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Geothermal Service of Canada

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LABORATORY AND FIELD STUDIES TO INVESTIGATE ISOTOPE EFFECTS OCCURRING DURING THE FORMATION OF PERMAFROST

F. Michel and P. Fritz
Waterloo Research Institute
University of Waterloo

65 pp. including figures

Price: $20.00

Earth Physics Branch Open File Number 79-16

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ABSTRACT

Significant and systematic variations in oxygen-18 and tritium contents were documented in field cores collected in 1974 along the Mackenzie Valley and Polar Gas pipeline routes. As a result of these findings a laboratory program was initiated in the fall of 1977 to investigate these isotope variations under controlled conditions which simulate the growth of permafrost. This report describes the work completed during the second year of the program in developing the equipment and experimental procedures. Data obtained during the first five experimental runs are discussed in relation to fundamental guidelines for future experiments and in relation to the effect the variations produced or not produced will have on the interpretation of the naturally occurring isotopic variations.

RESUME

Des variations systématiques et importantes dans le contenu d'oxygène-18 et de tritium furent documentées dans des carottes ramassées en 1974 le long des routes de pipe½line de la Vallée du Mackenzie et de Polar Gas. Suite à ces découvertes un programme de laboratoire pour étudier les variations de ces isotopes sous des conditions contrôlées et simulant la croissance du pergélisol fut initié en 1977. Ce rapport décrit le travail accompli sur le développement de l'équipement et des méthodes expérimentales durant la deuxième année de ce programme. On discute des données obtenues durant les cinq premiers essais expérimentaux par rapport à l'effet que les variations, produites ou non, auront sur l'interprétation des variations isotopiques dans la nature.

OFFICE OF RESEARCH ADMINISTRATION

UNIVERSITY OF WATERLOO

INCORPORATING THE

WATERLOO RESEARCH INSTITUTE

Project No. 606-12-03

Laboratory and Field Studies To Investigate Isotope Effects Occurring During The Formation of Permafrost

Contract Serial #OST78-00092

Final Report

Prepared For

Department of Energy, Mines and Resources

F. Michel

P. Fritz

1979

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1. INTRODUCTION

1.1 Previous Studies

During the summer of 1974, field cores were collected from various locations along the Mackenzie Valley and Polar Gas pipeline routes as part of WRI project #606-12 (DSS file #06SU.23235-6-0681). In that study, significant and systematic variations in oxygen-18 and tritium contents were documented (Fritz and Michel, 1977). A paper on the results of this study was presented at the 3rd International Permafrost Conference in Edmonton, during July 1978 (Michel and Fritz, 1978b).

As a result of these findings, a laboratory program was initiated in the fall of 1977 in order to investigate these isotope variations under controlled conditions which simulate the growth of permafrost. The progress made during the initial year of this program (WRI project #606-12-02, DSS file #02SU.23235-7-0768) was reported at the end of the contract period (Michel and Fritz, 1978a).

1.2 Terms of Reference

This study was developed as a continuation of the laboratory experiments initiated during the previous contract and was designed to improve upon the experimental procedure and to initiate the actual experimental work. This work would aid in attempting to quantify the effects creating the isotope variations in permafrost related waters described previously. As a result of quantifying these effects a more detailed discussion of the formation and stability of permafrost should be possible. In addition to the experimental work additional field data was to be collected from the Foothills Alaska Highway pipeline route in order to increase the data base of observed natural isotope variations.

1.3 Scope of Present Study

This report describes the work completed to date in developing the equipment and experimental procedures. Data obtained during the first five experimental runs are discussed in relation to fundamental guidelines for future experiments and in relation to the effect the variations produced or not produced will have on the interpretation of the naturally occurring variations. During the course of this study the Foothills cores were not available for the collection of additional data and, therefore, only a limited amount of work was possible on this aspect. The additional data collected are discussed with respect to the original data. Finally, this report suggests a course along which further work should be directed.

2. WORK COMPLETED

2.1 Equipment Development and Modification

2.1.1 Column Design and Assembly

As noted in the report submitted last year describing the initial design and testing of laboratory equipment (Michel and Fritz, 1977a), several modifications were recommended for the overall equipment design. In keeping with these recommendations, ports were added to a number of additional PVC rings so that water may be injected or withdrawn from specific levels during the course of future experiments. The columns are assembled in a similar fashion to that outlined last year.

As a result of changes in the cold source, loose vermiculite is no longer employed as the insulation. In its place, a series of 5 cm thick blue styrofoam blocks have been constructed to fit around the column. A small air space approximately 1 cm in thickness exists between the column and the styrofoam. The individual blocks are stacked and fitted tightly together using 6 cm long spiral 'ARDOX' nails. Each block has outside dimensions of 20.3 cm by 40.6 cm, with a pair of blocks fitting together around the column. This provides a minimum of 12 cm of insulation. Figure 1 illustrates the relationship of the insulation and column.

2.1.2 Temperature Monitoring

During the initial development and design work, teflon coated thermocouples were employed because of the severe cold created by the use of dry ice as the cold source. With the introduction of a more moderate cold source, nylon coated thermocouples were selected to replace the teflon ones. The thermocouples (N/N 20T) contains 20 gauge

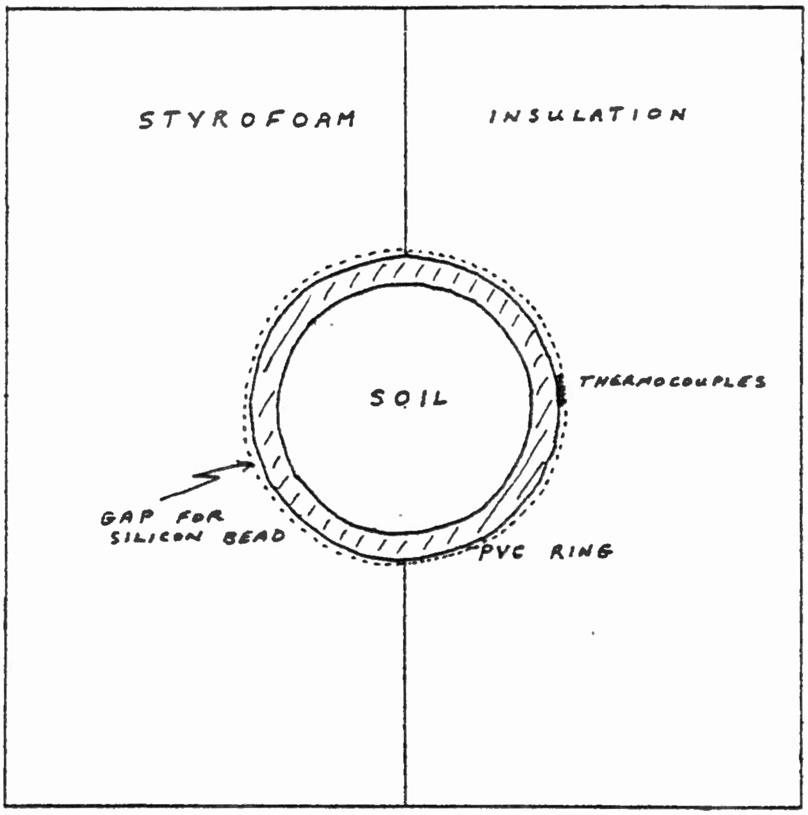


FIGURE 1

Plan view of column and insulation drawn at a scale of 1.4

copper constantine with a temperature range to -85°F (-65°C) and an error of ± 0.75°F (± 0.42°C). This change was mainly because of the poor sealing quality attained between the teflon, silicon and PVC.

The nylon thermocouples provide a better quality seal although they have proved to be less flexible even at the more moderate temperatures and they still require careful handling after sealing to prevent leaks from developing.

Measurements of the temperature were made using the Dorin Trendicator 400 A Type T model meter purchased last year. This meter is capable of reading to 0.1° C. The fact that the thermocouple wire has error limits of ± 0.42° C is of little importance in these experiments since all of the thermocouples were constructed from the same roll of wire. Therefore, every thermocouple should experience a similar error. The maximum error is largest near the limits of the temperature range. At temperatures close to 0° C, the error should be considerable less than the 0.4° C.

2.1.3 Cold Source

The experimental design during initial development employed dry ice as the cold source. The dry ice was placed within a copper based cylinder set on top of the soil column to initiate freezing from the top downwards. Because of the severe temperature gradients created and due to a few technical problems, this system was abandoned during the present contract.

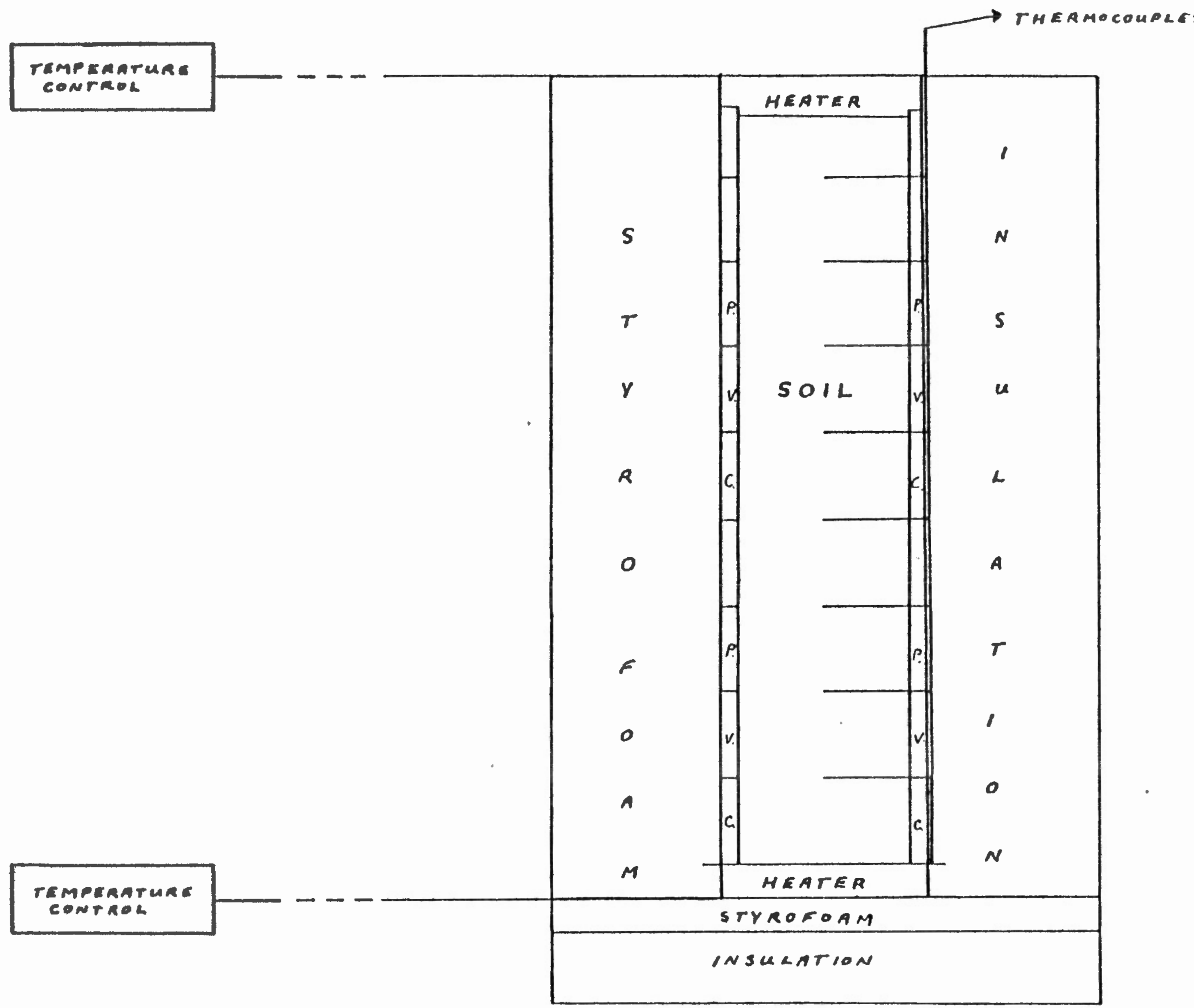
In its place, an electrical system was designed. For this system, the soil column and insulation were placed within a 22.1 cu. ft. Kenmore chest type freezer (model no. 36220). The freezer provided the cold air necessary to produce freezing.

A wooden rack was placed on the floor of the freezer to allow for circulation of the cold air. Three inches (7.5 cm) of insulation was laid on the rack to help prevent the bottom of the soil column from freezing.

To control the temperature of the freezing front and the thermal gradient along the column, heaters were placed on either end of the column. The overall experimental design is shown in Figure 2 with the heater system illustrated in detail in Figure 3.

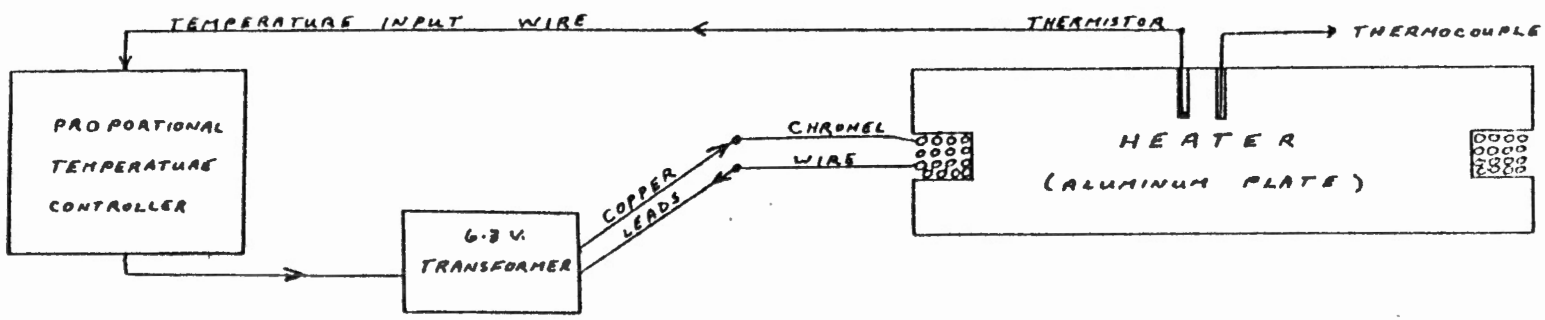
The heater blocks are constructed from a 5 cm thick slab of aluminum. Chromel (nickel-chromium) wire with an asbestos insulation covering was wrapped around the heater block and attached to copper lead wires. The 26 gauge chromel wire used has a resistance of 8.43 ohms per metre. To reduce the amount of chromel wire required, the lead wires were connected to a 6.3 volt, 1 amp. Hammond transformer (model no. 166 J 6) which in turn was connected to the main temperature control unit. This control unit is a Versa-Therm proportional temperature controller (model no. 2156) with a temperature range of -100 to + 500°F (-73 to + 260°C). The unit features temperature controls that allow the temperature to be set within 0.05° F (0.03° C) and a voltage limit controller that eliminates temperature overshoot and undershoot problems. To provide this voltage control a YSI thermistor (model no. 44004), with a tolerance of 0.2° C, was installed in the center of the heating block and connected directly to the temperature control unit. A regular thermocouple was also installed in the block so that the temperature of the heater could be measured.

FIGURE 2



Diagrammatic sketch of assembled equipment

FIGURE 3



Diagramatic sketch of heater system

Calculations for sizing of the heaters were made using the heat loss equation:

$$H.\,L. = S \times \Delta T/u \times t \qquad (1)$$

where H. L. = heat loss (B.T.U.'s/hr)

S = surface area of the column (sq. ft.)

ΔT = difference in temperature between the column and the freezer (°F)

u = thermal resistance of insulation (u = 10.0 for blue styrofoam) and

t = insulation thickness (inches)

To B.T.U.'s/hr. into watts a division factor of 3.4 was used.

Once the potential heat loss was calculated, the value was used to calculate the amount of heat input that would be required in order to prevent uncontrolled freezing. For the heat input per heater the heat loss was multiplied by a safety factor of 2.5. Using this value for the power required, the following equation was then employed to calculate the amount of chromel wire required.

$$P = V^2/R \qquad (2)$$

where P = power (watts)

V = line voltage (volts)

R = resistance (ohms)

Since P and V are known, R can be calculated. To reduce the amount of wire, the transformer added to the system lowered the value of V from 117 to 6.3 volts. From R, the number of metres of wire required were determined using the value of 8.43 ohms per metre as given by the manufacturer.

After the initial two experimental runs, a pair of small electric fans were placed in the freezer to circulate the air and thereby eliminate any temperature stratification within the freezer.

2.2 Equipment Performance

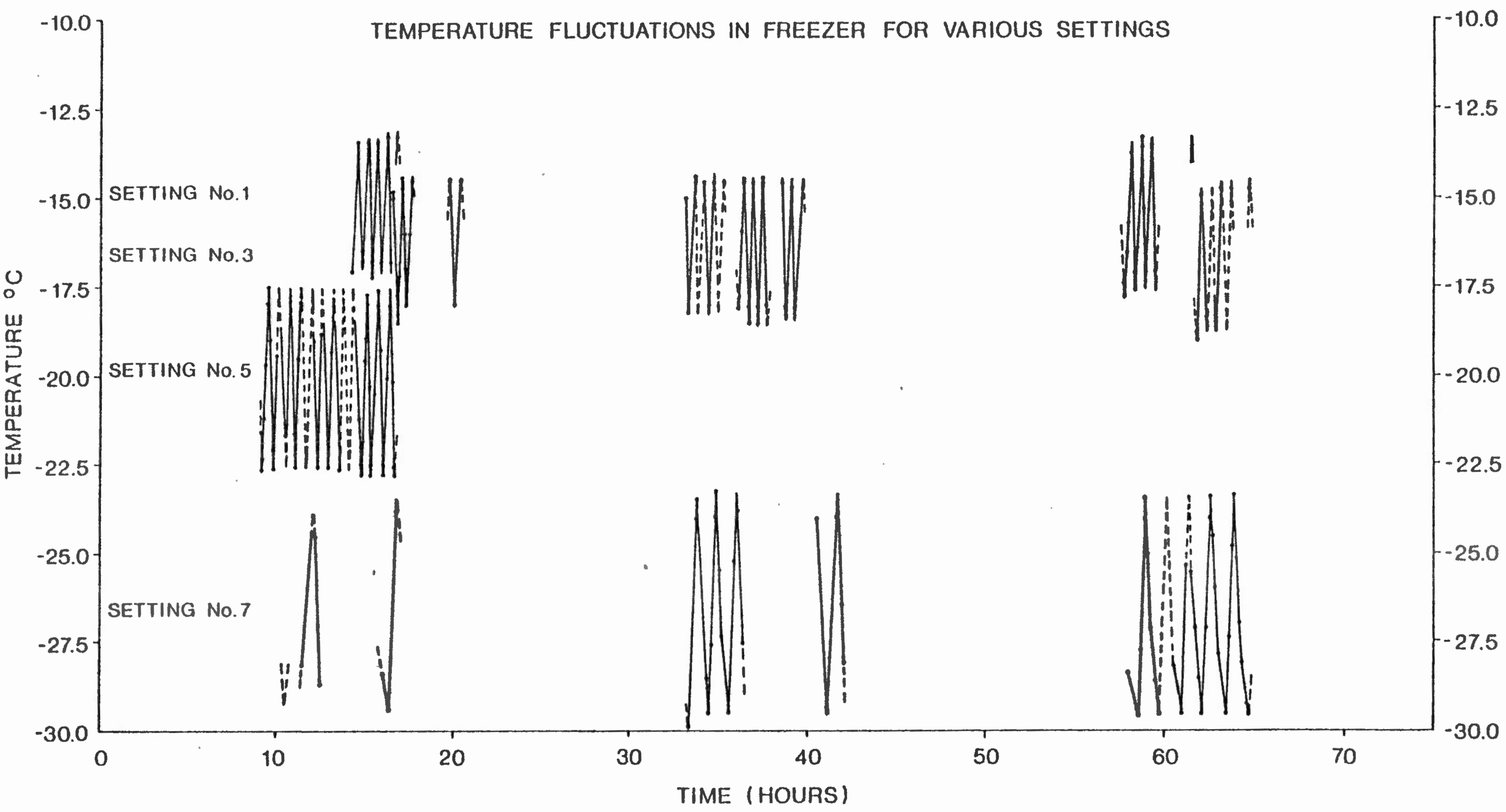
2.2.1 Freezer Performance

Freezers, like the one used during this contract period, do not maintain a constant temperature continuously. Instead, they operate on a cycle which allows the temperature to fluctuate over a specific range which is dependent upon the freezer setting. When the temperature rises above the upper limit, the freezer automatically activates the cooling system which lowers the temperature to a lower limit. At this point the freezer then shuts the cooling unit off and the temperature once again begins to rise.

In order to document the temperature ranges, to examine fluctuations in the range with time and to help in selecting the most suitable range for the experiments to be conducted, a monitoring program was undertaken. Figure 4 graphically displays the temperature fluctuations in the freezer for various settings over a period of time. From this figure, several features of the freezer become obvious. The most obvious is that the lower the freezer setting, the higher the temperature. Also, the lower settings produce a smaller range in temperatures than the higher settings. Because of the smaller range, the cycling frequency is higher for the lower settings, which in turn means a more constant temperature, relatively speaking.

Although not quite as obvious, the lowering of temperature with the cooling unit occurs in a slightly shorter period of time than the rise in temperature once the cooling unit shuts itself off. Once

FIGURE 4


TEMPERATURE FLUCTUATIONS IN FREEZER FOR VARIOUS SETTINGS
SETTING No.1
SETTING No.3
SETTING No.5
SETTING No.7
TEMPERATURE °C
-10.0
-12.5
-15.0
-17.5
-20.0
-22.5
-25.0
-27.5
-30.0
0
10
20
30
40
50
60
70
TIME (HOURS)

the range limit is reached and the cooling unit either turns on or shuts off, there is a small overshoot in the temperature before the trend reverses. This overshoot phenomena is always largest at the top end of the temperature range and largest with the highest freezer setting (7).

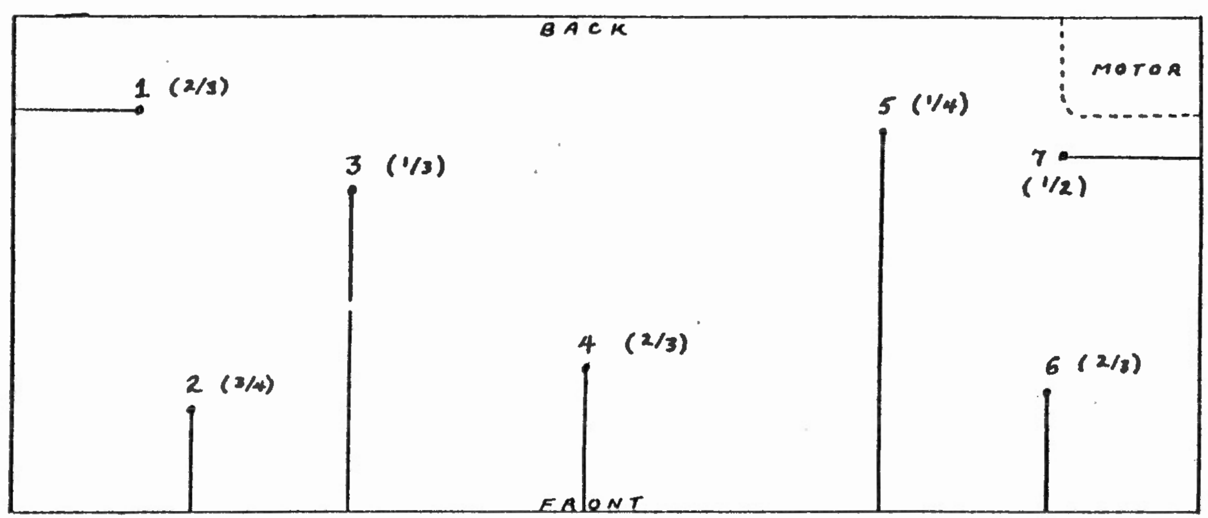
The temperature ranges for each setting remained constant over the test period of up to 65 hours. Random measurements taken immediately after the setting was changed, indicated that the freezer reaches its new temperature range within the first few cycles. It must be pointed out that during this testing, the highest setting (7) was examined first with each subsequent change lowering the setting.

As a result of the information acquired during these tests, it was decided to use setting number one for all column experiments. By keeping the temperature as close to zero as possible, the difference in temperature between the freezer and the outside air would be kept to a minimum, thereby allowing for lower heat losses.

To look at variations in temperature within the freezer at any point in time, a series of seven thermocouples were installed at different points throughout the freezer. The approximate locations of these thermocouples are shown in Figure 5. The cooling unit consists of small diameter tubes within the freezer walls. Therefore, thermocouples at the same depth but at different distances from the walls produced slightly different temperatures. The data collected for thermocouple number one was used in plotting the temperature ranges of Figure 4.

The major differences in temperature were found to occur as horizontal stratifications with the warmest air at the top of the freezer and the cold air sinking to the bottom. The data listed in Table 1 demonstrates the temperature stratification for the various freezer settings.

FIGURE 5



Location of thermocouples (and depth) in freezer during freezer performance test

TABLE 1

Date of Temperature Distribution Within the Freezer for Various Settings

Thermocouple No.	1	2	3	4	5	6	7
Depth Setting	(2/3)	(3/4)	(1/3)	(2/3)	(1/4)	(2/3)	(1/2)
7	*-24.9	-24.9	-23.3	-24.4	-22.8	-24.3	-24.7
	-29.5	-29.5	-28.3	-29.3	-28.0	-29.0	-29.5
	*-29.8	-29.8	-28.5	-29.5	-28.2	-29.4	-29.6
	*-28.4	-28.5	-27.2	-28.3	-26.6	-28.2	-28.5
5	-22.4	-22.6	-21.2	-22.4	-20.9	-22.4	-22.7
	*-21.6	-21.8	-20.6	-21.6	-20.4	-21.6	-21.6
	-22.6	-22.6	-21.6	-22.4	-21.2	-22.3	-22.4
	-17.8	-17.8	-17.1	-17.9	-16.9	-17.8	-18.2
	*-22.8	-22.8	-21.5	-22.5	-21.0	-22.4	-22.2
	*-17.6	-17.8	-17.0	-17.8	-16.7	-17.7	-17.9
3	-15.0	-14.9	-14.1	-14.8	-13.8	-14.8	-15.0
	*-14.7	-14.7	-14.0	-14.4	-13.5	-14.4	-14.4
1	*-16.8	-17.0	-16.2	-16.7	-15.8	-17.0	-17.0
	-17.0	-17.8	-17.0	-17.5	-16.6	-17.7	-17.7
	*-13.3	-13.4	-12.8	-13.1	-12.4	-13.1	-13.1

* Value plotted in Figure 6

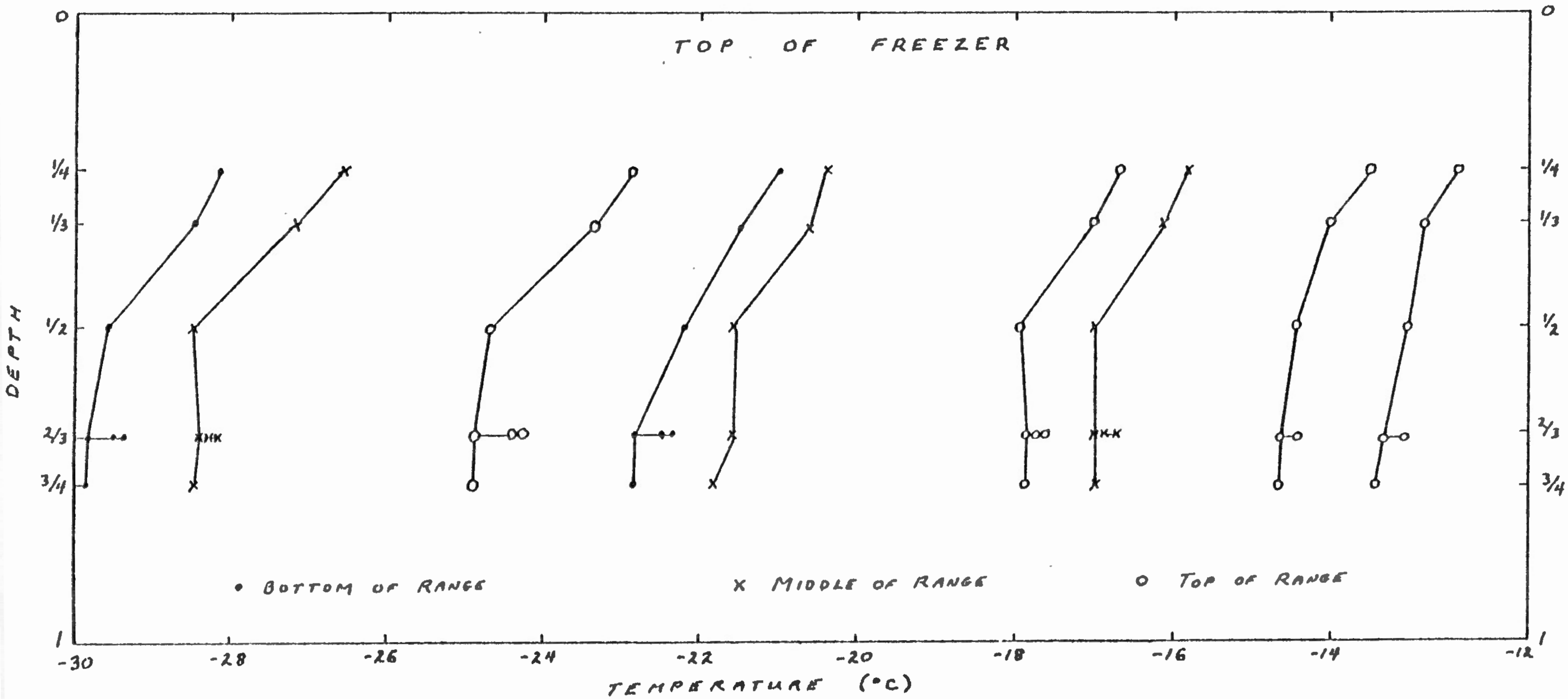
These data are plotted graphically in Figure 6 to better show the higher freezer settings. The three thermocouples at the 2/3 depth level demonstrate the type of variation that can be found at one depth.

It was found that when the insulated columns were placed in the freezer, the circulation of air was greatly hampered. The top of the freezer, at a setting of one, reached a temperature of -2 to -6° C while the bottom had a range of -11 to -17° C. To counteract this problem, a pair of small electrical fans were placed in the lower half of the freezer. With these fans in place, the temperature between the top and bottom of the freezer did not differ by more than 0.5° C at anytime during the freezer cycle. There was at times a temperature difference of up to 1.0° C between the top of the freezer and the side furthest from the fans. It was felt that this small difference would not affect the experiments and, therefore, an additional fan on the far side was not added. There was no noticeable heat affect produced by the presence of the two fans.

2.2.2 Heater Performance

The information obtained on the characteristics of the freezer as described in the previous section permitted the sizing of the heaters to be calculated with some degree of confidence as outlined in Section 2.1.3. During construction of the heaters, an overnight test was conducted to verify the calculations. The heater, after being left on overnight, was approximately 10° C above room temperature the following morning. No insulation was placed around the heater and the temperature attained represents non-insulated conditions.

FIGURE 6



Plot of temperature stratification in freezer throughout the freezer range

During the second column experiment, it appeared as if the heaters were not working. Freezing from the top and bottom was occurring with the temperature of the heater blocks apparently being controlled by the freezer.

Because of this failure, the heaters were tested again under room temperature, non-insulated conditions. Over a period of 24 hours, both of the heaters failed to produce enough heat to raise the temperature of the blocks above that of the room. Throughout the final 18 hours of the test, the heaters were set for maximum power output and insulation was added for the last half of the test.

Upon termination of the test, an investigation revealed that the 1/10 amp fuses in each unit had blown and that the transformer for one of the heaters had also malfunctioned. In order to correct these problems, minor modifications were made to the heater system. These modifications included increasing the size of the fuses to 1/8 amp, replacing the one transformer and the addition of a resistor to each transformer to reduce any sudden fluctuations in the field created by cycling of the temperature controller.

With these changes in place, another test was performed to examine the performance of the heaters. Both of the temperature controllers were set to provide 50% of the total power output. The heater blocks were insulated in a fashion similar to an experimental run, but they were tested at room temperature rather then in the freezer. Three thermocouples were placed within the room so that variations in room temperature could be monitored. Table 2 lists the results of this test with the heater data plotted in Figure 7. Time zero is set at midnight of the day the test began with the actual start occurring at

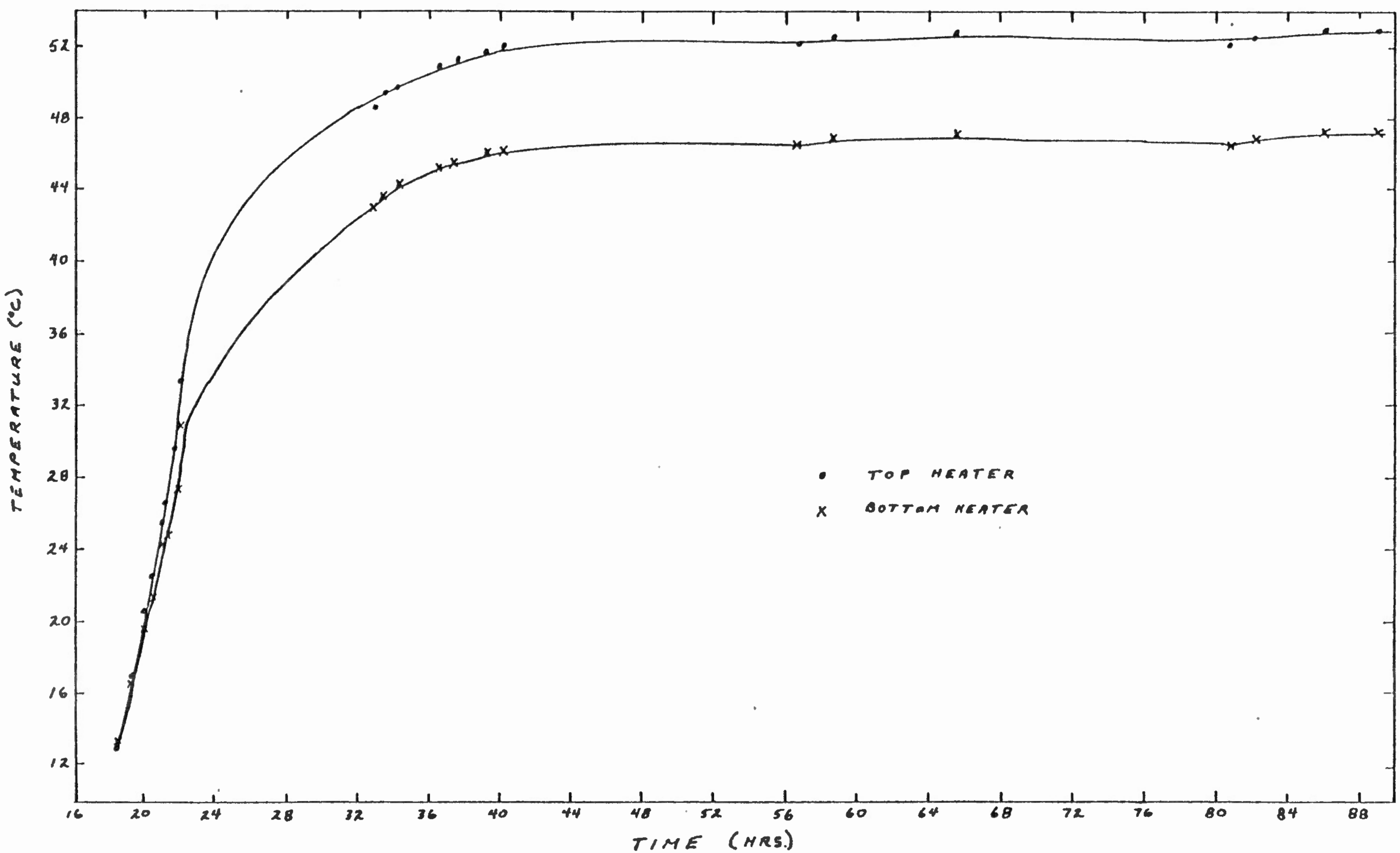
TABLE 2

Heater Test Data
Heaters were set at 50% of Maximum Power Output

Temperature (°C)

Time (Hours)	HEATERS Top	HEATERS Bottom	ROOM THERMOCOUPLES 1	ROOM THERMOCOUPLES 2	ROOM THERMOCOUPLES 3
18:30	13.0	13.2	13.5	15.4	14.4
19:20	17.1	16.8	12.2	12.8	12.2
19:55	20.5	19.7	12.1	12.7	12.1
20:20	22.6	21.5	12.1	12.8	12.0
21:00	25.7	24.2	12.0	12.8	12.0
21:10	26.5	24.8	12.2	12.9	12.1
21:55	29.7	27.6	12.1	12.8	12.1
22:00	33.7	31.0	12.1	12.7	12.2
32:55	48.6	43.1	10.2	10.9	10.6
33:35	49.4	43.8	10.9	11.6	11.2
34:05	49.7	44.2	11.2	11.8	11.4
36:35	51.0	45.4	11.8	12.4	11.9
37.45	51.4	45.7	11.8	12.2	12.0
39:10	51.8	46.1	11.8	12.6	12.0
40:10	52.0	46.2	11.6	11.9	11.7
56:50	52.3	46.6	10.3	11.0	10.6
58.45	52.8	47.2	11.6	12.2	11.7
65:50	53.0	47.6	11.1	11.8	11.3
81:00	52.2	46.4	10.8	11.5	11.1
82:10	52.7	46.9	11.5	12.1	11.6
85:55	53.0	47.4	12.0	12.3	12.0
89:00	53.0	47.4	11.6	12.6	12.2
89:00	TEST TERMINATED. HEATERS OFF.				
106:00	14.2	13.8	10.7	11.0	10.8

FIGURE 7



Plot of heater temperature with time during testing of the heaters

18:30. Fluctuations in room temperature were the result of several influences, including outside air temperature, the temperature of the adjacent room when the door was open, fluorescent lights and sunlight. Since the heaters were insulated only on the sides, their temperature was influenced to some degree by the surrounding air temperature. This is the main reason for the minor drop in temperature around 81:00 hours.

As is apparent from Figure 7, each heater has slightly different outputs from what is assumed to be initially equal power inputs. This is due to slight differences in the efficiency of the various components of which the heater is composed. The bottom heater, although having a lower efficiency than the top heater, still was able to raise the block temperature almost 35° C above room temperature with 50% of the total power available. Using a freezer setting of one, a temperature difference of 12 to 18° C exists between the heater and the freezer. There should, therefore, be no problem in producing sufficient heat from these heaters during the column experiments.

In the chapter of discussion on each of the column experiments performed, the temperature of the heaters is listed with their respective output settings. As can be seen from these data, the heaters did not encounter any problems in supplying the required heat. The major problem which still exists concerns the temperature control unit itself. Since it is a proportional controller, the temperature will change as the heater block temperature changes with freezer fluctuations. Therefore, until the heaters reach equilibrium with the freezer, some change continually occurs in the temperature of the blocks. This problem can be overcome by more continuous monitoring of the temperature with time. In experiment five, equilibrium was reached within a short period of time and changes in temperature were gradual and easily controlled.

2.2.3 Thermocouple Performance

Throughout every aspect of the experimental work , thermocouples were employed to monitor temperature. In order to interpret the temperature data collected, it is necessary to know the accuracy of the thermocouples with respect to one another. After monitoring the temperature variations within the freezer, the thermocouples were bundled together and placed with the tips located in the center of the freezer which had been set to one. All of the thermocouples should have measured the same temperature, at the same location and at the same time. They were tested over a period of eight days with the resulting data tabulated in Appendix I. The bead on thermocouple #3 broke near the beginning of the test and was not, therefore, measured. Thermocouples were read in order with #1 being remeasured at the end. As can be seen from the data, the change in temperature during the time involved in taking the readings was never greater than 0.2° C. Variations between the thermocouples were usually no larger than 0.2° C with only a few instances of variations reaching differences of 0.4° C during a single set of readings.

When thermocouples were prepared for installation into the columns, they were tested with respect to one another in order to detect any faulty thermocouples which might have been included. In all cases, when the thermocouples were read with the freezer off, variations were confined to 0.2° C in size.

The reproducibility of the measurements suggest that readings made during the column experiments can be considered as accurate to within ± 0.2° C. In some instances the accuracy may be within ± 0.1° C, but for convenience, the former error range is used during all discussions of the data.

2.3 Analytical Work

Upon dissection of the frozen column, each interval was analysed for its moisture content. Other samples were then squeezed to obtain water for analysis of oxygen-18 and deuterium contents. As described in the first chapter, core was not made available during the past year by Foothills Pipe Lines Ltd. Analyses were, therefore, confined to examining the deuterium contents of the Mackenzie Valley core samples which had previously been examined for their oxygen-18 contents. A single sample of lake water from Illisarvik, an experimental drained lake site, was analysed for its oxygen-18, deuterium and tritium contents.

3. DISCUSSION OF RESULTS

3.1 Analysis of Mackenzie Valley Cores

The initial oxygen-18 analyses obtained on these cores were reported by the authors in 1977 (Fritz and Michel, 1977). As a result of our findings, the current experimental program was initiated in 1978.

Although the cores are now almost four years old, it was decided that an attempt should be made to obtain deuterium contents to compliment the earlier oxygen-18 work. After examining the samples available and the oxygen-18 curves, cores 75-2-1 and 75-4-1 were chosen for deuterium analyses. Selected samples were picked from along the entire length of the core in order to fully characterize the isotopic shift. In all, 11 samples were analysed for deuterium. The deuterium and the previously reported oxygen-18 results are listed in Table 3.

Shifts similar to the oxygen-18 profile are readily apparent from the deuterium data. When the data from Table 3 are plotted against one another, a best fit meteoric water line can be drawn. As shown in Figure 8, this line can be described by the equation

$$\delta D = 8.33\ \delta^{18}O + 16.65 \qquad (3)$$

Because of the small amount of data used in defining this line, it is not possible at this time to say whether or not there is a statistically significant difference between this line and the average, world wide meteoric water line described by Craig (1961) as

$$\delta D = 8\ \delta^{18}O + 10 \qquad (4)$$

Nevertheless, it is important to note that the isotopic contents of the waters from both sides of the major shift continue to lie along the

TABLE 3

Isotope Data for Selected Samples from Cores 75-2-1 and 75-4-1 Plus a Single Sample of Lake Water from Illisarvik.

		Foothills Core	
		(1976)	(1979)
Sample	Depth (Ft.)	^{18}O	D
75-2-1-5	3.08 - 3.92	-23.8	-171
75-2-1-6	3.92 - 4.25	-24.3	-176
75-2-1-7	4.25 - 5.17	-24.2	-178
75-2-1-24	36.17 - 37.5	-29.1	-220
75-2-1-29	56.5 - 57.25	-27.3	-215
25-2-1-30	57.25 - 58.42	-27.3	-212
75-4-1-5	4.0 - 6.0	-21.5	-173
75-4-1-12	20.0 - 22.0	-28.9	-233
75-4-1-18	39.0 - 41.0	-31.5	-246
75-4-1-20	47.0 - 48.0	-31.2	-236
75-4-1-21	49.0 - 51.0	-30.9	-243
Illisarvik Lake	^{18}O	D	^{3}T
	-14.4	-46.5	141 ± 8

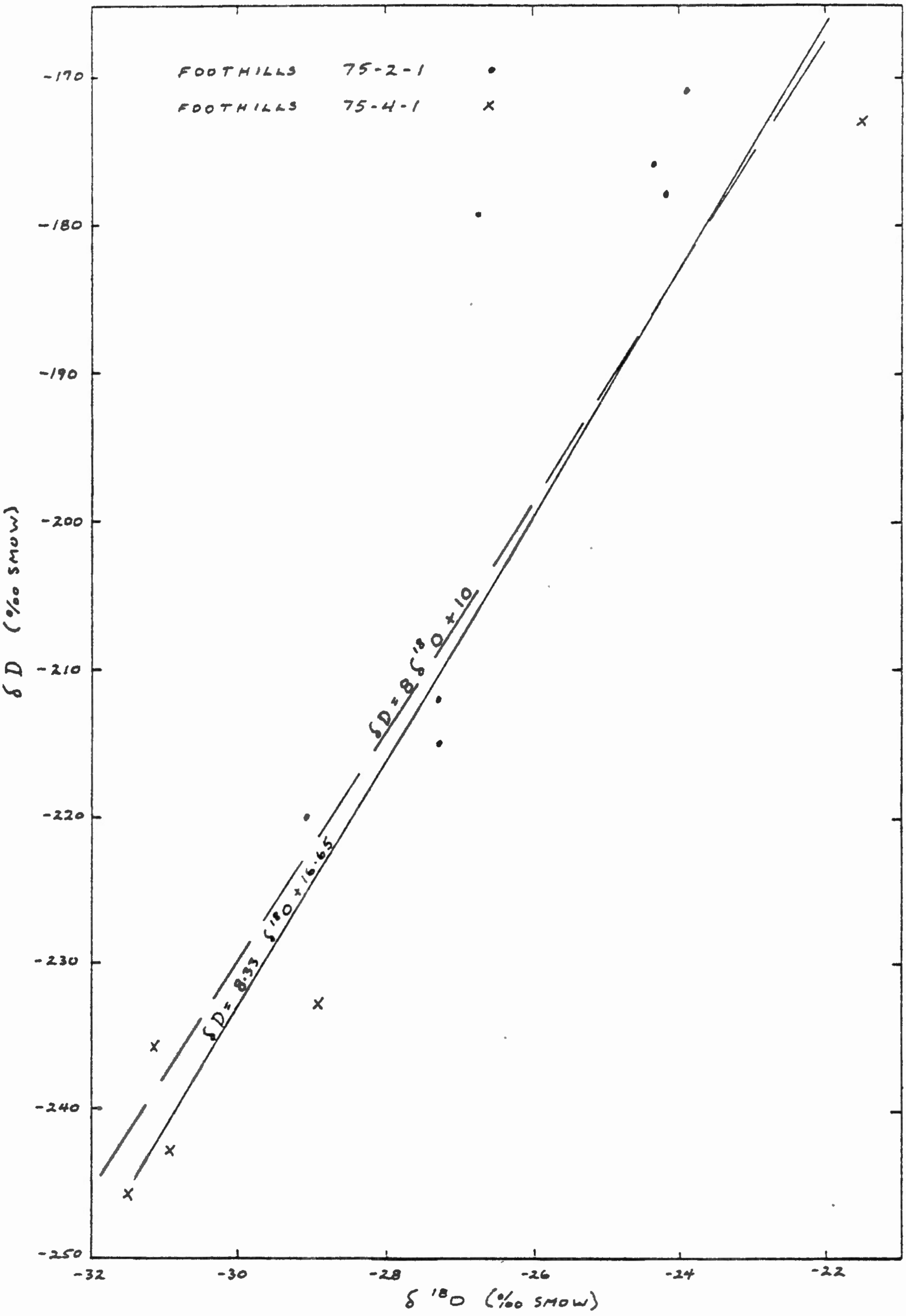


FIGURE 8

Relationship of D - ^{18}O for Foothills cores from the Mackenzie Valley. Solid line represents best fit for data. Dashed line is average worldwide meteoric water line as defined by Craig (1961).

meteoric water line. Therefore, whatever the process might be which has produced these large isotope variations, that process does not shift the isotopic contents of the water off the meteoric water line.

The analysis of the one sample from Illisarvik, indicates that the lake water was subjected to a high rate of evaporation. The analysis of the oxygen-18 and deuterium contents would plot well off the meteoric water line. It is not known whether the isotopic composition of water in the bottom sediments would also have been altered by evaporation. The presence of tritium in the water is indicative of modern surface waters. The lake probably receives a large influx of snow melt water in the spring which then evaporates during the summer.

3.2 Laboratory Experiments

3.2.1 Introduction

Since the modification of the equipment constructed for this research, a total of five experiments have been performed. Throughout these initial few runs, minor problems were encountered with various pieces of equipment. It is felt that most of the problems have been overcome and that a complete laboratory investigation will soon be underway. The equipment as presently designed and previously described can provide sufficient controls to allow for the investigation of a number of different parameters.

In four of the five experiments conducted, the medium grained Hawkesville sand described in last year's report was used (Michel and Fritz, 1978a). In experiment four, a water column containing deionized water was frozen. In the following sections, each experiment is described in detail with all of the temperature data recorded in appendices at the end of this report. Moisture contents are calculated as a percent of the dry weight of the soil. Oxygen-18 analyses have been completed for the first two experiments only.

3.2.2 Experiment 1

For this first experiment, a 50 cm long column was packed with a saturated sand mixture. The excess water was removed after the column had been filled to within 1 cm of the top. The column was fully insulated on the sides with the styrofoam blocks while above and below the column, a one inch thick sheet of styrofoam was placed. No heaters were used in this run. A 5 cm space located where the heaters would normally be placed above and below the column was left to provide an air pocket which acted as the cold source. The temperature of the freezer determined the rate of freezing.

The experiment was conducted over a period of 178.5 hours. The temperature readings taken during the duration of the run (see Appendix II) indicate that freezing occurred from the bottom upwards to the top. Stratification of temperatures within the freezer maintained near zero temperatures at the top of the column through the first 24 hour period. Within this time, the temperature along the entire length of the column dropped to below zero degrees centigrade.

After nearly 48 hours, the temperature at the top of the column finally decreased below those being recorded within the column. From this time on, both ends of the column registered negative temperatures which rose towards the centre of the column.

At the end of the experiment, the column was removed from the freezer and immediately sectioned. When the column was removed from the freezer, a 3 mm thick ice lense was noticed at the 25 cm level. Because only a small amount of material was available for analysis, the oxygen-18 content could not be determined. The central portion of the column which remained above -1.0° C, contained partially unfrozen material. From this interval several millilitres of water were obtained for analyses.

In Table 4, the moisture contents are listed for each section of the column. The top 1 cm of the soil was completely dry, probably due to evaporation of the water during the course of the experiment. It is not known why the minor variations exist. The slight increase through the 15 to 25 cm interval might be due to expulsion of water during freezing at the ends of the column. This central portion, as noted earlier, was still partially unforzen at the end of the experiment. If pore water was expelled during freezing, it would most likely accumulate in this section.

The isotope data of Table 5, indicate that fractionation did not occur. The top 5 cm was affected by evaporation as observed in the upper 1 cm of dry sand. The ice lense at the 25 cm level shows minor enrichment in the deuterium contents with this value being substantiated by the adjacent frozen soil. Unfortunately, the frozen soil does not show a similar trend in the oxygen-18 and, therefore, the significance of these two numbers is unknown. Water from the partially unfrozen core also shows some minor enrichment in comparison to the adjacent material. Because of the difficulty in obtaining this sample, the authors do not wish to place any significance on this value.

TABLE 4

Moisture Contents of Saturated Soil in Column 1,
Listed as % Dry Soil Weight

Sample	Depth (cm)	Moisture Content (%)
1 - 1	1 - 5	21.0
1 - 2	5 - 10	21.3
1 - 3	10 - 15	20.7
1 - 4	15 - 20	22.7
1 - 5	20 - 25	22.2
1 - 6	25 - 30	19.3
1 - 7	30 - 35	19.4
1 - 8	35 - 40	19.7
1 - 9	40 - 45	19.2
1 - 10	45 - 49	19.4
1 - 10u	49 - 50	18.6

u represents unfrozen material.

TABLE 5

Isotope Data for Column 1, Expressed as °/oo SMOW

Sample	Depth	$\delta^{18}O$	δD
Std. Water	-	-11.1	-78
Tap Water	-	-11.1	-78
Coln. #1	-	-10.8	-68
1 - 1	1 - 1	- 9.7	-75
1 - 2	5 - 10	-10.6	-
1 - 3	10 - 15	-10.7	-77
1 - 4	15 - 20	-10.7	-71
1 - 4u	15 - 20	-10.7	-76
1 - 4w	-	-10.0	-70
1 - 5	20 - 25	-10.7	-70
1 - 5u	20 - 25	-	-75
1CE	25	-	-67
1 - 6	25 - 30	-10.7	-68
1 - 6u	25 - 30	-10.6	-73
1 - 7	30 - 35	-10.8	-71
1 - 8	35 - 40	-10.7	-
1 - 9	40 - 45	-10.7	-70
1 - 10	45 - 49	-10.8	-77

u represents unfrozen material.

w indicates excess liquid water present.

In summary, this experiment did not provide any definite evidence with which to evaluate fractionation produced during freezing of the soil column.

3.2.3 Experiment 2

In this experiment a 50 cm long column was again packed with a saturated sand mixture. The excess water was removed after filling and the column was then insulated similar to column 1. Heaters were placed on both ends of the column. This experiment was conducted over a 178.5 hour period.

Unfortunately, both heaters are believed to have failed within the first hour of the experiment. Temperature stratification of the air in the freezer again delayed freezing at the top of the column. As a result of these problems the temperature data of Appendix III are similar to those of experiment 1. The main difference between the temperature data of these two experiments is the larger decrease in the bottom values in experiment 2. The aluminum heater block appears to have decreased the value of the basal insulation sheet. As a result, by the end of the experiments, the lower portion of the column had markedly lower temperatures in column 2 than in the first column.

When the top heater plate was removed during sectioning, a thin veneer of ice was found covering the soil. No other features were noted during sectioning. Unlike the column in the first experiment, this column was frozen throughout its entire length, with the exception of the bottom 1 cm.

The moisture contents of Table 6 contain minor variations similar to the first column. However, no pattern is evident to indicate that expulsion of water during freezing could account for these variations.

TABLE 6

Isotope Data for Column 2,
Expressed as °/₀₀ SMOW

Sample	Depth (cm)	Moisture Content (%)
2 - 1	1 - 5	20.5
2 - 2	5 - 10	19.6
2 - 3	10 - 15	20.4
2 - 4	15 - 20	20.1
2 - 5	20 - 25	21.7
2 - 6	25 - 30	20.2
2 - 7	30 - 35	18.8
2 - 8	35 - 40	20.4
2 - 9	40 - 45	18.5
2 - 10	45 - 49	19.1

Determination of the oxygen-18 contents indicates that no fractionation occurred during this experiment (Table 7). The deuterium contents vary slightly more than the oxygen data, but except for a small enrichment at the bottom of the column, there is no evidence of fractionation. The two samples showing enrichment in the deuterium data would have been the first part of the soil column to freeze. If enrichment were to be found, it would be expected to occur in this section.

3.2.4 Experiment 3

After modifying the heater systems to prevent failures during future experiments, a 50 cm long column was again packed with a saturated medium sand. A heater was set up beneath the column with three inches of styrofoam beneath the heater. The top of the column was covered with a sheet of plastic to prevent moisture loss by evaporation. For this experiment, the freezer was used directly as the cold source. Two small fans were installed in the freezer to help circulate the air and prevent the temperature stratification present during the first two experiments.

The temperature data, listed in Appendix IV indicate that freezing occurred from the top down. The temperature gradient prior to the initiation of freezing (30 hrs.) was approximately 7° C per metre. When the next set of readings were taken some 13 hours later, almost the entire column recorded negative temperatures. However, the gradient had decreased to less than 0.1° C per metre in the frozen section. Temperatures held continuously at around -0.2° C ± 0.1 for a considerable length of time. Freezing continued to decrease the temperature of the upper 5 cm of the column at a gradual rate throughout

TABLE 7

Isotope Data for Column 2,
Expressed as °/₀₀ SMOW

Sample	Depth (cm)	$\delta^{18}O$	δD
Std. Water	-	-11.1	-78
Tap Water	-	-11.1	-78
Coln. #2	-	-10.8	-
ICE	0 - 0.5	-	-75
2 - 1	0.5 - 5	-10.8	-77
2 - 2	5 - 10	-10.7	-72
2 - 3	10 - 15	-10.7	-72
2 - 4	15 - 20	-10.6	-70
2 - 5	20 - 25	-10.8	-76
2 - 6	25 - 30	-10.7	-71
2 - 7	30 - 35	-10.7	-70
2 - 8	35 - 40	-10.6	-73
2 - 9	40 - 45	-10.8	-74
2 - 10	45 - 49	-10.7	-61
2 - 10u	49 - 50	-10.5	-67

u represents unfrozen material

the experiment. It is interesting to note that a temperature difference of approximately 1.2° C was required before the temperature of the underlying 5 cm column section dropped below the -0.2° C value. This would translate into a 1.2° C per 5 cm gradient or 24° C/metre. This size of gradient was required for each section of the column. Once the temperature was reduced, the gradient decrease gradually from 20° C per metre (100 hrs.) to 8° C per metre at the end of the experiment (217 hrs.). Fluctuations, created because of repairs being undertaken on the university power supply between 100 and 105 hours, did not affect the column temperatures. The bottom heater, however, did undergo a sharp rise in temperature which quickly dropped once the normal power supply was returned to operation.

Dissection of the column revealed the presence of frost on the lower surface of the plastic sheet and a thin veneer of dry soil beneath. The column had separated slightly at the 35 cm level. All of the material was frozen and no loss of water was apparent.

The moisture content of the column (Table 8) generally increases with depth. This is similar to the earlier experiments in that the water appears to be expelled during freezing, accumulating in the portion of the columm which freezes last. The slight increase in moisture content at the 10 to 20 cm level cannot be explained by this method, however. This anomaly correlates with a slight depletion in deuterium as seen in Figure 9.

The fluctuations present in the graph, may indicate the presence of some less permeable material retarding the movement of the moisture downwards. The depletion and slight enrichment near the top of the column is probably due to fractionation during formation of the frost.

TABLE 8

Moisture Content of Saturated Soil in Column 3,
Listed as % of Dry Soil Weight

Sample	Depth (cm)	Moisture Content (%)
3 - 1	0 - 5	21.0
3 - 2	5 - 10	21.0
3 - 3	10 - 15	22.0
3 - 4	15 - 20	22.5
3 - 5	20 - 25	21.4
3 - 6	25 - 30	21.7
3 - 8	35 - 40	21.3
3 - 9	40 - 45	22.2
3 - 10	45 - 50	23.1

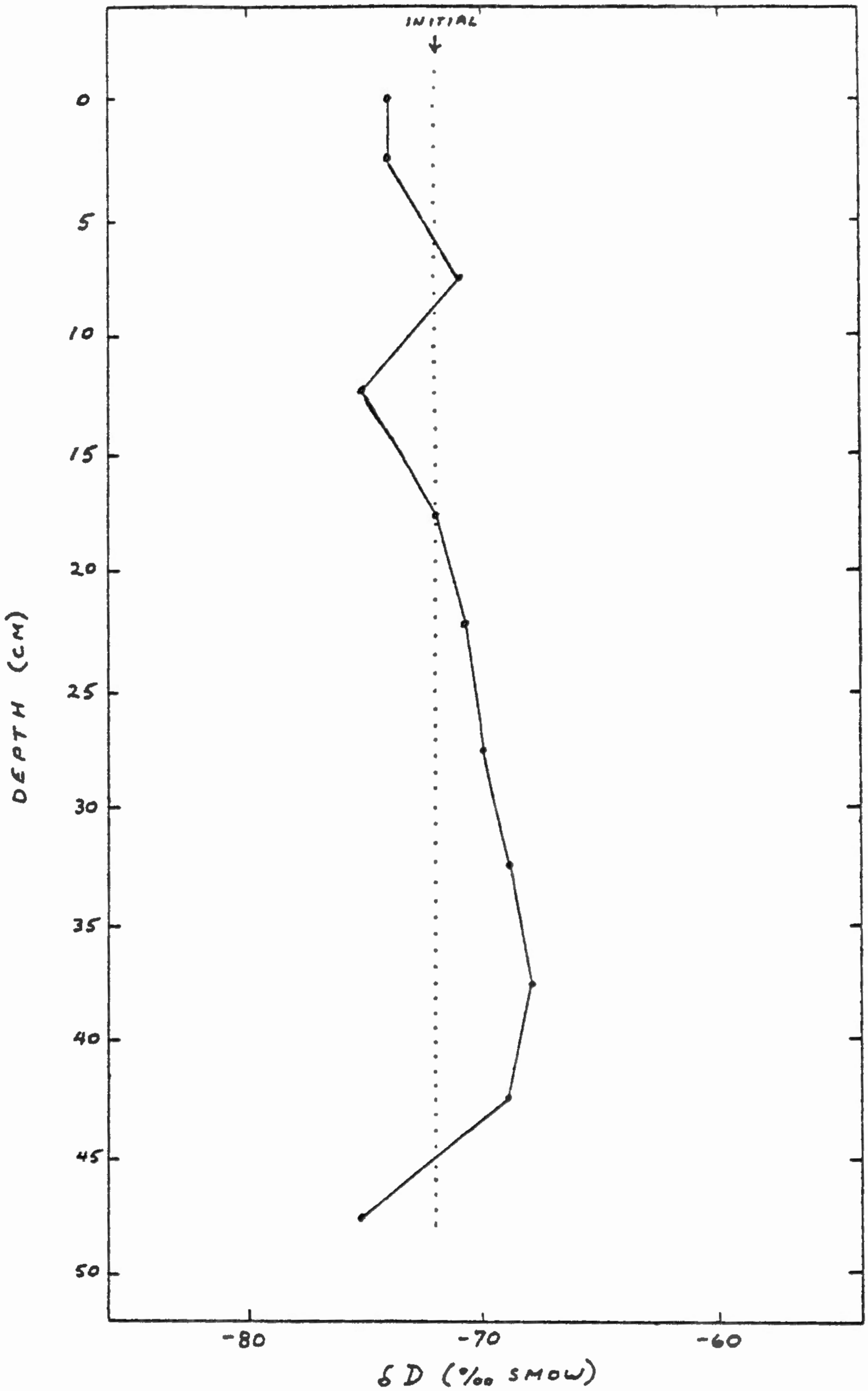


FIGURE 9

Variation in deuterium with depth in
Column No. 3

From the 20 cm level, the data (Table 9) indicate a gradual enrichment of the soil water in deuterium. The sudden depletion near the base of the column is indicative of a reservoir effect which would be expected for the last water to freeze. The gradual enrichment, however, was not expected as this is the reverse of what should have occurred. Variations in the deuterium values of earlier experiments to a similar degree, without corresponding variations in the oxygen-18 data, provide some doubt as to the significance of the 4°/₀₀ shift. It should be noted, however, that the deuterium contents are preserved, indicating that no loss has occurred. The reason for the variations are, therefore, unknown at this time.

3.2.5 Experiment 4

For this experiment, a 40 cm column was filled with deionized water to within 2 cm of the top. A plastic sheet was placed over the top of the column to prevent moisture loss. Beneath the bottom heater a total of five inches of insulation was inserted. The surrounding insulation was assembled in the same fashion as the previous experiments.

The temperature data compiled in Appendix V indicate that thorough mixing of the water column was occurring throughout the first 25 hours of the experiment. This is believed to be due to temperature related density changes which caused the colder surface waters to sink. Throughout this experiment, freezing was definitely occurring from the top down.

Water attains its maximum density at approximately 4.0° C. According to the data for this experiment, the stratification of the water column began once the temperature dropped to 3.8° C (at 30 hrs.).

TABLE 9

Isotope Data for Column 3,
Expressed as °/₀₀ SMOW.

Sample	Depth (cm)	δD
Std. Water	-	-78
Tap Water	-	-78
Coln. #3	-	-72
Frost	Top	-74
3 - 1	0 - 5	-74
3 - 2	5 - 10	-71
3 - 3	10 - 15	-75
3 - 4	15 - 20	-72
3 - 5	20 - 25	-71
3 - 6	25 - 30	-70
3 - 7	30 - 35	-69
3 - 8	35 - 40	-68
3 - 9	40 - 45	-69
3 - 10	45 - 50	-75

The 0.2° C difference is of the same magnitude as the previously noted stabilization temperature. In all of the experiments completed to date, the temperatures levelled off at -0.2° C and maintained this temperature, for considerable periods of time. This similarity might indicate that all of the thermocouples are recording temperatures which are 0.2° C lower than the actual temperature.

Nevertheless, once the temperature decreased below the maximum density point, the column became stratified from top to bottom. The temperature gradient gradually decreased from 8° C per metre immediately after stratification to less than 0.1° C per metre at the time of freezing. Temperatures of -0.2° C were maintained for nearly 12 hours before the upper water temperature began to drop. It took over 50 hours for the freezer to cool this upper water (ice) to the point that the next section of the water column began to experience decreased temperatures. During this time a gradient of approximately 45° C per metre was generated over the 5 cm interval. This is twice the gradient generated in the soil - water system before the temperature decreases occurred.

Once the temperature dropped below this critical point (-0.2° C), the gradient in the column steadily decreased to approximately 10° C per metre at the end of the experiment. This is slightly higher than the soil-water system which decreased to 8° C per metre. Further reductions might have occurred if the experiment had been continued.

Upon completion of the experiment, the column was removed from the freezer for dissection. The top 1 cm, immediately beneath the plastic sheet, contained frost. The silicon seal at the 35 cm level was split with the PVC ring and base plate at 40 cm almost completely separated.

Some water had escaped from this lowermost crack and was frozen shortly afterwards. Within the ice column a hole up to 1 cm in diameter and 2.5 cm from the edge of the column was found. It was continuous from 14 cm to 35 cm. Surrounding the hole were small air bubbles oriented vertically along the hole and horizontally near the top and bottom of the hole. This hole appears to have been created by vertically flowing water through a semi-frozen liquid.

The isotope data (Table 10) when plotted as in Figure 10 provides answers to several questions. The large negative shift at the very top of the column (24 °/₀₀) is due to fractionation in the liquid-vapour system. The vapour was recondensed as frost on the plastic sheet. The enrichment of the upper ice core results from the preferential uptake of the heavier deuterium into the ice lattice. The higher energy of the hydrogen allows it to remain in the liquid phase. Continued depletion of the deuterium should cause the isotopic contents to shift along the Rayleigh distillation model line (dashed line, Figure 10). This asymtotic line would eventually indicate that the final residual fraction of water would not contain any deuterium whatsoever. Of course, this point is never reached in natural systems.

The deviations from the theoretical line in Figure 10 occur in the 14 to 35 cm range. Thorough mixing of the water during freezing would account for the lack of fractionation in this interval. The hole and vertically oriented bubbles may be the physical evidence of this mixing . Conservation of the isotopes indicates that no appreciable loss of water occurred from the system. The minor enrichment of the basal water which did escape from the column is probably from the reservoir when the deuterium content of the water was -96 °/₀₀.

TABLE 10

Isotope Data for Column 4,
Expressed as °/₀₀ SMOW.

Sample	Depth (cm)	δD
Std. Water	-	-78
Bucket Water	-	-73
Coln. #4	-	-79
FROST	Top	-89
4 - 1	1 - 5	-65
4 - 2	5 - 10	-68
4 - 3	10 - 15	-71
4 - 4	15 - 20	-74
4 - 5	20 - 25	-81
4 - 6	25 - 30	-81
4 - 7	30 - 35	-82
4 - 8	35 - 40	-99
4 - Base	40	-96

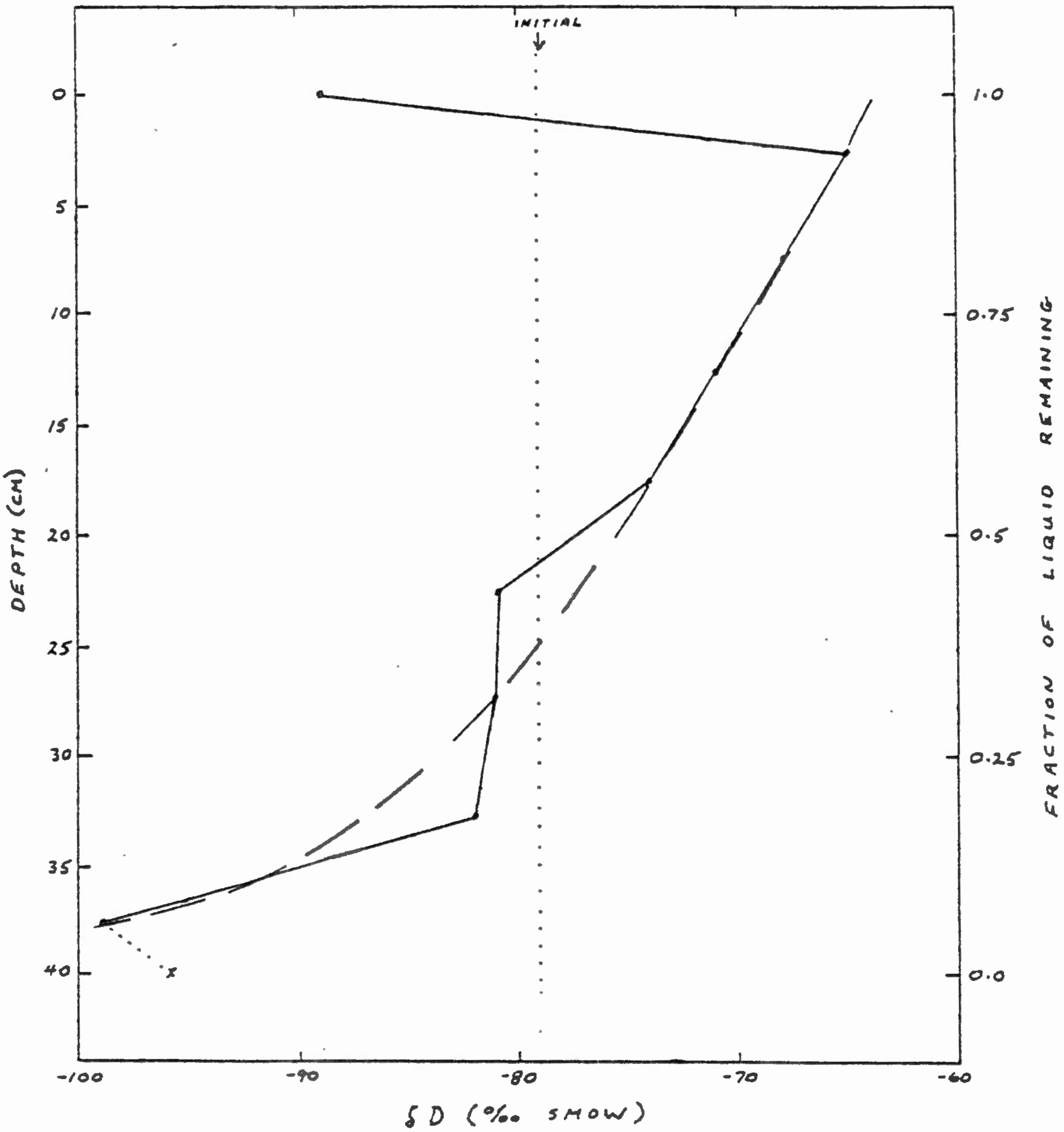


FIGURE 10

Variation in deuterium with depth in ice column (experiment No. 4). Dashed line represents Rayleigh distillation curve.

The experiment has clearly demonstrated that reservoir effects can cause variations in the isotopic content of ice. Most of the fractionation occurs when less than 25% of the liquid remains. If such were the case in the field, one would expect to see a gradually increasing variation with depth followed by a rapid return to the isotopic content of the frozen material beneath. This may be the process to explain the small variations detected in the detailed core, but it cannot explain the large, sudden shift noted in the other cores.

3.2.6 Experiment 5

This was the final experiment conducted within the time available. Additional experiments will be conducted during the upcoming months to further investigate isotope effects resulting from freezing of the soil.

In this experiment a 45 cm column was filled with the saturated sand. After filling, a plastic sheet was set over the top of the column and the bottom part was opened to allow drainage of the excess water. A sample of the initial water (EXCESS-1) was collected followed by a series of samples taken at ten minute intervals. Drainage of the column continued for one-half hour at which time the port was closed and the plastic removed. The column was only partially drained.

Heaters were placed at both ends of the column. The bottom heater was set on top of three inches of insulation. The column was insulated in a manner similar to the previous experiments, except that no material was packed in the space between the column and the insulation. In this experiment, the temperature gradient and rate of freezing were to be controlled as carefully as possible. Unfortunately, the lack of packing between the column and insulation resulted in some freezing from the sides occurring.

Because of the presence of saturated and unsaturated zones, the temperature of the column did not decrease as uniformly as in the fully saturated columns. The highest temperature in the column was recorded from the section with the lowest moisture content. Temperature in general, during the first 14 hours was controlled to some extent by the moisture content of the soil.

The temperature gradient prior to freezing ranged from 4 to 5° C per metre (21 to 28 hours, Appendix VI). From the initiation of freezing at 30 hours, the temperature of the column remained in the -0.2 to -0.4° C range for over 55 hours. During this period the gradient was less than 0.1° C. The gradient required to initiate downward movement of the temperature was approximately 0.4° C per 5 cm or 8° C per metre for the unsaturated zone. This is the lowest gradient required in any of the experiments conducted. It would appear that the higher the moisture content, the higher the gradient required to initiate freezing to temperatures below the -0.2° C level. As discussed in the section on the previous experiment, the -0.2° C readings may in fact be 0.0° C and the steady temperatures result from the phase change of water to ice.

The temperature anomaly indicating freezing from the sides was first registered at the 100 hour mark. Throughout the remainder of the experiment this problem became worse as temperatures in the column decreased to values less than either heater.

When the column was dismantled, a thin layer of frost was discovered on the lower surface of the top heater. During sectioning about 2 cc. of water were recovered from the 30 cm level. It was noted during sectioning that the central portion of the column was considerably drier than the edges. Because of the side-wall freezing, it was decided to keep separate these two parts of the column.

Analysis of the samples for their moisture contents (Table II) clearly shows the water table at the 30 cm level. Within the saturated zone, the water contents are within 2% of one another (Figure II). However, in the unsaturated zone the water contents are very different. The central core of the column drained to approximately a 4 to 6% water content. The edges of the column however, only drained to a water content of 13 to 16%. It is not known whether this difference is due to drainage or whether this is a function of freezing from the walls inwards. The earlier experiments indicated that during freezing water was expelled from the freezing soil into the unfrozen material. If this were true for this experiment, then the difference in moisture content cannot be due to freezing.

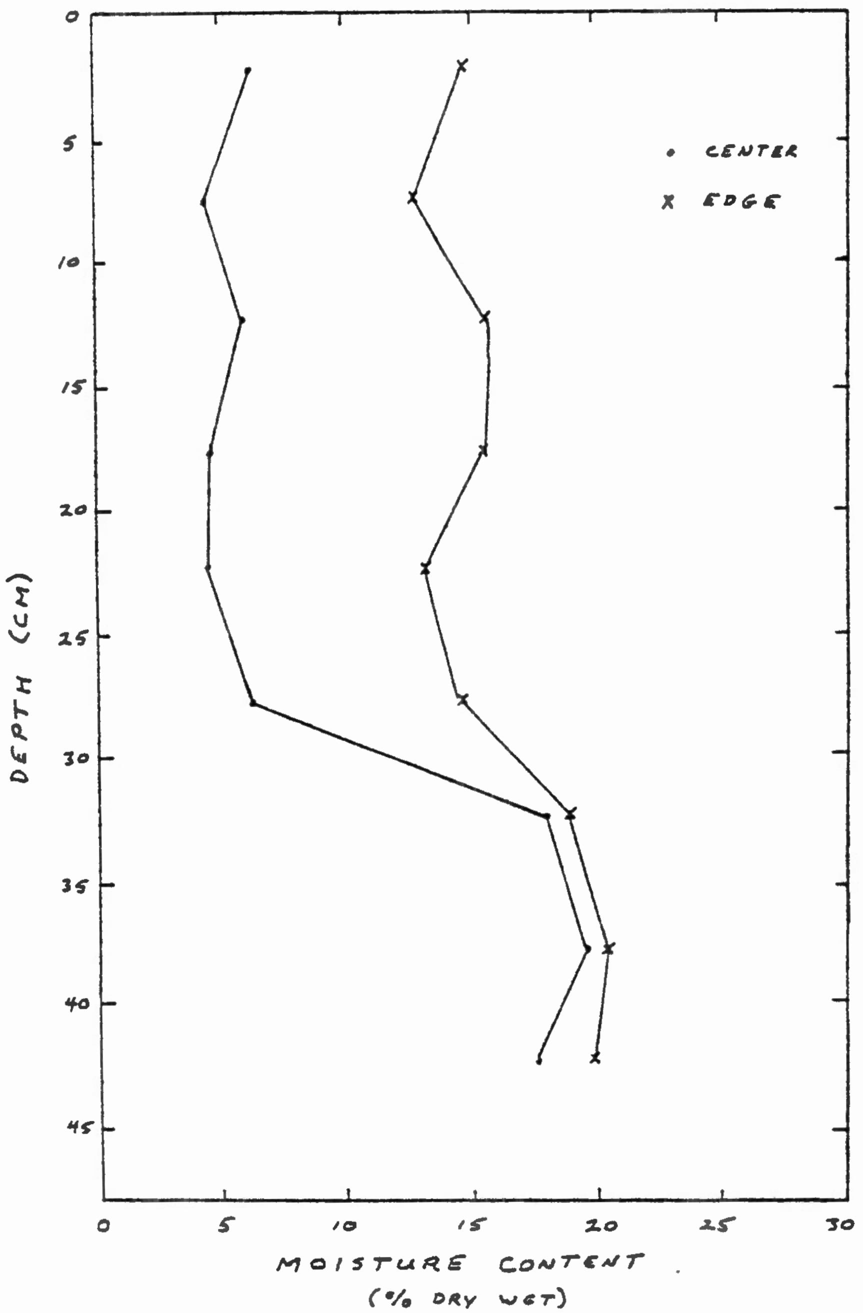
From the isotope data in Table 12, the effects of freezing from the walls inwards can be seen. The temperature data indicate that side-wall freezing began at the 35 cm level. Enrichment in the initial ice would be followed by gradual depeletion during freezing. The most highly enriched values are found around the 35 cm level (Figure 12). Gradual freezing towards the centre of the column and upwards produces a complex pattern which appears to show depletion. Unfortunately, many of the upper samples did not yield sufficient water for analyses. The incomcompleteness of the data does not permit the system to be fully understood at this time. The frost value of the top of the column indicates that some evaporation of the sample has occurred.

TABLE 11

Moisture Content of Partially Drained Soil in Column 5,
Listed as % of Dry Soil Weight

Sample	Depth (cm)	Moisture Content (%) Centre	Edge
5 - 1	0 - 5	6.1	14.9
5 - 2	5 - 10	4.5	12.8
5 - 3	10 - 15	5.9	15.6
5 - 4	15 - 20	4.8	15.5
5 - 5	20 - 25	4.6	13.2
5 - 6	25 - 30	6.1	14.7
5 - 7	30 - 35	18.0	18.9
5 - 8	35 - 40	19.7	20.5
5 - 9	40 - 45	17.8	19.9

FIGURE 11



Moisture content variations with depth
Column No. 5

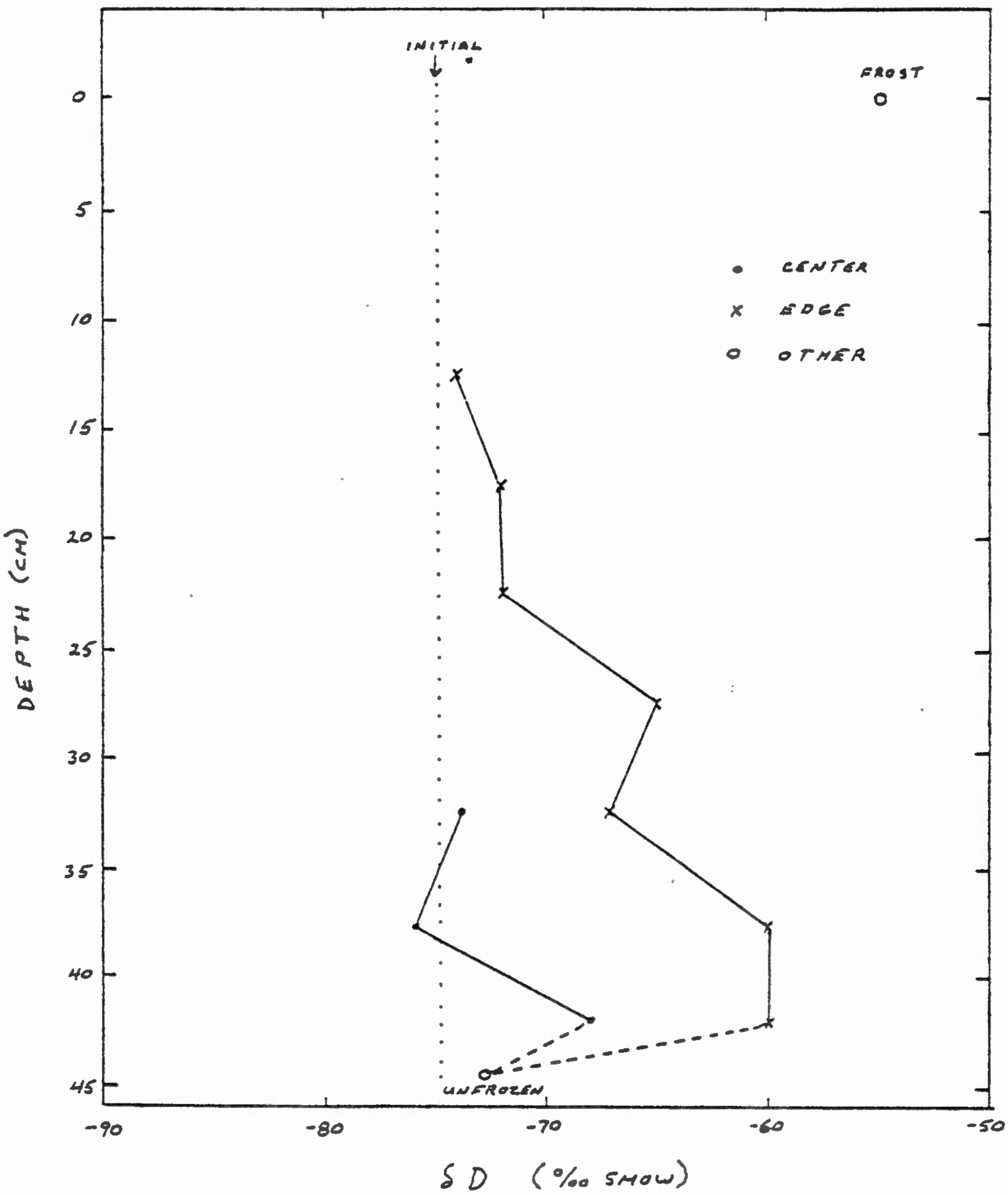
TABLE 12

Isotope Data for Column 5,
Expressed as °/∘∘ SMOW.

Sample	Depth (cm)		δD	
		Centre		Edge
Std. Water	-		-78	
Tap Water	-		-76	
Bucket Water	-		-82	
Coln. #5	-		-75	
Excess -1	-		-78	
Excess -2	-		-73	
Excess -3	-		-76	
Excess -4	-		-73	
End Tube	-		-66	
FROST	Top		-55	
5 - 1	0 - 5	-		-
5 - 2	5 - 10	-		-
5 - 3	10 - 15	-		-74
5 - 4	15 - 20	-		-72
5 - 5	20 - 25	-		-72
5 - 6	25 - 30	-		-65
5 - 6w	-		-66	
5 - 7	30 - 35	-74		-67
5 - 8	35 - 40	-76		-60
5 - 9	40 - 44	-68		-60
5 - 9u	44 - 45		-73	

u represents unfrozen material.
w indicates excess liquid water present.

FIGURE 12



Variation in deuterium with depth in Column No. 5

In order to prevent future problems of this type, insulation such as rock wool will be wrapped around the column before placing it within the styrofoam blocks.

4. CONCLUSIONS

4.1 Laboratory Equipment and Procedures

Modifications to the original equipment design have successfully resulted in a system that can be used to investigate isotope fractionation effects created during freezing. The cost of the equipment described within this report is relatively low. Automation of the system would add to the expense, but if a large number of experiments were to be run for various purposes, it would well be worth the cost. Care must be taken to ensure that freezing does not occur from the sides. Wrapping of the column in insulation or with heating tape should rectify this problem. To derive the maximum from each experiment, readings should be taken throughout the experiment at least every 3 to 4 hours. In general, the system can be set up in any room or laboratory, although a cold room is still the best, and used for various freezing experiments.

4.2 Experimental Findings

Of the five experiments conducted to date, the freezing of the water column (Experiment 4) has yielded the best results. Evaporation-condensation effects and reservoir effects were clearly documented during this run. Although the evaporation-condensation effects are not considered to be important at depth in a saturated soil system, they may be important in looking at vapour transfer in the unsaturated system. This system could have existed in the past and has been replaced by saturated conditions now. Nevertheless, the effects of the unsaturated system may still be present at depth. The Rayleigh equilibrium fractionation path followed during freezing of the water suggests that reservoir effects may be responsible for the minor variations and the isotope couplets seen in the detailed core.

Minor fractionations were produced during Experiments 3 and 5, but they were inclusive in helping to determine the size to which fractionations could occur. The first two experiments failed to produce any isotope effects.

Expulsion of water from the freezing front area and into the unfrozen material appeared to occur in all the saturated soil columns tested. The importance of this moisture migration for frost heave and ice lensing experiments has still to be investigated at a future date.

Analysis of two of the cores from the Mackenzie Valley for deuterium enabled a more detailed investigation of the material system to be conducted. Shifts similar to the oxygen-18 variations described in previous reports were found in the deuterium data. Plotting of the oxygen-18 and deuterium data against one another indicate that the waters at all the depths surveyed fall on the meteoric water line. The equation best describing this line for the data available is

$$\delta D = 8.33\ \delta^{18}O + 16.65$$

The significance of any change from the world-wide meteoric line cannot be determined at this time because of the sparse amount of data. The fact that all data points fall onto the meteoric water line rules out all non-equilibrium fractionation processes as possible processes responsible for the large shifts in isotope contents seen in the field. Further testing in the laboratory should reduce the possible number of processes that can be considered.

Finally, the one sample analysed from the lake at Illisarvik, indicates that the water is modern water probably derived from local surface runoff. High evaporation losses are indicated by the isotope contents of the sample analysed, probably reflecting the time of the year in which the sample was taken.

4.3 Suggestions for Continued Work

Now that the laboratory equipment has been modified successfully, a series of experiments can be undertaken during the upcoming year. These experiments should examine various parameters such as moisture content, grain size, freezing temperature, rate of freezing, saturated and unsaturated conditions etc.

Further field work should also be conducted in order to investigate the distribution of the isotope shift throughout the Arctic. A field program is expected to be undertaken at Illisarvik during the upcoming spring. Detailed drilling of modern permafrost and, hopefully, relic permafrost will be undertaken during this program.

The cores from the Alaska highway route which were to be obtained from Foothills during the present contract should be available during the upcoming year. Analysis of these cores and any other cores which may be obtained during the next year should be considered in order to increase the data base.

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APPENDIX I

Temperature Data for Thermocouples Used in Freezer Tests

	Thermocouple No. /Temperature (°C)						
Time (hrs.)	1	2	4	5	6	7	1
09:30	-14.9	-14.9	-14.9	-14.7	-14.8	-14.8	-14.8
11:10	-16.7	-16.6	-16.6	-16.6	-16.6	-16.6	-16.6
12:20	-16.8	-16.7	-16.7	-17.0	-16.7	-16.7	-16.7
15:10	-13.6	-13.6	-13.6	-13.4	-13.5	-13.6	-13.6
40:12	-15.4	-15.3	-15.3	-15.7	-15.6	-15.3	-15.3
40:14	-15.9	-15.8	-15.8	-15.2	-15.9	-15.9	-16.0
59:11	-15.2	-15.2	-15.2	-15.0	-15.1	-15.2	-15.1
59:16	-14.2	-14.2	-14.2	-14.1	-14.1	-14.2	-14.2
59:23	-13.6	-13.6	-13.6	-13.6	-13.6	-13.6	-13.7
60:25	-14.6	-14.6	-14.6	-14.4	-14.4	-14.5	-14.5
60:28	-14.0	-14.0	-14.0	-13.8	-13.9	-14.0	-13.9
60:32	-13.5	-13.5	-13.5	-13.3	-13.4	-13.5	-13.5
60:36	-14.3	-14.2	-14.3	-14.6	-14.3	-14.2	-14.5
60:39	-15.4	-15.3	-15.3	-15.6	-15.4	-15.2	-15.6
60:42	-16.2	-16.1	-16.1	-16.4	-16.1	-16.2	-16.4
60:44	-16.8	-16.6	-16.6	-17.0	-16.8	-16.6	-16.9
60:46	-17.0	-16.9	-16.9	-17.1	-16.9	-16.9	-17.0
60:49	-16.5	-16.6	-16.6	-16.4	-16.5	-16.5	-16.5
60:53	-16.0	-16.0	-16.0	-15.9	-16.0	-16.0	-16.0
60:58	-15.0	-15.0	-15.0	-14.8	-15.0	-15.0	-14.9
61:01	-14.4	-14.5	-14.5	-14.3	-14.4	-14.4	-14.4
61:04	-14.1	-14.1	-14.1	-13.9	-13.9	-14.0	-14.0
61:07	-13.6	-13.6	-13.5	-13.4	-13.5	-13.5	-13.5
61:50	-15.4	-15.3	-15.3	-15.6	-15.4	-15.2	-15.6
61:52	-16.1	-16.0	-16.0	-16.3	-16.0	-15.9	-16.3
63:06	-17.0	-16.9	-16.9	-17.1	-16.9	-16.9	-17.0
179:41	-16.6	-16.6	-16.6	-16.9	-16.6	-16.5	-16.8
179:42	-16.8	-16.7	-16.7	-17.0	-16.7	-16.7	-16.9
179:43	-16.9	-16.8	-16.8	-17.1	-16.8	-16.8	-17.0
179:44	-17.0	-16.9	-16.9	-17.0	-16.8	-16.8	-16.9
179:46	-16.6	-16.6	-16.6	-16.5	-16.5	-16.6	-16.5
179:47	-16.4	-16.4	-16.4	-16.3	-16.3	-16.4	-16.3
179:50	-16.0	-16.0	-16.1	-15.9	-16.0	-16.0	-16.0
179:52	-15.6	-15.6	-15.6	-15.5	-15.6	-15.6	-15.6
179:55	-15.2	-15.2	-15.2	-15.0	-15.1	-15.2	-15.0
179:57	-14.8	-14.8	-14.8	-14.6	-14.8	-14.8	-14.7
179:59	-14.5	-14.5	-14.5	-14.3	-14.4	-14.4	-14.4
180:01	-14.1	-14.1	-14.1	-13.9	-14.0	-14.1	-14.0
180:03	-13.8	-13.8	-13.8	-13.6	-13.7	-13.8	-13.7

Temperature Data for Thermocouples Used in Freezer Tests Cont'd

	Thermocouple No. /Temperature (°C)						
Time (hrs.)	1	2	4	5	6	7	1
180:05	-13.4	-13.5	-13.5	-13.3	-13.4	-13.4	-13.4
180:07	-13.3	-13.3	-13.3	-13.3	-13.3	-13.3	-13.4
180:09	-13.7	-13.6	-13.7	-13.8	-13.7	-13.6	-13.8
180:11	-14.3	-14.2	-14.2	-14.5	-14.3	-14.2	-14.5
180:13	-15.1	-15.0	-14.9	-15.3	-15.0	-14.9	-15.3
180:15	-15.8	-15.7	-15.7	-16.1	-15.8	-15.6	-16.0
180:17	-16.4	-16.4	-16.4	-16.7	-16.4	-16.4	-16.6
180:19	-16.9	-16.8	-16.8	-17.0	-16.8	-16.7	-16.9
180:21	-16.8	-16.8	-16.8	-16.8	-16.8	-16.8	-16.8
180:23	-16.5	-16.5	-16.5	-16.4	-16.4	-16.5	-16.4
180:25	-16.2	-15.2	-16.2	-16.1	-16.1	-16.2	-16.1
180:27	-15.8	-15.8	-15.9	-15.7	-15.7	-15.8	-15.7
180:29	-15.4	-15.5	-15.5	-15.3	-15.4	-15.5	-15.3
180:31	-15.1	-15.2	-15.2	-15.0	-15.1	-15.2	-15.0
180:33	-14.7	-14.8	-14.8	-14.6	-14.7	-14.8	-14.7
180:35	-14.4	-14.4	-14.4	-14.3	-14.4	-14.4	-14.4
180:37	-14.1	-14.1	-14.1	-13.9	-14.0	-14.1	-14.0
180:39	-13.7	-13.8	-13.8	-13.6	-13.7	-13.7	-13.7
180:41	-13.4	-13.4	-13.4	-13.2	-13.3	-13.4	-13.3
180:43	-13.3	-13.3	-13.3	-13.3	-13.3	-13.3	-13.4
180:45	-13.8	-13.8	-13.7	-14.0	-13.8	-13.7	-13.9
180:47	-14.5	-14.4	-14.4	-14.7	-14.4	-14.3	-14.6
180:49	-15.1	-15.0	-15.0	-15.4	-15.2	-15.0	-15.3
180:51	-15.8	-15.8	-15.8	-16.1	-15.8	-15.7	-16.0
180:53	-16.5	-16.4	-16.4	-16.8	-16.4	-16.4	-16.7
180:55	-16.8	-16.8	-16.8	-16.9	-16.7	-16.8	-16.8
180:57	-16.7	-16.6	-16.7	-16.7	-16.6	-16.6	-16.6
180:59	-16.4	-16.4	-16.4	-16.3	-16.3	-16.4	-16.3

APPENDIX II

Temperature Data for Experiment #1

Time (Hrs:Mins)	Temperature (°C) / Thermocouple Depth (cm)								
	5	10	15	20	25	30	35	40	45
0:15	15.7	15.7	15.6	15.6	15.6	15.5	15.5	15.5	15.4
8:30	9.4	9.8	9.7	9.4	8.8	8.1	7.1	5.9	4.8
10:30	8.1	8.4	8.3	7.9	7.3	6.4	5.5	4.4	3.3
21:30	1.0	1.1	0.8	0.6	0.2	-0.1	-0.5	-0.7	-0.8
22:12	1.1	1.1	0.9	0.7	0.3	0.0	-0.3	-0.4	-0.4
25:40	-0.6	-0.5	-0.6	-0.6	-0.7	-0.7	-0.7	-0.7	-0.7
27:21	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
32:10	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
32:22	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
33:30	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
45:30	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.7
49:25	-0.7	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-1.0
52:57	-1.3	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-1.6
70:08	-2.2	-1.3	-0.8	-0.7	-0.7	-0.7	-1.6	-2.6	-3.4
74:10	-2.2	-1.4	-0.5	-0.4	-0.4	-0.8	-2.0	-2.9	-3.6
74:59	-2.4	-1.5	-0.6	-0.4	-0.4	-0.9	-2.1	-3.1	-3.8
78:24	-2.7	-1.9	-1.0	-0.6	-0.7	-1.6	-2.8	-3.7	-4.3

APPENDIX III

Temperature Data for Experiment #2

Time (Hrs:Mins)	Top Heater	Temperature (°C)/Thermocouple Depth (cm) 5	10	15	20	25	30	35	40	45	Bottom Heater
0:15	16.0	15.3	15.4	15.3	15.1	15.0	15.0	14.9	14.8	14.8	15.0
8:30	9.8	9.8	9.4	8.6	7.9	7.0	6.4	5.2	4.2	3.2	1.6
10:30	8.5	8.4	7.9	7.0	6.2	5.3	4.7	3.4	2.6	1.6	0.1
21:30	1.3	1.0	0.6	0.0	-0.2	-0.5	-0.6	-0.6	-0.6	-0.6	-2.4
22:12	1.4	1.0	0.6	0.2	-0.1	-0.2	-0.3	-0.4	-0.4	-0.4	-2.0
25:40	-0.2	-0.4	-0.5	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-2.6
27:21	-0.8	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-2.5
32:10	-1.0	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-1.0	-3.3
32:22	-0.7	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.9	-3.1
33:30	-0.7	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-1.0	-3.1
45:30	-0.8	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.8	-3.0	-4.6
49:25	-0.9	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.2	-2.6	-3.8	-5.2
52:57	-1.3	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-2.4	-3.7	-4.8	-6.1
70:08	-1.9	-1.1	-0.8	-0.8	-2.5	-4.0	-4.6	-6.0	-6.8	-7.4	-8.4
74:10	-1.6	-0.9	-0.4	-1.7	-3.1	-4.5	-5.2	-6.3	-7.0	-7.6	-8.4
74:59	-1.7	-1.0	-0.4	-2.0	-3.4	-4.7	-5.3	-6.4	-7.1	-7.7	-8.6
78:24	-2.1	-1.6	-0.9	-3.1	-4.3	-5.5	-6.0	-7.1	-7.7	-8.3	-9.0

Appendix VI

Temperature Data for Experiment #5

(Hrs:mins)	Top Heater	Temperature (°C)/Thermocouple Depth (cm) 5	10	15	20	25	30	35	40	Bottom Heater
0	17.1	18.0	18.3	18.4	18.6	18.7	18.8	18.7	18.3	16.7
0:15	18.5	18.2	18.5	18.7	18.9	19.0	19.0	18.9	18.5	18.3
0:30	19.0	18.4	18.6	18.8	18.9	19.0	19.0	18.9	18.6	19.2
0:45	18.2	18.4	18.6	18.7	18.9	19.0	19.0	18.9	18.8	19.4
1:00	17.2	18.4	18.6	18.7	18.9	19.0	19.0	18.8	18.8	19.2
1:30	14.9	18.4	18.6	18.7	18.9	18.9	18.8	18.6	18.4	18.4
2:00	12.6	18.0	18.4	18.5	18.6	18.5	18.1	17.7	17.4	16.8
3:00	11.0	17.0	17.6	17.8	17.8	17.5	16.8	16.0	15.3	14.4
4:00	9.8	15.7	16.4	16.7	16.5	16.0	14.9	14.0	13.0	12.2
5:00	8.6	14.6	15.3	15.6	15.2	14.7	13.4	12.4	11.5	11.6
6:00	7.3	13.3	14.0	14.2	13.8	13.2	11.8	10.9	10.4	11.4
7:00	6.3	12.1	12.8	12.9	12.4	11.8	10.6	9.8	9.6	11.0
8:45	5.6	11.1	11.7	11.8	11.4	10.8	9.7	9.0	8.9	10.7
10:05	4.0	8.8	9.3	9.4	9.0	8.6	7.8	7.4	7.9	10.7
13:20	2.3	6.1	6.5	6.7	6.6	6.4	6.2	6.2	7.2	10.6
17:40	0.6	3.6	4.0	4.3	4.5	4.5	4.6	4.6	5.4	7.9
21:00	-0.4	2.2	2.6	2.9	3.1	3.2	3.2	3.3	4.1	6.5
24:20	-1.2	1.0	1.3	1.6	1.8	1.9	2.1	2.2	3.2	6.2
25:55	-1.0	0.6	0.9	1.1	1.4	1.5	1.7	1.9	2.9	5.3
27:50	-0.7	0.2	0.4	0.6	0.8	1.0	1.2	1.3	1.8	3.5
29:50	-0.9	-0.2	-0.0	0.1	0.3	0.4	0.5	0.5	1.0	2.3
31:50	-1.1	-0.4	-0.3	-0.2	0.0	0.0	0.1	0.1	0.5	1.8
35:20	-0.8	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	0.1	1.4
36:50	-0.8	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.1	1.3
38:15	-0.8	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	0.2	1.4
41:15	-0.8	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.1	1.2
45:10	-1.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	1.1
47:05	-1.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.1	1.1
48:50	-1.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.1	1.0
50:50	-1.1	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	0.0	1.9
52:50	-1.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.0	1.2
54:55	-1.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.0	1.0
57:15	-0.8	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.0	1.1
59:30	-0.9	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.1	1.1
60:45	-0.7	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.0	1.1
71:15	-1.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.2	1.0
75:15	-1.1	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.2	1.0
78:00	-1.1	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-3.0	0.8

Temperature Data for Experiment #5

(Hrs:Mins)	Top Heater	Temperature (°C)/Thermocouple Depth (cm) 5	10	15	20	25	30	35	40	Bottom Heater
80:55	-0.1	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.2	0.8
83:00	-0.8	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.1	1.0
85:25	-1.0	-0.4	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.1	1.0
95:10	-1.3	-0.8	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	0.7
97:20	-1.3	-0.8	-0.5	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	0.7
100:50	-1.4	-0.9	-0.7	-0.4	-0.4	-0.4	-0.4	-0.5	-0.4	0.6
103:40	-1.4	-1.0	-0.8	-0.4	-0.4	-0.4	-0.4	-0.5	-0.4	0.5
107:15	-1.3	-1.0	-0.8	-0.4	-0.3	-0.3	-0.3	-0.7	-0.4	0.7
109:50	-1.4	-1.1	-1.0	-0.5	-0.3	-0.3	-0.6	-0.8	-0.5	0.7
110:50	-1.5	-1.2	-1.0	-0.6	-0.3	-0.3	-0.7	-0.8	-0.5	0.7
120:40	-2.0	-2.2	-2.2	-2.2	-2.2	-2.1	-2.0	-1.9	-1.4	0.3
122:30	-2.0	-2.5	-2.6	-2.6	-2.6	-2.5	-2.4	-2.4	-1.9	0.3
124:30	-2.2	-2.8	-2.9	-2.9	-2.9	-2.8	-2.7	-2.5	-1.9	0.5
127:37	-2.4	-3.2	-3.3	-3.3	-3.2	-3.1	-2.9	-2.7	-2.0	0.5
129:35	-2.5	-3.4	-3.5	-3.5	-3.4	-3.3	-3.0	-2.7	-2.0	0.5
131:30	-2.6	-3.6	-3.7	-3.6	-3.6	-3.4	-3.0	-2.8	-2.1	0.5
133:00	-2.6	-3.7	-3.8	-3.8	-3.6	-3.4	-3.1	-2.8	-2.0	0.5
142:05	-3.0	-4.0	-4.1	-4.0	-3.9	-3.6	-3.3	-3.0	-2.2	0.4
144:10	-3.0	-4.0	-4.2	-4.1	-3.9	-3.7	-3.3	-3.0	-2.2	0.4
146:20	-3.0	-4.1	-4.2	-4.1	-3.9	-3.7	-3.3	-3.0	-2.2	0.5
148:00	-2.9	-4.1	-4.3	-4.2	-4.0	-3.7	-3.3	-3.0	-2.2	0.4
149:40	-2.9	-4.1	-4.2	-4.1	-3.9	-3.7	-3.3	-2.9	-2.1	0.6
151:15	-2.8	-4.0	-4.2	-4.3	-4.1	-3.9	-3.6	-3.3	-2.9	0.6
154:00	-2.7	-4.0	-4.3	-4.1	-3.9	-3.6	-3.3	-2.9	-2.0	0.7
157:30	-2.6	-4.0	-4.1	-4.0	-3.8	-3.6	-3.1	-2.8	-1.9	0.8
165:20	-2.6	-4.0	-4.0	-4.0	-3.7	-3.5	-3.0	-2.7	-1.9	0.8
167:25	-2.6	-4.0	-4.1	-4.0	-3.8	-3.5	-3.1	-2.7	-1.9	0.8
169:30	-2.4	-3.9	-4.0	-3.9	-3.7	-3.5	-3.0	-2.7	-1.9	0.8
172:05	-2.4	-3.9	-4.0	-3.9	-3.7	-3.5	-3.0	-2.7	-1.8	0.8

APPENDIX V

Temperature Data for Experiment #4

Time (Hrs:Mins)	Temperature (°C)/Thermocouple Depth (cm)							
	5	10	15	20	25	30	35	Bottom Heater
0	12.1	12.1	12.0	12.1	12.2	12.2	12.2	12.7
0:30	12.5	12.5	12.4	12.5	12.5	12.5	12.5	14.0
1:00	12.5	12.4	12.4	12.5	12.5	12.5	12.5	14.4
1:30	12.3	12.4	12.3	12.3	12.3	12.3	12.2	14.2
2:00	12.0	11.9	12.0	12.0	12.0	11.9	11.8	13.5
2:30	11.6	11.6	11.6	11.6	11.6	11.5	11.4	13.8
3:00	11.2	11.2	11.2	11.2	11.2	11.1	11.1	13.9
3:30	10.9	10.9	10.9	10.9	10.9	10.8	10.8	15.2
4:00	10.7	10.6	10.7	10.6	10.6	10.6	10.6	16.0
4:30	10.3	10.3	10.3	10.2	10.3	10.3	10.3	15.8
11:00	7.8	7.8	7.8	7.8	7.8	7.8	7.8	13.6
20:30	5.1	5.1	5.1	5.1	5.1	5.1	5.0	11.4
25:00	4.7	4.7	4.7	4.7	4.7	4.7	4.7	9.8
30:00	2.2	3.3	3.8	3.8	3.8	3.8	3.8	8.0
43:15	0.1	0.8	1.4	1.9	2.5	3.9	4.0	7.9
45:00	0.0	0.6	1.1	1.6	2.2	3.0	4.0	6.8
47:15	0.0	0.4	1.0	1.4	1.9	2.4	3.4	6.5
49:15	-0.1	0.3	0.8	1.2	1.6	1.9	2.9	6.4
51:00	-0.0	0.3	0.6	1.0	1.4	1.7	2.6	6.5
54:30	-0.2	0.0	0.2	0.6	0.9	1.2	2.1	6.6
57:30	-0.2	-0.1	0.0	0.3	0.6	0.9	1.7	5.7
68:00	-0.2	-0.3	-0.2	-0.2	-0.2	-0.2	0.0	3.9
70:00	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	3.7
72:15	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	3.6
75:15	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	3.5
77:00	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.0	3.5
80:00	-0.4	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	3.6
92:00	-0.9	-0.2	-0.2	-0.2	-0.1	-0.1	-0.0	3.2
95:30	-1.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	3.2
100:00	-1.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	2.9
105:00	-1.4	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	4.1
117:00	-1.9	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	2.3
123:00	-2.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	2.1
130:30	-2.4	-0.6	-0.2	-0.1	-0.1	-0.1	-0.1	2.0

Temperature Data for Experiment #4
Cont'd

(Hrs:Mins)	Temperature (°C)/Thermocouple Depth (cm) 5	10	15	20	25	30	35	Bottom Heater
140:00	-2.8	-1.1	-0.2	-0.2	-0.2	-0.2	-0.2	1.7
145:30	-3.0	-1.4	-0.2	-0.2	-0.2	-0.2	-0.2	1.4
154:00	-3.4	-1.9	-0.2	-0.2	-0.2	-0.2	-0.2	0.4
166:00	-3.8	-2.4	-0.6	-0.2	-0.2	-0.2	-0.2	3.5
172:00	-4.1	-2.8	-1.2	-0.2	-0.2	-0.2	-0.2	1.6
178:00	-4.5	-3.3	-1.8	-0.2	-0.2	-0.3	-0.3	1.2
180:30	-5.3	-4.2	-3.0	-1.5	-0.6	-0.6	-0.5	1.3
195:00	-5.9	-4.9	-3.9	-2.8	-1.6	-1.1	-0.9	1.7
201:30	-6.7	-5.8	-5.0	-4.3	-3.4	-2.4	-1.3	1.8
212:30	-8.7	-8.1	-7.5	-6.9	-6.2	-5.3	-4.3	0.7
217:00	-9.4	-8.8	-8.3	-7.8	-7.3	-6.6	-5.8	-0.7

APPENDIX IV

Temperature Data for Experiment #3

Time (Hrs:Mins)	Temeprature (°C)/Thermocouple Depth (cm) 5	10	15	20	25	30	35	40	45	Bottom Heater
0	12.0	12.2	12.2	12.3	12.4	12.3	12.5	12.6	12.6	12.6
0:30	12.4	12.6	12.6	12.7	12.8	12.9	13.0	13.0	13.1	13.7
1:00	12.0	12.5	12.6	12.7	12.8	12.8	13.0	13.0	13.2	14.0
1:30	11.3	12.4	12.6	12.7	12.8	12.8	12.9	12.9	13.0	13.6
2:00	10.4	11.9	12.4	12.6	12.8	12.7	12.7	12.4	12.2	12.4
2:30	9.8	11.4	12.1	12.4	12.5	12.4	12.3	11.8	11.4	12.3
3:00	9.1	10.9	11.8	12.1	12.3	12.0	11.8	11.2	10.9	12.0
3:30	8.6	10.5	11.4	11.8	12.0	11.6	11.4	10.7	10.4	13.1
4:00	8.1	10.0	11.0	11.5	11.6	11.2	11.0	10.3	10.3	13.8
4:30	7.6	9.6	10.6	11.1	11.2	10.9	10.6	10.0	10.3	14.9
11:00	3.5	5.2	6.4	7.4	8.1	8.5	8.9	9.8	11.8	19.0
20:30	0.3	1.8	2.9	4.0	5.0	5.5	6.2	7.0	8.6	14.2
25:00	0.5	1.6	2.6	3.5	4.3	4.8	5.1	5.5	6.2	9.4
30:00	0.2	0.9	1.5	2.1	2.7	2.8	3.0	3.1	3.5	5.6
43:15	-0.2	-0.2	-0.2	-0.3	-0.2	-0.3	-0.2	-0.1	0.4	2.8
45:00	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	0.3	2.6
47:15	-0.6	-0.2	-0.3	-0.3	-0.2	-0.2	-0.2	-0.1	0.3	2.7
49:15	-0.7	-0.2	-0.3	-0.3	-0.2	-0.3	-0.2	-0.1	0.3	2.7
51:00	-0.8	-0.2	-0.2	-0.2	-0.2	-0.3	-0.2	-0.0	0.4	2.8
54:30	-1.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	0.3	2.8
57:30	-1.2	-0.1	-0.1	-0.2	-0.1	-0.3	-0.1	-0.0	0.3	2.3
68:00	-2.0	-0.7	-0.2	-0.3	-0.2	-0.3	-0.2	-0.2	0.0	1.7
70:00	-2.1	-0.9	-0.2	-0.3	-0.2	-0.3	-0.2	-0.2	0.0	1.7
72:15	-2.2	-1.1	-0.2	-0.3	-0.2	-0.3	-0.2	-0.2	0.0	1.7
75:15	-2.3	-1.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	1.7
77:00	-2.4	-1.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	1.7
80:00	-2.6	-1.4	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	1.9
92:00	-3.2	-2.2	-1.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	1.6
95:30	-3.4	-2.4	-1.4	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	1.9
100:00	-3.6	-2.6	-1.6	-0.6	-0.2	-0.2	-0.2	-0.2	-0.0	1.5
105:00	-3.8	-2.8	-1.9	-0.9	-0.2	-0.2	-0.2	-0.2	0.0	2.7
117:00	-4.2	-3.3	-2.5	-1.6	-0.4	-0.3	-0.2	-0.2	-0.1	1.6
123:00	-4.3	-3.4	-2.6	-1.9	-0.8	-0.2	-0.2	-0.3	-0.1	2.2
130:30	-4.6	-3.8	-3.1	-2.4	-1.4	-0.7	-0.2	-0.5	-0.2	1.6
140:00	-5.6	-5.0	-4.5	-4.1	-3.7	-3.4	-3.3	-2.9	-2.1	1.2
145:30	-6.8	-6.3	-6.0	-5.7	-5.5	-5.4	-5.4	-5.2	-4.8	0.0
154:00	-8.5	-8.0	-7.6	-7.4	-6.9	-6.6	-6.3	-5.9	-5.1	1.2
166:00	-8.6	-8.1	-7.6	-7.1	-6.4	-6.0	-5.5	-4.7	-3.6	4.9

Temperature Data for Experiment #3

Cont'd

Time (Hrs:Mins)	Temperature (°C)/Thermocouple Depth (cm) 5	10	15	20	25	30	35	40	45	Bottom Heater
172:00	-8.5	-8.0	-7.6	-7.1	-6.6	-6.2	-5.9	-5.4	-4.6	1.9
178:00	-8.8	-8.3	-7.9	-7.4	-7.0	-6.6	-6.3	-5.8	-5.0	1.2
188:30	-9.4	-8.9	-8.6	-8.2	-7.8	-7.5	-7.2	-6.8	-6.2	-0.7
195:00	-9.5	-9.0	-8.6	-8.1	-7.5	-7.0	-6.6	-5.7	-4.6	-3.5
201:30	-9.3	-8.8	-8.3	-8.0	-7.4	-7.1	-6.8	-6.2	-5.5	0.3
212:30	-9.4	-9.0	-8.6	-8.2	-7.7	-7.3	-7.0	-6.5	-5.7	0.6
217:00	-9.5	-9.0	-8.6	-8.2	-7.7	-7.3	-6.9	-6.3	-5.4	1.4