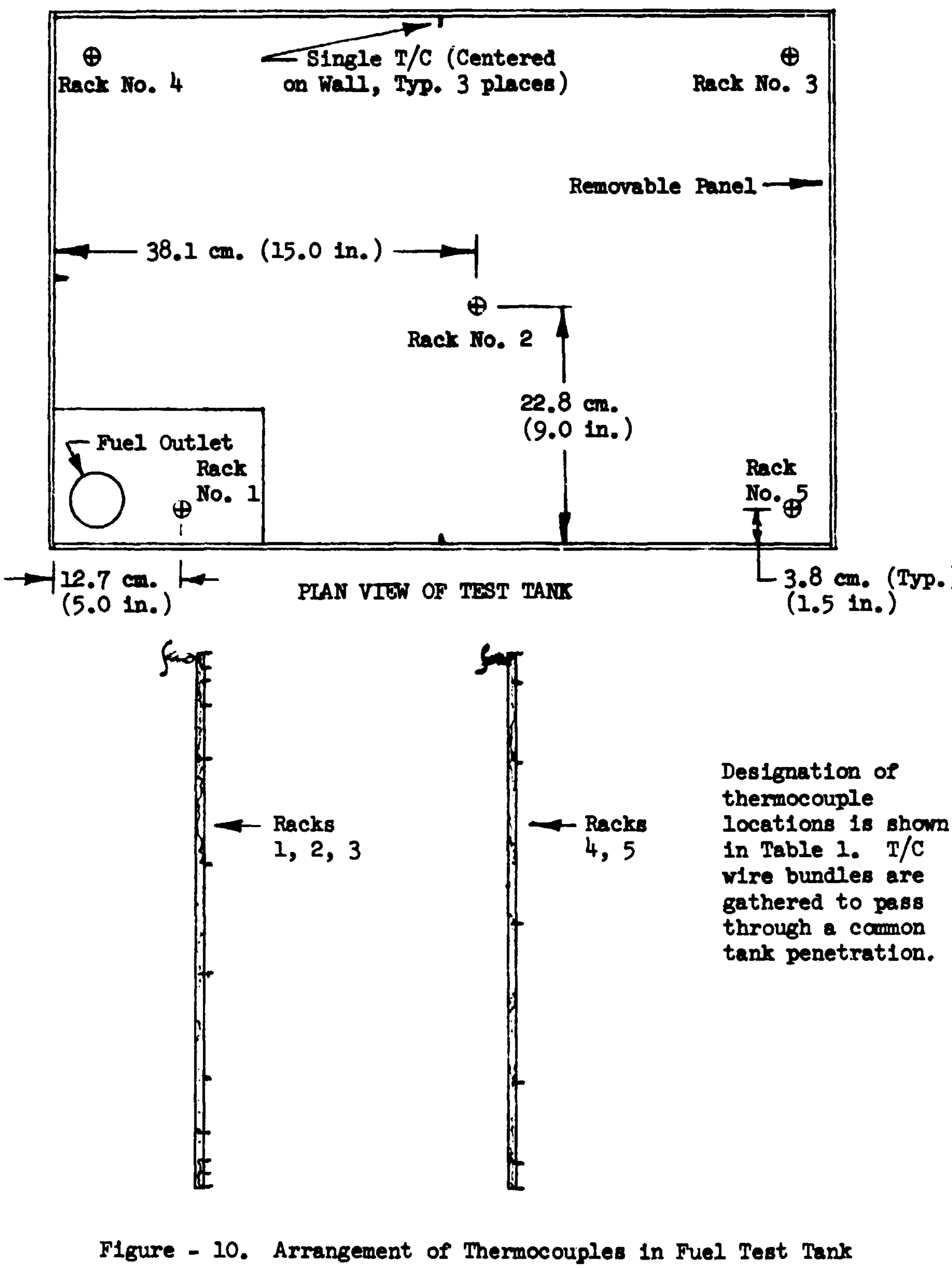

Figure - 10. Arrangement of Thermocouples in Fuel Test Tank

TABLE 1

DESIGNATION OF THERMOCOUPLE LOCATIONS

HEIGHT ABOVE BOTTOM		INITIAL LOCATION					T58 thru 100	
Cm.	In.	Rack 1	Rack 2	Rack 3	Rack 4	Rack 5	Rack 2	Rack 3
0	0	1	13	25	37	44	13	25
0.6	0.25	-	-	-	-	-	14	26
1.3	0.50	2	14	26	-	-	15	27
2.5	1.00	3	15	27	38	45	-	-
5.1	2.00	4	16	28	-	-	16	28
10.2	4.00	5	17	29	39	46	17	29
20.3	8.00	6	18	30	-	-	18	30
25.4	10.00	-	-	-	40	47	-	-
30.5	12.00	7	19	31	-	-	19	31
40.6	16.00	8	20	32	41	48	20	32
45.7	18.00	9	21	33	-	-	21	33
48.3	19.00	10	22	34	42	49	22	34
49.5	19.50	11	23	35	-	-	-	-
50.2	19.75	-	-	-	-	-	23	35
50.9	20.00	12	24	36	43	50	24	36

Thermocouples 51, 52, and 53 at centers of tank wall [illegible] panels).

Thermocouples 54 and 55 on upper skin each side of longitudinal center.

Figure 11 is a block diagram of the automatic data acquisition system. Signals from the thermocouples and the flow transmitter frequency converters were introduced into the 96 - channel Neff 620 Series 400 multiplexer. This fed into the Hewlett-Packard 9825A calculator at predetermined intervals and/or upon command at the rate of 100 channels per second. A Hewlett-Packard digital clock furnished the time at which the data was recorded. The output of the calculator was recorded on a high speed tape cartridge which was used as the input for the Rye Canyon data system. The calculator also provided a paper tape at scheduled times or upon command. From the Rye Canyon data system computer, numerical printouts of temperatures and flow rates in tabular form could be produced, as well as graphs showing a time history of each data channel.

An example of the tabulated computer printout of temperatures is shown in Table 2, which reproduces a portion of the listing for Test 99. Channels 016, 032, and 048 were reserved as references to monitor equipment temperatures. Hence, channel numbers shown as CH001 on the printout do not correspond to thermocouple numbers, shown as C1 on the printout, from channel 016 on.

Figure 12 is an example of the computer generated time histories. These are plots of temperature against time for the first six channels of Test 99, listed in Table 2.

3.13 ADDITIONAL DATA ACQUISITION

Test data was also acquired by means other than the automatic system. Coolant temperature was monitored on a strip chart whose pens indicated temperatures at the reservoir and at the inlet to the test tank cooling panels. Fuel discharge quantity was measured by weighing fuel on a platform scale of 227 kilograms (500 pounds) capacity. On the scale platform, a clean drum was positioned to contain fuel pumped or drained from the tank. Fuel boost pump pressure was observed visually and recorded manually as required. Qualitative observations of the nature of the solid fuel buildup in the tank and other remarks were recorded in a permanent notebook for each test. Photography provided black and white prints, color slides, and color motion pictures.

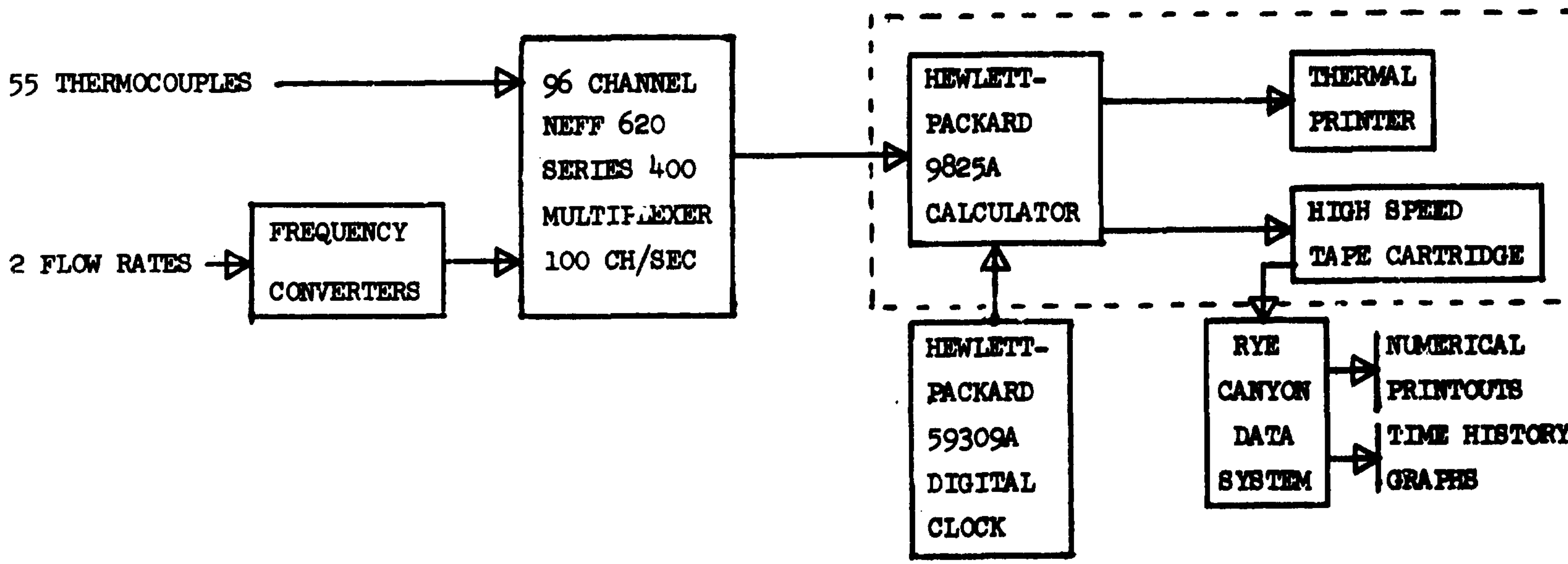

Figure - 11. Block Diagram of Automatic Data Acquisition System

TABLE 2
EXAMPLE OF COMPUTER LISTINGS OF TEMPERATURES

NASA - FUELS AT LOW TEMPERATURES - 99
TEST: 6325
SPS : 1
DATE: 12-22-78

(FUEL No. 7, LFP-5 + 0.1% OF PARADYNE 25
POUR POINT DEPRESSANT)
STATIC TEST. 10.2% HOLDUP.

OFFSETS			.000	.000	.000	.000	.000	.000	.000	.000	.000
RUN	LOAD	TIME	CH 001	CH 002	CH 003	CH 004	CH 005	CH 006	CH 007	CH 008	CH 009
			C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9
1	.0	8:52:00	8.56	8.30	8.42	8.56	8.56	8.30	8.42	8.56	9.03
2	.0	9:02:04	2.42	6.78	7.18	7.65	7.65	7.79	7.53	7.65	7.27
3	.0	9:14:38	-5.94	.78	1.77	2.42	3.80	4.02	4.02	3.80	3.15
4	.0	9:36:16	-16.35	-9.46	-8.95	-6.87	-4.22	-2.31	-2.31	-2.19	-2.81
5	.0	9:51:59	-20.10	-15.54	-15.27	-11.99	-11.08	-6.47	-6.11	-6.73	-6.47
6	.0	10:14:54	-25.63	-21.74	-21.86	-19.88	-15.79	-11.08	-11.08	-11.62	-12.26
7	.0	10:31:26	-27.17	-24.88	-25.03	-23.82	-19.41	-14.17	-14.44	-14.98	-14.44
8	.0	10:51:59	-29.53	-27.52	-27.67	-27.52	-22.82	-17.40	-17.53	-17.80	-18.19
9	.0	11:21:26	-31.02	-29.63	-29.78	-29.63	-26.16	-21.31	-21.46	-21.86	-21.86
10	.0	11:51:59	-31.67	-30.55	-30.97	-30.68	-28.93	-24.65	-24.91	-25.31	-25.31
11	.0	12:23:18	-29.11	-27.62	-30.61	-30.99	-29.89	-27.22	-26.94	-27.87	-27.62
12	.0	12:51:59	-30.11	-32.21	-31.77	-30.40	-30.97	-29.03	-28.80	-29.46	[illegible]
13	.0	13:22:29	-33.06	-31.95	-30.99	-30.84	-30.27	-30.27	-30.43	-30.84	-32.62
14	.0	13:38:11	-32.60	-30.37	-30.24	-30.11	-29.96	-30.37	-30.37	-40.47	-43.43
15	.0	13:51:59	-30.76	-30.19	-30.19	-30.19	-29.78	-36.43	-38.62	-41.70	-44.39
16	.0	13:59:27	-35.21	-32.57	-29.71	-29.71	-29.94	-37.82	-39.19	-41.17	-44.12

OFFSETS			.000	.000	.000	.000	.000	.000	.000	.000	.000
RUN	LOAD	TIME	CH 010	CH 011	CH 012	CH 013	CH 014	CH 015	CH 017	CH 018	CH 019
			C 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	C 18
1	.0	8:52:00	10.03	10.54	10.65	9.17	8.30	8.16	8.28	8.14	8.02
2	.0	9:02:04	7.41	7.41	-3.41	-17.62	-1.11	4.67	6.45	7.46	7.72
3	.0	9:14:38	3.29	2.89	-10.42	-30.04	-15.91	-9.17	-.01	3.59	3.85
4	.0	9:36:16	-2.55	-3.19	-16.62	-39.32	-29.81	-22.16	-8.88	-2.88	-2.50
5	.0	9:51:59	-6.35	-6.47	-18.80	-41.11	-32.80	-27.09	-14.71	-7.06	-6.44
6	.0	10:14:54	-11.42	-11.35	-24.43	-45.24	-36.94	-31.15	-21.26	-12.48	-11.30
7	.0	10:31:26	-14.83	-14.83	-25.96	-45.58	-38.39	-33.01	-24.98	-15.69	-14.41
8	.0	10:51:59	-17.67	-17.67	-30.63	-47.82	-40.45	-34.77	-28.40	-19.31	-17.40
9	.0	11:21:26	-21.59	-21.59	-34.72	-50.33	-42.95	-37.90	-33.53	-23.80	-21.61
10	.0	11:51:59	-25.03	-25.71	-37.72	-50.74	-45.02	-40.93	-37.38	-26.94	-25.23
11	.0	12:23:18	-27.75	-27.87	-39.97	-51.07	-46.33	-43.08	-39.71	-29.51	-27.37
12	.0	12:51:59	-29.58	-29.73	-43.03	-52.50	-47.58	-44.73	-41.32	-31.49	-29.18
13	.0	13:22:29	-32.62	-33.45	-44.33	-51.35	-48.46	-45.90	-42.68	-32.36	-30.32
14	.0	13:38:11	-43.03	-42.58	-47.55	-52.31	-48.54	-46.28	-43.03	-32.03	-30.66
15	.0	13:51:59	-43.83	-43.83	-48.22	-52.55	-48.80	-46.41	-43.27	-26.97	-37.38
16	.0	13:59:27	-43.59	-43.29	-47.26	-51.56	-48.96	-46.67	-43.16	-39.06	-39.22

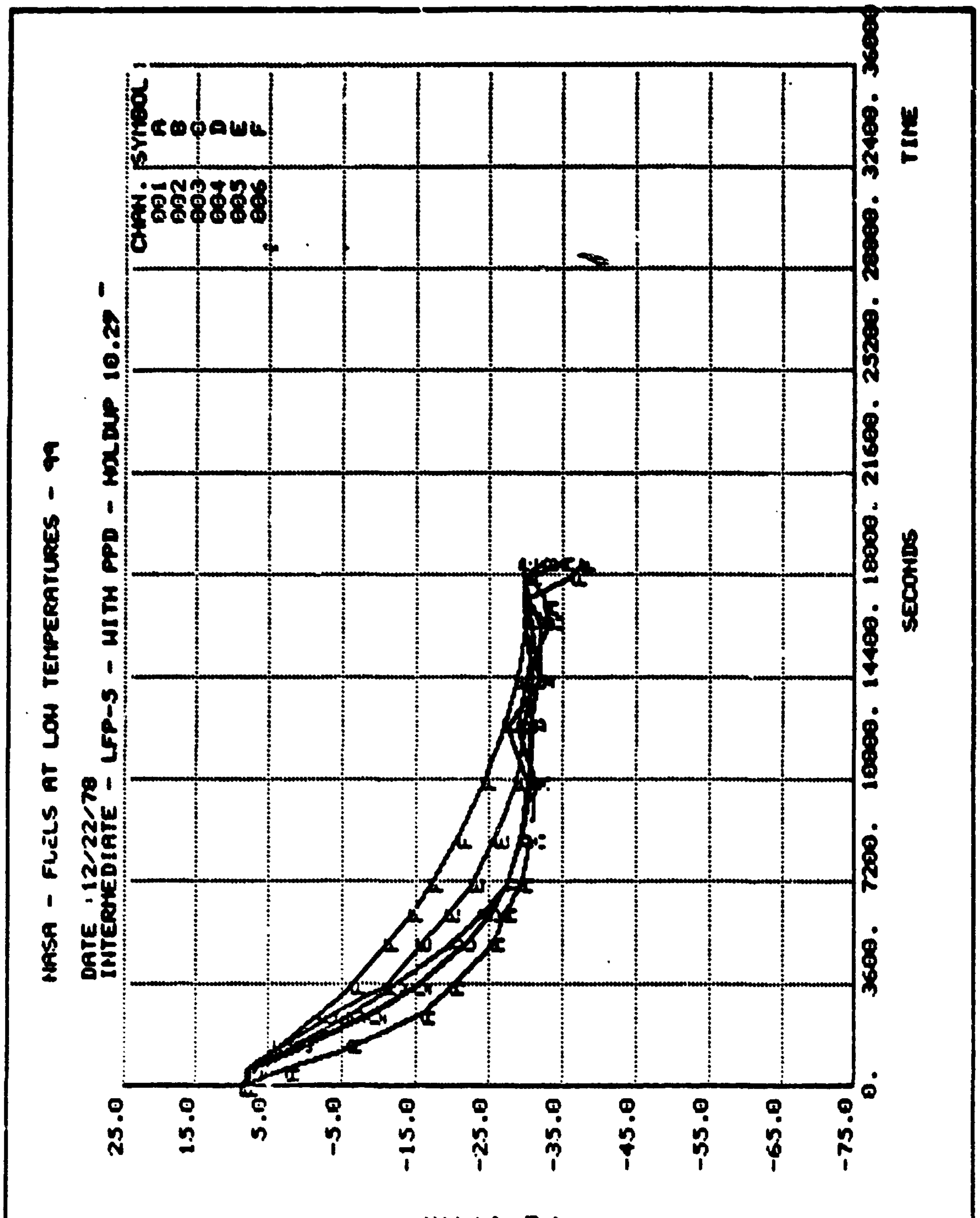

Figure - 12. Example of Computer-Generated Temperature History.

4.0 TESTING PROCEDURES

This section describes procedures employed for the various types of tests performed during the program. Test types were: Static; Recirculation; Sloshing; Divider; Ejectors; Dry Fuel; Scheduled Withdrawal.

In general, fuel was loaded into the test tank, and the test time commenced when the coolant circulation system was activated. Minimum skin temperature was controlled and duration of testing was varied as dictated by such factors as type of fuel and estimated gravity holdup. The end of the test was considered to be the time at which pumpout of the fuel commenced to determine the gravity holdup, that is, the solid fuel that could not be withdrawn from the tank. Fuel was normally removed by means of the boost pump, with the ejectors scavenging fuel from the stringer bays into the surge box surrounding the fuel exit; from that point fuel flowed by gravity to the boost pump in its chamber below the test tank. Gravity holdup was determined after the pump ceased to deliver fuel. Photography was employed to document both representative and unusual test results.

4.1 STATIC TESTS

These tests were performed with the fuel quiescent until the end of the test. At the appropriate time or temperature the fuel was pumped out and weighed. The quantity which did not flow by gravity to the boost pump constituted the gravity holdup.

4.2 RECIRCULATION TESTS

Fuel flowing by gravity to the boost pump chamber was recirculated through the perforated distribution tube at the opposite end of the test tank. Initially, the nominal recirculation rate was 10 liters per minute. Later this was reduced to a nominal 6 liters per minute as being more appropriate to the tank volume of approximately 193 liters. Recirculation continued throughout the test. At the end of the test the valving was adjusted to halt the recirculation and commence pumpout. Gravity holdup was determined when the pump ceased to deliver fuel.

During a few tests in the early part of the program, brief periods of recirculation were employed for a portion of the cooldown of an otherwise static test. This was done in an attempt to reduce the temperature difference between the chilled walls and the bulk fuel.

4.3 SLOSHING TESTS

In these tests the tank was oscillated at a rate of 39 to 40 cycles per minute at an amplitude of plus and minus 50.8 millimeters (2.0 inches) from the neutral position. Sloshing continued throughout the test, and was discontinued when pumpout was initiated.

Three tests were performed with sloshing only, and the tank approximately half full. The other sloshing tests employed recirculation also, with the tank full.

During a few tests in the early part of the program, as with recirculation, periodic sloshing was employed for a portion of the cool-down period in an attempt to reduce the temperature difference between the chilled walls and the bulk fuel.

4.4 DIVIDER TESTS

These were static tests for which the test tank had been modified by installing a divider plate approximately midway between the removable end and the fuel exit end to represent a baffle within an airplane fuel tank. The divider was 30.5 centimeters (12 inches) high, with generous cutouts at the bottom to clear the lower stringers.

Figure 13 shows the divider installed in the test tank. Note that both sides of the divider can be seen through the viewing port at the right hand side of the photograph.

4.5 EJECTOR TESTS

Two tests were performed in which fuel was recirculated through the ejectors as well as through the performated distribution tube. This combination provided flow parallel to the lower stringers from the recirculation system, and flow across the exit end of the tank by ejector action. The combined circulation was maintained throughout the tests, which were otherwise the same as the recirculation tests.

As with recirculation and sloshing, during the early part of the program the ejectors were operated periodically in an attempt to reduce the temperature difference between the chilled walls and the bulk fuel. They were also put to good use during pumpout, to scavenge fuel from the stringer bays.

4.6 DRY FUEL TESTS

Four tests were performed in the same manner as static tests except that dry nitrogen had been bubbled through the fuel in the tank at a rate of 195 liters (6.9 cubic feet) per hour for a minimum of 3 hours prior to the start of the test. This procedure was designed to carry off atmospheric moisture which is normally dissolved in the fuel.

4.7 SCHEDULED WITHDRAWAL TESTS

In most tests, the tank skin was chilled and maintained at a reasonably constant temperature. Fuel was withdrawn rapidly when the desired fuel temperature was attained. Several tests were conducted with the skin temperature varied according to a prescribed schedule, with fuel withdrawn at a slow rate during the last part of the test. This procedure, called scheduled

Figure -13 . Divider Installed in Test Tank.

withdrawal, represented the condition in an aircraft fuel tank during long-range flight. For these scheduled withdrawal tests, the skin, using the bottom center of the tank as a control reference, was chilled in accordance with the time schedule shown in Figure 14. This schedule is based on a 0.3% (one day per year) probability of extreme cold temperature encountered on a long range flight of a commercial airplance (Ref. 11). The test was the same as a static test for 8.3 hours, at which time fuel was withdrawn at a rate that would leave a small quantity of fuel in the tank at the end of the test at 11.3 hours. In an airplane this would be reserve fuel. The fuel tank skin temperature shown in Figure 14 is based on the total air temperature of Reference 11, corrected to an adiabatic wall recovery of 90%.

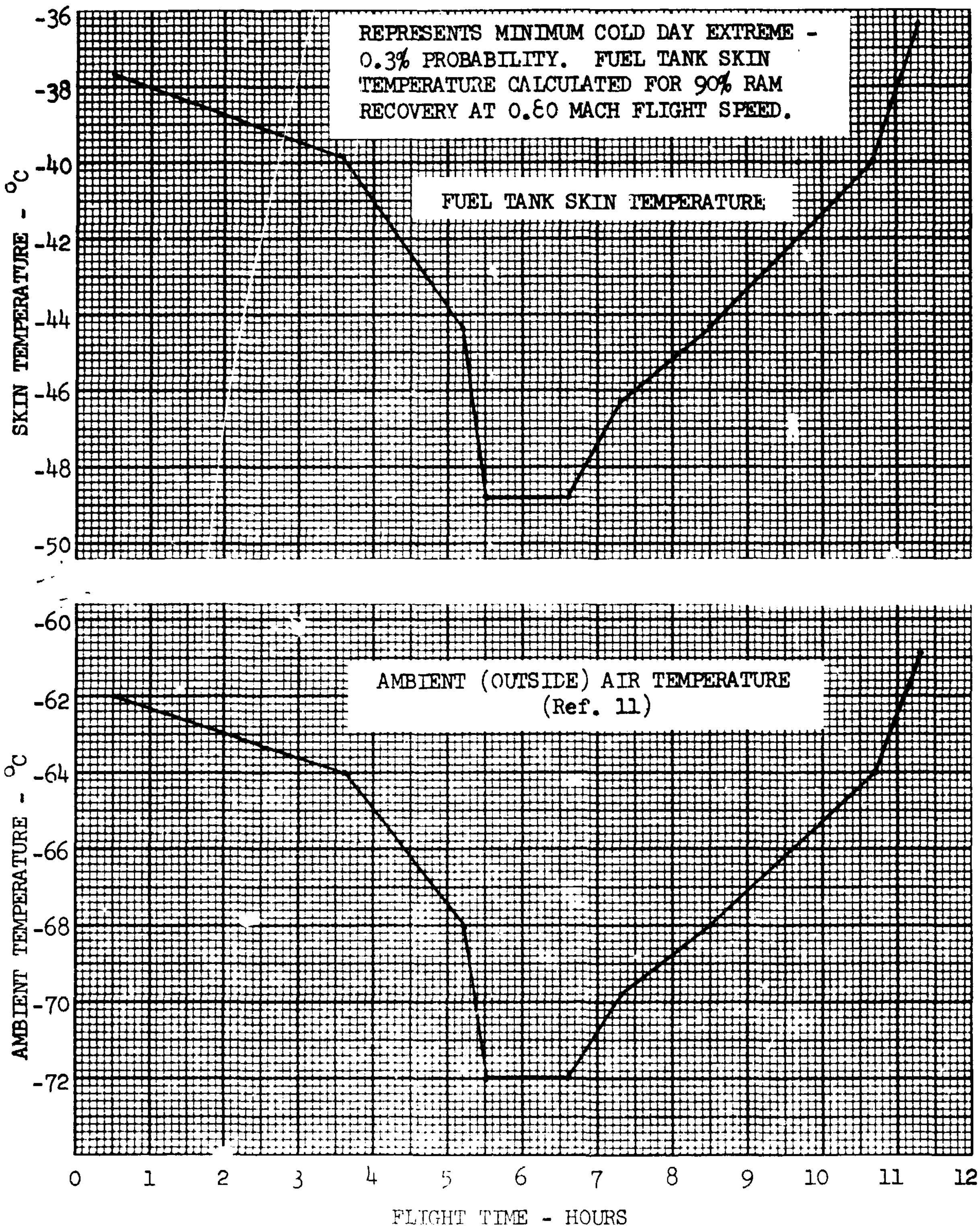

Figure - 14. Temperature Schedule for Scheduled Withdrawal Tests

5.0 FUELS

This section describes the fuels used in the test program. Table 3 lists the fuels and their key characteristics. Fuels LFP-1 through LFP-9 were a group of fuels from known crude petroleum sources, furnished for test purposes through the courtesy of the Coordinating Research Council (CRC) Group on Low Temperature Flow Performance of Aviation Turbine Fuels. There were three types of these fuels: a jet fuel conforming to the commercial specification Jet A; a distillate comparable to Diesel D-2; and a refinery stream distillate intermediate to the first two fuels with respect to freeze point. The fuels were selected refinery samples representing a range of compositions and freezing points, but they were not necessarily finished to meet all commercial specifications. The crude petroleum sources are identified as naphthenic or paraffinic according to the usual definitions in the petroleum industry. A paraffinic crude has a preponderance of saturated aliphatic hydrocarbons; a naphthenic crude has a preponderance of saturated cyclic hydrocarbons. Analyses of the fuel products obtained by distillation from these crudes, however, do not necessarily show hydrocarbon type distribution in agreement with the crude characterization.

Table 3 identifies the fuels used in this program by a fuel number; these designations will be used throughout the report.

Four fuels in Table 3 are identified by numbers other than the LFP designation. Fuels No. 1 and No. 3 were fuels obtained from the Lockheed Company stock, used in the initial tests. Fuel No. 7 was LFP-5 to which had been added a polymeric pour point depressant. This addition affects only the low temperature behaviour of the fuel. Small discrepancies noted in Table 3 and other property data charts between Fuel No. 7 and LFP-5 are simply the result of imprecision of various characterization tests. Fuel No. 8 was a special fuel derived from processed shale oil, meeting most of the specifications (but not freezing point) of JP-5, a Navy jet fuel. Table 3 also lists the approximate freezing point, final boiling point, and specific gravity of each fuel. Boiling range is presented in a standard series of curves of vapor temperature versus percent recovered in Figure 15. Specific gravity as a function of temperature is presented in Figure 16. More extensive data on comparative fuel properties, composition, and laboratory low temperature performance tests are included as Appendices A and B of this report. These data were furnished by cooperative testing, courtesy of the CRC Group on Low Temperature Performance of Aviation Turbine Fuels.

TABLE 3 - FUELS EMPLOYED IN TEST PROGRAM

FUEL IDENTIF'N.	FUEL TYPE	CRUDE SOURCE	APPROX. FREEZE POINT, °C	APPROX. FINAL BOIL. PT., °C	SPECIFIC GRAVITY, 15°C
No. 1	Jet A	Unknown	-44	257	0.8132
No. 3	Distillate (Diesel D-2)	Unknown	+ 2	326	0.8612
No. 7	Intermediate with Additive	Paraffinic, Same as LFP-5	-31	294	0.8294
No. 8	JP-5	Shale Oil	-34	261	0.8029
LFP-1	Jet A	Paraffinic	-41	267	0.8017
LFP-3	Distillate	Paraffinic	-17	314	0.8285
LFP-4	Distillate	Naphthenic	-14	346	0.8545
LFP-5	Intermediate	Paraffinic	-28	295	0.8299
LFP-6	Intermediate	Naphthenic	-28	282	0.8478
LFP-7	Distillate	Paraffinic, Same as LFP-1	-10	316	0.8251
LFP-8	Jet A	Naphthenic, Same as LFP-6	-52	263	0.8273
LFP-9	Jet A	Paraffinic, Same as LFP-3	-46	255	0.8001

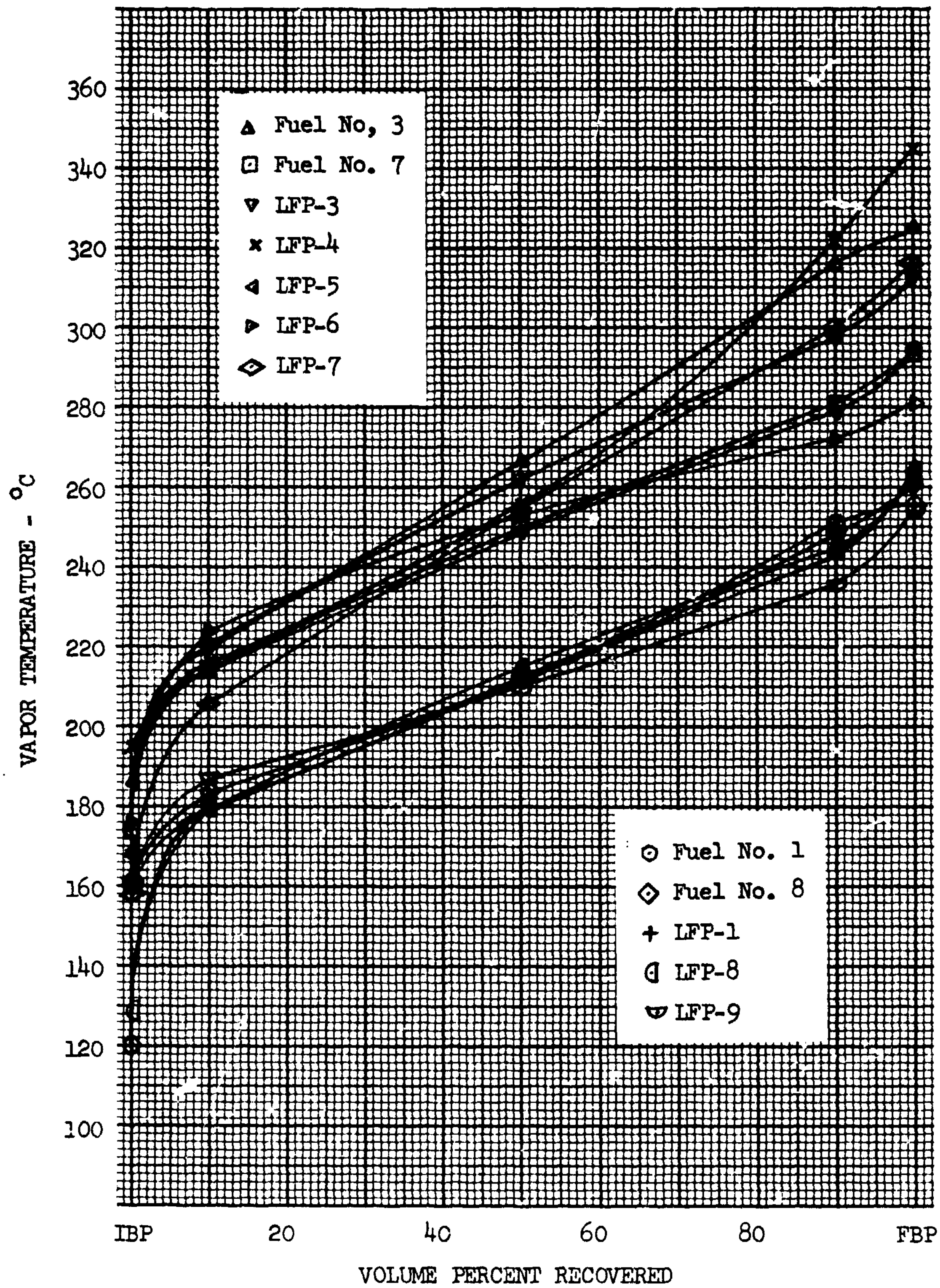

Figure - 15. Distillation Characteristics of Test Fuels, ASTM Method D-86 (Ref. 8)

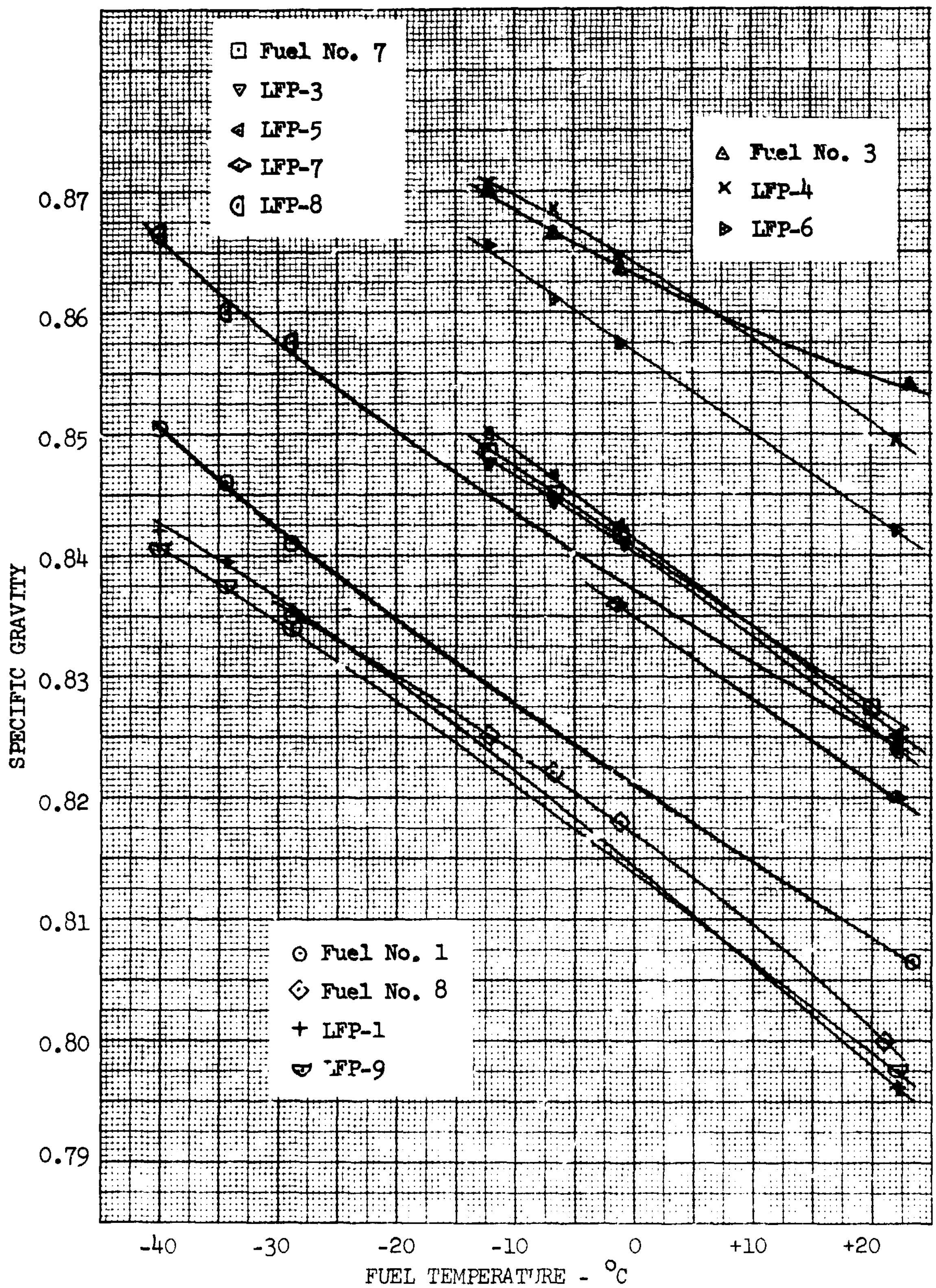

Figure - 16. Specific Gravity of Test Fuels

6.0 RESULTS

6.1 TESTING RECORD

Table 4 lists the tests by number, identifying the fuel type and the test type. The division into two categories is arbitrary. Early tests included initial checkout runs and tests on the Diesel and other fuels. Comprehensive tests started with Test 58, which used a slightly revised thermocouple arrangement. The comprehensive tests aimed at determination of low holdup conditions, and flight simulation by scheduled withdrawal.

A chronological table listing all test runs may be found in Appendix C.

6.2 INITIAL TESTS AND OBSERVATIONS

Testing commenced on 26 May 1978, using fuel No. 1, a commercial Jet A. Subsequent early tests employed the Diesel fuels, then the intermediate fuels and a Jet A. Observation of the interior of the test tank was unobscured at the beginning of the tests, as shown in Figure 17. This photograph shows the stringers, ejectors, surge box, and thermocouples in a fuel-filled tank. After some chilling, however, a "fog" of water condensation appeared in the fuel in some tests, obscuring the tank internals (Figure 18). As the fuel temperature continued to decrease, solids eventually began to form. During static tests, these solids began to accumulate on the bottom of the tank, then progressed upwards onto the bottom stringers. When the fuel was moving, as in recirculation, ejector, and sloshing tests, suspended particles were apparent sooner than during static tests.

There was no difficulty in withdrawing the two phase fuel with suspended solids. Holdup occurred when solid fuel accumulated in the bottom of the tank. At sufficiently low temperatures, solid fuel would form on the top and vertical surfaces of the tank as well as on the bottom. Figure 19 illustrates this situation. In severe cases, solid material deposited on the bottom and/or detached from the top and vertical surfaces, could block the tank discharge line, surge box, or check valve, terminating fuel discharge abruptly.

6.3 STATIC TESTS

The bulk of the testing consisted of static testing, where fuel was chilled without recirculation. Static tests were performed with all the fuels. Tests were conducted at several temperatures with each fuel to establish a relationship of the holdup of unpumpable fuel as a function of temperature. The early test runs attempted to reduce the bulk temperature of the fuel to desired temperatures near the specification freezing point. Consequently, relatively large fractions of fuel remained in the tank as solid deposits on all surfaces at the conclusion of the tests. Often portions of the solid deposits broke off the upper and/or vertical surfaces and formed dams, trapping liquid fuel; an example of this is shown in Figure 20. The liquid holdup in such cases was small, however, and physical rocking of the tank to dislodge or rearrange the solid particles released only small quantities of additional liquid discharge.

TABLE 4 - FUEL UTILIZATION BY TYPE OF TEST AND TEST NUMBER

	STATIC					RECIRCULATION			SLOSH ONLY	SLOSH +REC.	EJEC. +REC.	DRY FUEL	DIVIDER		SCHED WITHDL.
EARLY TESTS															
NO. 1	2	3	6	10	53	4	5	11	8	54	-	-	-	-	-
NO. 3	12	15	18	19	-	13	-	-	14	-	20	-	-	-	-
LFP-1	31	36	55	56	57	32	-	-	-	34	-	-	-	-	-
LFP-3	50	51	-	-	-	52	-	-	-	-	-	-	-	-	-
LFP-4	47	48	-	-	-	49	-	-	-	-	-	-	-	-	-
LFP-5	21	-	-	-	-	28	-	-	29	26	24	-	-	-	-
LFP-6	39	40	41	42	-	43	-	-	-	44	-	-	-	-	-
LFP-7	37	45	-	-	-	46	-	-	-	-	-	-	-	-	-
COMPREHENSIVE TESTS															
NO. 7	99	100	(LFP-5 TEST 57 IS BASELINE)					-	-	-	-	-	-	-	-
NO. 8	78	79	80	-	-	81	-	-	-	-	-	82	--	-	95
LFP-1	58	59	60	-	-	-	-	-	-	-	-	-	85	-	-
LFP-5	57	68	71	77	97	69	-	-	-	-	-	70	86	-	98
LFP-6	61	62	63	65	-	64	-	-	-	-	-	66	83	84	87
LFP-8	90	91	92	-	-	96	-	-	-	-	-	-	88	-	93
LFP-9	72	73	74	-	-	75	-	-	-	-	-	76	-	-	94

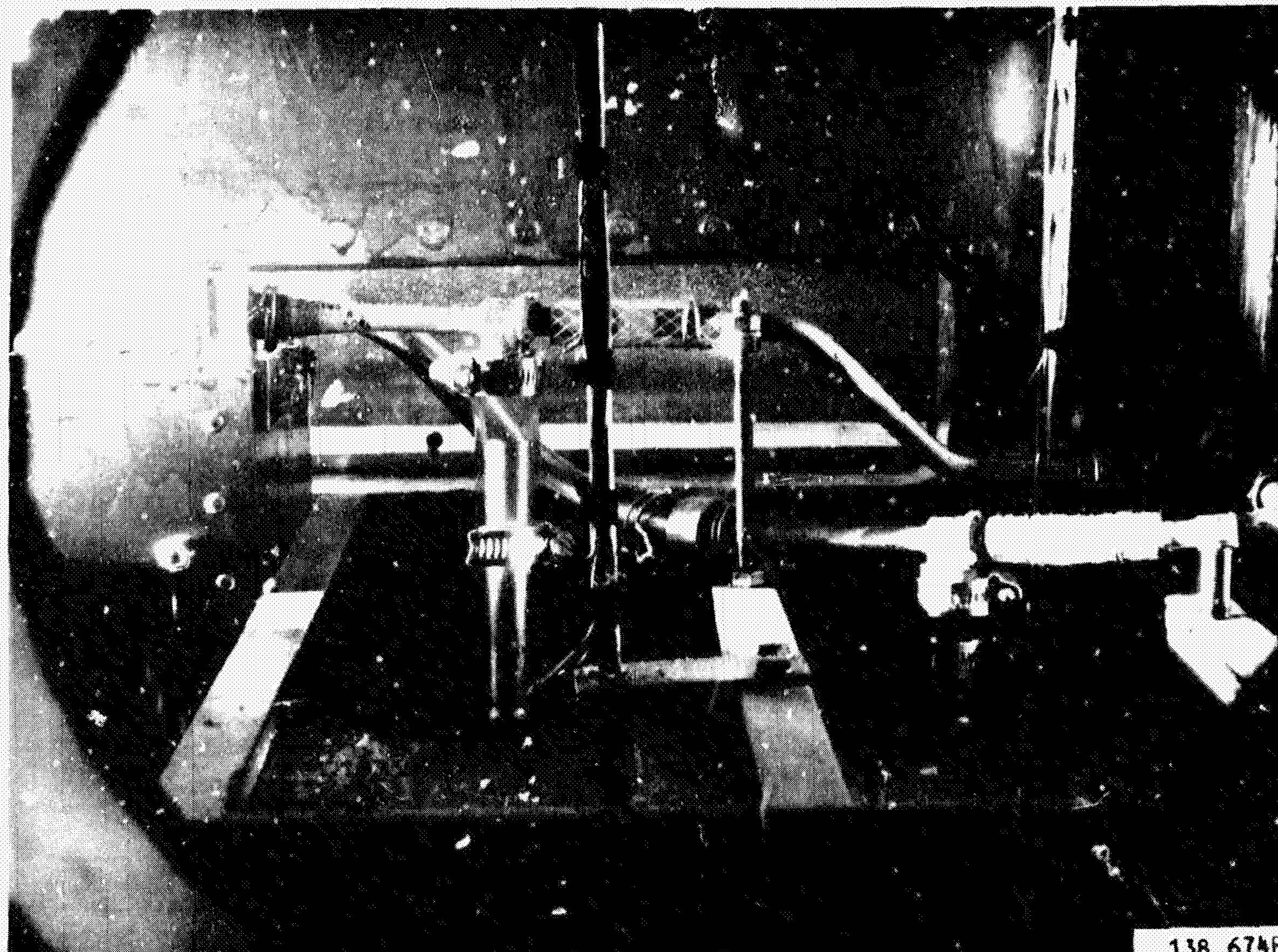

Figure - 17. Looking Through Fuel in Tank at Start of Test 3.

Figure - 18. Visual Obscuration Due to "Fog" After 48 Minutes of Test 3.

Figure - 19. Solids Deposited in Tank After Removal of Fuel, Test 1C.

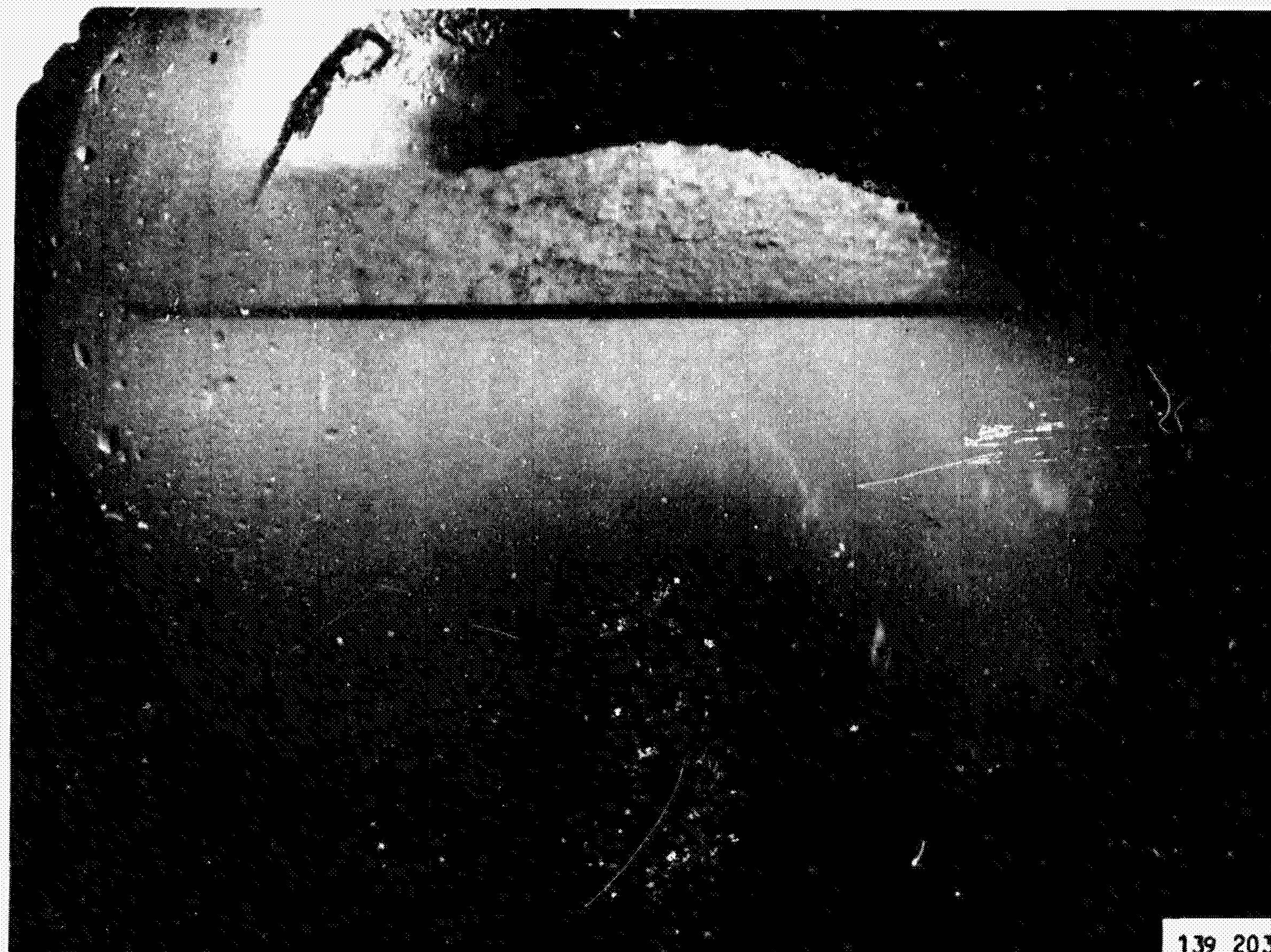

Figure - 20. Entrapment of Liquid Fuel at End of Test 36.

After examination of early runs, static tests after Test 40 incorporated some revisions to procedures. Fuel temperature variations were defined in terms of the lower surface boundary layer. Tests were conducted at constant tank skin temperature, -50°C in most cases. The chilling time to pumpout determined the fuel temperature. Tests were conducted with the tank completely filled with fuel, in contrast to a 2% vent space allowed in the early tests. The filled tank promoted maximum convection currents in the tank. This is illustrated by comparison of Figures 21 and 22, both representing tests of intermediate fuel LFP-5. The early test in Figure 21 shows more vertical and horizontal temperature variation. It is interesting that the test with the filled tank (Figure 22) represents the profile after 4½ hours of chilling, in contrast to 7½ hours for the earlier test. The temperature discrepancy seen near the bottom for thermocouple rack No. 1 in Figure 21 probably is the result of the buildup of solid fuel at the surge box. Holdup was the same for both cases illustrated, a nominal 20%.

Static tests subsequent to Test 40 concentrated on the Jet A, intermediate, and JP-5 fuels as more representative of current and future aviation fuels. Tests from Test 58 on were also performed with several thermocouples relocated for more precise definition of boundary layer temperatures.

6.4 RECIRCULATION, SLOSHING, AND EJECTOR TESTS

At least one test was conducted with each fuel incorporating fuel recirculation during the chilldown time. The effect of recirculation is best illustrated by a comparison of the temperature distribution shown in Figures 23 and 24, for Jet A fuel LFP-9. Figure 23 represents Test 76, a static test, while Figure 24 represents Test 75, a recirculation test. Boundary layer temperatures were similar for both tests, and holdup was identical. The static test profiles show a greater degree of non-uniformity. Recirculation obviously promotes mixing and yields a profile with a constant bulk temperature over most of the tank height. Convection is evident in both cases in the much wider lower surface boundary layer, a characteristic of all tests with completely filled tanks.

Sloshing was incorporated in several of the early runs, and in some cases sloshing and recirculation were combined. Sloshing also improved the mixing of chilled fuel and reduced temperature gradients, but sloshing had no apparent effect on the discharge of liquid fuel or of fuel containing suspended solids.

The dynamic effect of sloshing on chilldown temperature profiles is illustrated in Figures 25 and 26, which are temperature time histories for early tests with Fuel No. 3, a Diesel D-2. In Figure 25, during sloshing, temperature indications for the five interior thermocouples are so close as to be indistinguishable from each other. The temperature difference between these thermocouples and the skin thermocouple is almost the same throughout the period of testing. Figure 26 illustrates a subsequent test in which sloshing was terminated after 1.5 hours (5400 seconds). Vertical temperature gradients were quickly established for the static condition when sloshing ceased.

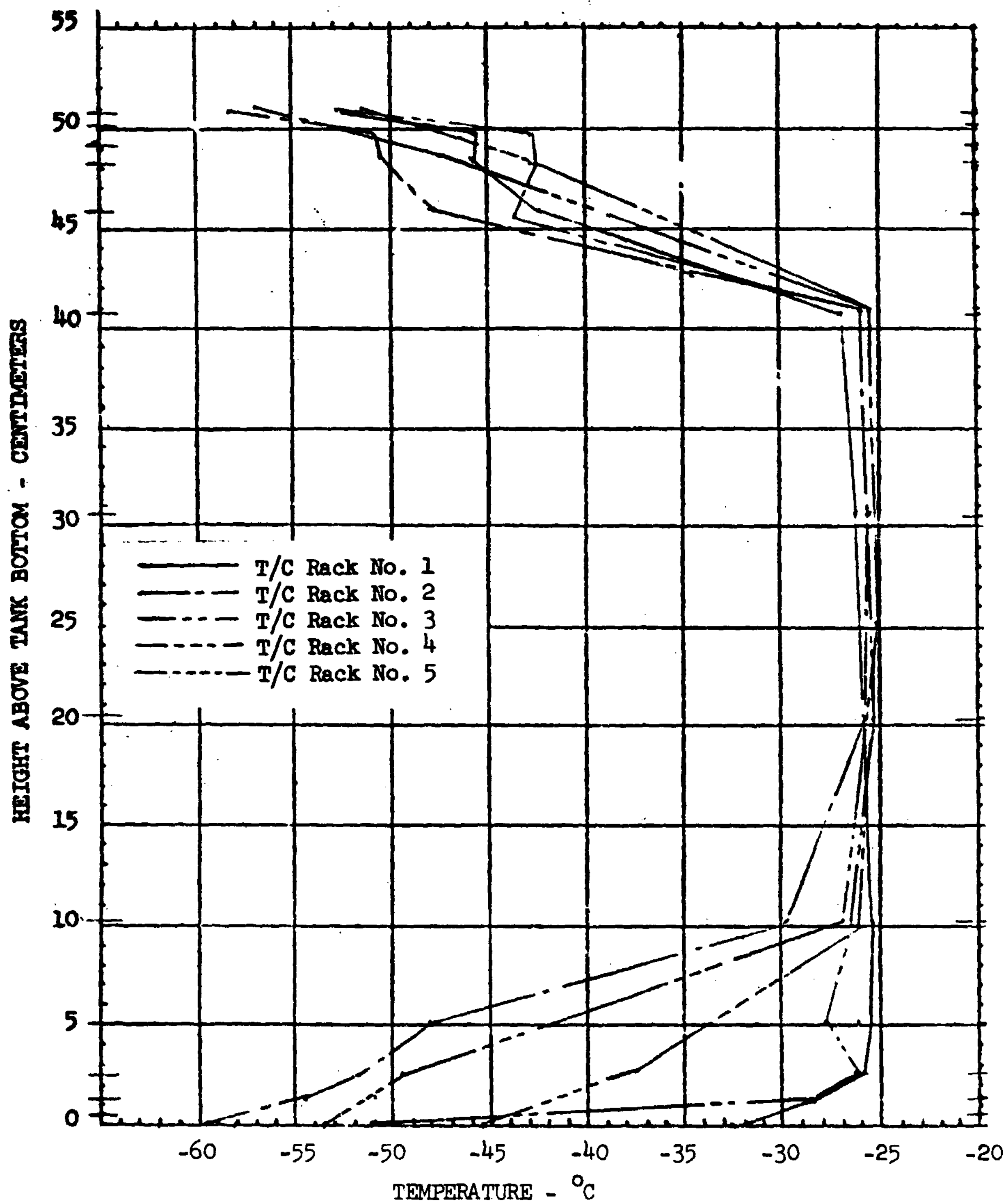

Figure - 21. Temperature Distribution at End of Test 28

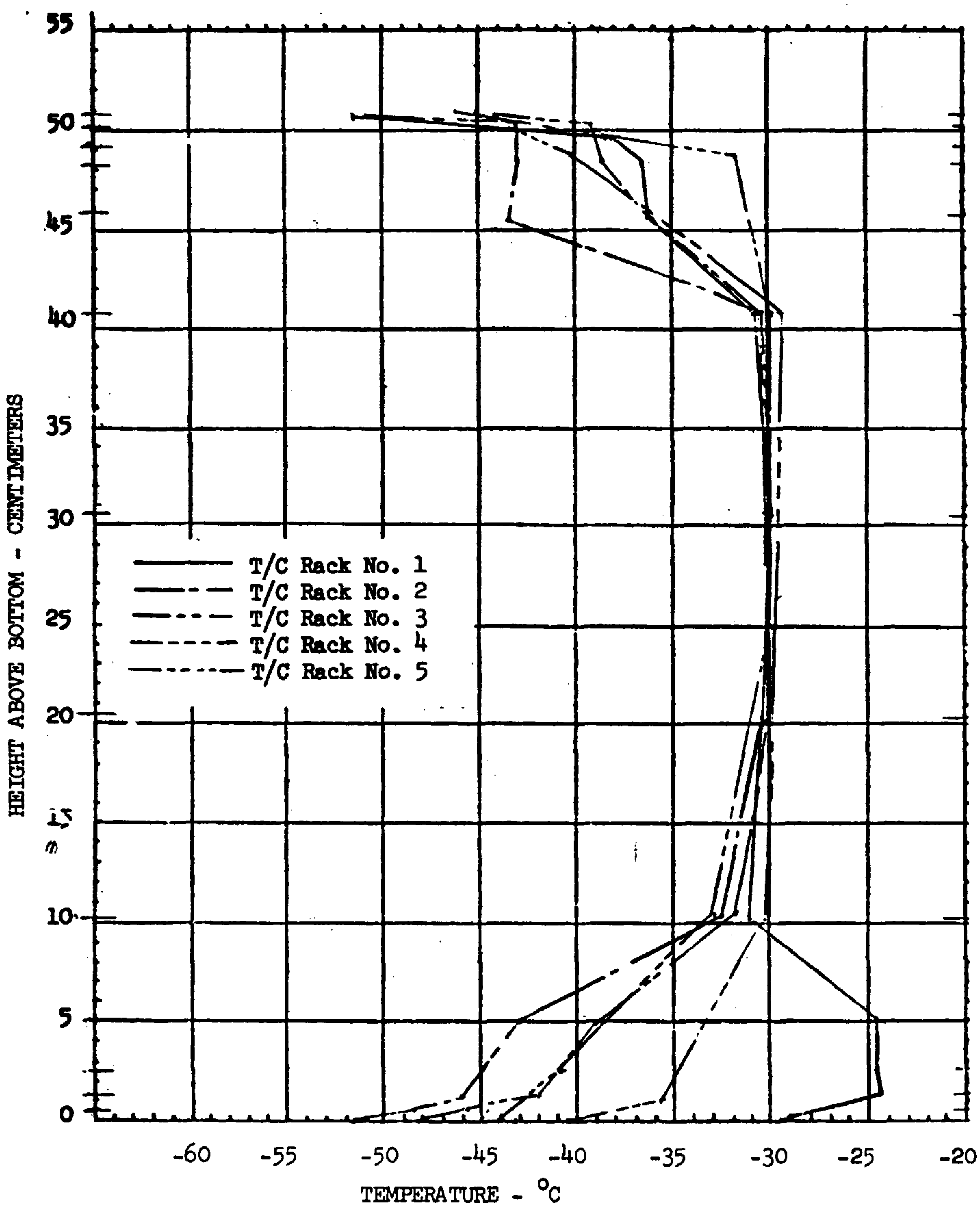

Figure - 22. Temperature Distribution at End of Test 97

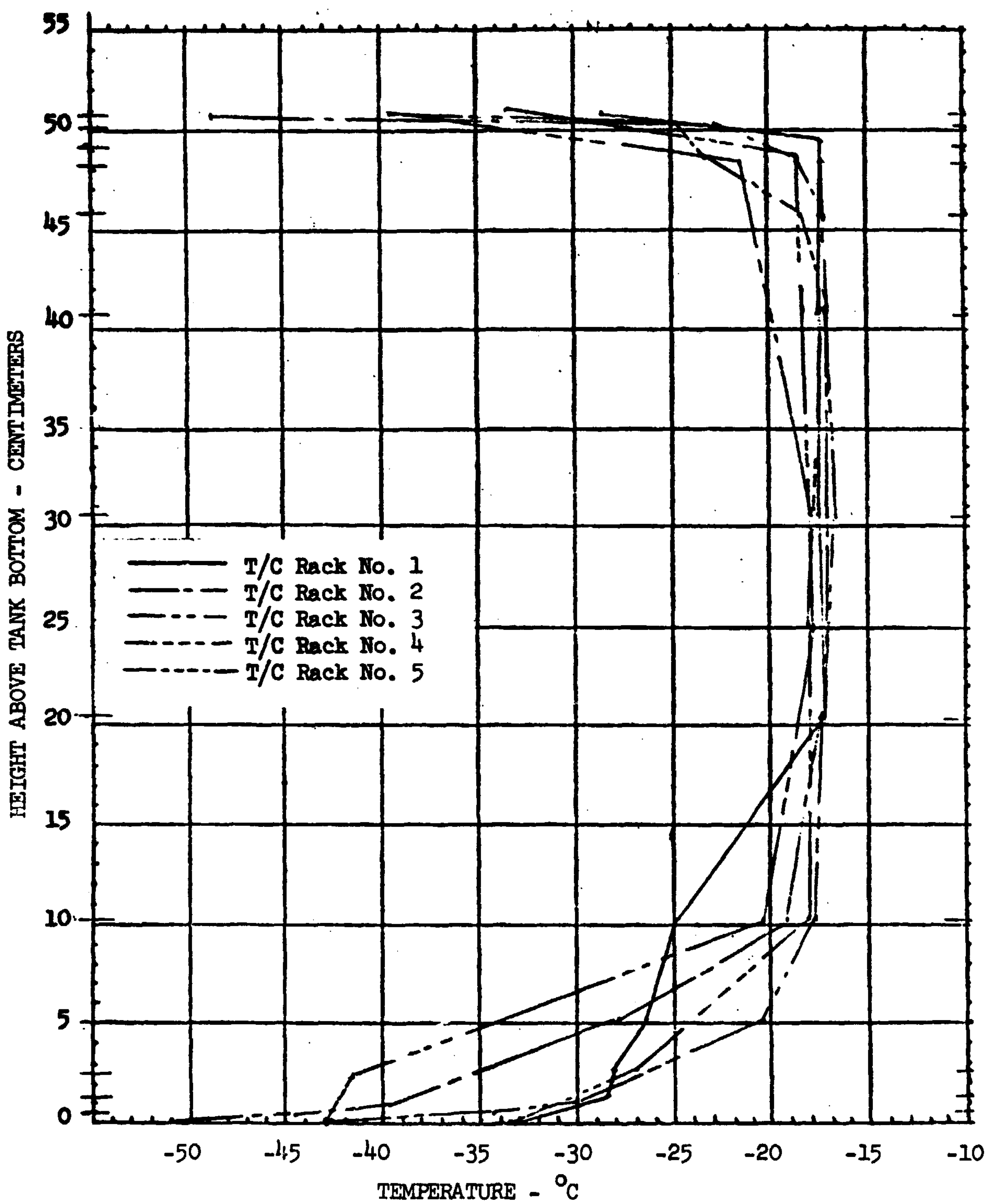

Figure - 23. Temperature Distribution at End of Test 76

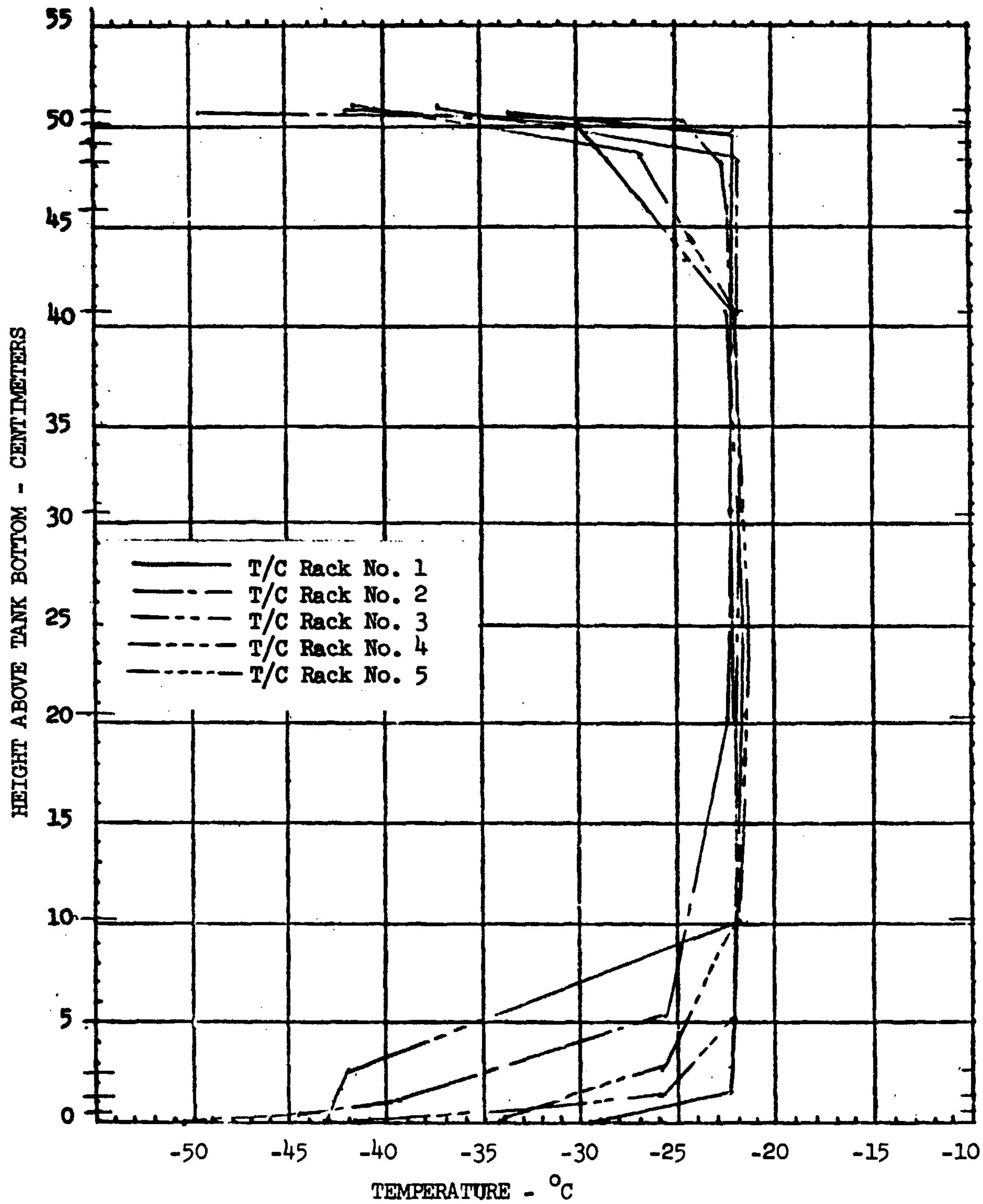

Figure - 24. Temperature Distribution at End of Test 75

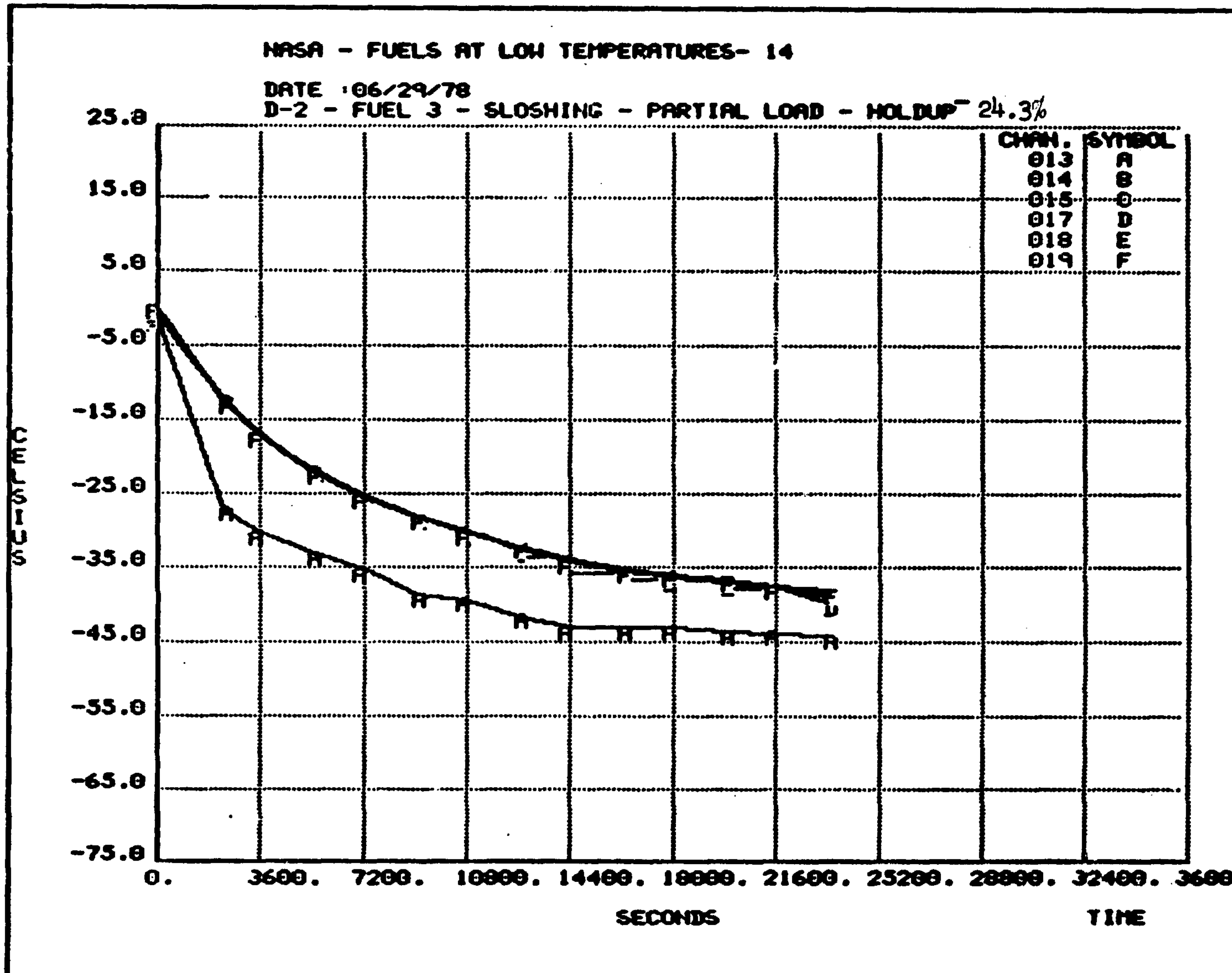

Figure - 25. Time History of Temperatures, Tank Half Full, Test 14.

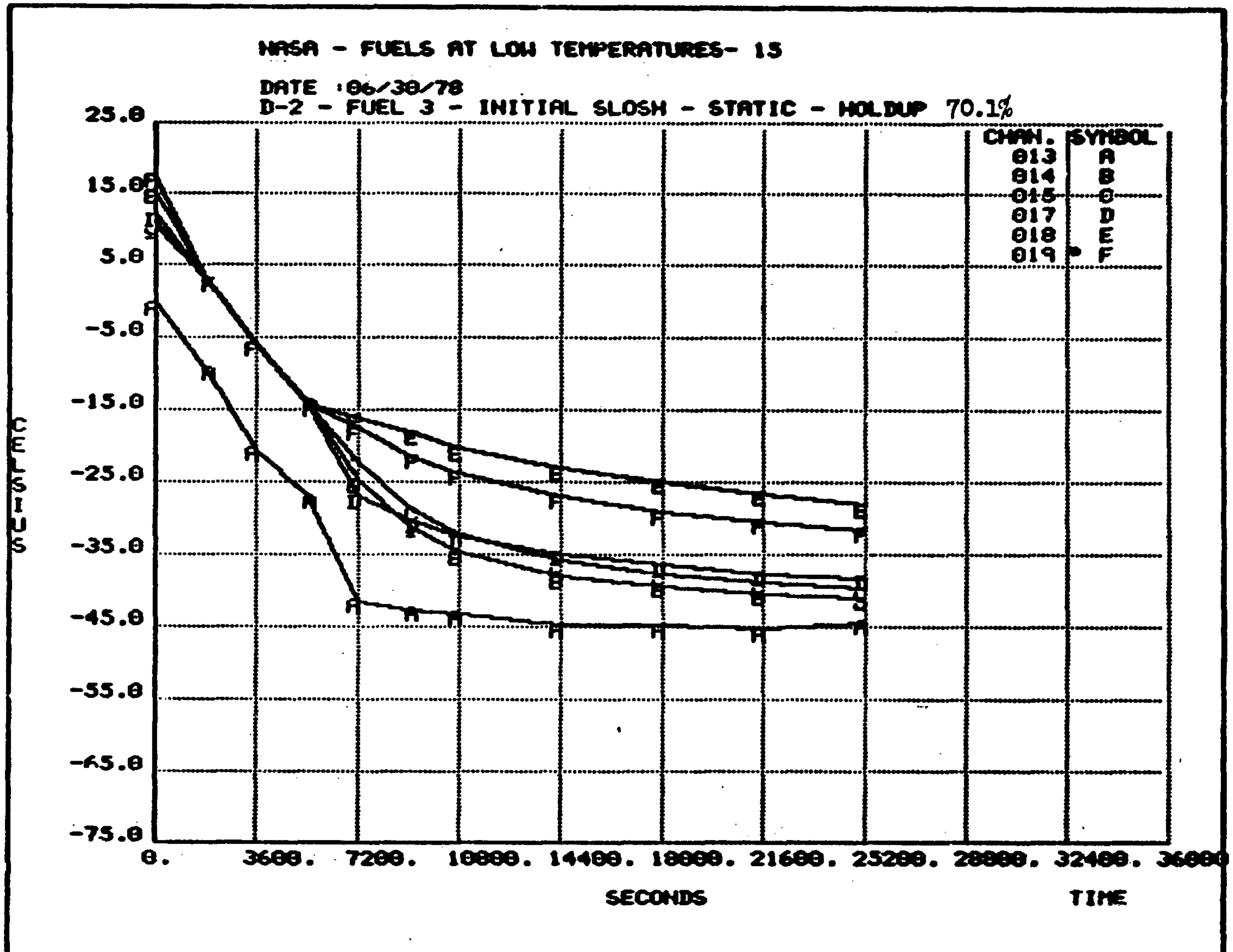

Figure - 26. Time History Showing Change in Temperature Distribution at Termination of Sloshing, Test 15

Two runs employed the ejectors during the chilldown in combination with recirculation to promote flow between the bottom stringers in addition to the flow from the perforated return tube. Temperature profiles with the ejectors and recirculation mixing appeared indistinguishable from those with recirculation alone.

6.5 DRY FUEL TESTS

Dry fuel tests were conducted with the intermediate fuels LFP-5 and LFP-6, Jet A LFP-9, and the shale-derived Fuel No. 8. Fuels were passed through a filter-separator prior to testing to remove any suspended water, in accordance with usual aviation fueling practices. The intermediate and Jet A fuels had 30 to 35 parts per million dissolved water content; the shale-derived fuel had 48 parts per million. Dry nitrogen pretreatment removed most of the water prior to the dry fuel runs. Holdup and temperature profile results for dried and untreated fuels were identical. Drying reduced the condensed water "fog" that appeared in some cases during chilldown, and improved the visual observation of fuel behavior.

6.6 DIVIDER TESTS

Tests were conducted with jet fuels LFP-1 and LFP-8, and with intermediate fuels LFP-5 and LFP-6, with a divider plate in the test tank. For runs in which the holdup was about 7% or less, the stringer cutouts at the bottom of the divider plate were only partially obstructed. Test results were identical to performance with no divider. Test 84 with intermediate LFP-6 fuel produced 10.7% gravity holdup. This amount proved sufficient to obstruct the stringer cutout openings; liquid fuel was able to pass through the slot between the divider and the viewing port. A small amount of fuel appeared to be trapped by the blockage of the stringer cutouts. The deposits did not "climb" the divider.

Test 84 temperature profiles are compared to profiles of tests without the divider in Figure 27. The readings of the center thermocouple rack, nearest the divider, are plotted in this figure. The conditions for the two tests were not identical. The non-divider test was conducted at a slightly higher bulk and boundary layer temperature, producing 8.8% holdup compared to 10.7% for the divider test. The difference in gravity holdup is as expected for the temperature differences. These results and the good correspondence in temperature profiles imply that the divider had little or no effect on conduction or convective heat transfer within the test tank.

6.7 SCHEDULED WITHDRAWAL TESTS

Scheduled withdrawal tests were conducted with intermediate fuels LFP-5 and LFP-6, jet fuels LFP-8 and LFP-9, and the shale-derived Fuel No. 8. The skin temperature schedule for these runs has been presented as Figure 14. For LFP-8, because of the low freezing point of the fuel, the skin temperature schedule was modified to a minimum of $-55^{\circ}C$ instead of $-49^{\circ}C$. This was done to assure some fuel holdup during the scheduled withdrawal test. The modified schedule is shown in Figure 28. Data points on this figure show

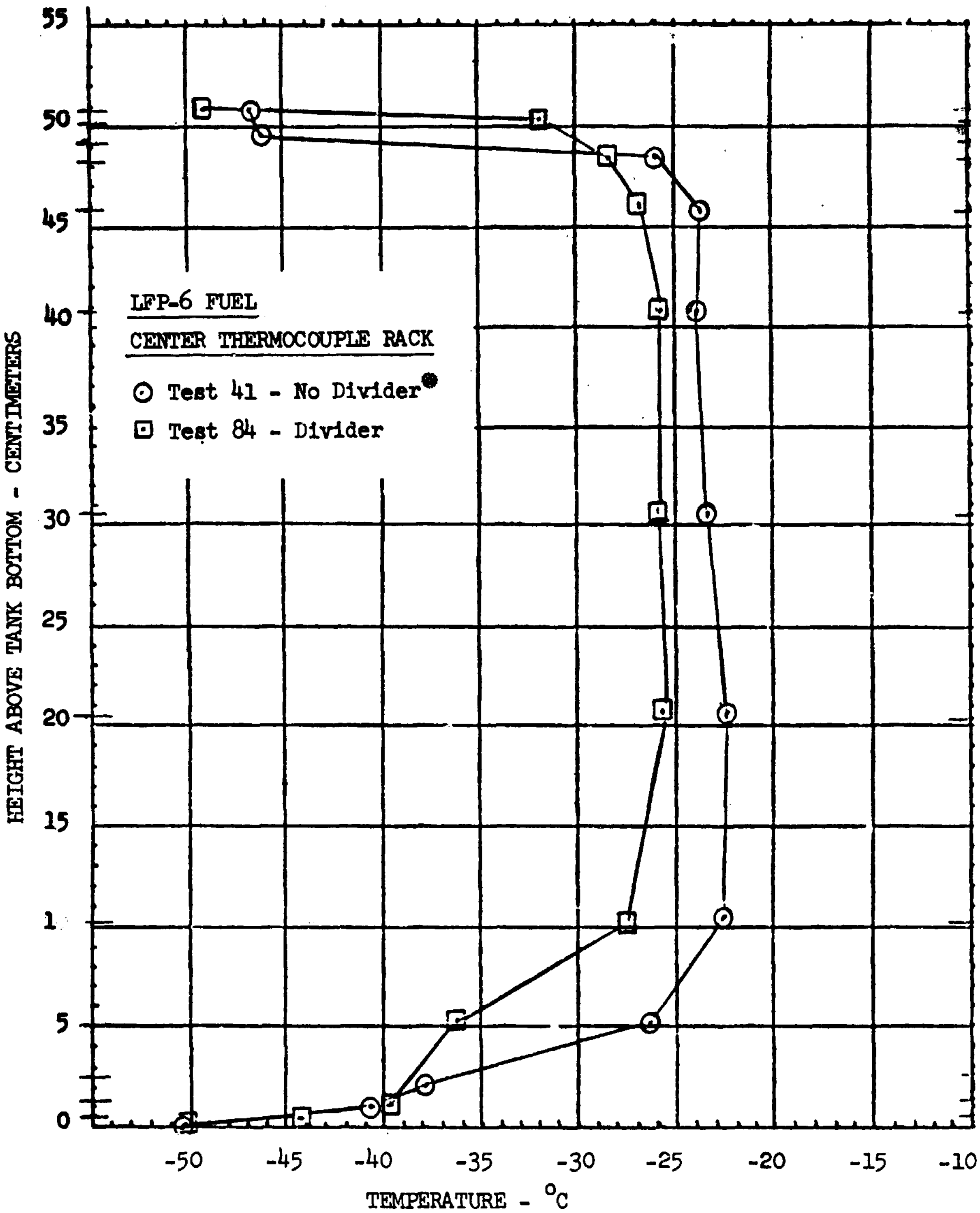

Figure - 27. Temperature Distribution at End of Tests With and Without Divider

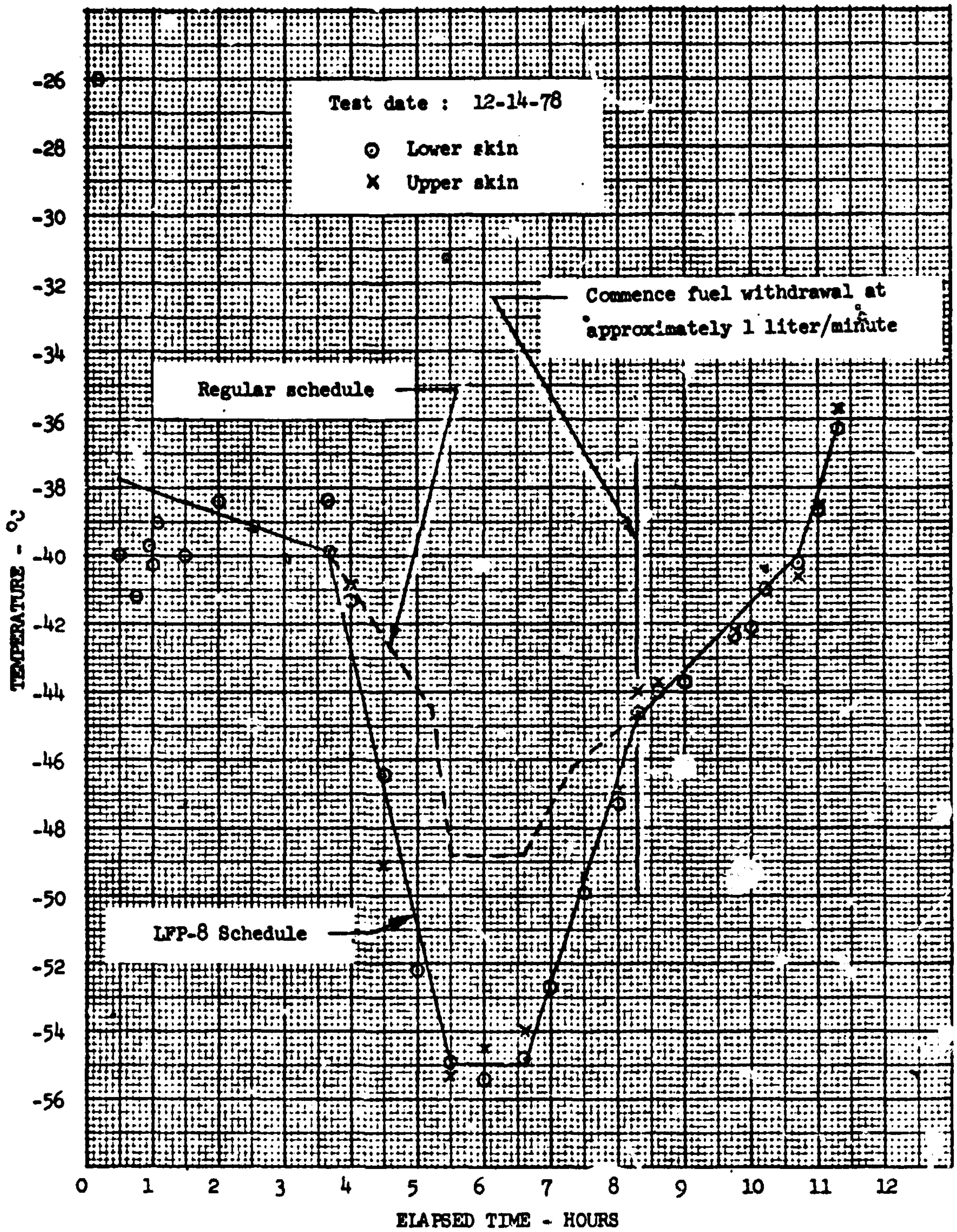

Figure - 28. Modified Temperature Schedule for LFP-8 Scheduled Withdrawal, Test 93 actual skin temperatures measured during the test, and this correspondence between test and scheduled temperature is also representative of scheduled withdrawal tests with the other fuels.

Figure 29 shows the temperature profiles at the center of the tank at various time intervals for the scheduled withdrawal test with LFP-9 fuel. Profile patterns were identical to those obtained with static tests up to the time that the skin temperature was warmed according to schedule (about 6.6 hours). The warming skin reduced the boundary layer gradients and produced an almost uniform fuel temperature at the end of the run. The withdrawal of fuel had a small effect distorting the profile as can be observed at the curve for 9.5 hours. [illegible]re was no holdup of fuel at the conclusion of the test; that is, the fuel remaining after the withdrawal schedule could be completely discharged after the test. However, an interesting comparison can be made with a corresponding static test. In Figure 30, the center temperature profile at the coldest time of the scheduled withdrawal test, 6.6 hours, is shown along with a temperature pro[illegible]ile from the end of a static test with the same fuel. The bulk temperature averaged 10°C higher for the static test, reflecting the shorter test time of 3 hours.

Skin and boundary layer temperatures are nearly the same f[illegible] the two tests. Since the static test exhibited a holdup of 1.2%, it is reasonable to assume that the withdrawal test would have at least that much holdup, considering the similar boundary layer and colder bulk temperatures. Solid dispersion was not observed during the withdrawal test, but it appears that conditions favored a small amount of solid precipitation with subsequent melting during the last hours. Similar test results and comparisons were observed with LFP-8 fuel.

Conditions for the scheduled withdrawal tests with LFP-5 and LFP-6 fuels were more severe because of the high freezing points of these fuels. Temperature profiles for fuel LFP-6, shown in Figure 31, show appreciable distortion before and during withdrawal due to the heavy buildup of solid material. Aft[illegible]r 2 hours, solids had begun to form on the bottom. Deposits increased, and during the minimum temperature period between 5.5 and 6.6 hours solids were observed suspended in the liquid fuel. At the start of withdrawal some agglomeration of the suspended solids evidently had occurred, so that the solids looked almost like small pieces of cotton. As the fuel level receded during withdrawal, solids were observed on the upper surface with gaps indicating that chunks had fallen. There was a light coating on the vertical panels. At the end of the test, gravity holdup was 25.5%. Results with LFP-6 were similar and in fact the buildup of solids was so severe that a reduced withdrawal flow rate was used to prevent premature depletion of the liquid fuel.

6.8 TESTS WITH FUEL NO. 8

The apparent temperature profiles and test results with the shale-derived Fuel No. 8 were different enough from the other fuels that they could not be compared or correlated with data from the other fuels. The scheduled withdrawal temperature profiles are plotted in Figure 32 as an example. Most

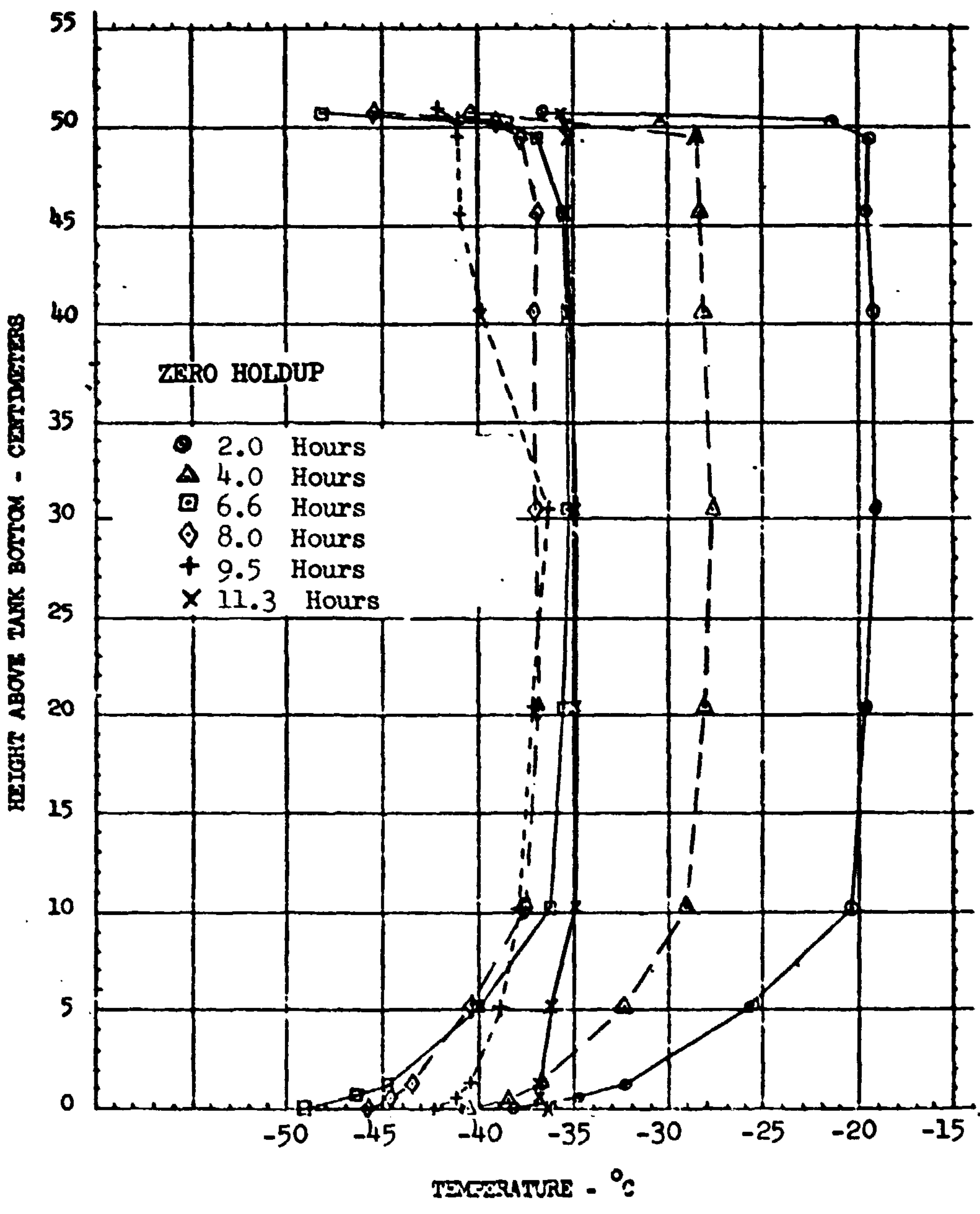

Figure - 29. Temperature Profiles at Center of Tank, Test 94 Scheduled Withdrawal, LFP-9 Fuel

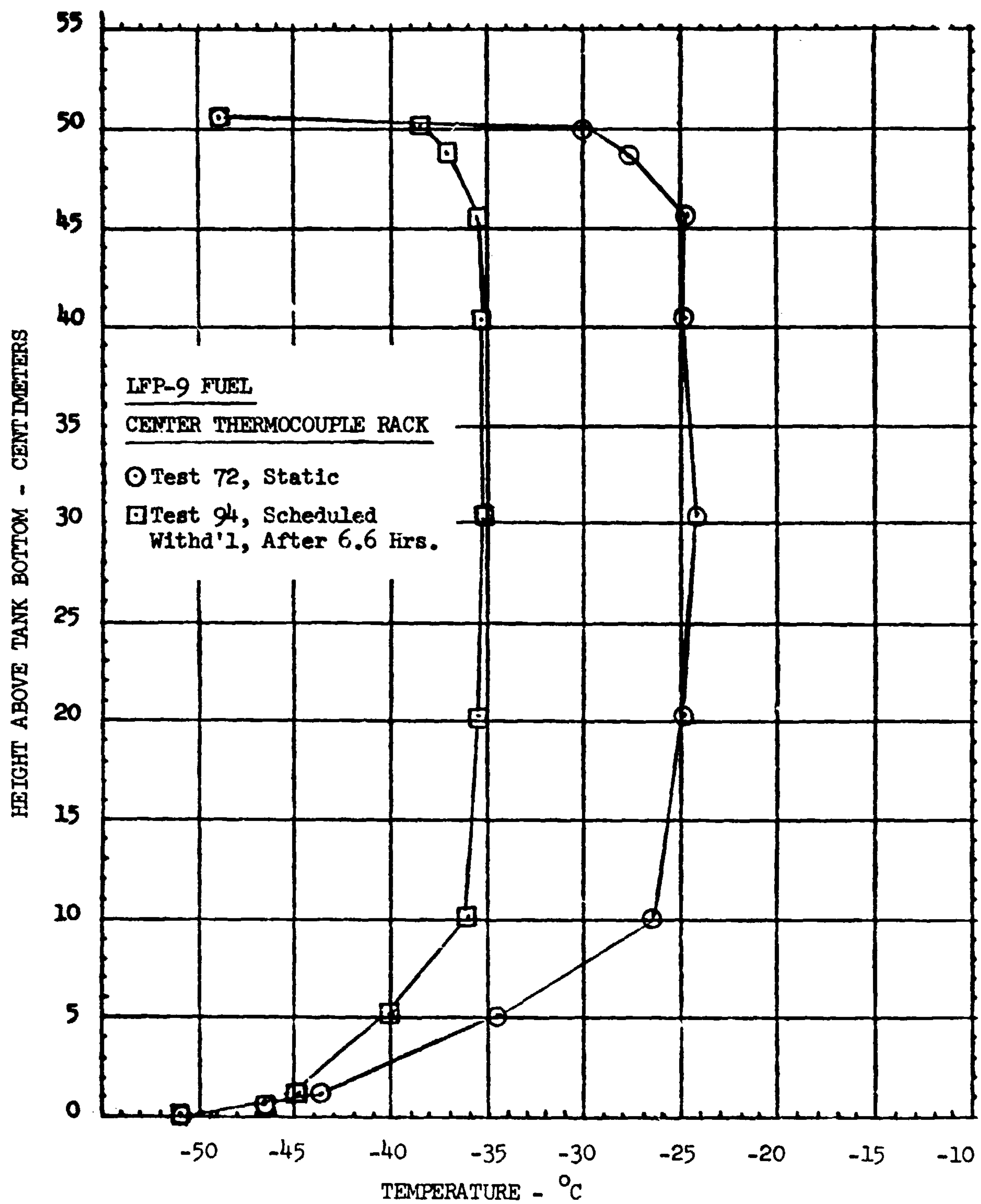

Figure - 30. Comparison of Static and Scheduled Withdrawal Test Temperature Profiles

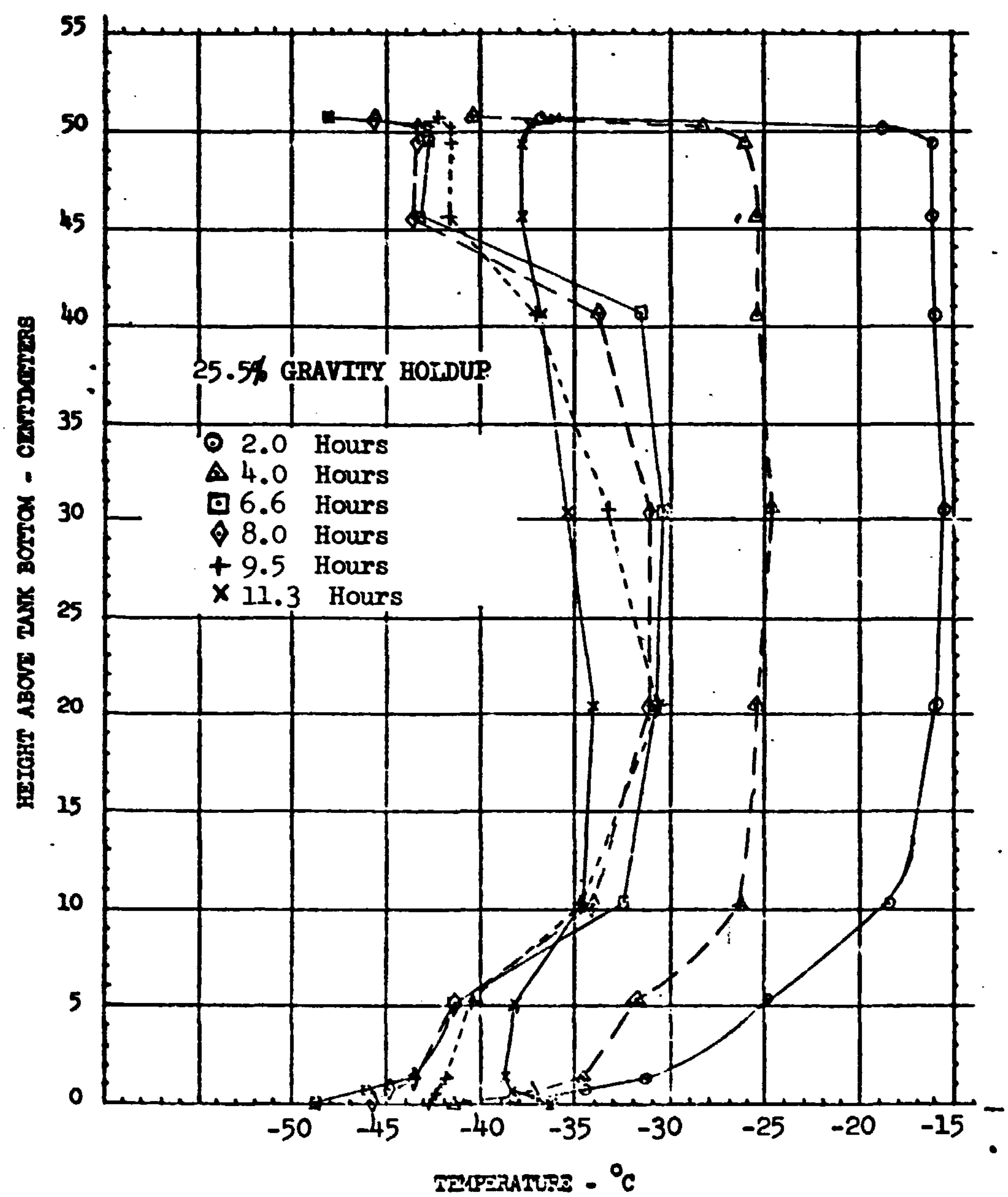

Figure - 31. Temperature Profiles at Center of Tank, Test 98 Scheduled Withdrawal, LFP-5 Fuel

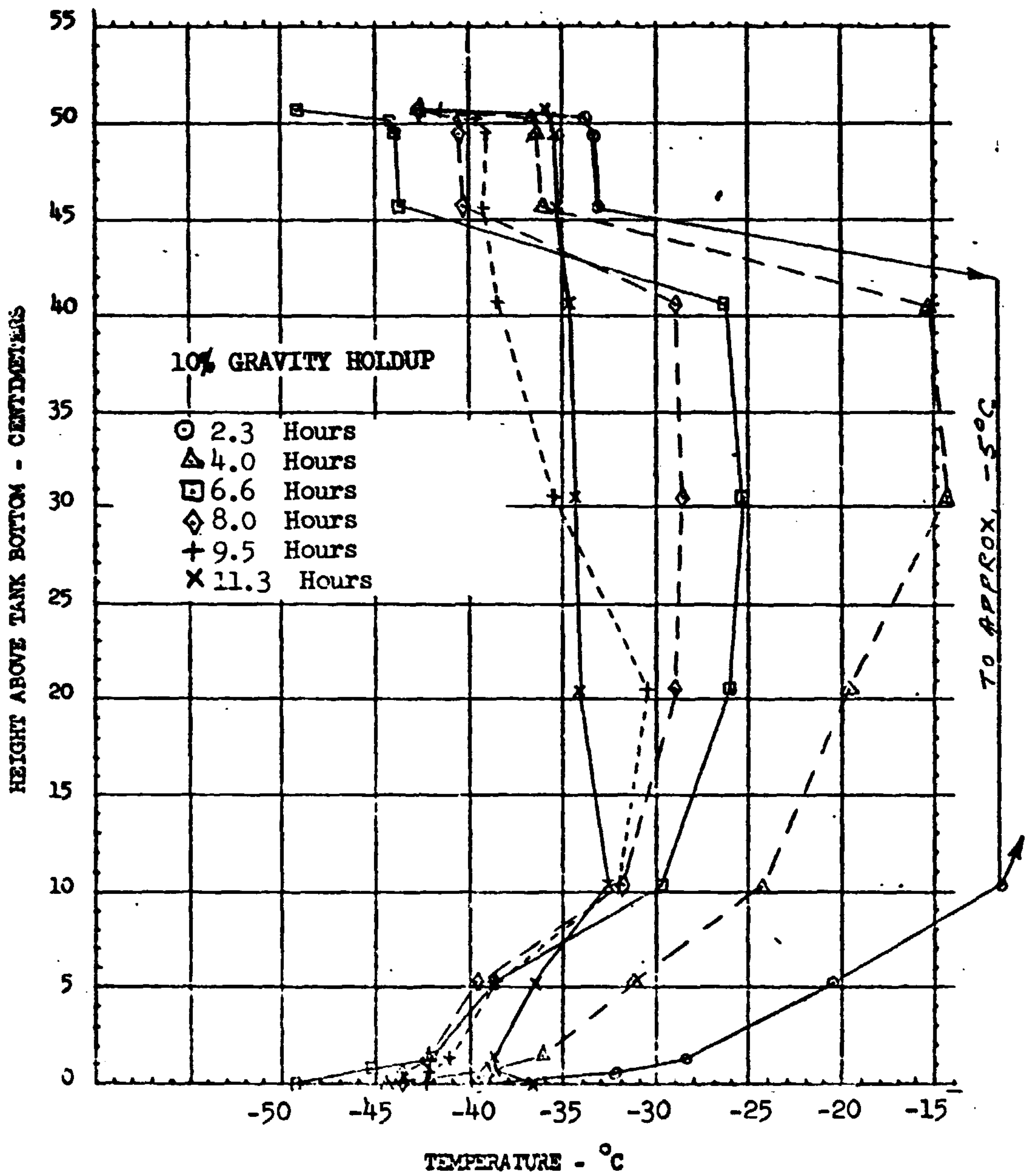

Figure - 32. Temperature Profiles at Center of Tank, Test 95 Scheduled Withdrawal, Fuel Number 8 of the problem with this fuel, however, very probably was an insufficient supply, so that the test tank could not be operated completely filled. Thus it was not possible to distinguish the behavior of this fuel from the reduced convection effects produced by partial tank operation. (It appears that there was about a 5 centimeter vapor space at the top of the tank.) Solids deposited by this fuel formed needle-like crystals different in appearance from those of the other fuels.

6.9 TESTS WITH POUR POINT DEPRESSANT ADDITIVE

Three tests were performed to evaluate the effect of a pour point depressant additive on the low temperature behavior of an intermediate fuel. The pour point depressant is a proprietary polymeric material which disperses the solid fuel particles, preventing solid coagulation and buildup. These additives are commonly used for winter service of Diesel and fuel oils, but ordinarily they are not used with jet fuels. The additive used in these tests, designated as Paradyne 25, was added in a concentration of 0.10% by weight to LFP-5. Laboratory tests indicated that the pour point of the fuel decreased from -31°C to -40°C with this additive (see fuel data in Appendix A).

One of these tests, Test 97, was conducted with the undoped fuel at a skin temperature of -51.7°C and a boundary layer temperature (1.2 centimeters from the bottom skin) of -46.0°C. These conditions produced a holdup of 20.7%. After the pour point depressant was added to LFP-5, it was designated as Fuel No. 7. Test 99, which maintained the identical conditions of Test 97 within 0.3°C, resulted in a reduction of holdup to 10.2% for the treated fuel.

Finally, the third test (Test 100) was performed with Fuel No. 7 at a skin temperature of -63.5°C, boundary layer temperature of -55.9°C, or 10°C to 12°C below baseline temperature conditions. Holdup results were 17.1%, even better than the baseline test results. These limited tank tests surpassed the laboratory results of a reduction of 9°C in pour point due to the addition of the pour point depressant.

6.10 SUMMARY OF TEMPERATURE PROFILES

Results of the tests are summarized by the plots of temperature profiles in Figure 33 through 45. These show the indications of the center thermocouple rack, which was considered to be the most representative measurement at the conclusion of each test when fuel was withdrawn from the tank. (Data for LFP-5 and LFP-6 are presented on two figures each.) Test numbers shown on the legend of each figure can be used for reference to the table in Appendix C for further details on each test. A few sloshing runs with abnormal profiles were omitted.

An interesting aspect of Figures 33 through 45 is the cusp which appears in most of the curves at just above 5 centimeters. This is probably due to the thermal conductivity of the lower stringers, whose upper surface is at the 6.1 centimeter level. This effect is not evident in the recirculation tests and the sloshing tests.

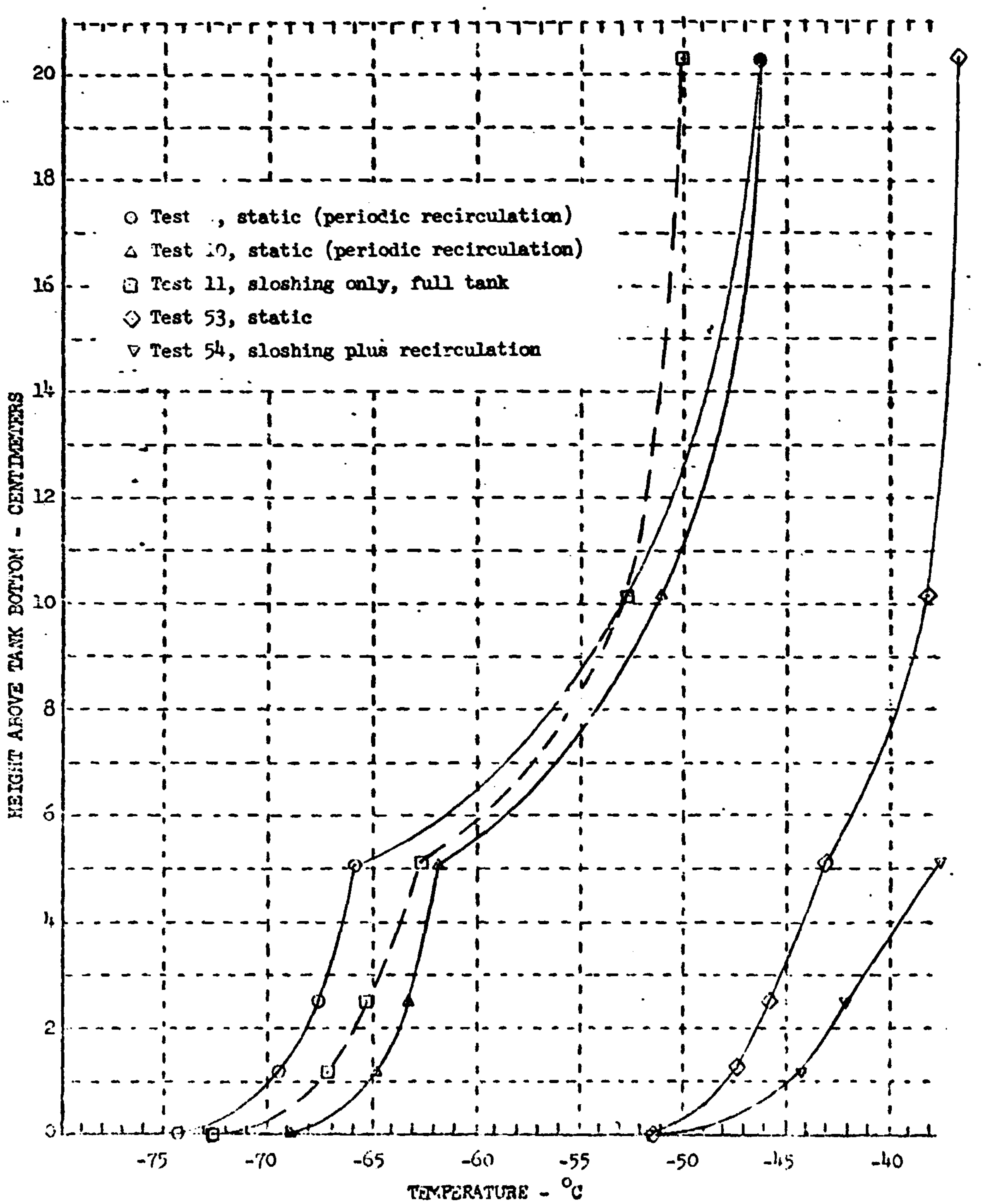

Figure - 33. Temperature Profiles from Center of Tank at End of Tests - Fuel Number 1

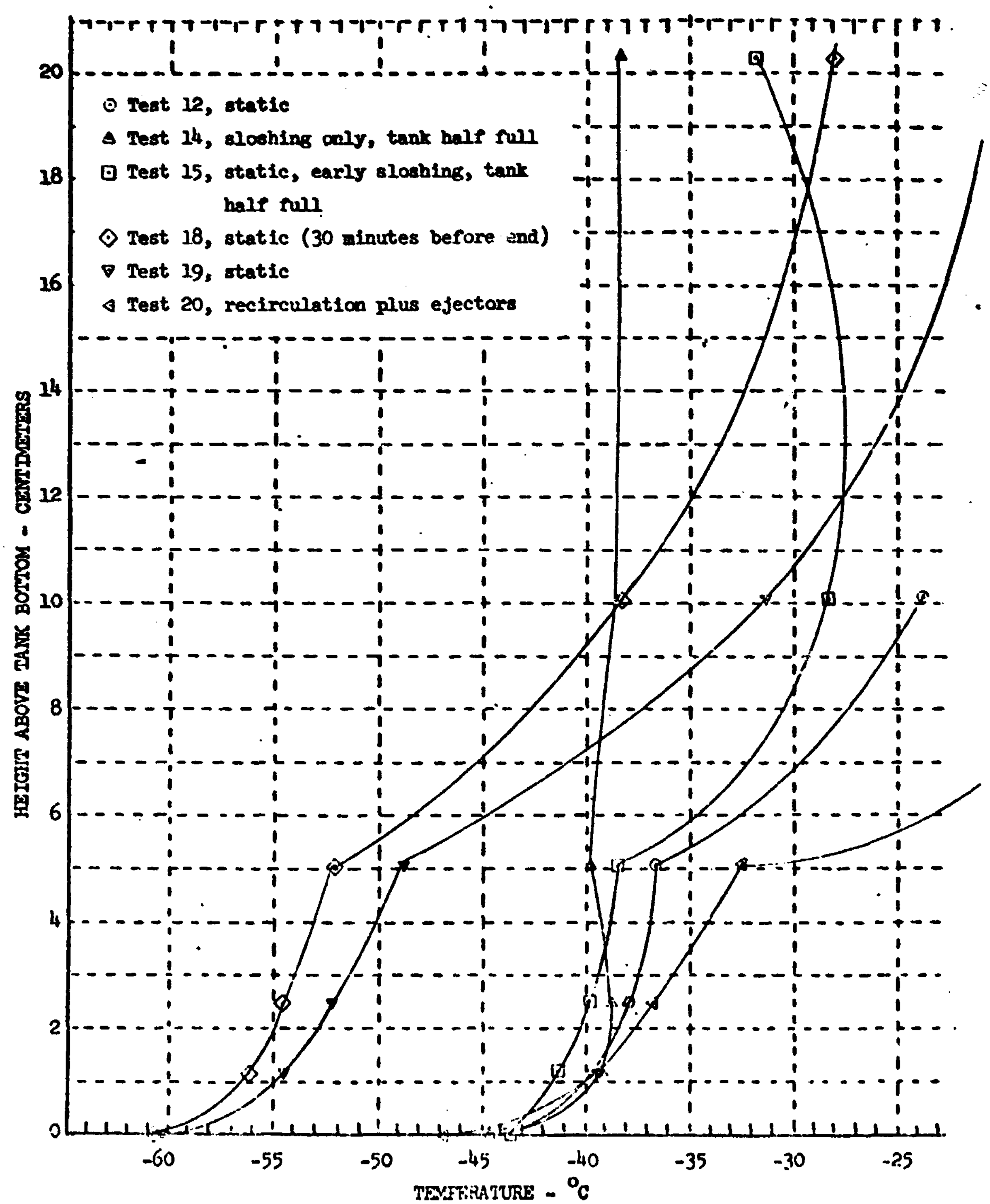

Figure - 34. Temperature Profiles from Center of Tank at End of Tests - Fuel Number 3

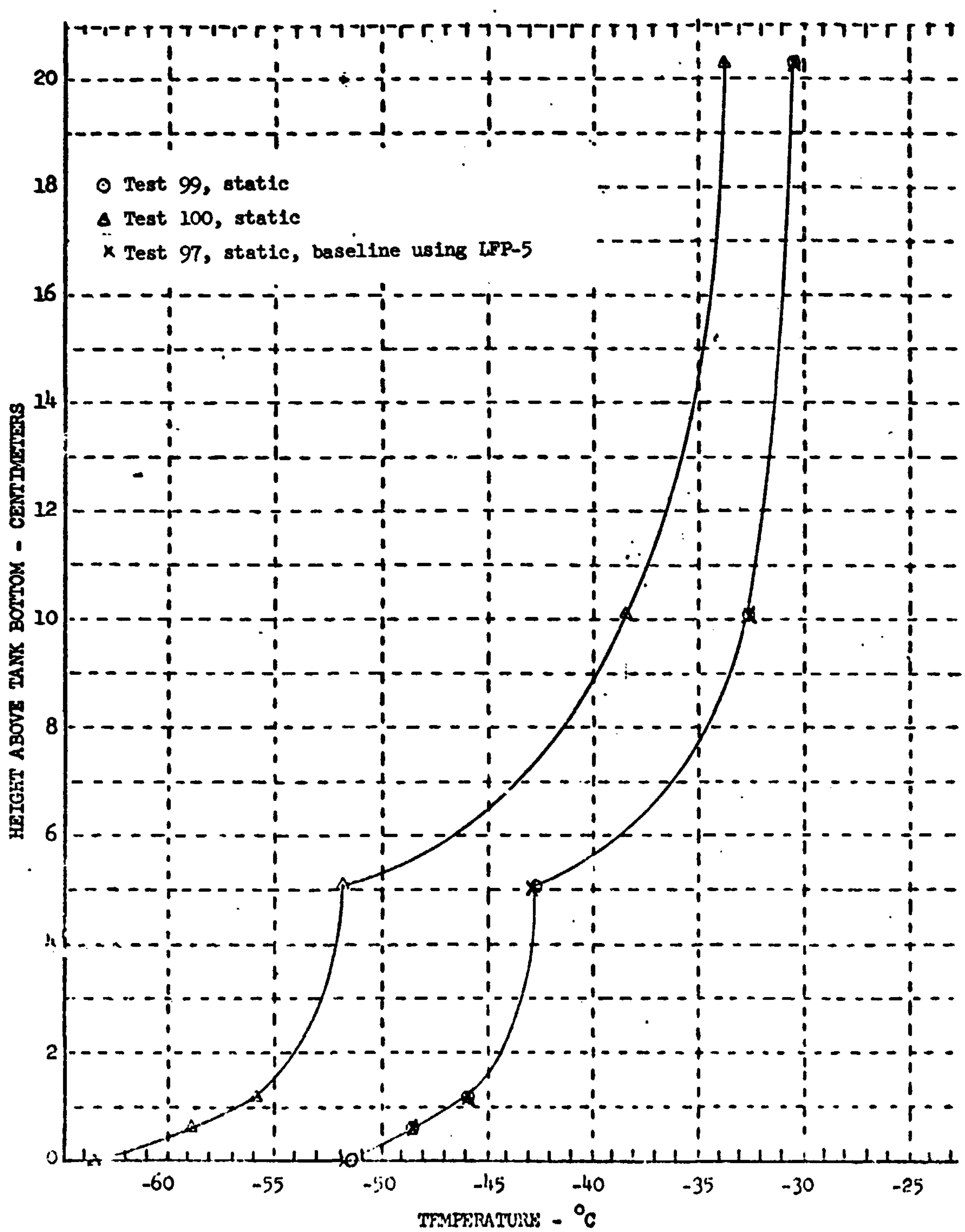

Figure - 35. Temperature Profiles from Center of Tank at End of Tests - Fuel Number 7

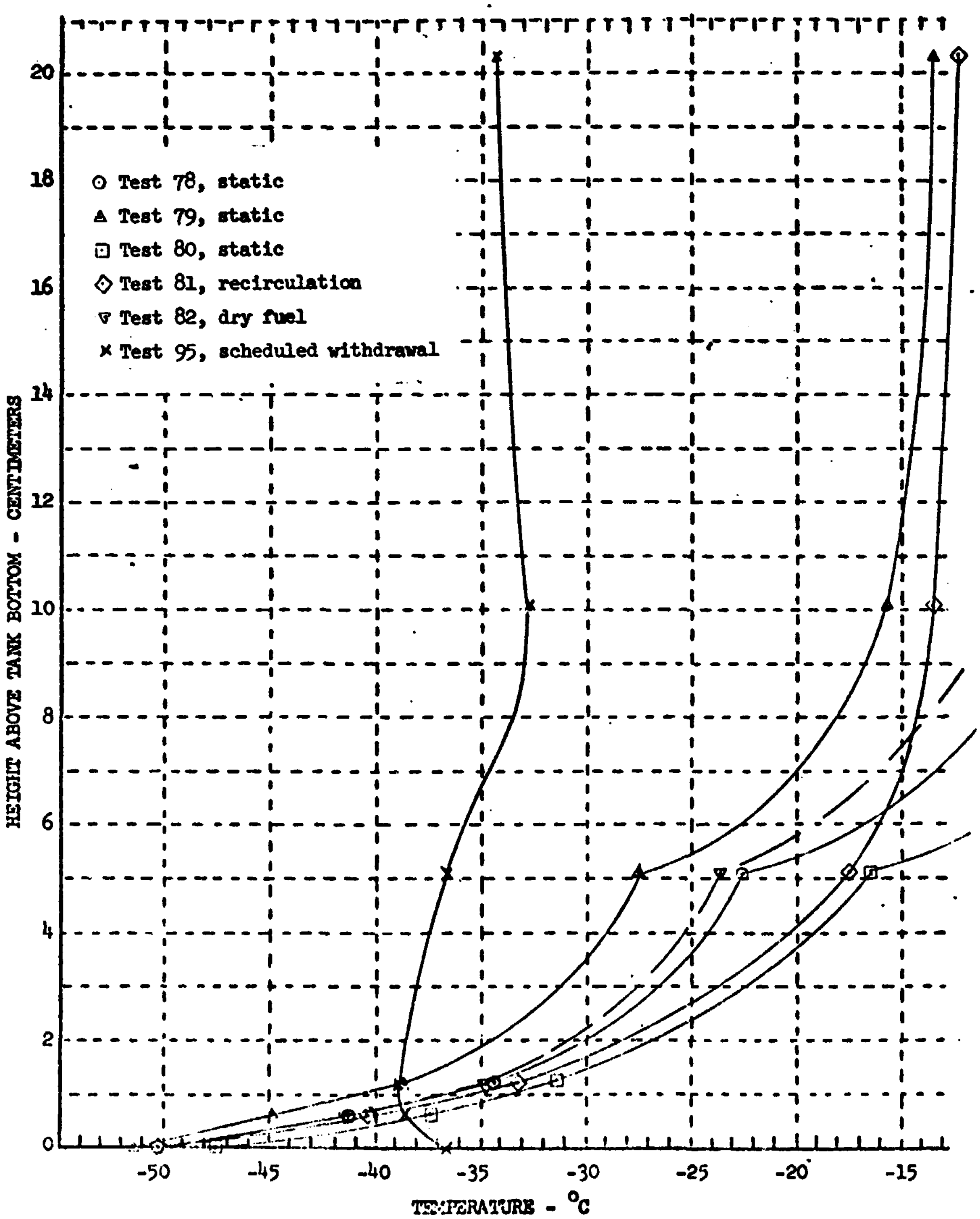

Figure - 36. Temperature Profiles from Center of Tank at End of Tests - Fuel Number 8

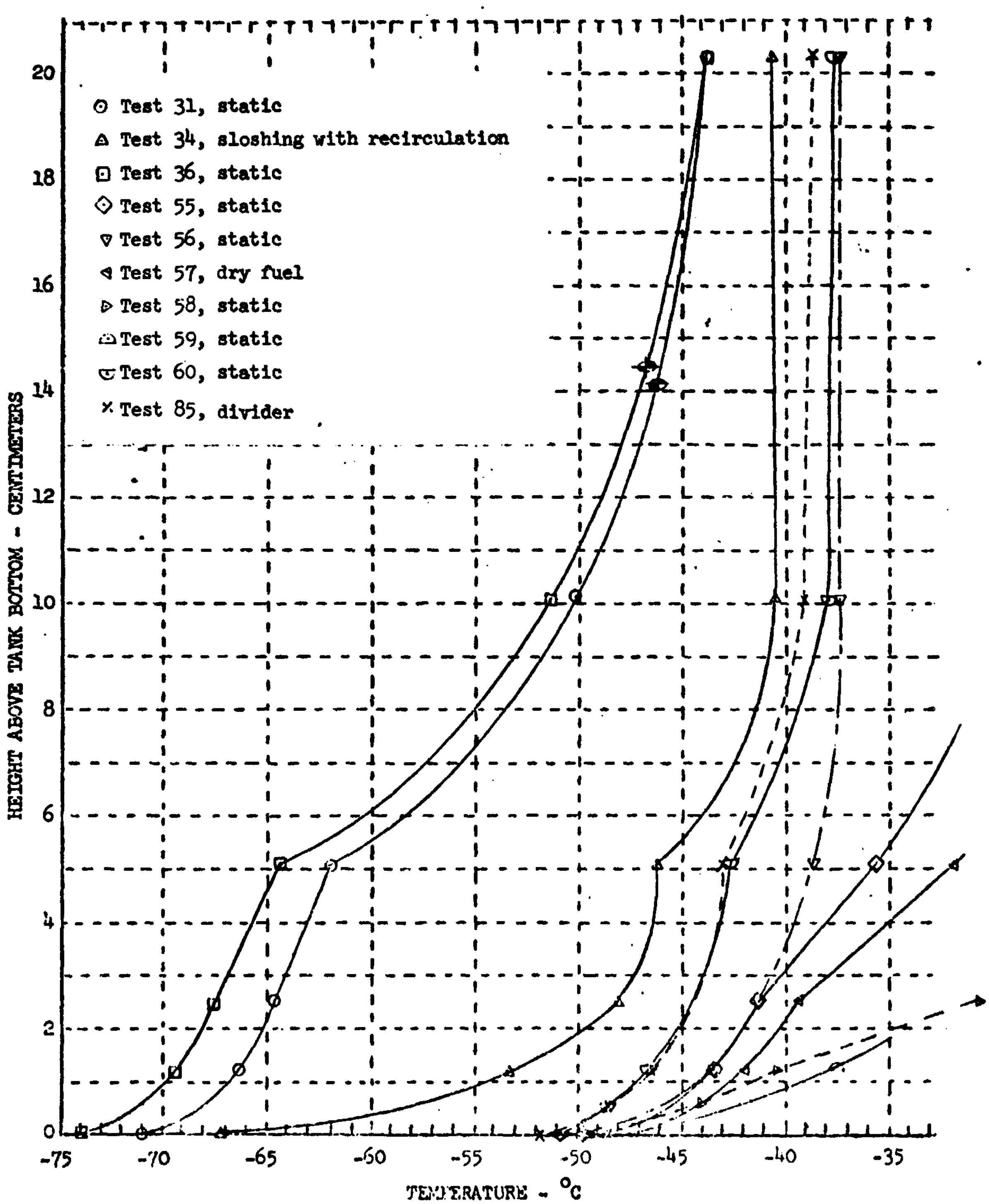

Figure - 37. Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-1

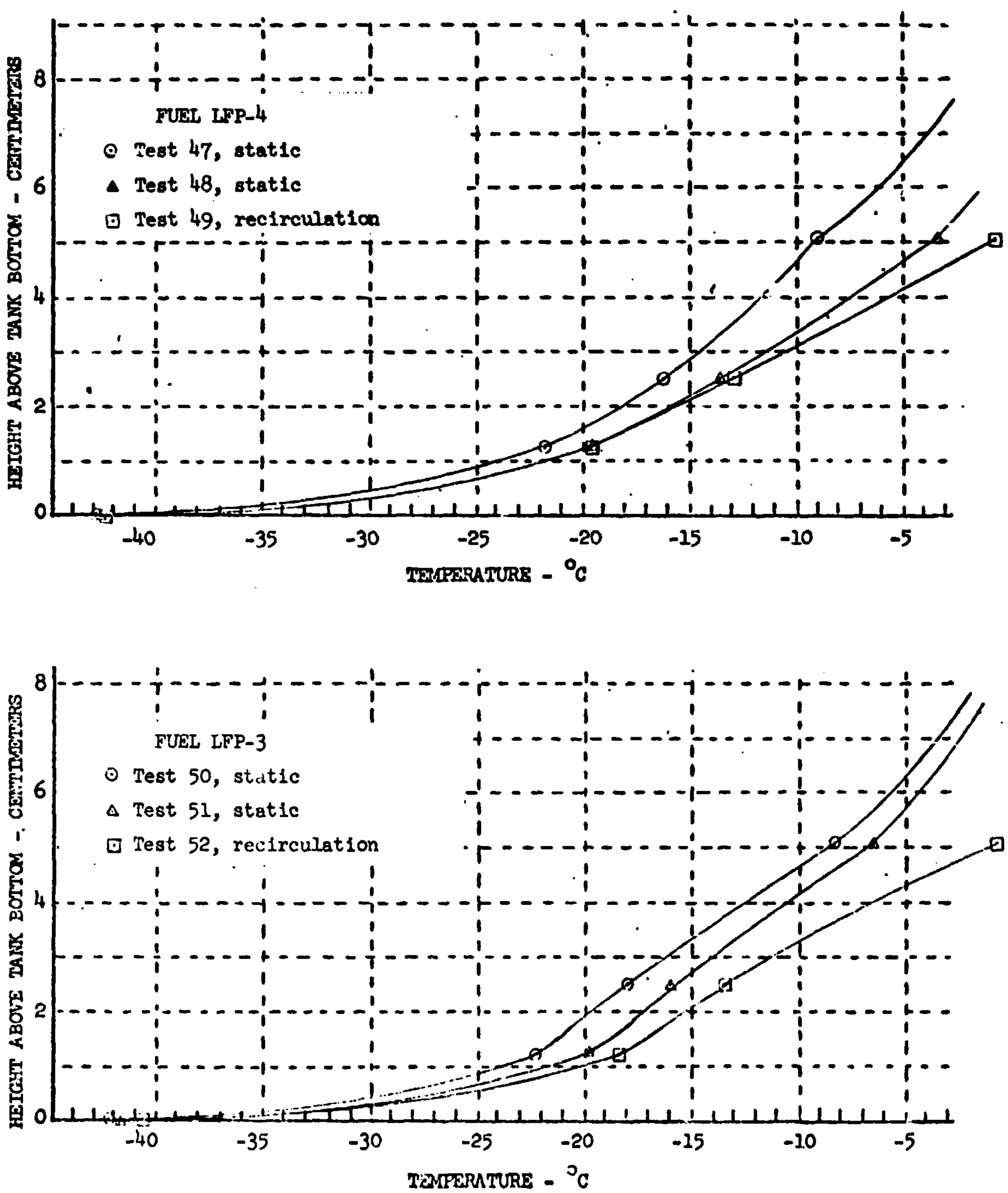

Figure - 38. Temperature Profiles from Center of Tank at End of Tests - Fuels LFP-3/LFP-4

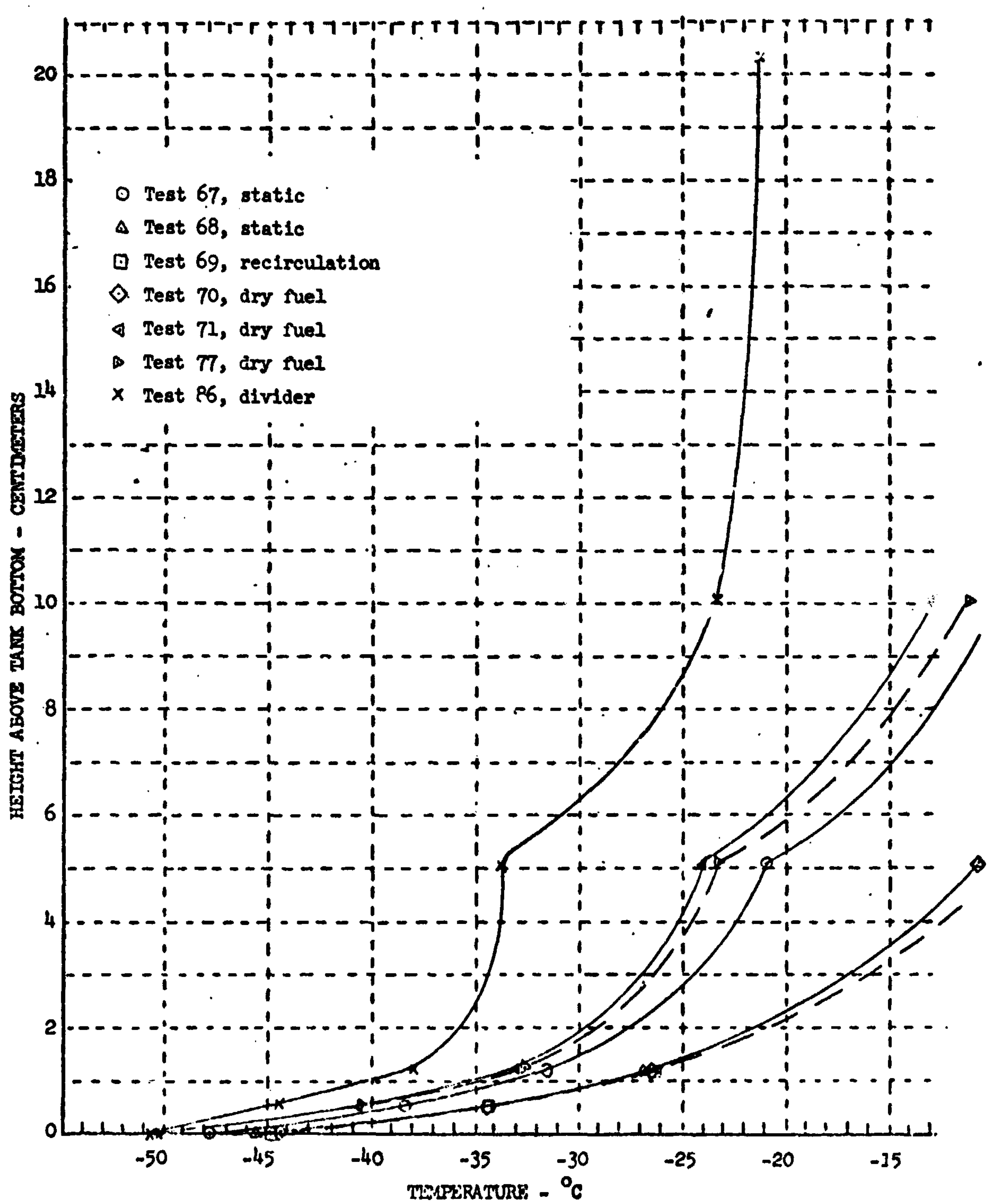

Figure - 39. Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-5

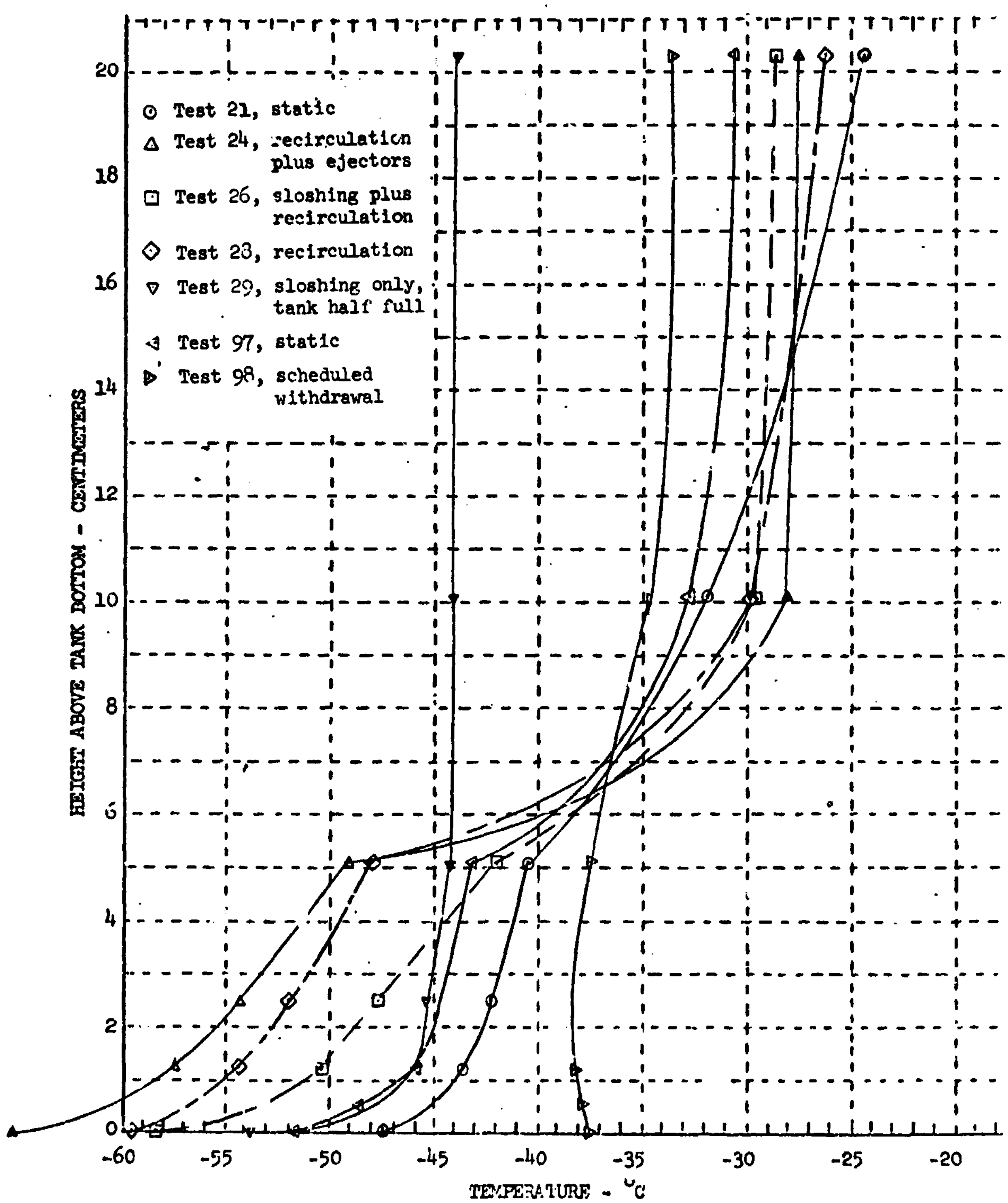

Figure - 40. Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-5

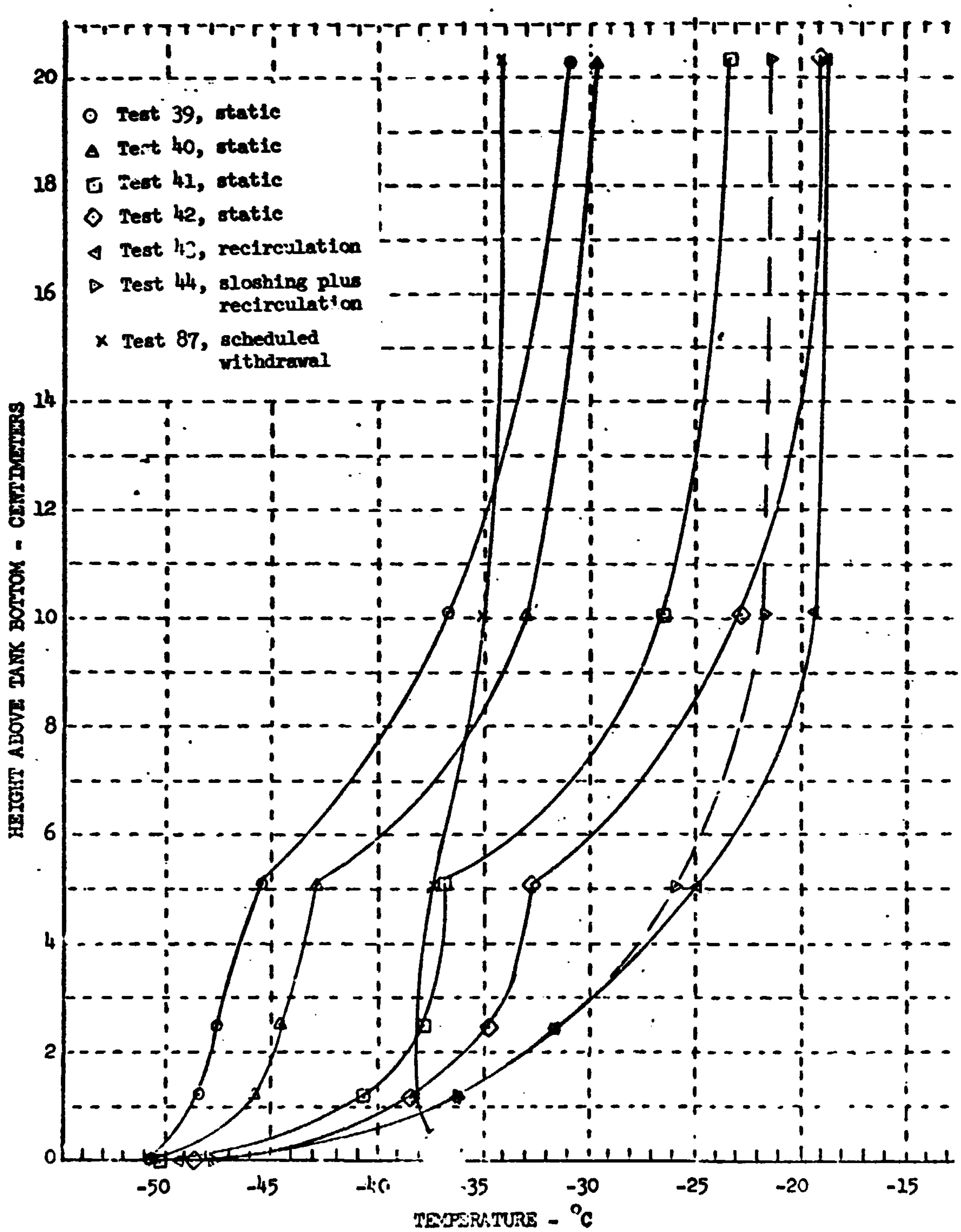

Figure - 41. Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-6

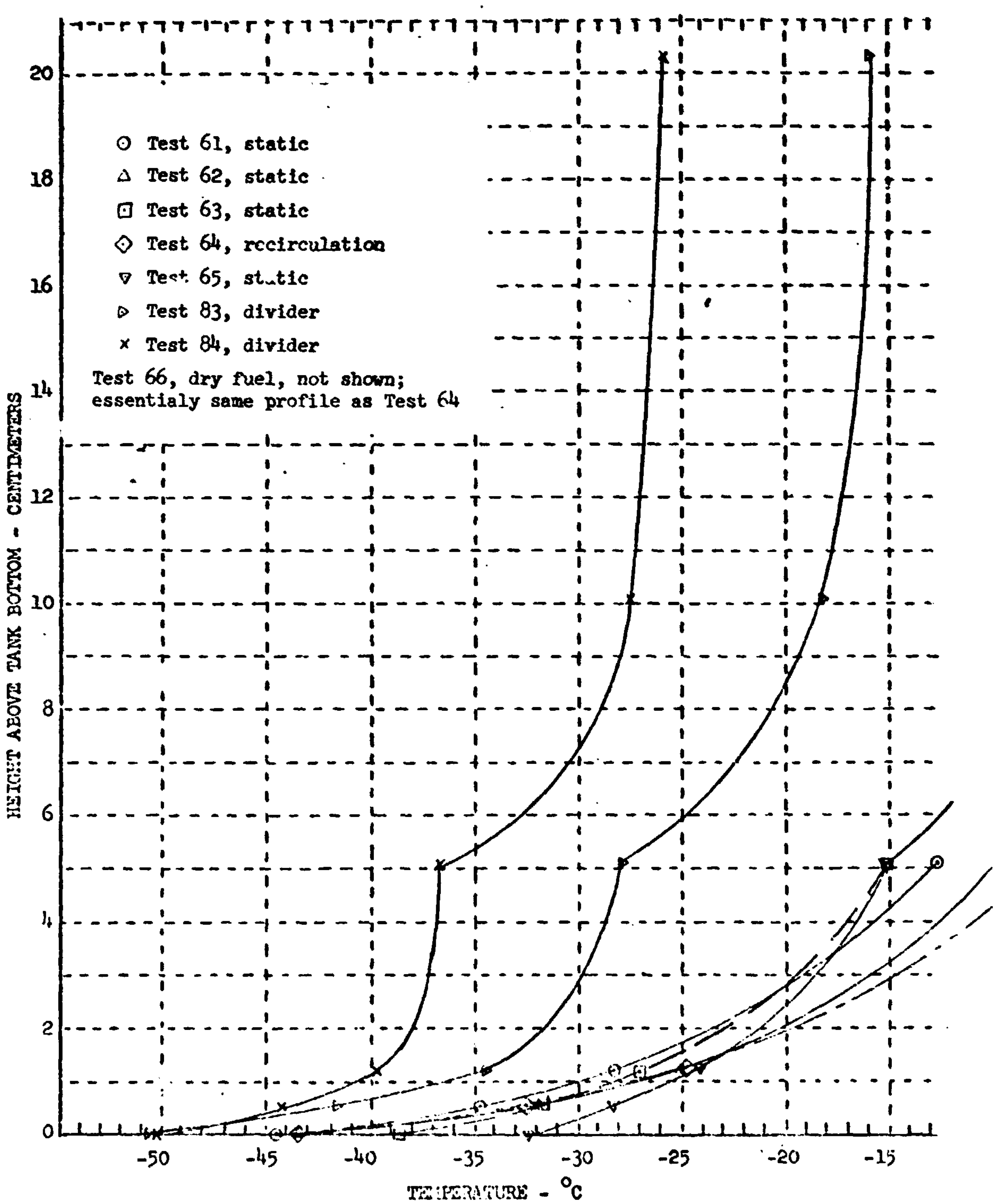

Figure - 42. Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-6

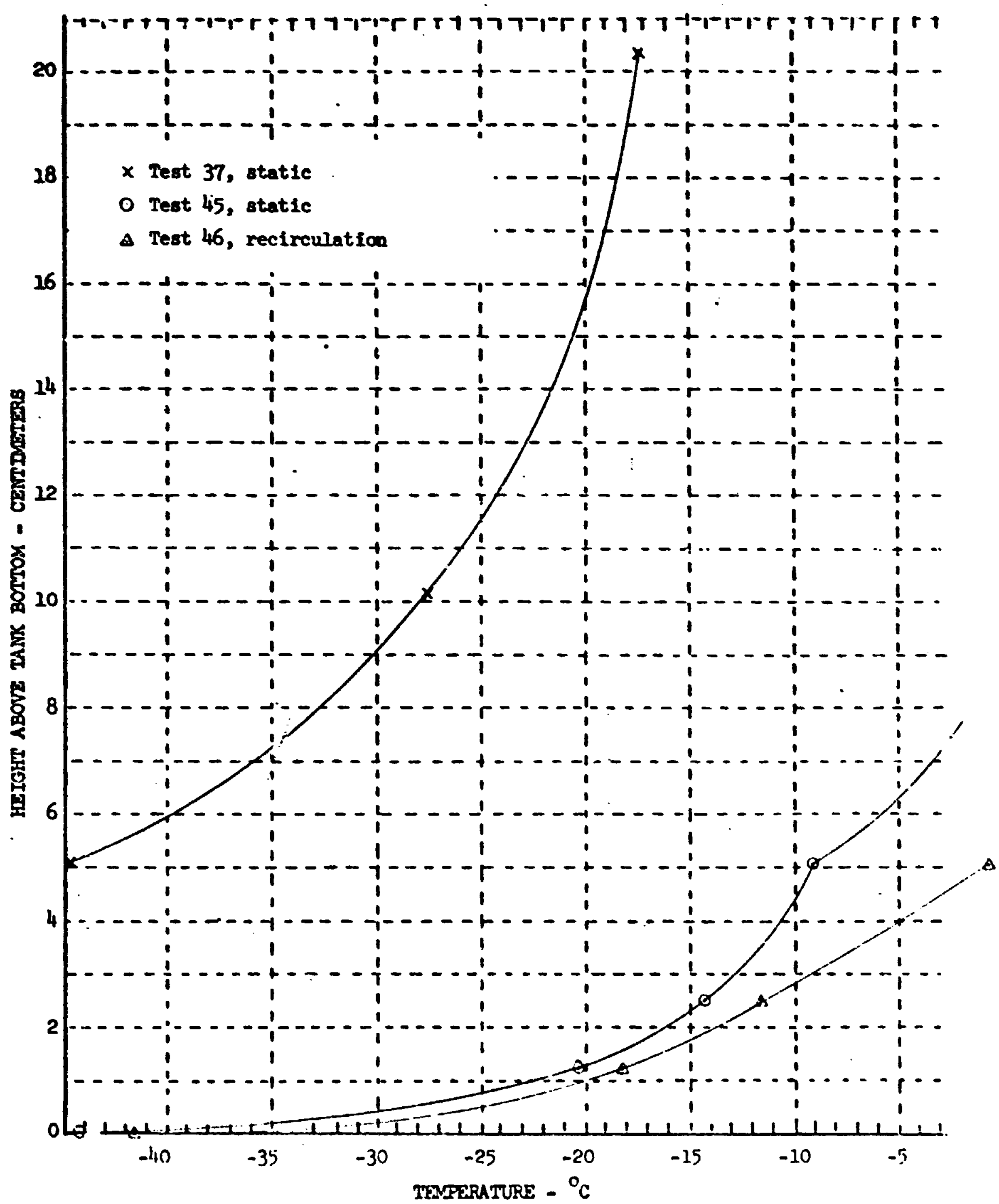

Figure - 43. Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-7

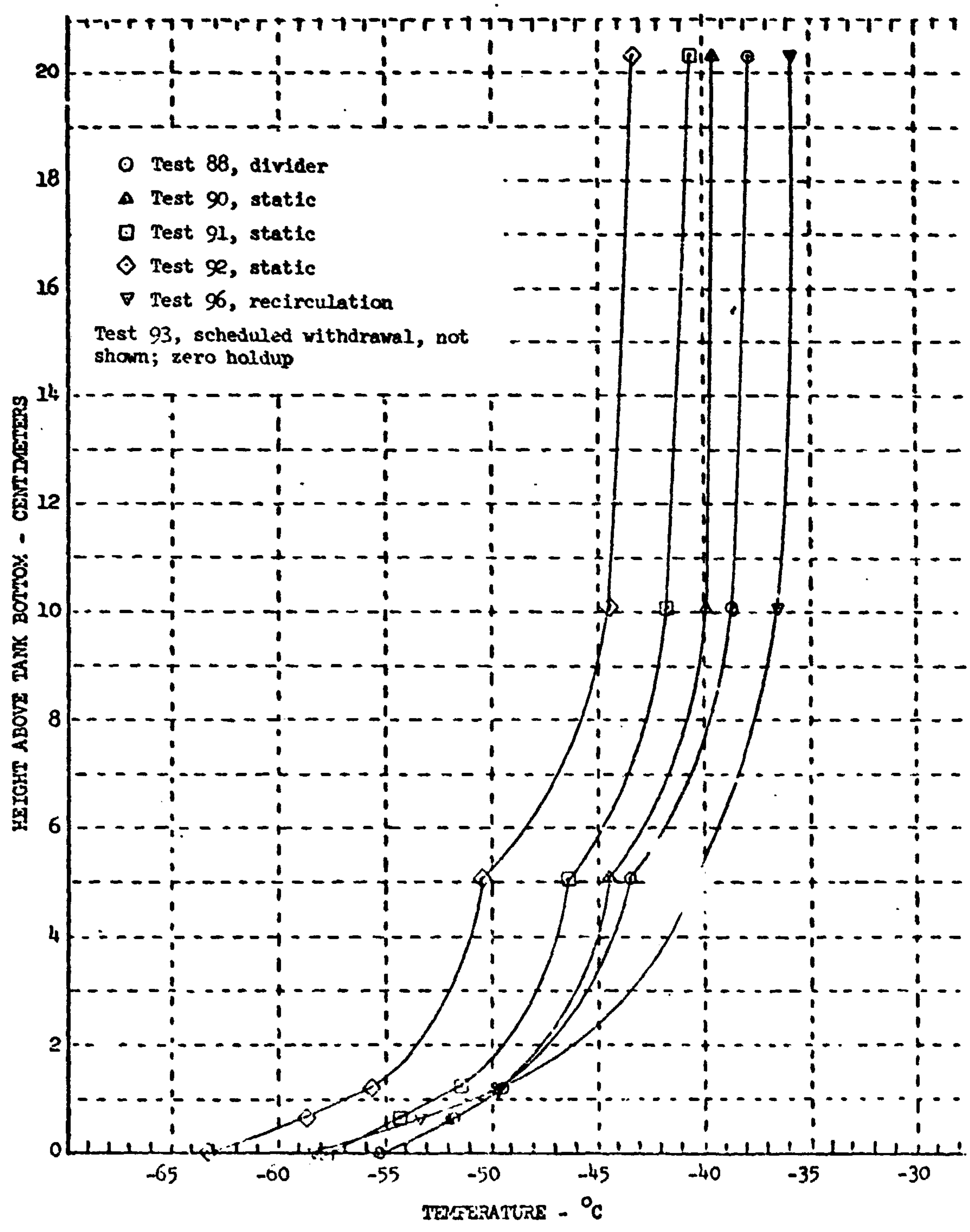

Figure - 44. Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-8

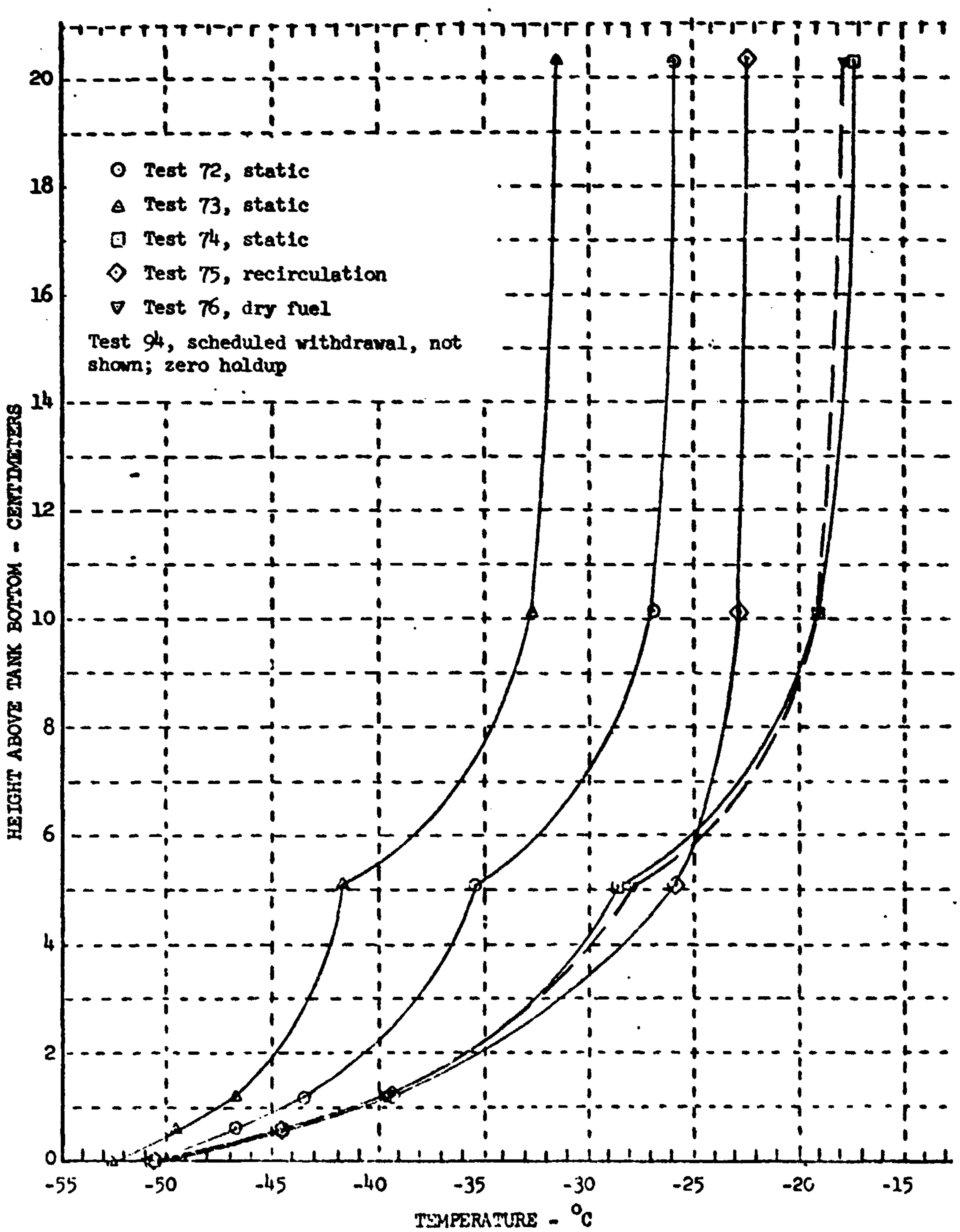

Figure - 45. Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-9

7.0 DISCUSSION

During the performance of this program a considerable amount of test data was accumulated. In this report, analysis of the data will be confined to those aspects which are considered most relevant to the possible future use of a higher freeze point fuel for turbine engine powered commercial aircraft.

In commercial service on a standard day, a typical commercial jet airplane could climb to a cruise altitude of 11,278 meters (37,000 feet) within 30 minutes of takeoff. Since this is above the 11,000 meter isothermal altitude, the ambient temperature would be -56.5°C (-69.7°F). (Reference 12.) At Mach 0.80, a 90% recovery of ram temperature rise would result in an adiabatic wall (wing skin) temperature of -31.5°C; at Mach 0.85 this temperature would be -28.3°C. Present specification jet fuels with a maximum freezing point of -40°C, or even those with higher freezing points, would be usable at these standard day conditions. What is of real concern is the flight which was represented in Figure 14 for a one-day-per-year probability of an extreme low temperature, in which skin temperature at Mach 0.80 would attain a minimum of -48.8°C.

Early in the testing phase there was always a considerable temperature differential between the inner cooling surfaces (skins) and the center of the test tank during static tests and recirculation tests. Sloshing with the tank half full greatly decreased the temperature variation, but resulted in only a small decrease in temperature variation with the tank full of fuel. A more even temperature distribution could have been achieved by gradual reduction of skin temperature and extended soak time at the final temperature. However a unique feature of this testing program was a realistic representation of the aircraft wing tank environment. The chilldown procedure employed was a simulation of conditions to which aircraft are subjected.

Visual observations proved to be an important means of data acquisition, both for interpreting data gathered through instrumentation and for understanding the process of formation and deposition of solids as described below.

As the upper and lower surfaces are cooled, heat is transferred from the fuel to the coolant. In particular, fuel cooled by the upper surface becomes more dense; the resultant density gradients set up a convective flow of dense, colder fuel toward the bottom of the tank. As profiles are fully developed in the completely filled tank, the center of the tank has a well mixed uniform temperature, with gradients to the skin temperature over a considerably greater distance at the bottom compared to the top. Condensation of solid fuel during the chilling is also influenced by the convection currents set up by the density gradients. The first visual evidence of solids is a dulling of the lower surface of the tank. As cooling continues, the dull area spreads along the bottom, then commences to climb the vertical webs of the lower stringers and later to spread across the upper horizontal flanges of the stringers. During this process the dulling becomes identifiable as solid deposits increasing in depth on the bottom and to a lesser extent on the stringers. Eventually, the deposits form on the upper surfaces and vertical panels.

In most cases, solids suspended in the fuel became evident after the lower surfaces had become coated with deposits, although in a few cases some small particles in the fuel were observed early in the cooldown. The solids were of various shapes and sizes, ranging from particles less than one millimeter in diameter to slender strands 6 to 8 millimeters long. In many tests the suspension of solid fuel was dense enough that visibility in the test tank was limited to a distance of a few centimeters. During several tests which produced large gravity holdups, buildup of deposits on the vertical panels and upper surfaces could be seen. Judging from slosh tests and the appearance of the deposits for large gravity holdups, it can be concluded that accumulated solids mat together to form a lattice or matrix which in turn can trap liquid fuel. When sloshing is energetic and continuous, this entrapment of liquid fuel is minimized because the matrix is continually being broken up and dispersed.

Examples of the appearance of the solid fuel holdup are shown in several photographs which illustrate a range of low to high gravity holdup results.

Figure 46 shows a 3.2% gravity holdup of LFP-9 Jet A, with deposits on the bottom and partially covering the stringers.

Figure 47 shows a 4.3% gravity holdup of No. 1 Jet A, featuring the crystalline appearance of the deposits which cover the lower stringers and the bottom of the tank.

Figure 48 shows approximately the same gravity holdup for the distillate fuel LFP-7. For this test, the deposits consisted of tiny crystals, in marked contrast to the coarse crystals shown in Figure 47. The smaller, smooth crystalline deposition is most likely the result of more rapid chilling in this test (Test 46), rather than the result of the difference in fuel properties.

Figure 49 shows an 8.8% gravity holdup of LFP-5 intermediate fuel, and hints of liquid entrapment in the stringer bays.

Figure 50 shows a 57.2% gravity holdup of LFP-1 Jet A, with solids adhering to thermocouple racks and vertical panels, and the reflections of the thermocouple racks providing evidence of liquid entrapment.

From the photographs and other visual observations it appeared that the height of the deposits in the tank could be correlated with the measured gravity holdup. At gravity holdups up to 1%, deposits were on the bottom skin only, between the lower stringers. By 4% gravity holdup, a thin film had covered the vertical webs and upper flanges of the lower stringers. At about 6% holdup, a very slight film was forming on the upper surfaces. Deposits were evident on the vertical panels at about 10% holdup, and by 20% holdup the distribution was approximately 16% on the bottom (covering the lower stringers), and 4%

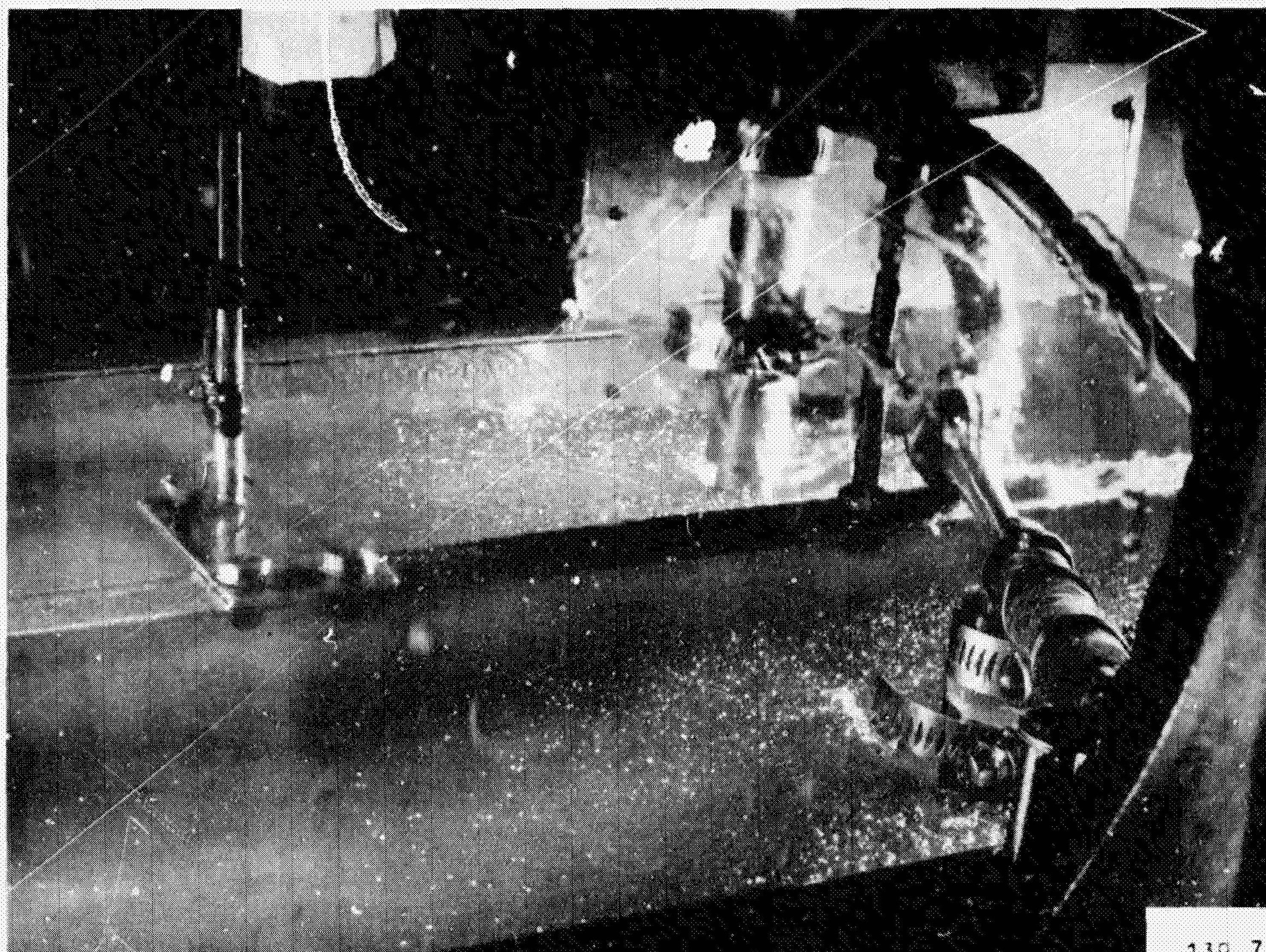

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Figure - 46. Gravity Holdup of 3.2% at End of Test 73, LFP-9 Fuel.

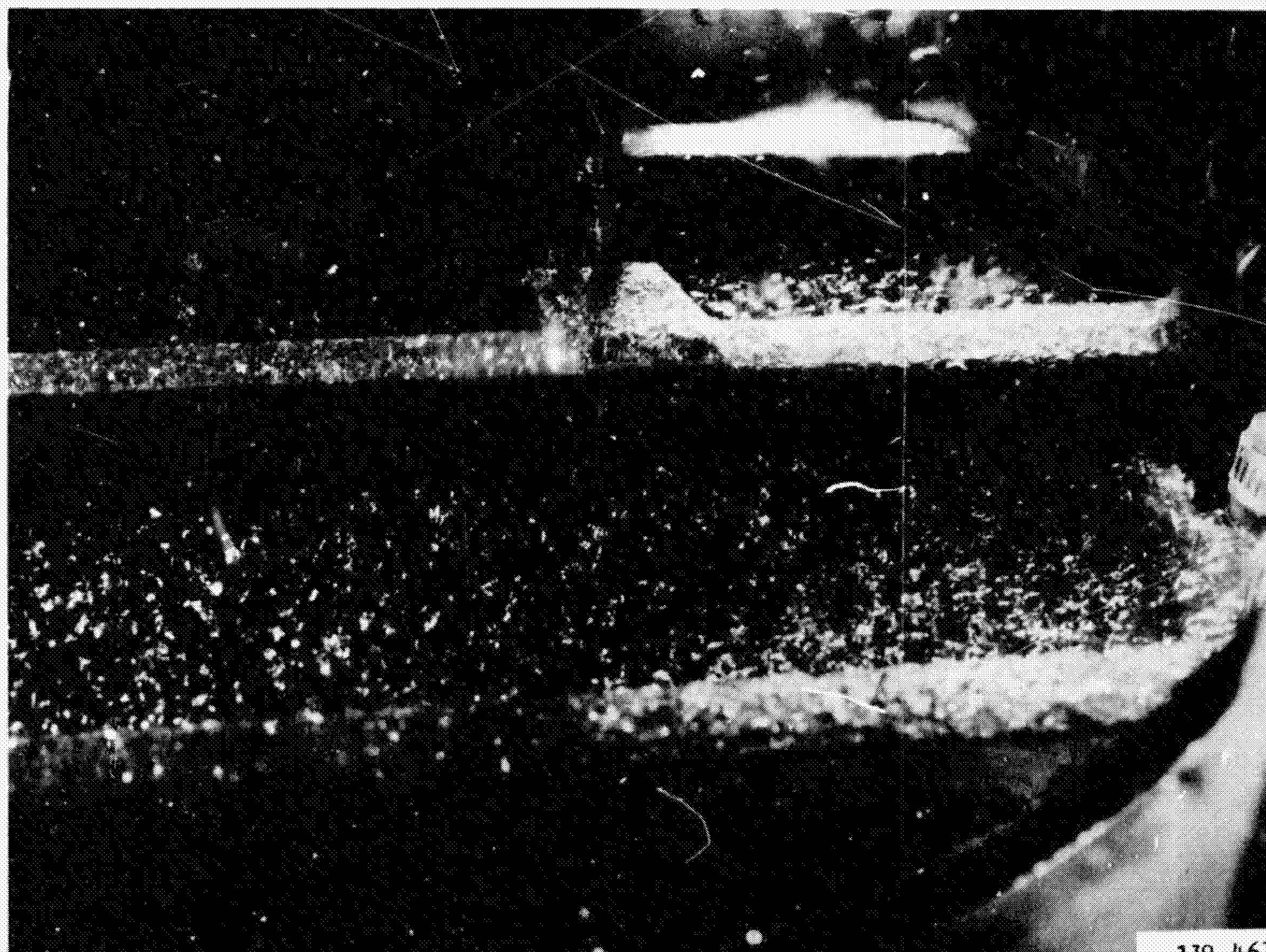

Figure - 47. Gravity Holdup of 4.3% at End of Test 53, Fuel Number 1.

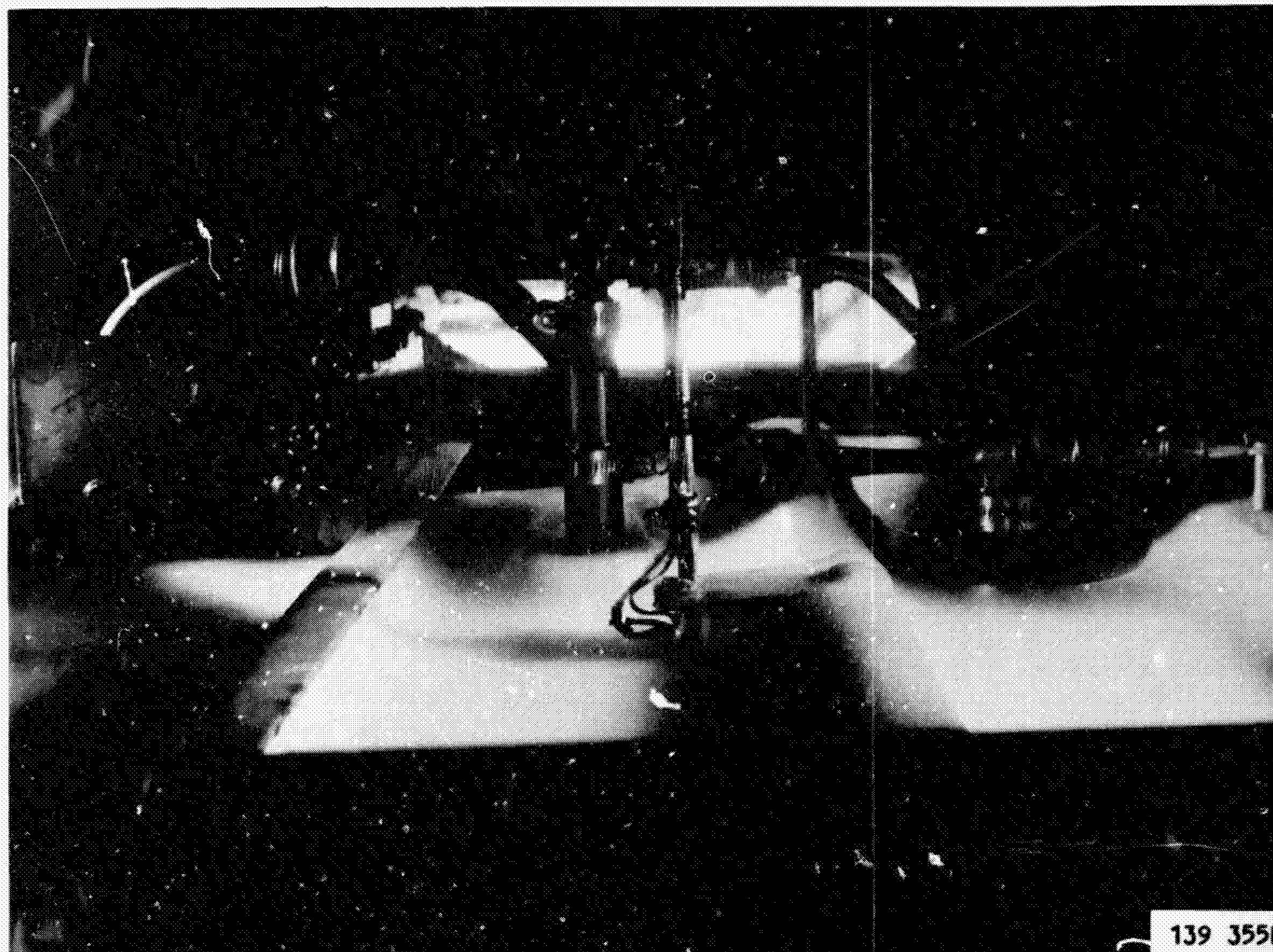

Figure - 48. Gravity Holdup of 4.5% at End of Test 45, LFP-7 Fuel.

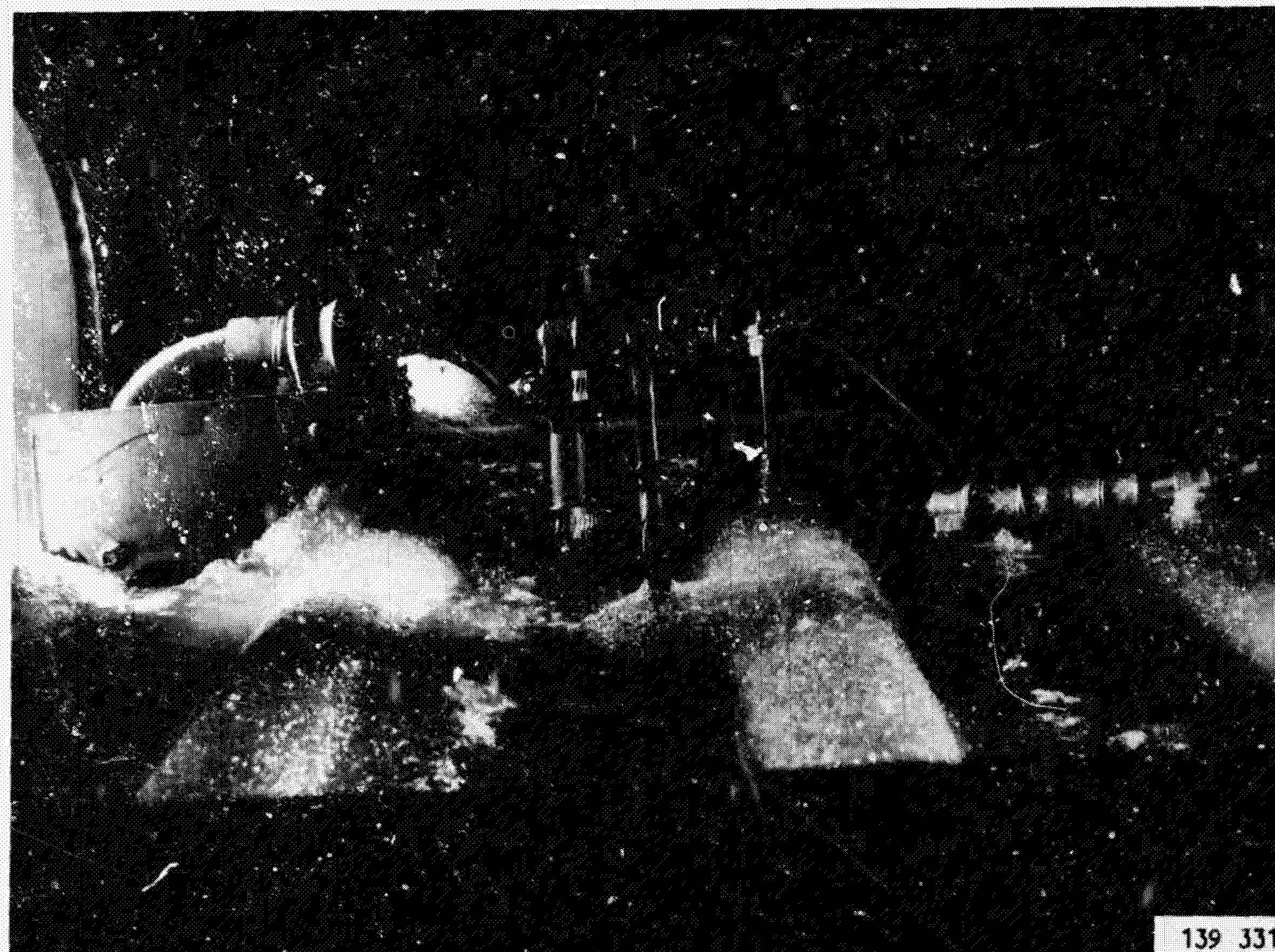

Figure - 49. Gravity Holdup of 8.8% at End of Test 41, LFP-6 Fuel.

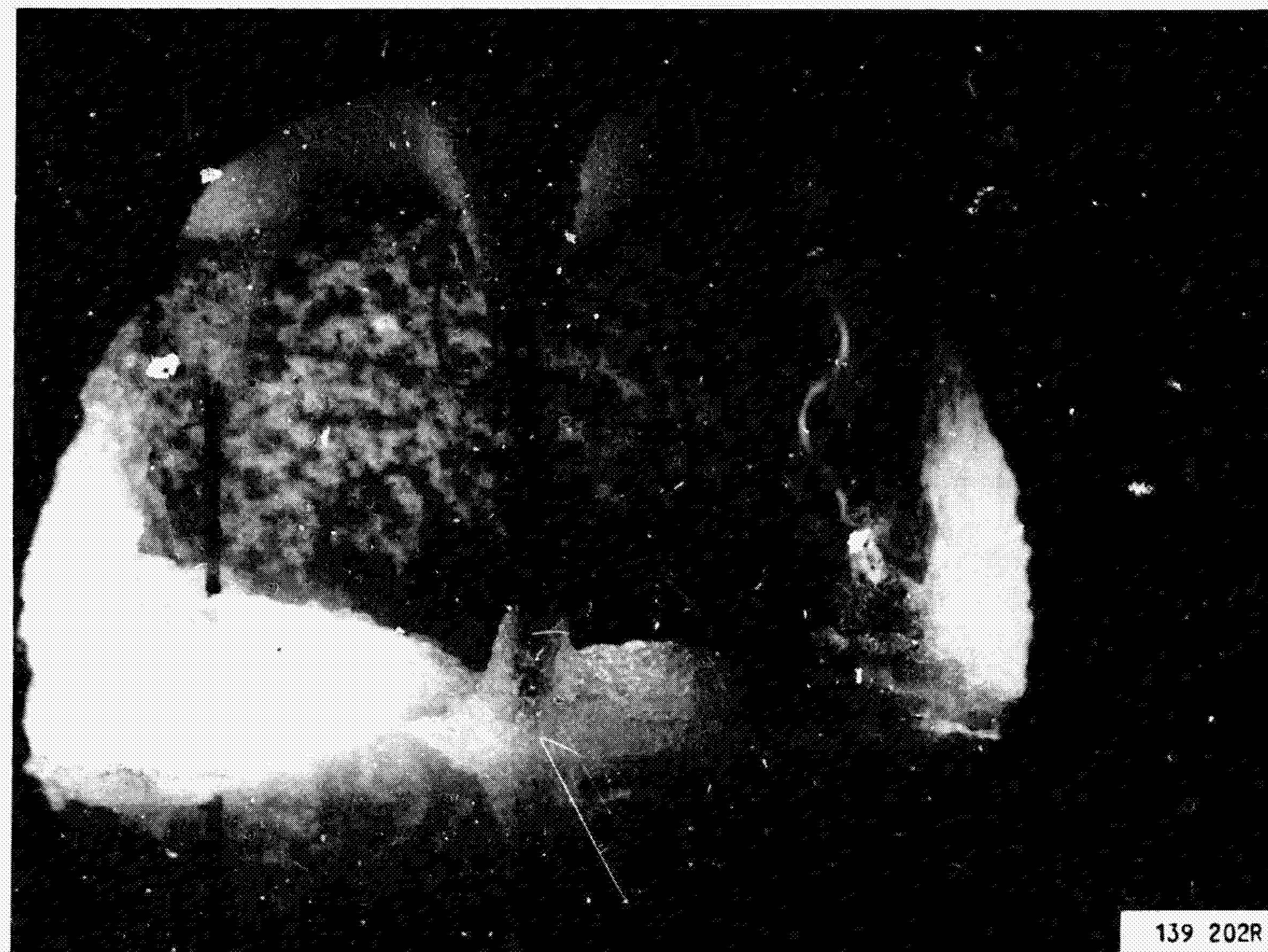

Figure - 50. Large Gravity Holdup at End of Test 36.

over the remainder of the tank. At about 60% holdup, approximately 36% was on the bottom and 24% on the top and sides. From these observations and the volume-height ratio of the tank, a plot of the height of bottom deposits against gravity holdup was developed (Figure 51).

A major objective of the analysis of temperature and visual observations is definition of the condition(s) at which gravity holdup initially occurs. One premise is that when gravity holdup occurs in conjunction with a temperature gradient, a line of demarcation could be the interface between the top of the solid deposition and the liquid above. Therefore, it is interesting to determine the apparent solid-liquid interface for each fuel. This was done by comparison of the measured gravity holdup with the calculated height of deposits (Figure 51) and the corresponding temperature at that height from the temperature profile (Figure 33 through 45). Table 5 summarizes the results of this analysis. For each fuel, the test numbers, gravity holdup, and estimated solid-liquid interface temperatures are shown. Mean temperatures are calculated for each fuel, excluding a few abnormal values, as noted in Table 5.

Table 6 compares the estimated interface temperatures with several other values for each fuel, taken from mean measurements shown in Appendix A. The comparison values include freezing point, pour point, and a cold flow temperature defined in Appendix B. The solid-liquid interface temperature lies between the freezing point and the pour point. The interface temperature measurement, however, is highly dependent on the temperature profile, and in turn on the chilling rate and apparatus configuration. Hence, the estimated interface temperatures reported here should not be considered as reproducible fuel characteristics without further analysis.

Another method of analysis is shown in Figure 52, where temperatures 1.2 centimeters above the bottom skin at the conclusion of each test are plotted against percent gravity holdup. The curves are extrapolated to zero holdup to define a freezing temperature. However, the freezing temperature obtained in the figure may be in error. This method of plotting gravity holdup against temperature has been used previously by other experimenters to determine low temperature fuel flowability in isothermal tests (Ref. 9 and 10). In the present study with temperature gradients, it appears that definition of a zero holdup temperature is difficult. Further analysis is required.

From the standpoint of aircraft operation, it should be noted that temperature probes transmitting "bulk fuel" temperatures to the cockpit are usually located 9 or more centimeters above the lower skin. There remains some concern that the fuel temperature indication may not provide adequate warning of the incipient formation of unusable solids during extreme low temperature conditions. For example, note the temperature profile for Test 72 (⊙) in Figure 45 for LFP-9 fuel, which meets commercial Jet A specifications. A wing tank thermocouple at 9 centimeters would indicate -28°C, well within operating margins with this fuel. However, the skin temperature and gradients, representative of extreme flight conditions, produced a gravity holdup of 1.2% unusable fuel. This quantity is less than the reserves and would melt during descent. This is evident by the results of the scheduled withdrawal tests where simulated

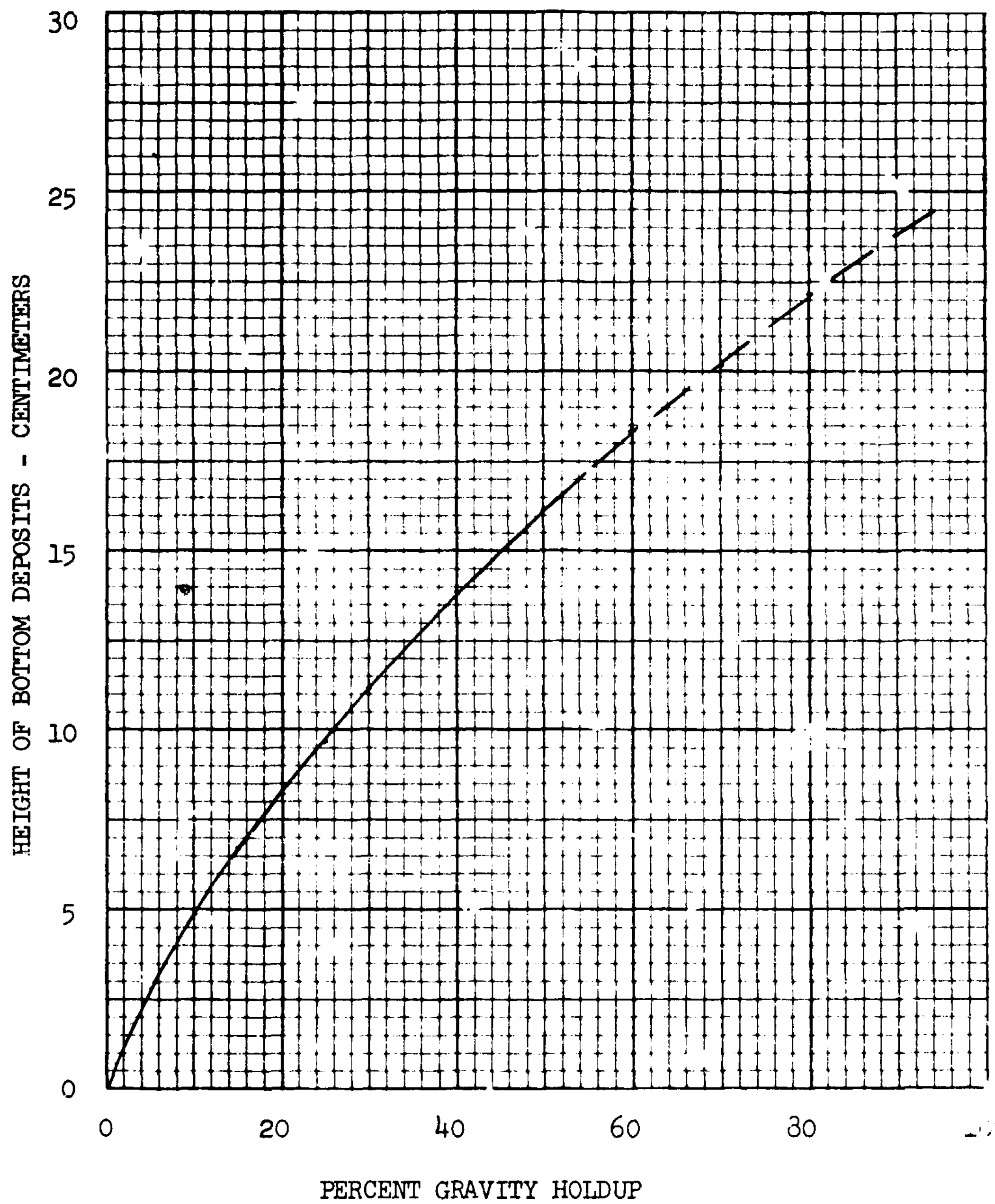

Figure - 51. Observed Height of Bottom Deposits

TABLE - 5. SUMMARY OF ESTIMATED SOLID/LIQUID INTERFACE TEMPERATURES (Sh. 1)

TEST NO.	°C	HOLDUP
FUEL No. 1		
6	-50	36.3%
10	-49	33.7%
11*	-54	21.9%
53	-46	4.3%
54	-44	2.6%
MEAN	-47.2	
FUEL No. 3		
12	-20	42.2%
14*	[illegible]	24.3%
15		70.1%
18	-28	76.8%
19	-22	68.1%
20	-23	13.5%
MEAN	-24.4	
FUEL No. 7		
99	-47	10.2%
100	-43	17.1%
MEAN	-45	

TEST NO.	°C	HOLDUP
FUEL No. 8		
78	-33	2.5%
79	-32	5.2%
80	-36	1.2%
81	-31	2.7%
82	-32.5	2.7%
95	-35	10.7%
MEAN	-33.2	
FUEL LFP-1		
31	-44.5	55.7%
34	-42.5	17.1%
36	-45	57.2%
55	-45	1.3%
56	-43	2.5%
57	-43	1.5%
58	-46	0.4%
59	-46	0.2%
60	-43.5	6.5%
85	-45	4.2%
MEAN	-44.4	
FUEL LFP-3		
50	-21.5	2.3%
51	-18.5	2.4%
52	-19	1.7%
MEAN	-19.7	

TABLE - 5. SUMMARY OF ESTIMATED SOLID/LIQUID INTERFACE TEMPERATURES (Sh. 2)

TEST NO.	°C	HOLDUP
FUEL LFP-4		
47	-21.5	2.1%
48	-24.5	1.1%
49	-21	1.7%
MEAN	-22.3	
FUEL LFP-5		
21	-36	16.7%
24	-32	19.3%
26	-29.5	27.1%
28	-33	20.8%
29*	-44	39.1%
67	-29	3.0%
68	-30	1.4%
69	-27	1.7%
70	-27	1.7%
71	-28	4.8%
77	-28.5	3.6%
86	-34	6.8%
97	-30.5	20.7%
98	-34.5	25.5%
MEAN	-30.6	
FUEL LFP-8		
88	-53	0.6%
90	-53	0.6%
91	-54	1.1%
92	-52.5	5.2%
96	-56	0.4%
MEAN	-53.7	

TEST NO.	°C	HOLDUP
FUEL LFP-6		
39	-32	56.1%
40	-34.5	21.3%
41	-37	8.8%
42	-33.5	6.6%
43	-30.5	5.2%
44	-30.5	5.2%
61	-33	1.1%
62	-33.5	0.7%
63	-29	1.5%
64	-34	0.6%
65	-30.5	0.3%
66	-31.5	1.0%
83	-31	4.6%
84	-28.5	10.7%
87	-34	41.2%
MEAN	-32.2	
FUEL LFP-7		
37**	-16.8	100%
45	-12	6.8%
46	-12	4.5%
MEAN	-12	
FUEL LFP-9		
72	-46	1.2%
73	-45	3.2%
74	-47.5	0.4%
75	-45.5	0.7%
76	-45.5	0.7%
MEAN	-45.9	

* Sloshing test, excluded from calculation of mean interface temperature.

** 100% holdup, excluded from calculation of mean interface temperature.

TABLE - 6. COMPARISON OF SOLID-LIQUID TEMPERATURES

CHARACTERISTIC	FUEL No. 1	FUEL No. 3	FUEL No. 7	FUEL No. 8	FUEL LFP-1	FUEL LFP-3	FUEL LFP-4	FUEL LFP-5	FUEL LFP-6	FUEL LFP-7	FUEL LFP-8	FUEL LFP-9
Average Freeze Point (from Appendix A)					-41	-17	-14	-28	-28	-10		-46
NASA Freeze Point	-38	-14	-31	-34	-42	-19	-16	-30	-29	-7	-52	-45
Shell Cold Flow Test, Zero Holdup					-43	-15	-24	-30	-30	-15		-45
Shell Pour Point					-47	-30	-37	-32	-36	-18		-48
Lockheed Pour Point	-52	-21	-46	-37	-51	-27	-26	-38	-38	-18	-53	-48
Solid/Liquid Interface	-47	-24	-45	-33	-44	-20	-22	-31	-32	-12	-54	-46

(All temperatures in °C)

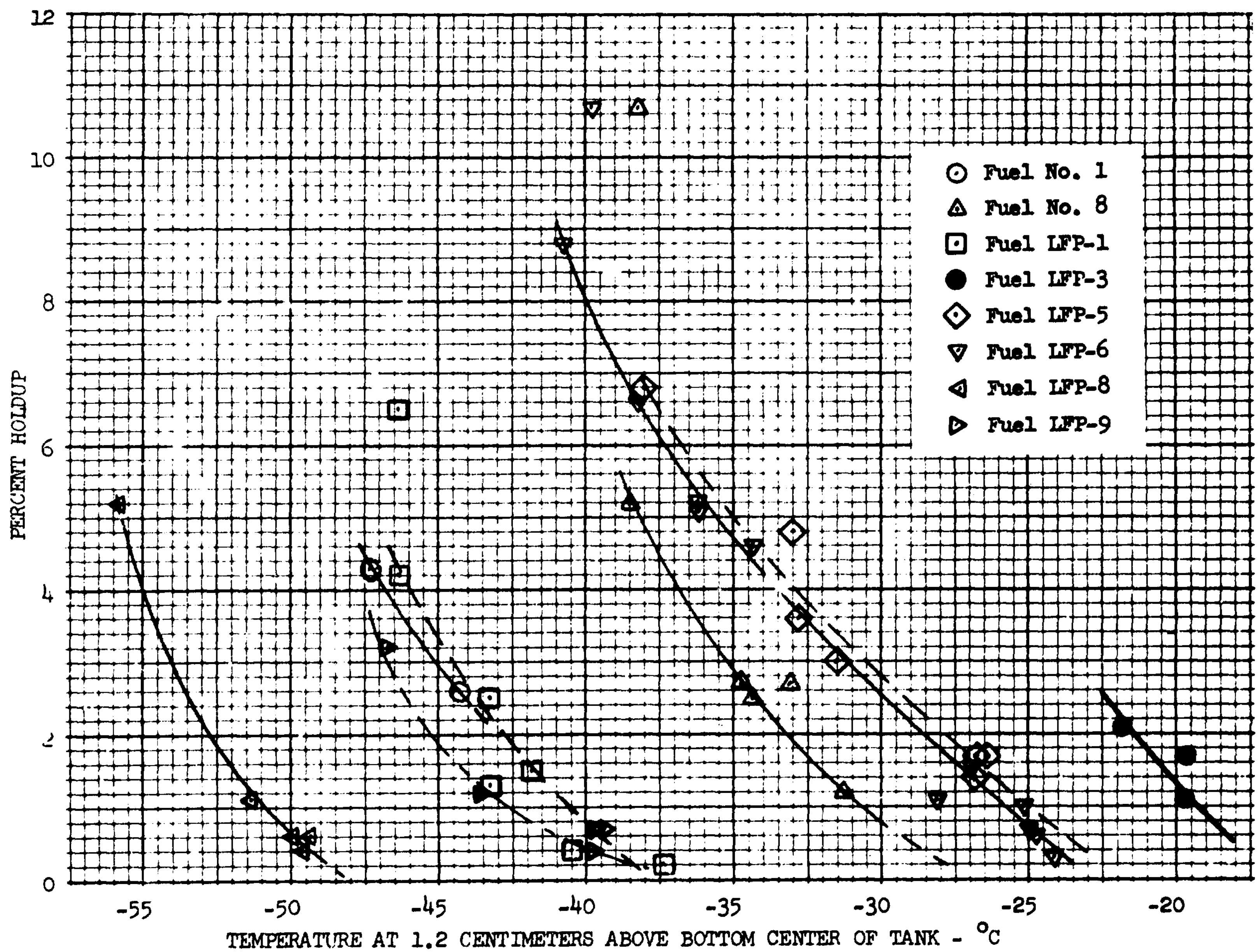

Figure - 52. Temperature at 1.2 Centimeters Above Bottom vs Percent Holdup extreme-condition flight temperature histories produced no holdup for the jet fuels LFP-8 and LFP-9, despite intermediate temperatures likely to cause some frozen fuel accumulation (see Figures 29 and 30).

In order to conserve the stock of the special fuels, after each test the test tank was allowed to warm and the frozen held-up fuel melted. This material was withdrawn from the tank and blended with the liquid fuel previously drained during the test, to reconstitute the original fuel. Laboratory freezing point tests were conducted to determine if fuel low-temperature behavior was altered by the freezing and melting history. These tests were performed on Fuel No. 7 and LFP-9 after they had been subjected to cold tests. The "before and after" values were 30.6°C and 29.8°C for Fuel No. 7, and 46.7°C and 46.1°C for LFP-9, indicating no significant change in that property as a results of testing.

8.0 CONCLUSIONS

Experimental tests were conducted with aviation fuels subjected to low temperatures in a test tank. The physical dimensions of the test tank represented a section of a wing tank of a wide-bodied commercial airplane, and chilling was such that internal temperature profiles were comparable to those encountered in flight. Twelve fuels were tested, including aviation turbine fuels and high boiling range fuels approaching Diesel fuel oils. Flowability of the fuels was determined by withdrawing the fuel from the test tank and measuring the gravity holdup, or unpumpable fuel remaining in the tank.

The following conclusions resulted from this investigation:

1. Low temperature liquid or two-phase fuel is readily withdrawn from the test tank by gravity. Suspended solids do not clog the pump screen and can be pumped readily. Holdup consists of an accumulation of solid deposits initially at the bottom of the tank. For several low-temperature conditions, resulting in a nominal 20% holdup or greater, flow to the pump was halted by blockage of the pump inlet surge box and its check valve. Solid fuel deposits would fall from the upper and vertical surfaces to contribute to this blockage.

2. At higher percentage holdups, there was visual evidence that liquid fuel was trapped in the matrix of solids which had formed. Manual sloshing of the tank to dislodge the solids released very little of the liquid. The holdup of a solid-liquid gel matrix appears to be a reproducible result.

3. On an airplane, a fuel temperature probe located 9 centimeters or higher above the bottom tank skin provides a good indication of bulk fuel temperature. However, the probe readout indicates a temperature higher than that of the fuel near the skin, which may be cold enough to form and accumulate solid particles. Tests were conducted at varying skin temperatures representing a long-range commercial flight at extreme winter conditions, with fuel withdrawal over a 3 hour period. Results of these scheduled withdrawal tests indicated holdup comparable to the static, rapid withdrawal tests. There is evidence, however, that solid fuel deposits may have occurred at the coldest time of the tests, and later melted when the skin temperature warmed near the end of the tests.

4. Most tests were conducted under static conditions with no disturbance of the natural convection within the tank. Tests with recirculation of fuel within the tank, sloshing, or internal fuel movement by ejectors had no direct effect on solid formation or pumpability. These dynamic actions did influence the chilldown rate and produced smoother temperature gradients than experienced with static tests. The change in temperature distribution with the recirculation and sloshing tests had an indirect influence on the time required for deposit formation.

5. Addition of a flow improving pour point depressant provided a significant reduction in gravity holdup of fuel for a given test condition. Results were in agreement with laboratory tests. The pour point depressant was added to only one fuel, a distillate with a higher temperature than commercial jet fuels.

6. Tests with a divider installed to represent a fuel tank baffle showed no difference from those without the divider, except that a sufficient depth of deposits could block the divider openings through which the tank stringers passed, and impede the flow of fuel to the tank outlet.

7. Dehydrating the fuel had no effect on the low temperature flowability, but eliminated a haze produced by condensation of dissolved water.

9.0 RECOMMENDATIONS

Based upon the low temperature tank tests conducted in this study, and the conclusions in the previous section, the following recommendations are made for future work:

1. A large amount of data was generated during this program. Further analyses of these data and comparisons with fuel properties may provide correlations of the low-temperature behavior.

2. For gravity holdup tests, avoid reducing skin temperature too far below the freeze point of the fuel; pour point may be a useful minimum. This should reduce the temperature gradient through the fuel, and improve accuracy in determining the temperature at which solid deposits begin to accumulate.

3. Similar tests in the future should investigate the effects of airplane vibration, and possibly sloshing, based on airplane experience.

4. Tests should investigate whether solid fuel holdup affects capacitance type fuel quantity gauging systems. If the dielectric constant of the fuel changes, capacitance will change and alter the quantity indication. It is even possible that a significant change in dielectric constant could lead to development of a gravity holdup warning device.

APPENDIX A

SUMMARY OF CRC DATA ON LOCKHEED TEST FUELS

INTRODUCTION

The CRC Group on Low Temperature Flow Performance of Aviation Turbine Fuels was formed with the following objectives in mind:

1. Review the proposed Lockheed studies (NASA Contract NAS3-20814) and recommended to NASA suggestions for test equipment design and operation that might be adopted without changing the scope of the contracted research.

2. Suggest test fuels for the research studies.

3. Conduct a variety of laboratory tests on the test fuels which might be used to describe low temperature handling characteristics.

TEST FUELS

The Group recommended and supplied nine of the test fuels used in Lockheed test program. These included eight fuels selected from widely different crude sources and with a range of freezing points. The ninth fuel was one fuel containing a flow improver.

Table I provides a brief description of the eight base fuels. Three of the fuels (LFP-4, 6, and 8) were from predominately naphthenic crudes, and five were from paraffinic crudes. Two fuels (LFP-1 and 9) were production Jet A with freeze points near the specification limit of -40°C. Five (LFP-3-7) were refinery streams or No. 2 diesel fuels with freeze points in the range of -10°C to -30°C. Fuel LFP-8 was a Jet A blending stock with a freeze point of -50°C.

It was desired to provide one test fuel for test by Lockheed containing a flow improver. Base Fuels LFP-5 and LFP-6 were considered as the best candidates for this study because they had freeze points higher than -40°C, the specification limit for Jet A. The objective was to select an additive that would decrease the ASTM pour point to -40°C from the -31°C pour point of the base fuels.

Two commercial additives were evaluated in each fuel, and the results are presented in Table II. As a result of these data, it was recommended to NASA that a suitable pour-depressed fuel would be Fuel LFP-5 containing 0.1 wt % of Paradyne 25. This additive-containing fuel was identified as Fuel No. 7.

LOW TEMPERATURE INSPECTION TESTS

Standard inspection tests were made by NASA on all Lockheed test fuels and are presented in Table III.

TABLE I

GENERAL DESCRIPTION OF TEST FUELS

LFP-1	Jet A--At time of manufacture, crude run was 59% Indonesian and 41% Persian Gulf crude. Both of these crudes are considered paraffinic in nature.
LFP-7	An intermediate refinery stream having properties similar to a No. 2 diesel fuel. Crude source is the same as for LFP-1.
LFP-9	Jet A--Produced from a crude mix approximated at 90% Arabian Light and 10% Iranian Light.
LFP-5	A diesel fuel produced from North Louisiana and other domestic crudes. These crudes are considered paraffinic in nature.
LFP-3	An intermediate refinery stream having properties similar to a No. 2 diesel fuel. Crude source was 100% Arabian Light. This product is from almost the same crude as LFP-9.
LFP-4	A No. 2 diesel fuel produced from 100% mixed California valley crudes. These crudes are considered naphthenic.
LFP-6	An intermediate refinery stream used as a diesel fuel blending stock. Crude sources were 90% Alaskan North Slope, 9% California, and 2% miscellaneous. These are considered naphthenic crudes.
LFP-8	An intermediate treated refinery stream used for manufacture of Jet A. Same crude mix as LFP-6.

Table II

RESPONSE OF AVIATION TURBINE FUELS TO POUR DEPRESSANT ADDITIVES

Additive Conc., Wt. %	LFP-5 ASTM Pour Point, °C ECA 7305	LFP-5 ASTM Pour Point, °C PARADYNE 25	LFP-6 ASTM Pour Point, °C ECA 7305	LFP-6 ASTM Pour Point, °C PARADYNE 25
0	-31	-31	-31	-31
0.02	-31	-31	-31	-31
0.04	-31	-40	-36	-31
0.06	-40	-40	-31	-31
0.08	-40	-40	-31	-31
0.10	-45	-40/-48	-31	-31
0.12	-51	-45		
0.14	-51	-48		

Table III

LOCKHEED FUEL CHARACTERIZATIONS

NASA LEWIS RESEARCH CENTER

DISTILLATION, °F	#1-Jet A	#3-D2	#7-(LFP-5)	#8 (JP-5 SHALE)	LFP-1	LFP-3	LFP-4	LFP-5	LFP-6	LFP-7	LFP-8	LFP-9
I.B.P.	305	370	338	312	288	350	361	345	324	314	270	310
5%	348	.425	398	353	330	409	396	396	404	374	329	360
10%	360	446	416	368	344	426	419	416	430	398	352	369
20%	374	471	440	381	362	455	436	441	454	433	386	379
30%	389	491	454	395	380	474	453	458	468	454	400	[illegible]
40%	403	508	469	406	395	490	472	471	478	474	411	400
50%	420	522	484	417	416	502	494	484	485	490	420	410
60%	433	538	496	430	424	516	516	494	493	507	428	418
70%	450	558	501	444	437	529	542	506	502	520	439	430
80%	468	579	516	460	450	544	570	518	511	538	449	442
90%	491	608	534	472	459	566	607	537	520	567	461	460
F.B.P.	530	631	561	476	460	582	624	566	541	591	461***	504
SP. G, 60/60	.8132	.8612	.8294	.8029	.8017	.8285	.8545	.8299	.8478	.8251	.8273	.8001
Freezing Pt., °C	-38	-14	$-31^{o} \pm 2^{o}$	$-34^{o} \pm 2^{o}$	-42	-19	-16	-30	-29	-7	**$<-52^{o} \pm 2^{o}$	-45
Pour Pt., °C	<-48	-26	*$<-48^{o} \pm 2^{o}$	$-38^{o} \pm 2^{o}$	-50	-33	-42	-35	<-38	-17	**$<-52^{o} \pm 2^{o}$	<-48
Saturates, Vol. %	81.6	55.7	81.5	75.8	78.9	81.1	83.5	82.4	67.3	81.5	76.3	82.2
Olefins, Vol. %	0.5	5.6	0.6	1.1	0.	0.9	0.8	0.8	1.0	0.6	0.5	0.6
Aromatics, Vol. %	17.9	38.7	18.4	23.1	20.4	18.5	15.8	16.7	31.8	17.9	23.0	17.2
Viscosity at -10°F, CS	6.5	32	3.25	1.92	5.9	17.6	24	15.5	16.5	20	1.97	6.7

* Temperature would go no lower than $-48^{o} \pm 2^{o}C$

**Could not bring sample to freezing point or pour point. Temperature would go no lower than $-52^{o} \pm 2^{o}C$

*** Highest Temperature Reached

Additional inspections were made on only seven of the eight CRC-supplied base fuels. LFP-8 was not supplied until late in the test program and, hence, not included in all of the special tests made.

Table IV presents all data submitted on standard tests, such as freeze point, cloud point, and pour point. Also shown are special low temperature tests that have been used predominately to demonstrate performance of diesel fuel and/or flow improvers. One test, the Shell Cold Flow Tester, was developed specifically to determine the extent to which aviation turbine fuels would flow under gravity low temperature conditions. A brief description of the nonstandard tests referred to in Table IV is provided in Appendix B.

Brookfield viscometer tests were made over a wide temperature range and are shown in Table V. Although two ASTM methods have been written around this viscometer, neither D 2669 (apparent viscosity of hot melts) nor D 2983 (apparent viscosity of gear oils at low temperatures) is suitable for fuels. In both methods, the fluid is brought to an equilibrium temperature; the viscometer is started; and an equilibrium temperature/apparent viscosity is obtained. For such results to be valid, the fluid has to be a single phase. In the case of a two-phase system which is changing at constant temperature — as crystalization continues — it is not possible to obtain a significant result. Also, if the fuel is cooled significantly below the freezing point, is held at that temperature, and the viscometer is then started, the resultant viscosity tends to be a breakaway torque rather than an apparent viscosity.

The following approach was, therefore, taken. Two fuel samples were placed into pour point vials and then into a pour point bath. One vial contained a No. 1 spindle of the Brookfield viscometer, the other a thermometer. (It was not readily possible to measure the temperature in the vial where viscosity was measured.) The viscometer was run continuously as the fuel temperature dropped, and readings were taken at the indicated temperatures. As viscosity increased, the viscometer speed had to be decreased to stay within the scale of the instrument. Viscosities, therefore, could not be run at a single shear rate for a given fuel.

There are a number of limitations to these results. The constant stirring quite likely had an effect on wax crystalization. The temperature in the two vials possibly differed slightly because of the small heat input due to stirring. While an average shear rate can be calculated, its significance is dubious because of the relatively large clearance between the viscometer rotor and the inside surface of the vial. Lastly, the technique described is not a standard technique; and its significance for two-phase systems has not been established.

Hydrocarbon composition was measured by mass spectrometer and gas chromatography. The latter was used to identify the amount of n-Alkanes. The results of two investigations are presented in Tables VI and VII.

TABLE IV

SUMMARY OF SPECIAL LOW TEMPERATURE TESTS

	LFP-1	LFP-3	LFP-4	LFP-5	LFP-6	LFP-7	LFP-9	Ref.*
Freeze Point, °C (D 2386)	-40	-15	-11	-26	-27	-9	-43	(1)
	-40	-15	-12	-27	-26.5	-11	-49	(2)
	-41	-17	-17	-28	-31	-11	-46	(4)
	-42	-19	-16	-30	-29	-7	-46	(5)
	-41 (8)	-17 (6)		-28 (7)			-46 (6)	
Pour Point, °C	-46	-26	-26	-34	-37	-18	-51	(1)
				-31	-31			(3)
	-43	-21	-21	-32	-34	-15	-46	(4)
	-50	-33	-42	-35	-38	-17	-48	(5)
		-20 (6)				-15 (8)		
Cloud Point, °C	-41	-21	-14	-31	-32	-12	-47	(1)
	-44	-20	-16	-30	-31	-12	-4[illegible]	(4)
		-15 (6)				-11 (8)		
Cold Flow Zero Holdup	-43	-15	-24	-30	-30	-15	-45	(2)
Shell Cloud/Pour Analyzer								
TXP, °C	-37	-15	-	-24	-27	-11	-36	(2)
TSP, °C	-47	-30	-37	-32	-36	-18	-48	(2)
Setapoint Detector, °C	-42	-19	-18	-30	-30	-15	-45.5	(2)
Enjay Fluidity Test	-40	-18	-20	-29	-2[illegible]	-16	-43	(4)
Cold Filter Plugging Point Test	-47	-22	-16	-32	-34	-16	-52	(4)

*Numbers in () refer to data source:
(1) Ltr, CJNowak-JABert, 4-3-79
(2) Ltr, RTHolmes -JABert, 3-23-79
(3) Ltr, RLElliot-FJStockemer, 11-27-78
(4) Ltr, RLElliot-JABert, 11-22-78
(5) Ltr, RFriedman-JABert, 4-24-79
(6) Ltrs, WASutton-CRC Group, 6-5-78 and 6-2-78
(7) Ltr, WGDukek-CRC Group, 6-27-78
(8) Ltr, KHStrauss-FJStockemer, 6-1-78

Table V

BROOKFIELD VISCOMETER MEASUREMENTS OF LOCKHEED FUELS

PART 1

LFP-1

TEMP. °C	c'poise	c'stoke
15.5	9.6	12.0
10	10.8	13.4
4.5	12.6	15.6
- 1	13.	16.2
- 6.5	16.1	19.7
-12	17.6	21.4
-18	19.6	23.7
-23.5	21.1	25.4
-29	23.8	28.5
-34.5	25.6	30.5
-37	33.6	40.0
-39	43.1	51.2
-40	71.2	84.6
-41	113	134
-42	193	229
-43.5	450	533
-44.5	1800	2128

LFP-3

TEMP. °C	cp.	cs.
15.5	9.1	11.0
10	9.1	11.0
4.5	9.1	10.9
- 1	9.1	10.8
- 6.5	10.1	12.0
-12	11.1	13.1
-15	12.1	14.2
-18	13.2	15.5
-20.5	14.1	16.5
-23.5	24.2	28.2
-24.5	33.3	38.9
-25.5	55.2	64.3
-26.5	89	104
-27	117	136
-28	184	213
-28.5	275	319
-29	475	551
-29.5	593	688

LFP-4

TEMP. °C	cp.	cs.
15.5	7.1	8.3
10	7.9	9.2
4.5	8.6	10.0
- 1	9.6	11.1
- 6.5	10.9	12.5
-12	13.1	15.0
-18	15.8	18.0
-20.5	18.8	21.3
-23.5	39.6	44.8
-25.5	69.0	77.9
-26	80.2	90.5
-26.5	94.0	106
-28	133	150
-28.5	164	184
-29	255	287
-29.5	384	432
-30	450	506
-30.5	605	679
-31	706	792
-31.5	828	929
-32	981	1101
-33	1280	1437
-33.5	1780	1993

LFP-5

TEMP. °C	cp.	cs.
15.5	7.3	8.8
10	7.6	9.1
4.5	10.5	12.5
- 1	11.4	13.5
- 6.5	12.3	14.5
-12	13.8	16.2
-18	16.0	18.7
-23.5	18.6	21.7
-26	20.5	23.8
-29	25.6	29.7
-30	29.3	[illegible]
-31	31.0	35
-32	34.0	39.3
-33.5	37.2	42.9
34.5	43.0	49.5
-35.5	61.0	70.3
-36	85.0	97.8
-36.5	123	142
-37	173	199
-38	259	298
-38.5	356	410
-39	680	781
-39.5	845	970

LFP-5 + 0.1% Paradyne

TEMP. °C	cp.	cs.
15.5	6.1	7.3
10	6.1	7.3
4.5	6.8	8.1
- 1	7.9	9.4
- 6.5	9.1	10.7
-12	10.7	12.6
-18	13.1	15.3
[illegible]	[illegible]	19.1
-29	20.4	23.6
33.5	36.7	42.3
-35	46.4	53.4
-36.5	57.6	66.1
-38	64.1	73.7
-39	69.1	79.2
-40	75.2	86.2
-40.5	83.1	95.3
-41	99.6	114
-41.5	130	149
-42	176	201
-43	244	279
-43.5	310	354
-44	350	400
-44.5	408	466
-45.5	510	582
-46.5	550	628
-49	640	729

C-2

Table V

BROOKFIELD VISCOMETER MEASUREMENTS OF LOCKHEED FUELS

PART 2

LFP-6

TEMP. °C	cp.	cs.
15.5	6.4	7.5
10	6.4	7.5
4.5	7.1	8.3
- 1	8.0	9.3
- 6.5	9.2	10.6
-12	11.0	12.7
-18	13.1	15.0
-23.5	15.7	17.9
-26	18.1	20.6
-29	20.1	22.8
-31	21.6	24.4
-32	22.6	25.6
-33	128	145
-33.5	238	269
-34	278	314
-34.5	475	536
-35	615	694
-35.5	705	796
-36	1550	1745

LFP-7

TEMP. °C	cp.	cs.
15.5	6.7	8.1
10	9.5	11.5
4.5	15.1	18.1
- 1	17.6	21 0
- 4	19.4	23.1
- 6.5	22.8	27.1
- 9.5	35.1	41.6
-12	59.1	69.9
-14	405	478
-14.5	1000	1179
-15	1920	2264

LFP-9

TEMP. °C	cp.	cs.
15.5	7.1	8.9
10	7.8	9.7
4.5	8.1	10.0
- 1	8.1	10.0
- 6.5	8.1	9.9
-12	8.1	9.9
-18	8.2	10.0
-23.5	10.1	12.2
-29	11.3	13.6
-34.5	13.3	15.9
-40	15.4	18.3
-45.5	18.1	21.4
-46	23.1	27.4
-46.5	33.1	39.2
-47	40.7	48.1
-48	46.7	55.2
-48.5	80.7	95.4
-49.5	116.6	138
-50	173	204
-51	330	389
-52	442	521
-53.5	860	1012

Fuel-8 Shale

TEMP. °C	cp.	cs.
15.5	6.8	8.4
10	7.6	9.4
4.5	8.1	10.0
- 1	8.7	10.6
- 6.5	9.5	11.6
-12	10.6	12.8
-18	13.3	15.6
-23.5	15.1	18.1
-29	20.6	24.6
-31.5	24.7	29.4
-33.5	27.1	32.2
-34.5	34.4	40.9
-35.5	36.6	43.5
-37	44.6	52.9
-39	170	201
-39.5	360	426

LFP-8 JET A

TEMP. °C	cp.	cs.
15.5	9.0	10.9
10	9.0	10.8
4.5	9.7	11.6
- 1	11.1	13.2
- 6.5	12.4	14.7
-12	14.3	16.8
-18	16.2	19.0
-23	18.2	21.2
-29	21.9	25.4
-34.5	26.7	30.8
-40	31.6	36.3
-45.5	61.7	70.5
-48	79.0	90.3
-49.5	160	183
-50	270	308
-50.5	395	450
-51	716	815
-51.5	990	1128

Table VI

n-Alkanes in Jet Fuels*

n-Alkane	LFP-1 Jet A	LFP-3 Distillate (Paraffinic)	LFP-4 Distillate (Naphthenic)	LFP-5 Intermediate (Paraffinic)	LFP-6 Intermediate (Naphthenic)	LFP-7 Distillate (Paraffinic)	LFP-9 Jet A
C-8	.58	.01	.01	.08	.08	.21	.16
C-9	1.62	.24	.05	.22	.15	.47	.86
C-10	3.08	.57	.18	.56	.32	1.02	2.56
C-11	4.61	1.06	1.14	1.07	.56	1.51	4.49
C-12	5.78	1.64	.98	1.91	.93	1.70	5.16
C-13	5.41	2.36	1.07	2.47	1.77	2.35	4.23
C-14	2.82	2.76	.85	2.31	2.37	2.89	2.07
C-15	1.19	2.93	.89	2.42	2.80	3.01	.70
C-16	.51	2.37	.87	1.51	1.83	2.35	.20
C-17	.27	1.95	.86	.82	1.06	1.81	.07
C-18	.16	1.32	.73	.38	.37	1.11	.04
C-19	< .01	.77	.57	.13	.09	.64	< .01
C-20	< .01	.31	.37	.06	.09	.33	< .01
C-21	-	-	.19	-	-	.16	-
Total	26.03	18.38	8.76	13.94	12.42	19.56	20.56

* - Analytical precision was ± 5.6 percent.

TABLE VII

LIQUID VOLUME PERCENT OF HYDROCARBONS IN TEST FUELS

Hydrocarbon Class	LFP-1	LFP-3	LFP-4	LFP-5	LFP-6	LFP-7	LFP-9
Paraffins	46.8	46.1	25.3	36.6	27.7	45.6	46.9
Cycloparaffins	17.7	16.3	22.6	21.1	20.9	16.3	20.4
Dicycloparaffins	11.4	8.9	19.6	13.1	15.8	12.2	9.6
Tricycloparaffins	4.5	9.0	13.7	12.0	12.0	9.3	2.8
Alkylbenzenes	12.6	9.2	4.5	6.6	6.6	6.3	14.0
Indans/Tetralins	6.5	4.6	6.8	4.1	6.4	5.4	6.0
Benzodicycloparaffins	0.4	1.4	1.9	1.5	2.2	1.3	0.3
Naphthalenes	0.1	4.0	4.9	4.4	7.5	3.3	0
Benzoindans/Bensotetralins	0	0.5	0.7	0.6	0.9	0.3	0
<u>Paraffins Breakdown</u>							
Iso C_8	0.57						
nC_8	0.15						
Iso C_9	3.19					0.47	0.74
nC_9	1.95					0.04	
Iso C_{10}	8.48	1.07	0.64			3.04	8.59
nC_{10}	3.51	0.97	0.07			1.86	2.55
Iso C_{11}	11.58	2.38	13.47	4.75	0.69	3.41	15.03
nC_{11}	7.02	2.67	3.44	2.91	0.53	4.15	6.01
Iso C_{12}	14.71	3.94	17.34	6.47	3.34	2.47	20.14
nC_{12}	8.35	4.32	2.67	6.58	1.09	4.38	6.86
Iso C_{13}	16.56	7.20	19.70	13.69	11.16	5.95	19.53
nC_{13}	8.07	6.76	2.74	9.60	2.29	6.86	5.79
Iso C_{14}	8.27	9.50	11.42	11.21	19.54	9.16	9.68
nC_{14}	4.36	9.62	4.90	13.62	3.89	11.23	3.52
Iso C_{15}	1.36	6.45	5.51	6.94	24.68	6.21	0.35
nC_{15}	1.54	9.56	3.18	7.76	4.07	11.16	0.94
Iso C_{16}	-	4.32	0.59	3.34	19.11	2.79	0.05
nC_{16}	0.34	8.37	2.58	6.06	3.27	8.84	0.24
Iso C_{17}		5.21	2.64	2.41	5.43	2.91	
nC_{17}		6.83	3.90	3.98	0.91	8.43	
Iso C_{18}		4.42	1.71	-		0.96	
nC_{18}		4.82	2.50	0.69		3.85	
Iso C_{19}		-	-			-	
nC_{19}		1.58	0.75			1.68	
nC_{20}			0.27				

APPENDIX B

BRIEF DESCRIPTION OF SPECIAL LOW TEMPERATURE TESTS

SHELL CLOUD/POUR ANALYZER

This is an automatic instrument that measures the thermal crystal point (TXP) or temperature at which wax is initially separated during controlled cooling. This temperature is detected by thermal analysis. The instrument also measures a solid point (TSP) by a falling-ball technique. Experience has indicated that the TXP and TSP predict cloud and pour point, respectively.

SHELL COLD FLOW TEST

The tester is comprised of two fuel compartments, separated by a poppet valve. A measured volume of fuel is placed in the upper compartment of the tester and cooled to the test temperature. The poppet valve is then opened for a fixed time and the amount of fuel drained to the lower compartment measured. The test is repeated at different test temperatures to establish the minimum temperature at which all fuel will drain from the top to bottom compartments of the tester. Complete test details are given in the Journal of the Institute of Petroleum, November 1962.

COLD FILTER PLUGGING POINT TEST (CFPP)

The test sample (45 cm^3) is cooled at a rate of 40°C per hour to the desired test temperature. At intervals of 1°C, a vacuum of 200 mm water gauge is applied to draw the fuel through a 45-micron wire mesh filter. The CFPP is defined as the highest temperature at which the fuel will not flow through the filter or require more than 60 seconds for passage of 20 cm^3 of fuel.

THE ENJAY FLUIDITY TEST (EFT)

The fluidity tester consists of two graduated transparent-plastic cylinders (3.8 mm in diameter) which are screwed together to form two compartments with an interconnecting brass capillary (2.54 mm in diameter). A fuel sample of 40 ml is placed in the lower compartment and cooled in a cold temperature bath at 4°F per hour to the test temperature. The tester is inverted and the volume of fuel recovered in the lower compartment after three minutes is measured. This procedure is repeated at several test temperatures to determine the temperature at which 80 vol % is recovered in the lower compartment.

SETAPOINT DETECTOR

This instrument is designed to predict the freezing point of aviation turbine fuel. About 6 ml of fuel is contained in a sample chamber bored into the center of an aluminum block with an illuminated viewing window. The fuel is circulated at 1 ml per second at 10 mm Hg pressure through a 400-mesh (33 microns), stainless steel filter. The aluminum block temperature is controlled by compressor refrigeration and thermoelectric cooling. The temperature at which either the filter plugs or when the first crystal is observed can be used to define low temperature operating limits.

APPENDIX C

CHRONOLOGICAL SUMMARY OF TESTS

This Appendix provides an itemized summary of the tests performed during this program, including fuel identification, type of test, percent holdup, and total test time, arranged in chronological order. In compliance with the system for maintaining data acquisition records, a test number was assigned for each test, or for each day's effort when pre-cooling of the fuel was performed. These preparatory procedures, as well as several aborted tests, are indicated by dashes in the "Type of Test" columns, as well as by explanations under "Remarks". After allowing for two checkout tests, three aborted tests, and ten pre-coolings, the net result was a total of 85 completed tests.

Number in the "Data Ref. No." column identify Lockheed-California Co. Research Laboratory records. All other items are self-explanatory.

CHRONOLOGICAL SUMMARY OF TESTS

Sheet 1 of 6

Test No.	Date	Fuel Identif. No.	Fuel Type	Static	Recircu-lation	Sloshing	Ejectors	Divider	Dry Fuel	Sched. W'drawal	% Holdup	Total Test Time-Min.	Photos / Movies	Remarks	Data Ref. No.
1	(1978) 5-26	No. 1	Jet A	X								--		System checkout. Did not record on tape.	-
2	5-30	No. 1	Jet A	X								--		System checkout. Fuel clear at start, "Fog" appeared at about 15 min.	3322
3	6-1	No. 1	Jet A	X								315	P	Normal cooldown. Large temperature gradient lower 10 cm skin to -51°C	3380
4	6-2	No. 1	Jet A		X							351		Flowmeters not quite agreeing. Skin to -48.5°C. Temperature gradient less	3417
5	6-7	No. 1	Jet A		X							450		Double filtered fuel. Cooling similar to Test 4. Skin to -55°C.	3483
6	6-8	No. 1	Jet A	X	P						36.3	381		Periodic circulation, early part of test skin to -74°C, center -45°C.	3523
7	6-12	No. 1	Jet A			-						--		Tried sloshing with tank 1/2 full. Aborted test because of methanol leak	-
8	6-13	No. 1	Jet A			X						420		Tank 1/2 full. Slosh only at 40 cycles/min. Skin to -55°C. Fuel milky-white.	3574
9	6-20	No. 1	Jet A	-								240		Aborted test when CO_2 was inadvertently depleted.	3616
10	6-22	No. 1	Jet A	X	P						33.7	420	P / M	Periodic circulation, skin to almost -69°C, center -46°C, solids on walls.	3682
11	6-23	No. 1	Jet A			X					21.9	403	P / M	Skin below -72°C. Solids on walls, some appears "foamy".	3695
12	6-27	No. 3	D-2	X							42.2	420	P	Dark colored fuel. Skin to -44°C. Reddish brown slush on walls and stringers	3720
13	6-28	No. 3	D-2		X							410		Skin to -43.7°C, center to -11°C. Did not pump out - appeared fairly liquid.	3748
14	6-29	No. 3	D-2			X					24.3	390	M	Tank 1/2 full. Slosh only at 39 cycles/min. check valve opens. Slow pumpout	3771
15	6-30	No. 3	D-2	X		F					70.1	420		Tank 1/2 full. Slosh until center at -14°C Final skin to -44.8°C, center -31.9°C	[illegible]
16	7-5	No. 3	D-2	-		-						414		Pre-cooling for Test 18. Periodic sloshing. Full tank.	3785
17	7-6	No. 3	D-2	-		-						480		Pre-cooling for Test 18. Periodic sloshing. Full tank.	3794

CHRONOLOGICAL SUMMARY OF TESTS

Sheet 2 of 6

Test No.	Date	Fuel Identif. No.	Fuel Type	Static	Recircu-lation	Sloshing	Ejectors	Divider	Dry Fuel	Sched. W'drawal	% Holdup	Total Test Time-Min.	Photos / Movies	Remarks	Data Ref. No.
18	(1978) 7-7	No. 3	D-2	X							76.8	390		Skin at -60°C. Center at -28°C at end of test. Warmed, holdup 71.3%	3802
19	7-12	No. 3	D-2	X							68.4	360		Skin at -60°C. Center at -19.5°C at end of test. Solids top and bottom, liquid	3824
														came from center. Warming reduced holdup to 36.6%, then to 24.6%.	-
20	7-13	No. 3	D-2		X		X				13.5	438		Skin at -46.5°C. Center at -13°C at end of test. Solids on walls, top, bottom	3827
21	7-17	LFP-5	Interm.	X							16.7	443		Fuel "water white", but dark in tank. Skin -47.2°C, center -29.2°C at finish.	3871
22	7-18	LFP-5	Interm.		-		-					461		Pre-cooling for Test 24. Attempt to reduce temperature gradient.	3888
23	7-19	LFP-5	Interm.		-		-					420		Pre-cooling for Test 24. Skin -55°C, center -25.5°C	3924
24	7-20	LFP-5	Interm.		X		X				19.3	419		Skin -65°C, center -27°C at end of test. Deposits all surfaces, ch. valve closed.	3958
25	7-24	LFP-5	Interm.		-		-					402		Pre-cooling for Test 26. Slosh rate 38 cycles/min. Skin -53°C, center -29°C.	4012
26	7-25	LFP-5	Interm.		X	X					27.1	420		Slosh rate 38 cycles/min. Full tank. Skin -59°C, center -28.7°C at end of test.	4061
27	7-26	LFP-5	Interm.		-							394		Pre-cooling for Test 28	4077
28	7-27	LFP-5	Interm.		X						20.8	444		Skin -60°C, center -26°C at end of test. Deposits all surfaces, ch. valve closed.	4106
29	7-28	LFP-5	Interm.			X					39.1	420		Tank 1/2 full. Obvious thickening of fuel Skin -53.9°C at end of test.	4125
30	7-31	LFP-1	Jet A	-								360		Pre-cooling for Test 31.	4129
31	8-1	LFP-1	Jet A	X							55.7	453		Solids 3.8cm thick on walls. Crystals in liquid phase. Skin -70°C, center -43°C	4150
32	8-2	LFP-1	Jet A		X							720		At finish, skin -60°C, center -35°C. Did not pump out to determine holdup.	4185
33	8-3	LFP-1	Jet A	-	-	-						494		Pre-cooling for Test 34. Skin to -63°C, center to -41°C.	4227

CHRONOLOGICAL SUMMARY OF TESTS

Test No.	Date	Fuel Identif. No.	Fuel Type	Static	Recircu-lation	Sloshing	Ejectors	Divider	Dry Fuel	Sched. W'drawal	% Holdup	Total Test Time-Min.	Photos / Movies	Remarks	Data Ref. No.
34	(1978) 8-4	LFP-1	Jet A		X	X					17.1	480		At finish, skin -67°C, center -40.7°C. Solids top & bottom. Particles in liquid.	4280
35	8-7	LFP-1	Jet A	-		-						409		Pre-cooling for Test 36. Skin to -65°C, center to -41°C.	4297
36	8-8	LFP-1	Jet A	X							57.2	436	P	AC finish, skin -74°C, center -44°C. Solids on all surfaces.	4346
37	8-10	LFP-7	D-2	X							100	448		Buildup visible during much of test. At finish, skin -55°C, center -17°C.	4461
38	8-15	LFP-6	Interm.	-								161		Pre-cooling for Test 39. Skin to -54°C, center -18°C. Solids visible	4581
39	8-16	LFP-6	Interm.	X							56.1	420		Skin at -50°C, center -31°C at finish. Thick deposits all surfaces.	4623
40	8-23	LFP-6	Interm.	X							21.3	360		At finish, skin -51°C, center -29.7°C. Some solids on walls, most top & bottom	4763
41	8-24	LFP-6	Interm.	X							8.8	200	P	At finish, skin -50°C, center -23°C. Solids mainly on bottom.	4790
42	8-25	LFP-6	Interm.	X							6.6	139		At finish, skin -48.5°C, center -19°C. Solids mainly on bottom.	4798
43	8-28	LFP-6	Interm.		X						5.2	173		At finish, skin -49°C, center -18.5°C. Solids almost all on bottom.	4855
44	8-29	LFP-6	Interm.		X	X					5.1	180		Slosh 70 cycles/min. At finish, skin -48.6°C, center -21.2°C. Solids on bottom	4873
45	8-30	LFP-7	D-2	X							6.8	51	P	At finish, skin -44°C, center +4.2°C. Solids all on bottom, smooth texture	4884
46	8-31	LFP-7	D-2		X						4.5	53		At finish, skin -41.6°C, center +3.6°C. Solids all on bottom, smooth.	4890
47	9-1	LFP-4	D-2	X							2.1	51		At finish, skin -42.9°C, center +4°C. Solids all on bottom, smooth.	4899
48	9-1	LFP-4	D-2	X							1.1	37		At finish, skin -42.7°C, center +8.6°C. Solids all on bottom, thin.	5012
49	9-5	LFP-4	D-2		X						1.7	63		At finish, skin -42.2°C, center +3.7°C. Solids all on bottom.	5014
50	9-6	LFP-3	D-2	X							2.3	46		At finish, skin -42.1°C, center +3.1°C. Solids all on bottom, crystalline.	5016

CHRONOLOGICAL SUMMARY OF TESTS

Sheet 4 of 6

Test No.	Date	Fuel Identif. No.	Fuel Type	Static	Recircu-lation	Sloshing	Ejectors	Divider	Dry Fuel	Sched. W'drawal	% Holdup	Total Test Time-Min.	Photos / Movies	Remarks	Data Ref. No.
51	(1978) 9-7	LFP-3	D-2	X							2.4	30		At finish, skin -41.7°C, center +2.1°C. Solids all on bottom, like "rough ice".	4996
52	9-7	LFP-3	D-2		X						1.7	34		At finish, skin -40.7°C, center -4.5°C Solids all on bottom.	5001
53	9-11	No. 1	Jet A	X							4.3	300	P	At finish, skin -51.3°C, center -36.6°C Solids all on bottom; long crystals	5006
54	9-12	No. 1	Jet A		X	X					2.6	300	P	At finish, skin -51.4°C, center -35.7°C Solids all on bottom.	5009
55	9-13	LFP-1	Jet A	X							1.3	195		At finish, skin -49.7°C, center -26.2°C. Solids all on bottom, fairly clear.	5011
56	9-14	LFP-1	Jet A	X					-		2.5	277		Some drying with nitrogen, flow unknown. At finish, skin -50.9°C, center -37.3°C.	5034
57	9-15	LFP-1	Jet A						X		1.5	144		At finish, skin -49.6°C, center -20.9°C No fog. Nitrogen 6.9cfh for 2 hours	5020
58	9-26	LFP-1	Jet A	X							0.4	104		Relocated six thermocouples. At finish, skin -50°C, center -17°C. Solids at bottom	5063
59	9-27	LFP-1	Jet A	X							0.2	96		At finish, skin -48°C, center -28°C. Very thin deposits, bottom only.	5072
60	9-27	LFP-1	Jet A	X							6.5	352	P	At finish, skin -50.8°C, center -37.4°C. Solids on bottom skin and stringers.	5077
61	10-2	LFP-6	Interm.	X							1.1	94		At finish, skin -44°C, center +0.4°C. Solids on bottom only.	5131
62	10-3	LFP-6	Interm.	X							0.7	40		At finish, skin -43°C, center +0.2°C. Solids on bottom only.	5147
63	10-3	LFP-6	Interm.	X							1.5	75		At finish, skin -38°C, center -3.9°C. Solids on bottom only.	5159
64	10-4	LFP-6	Interm.		X						0.6	60		At finish, skin -43°C, center -1.1°C. Solids on bottom only.	5169
65	10-4	LFP-6	Interm.	X							0.3	91		At finish, skin -32.3°C, center -7.3°C. Trying for low holdup. Solids bottom only.	5170
66	10-5	LFP-6	Interm.						X		1.0	53		At finish, skin -41°C, center +1.5°C. Solids on bottom only.	5175
67	10-6	LFP-5	Interm.	X							3.0	94		At finish, skin -47°C, center -7.6°C. Solids on bottom only, granular	5190

CHRONOLOGICAL SUMMARY OF TESTS

Set 5 of 6

Test No.	Date	Fuel Identif. No.	Fuel Type	Static	Recirculation	Sloshing	Ejectors	Divider	Dry Fuel	Sched. W'drawal	% Holdup	Total Test Time-Min.	Photos / Movies	Remarks	Data Ref. No.
68	(1978) 10-9	LFP-5	Interm.	X							1.4	53		At finish, skin -45.5°C, center +0.8°C. Solids on bottom only, coarse appearance.	5191
69	10-9	LFP-5	Interm.		X						1.7	52		At finish, skin -44.9°C, center -4.3°C. Solids on bottom only.	5194
70	10-10	LFP-5	Interm.						X		1.7	54		At finish, skin -44°C, center -0.1°C. Visibility good. Solids form, skin -33°C.	5207
71	10-11	LFP-5	Interm.						X		4.8	103	M	Attempt time-lapse movie. At finish, skin -50°C, center -11°C. Movie jerky.	5233
72	10-12	LFP-9	Jet A	X							1.2	191		At finish, skin -50.6°C, center -25.9°C. Solids on bottom only.	5241
73	10-13	LFP-9	Jet A	X							3.2	305	P	At finish, skin -52.4°C, center -36.4°C. Solids on bottom, thin layer stringers.	5247
74	10-16	LFP-9	Jet A	X							0.4	132		At finish, skin -50.5°C, center -17.1°C. Solids on bottom only.	5261
75	10-17	LFP-9	Jet A		X						0.7	159		At finish, skin -50.6°C, center -22.3°C. Solids on bottom only.	5277
76	10-18	LFP-9	Jet A						X		0.7	107		At finish, skin -51°C, center -17.6°C. Temp. at 0.6cm same as Test 75.	5294
77	10-23	LFP-5	Interm.						X		3.6	109	M	Attempt time-lapse movie. Solids on bottom and on lower stringers.	5336
78	10-24	No. 8	JP-5	X							2.5	100		Clear amber color. At finish, skin -50.3°C, center -0.5°C. Solids like small crystals.	5347
79	10-25	No. 8	JP-5	X							5.2	157		Some convection. At finish, skin -52.0°C, center -13.8°C. Solids lower surfaces.	5369
80	10-25	No. 8	JP-5	X							1.2	60		At finish, skin -47.3°C, center +3.1°C. Solids on bottom only.	5372
81	10-26	No. 8	JP-5		X						2.7	121		At finish, skin -50.1°C, center -12.3°C. Solids bottom only, large crystals.	5400
82	10-27	No. 8	JP-5						X		2.7	118	P / M	At finish, skin -50.4°C, center -2.7°C. Solids bottom only.	5413
83	10-31	LFP-6	Interm.					X			4.6	111		At finish, skin -50.7°C, center -15.8°C. Solids on bottom and lower stringers.	5469
84	11-1	LFP-6	Interm.					X			10.7	185		At finish, skin -50.2°C, center -25.8°C. Solids remain in divider cutouts.	5492

CHRONOLOGICAL SUMMARY OF TESTS

Sheet 6 of 6

Test No.	Date	Fuel Identif. No.	Fuel Type	Static	Recircu-lation	Sloshing	Ejectors	Div'rs	Dr F +	Sched. W'drawal	% Holdup	Total Test Time-Min.	Photos / Movies	Remarks	Data Ref. No.
85	(1978) 11-2	LFP-1	Jet A					X			4.2	360		At finish, skin -51.8°C, center -38.6°C. Solids partially block divider cutouts.	5503
86	11-3	LFP-5	Interm.					X			6.8	146		At finish, skin -50.6°C, center -21°C. Solids partially block divider cutouts.	5510
87	12-5	LFP-6	Interm.					+		X	41.2	678		Solids forming in less than an hour. Fibrous appearance. Solids on most surfaces.	6046
88	12-6	LFP-8	Jet A					X			0.6	262	P	At finish, skin -55.2°C, center -37.8°C. Solids on bottom only, smooth.	6063
89	12-8	LFP-8	Jet A								-	-		Aborted test due to inadvertent CO_2 shortage.	6137
90	12-11	LFP-8	Jet A	X							0.6	248		At finish, skin -55.3°C, center -39.4°C. Solids on bottom only.	6175
91	12-12	LFP-8	Jet A	X							1.1	311		At finish, skin -57.9°C, center -40.6°C. Solids bottom only, translucent.	6192
92	12-13	LFP-8	Jet A	X							5.2	315		At finish, skin -63.1°C, center -43.1°C. Solids on bottom and lower stringers.	6203
93	12-14	LFP-8	Jet A							X	0	678		Reversal of temp. gradient as skin warmed. Coldest at skin -55.4°C.	6218
94	12-15	LFP-9	Jet A							X	0	678		Coldest at skin -49.1°C.	6249
95	12-18	No. 8	JP-5							X	10.7	678		Some solids at 4 hours. Coldest at skin -49.1°C. No solids sides or top.	6279
96	12-19	LFP-8	Jet A		X						0.4	315		At finish, skin -58.2°C, center -35.9°C. Solids on bottom only.	6302
97	12-20	LFP-5	Interm.	X							20.7	273		Baseline test before adding P.P.D. for Tests 99 and 100.	6303
98	12-21	LFP-5	Interm.							X	25.5	678		Solids apparently formed on upper skin & later fell off, so most was on bottom.	6312
99	12-22	No. 7	Interm. +P.P.D.	X							10.2	271		Similar to Test 97. P.P.D. reduced holdup At finish, skin -51.3°C, center -30.3°C.	6325
100	(1979) 1-2	No. 7	Interm. +P.P.D.	X							17.1	351		Reduced temp. as another check on P.P.D. At finish, skin -63.4°C, center -33.8°C.	6328

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