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POINT VALUES FOR BOILING HEAT TRANSFER TO LIQUID NITROGEN IN A VERTICAL CYLINDER

By

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ABSTRACT

This study was conducted to measure boiling behavior of liquid nitrogen in a 3-inch vertical cylinder. This measurement was accomplished by electrically heating a stainless-steel cylinder containing liquid nitrogen and determining wall temperature with copper-constantan thermocouples embedded in the wall. Point values of ΔT between the wall and boiling liquid nitrogen were measured at various heat fluxes, vertical locations on the cylinder wall, and pressures.

As expected, the surface temperature for a given heat flux minimized at a pressure somewhat above atmospheric, and ΔT values much larger than those for tiny surface elements in large volumes were observed. However, the sharp critical transition between regimes of nucleate and film boiling was less pronounced and somewhat obscured by a metastability of the nucleate-boiling regime, as compared with boiling curves for other shapes and sizes of heat-transfer elements.

Existing dimensionless correlations do not very well predict the critical heat flux or the ΔT for the experiments performed in this study, but may be modified so as to give reasonable correlation.

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ACKNOWLEDGMENTS

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INTRODUCTION

This investigation was made to determine the heat-flux regime of nucleate boiling and the heat-transfer coefficients at low pressures in cylinders approximately 3 inches in diameter, containing liquid nitrogen. This phenomenon is not described by so-called boiling curves involving tiny elements of heat-transfer surface, such as wires or small plates in large, effectively infinite containers, nor by the relationships for high velocity in pipes, as in forced convection, or in a boiler tube.

In nucleate boiling on tiny elements, bubbles are formed at active points on the surface, called nuclei, and are free to escape in a large volume of liquid. The escaping bubbles are displaced by liquid rushing in, and it is thought that this phenomenon is responsible for the high heat-transfer coefficients commonly experienced in nucleate boiling. As heat flux rises past a critical limit, the increased volume of bubbles is no longer able to escape continuously and be displaced by liquid. The bubbles coalesce to form a continuous vapor film over the surface, and the surface temperature increases drastically. This phenomenon is called the "boiling crisis." The continuation of boiling with heat transfer through the vapor film is called "film boiling." If the temperature rise is sharp enough to destroy the heat-transfer element, the term "burnout" is appropriate. However, one finds the term used to indicate film boiling when no destruction of apparatus is apparent.

The critical limit of the nucleate boiling regime inside cylinders has apparently not been intensively studied. This fact is somewhat surprising considering the close relation to boiling kettles and tubes, which are common enough in processing and power-generation industries. In fact, some previous work which was uncovered during literature search was done quite early.

The reason for this lack of study may be the extreme complexity of the phenomenon. Even for small heat-transfer elements such as wires and small plates in large, effectively infinite volumes of liquid, the crisis in nucleate boiling is not well understood. When the container walls constrain the vapor to flow over the upper part of the heat-transfer surface and slip flow and agitation by the vapor are involved, the problem becomes "enormously complicated" (1).

The present study is focused on the behavior of a cryogen and the limiting heat flux of the nucleate-boiling regime. Both of these general areas of research have been extremely active in the past several years.

Nukiyama clearly recognized in 1934 that several regimes of boiling exist (2). "Boiling curves" showing the nucleate and film boiling ranges for various heat-transfer elements in liquid nitrogen have been prepared by Forster and Greif (3), Bromley (4), Hasselden and Peters (5), Flynn, Draper, and Roos (6), McNelly (7), and Forster and Zuber (8). A broader discussion of critical heat fluxes is given by Kutateladze (9).

Sydoriak and Roberts have studied nitrogen boiling in channels for magnet cooling (10). Old studies by Stroebe et al. (11) and Brooks et al. (12) of water boiling in 1-inch-diameter tube evaporators may be considered somewhat pertinent. However, none of these studies predicts boiling in a short vertical cylinder where slip flow of the bubbles through the liquid is required to maintain a liquid continuous phase.

The study was directed, primarily, to appraise pool boiling in short vertical cylinders as a possible heat sink for cryopumping. Freon gas was to be condensed on the shell side of the exchanger. The combination of materials chosen made it mandatory that the wall temperature be kept close to the nitrogen boiling point. Film boiling or a vapor continuous phase could not be tolerated. Forced convection boiling was considered, but the apparatus requirements and special techniques for pumping and de-entrainment seemed too formidable. Also, the increase in saturation temperature caused by pumping pressure was unfavorable. The simplicity and the possibility of achieving lower temperature by pool boiling made pool boiling greatly preferred.

Other possible applications of this type cooling include magnet cooling in accelerators and scintillator cooling in nuclear detectors.

The scope of the investigation was to make heat-flux and temperature measurements of nucleate-boiling heat transfer in liquid nitrogen in short vertical cylinders and to arrive at an equation for correlating the experimental data. The data were to be correlated by an existing equation or by revising the equation or developing a new one.

The method of measurement is discussed thoroughly in the experimental-results section immediately following.

EXPERIMENTAL RESULTS

Description of Apparatus

The general experimental problem was to provide a method of generating a precise heat flux in the wall of a cylinder, boiling nitrogen at various pressures in the cylinder, and measuring the temperature difference between the cylinder wall and the boiling fluid. In the initial design of the experiment, a very thin container was planned. The container itself was to serve as the resistance heating element. Difficulties were encountered in procuring the thin stainless steel and in making the required braze joints at the ends. Dimensional stability and safe pressure containment also appeared to be likely problems. For these reasons a design was chosen in which a thicker (0.050 inch) stainless-steel cylinder was wrapped by a helical stainless heating element. The material used for the cylinder was commercial stainless-steel pipe, nitric acid cleaned, and water washed. "Devcon-F" aluminum-filled epoxy cement was used as the electrical insulator between the cylinder and the heating element in a layer estimated to be 0.025 inches thick. This cement gave adequate electrical resistance with satisfactory thermal contact. A sketch and a photograph taken before insulation was applied are given in Figures 11 and 1, respectively. A calibrated clamp-on ammeter and Simpson voltmeter were used to measure power input to the heating element.

Pressurization was provided by an adjustable pressure-relief valve preset to the desired pressure level. At high heat fluxes it was necessary to aid the pressure-relief valve with a hand valve, but good pressure control was obtained.

Thermocouple attachment was provided by drilling the cylinder wall between succeeding loops of the heating element. A residual wall thickness of about 0.010 inch was left. The thermocouple was spot-welded to the bottom of the drilled well, then insulated with Devcon and fiberglass to minimize heat conduction from the heating element to the thermocouple junction. The thermocouple readings were recorded by Moseley recording potentiometers.

Difficulties in obtaining precise and reproducible temperature differences led to developing a certain temperature-measuring technique. The usual constant-temperature oven for the reference junction was substituted by a Dewar flask containing liquid nitrogen boiling at atmospheric pressure (approximately 10 pounds per square inch absolute pressure). All the ΔT data given in the experimental results section were measured by this technique and were not corrected or modified.

This differential-measuring technique gave much more accurate and precise results in these cryogenic experiments than an attempt to measure absolute temperature would have given. For instance, the cold junction would have had to be located inside the cylinder to measure wall temperature with respect to bulk fluid. Thermocouple location inside the cylinder would have required the development of bulkhead fittings. Junction-potential errors would have been involved.

The liquid nitrogen used was of high purity from air distillation and was purchased from various vendors such as Air Products Company. The nominal purity is 99.99 percent.

Unpressurized Pool Boiling

Tests were designated by a test number indicating the type of test and the number of the test in that series.

1. Test 1-SC, Runs 1-21

Purpose: To measure heat flux, ΔT values, and critical limits of a single vertical cylinder of liquid nitrogen in nucleate pool boiling.

Data required: Wall to bulk fluid ΔT as a function of heat flux. (Wall temperature 0.010 inch from surface).

Apparatus and test setup: A vertical 2 5/8-inch stainless-steel cylinder wound with an epoxy-insulated stainless-steel heating element. See Figure 1 for the particular cylinder used in this test, Figure 12 for the general test setup (Figure 12 shows a pressurized cylinder being tested), and Figure 2 for a sketch of the apparatus. An Airco alternating-current welder was used as power supply for the heating element.

Instrumentation: Two copper-constantan thermocouples thermally insulated from the heating element and embedded and spot-welded in the wall of the cylinder. These were 24-gauge wire, 4 feet long. The reference thermocouples were located in a Dewar cylinder of liquid nitrogen boiling at atmospheric pressure. A Moseley recording potentiometer was used to measure their output emf. A clamp-on ammeter and a calibrated Simpson voltmeter were used to measure the heat input to the heating element. The power factor was determined to be negligibly different from one.

Conclusions: The boiling curve did not show the typical nucleate-to-film crisis of a differential heat-transfer element in a large volume.

More thermocouples were added and point values were observed vertically along the wall. A deflector cone was added to obviate the wetting of the polyurethane insulation by liquid nitrogen which splashed over the edge during the run.

The temperature drop across the 0.010-inch residual wall from the thermocouple location to the surface contacting the nitrogen was calculated to be negligible.

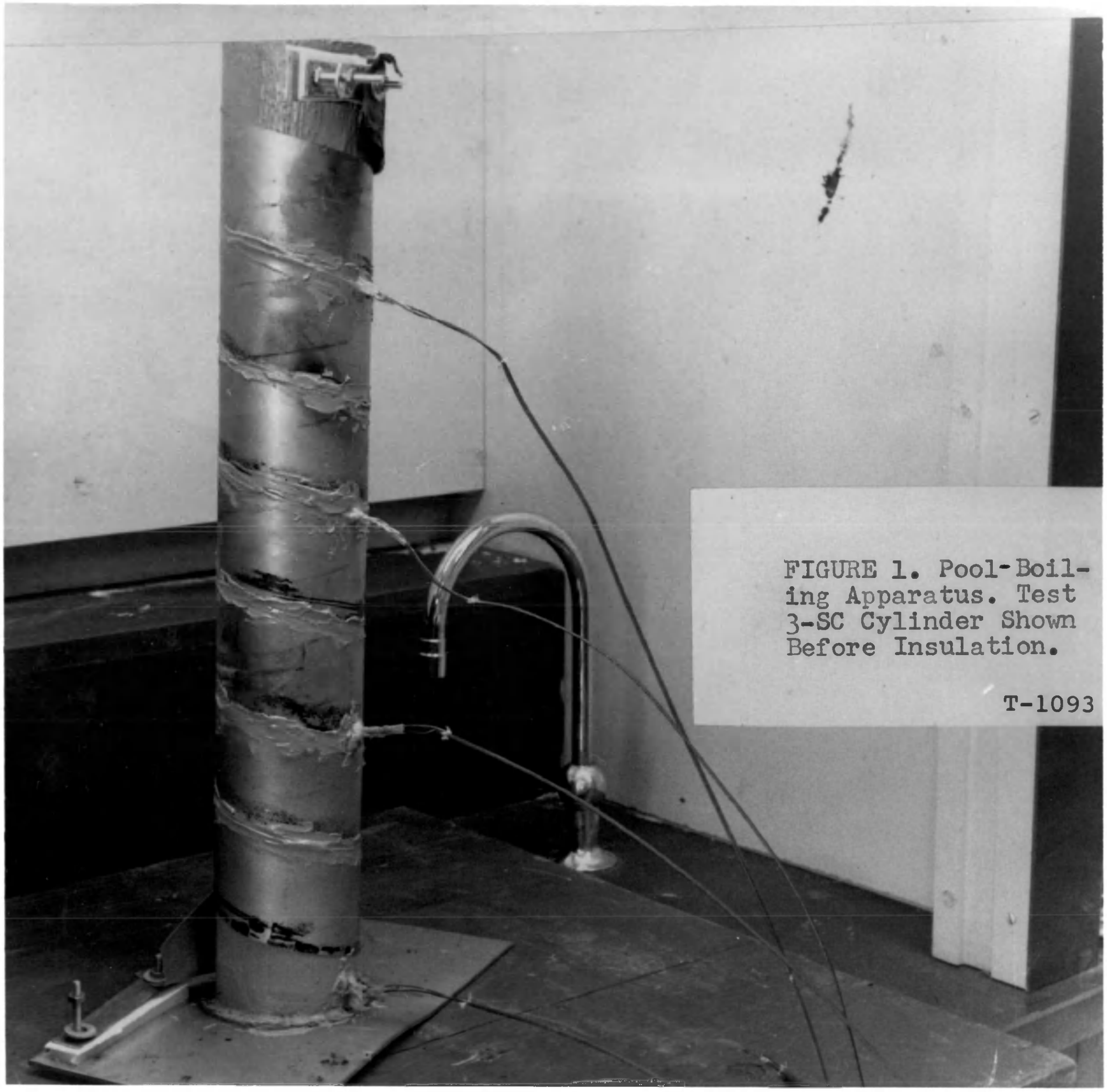

FIGURE 1. Pool-Boiling Apparatus. Test 3-SC Cylinder Shown Before Insulation.

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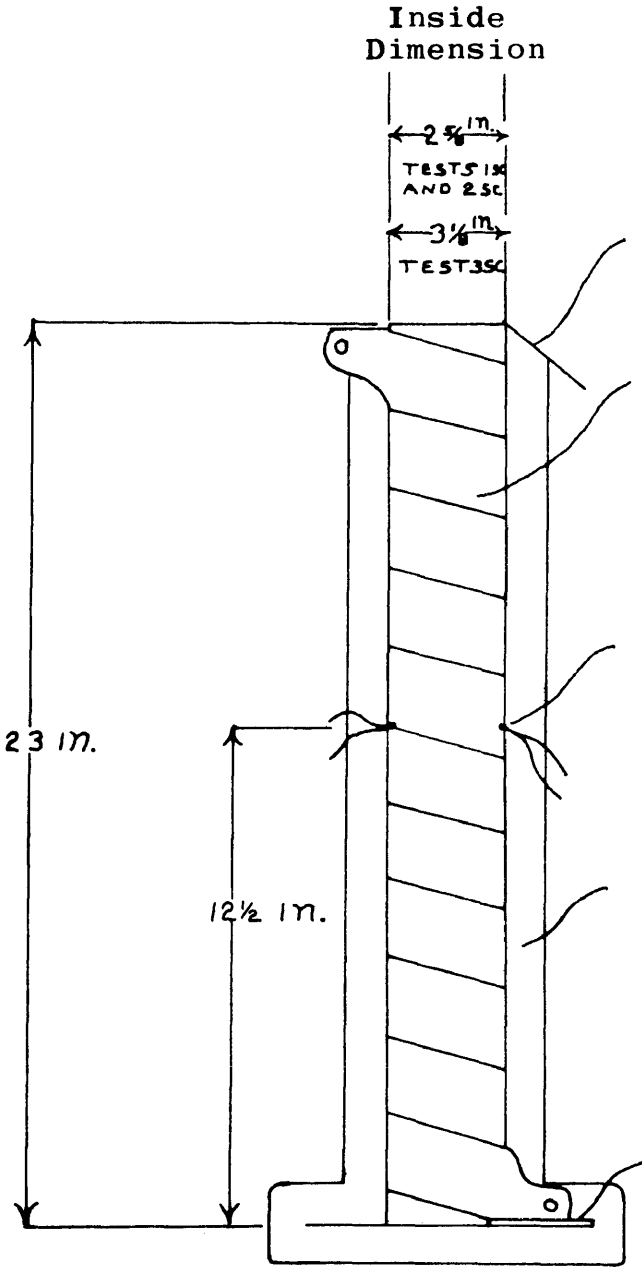


Deflector cone to prevent insulation being wet by boil-over.

Heating element: 0.012 in. x 2 in. stainless steel.

Thermocouple: 24-gauge copper-constantan to Moseley recording potentiometer. See Figure 1 for arrangement of thermocouples in Test 3-SC.

Insulation: Polyurethane 1 inch thick minimum.

Teflon block for electrically insulated support of heating element attachment.

FIGURE 2 - Sketch of Pool-Boiling Apparatus as Used for Tests 1-SC, 2-SC, and 3-SC (deflector cone was not used on Test 1-SC).

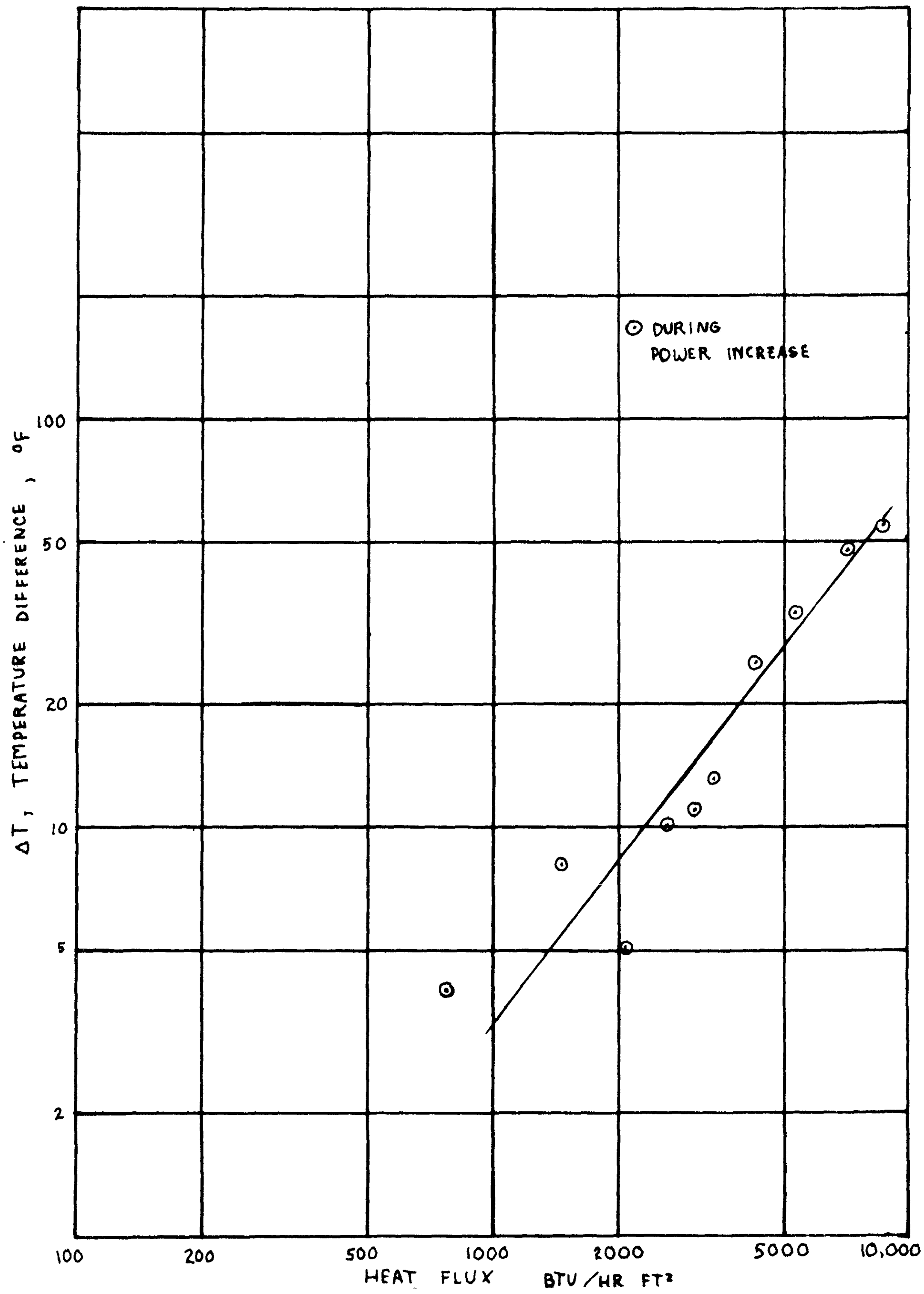


FIGURE 3 - TEST 1-SC, TC1 Unpressurized Pool Boiling in a 2 5/8-inch-Diameter Vertical Cylinder. Thermocouple No. 1, 12½ inches from Bottom.

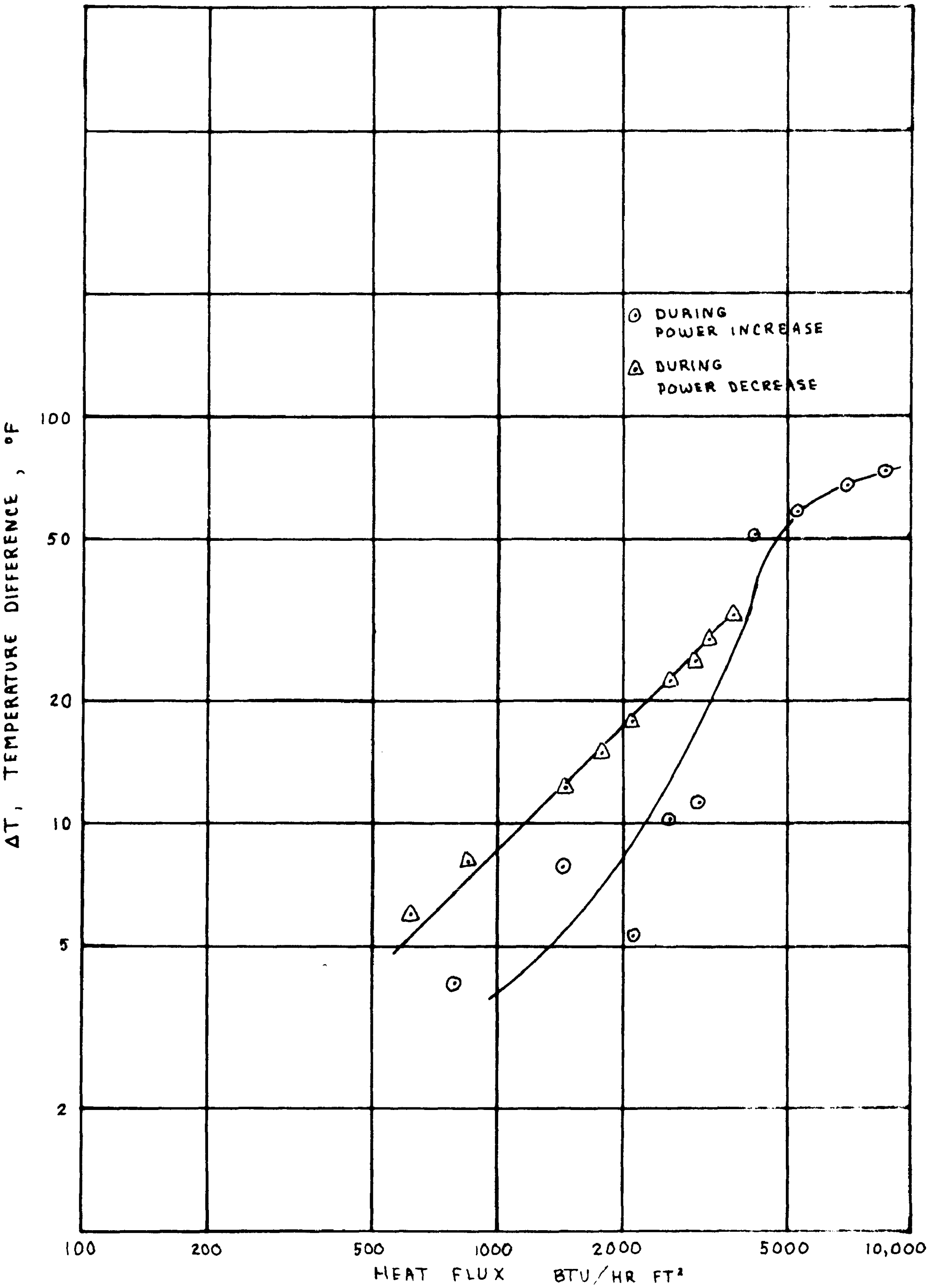


FIGURE 4 - TEST 1-SC, TC2 Unpressurized Pool Boiling in a 2 5/8-inch-Diameter Vertical Cylinder. Thermocouple No. 2, 12½ inches from Bottom.

TABLE 1 - TEST 1-SC Thermocouples 1 and 2.

Heat transfer to liquid nitrogen pool boiling at 1 atmosphere in a 2 5/8-inch-inside-diameter vertical cylinder. The thermocouples were 12½ inches from the bottom of the cylinder and were located opposite each other on the cylinder. Heat-transfer area 1.32 ft^2.

Current (Amps)	Voltage (Volts)	Power (Watts)	Heat Flux (Watts/cm^2)	Heat Flux (BTU/hr ft^2)	TC1 (^{o}F)	TC2 (^{o}F)
61	5.0	305	0.249	789.5	4.0	4.0
82	7.3	598	0.478	1515.6	7.9	7.9
94	8.6	808	0.660	2092.7	5.0	5.0
105	9.8	1029	0.840	2663.4	10.1	10.1
110	11.0	1210	0.987	3129.5	11.0	11.0
115	11.5	1325	1.081	3427.6	13.0	13.0
122	13.7	1671	1.365	4328.1	25.0	50.0
130	16.0	2080	1.700	5390.3	32.9	56.9
145	18.7	2710	2.210	7007.4	47.0	64.8
155	22.0	3410	2.780	8814.7	54.9	72.0
183	27.0	4440	4.040	12809.8	75.1	73.1
112	13.0	1455	1.190	3773.2		32.0
105	12.0	1260	1.030	3234.2		27.5
100	11.2	1120	0.915	2901.2		25.0
97	10.5	1018	0.813	2577.8		22.0
92	10.0	920	0.748	2371.7		20.0
87	9.3	809	0.661	2095.9		17.5
82	8.5	696	0.568	1801.0		14.9
74	7.6	563	0.459	1455.4		12.1
60	5.5	330	0.269	852.9		7.9
51	4.6	235	0.192	608.8		5.9

2. Test 2-SC, Runs 1-25

Single cylinder similar to 1-SC, but with thermal siphon.

Purpose: To determine the effect of a thermal siphon, consisting of an inner tube concentric with the cylinder, in nucleate pool-boiling behavior and thereby to understand the hydraulic mechanism better.

Data required: Wall-to-bulk-fluid ΔT as a function of heat flux from the cylinder wall.

Instrumentation: Two copper-constantan thermocouples at the 12½-inch level, Moseley recording potentiometer.

Conclusions: The thermal siphon, which was 1 inch in diameter and 1 foot long, suspended in the center of the cylinder, had a definite but not large effect on boiling performance.

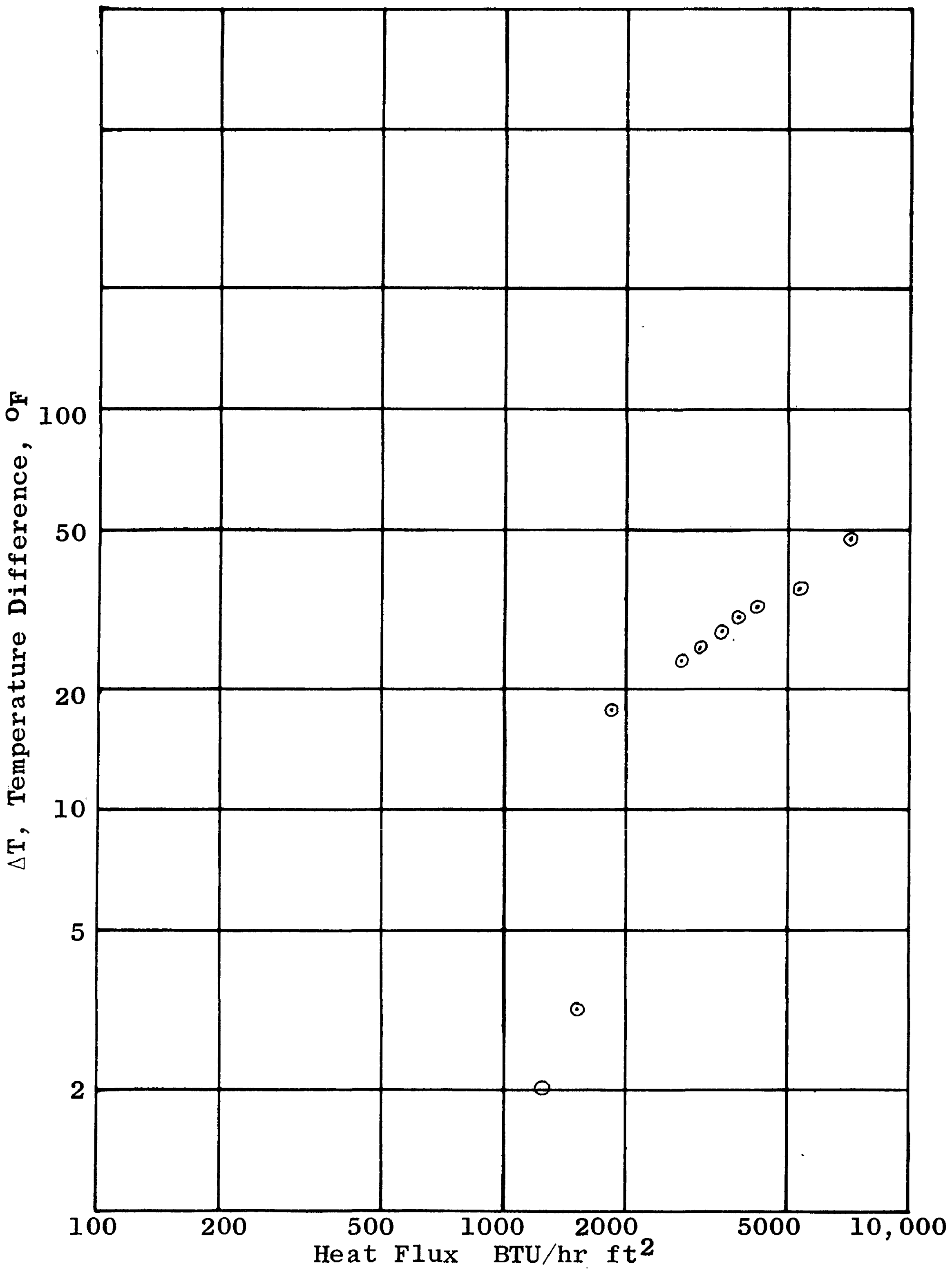


FIGURE 5 - TEST 2-SC, TC1 Unpressurized Boiling Nitrogen Employing a Thermal Siphon. Thermocouple No. 1, 12½ inches from the Bottom.

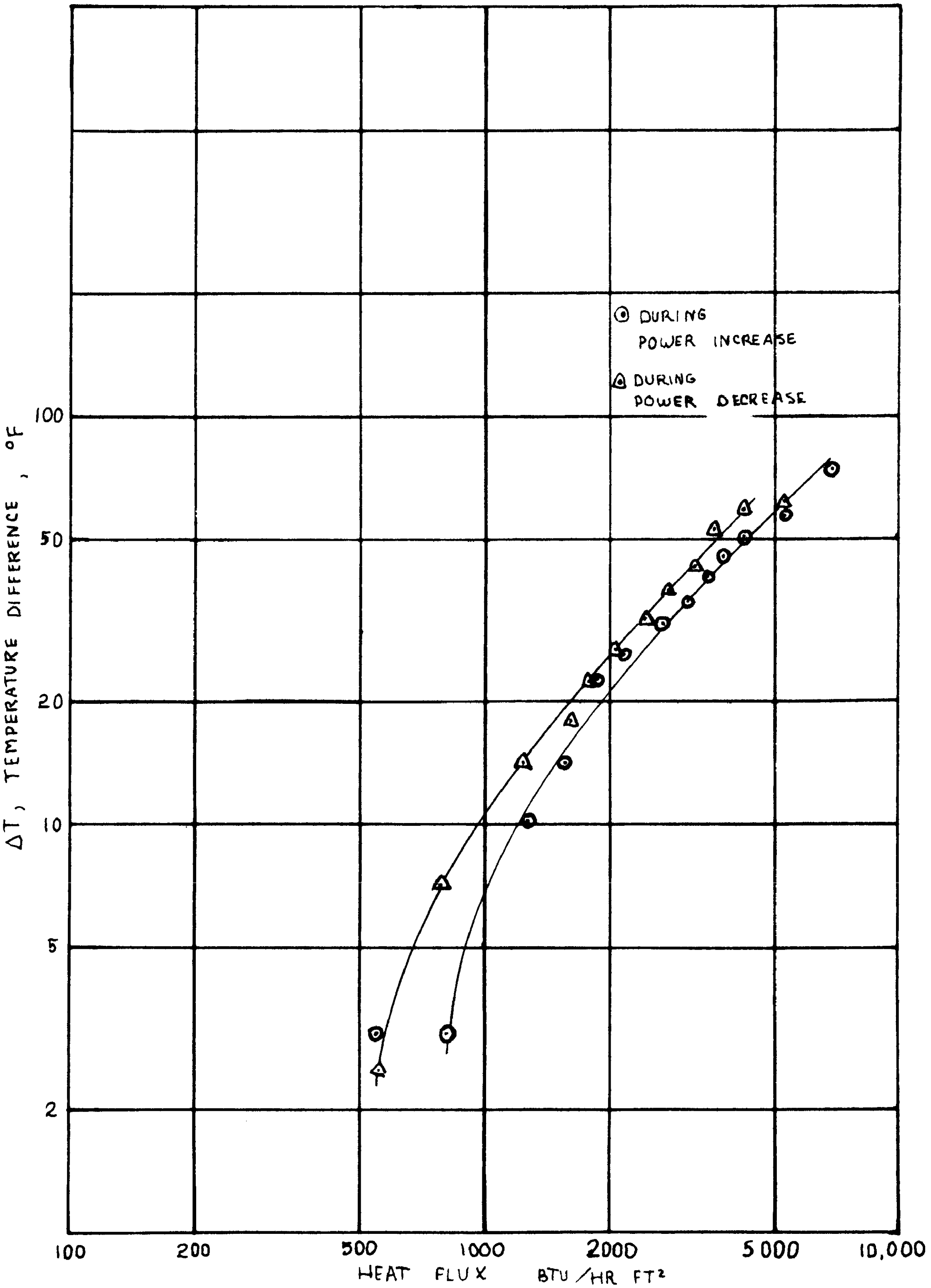


FIGURE 6 - TEST 2-SC, TC2 Unpressurized Boiling Nitrogen Employing a Thermal Siphon. Thermocouple No. 2, 12½ inches from Bottom.

TABLE 2 - TEST 2-SC Thermocouples 1 and 2.

Heat transfer to liquid nitrogen boiling at 1 atmosphere in a 2 5/8-inch-inside-diameter vertical cylinder, with a thermal siphon inside the cylinder. The copper-constantan thermocouples were located opposite each other 12½ inches from the bottom of the cylinder.

Current (Amps)	Voltage (Volts)	Power (Watts)	Heat Flux (Watts/cm^2)	Heat Flux (BTU/hr ft^2)	TC1 (°F)	TC2 (°F)
50	4.2	210	0.171	542.2	0.0	3.1
59	5.2	310	0.253	802.2	0.0	3.1
72	6.8	490	0.400	1268.3	2.0	10.1
80	7.6	610	0.447	1417.3	3.1	14.0
86	8.5	730	0.596	1889.8	17.5	22.5
92	9.1	840	0.685	2172.0	19.8	25.9
96	11.0	1050	0.856	2714.2	23.0	31.0
100	12.0	1200	0.980	3107.3	25.0	34.9
105	12.8	1350	1.100	3487.8	27.0	40.0
110	13.4	1470	1.200	3804.9	29.0	45.0
115	14.2	1630	1.330	4217.1	31.0	50.0
127	16.2	2060	1.680	5326.9	35.8	56.3
140	19.4	2710	2.200	6975.7	46.1	72.7
127	16.2	2060	1.680	5295.2	36.9	66.6
116	14.1	1630	1.330	4217.1	34.9	57.8
110	12.8	1410	1.150	3646.4	26.0	50.0
105	11.8	1250	1.020	3241.7	22.0	42.5
100	11.0	1100	0.898	2844.2	19.8	37.4
95	10.2	970	0.792	2511.2	19.1	31.0
90	9.4	850	0.694	2200.5	18.0	25.9
84	8.6	720	0.588	1864.4	16.0	22.0
80	7.8	620	0.506	1604.4	14.0	17.5
72	6.7	480	0.392	1242.9	4.0	14.0
58	5.1	300	0.245	776.8	2.0	7.0
49	4.2	210	0.172	545.4	1.1	2.5

3. Test 3-SC, Runs 1-18

3 inch single cylinder with 4 thermocouples for point values of heat-transfer coefficient.

Purpose: To measure point values of nucleate pool-boiling heat transfer in a single cylinder of liquid nitrogen.

Data required: Wall to bulk fluid ΔT as a function of heat flux at various points along the cylinder wall.

Instrumentation: Copper-constantan thermocouples at 4, 7, 12, and $17\frac{1}{2}$ inches from the bottom of the cylinder. TC details and recorders same as test 1-SC.

Conclusions: Same as test 1-SC, except that the respective thermocouples, vertically arranged, do show the effect on heat transfer in the upper parts of the cylinder of vapor rising from boiling in the lower part of the cylinder.

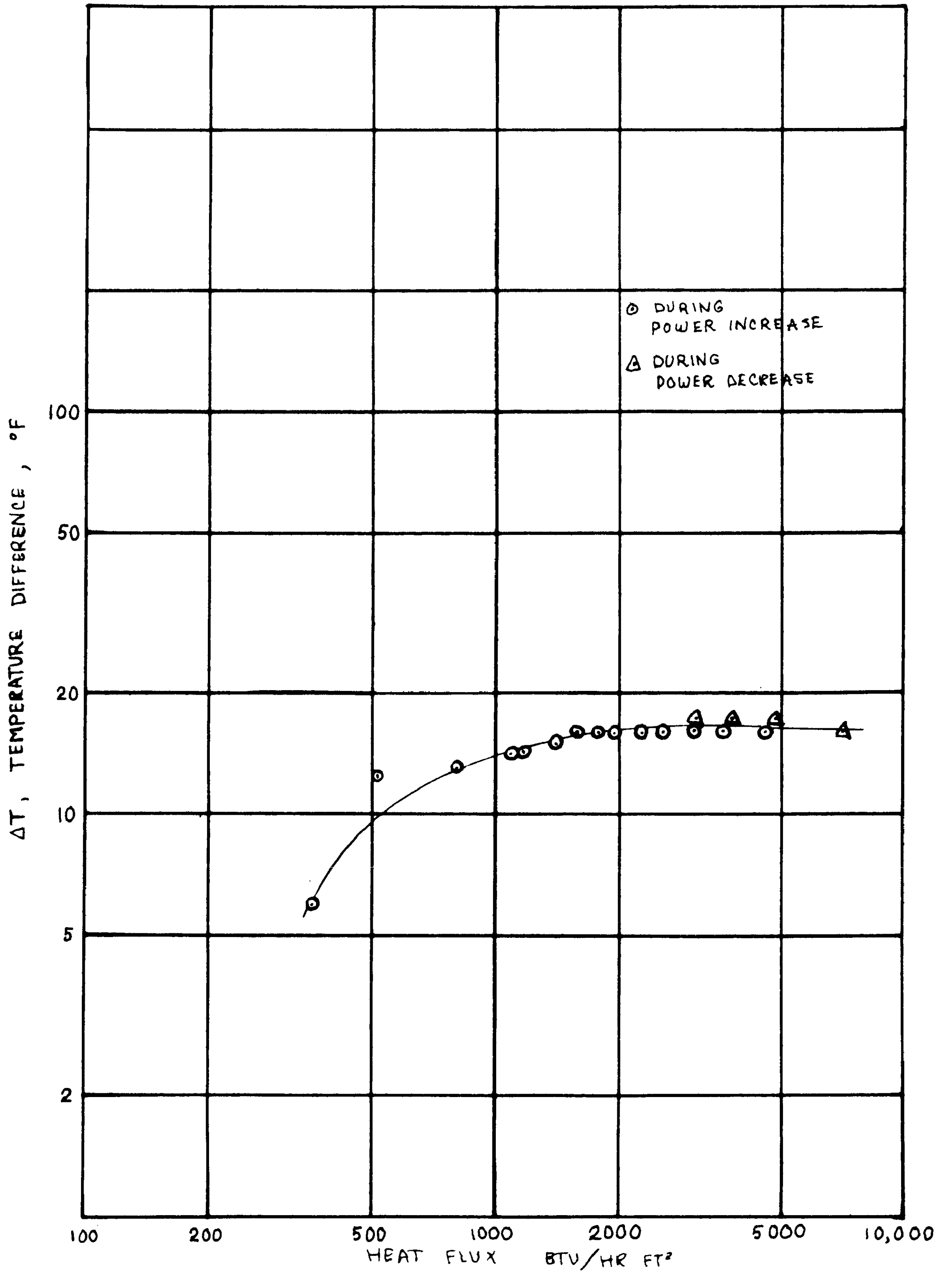


FIGURE 7 - TEST 3-SC, TC1 Unpressurized Pool Boiling in a 3-inch-Diameter Vertical Cylinder. Thermocouple No. 1, $\frac{1}{2}$ inch from Bottom.

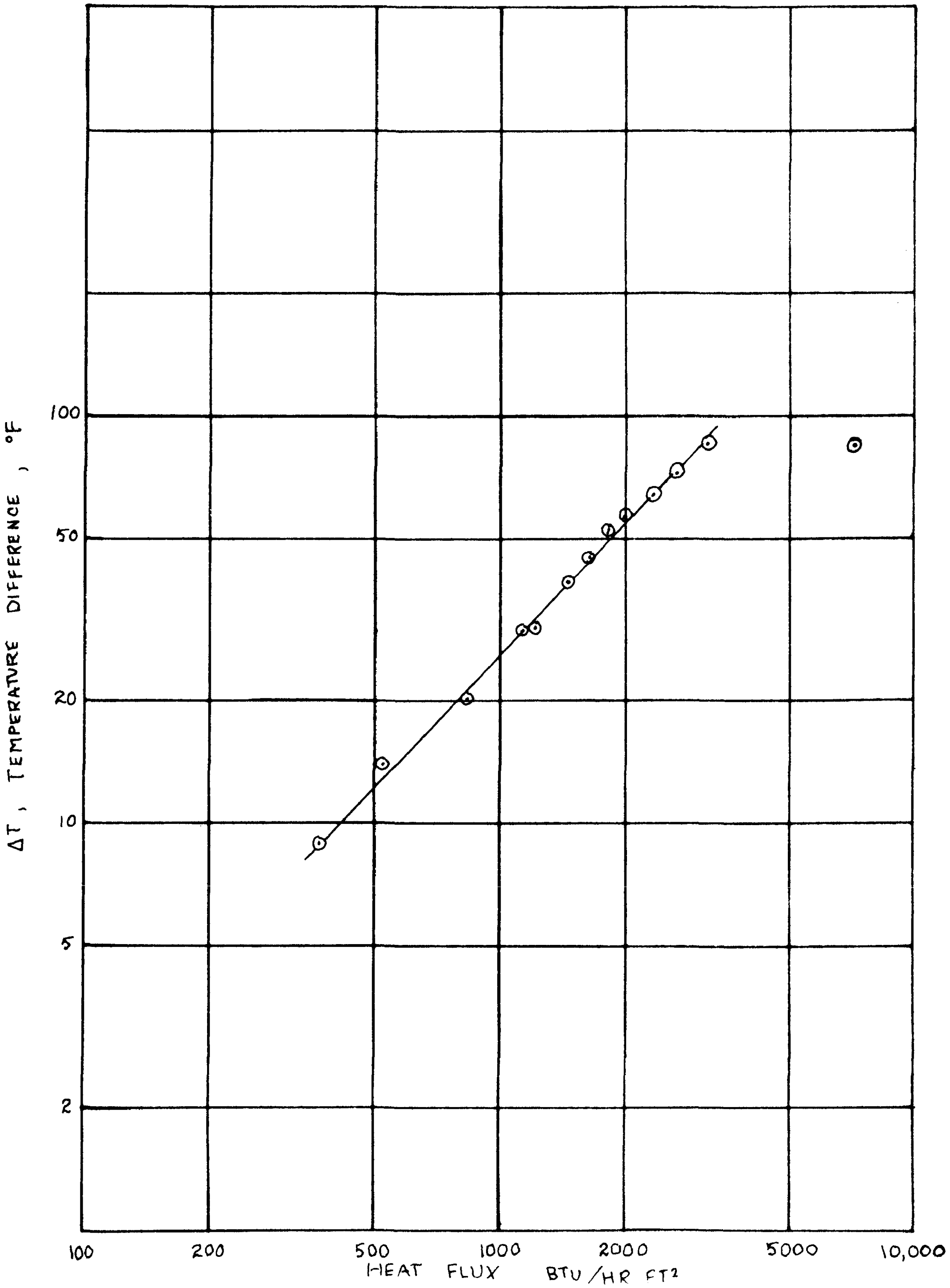


FIGURE 8 - TEST 3-SC, TC2 Unpressurized Pool Boiling in a 3-inch-Diameter Vertical Cylinder. Thermocouple No. 2, 7 inches from Bottom.

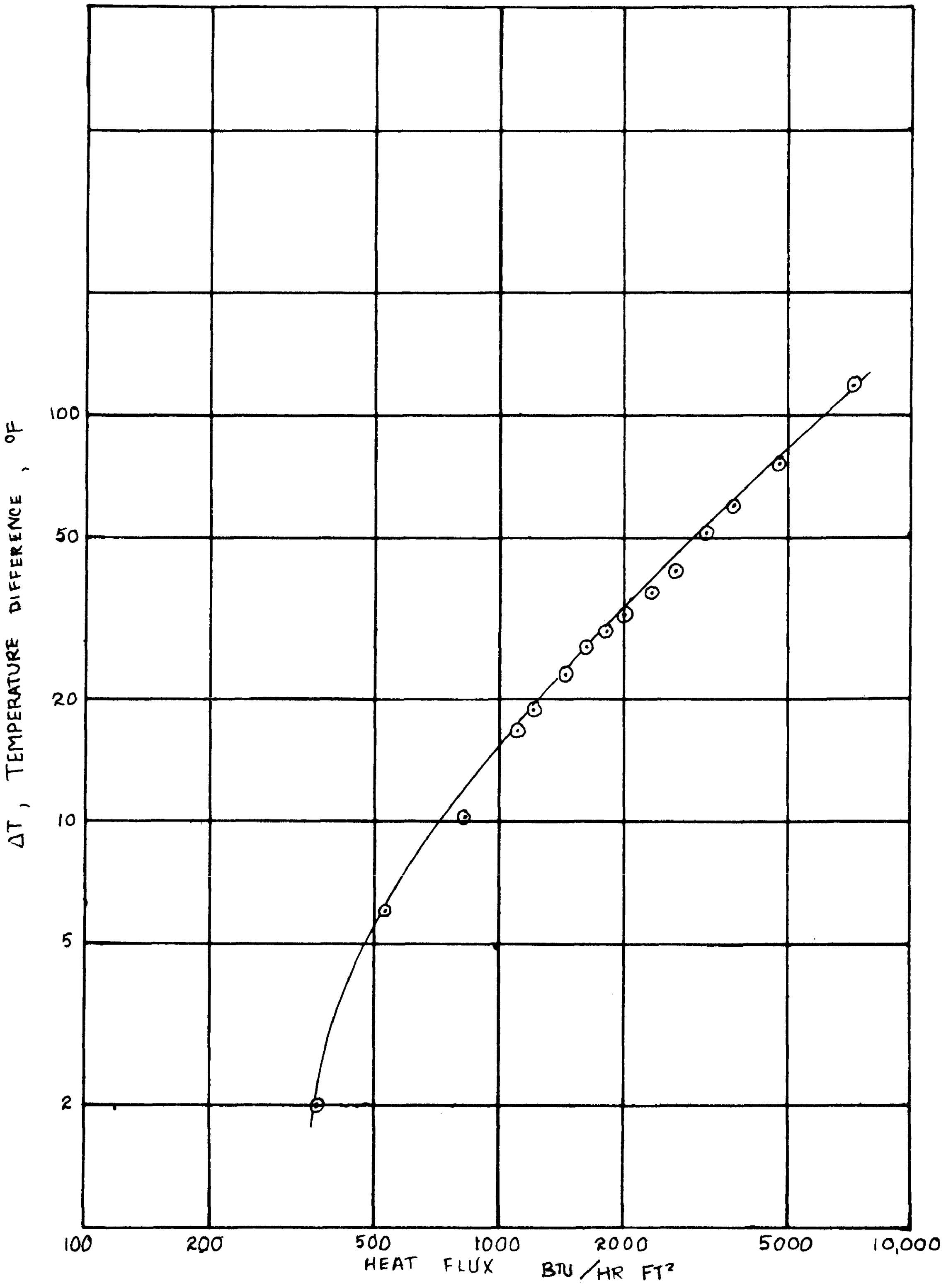


FIGURE 9 - TEST 3-SC, TC3 Unpressurized Pool Boiling in a 3-inch-Diameter Vertical Cylinder. Thermocouple No. 3, 12 inches from Bottom.

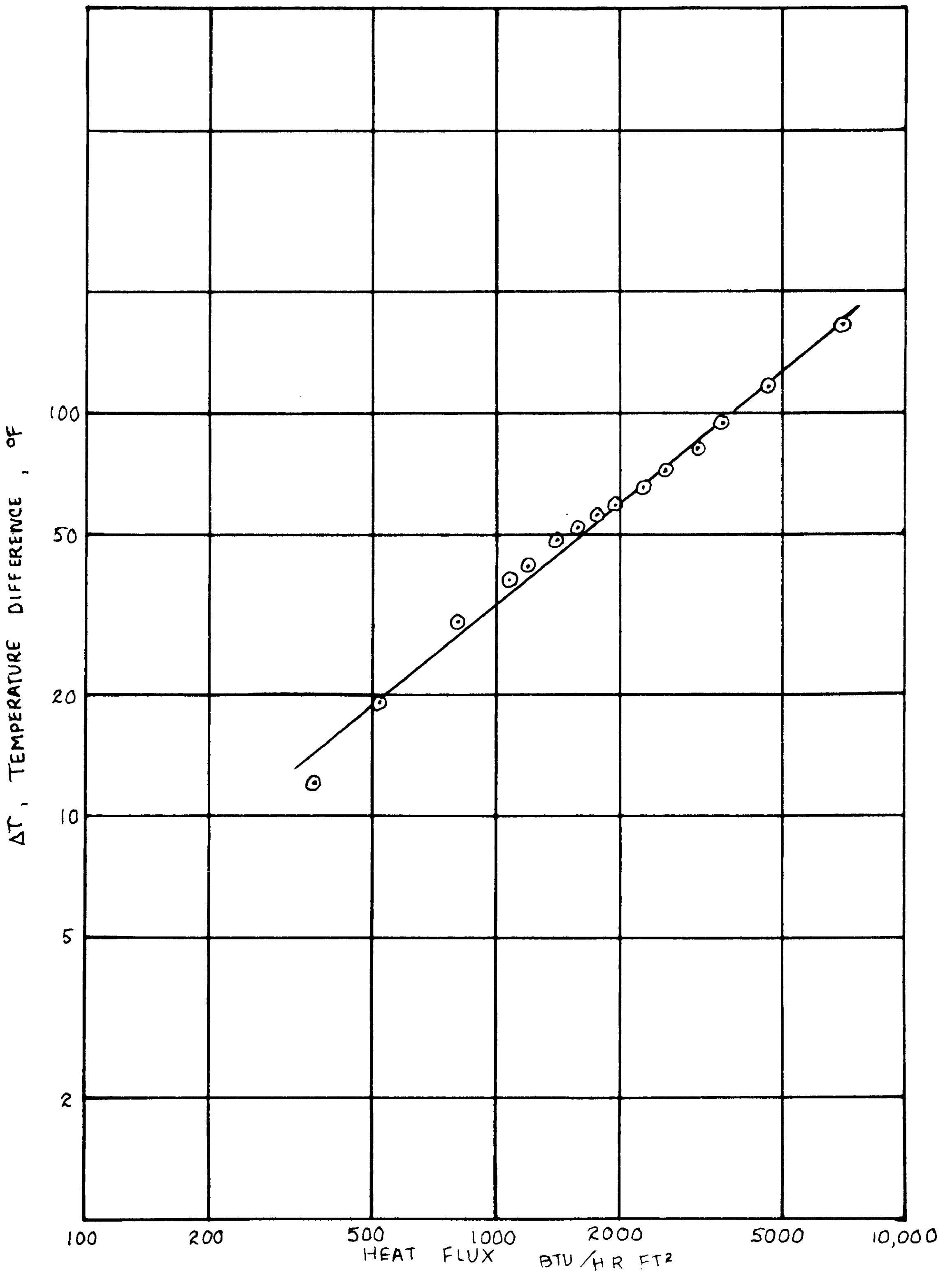


FIGURE 10 - TEST 3-SC, TC4 Unpressurized Pool Boiling in a 3-inch-Diameter Vertical Cylinder. Thermocouple No. 4, 17½ inches from the Bottom.

TABLE 3 - TEST 3-SC Thermocouples 1, 2, 3, and 4.

Heat transfer to liquid nitrogen pool boiling at 1 atmosphere in a 3-inch-inside-diameter vertical cylinder. The thermocouples were ½, 7, 12, and 17½ inches, respectively, from the bottom of the cylinder.

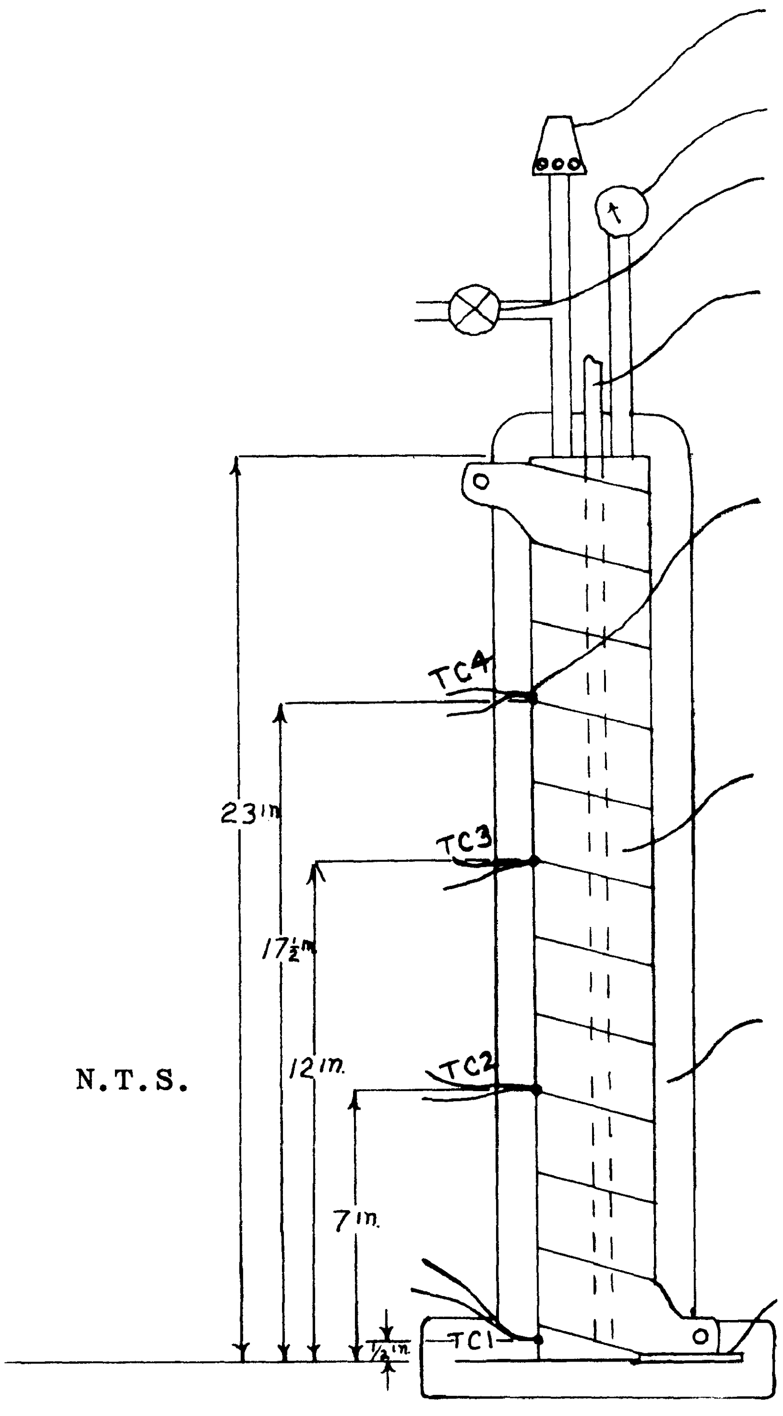
Current (Amps)	Voltage (Volts)	Power (Watts)	Heat Flux $\left(\frac{\text{Watts}}{\text{cm}^2}\right)$	Heat Flux $\left(\frac{\text{BTU}}{\text{hr ft}^2}\right)$	TC1 (°F)	TC2 (°F)	TC3 (°F)	TC4 (°F)
49	3.4	167	0.114	361.5	5.9	9.0	2.0	12.1
58	4.1	238	0.163	516.8	12.4	14.0	5.9	18.9
72	5.2	375	0.257	814.9	13.0	20.0	10.1	30.1
80	6.3	504	0.345	1093.9	14.0	29.0	16.9	37.8
85	6.5	553	0.379	1201.7	14.0	30.1	18.9	41.0
92	7.1	653	0.447	1417.3	14.9	37.1	23.0	47.5
96	7.7	740	0.506	1604.4	16.0	41.4	27.0	50.9
100	8.2	820	0.561	1778.8	16.0	51.1	29.0	54.7
105	8.6	904	0.619	1962.7	16.0	56.9	32.0	57.8
112	9.4	1054	0.733	2324.2	16.0	63.9	36.0	63.9
119	10.0	1190	0.815	2584.2	16.0	72.0	40.0	71.3
130	11.2	1459	0.999	3167.6	16.0	85.0	50.0	79.9
142	11.8	1678	1.149	3643.2	16.0	64.8	59.9	92.9
158	13.7	2160	1.480	4692.7	16.0	67.0	75.1	115.2
187	17.5	3280	2.250	7134.2	16.0	83.9	117.7	164.0
158	14.1	2230	1.530	4851.2	17.1	71.1	85.0	99.9
142	12.3	1750	1.200	3804.9	17.1	56.2	91.1	92.0
130	11.2	1458	0.999	3167.6	17.1	54.4	47.9	47.9

Pressurized Pool Boiling

From existing theory of boiling and observation of the boiling process, it is known that a critical or gradual change from the nucleate boiling mode will result at increased heat flux. Causes include a film at the wall, a vapor-continuous system developing in the upper part of the cylinder, and "flooding" and ejection of the liquid contents by a high volume rate of vapor flow.

In each case boiling performance may apparently be improved by a reduction of vapor volume. Therefore it seemed appropriate to take data at increased pressure levels. The mean barometric pressure at the laboratory was 10 pounds per square inch; gauge pressures can be converted to absolute pressures accordingly.

The pressurized pool-boiling tests were made with an apparatus similar to that used for unpressurized tests, except that the top of the cylinder was closed and vapor exhausted through a pressure reducing valve, which maintained the boiling contents at desired pressure. The pressure-relief valve was adjusted by means of the calibrated Bourdon-type gauge, mounted on an extension to prevent moisture condensation and freeze-up. A photograph of the apparatus is shown in Figure 12.



Pressure-reducing valve

Bourdon pressure gauge

Hand-operated relief valve.

Fill tube

Thermocouple: 24-gauge copper-constantan to Moseley recording potentiometer.

Heating element: 0.012 in. x 2 in. stainless steel.

Insulation: polyurethane 1 inch thick minimum.

Teflon block for electrically insulated support of heating-element attachment.

FIGURE 11 - Sketch of Pool-Boiling Apparatus Shown as Assembled for Pressurized Tests, with Insulation Cut Away to Show Heating Element and Thermocouples.

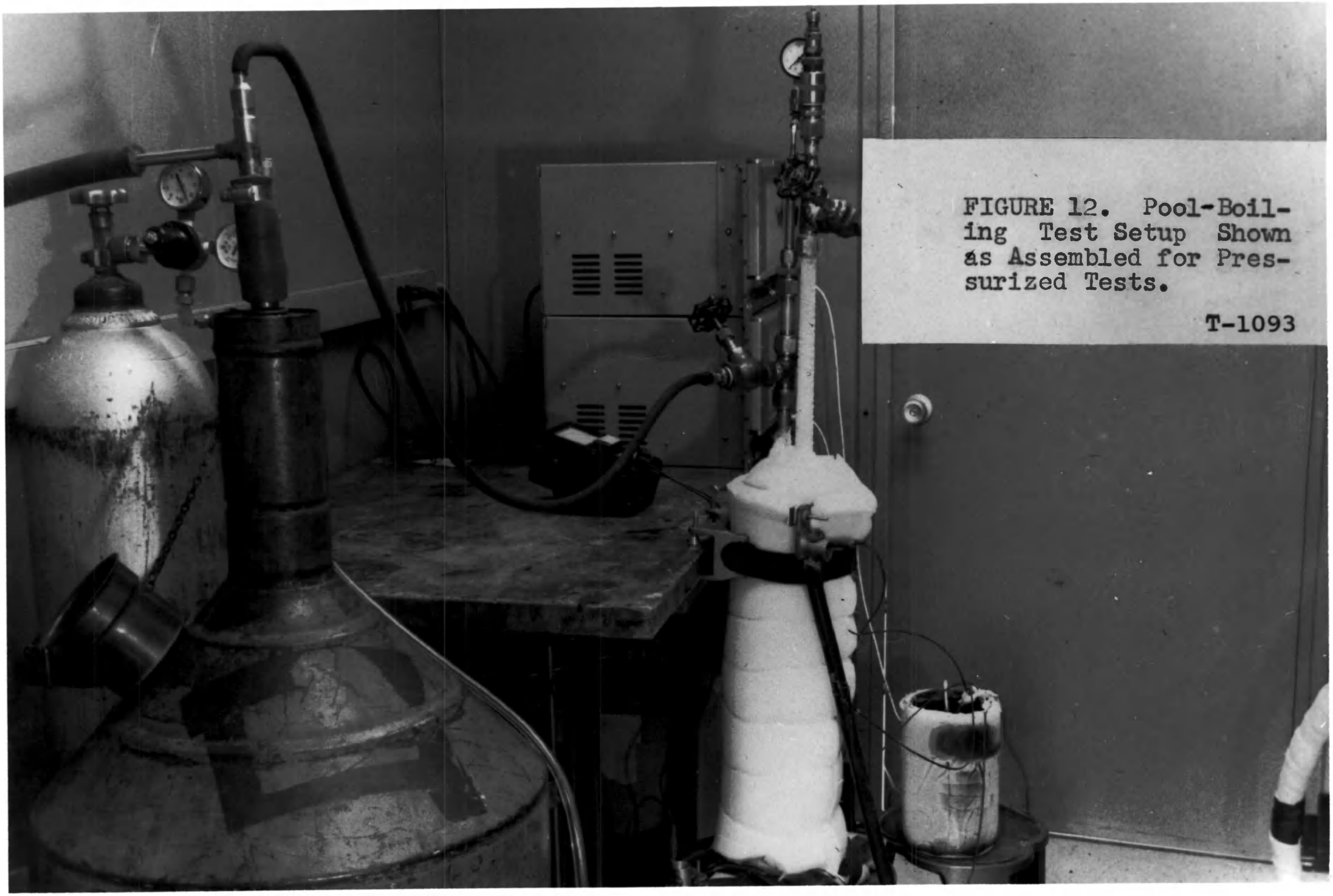


FIGURE 12. Pool-Boiling Test Setup Shown as Assembled for Pressurized Tests.

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1. Test 1-P

Purpose: Measure boiling performance at 10 psig (20 psia).

Data required: Wall temperature as a function of height in the cylinder.

Apparatus: Pressurized and insulated electrically heated stainless-steel cylinder, as discussed previously.

Instrumentation: Four copper-constantan thermocouples connected to Moseley recording potentiometers.

Conclusions: Correction of experimental difficulties occupied most of the time spent on this test; few valid data were secured. Test 2-P was rerun at the same pressure to get more data.

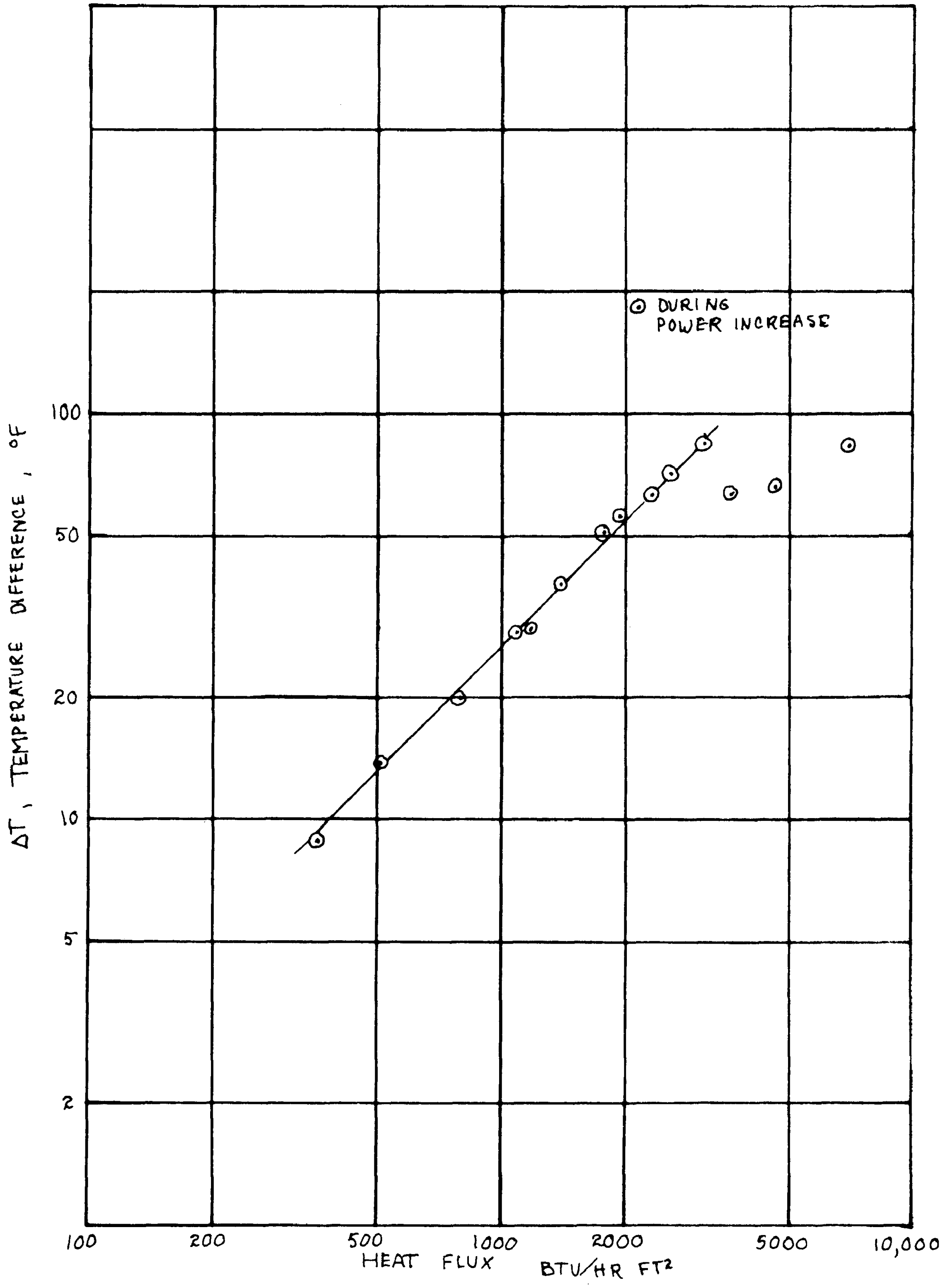

FIGURE 13 - TEST 1-P, TC2 Pressurized Pool Boiling at 10 psig. Thermocouple No. 3, 12 inches from the Bottom.

TABLE 4 - TEST 1-P Thermocouples 1, 2, 3, and 4.

Heat transfer to liquid nitrogen pool boiling at 10 psig in a 3-inch-inside-diameter vertical cylinder. The thermocouples were ½, 7, 12, and 17½ inches from the bottom, respectively. The recorder for thermocouple No. 2 failed during this series of tests.

Current	Voltage	Power	Heat Flux	TC1	TC2	TC3	TC4
(Amps)	(Volts)	(Watts)	$\left(\frac{BTU}{hr\ ft}\right)$	(°F)	(°F)	(°F)	(°F)
80	6.3	504	1093.9	22.0		14.9	14.9
80	6.3	504	1093.9	32.0	1.1	16.0	14.9
105	8.6	904	1962.7	59.9	2.0	50.0	30.1
115	9.6	1105	2403.4	68.0	3.1	79.9	50.0

2. Test 2-P

This was a rerun of Test 1-P. Apparatus and parameters were all the same.

Conclusion: A definite lowering of ΔT to the liquid and of wall temperature at the higher heat fluxes was obtained. A hysteresis of boiling mode was shown in the upper parts of the cylinder. See Figure 15 and compare temperature during power increase and power decrease.

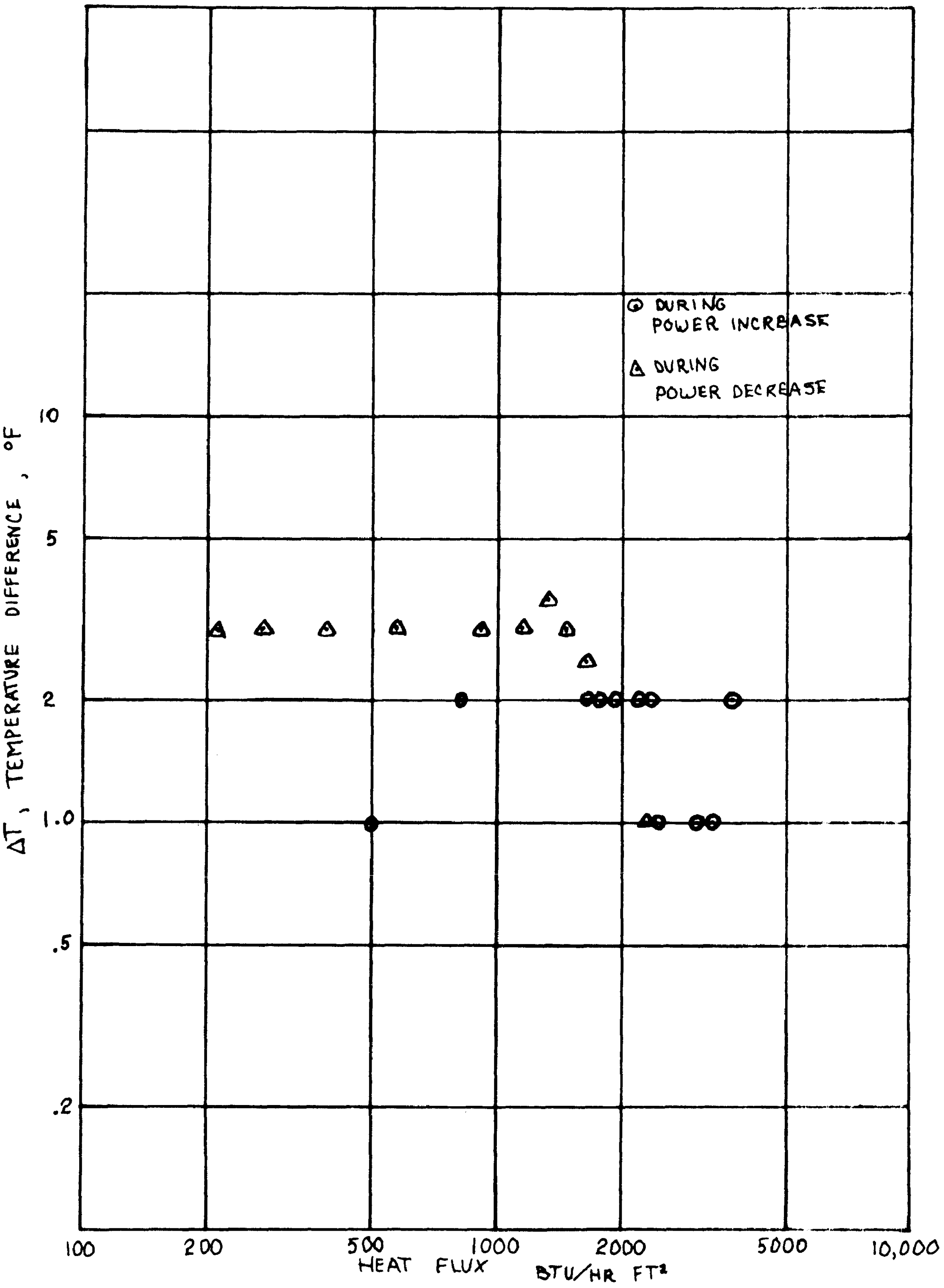

FIGURE 14 - TEST 2-P, TC1 Pressurized Pool Boiling at 10 psig. Thermocouple No. 1, ½ inch from the Bottom.

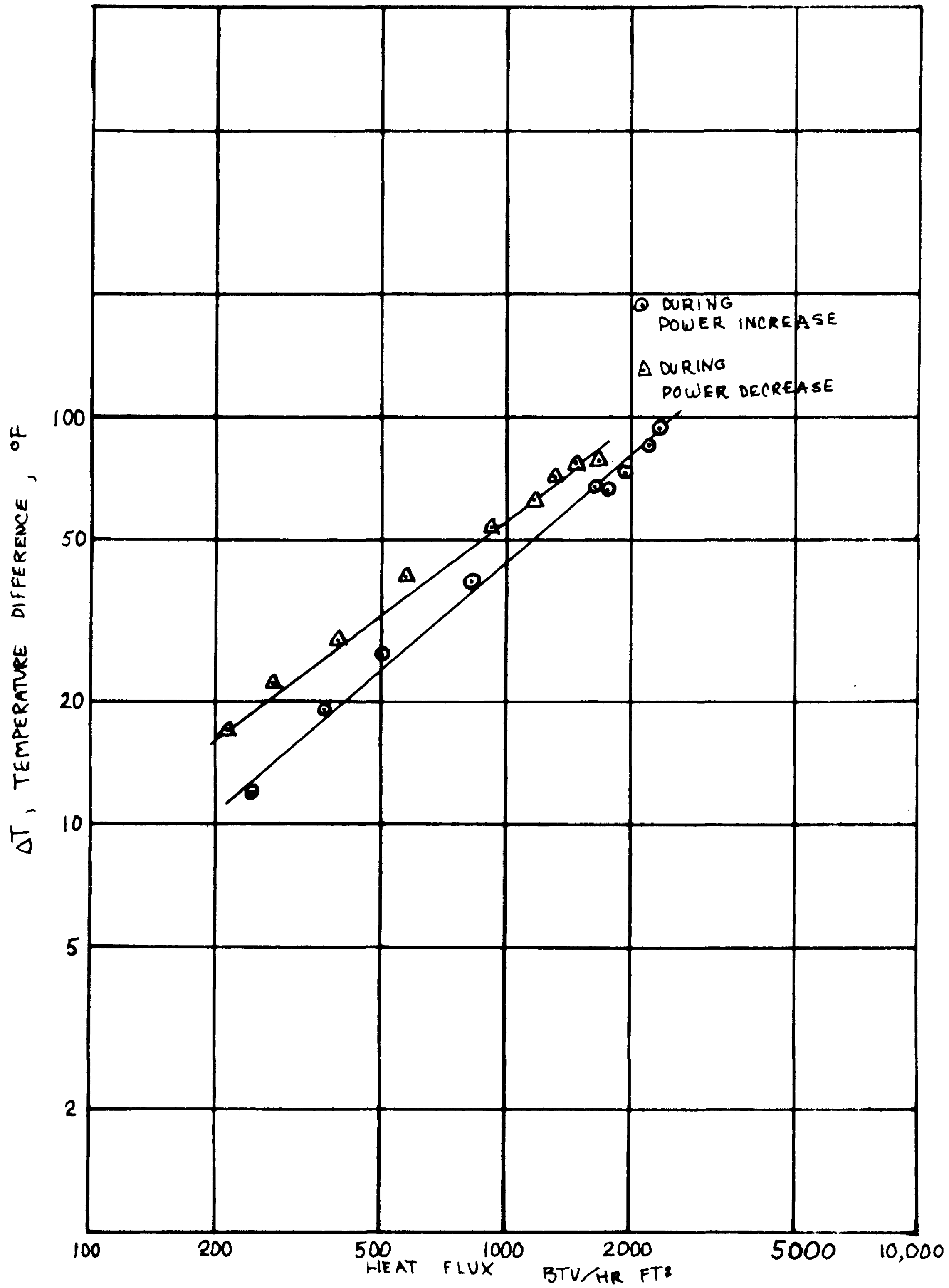

FIGURE 15 - TEST 2-P, TC2 Pressurized Pool Boiling at 10 psig. Thermocouple No. 2, 7 inches from the Bottom.

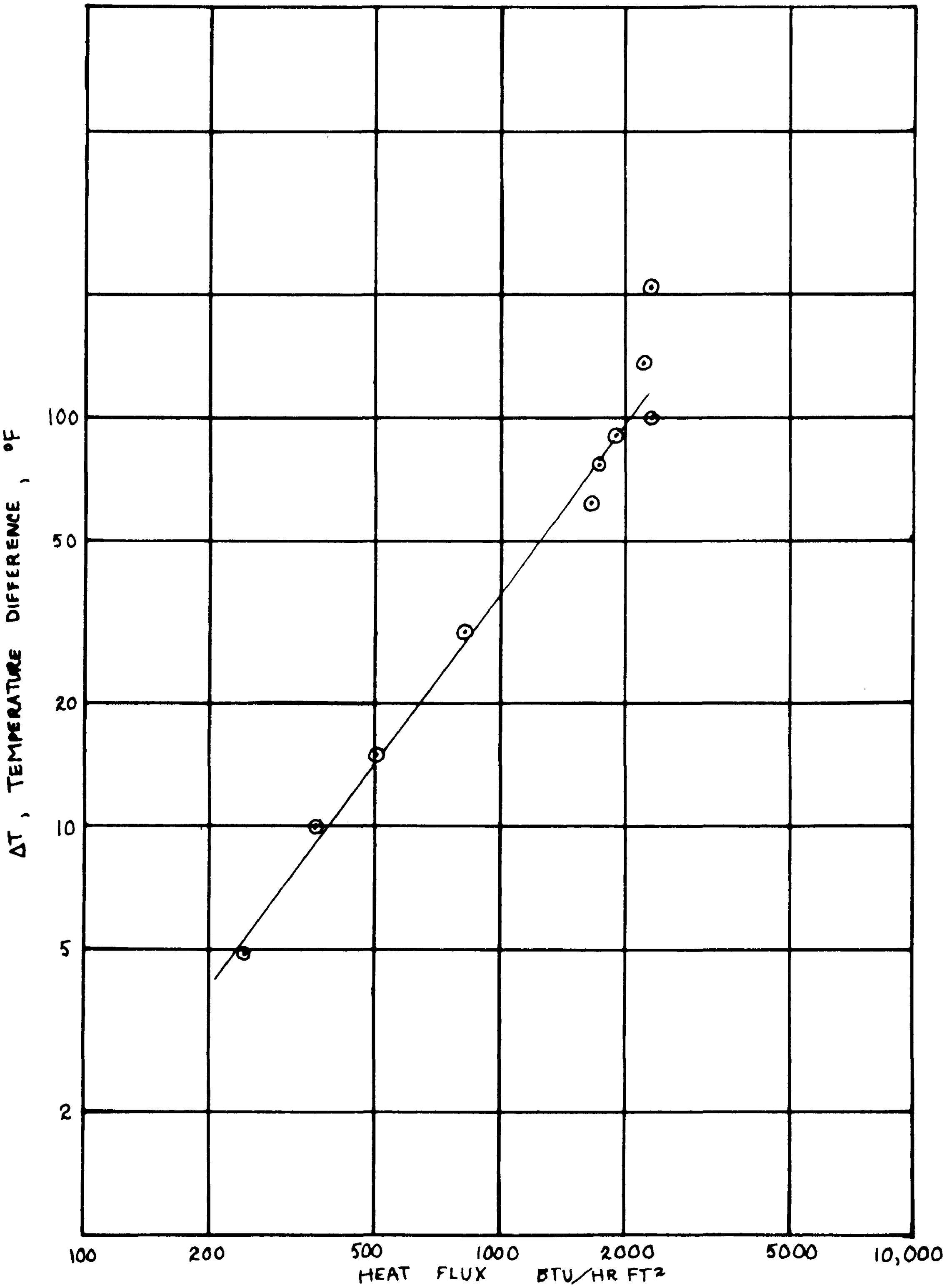

FIGURE 16 - TEST 2-P, TC3 Pressurized Pool Boiling at 10 psig. Thermocouple No. 3, 12 inches from the Bottom.

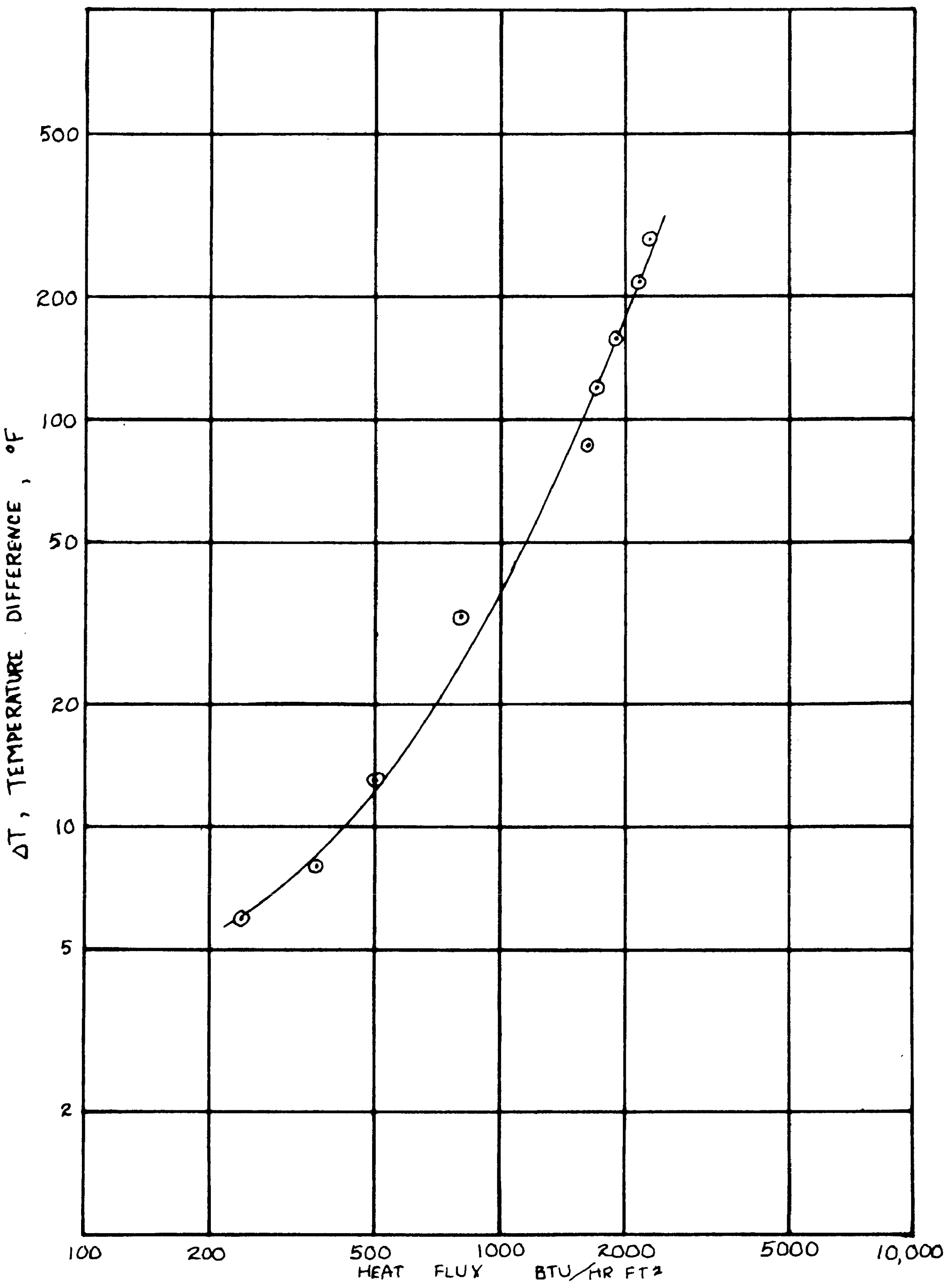

FIGURE 17 - TEST 2-P, TC4 Pressurized Pool Boiling at 10 psig. Thermocouple No. 4, 17½ inches from the Bottom.

TABLE 5 - <u>TEST 2-P Thermocouples No. 2, 3, and 4.</u>

Heat transfer to liquid nitrogen boiling at 10 psig in a 3-inch-inside-diameter vertical cylinder. The thermocouples were 7, 12, and 17½ inches from the bottom, respectively.

Current	Voltage	Power	Heat Flux	TC2	TC3	TC4
(Amps)	(Volts)	(Watts)	$\left(\frac{\text{BTU}}{\text{hr ft}^2}\right)$	(°F)	(°F)	(°F)
41	2.6	107	244	12	5	6
50	3.2	160	362	19	10	8
58	3.8	220	502	26	15	13
73	4.9	375	812	39	30	33
100	7.3	730	1660	66	63	86
87	8.7	766	1745	64	77	118
92	9.2	847	1925	72	90	156
98	9.9	970	2210	84	137	217
101	10.1	1020	2321	92	208	273
105	10.3	1081	2465	65*	65*	91*
110	12.0	1330	3010	98*	121*	184*
119	12.4	1478	3360	122*	164*	300*
129	12.9	1665	3785	156*	273*	426*
103	10.0	1030	2341	64	100	77
97	7.5	729	1659	77	112	108
92	7.1	654	1490	76	112	144
86	6.7	576	1310	70	111	173
81	6.4	518	1179	62	120	195
72	5.6	403	918	53	129	212
59	4.3	254	577	40	129	216
49	3.6	177	399	28	128	216
40	3.0	120	273	22		215
36	2.6	94	213	17		213

* unsteady value, not plotted in Figures 15, 16, or 17.

3. Test 3-P

Purpose: Measure the pool-boiling performance of liquid nitrogen in a vertical cylinder at 20 psig (30 psia).

Parameters, apparatus, and instrumentation were the same as in previous pressurized tests.

Conclusion: Wall-to-fluid temperature difference was further reduced compared with Tests 1-P and 2-P at lower pressure.

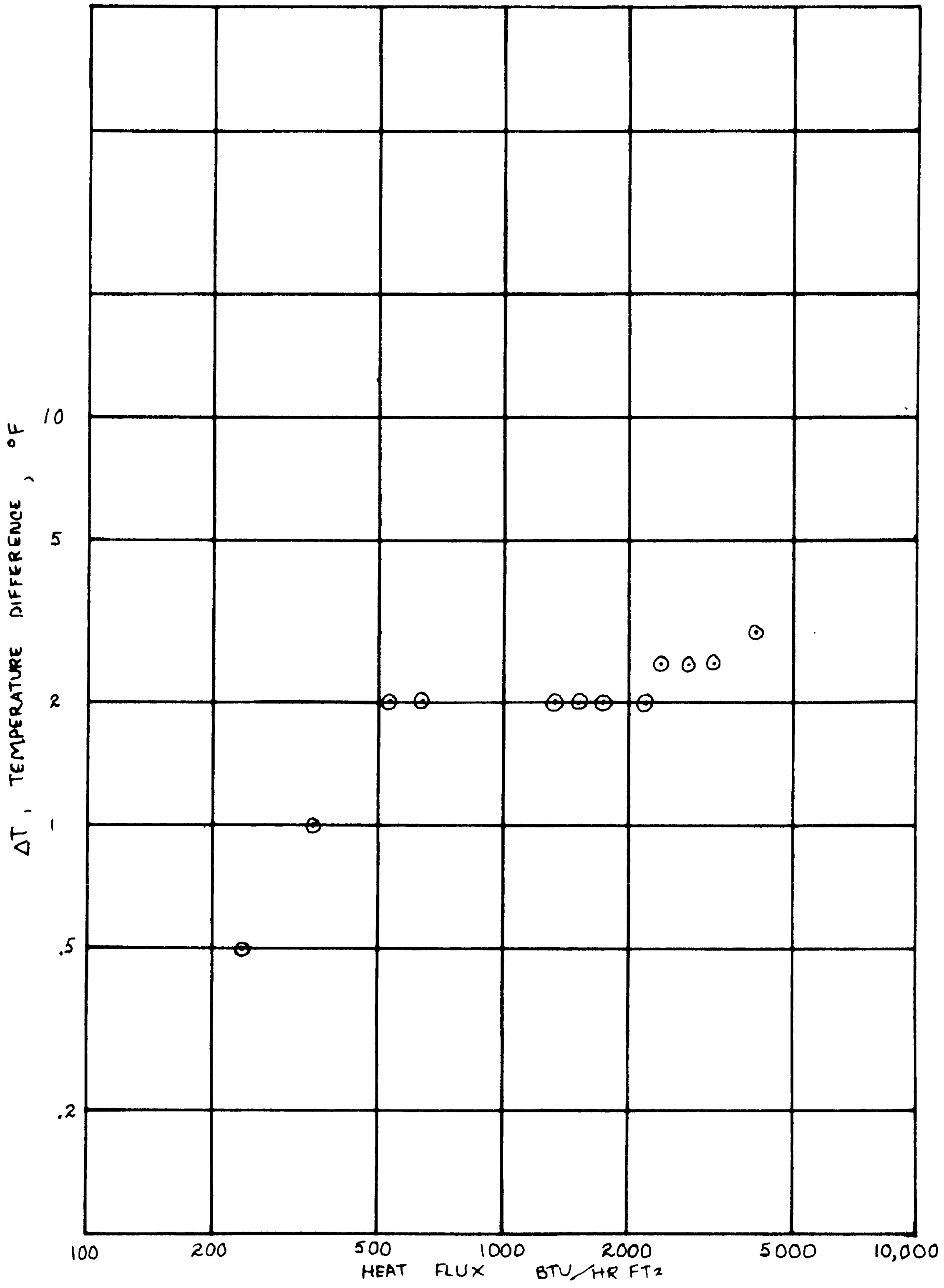

FIGURE 18 - TEST 3-P, TC1 Pressurized Pool Boiling at 20 psig. Thermocouple No. 1, ½ inch from the Bottom.

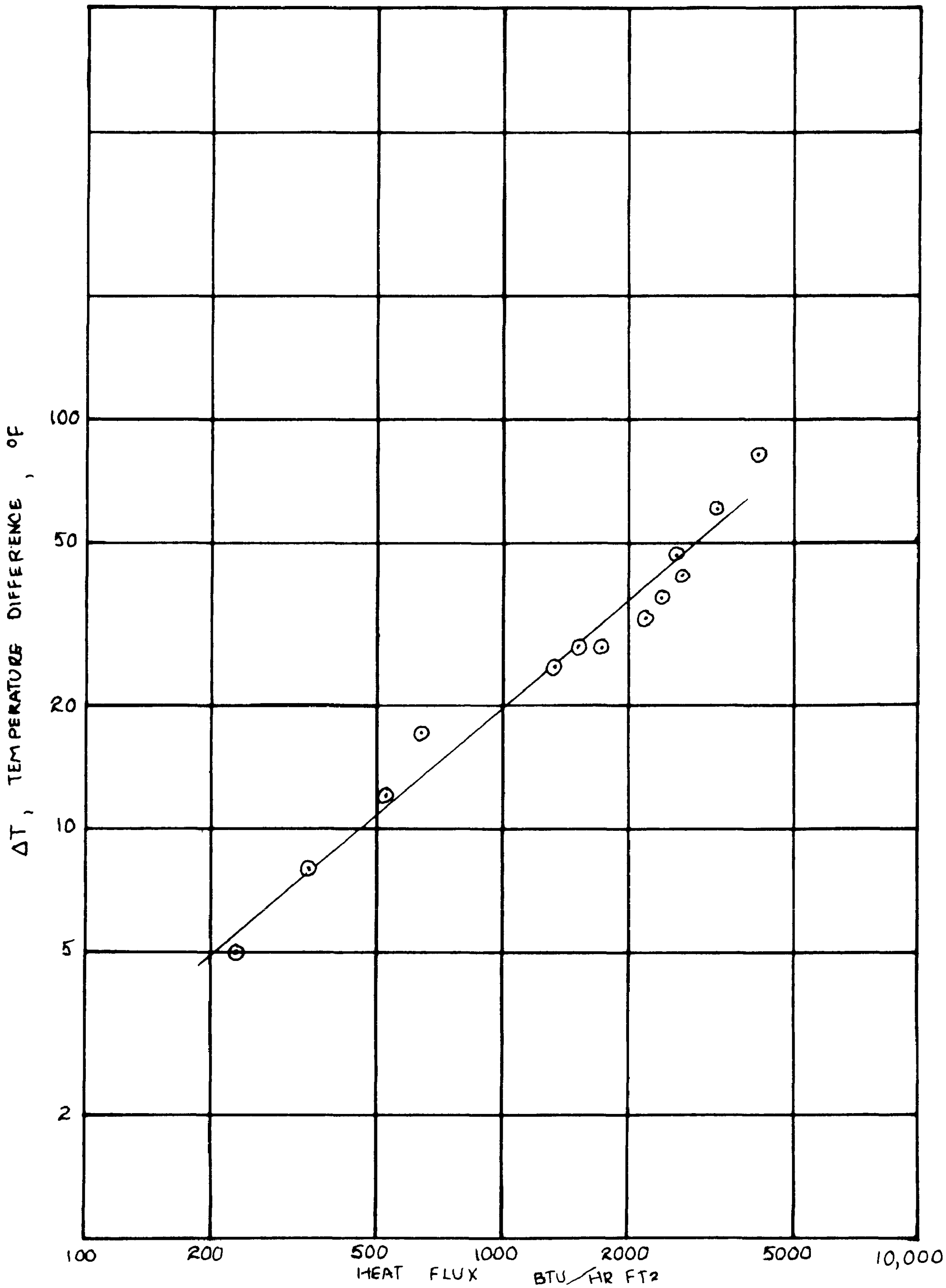

FIGURE 19 - TEST 3-P, TC2 Pressurized Pool Boiling at 20 psig. Thermocouple No. 2, 7 inches from the Bottom.

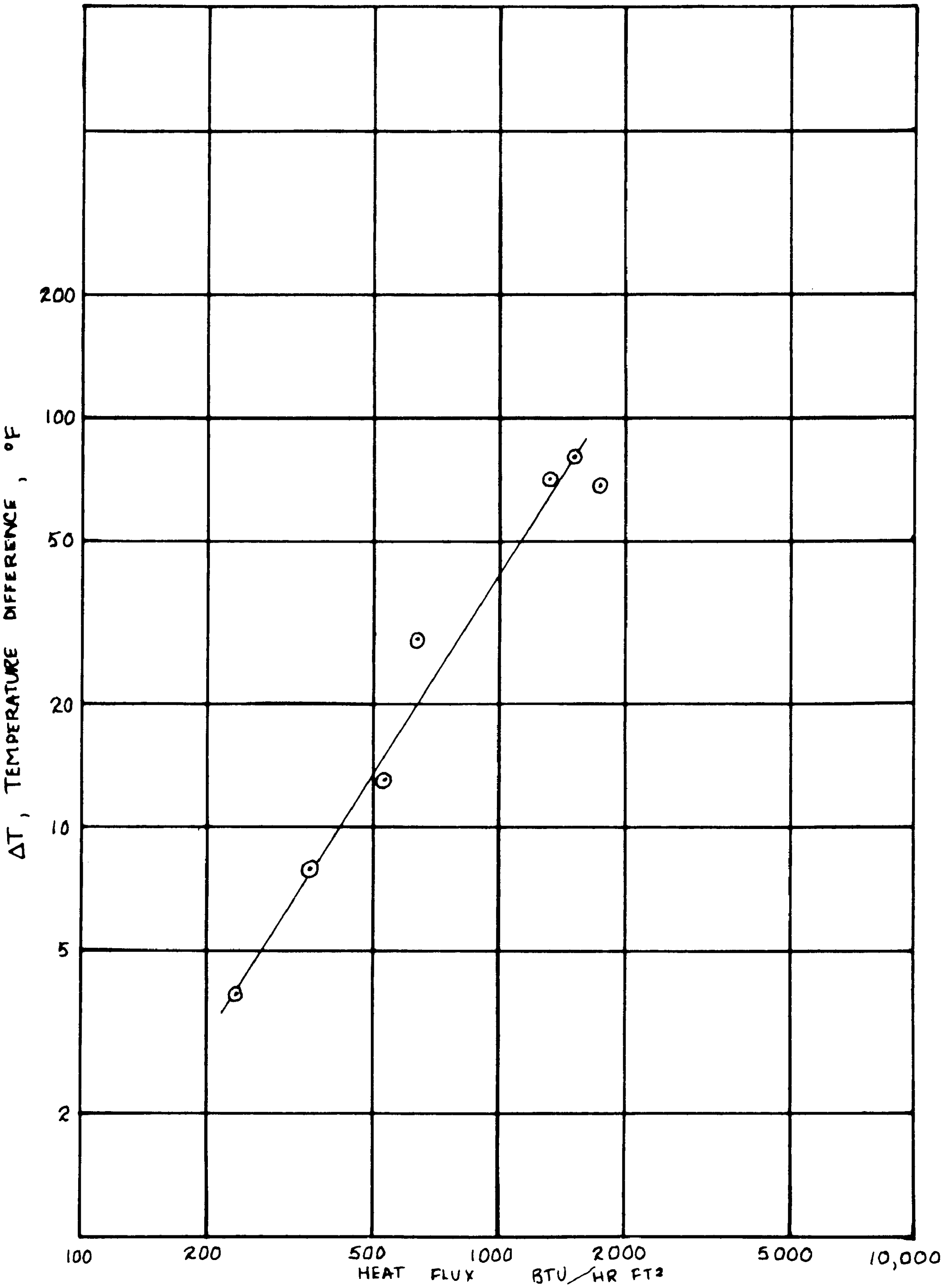

FIGURE 20 - TEST 3-P, TC3 Pressurized Pool Boiling at 20 psig. Thermocouple No. 3, 12 inches from the Bottom.

TABLE 6 - TEST 3-P Thermocouples 1, 2, and 3.

Heat transfer to liquid nitrogen boiling at 20 psig in a 3-inch-inside-diameter vertical cylinder. The thermocouples were $\frac{1}{2}$, 7, and 12 inches from the bottom, respectively.

Current	Voltage	Power	Heat Flux	TC1	TC2	TC3
(Amps)	(Volts)	(Watts)	$\left(\frac{\text{BTU}}{\text{hr ft}^2}\right)$	(°F)	(°F)	(°F)
40	2.6	104	236	0.5	5	4
48	3.2	154	351	1.0	8	8
59	4.0	236	536	2.0	12	13
73	5.2	380	644	2.0	17	29
100	7.6	760	1725	2.0	28	68
86	6.7	576	1312	2.0	25	71
92	7.2	663	1505	2.0	28	80
97	10.0	970	2202	2.0	33	113*
102	10.5	1071	2438	2.5	37	164*
106	11.2	1188	2701	2.5	42	215*
114	10.1	1152	2622	2.5	46	106*
120	12.0	1440	3280	2.5	62	165*
130	13.6	1768	4030	3.0	82	217*
118	12.7	1499	3410	2.5	80	262*
111	12.0	1332	3035	2.5	78	312*
106	11.8	1252	2850	2.5	130*	345*
102	10.0	1020	2312	2.0	42	72
97	7.7	746	1698		46	100
92	7.4	681	1546		45	106
87	6.9	600	1367	1.0	42	99
82	6.4	525	1197	1.0	38	92
70	5.3	371	844	1.0	35	89
57	4.2	239	543	1.0	30	91
50	3.6	181	412	1.0	27	102
40	3.0	120	274	1.0	25	105
35	2.6	91	207		23	102

* unsteady value, not plotted in Figures 19 or 20.

4. Test 4-P

Purpose: Further exploration of the boiling behavior of liquid nitrogen with pressure increased to 50 psig (60 psia).

Apparatus: Same as in Test 3-P.

Instrumentation: Same as in Test 3-P.

Conclusion: Minima in the wall temperature vs. pressure curves, with heat-flux constant along each curve, were found. This relationship is shown in Figure 32.

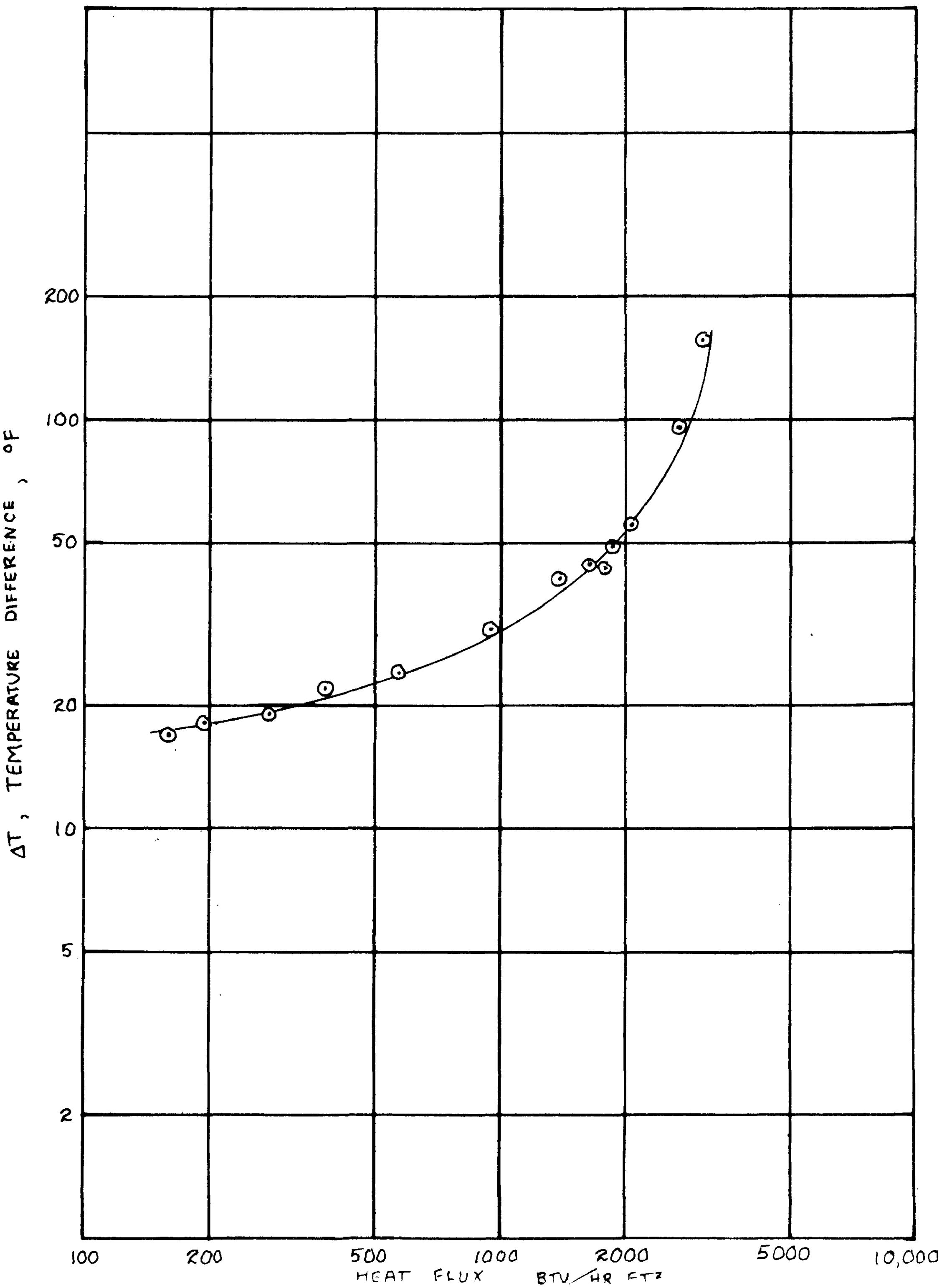

FIGURE 21 - TEST 4-P, TC 2 Pressurized Pool Boiling at 50 psig. Thermocouple No. 2, 7 inches from the Bottom.

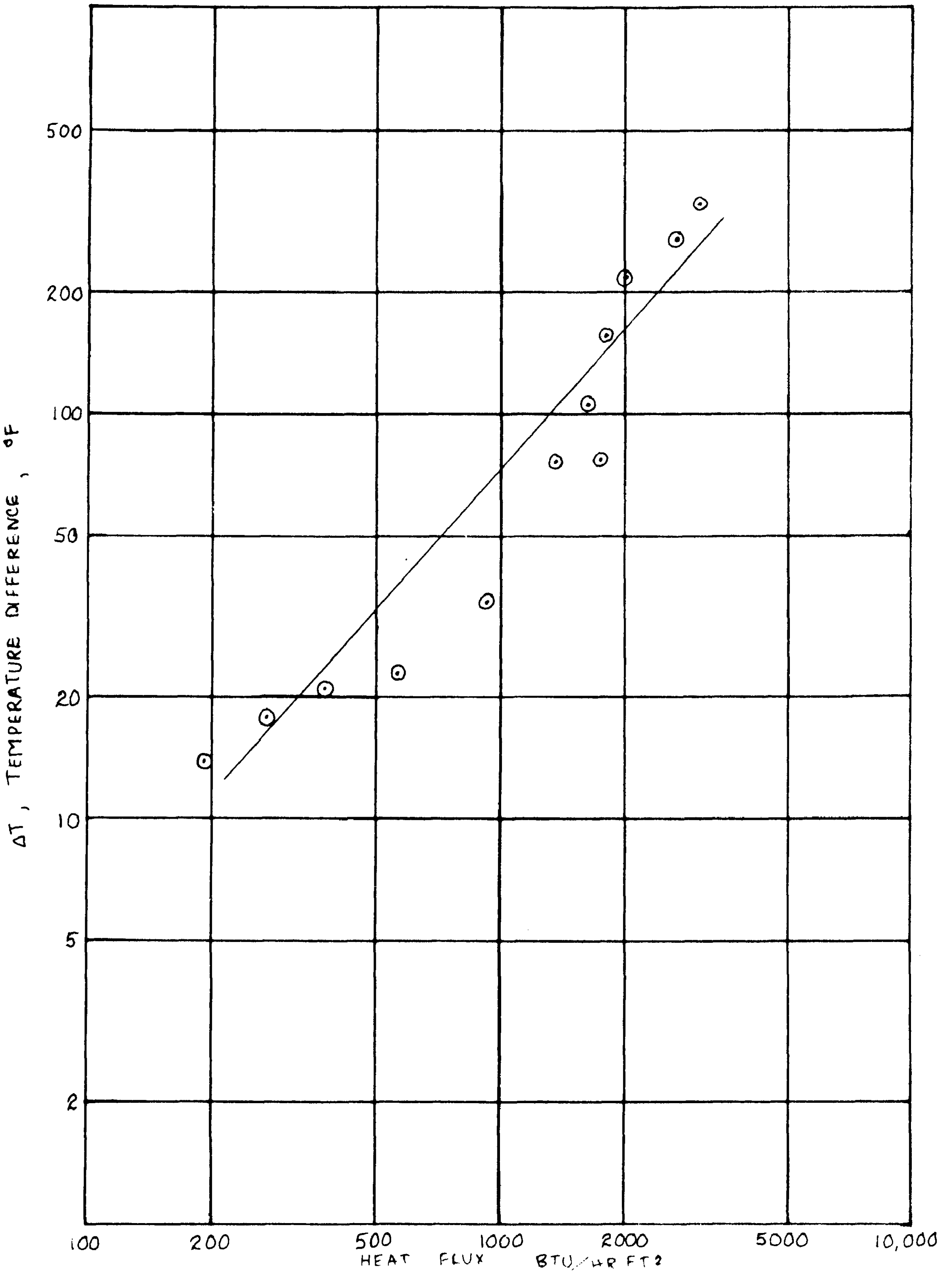

FIGURE 22 - TEST 4-P, TC3 Pressurized Pool Boiling at 50 psig. Thermocouple No. 3, 12 inches from the Bottom.

TABLE 7 - TEST 4-P Thermocouples 2 and 3.

Heat transfer to liquid nitrogen boiling at 50 psig in a 3-inch-inside-diameter vertical cylinder. The thermocouples were 7 and 12 inches from the bottom, respectively.

Current (Amps)	Voltage (Volts)	Power (Watts)	Heat Flux $\left(\frac{BTU}{hr\ ft^2}\right)$	TC2 (°F)	TC3 (°F)
32	2.2	70	160	17	
35	2.5	88	191	18	14
42	2.9	122	276	19	18
50	3.4	170	387	22	21
60	4.2	252	573	24	23
75	5.5	412	939	31	35
100	7.9	790	1790	43	77
87	7.0	608	1385	41	77
94	7.6	714	1625	44	107
98	8.2	804	1830	49	154*
102	8.7	888	2011	55	213*
105	11.3	1185	2700	93	268*
112	12.0	1345	3060	155	335*

* unsteady values

5. Test 5-P

Purpose: Better definition of the temperature-pressure boiling curves with heat flux as a parameter on the curve.

Apparatus: Same as in Test 3-P.

Instrumentation: Same as in Test 3-P.

Conclusion: Minima in the wall temperature vs. pressure curves at constant heat flux were between 25 and 30 psia.

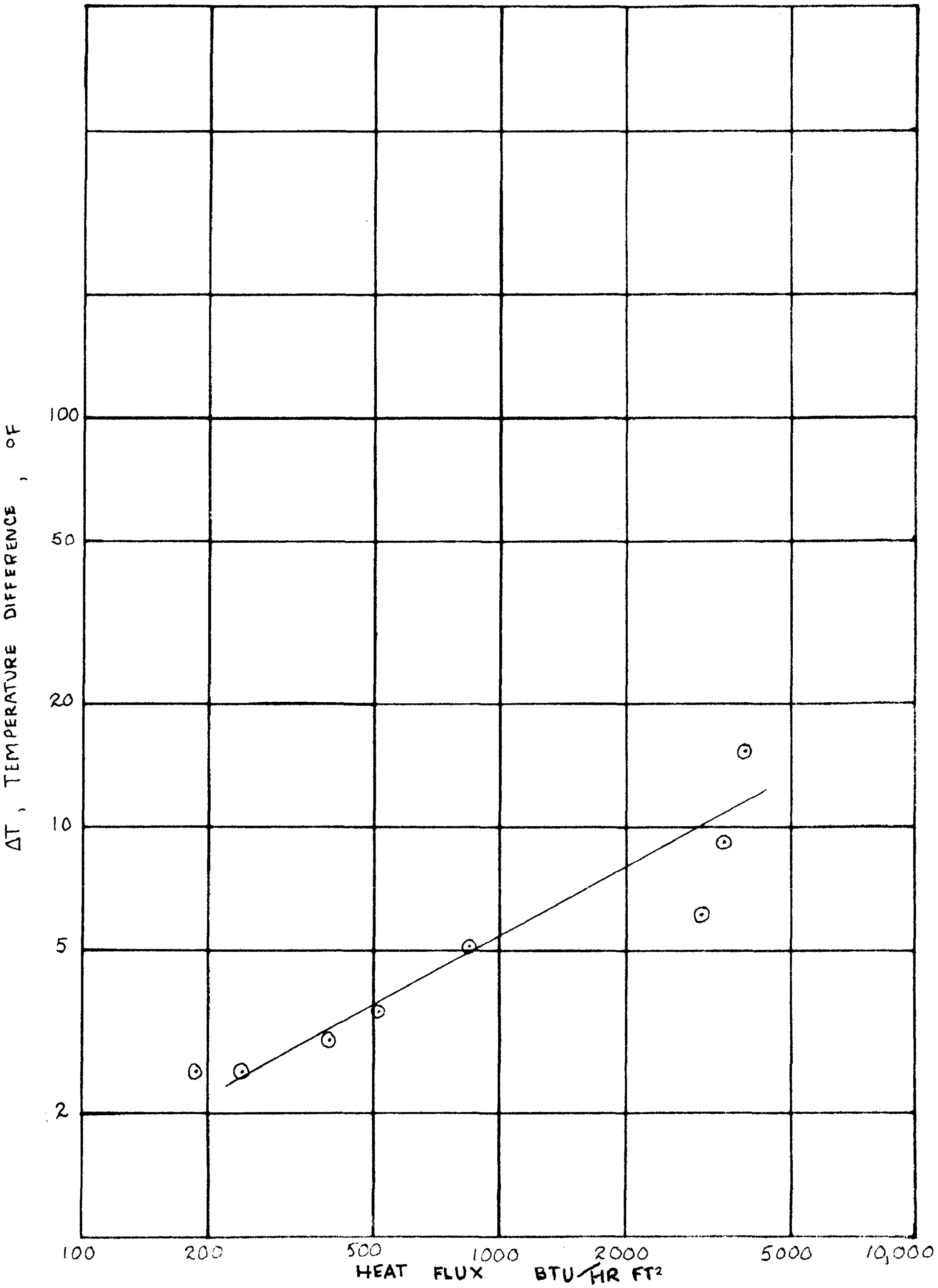

FIGURE 23 - TEST 5-P, TC1 Pressurized Pool Boiling at 15 psig. Thermocouple No. 1, $\frac{1}{2}$ inch from the Bottom.

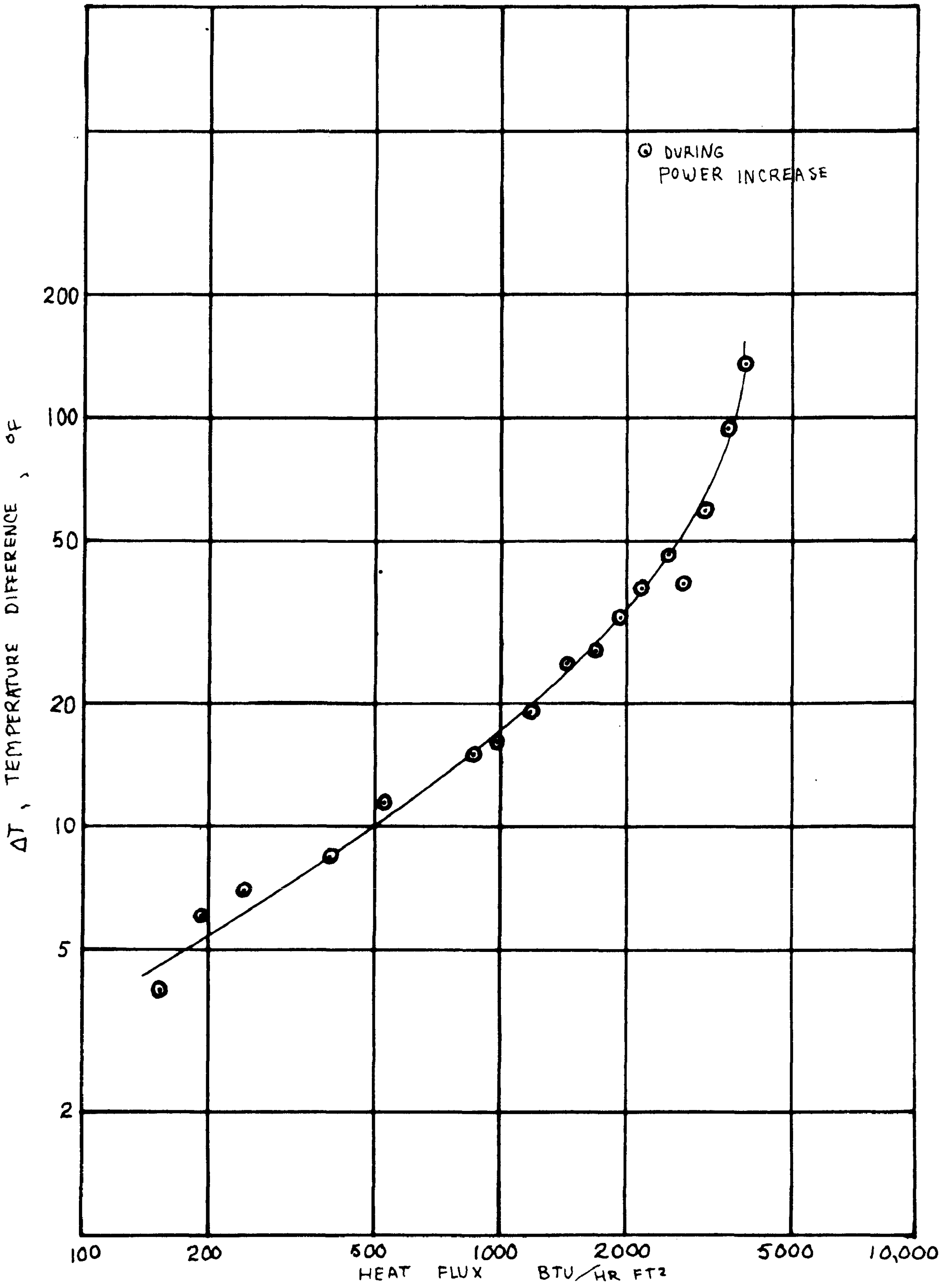

FIGURE 24 - TEST 5-P, TC2 Pressurized Pool Boiling at 15 psig. Thermocouple No. 2, 7 inches from the Bottom.

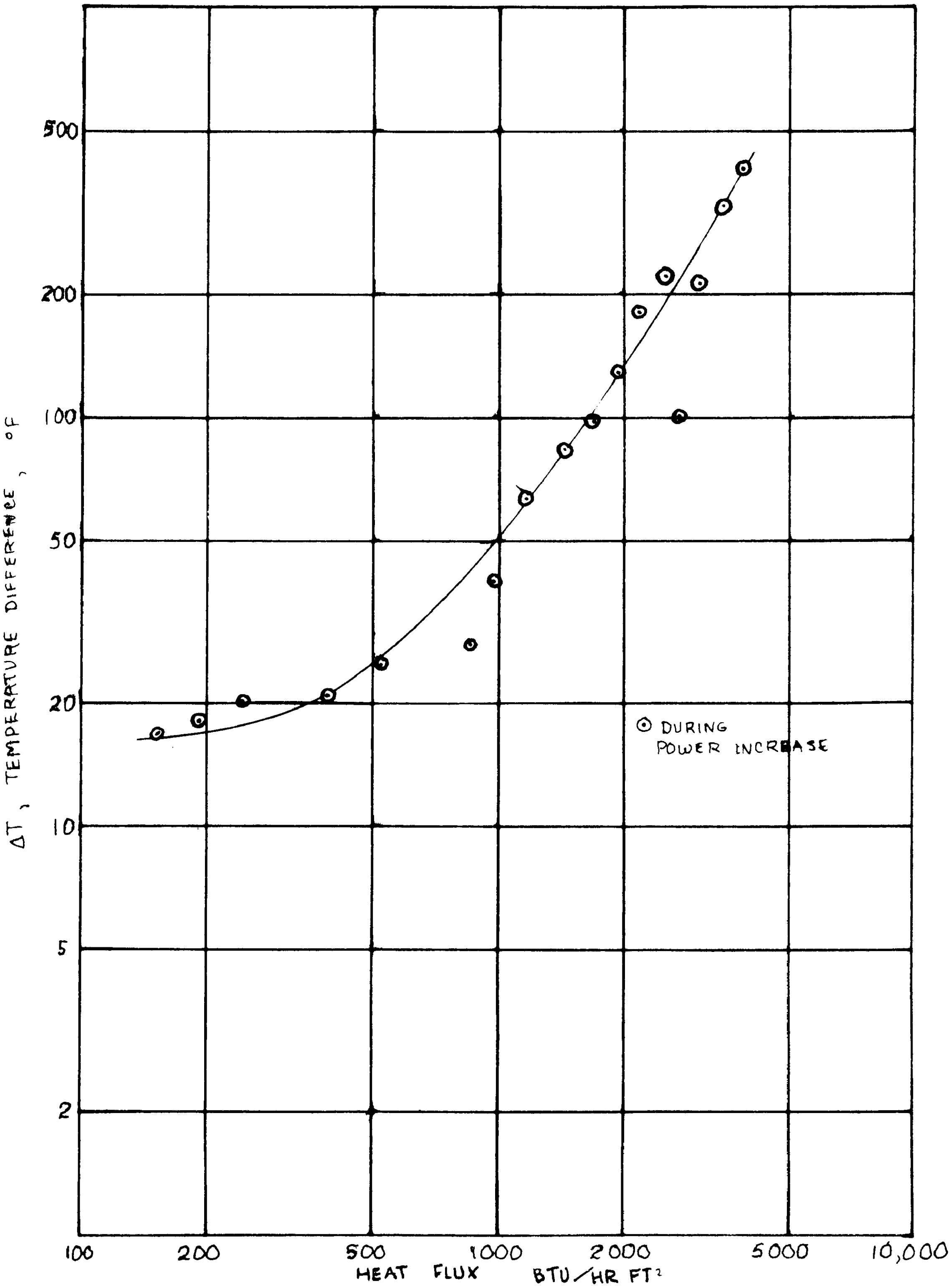

FIGURE 25 - TEST 5-P. TC3 Pressurized Pool Boiling at 15 psig. Thermocouple No. 3, 12 inches from the bottom.

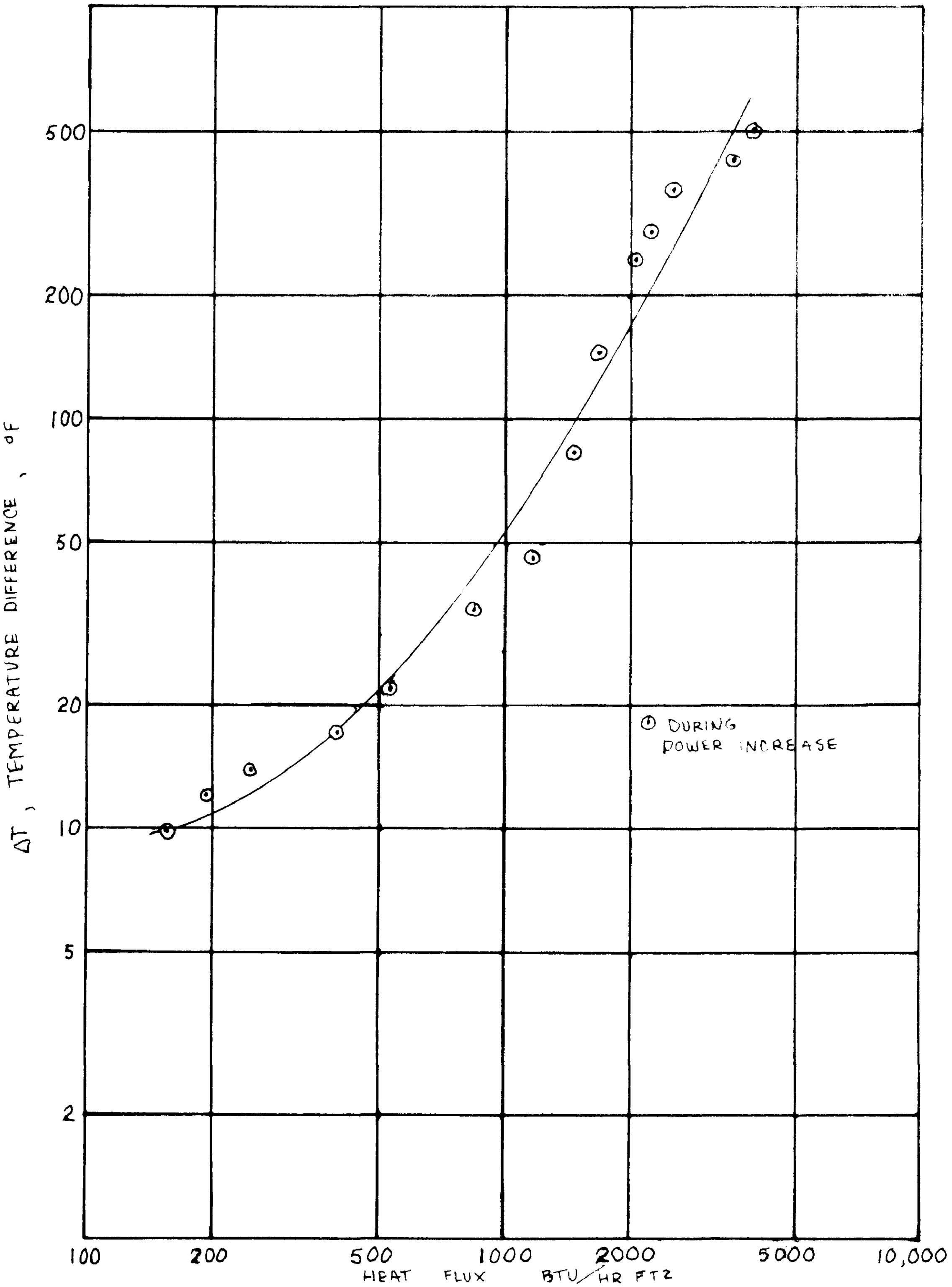

FIGURE 26 - TEST 5-P, TC4 Pressurized Pool Boiling at 15 psig. Thermocouple No. 4, 17½ inches from the Bottom.

TABLE 8 - TEST 5-P Thermocouples 1, 2, 3, and 4.

Heat transfer to liquid nitrogen boiling at 15 psig in a 3-inch-inside-diameter vertical cylinder. The thermocouples were $\frac{1}{2}$, 7, 12, and $17\frac{1}{2}$ inches from the bottom, respectively.

Current	Voltage	Power	Heat Flux	TC1	TC2	TC3	TC4
(Amps)	(Volts)	(Watts)	$\left(\frac{BTU}{hr\ ft^2}\right)$	(°F)	(°F)	(°F)	(°F)
32	2.1	67	153	0	4	17	10
35	2.4	84	191	2.5	6	18	12
40	2.7	108	246	2.5	7	20	14
51	3.4	174	395	3.0	9	21	17
58	4.0	232	528	3.5	12	25	22
73	5.2	380	864	5.0	15	28	32
79	5.5	435	991	2.0	16	40	27
85	6.2	527	1196	1.0	19	63	46
90	7.0	630	1432	3.0	25	82	83
97	7.7	747	1700	1.0	28	98	146*
102	8.3	847	1928	1.0	33	128*	214*
105	9.2	966	2200	1.5	38	179*	282*
111	10.0	1110	2525	1.0	46	217*	356*
122	10.0	1220	2785	4.0	39	100*	117*
129	10.3	1330	3012	6.0	59	210*	244*
144	10.7	1540	3500	9.0	93	320*	422*
159	10.9	1735	3950	15.0	135	400*	500*

* unsteady values

6. Test 6-P

Purpose: Test 6-P was run under steady conditions with the boiling liquid nitrogen being continually re-filled. The pressure level was the same as in 5-P.

Apparatus and instrumentation: Same as in 5-P, except that the liquid nitrogen supply reservoir was pressurized to 20 psig to provide sustained flow during the test. See Figure 27 for the test setup.

Conclusion: Data with steady flow were not appreciably different from batch-boiling measurements, confirming the validity of the previous tests.

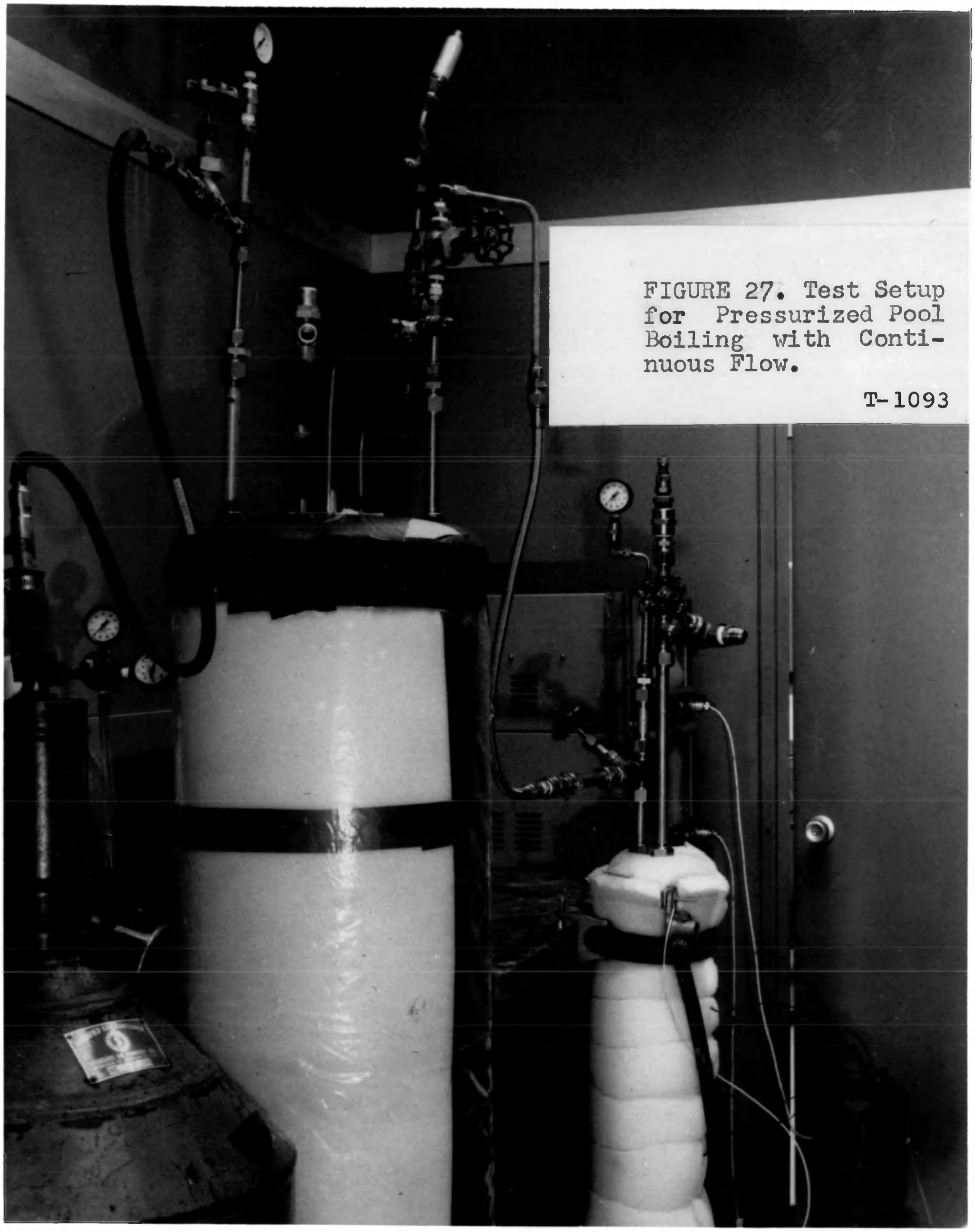

FIGURE 27. Test Setup for Pressurized Pool Boiling with Continuous Flow.

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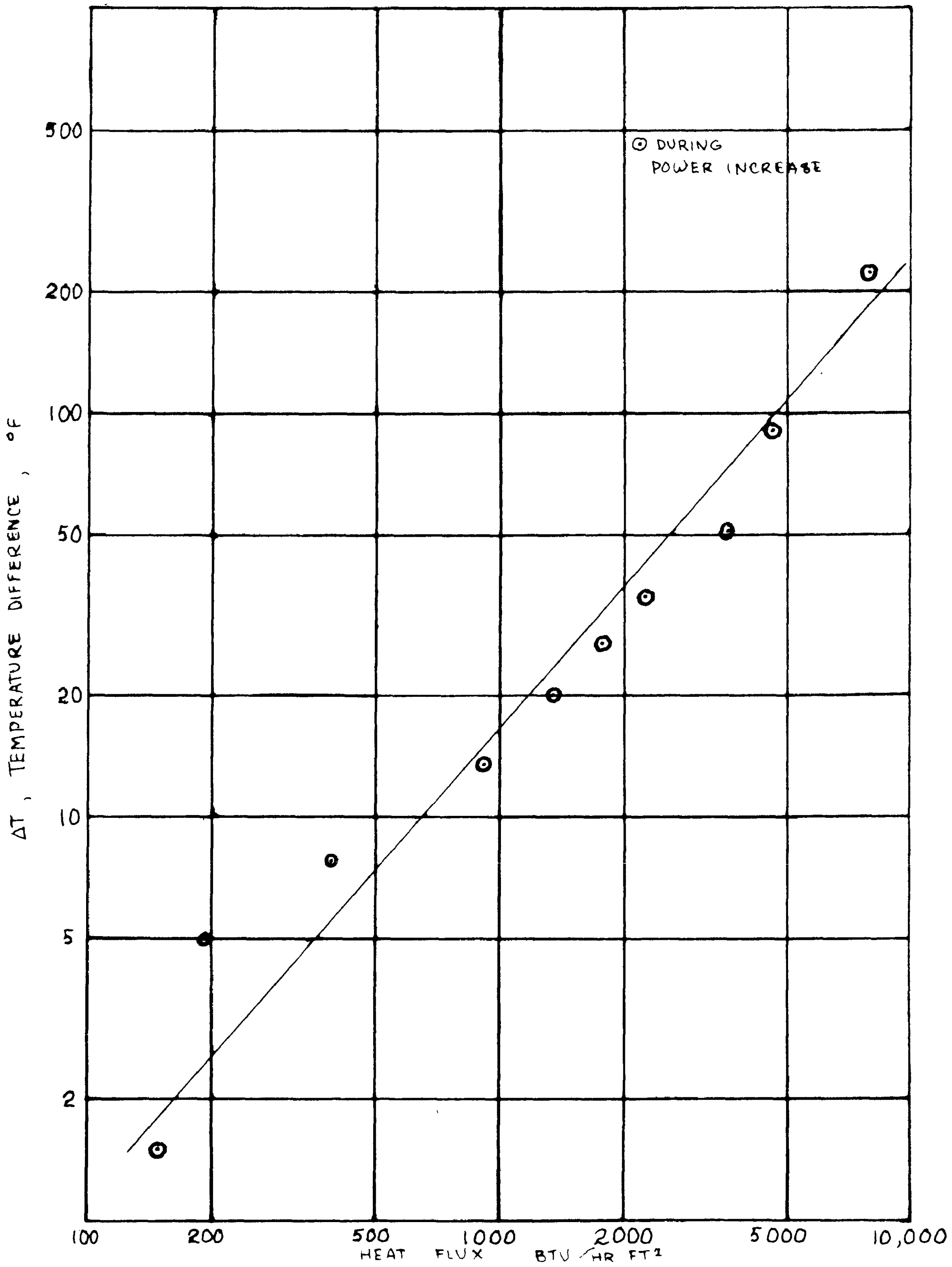

FIGURE 28 - TEST 6-P, TC2 Pressurized Pool Boiling at 15 psig, with Steady Flow of Liquid into the Boiling Cylinder. Thermocouple No. 2, 7 inches from the Bottom.

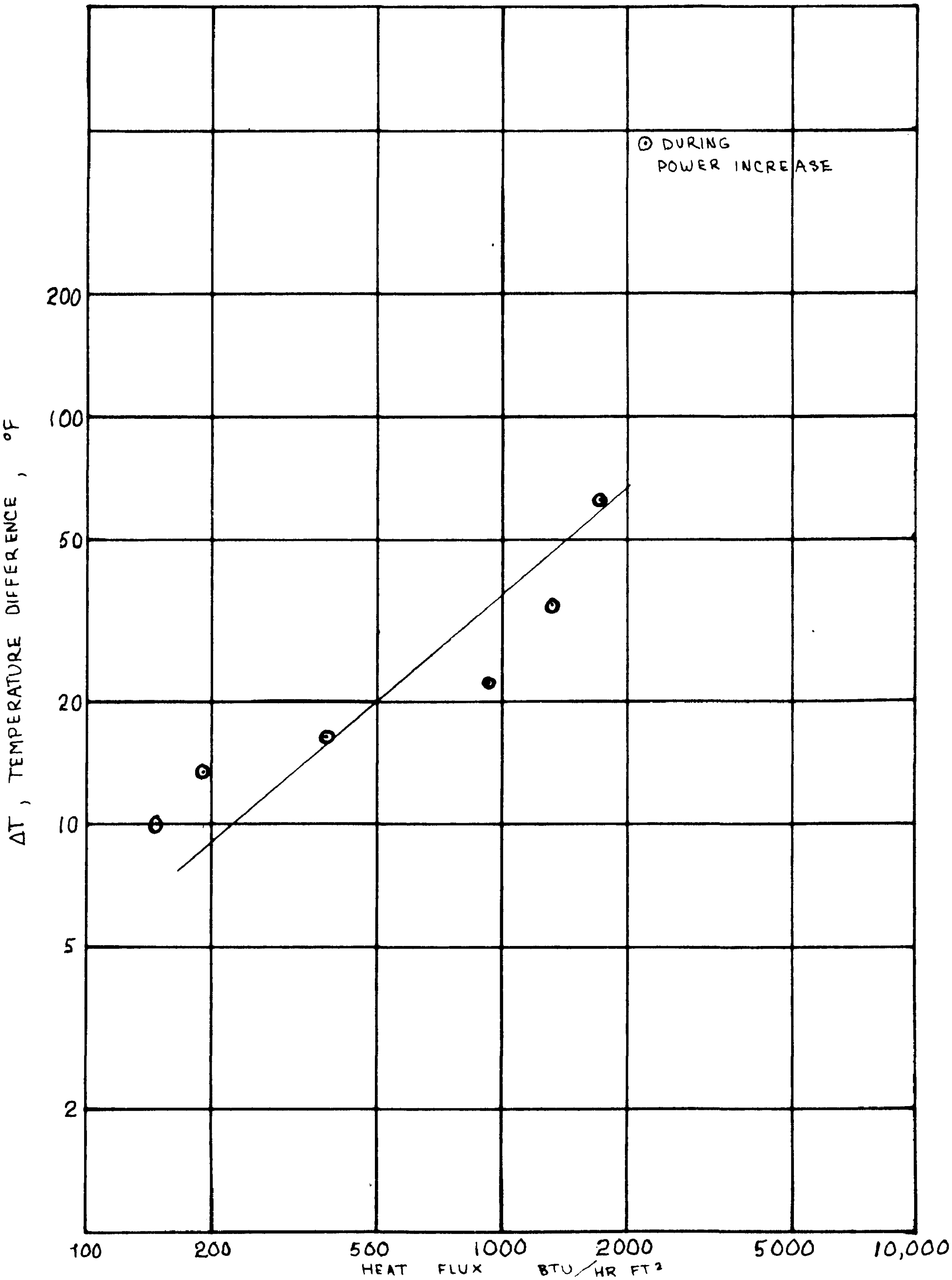

FIGURE 29 - TEST 6-P, TC3 Pressurized Pool Boiling at 15 psig, with Steady Flow of Liquid into the Boiling Cylinder. Thermocouple No. 3, 12 inches from the Bottom.

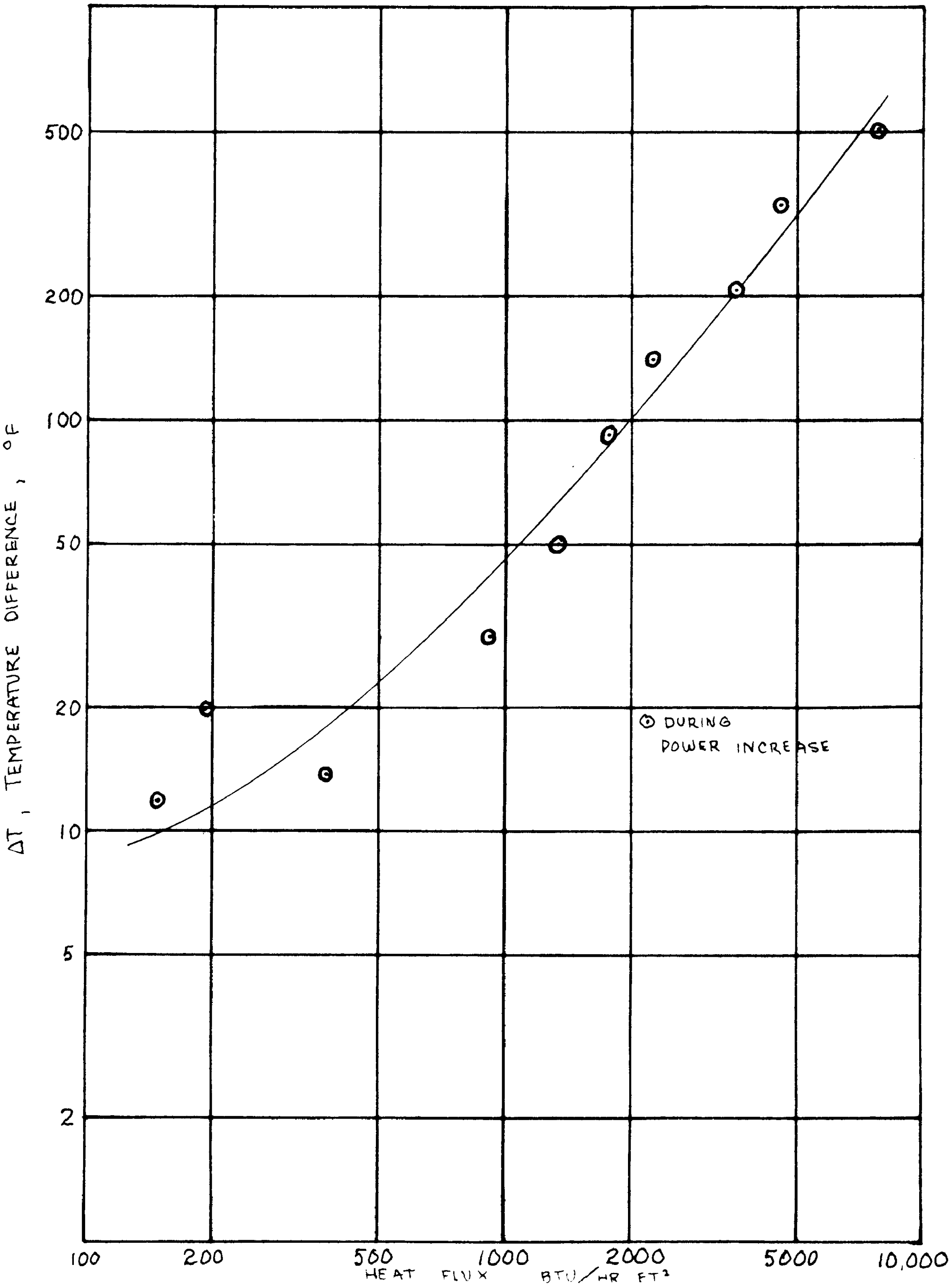

FIGURE 30 - TEST 6-P, TC4 Pressurized Pool Boiling at 15 psig, with Steady Flow of Liquid into the Boiling Cylinder. Thermocouple No. 4, 17½ inches from the Bottom.

TABLE 9 - TEST 6-P Thermocouples 2, 3, and 4.

Heat transfer to liquid nitrogen boiling at 15 psig in a 3-inch-diameter vertical cylinder. Steady liquid flow was provided into the bottom of the cylinder sufficient to maintain a liquid spray in the vapor boil-off throughout the test.

Current (Amps)	Voltage (Volts)	Power (Watts)	Heat Flux $\left(\frac{\text{BTU}}{\text{hr ft}^2}\right)$	TC2 (°F)	TC3 (°F)	TC4 (°F)
31	2.1	65	148	2	10	12
35	2.4	84	191	5	14	20
50	3.4	170	387	8	17	14
75	5.3	397	904	14	23	30
89	6.5	578	1312	20	35	50
100	7.6	760	1730	27	62*	92*
107	9.2	984	2240	35	90*	140*
145	10.8	1565	3560	51	120*	208*
147	13.4	1970	4480	90	191*	335*
193	18.0	3470	7900	222*	330*	500*

* unsteady values

DISCUSSION OF TEST RESULTS

Analysis of the test results serves two purposes: to derive general relations for boiling of liquid nitrogen, and to discover, if possible, the causes of any anomalies.

One such anomaly is the erratic behavior of thermocouple number-1, $\frac{1}{2}$ inch from the bottom. It was expected that the wall temperature at this point in the bottom of the cylinder might follow the classic boiling and burnout curve for small elements. However, an inspection of the number-1 thermocouple graphs shows erratic behavior. This behavior is apparently caused by end effects, because thermocouple number-1 was located at the very lower edge of the heating element. These data, included for the sake of the record, are not believed to be particularly useful for determining a regular boiling relation.

From erratic temperature readings at zero heat-flux early in the experiments, it was decided that the thermocouples were changing calibration when spot-welded to the stainless steel. Accurate ΔT values were calculated from the experimental data by using the recorder reading at low heat flux as the base line for temperature change. Thus two corrections are made: the correction for thermocouple calibration and the correction for change in saturation temperature with pressure. The corrections are not made in the values in the Experimental Results section, but are made in the present section, except for Figure 32.

Effect of Pressure

A minimum in wall temperature occurs at about 30 psia, as shown in Figure 32. This minimum in wall temperature is one of the more interesting results of the study, because of its application to cryopumping and other situations for cooling by cryogenic fluids. The effect was discussed briefly at the beginning of the pressurized boiling part of the Experimental Results section.

The effect of pressurization can be explained by assuming that the minimum ΔT will occur when the heat-exchange surface is completely covered with liquid. A displacement of liquid by vapor such as happens when film boiling occurs, or when bubbles rise from the surface elements below the local element being considered, will greatly increase the ΔT at a given flux. Inasmuch as buoyancy forces carry away the vaporized phase, and the

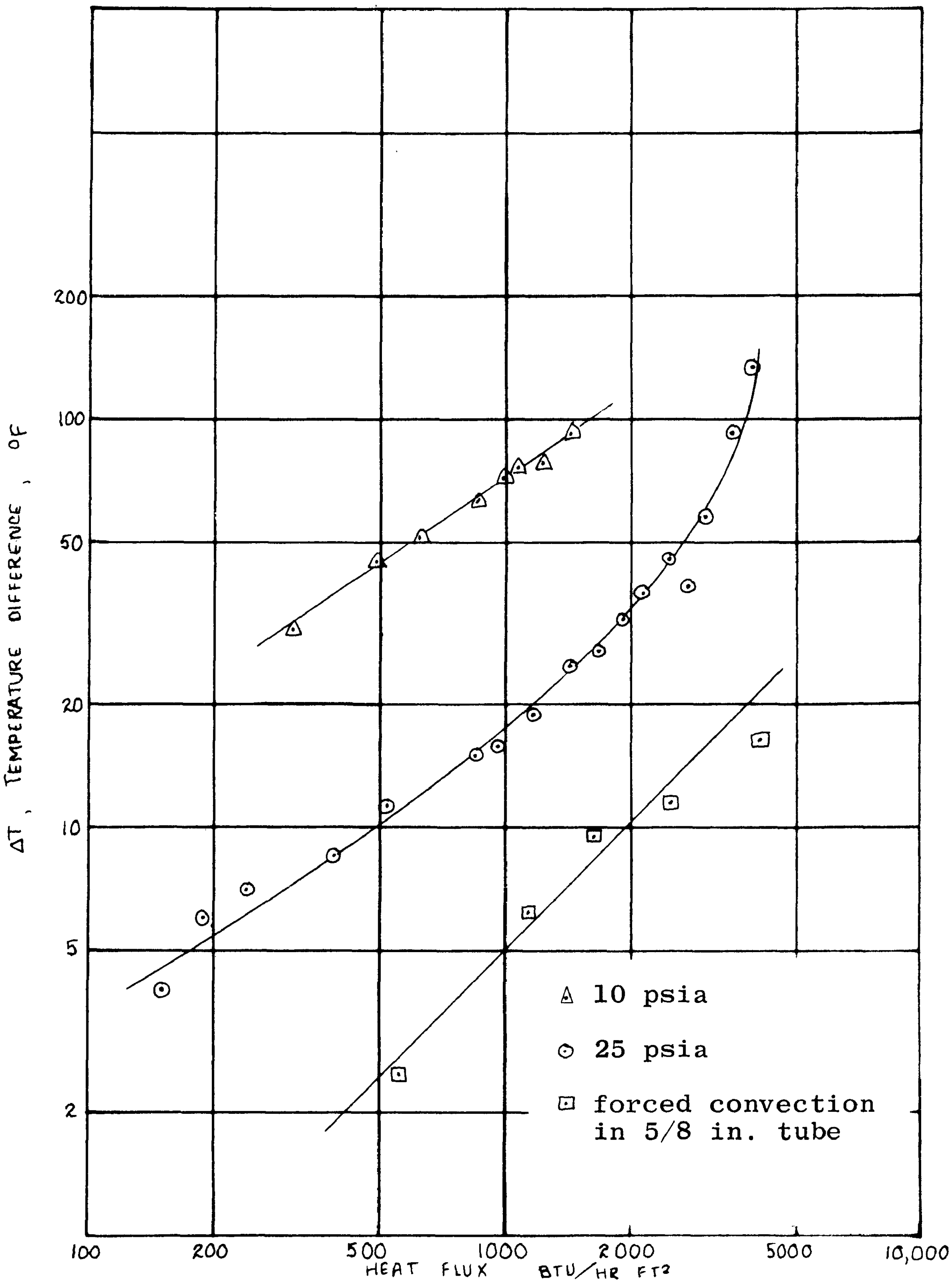

FIGURE 31 - Effect of Pressure on Wall-to-Bulk-Fluid Temperature Difference. Values given are for the 7-inch Level, Thermocouple No. 2.

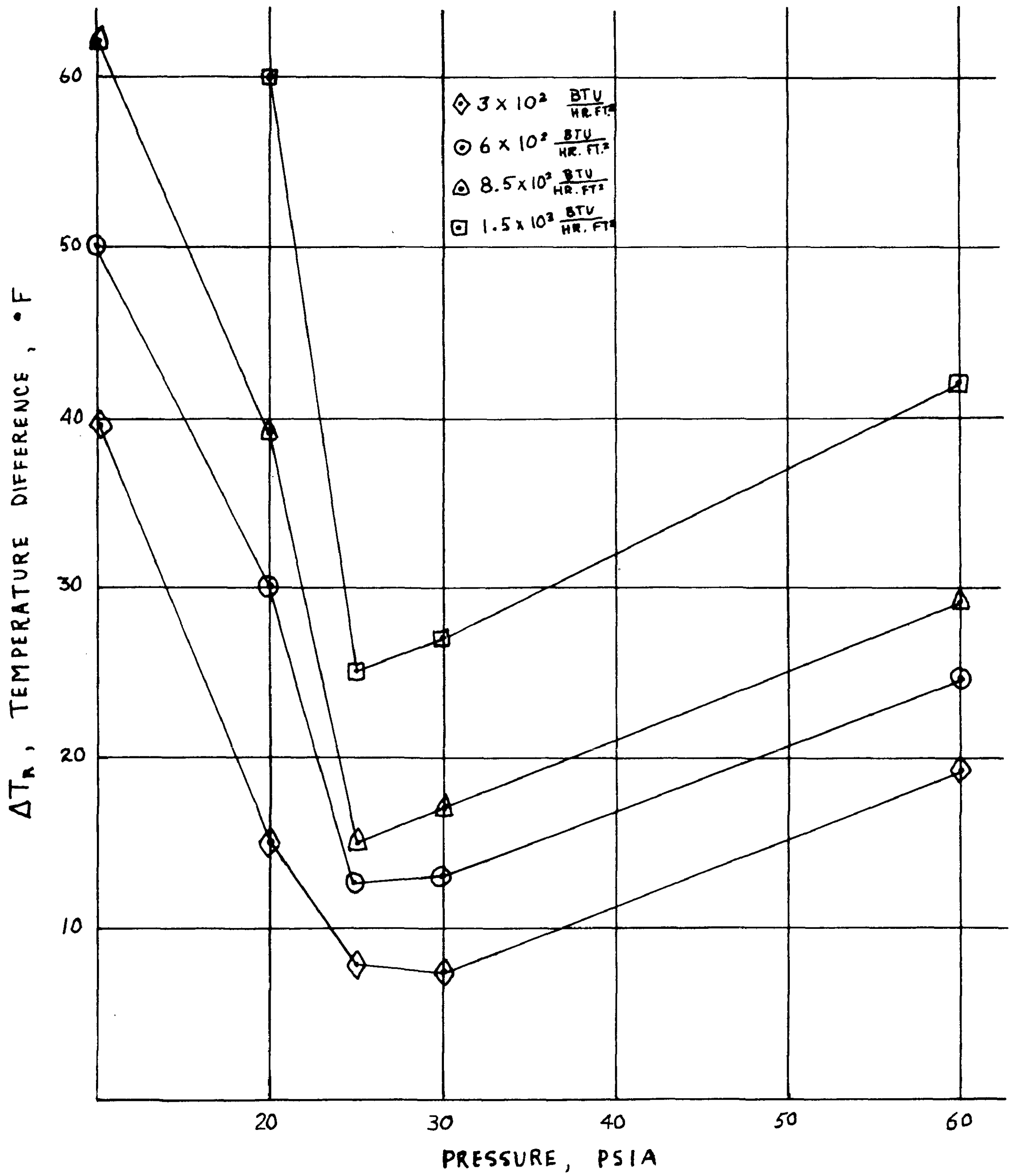

FIGURE 32 - Effect of Pressure on Wall Temperature.

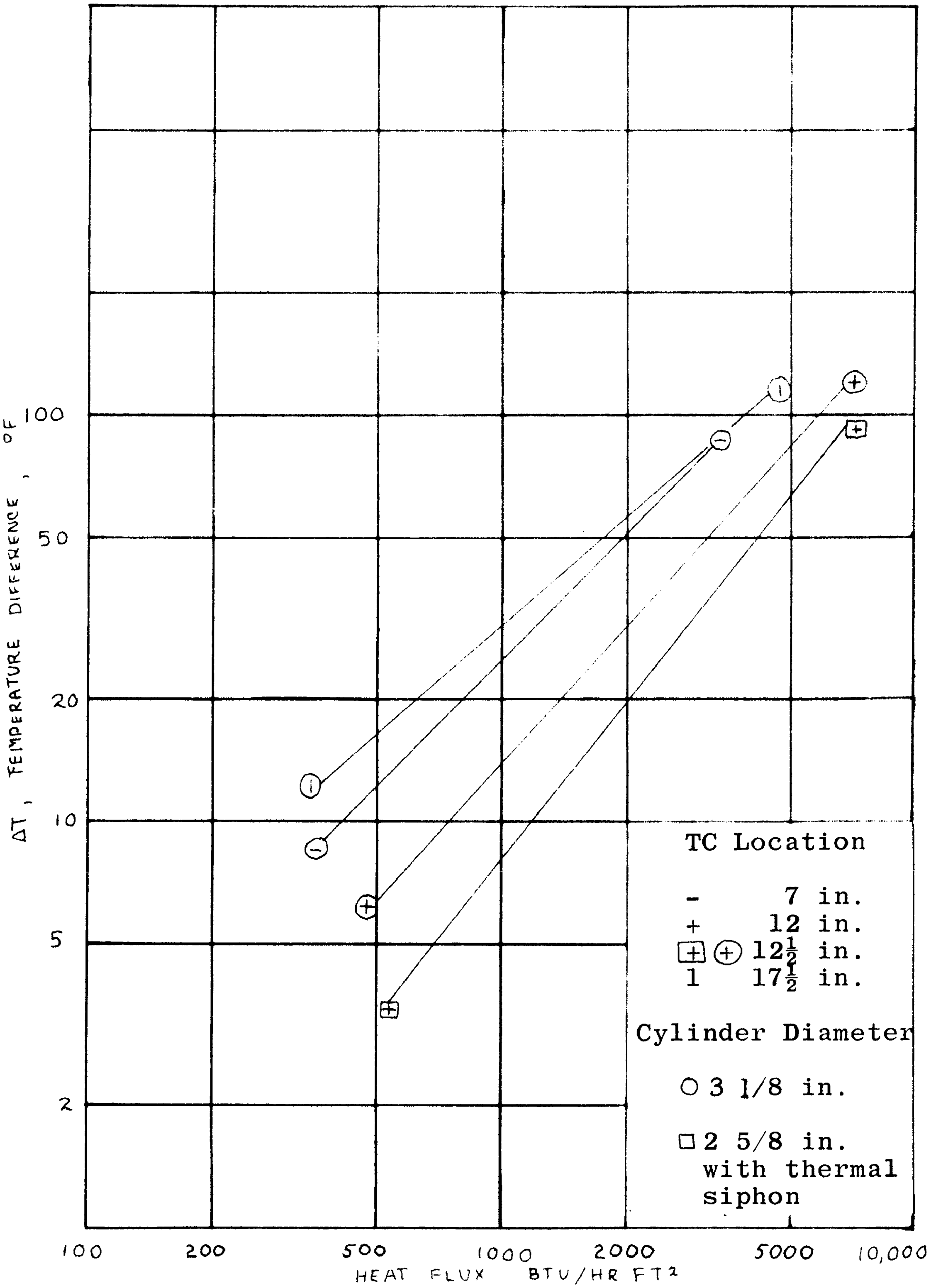

FIGURE 33 - Overall Results of Unpressurized Tests.

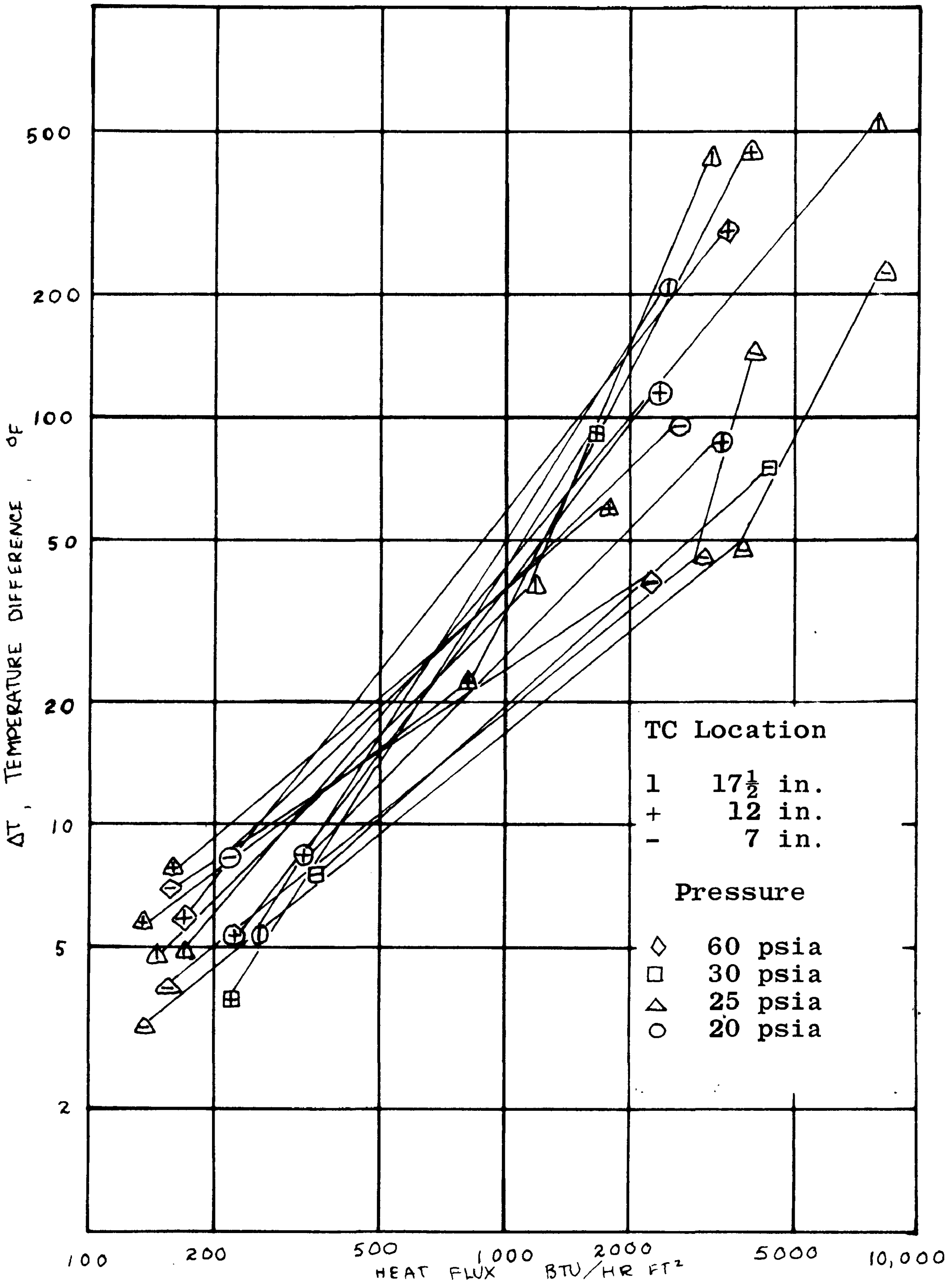

FIGURE 34 - Overall Results of Pressurized Tests.

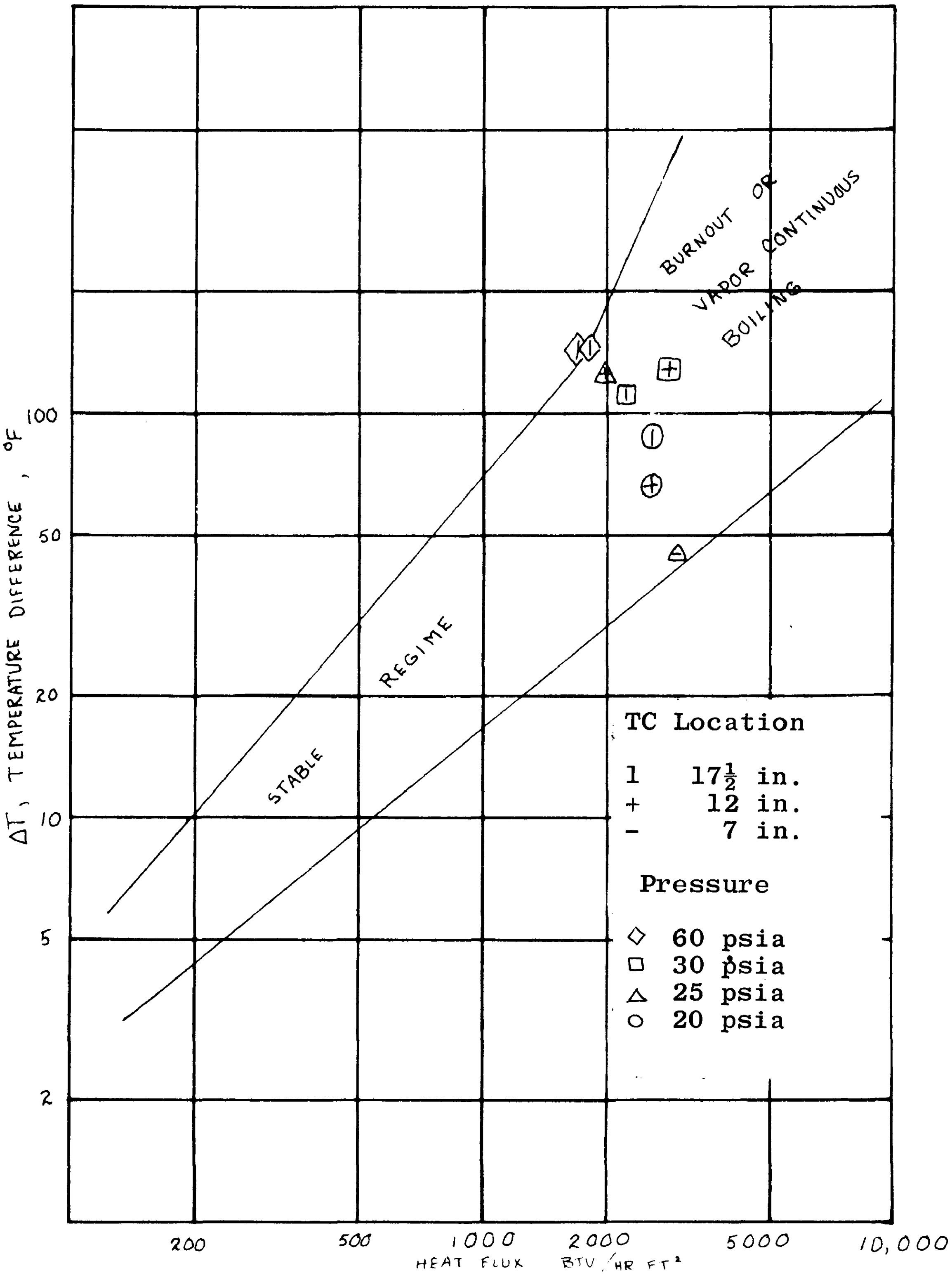

FIGURE 35 - Regime of Stable Boiling in a 3-by-23-inch Vertical Cylinder.

volume of vapor to be removed can be reduced, almost inversely with pressure, without appreciable loss of buoyancy force, cooling performance can be improved by pressurization. It was also recognized, and was confirmed experimentally, that an optimum pressure and a corresponding minimum wall temperature would be found, above which rising saturation temperature would eliminate the gain. This effect is seen clearly in Figure 32. A further extension of this aspect was made by comparing forced convection values of boiling heat transfer, Figure 1. The values in this low-pressure regime are much different from those obtainable at high pressures and flow rates. For example, Dean (13) shows a regime of nucleate boiling from 362,000 to 590,000 BTU/hr ft^2 with a temperature drop of 57 to 60°F, at a pressure of 300 psia and a velocity of 40 ft/sec. Of course, the operating temperatures are much higher than this study because of increased saturation temperature at the higher pressure level.

Container Geometry

The 3-by 23-inch cylinder geometry was chosen to maximize heat-transfer area, yet avoid a flooding-like phenomenon called geysering, which ejects the liquid contents and is dependent on L/D ratio, according to the

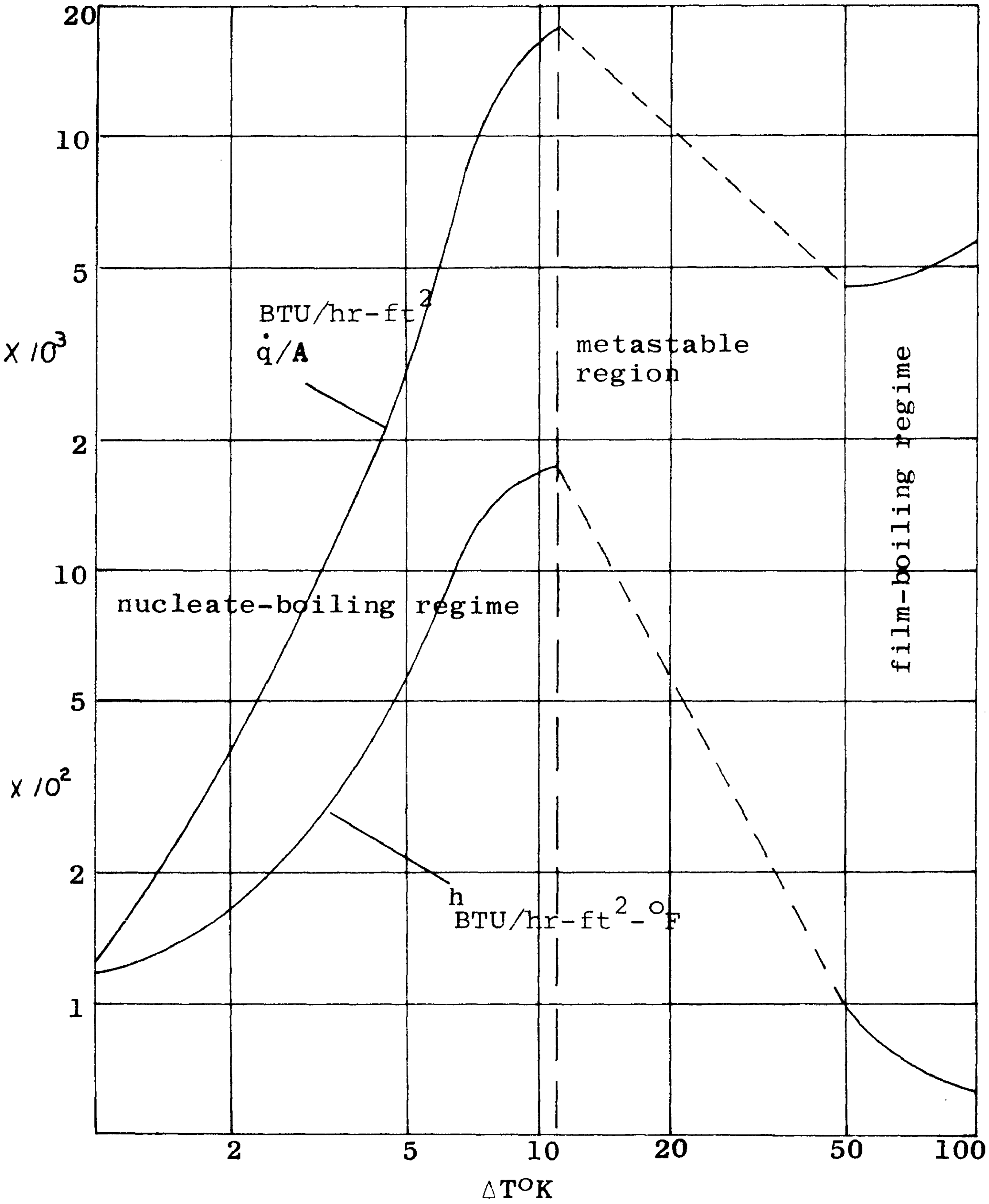

FIGURE 36 - The Nucleate and Film Boiling Curve of Liquid Nitrogen at One Atmosphere.

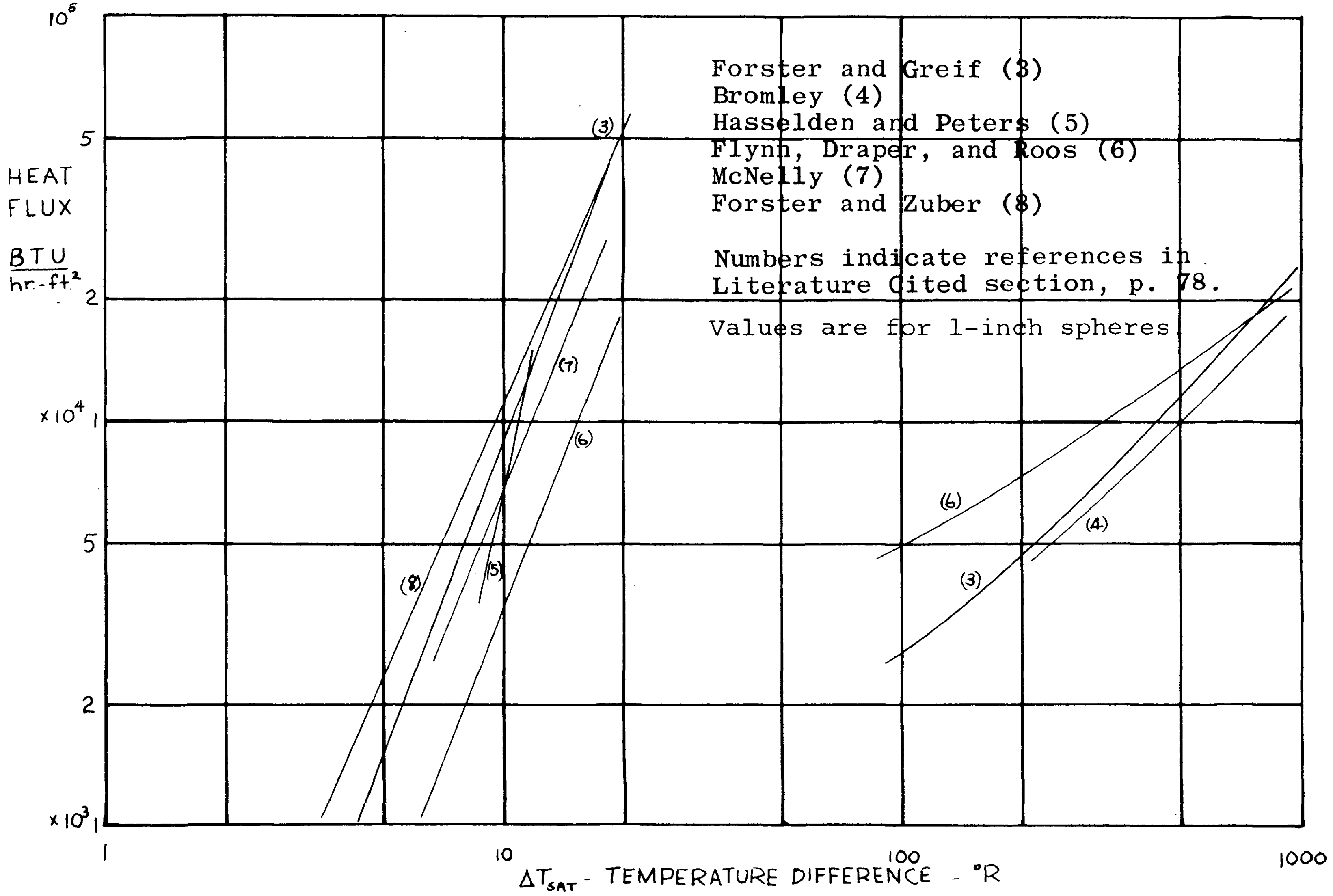

FIGURE 37 - Comparison of Liquid Nitrogen Boiling Curves from the Literature.

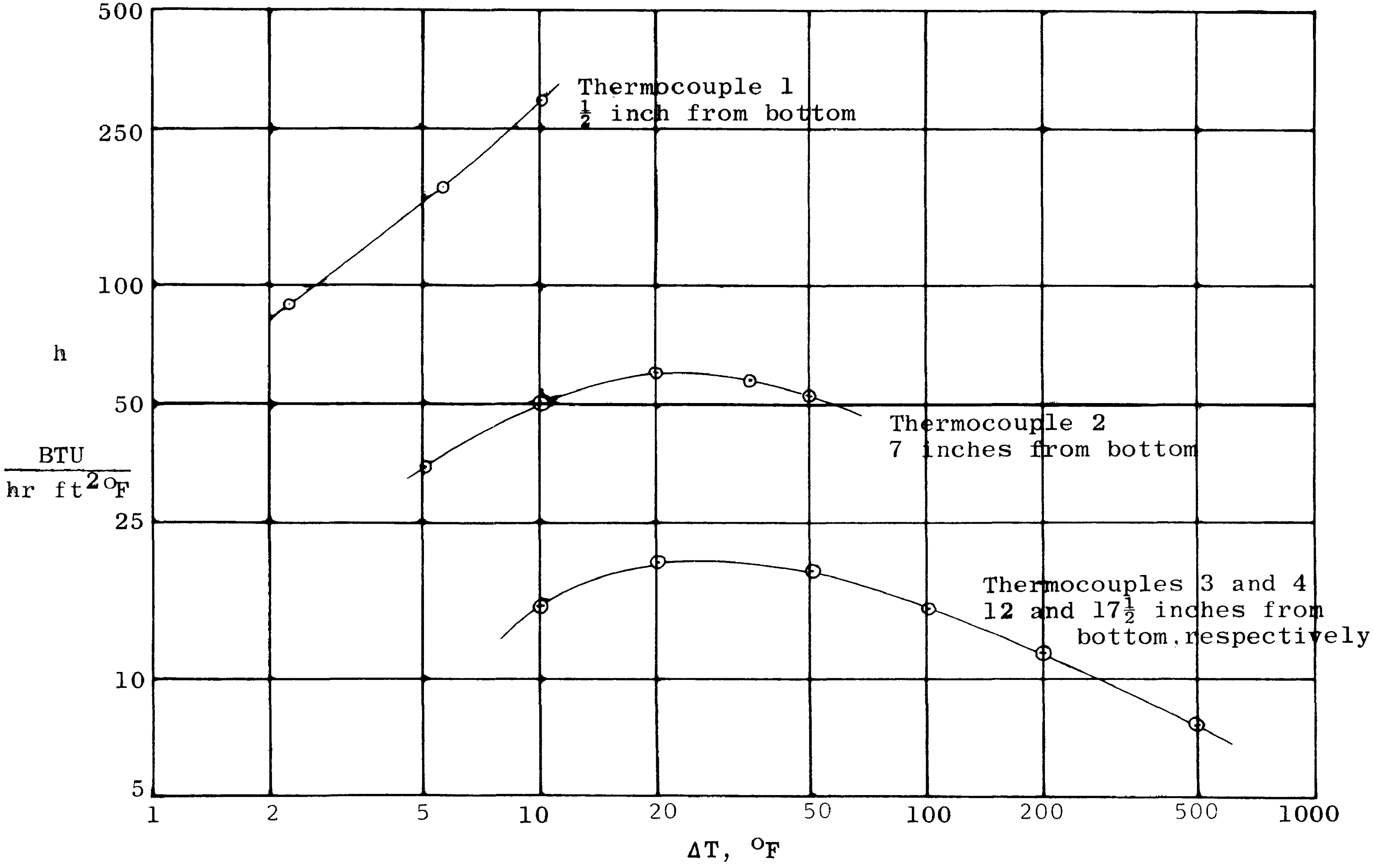

FIGURE 38 - Heat-Transfer Coefficient at Respective Vertical Positions on the Container Wall. Calculated from data of Test 5-P, which was run at 25 psia.

dimensional relation by Murphy (14).

$$\left(\frac{L}{D}\right)\left(D^{-0.68}\right) = 9.05\left(\frac{\dot{q}/AL}{12D\ (N_{pr})^{1/3}}\right)^{-0.05}$$

L - length of tube, inches

D - diameter of tube, inches

N_{pr} - Prandtl Number

$\dot{q}/A$ - heat flux, BTU/ft^2 hr

The equation is probably not applicable at the higher heat fluxes of the present study.

Comparison with Existing Equations for Boiling

Comparison of heat-transfer data is sometimes made difficult for two reasons; first, the various correlations chosen for the presentation of data and second, the varying use of terms. As McAdams (15) has pointed out, non-reproducibility (possibly involving hysteresis or metastability of the physical situation) can be obscured by the coordinates chosen. Secondly, the language of heat transfer, and boiling in particular, can be ambiguous. For example, the term "burnout" is used by some writers to mean destruction of apparatus and by others film boiling, not necessarily the same. An ambiguity is possible in this study in the term "pool boiling." As pointed out earlier, the mechanism is decidedly different from that operating when a small isolated element is boiling in an effectively infinite container. Yet because there is slip flow here, the mechanism is different from that in natural-convection tube exchangers in which the boiling liquid is carried out with the vapor, with little slip, and separated in a large, low-velocity de-entrainment section. So the term pool boiling seems justified and has been used, with the reservation that it does not indicate precisely the same phenomenon as when used in other studies. Likewise the boiling in the stable regime was believed to be nucleate, but because the film boiling crisis is less distinct here, the term "nucleate boiling" has usually been avoided. Considering all the above, it is not surprising if the results of the present experiments, operating in a regime of special container geometry, different thermal-hydraulic mechanism, and low heat flux, are not predicted by correlations for 1-inch tubes or isolated elements in large containers. Some 19 boiling regimes have been characterized by Bonilla (16), yet difference in container geometry changes mechanism so that even more variations or categories can be construed.

The most prominent boiling correlations include equations by Rosenhow, Kutateladze, Michenko, Gilmour, Zuber, Labountzov, and Levy (17). Useful influence coefficients are given by McAdams (18). As stated above, none of these correlations appears directly applicable, and little or no data exist for the present geometry, which is intermediate between a tube and a kettle. Some comparisons have been made below, and poor agreement will be noticed. The other problem with these existing correlations is that ΔT, which they predict, is often less important than critical flux bounding the phenomenon of useful boiling, which the extensive correlations do not predict.

The discussion by McAdams lists several characteristics of nucleate boiling which were compared with the results of this study. The effects of particular interest in McAdams include ΔT, pressure, nature of the liquid, and critical heat flux. The discussions of surface nature, addition agents, scale deposits, increased velocity, tube size, and natural circulation evaporators are either inapplicable or insufficient in scope to permit a real comparison.

Regarding ΔT, McAdams (19) gives an equation

$$q/A = a_1 \, \Delta T^n$$

"where n is a constant ranging from 3 to 4 and a_1 is a particular constant for each liquid, surface, and pressure."

A comparable equation derived from Figures 33 and 34

$$\varphi = a \Delta T^n$$

φ - heat flux, BTU/hr ft^2

a - a dimensional constant, mean value 31.3 BTU/hr - ft^2 - ΔT^n

ΔT - wall-to-bulk-fluid temperature difference ^{o}R

n - a constant. The range of n for all tests and data is from 0.84 to 1.67. However, n = 1 may be considered a good representative value.

Observed values for critical heat fluxes at various pressure, container geometry, and container position range from 1700 to nearly 10,000 BTU/hr ft^2, though no critical flux above 4,000 was found at the 17-inch level at any pressure.

McAdams (20) relation for critical heat flux is

$$\frac{\varphi_{cr}}{\lambda \rho_v \left(g \left(\frac{k}{\rho C_p} \right) \right)^{1/3}} = \text{function of } \frac{\rho_L - \rho_v}{\rho_v}$$

which predicts a critical heat flux 50 to 100 times greater than the relation derived above for the container geometry of this experiment.

Cichelli, Bonilla, and Kazakova (20), show that peak heat flux before burnout occurs at about 1/3 times critical pressure. Inasmuch as the critical pressure of nitrogen is 33.5 atmospheres, their analysis does not appear pertinent to the minimum ΔT observed.

Figure 32, made from number-2 thermocouple data gives an interesting effect of pressure on ΔT for the particular length/diameter ratio and vertical location. Wherever appropriate for general relations between parameters, the number-2 thermocouple readings at the 7-inch level were used because they were least erratic and unstable.

Another prediction of ΔT from heat flux may be made by the several equations quoted by Zuber (21). The equation derived by Gilmour (22) is particularly useful because the factors are all macroscopic observables.

$$\frac{h}{cG}\left(\frac{c\mu}{k}\right)^{0.6}\left(\frac{\rho_L \sigma}{p^2}\right)^{0.425} = \frac{b}{(DG/\mu)^{0.3}}$$

The notation for this and other equations in this section is

h - boiling heat-transfer coefficient BTU/hr ft^2 °F

g - acceleration of gravity

G - mass flow rate, lb/hr ft^2

C, c or c_p - heat capacity at constant pressure BTU/lb °F

φ - heat flux, BTU/hr ft^2

μ - viscosity, lb/hr ft

k - thermal conductivity, BTU/hr ft ^{o}F

ρ - density, lb$_m$/ft^3

V - vapor rate, lb/hr

A - surface area, ft^2

σ - surface tension, lb$_f$/ft

P - pressure, lb$_f$/ft^2

a - dimensional constant (McAdams' equation) or thermal diffusivity (Michenko's equation)

b - constant, 5.9 x 10^{-4}

D - diameter, ft

λ or h_{fg} - enthalpy of vaporization, BTU/lb

subscripts

L - liquid

v - vapor

cr - critical

m - mass

f - force

This equation is quite general and seemed most useful for nucleate boiling calculation: however, it gave a ΔT different by a factor of about 10 from the results of the stable nucleate boiling regime in this experiment.

A similar equation, using the same notation and dimensionless groups, has been derived by Michenko (23).

$$\frac{h}{k_L}\left(\frac{\sigma}{g(\rho_L-\rho_V)}\right)^{\frac{1}{2}} = 8.7\text{x}10^{-4}\left(\frac{1}{a}\ \frac{\varphi}{\rho_V\, h_{fg}}\left(\frac{\sigma}{g(\rho_L-\rho_V)}\right)^{\frac{1}{2}}\right)^{0.7}\left(\frac{P}{(\sigma g(\rho_L-\rho_V))^{\frac{1}{2}}}\right)^{0.7}$$

This equation gives generally good agreement over the middle of the range of stable nucleate boiling. Because the ΔT dependence is too strong in the equation, as noted earlier, values predicted are low by a factor of approximately 20 in the range of small ΔT, and high by a factor of 50 at the upper end of the fluxes in the present experiment. These discrepancies may be corrected by proper adjustment of the exponents and constant to give

$$\frac{h}{k_L}\left(\frac{\sigma}{g(\rho_L-\rho_V)}\right)^{\frac{1}{2}} = m\left(\frac{1}{a}\ \frac{\varphi}{\rho_V\, h_{fg}}\left(\frac{\sigma}{g(\rho_L-\rho_V)}\right)^{\frac{1}{2}}\right)^{0.11}\left(\frac{P}{\left[\sigma g(\rho_L-\rho_V)\right]^{\frac{1}{2}}}\right)^{0.7}$$

which correlates the data obtained from the present study within a factor of two, except at the very bottom of the cylinder. The constant m is 15.7×10^{-5} at the 7-inch level and 5.15×10^{-5} at the 12- and 17½-inch levels.

CONCLUSIONS

Pool boiling in short, vertical cylinders is a phenomenon involving a thermal-hydraulic mechanism different from that operating in heat transfer from small, isolated elements in large, effectively infinite pools, and different from that in high-pressure, high-velocity evaporator tubes, as in natural-circulation evaporators. The gross hydraulic mechanism of phase separation, i.e., slip flow, is apparently controlling. Critical heat flux in these experiments was lower, and ΔT was higher than existing correlations predict.

The critical heat flux for transition to film or vapor continuous boiling varied from 1700 to 10,000 BTU/hr ft^2, which is far below the classic boiling-curve prediction for small elements (Figure 36).

ΔT was correlated by the simple empirical expression

$$\varphi = a\Delta T^n$$

An equation containing fluid properties, of the type derived by Michenko, correlates the data satisfactorily when the exponents involving ΔT are corrected.

Boiling in these cylinders did not usually show the sharp film-boiling crisis associated with small elements in relatively large containers. The temperature difference would generally grade smoothly upward from gentle nucleate boiling to burnout. There was, however, some tendency toward a metastability, hysteresis, or double-valuedness of the temperature difference for a given heat flux, whereby boiling at a point on the wall would continue for minutes at a lower ΔT, then abruptly change to a higher ΔT.

LITERATURE CITED

1. Gröber, H., and Erk, S., Fundamentals of heat transfer: Berlin, Springer, p. 375, (1961).

2. Nukiyama, S., Tokyo Society of Mechanical Engineers, J. Soc. Mech. Eng'rs., v. 37, p. 367-374, (1934), cited in McAdams, W.H., Heat transmission: New York, McGraw-Hill, p. 370, (1954).

3. Forster, H.K., and Greif, R., Heat transfer to boiling liquid: mechanisms and correlations: ASME-AIChE Heat Transfer Conference, paper no. 58-HT-11 (Aug. 1958), cited in Timmerhaus, K.D., New York, Plenum Press, p. 544, (1962). University of Michigan 1961 Cryogenic Engineering Conference Aug. 15-17, 1961, Proceedings, Ann Arbor, Michigan.

4. Bromley, L.A., Heat transfer in stable film boiling: American Institute of Chemical Engineers, Chem. Eng. Progr., v. 46, p. 221, (1950), cited in Timmerhaus, op. cit., p. 544.

5. Hasselden, G.G., and Peters, J.I., Heat transfer to boiling liquid oxygen and liquid nitrogen: London, The Institute of Chemical Engineers, Trans. Inst. Chem. Eng'rs., v. 27, p. 201, (1949), cited in Timmerhaus, op. cit., p. 544.

6. Flynn, T.M., Draper, J.W., and Roos, J.J., The nucleate and film-boiling curve of liquid nitrogen at one atmosphere: Paper L-6, 1961 Cryogenic Engineering Conference, Ann Arbor, Michigan, cited in Timmerhaus, loc. cit.

7. McNelly, M.J., A correlation of rates of heat transfer to nucleate boiling liquids: The Imperial College of Chemistry, London, Jour. Imp. College Chem. Eng. Soc., v. 7, p. 18, (1953), cited in Timmerhaus, loc. cit.

8. Forster, H.K., and Zuber, N., Growth of a vapor bubble in superheated liquid: American Institute of Physics, New York, J. of Appl. Phys., v. 25, p. 474, (1954), cited in Timmerhaus, loc. cit.

9. Kutateladze, S.S., Fundamentals of heat transfer: London, Edward Arnold, Ltd., p. 352-398, (1962).

10. Sydoriak, S.G., and Roberts, T.R., Study of boiling in short narrow channels and its application to design of magnets cooled by liquid H_2 and N_2: Lancaster, American Institute of Physics, J. Appl. Phys., v. 28, p. 143-148, (1957).

11. Stroebe, G.W., et. al, Boiling film heat transfer coefficients in a long tube vertical evaporator: New York, American Institute of Chemical Engineers, Trans. AIChE, v. 35, p. 17-43, (1938).

12. Brooks, C.H., and Badger, W.L., Heat transfer coefficients in the boiling section of a long-tube, natural-circulation evaporator: New York, American Institute of Chemical Engineers, Trans. AIChE., v. 33, p. 392-416, (1937).

13. Dean, L., Heat transfer characteristics of liquid nitrogen: Wheatfield, Bell Aircraft Corp., Report 56-982-035, p. 1-17, (1955).

14. Murphy, Dale, Mechanics of geysering of cryogenics: Huntsville, Alabama, National Aeronautics and Space Administration, NASA Report CR-64-3, Issue 4, (1964).

15. McAdams, W.H., Heat transmission: New York, McGraw-Hill, p. 375, (1954).

16. Bonilla, C.F., Nuclear engineering: New York, McGraw-Hill, p. 400, (1957).

17. Zuber, Novak, and Fried, Erwin, Two-phase flow and boiling heat transfer to cryogenic liquids: New York, American Rocket Society, ARS Journal, v. 32, p. 1332-1340, (1962).

18. McAdams, W.H., op. cit., p. 377.

19. ———, op. cit., p. 378.

20. Cichelli, M.T., and Bonilla, C.F., Heat transfer lectures: New York, American Institute of Chemical Engineers, Trans. AIChE, v. 41, p. 755-787, (1945). Kazakova, E.A., Engineers Digest, v. 12, p. 81-85, (1951). Both are cited in McAdams, op. cit., p. 385.

21. Zuber, Novak, loc. cit.

22. Gilmour, C.H., Nucleate boiling - a correlation: New York, American Institute of Chemical Engineers, Chem. Eng. Progr., v. 54, p. 77-79, (1958), cited in Zuber, op. cit., p. 1334.

23. Michenko, N., On the problem of heat transfer in nucleate boiling, Moscow, Energomashinostroenie, no. 6, p. 17-21, (1960), cited in Zuber, op. cit., p. 1334.