FROST TUBE STUDY

by

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INTRODUCTION

To help eliminate some of the problems associated with foundation in areas of permafrost, a unit called the "Frost Tube" has been developed. The purpose of the Frost Tube is to remove the heat from the soil at a relatively fast rate during the winter season. Since the rate of heat flow back into the soil is much lower than the rate of heat flow out of the soil caused by the Frost Tube, the results of using a Frost Tube should be permanently frozen soil in its vicinity. As long as the soil is frozen, frost jacking of piles can be eliminated and the compressive strength of the soil is increased greatly.

The cooling of the ground by the Frost Tube is the result of a circulation cycle of the charging liquid within the tube. As the temperature of the charging liquid in the portion of the Frost Tube that is above the ground becomes colder, its density becomes greater and this liquid starts flowing down the circulation tube. (See Fig. 1) This forces the warmer liquid that was in the bottom portion of the tube to flow into the portion above the ground where it is cooled. While the top portion is cooling, the colder liquid in the bottom portion is removing heat from the soil and its temperature is rising. This cycle will continue as long as the air temperature is lower than the ground temperature.

The purpose of this study was to determine:

(1) Which ratio of downward flow area to upward flow area has the highest heat removal rate.

(2) Which circulation tube length has the highest heat removal rate.

Frost Tube Design

Three different Frost Tube designs were tested as the first phase of the program. A drawing of each Frost Tube is shown in Figs. 2, 3, and 4. The difference in design of the three tubes is in the ratio of the downward flow area to the upward flow area. The ratios used were: (1) Tube 1 - 2:1 , (2) Tube 2, 1:2, and Tube 3, 1:1.

The second phase of the program was to select one of the above Frost Tubes and run tests on this tube using circulation tubes of different lengths. Tube 3 was selected for this testing and the circulation tube lengths that were tested are shown in Fig. 5.

Both the outer case and the circulation tube are constructed from 1/16" thick copper tube. The circulation tube was insulated with a vermiculite filler as shown in Figs. 2, 3, and 4.

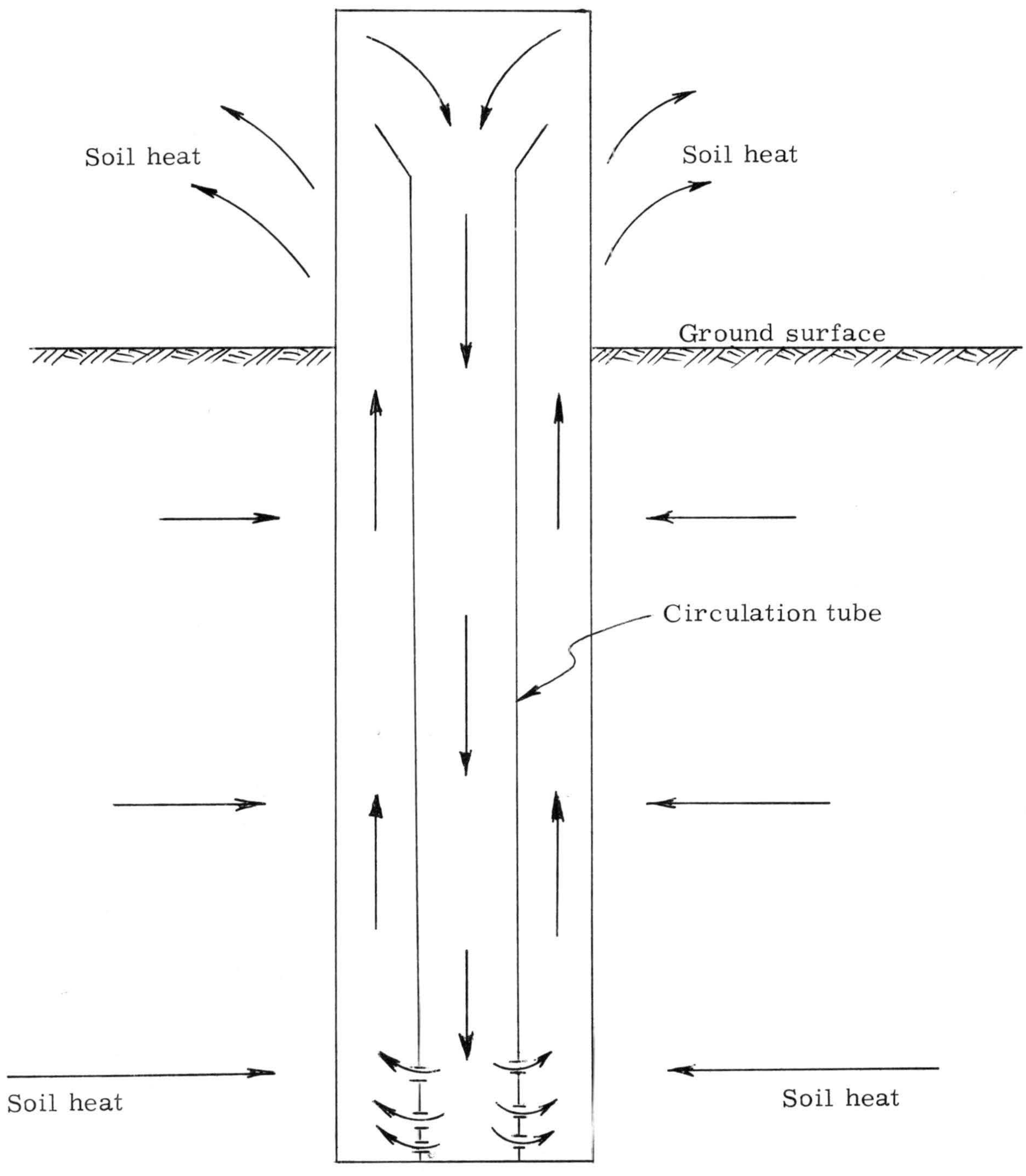

Fig. 1. Schematic of frost tube circulation cycle

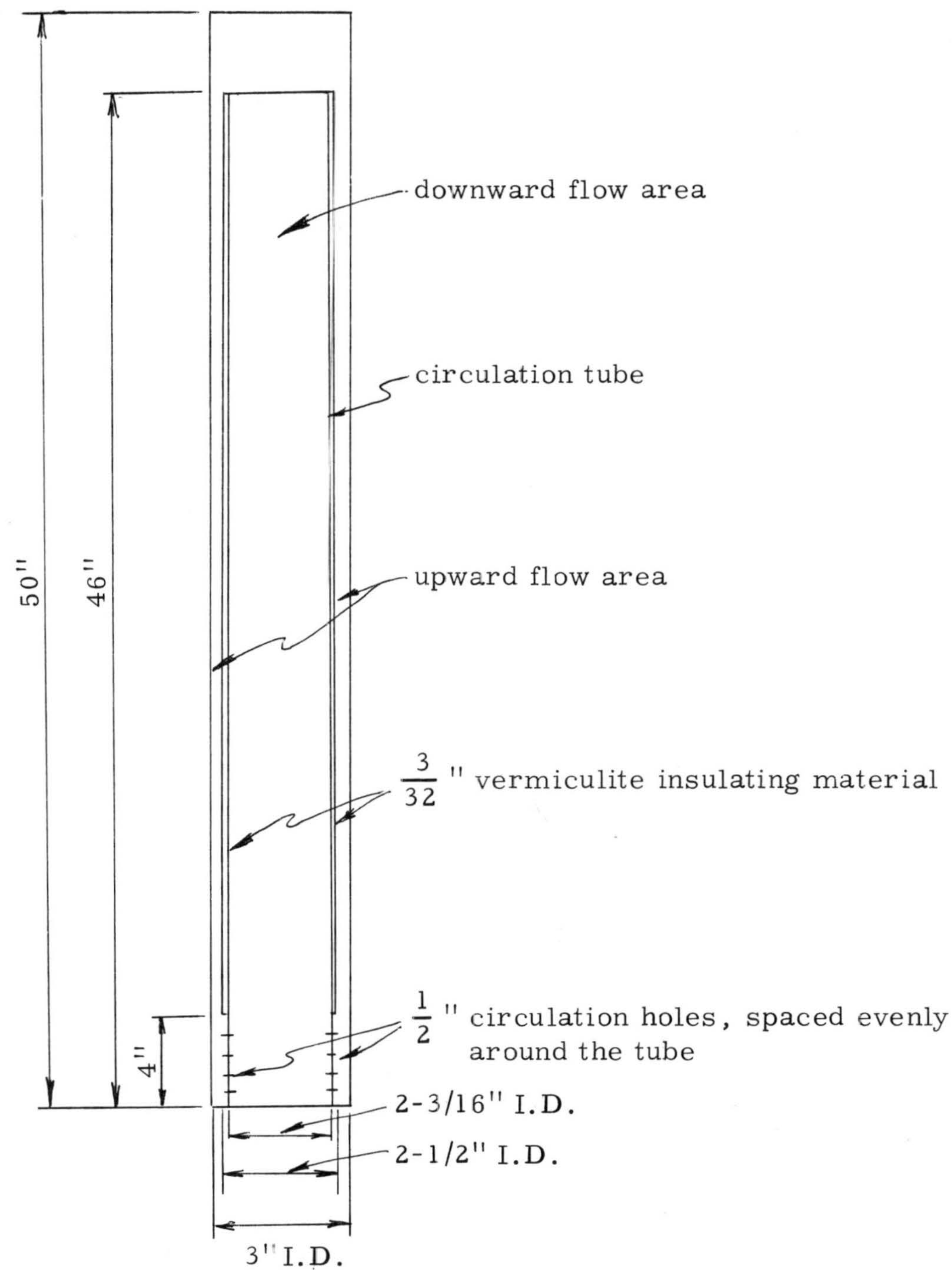

Fig. 2. Tube 1, 2:1

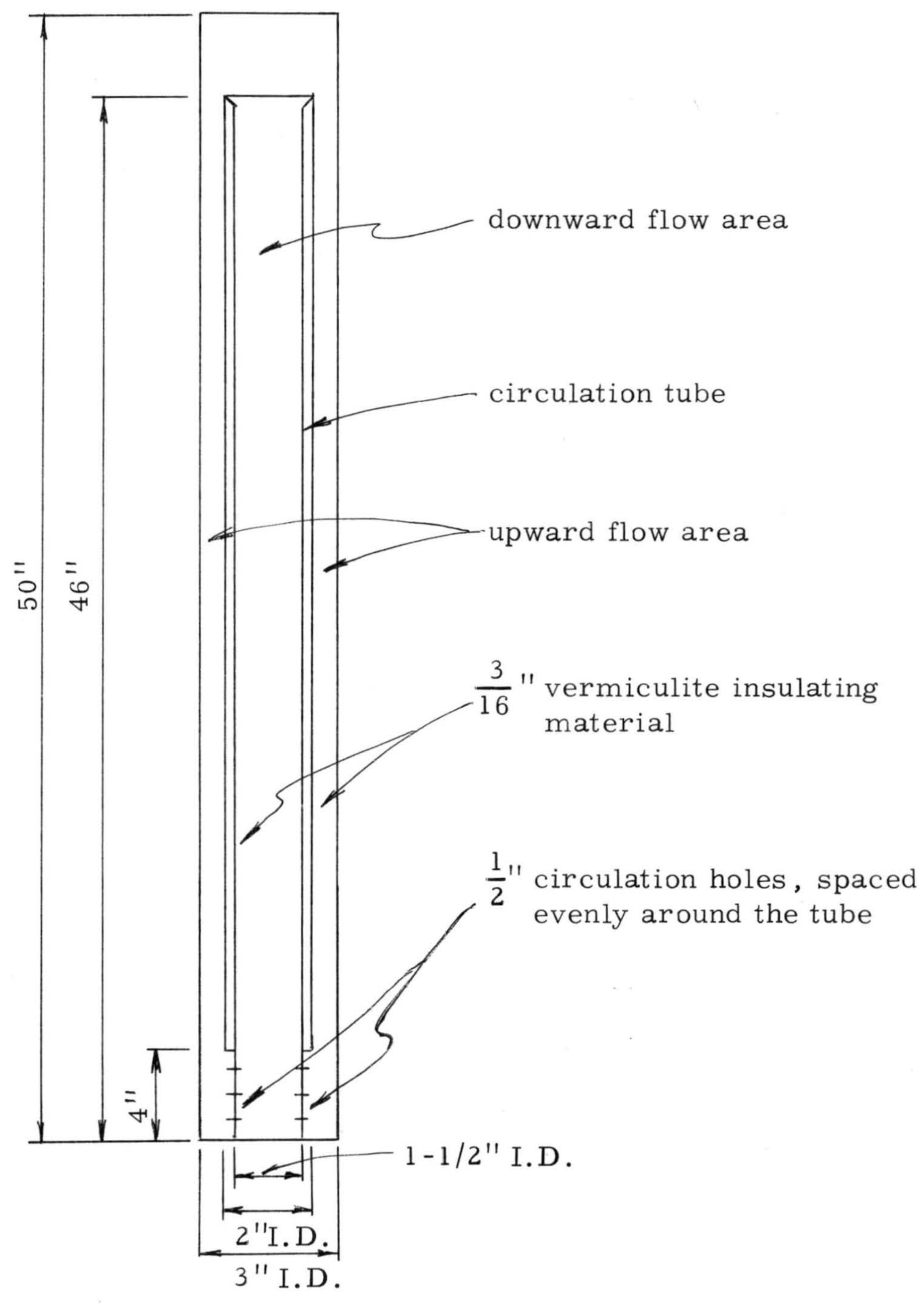

Fig. 3. Tube 2, 1:2

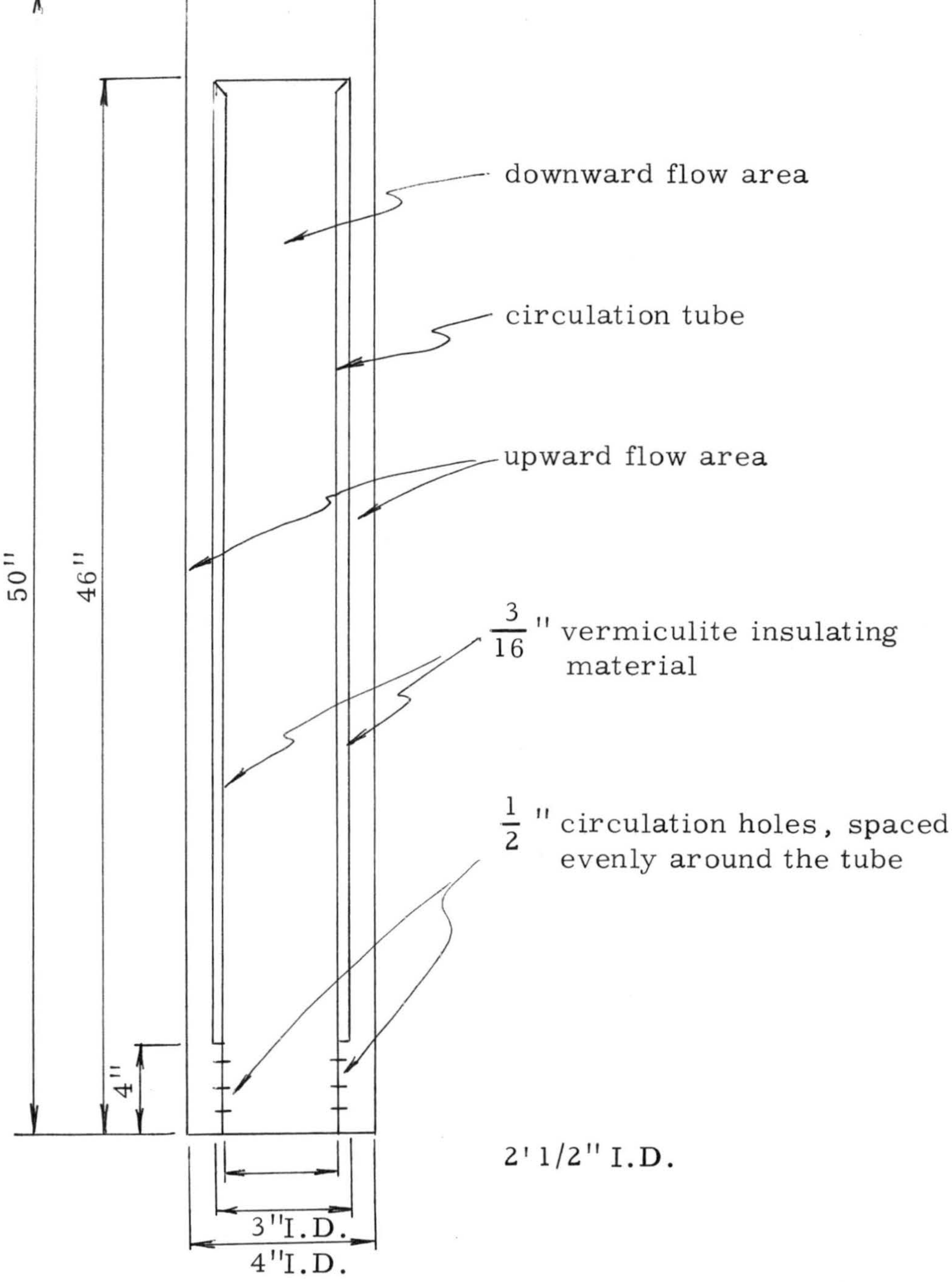

Fig. 4. Tube 3, 1:1

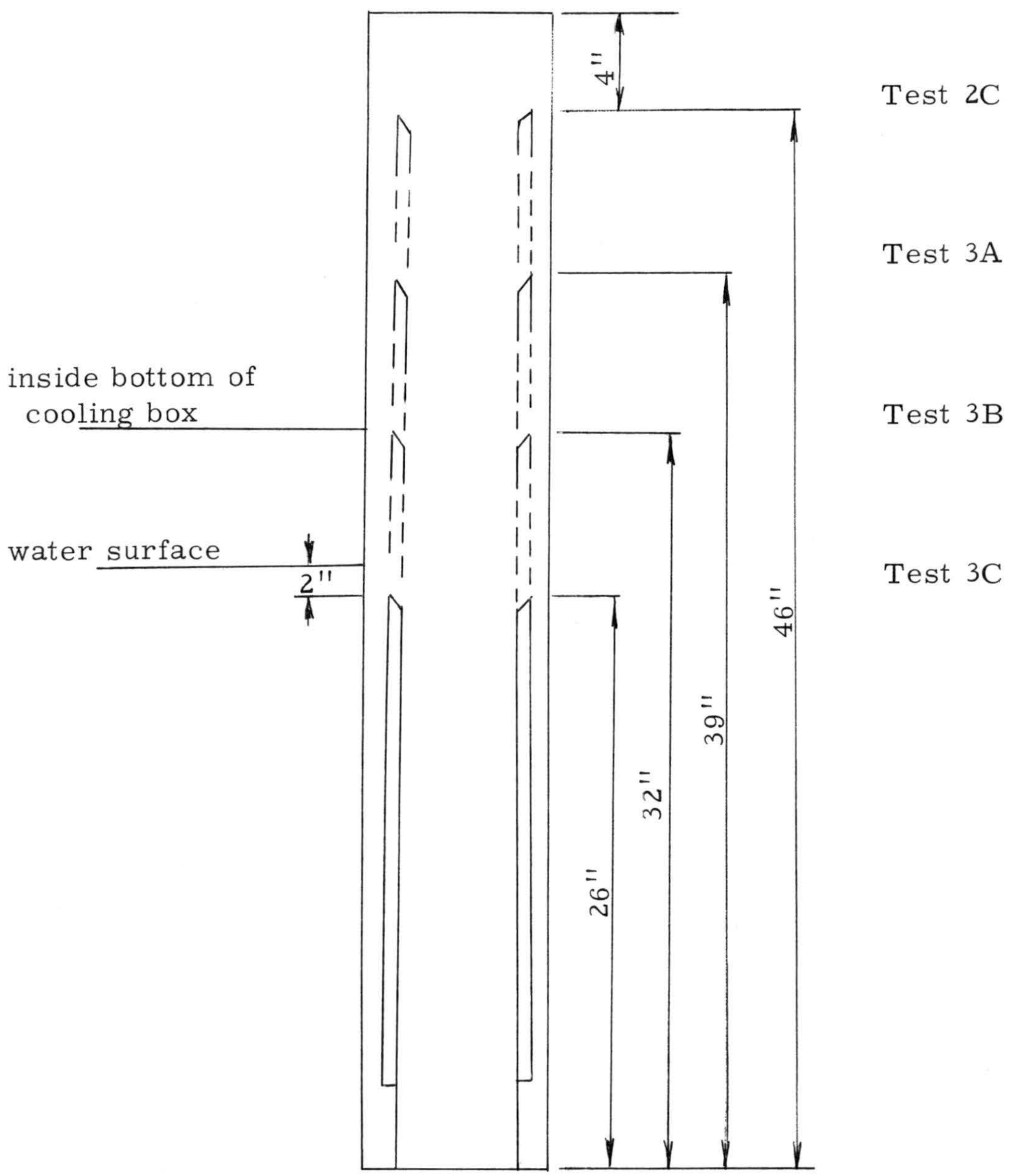

Fig. 5. Circulation tube lengths.

Test Equipment

To determine which design would be the most efficient, a laboratory setup, as shown in Fig. 6, was used. To help prevent the transfer of heat from the room into the water being cooled, a core from a hot water heater was placed inside a 55 gallon drum and the 3.5 inch space between the core and the drum was filled with a fiberglas insulating material. A 2 inch thick layer of fiberglas was placed between the 55 gallon drum and the floor. The top portion of the Frost Tube was cooled with two 1/8 hp refrigeration units. A small fan was placed inside the cooling box to provide circulation of air that would occur in a field installation of a Frost Tube. The charging liquid for the Frost Tube was alcohol.

The temperature of the water and the cooling box was measured with thermocouples and an Atkins unit. Three thermocouples were used to measure the water temperature and one thermocouple was used to measure the cooling box temperature. The location of the thermocouples are shown in Fig. 6.

Temperature measurements were usually taken twice a day and were read to the nearest $1/2^0$F. Each test was run until the water temperature reached a fairly constant temperature.

Listed below is a brief description of each test.

(1) Test 2A - Test 2A was run on Frost Tube 1, 2:1 area ratio. (See Fig. 2.) This test was run for a period of 91.7 hours at which time the change in water temperature was very small. The room temperature during the test ranged from 82^0F to 87^0F. The results of this test are tabulated in Table 1 and are plotted in Fig. 7.

(2) Test 2B - Test 2B was run on Frost Tube 2, 1:2 area ratio. (See Fig. 3.) This test was discontinued after 92 hours of testing. After 53 hours of testing, the circulation fan in the cooling box stopped. Without the circulation of air in the cooling box, the Frost Tube was not able to function properly and the water being cooled actually gained heat. This is shown in Table 2 and in Fig. 7. The room temperature during the test ranged from 82^0F to 89^0F.

(3) Test 2C - Test 2C was run on Frost Tube 3, 1:1 area ratio. (See Fig. 4.) This test was run for a period of 158 hours, but after 62 hours of testing, something happened to the cooling box and the cooling box temperature doubled, there was no immediate effect on the water temperature and the test was continued. The room temperature during the test ranged from 81^0F to 88^0F. See Table 3 and Figs. 7 and 8 for the results of this testing.

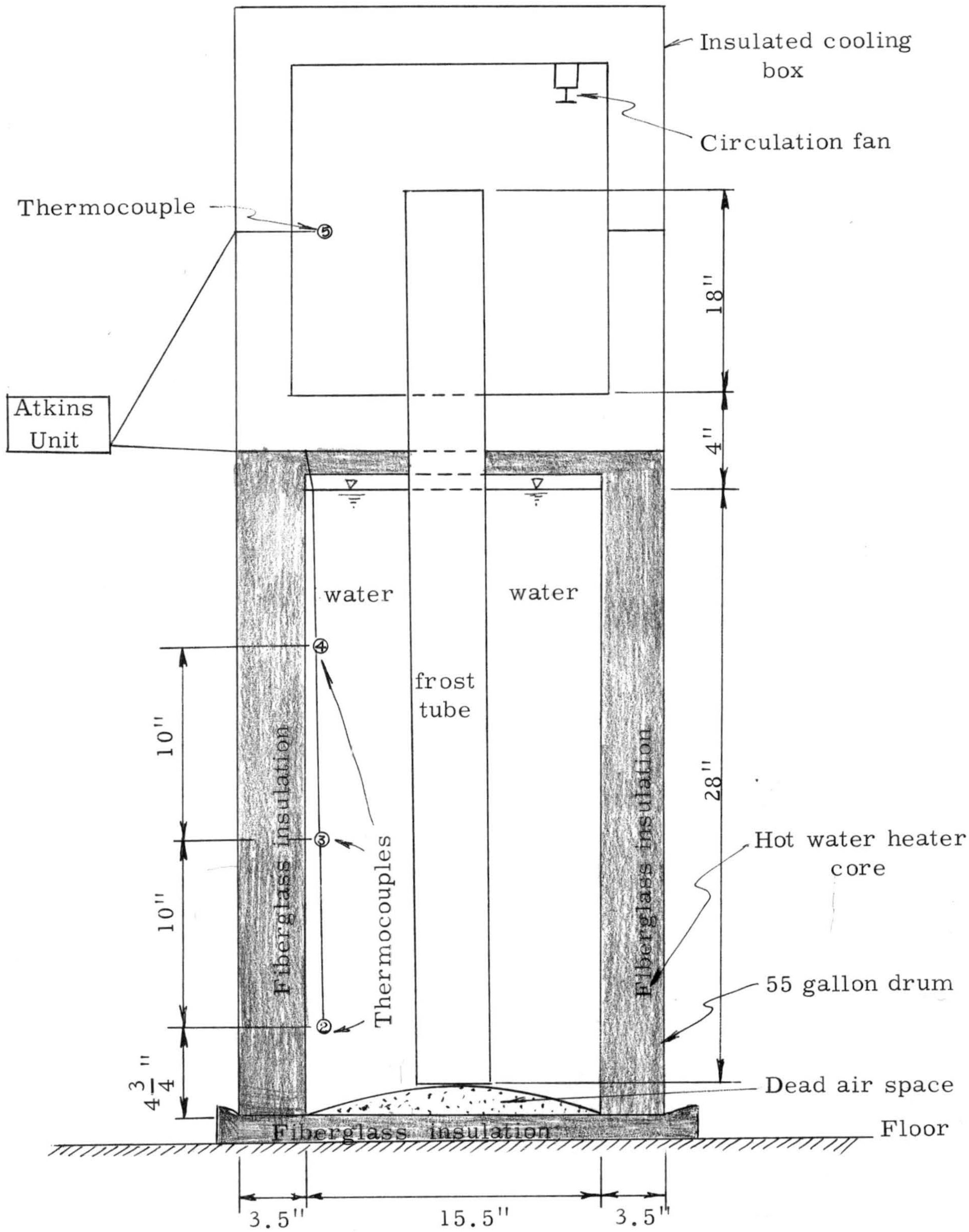

Fig. 6. Laboratory setup for testing the frost tube.

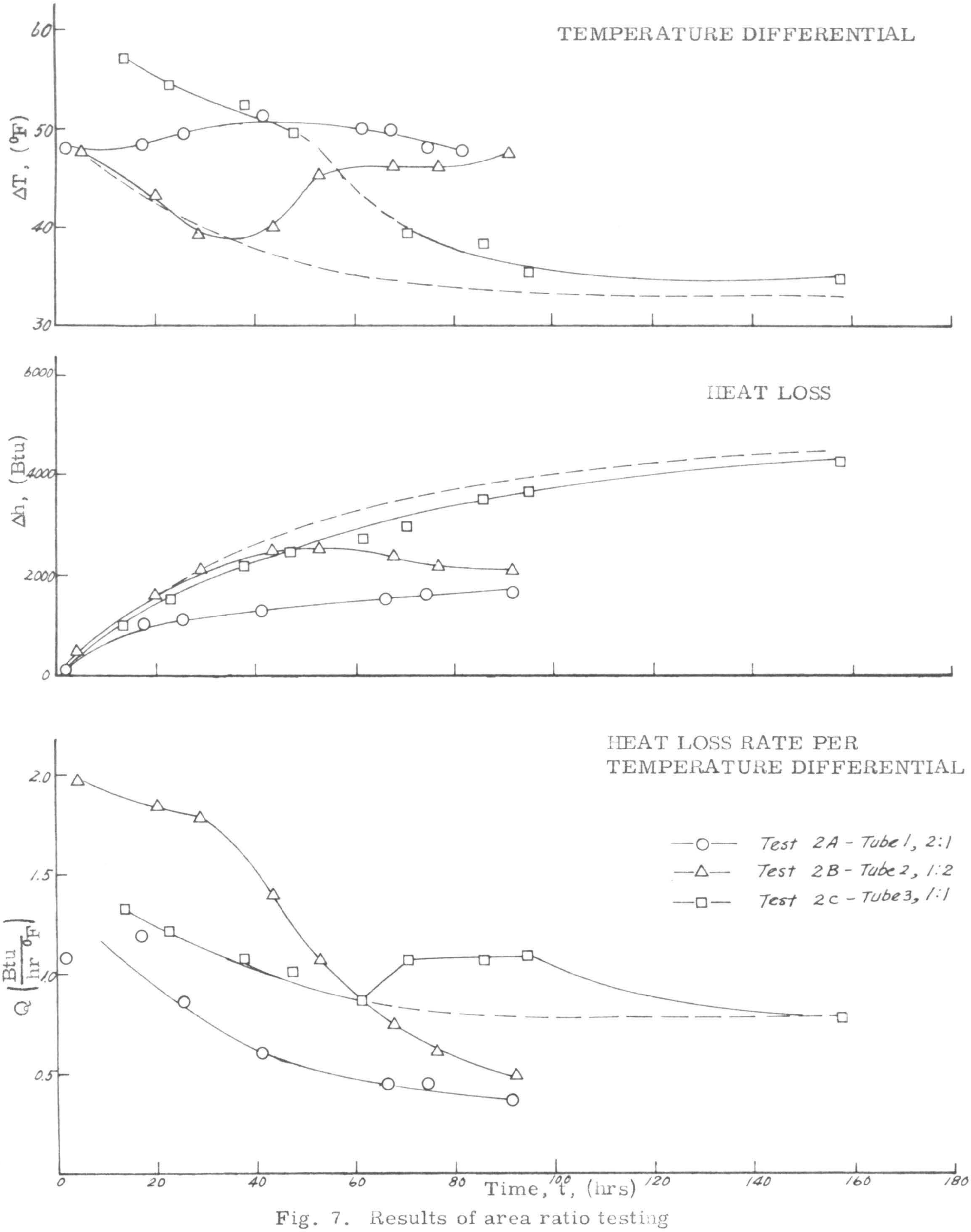

Fig. 7. Results of area ratio testing

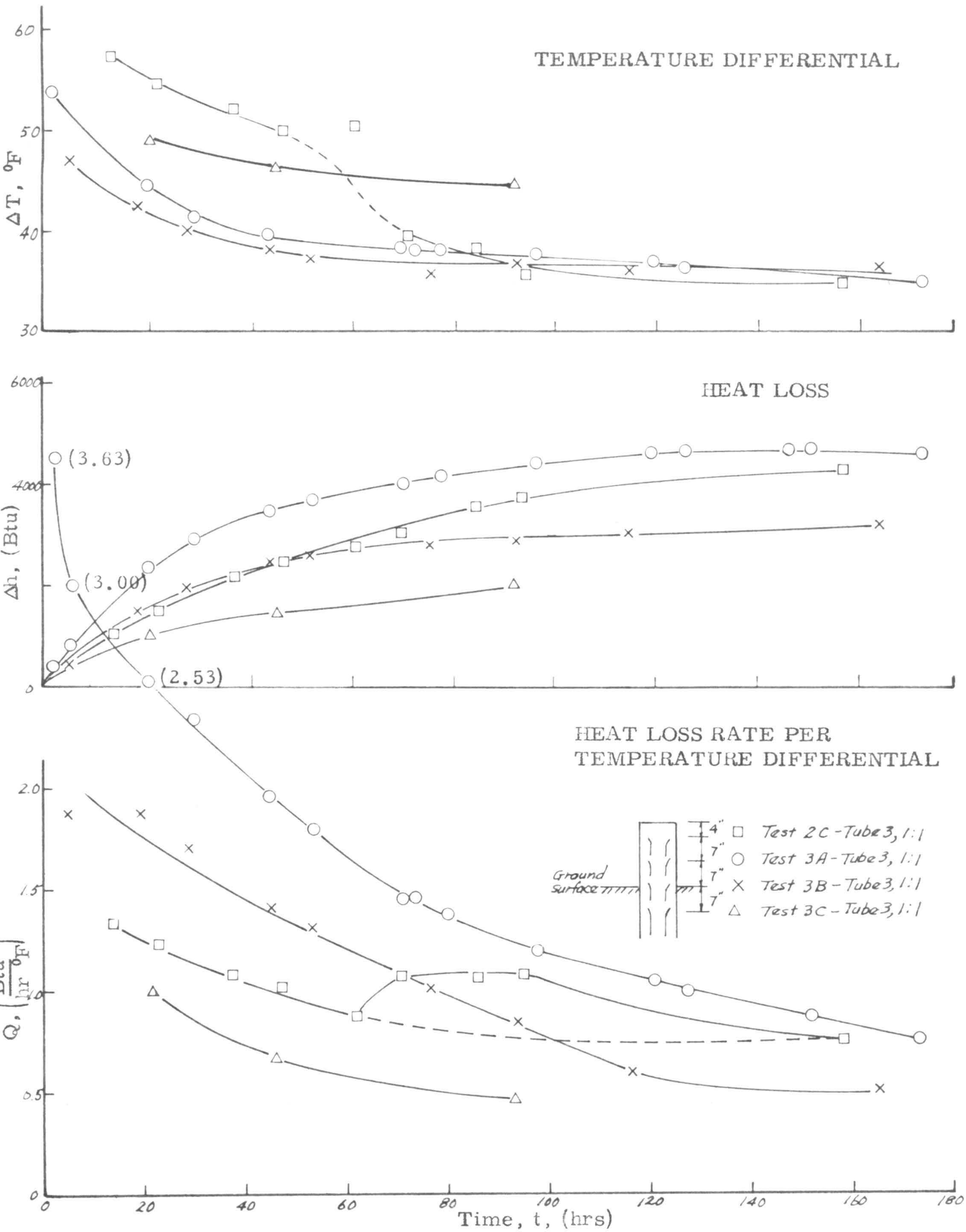

Fig. 8. Results of circulation tube length testing

TABLE 1. TEST 2A.

Frost Tube 1 - 2:1 ; 46" long circulation tube
Volume of water being cooled = 21 gallons = 175 lbs.

Time, t, (hrs)	Water Temp., T_w, (⁰F)	Cooling box Temp., T_i (⁰F)	ΔT, $T_w - T_i$, (⁰F)	Heat loss Δh, (Btu)	Heat loss Rate, g, $(\frac{Btu}{hr})$	Q $(\frac{Btu}{hr\,^0F})$
0	69.0	63.0	6.0	0	-	-
1.7	68.5	20.5	48.0	88	51.8	1.08
17.5	63.2	15.0	48.2	1015	58.1	1.20
25.7	62.7	13.5	49.2	1100	42.8	0.87
41.5	61.7	10.5	51.2	1280	30.8	0.60
66.2	60.3	10.5	49.8	1520	23.0	0.46
74.5	59.8	12.0	47.8	1610	21.6	0.45
91.7	59.7	12.0	47.7	1630	17.8	0.37

Note: 1, $\Delta h = (T_{w_o} - T_{w_n})\, W_w$

where, Δh = Heat Loss, Btu

T_{w_o} = Water temperature at time = 0, ^{0}F

T_{w_n} = Water temperature at time = n, ^{0}F

W_w = weight of water being cooled, lbs.

2, $g = \frac{\Delta h}{t_n}$

where, g = Heat loss rate, Btu/hr

t_n = Length of test, hrs.

3, $Q = g / \Delta T$

where, Q = Heat loss rate per temperature differential, $(\frac{Btu}{hr\,^0F})$

g = Heat loss rate, Btu/hr

ΔT = Temperature differential, ^{0}F .

TABLE 2 - TEST 2B.

Frost Tube 2 - 1:2 ; 46" long circulation tube
Volume of water being cooled = 21 gallons = 175 lbs.

Time, t, (hrs)	Water Temp. T_w, (°F)	Cooling box Temp., T_i, (°F)	ΔT, $T_w - T_i$, (°F)	Heat loss Δh, (Btu)	Heat loss Rate, g, $(\frac{Btu}{hr})$	Q $(\frac{Btu}{hr\,^\circ F})$
0	70.5	82.5	-	0	-	
5.0	67.8	20.0	47.8	470	94.0	1.97
20.0	61.5	18.5	43.0	1570	78.5	1.83
29.0	58.8	19.5	39.3	2040	70.4	1.79
44.0	56.5	16.5	40.0	2450	55.7	1.39
53.0	56.0	11.5	45.5	2540	48.0	1.05
68.0	57.0	11.0	46.0	2360	34.8	0.76
77.0	58.0	12.0	46.0	2190	28.4	0.62
92.0	58.5	11.0	47.5	2100	22.8	0.48

TABLE 3 - TEST 2C.

Frost Tube 3 - 1:1 ; 46" long circulation tube
Volume of water being cooled = 20.3 gallons = 169 lbs.

Time, t, (hrs)	Water Temp., T_w, (°F)	Cooling box Temp., T_i, (°F)	ΔT $T_w - T_i$, (°F)	Heat loss Δh, (Btu)	Heat loss Rate, g $(\frac{Btu}{hr})$	Q $(\frac{Btu}{hr\,^\circ F})$
0	73.0	79.0	-	0	-	-
14.0	66.7	9.5	57.2	1060	75.9	1.33
23.0	64.0	9.5	54.5	1520	66.1	1.22
38.0	60.3	8.0	52.3	2140	56.3	1.08
47.5	58.7	9.0	49.7	2420	51.0	1.02
62.0	57.0	7.0	50.0	2700	43.5	0.87
71.0	55.3	16.0	39.3	2990	42.1	1.07
86.0	52.3	14.0	38.3	3500	40.7	1.06
95.0	51.3	16.0	35.3	3660	38.5	1.09
158.0	48.0	13.5	34.5	4220	26.7	0.77

(4) Test 3A - Frost Tube 3 with a circulation tube length of 39 inches was used in this test. (See Fig. 5.) This test was run for a period of 173-1/2 hours at which time the change in water temperature was small. The room temperature during the test ranged from 76°F to 82°F. The results of this test are tabulated in Table 4 and plotted in Fig. 8.

(5) Test 3B - Frost Tube 3 with a circulation tube length of 32 inches was used in this test. (See Fig. 5.) The test was discontinued after 165 hours. During the test the room temperature ranged from 78°F to 82°F. The results of the test are tabulated in Table 5 and plotted in Fig. 8.

(6) Test 3C - Frost Tube 3 with a circulation tube length of 26 inches was used in this test. (See Fig. 5.) The test was discontinued after 93 hours. During the test the room temperature ranged from 73°F to 77°F. The results of the test are tabulated in Table 6 and plotted in Fig. 8.

Results

The results of the "area ratio testing" are shown in Tables 1-3 and in Fig. 7. As stated before, the cooling equipment did not function properly during all of Test 2B and Test 2C. Where it was possible, the results that occurred during the equipment failure have been estimated and are shown as dotted lines in Fig. 7. Because of this equipment failure, it is not possible to obtain a good comparison of the three tubes that were tested. Using the "Heat loss" curves, (Fig. 7), and the estimated curve for Test 2B, it indicates that the best downward flow area to upward flow area would be in the range of 1:1 to 1:2.

The results of the "circulation tube length testing" are shown in Tables 3-6 and in Fig. 8. The "Heat loss Rate per Temperature Differential" curve shows that Test 3A removed heat from the water at the highest rate and Test 3B was next. Therefore the length of the circulation tube should be equal to the length of the outer case that is below the ground plus 1/2 the length of the outer case that is above the ground.

TABLE 4 - TEST 3A.

Frost Tube 3 - 1:1 ; 39" long circulation tube
Volume of water being cooled = 20.3 gallons = 169 lbs.

Time, t, (hrs)	Water Temp., T_w, (°F)	Cooling box Temp., T_i, (°F)	ΔT, $T_w - T_i$, (°F)	Heat loss Δh, (Btu)	Heat loss Rate, g, ($\frac{Btu}{hr}$)	Q ($\frac{Btu}{hr\ °F}$)
0	70.0	68.0	-	0	-	-
2.0	67.7	14.0	53.7	390	195.0	3.63
5.5	65.0	14.0	51.0	840	152.8	3.00
21.0	56.0	11.5	44.5	2360	112.4	2.53
30.0	52.8	11.5	41.3	2900	96.7	2.34
45.0	49.5	10.0	39.5	3460	76.8	1.95
53.5	48.3	10.0	38.3	3670	68.6	1.79
71.5	46.5	8.0	38.5	3970	55.5	1.44
74.0	46.0	8.0	38.0	4060	54.9	1.44
79.0	45.5	7.5	38.0	4140	52.4	1.38
97.5	44.0	6.5	37.5	4390	45.0	1.20
120.8	42.8	6.0	36.8	4600	38.1	1.04
127.0	42.7	6.5	36.2	4610	36.3	1.00
147.0	42.5	7.0	35.5	4650	31.6	0.89
151.0	42.5	7.0	35.5	4650	30.8	0.87
173.5	42.8	8.0	34.8	4600	26.5	0.76

TABLE 5 - TEST 3B

Frost Tube 3 - 1:1; 32" long circulation tube
Volume of water being cooled = 20.3 gallons = 169 lbs.

Time, t, (hrs)	Water Temp. T_w (°F)	Cooling box Temp. T_i (°F)	ΔT $T_w - T_i$ (°F)	Heat loss Δh, (Btu)	Heat loss Rate, g, $(\frac{Btu}{hr})$	Q $(\frac{Btu}{hr\ {}^0F})$
0	63.3	68.0	----	0	----	----
5.0	60.7	14.0	46.7	440	88.0	1.88
19.0	54.3	12.0	42.3	1520	80.0	1.89
28.5	51.8	12.0	39.8	1940	68.1	1.71
45.0	48.8	10.5	38.3	2450	54.5	1.42
53.0	48.0	11.0	37.0	2580	48.7	1.32
76.5	46.7	11.0	35.7	2800	36.6	1.02
93.5	46.3	9.5	36.8	2870	30.8	0.84
116.0	45.5	9.5	36.0	3010	26.0	0.72
165.0	44.7	8.0	36.7	3140	19.0	0.52

TABLE 6 - TEST 3C

Frost Tube 3 - 1:1; 26" long circulation tube
Volume of water being cooled = 20.3 gallons = 169 lbs.

Time, t, (hrs)	Water Temp. T_w (°F)	Cooling box Temp. T_i (°F)	ΔT $T_w - T_i$ (°F)	Heat loss Δh, (Btu)	Heat loss Rate, g, $(\frac{Btu}{hr})$	Q $(\frac{Btu}{hr\ {}^0F})$
0	60.8	66.0	----	0	----	----
21.0	54.7	6.0	48.7	1030	49.1	1.01
46.0	52.2	6.0	46.2	1450	31.5	0.68
93.0	49.3	5.0	44.3	1940	20.9	0.47

Conclusions

The results of this testing prove that the "Frost Tube" can be used effectively in the removal of heat from the ground when properly designed. The recommended design that was obtained from the testing is:

(1) The ratio of downward flow area to upward flow area should be the range of 1:2 to 1:1.

(2) The length of the circulation tube should be equal to the length of the outer case that is below the ground surface plus 1/2 the length of the outer case that is above the ground surface. The construction of the tube would be the same as shown in Figs. 3 and 4 .