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INVESTIGATION OF MOISTURE MOVEMENTS AND STRESSES IN FROZEN SOILS

P.J. Williams and J.A. Wood

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Abstract

Long term permeameter results are reported for Allendale and and Castor soils at marginally sub-zero temperatures and temperature gradients of $0.17^{o}C\ cm^{-1}$. The flow regime is interpreted in terms of soil stress and the Clapeyron equation.

Résumé

Des résultats d'essais de perméamètres à long terme sont présentés pour deux sols, Allendale et Castor, à des températures négatives très proches de zéro et soumis à des gradients de température de $0.17^{o}C\ cm^{-1}$. L'interprétation du régime d'écoulement se fait en fonction de contraintes dans le sol et de l'équation de Clapeyron.

FINAL REPORT

Investigation of Moisture Movements and Stresses In Frozen Soils

by

P.J. Williams and J.A. Wood

to the

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TABLE OF CONTENTS

LIST OF FIGURES

I INTRODUCTION

In 1980-81 an apparatus was developed at the Geotechnical Science Laboratories for measuring temperature induced stress changes in frozen ground. This report summarizes the results from experiments conducted during the summer of 1982. Several experiments were also carried out under the present contract (OSU82-00226), during the period April - June 1982. These results, along with the basic theory behind the experiment are presented in the final report for the previous contract (OSU81-00119) submitted in June 1982.

The present work represents an extension of earlier research into the phenomenon of secondary frost heaving and water migration in frozen soils. Secondary frost heaving, that is, the temperature induced heaving of already frozen ground has been a subject of major concern in relation to the proposed buried gas pipelines in the Canadian Arctic. Prediction of the rate of heave is an essential element in the design of any major gas pipeline. Recent field investigations in the United States, Canada and the Soviet Union indicate that the rate of strain in frozen ground due to water migration, may be much greater than was previously envisaged.

However, models for estimating accurately, the frost heave in the field situation have not been successful. This is due primarily to a lack of information on the entire range of boundary conditions which define the growth of ice lenses in the soil, as well as the parameters governing the rate of growth.

New discoveries are continuously being made, adding further complexity to the existing theory of frost heaving. For example, it is now believed that the mechanism of water migration in frozen soils involves substantial movements of pore ice as well as liquid water in response to temperature gradients. Experiments conducted under the previous contract demonstrated the mobility of ice during regelation transport, (Williams and Wood, 1980). In addition, results from the present investigation indicate that the rise in heaving stress is dependent upon the mechanical properties of the soil as well as the thermodynamic and hydrodynamic conditions. Thus it appears that further research on the fundamental properties of frozen soils will be required before a realistic model of frost heaving can be developed.

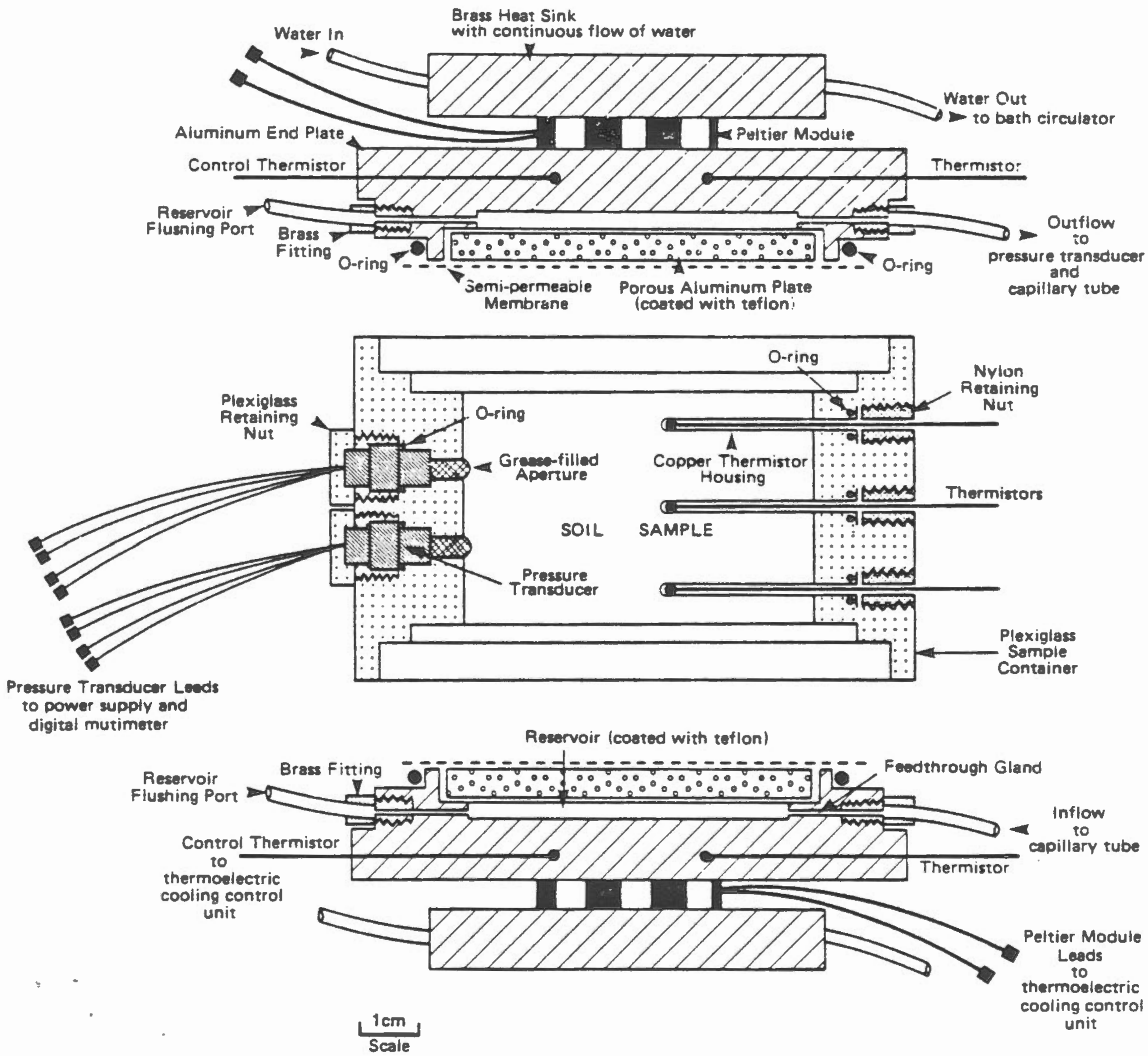
II NATURE OF THE EXPERIMENT

1. Apparatus and Procedure

The apparatus consists of a cylindrical perspex sample holder (3.50 cm long, internal diameter = 5.40 cm) which is interposed between two aluminum end plates containing small end reservoirs filled with lactose solution. (see scale drawing Figure 2.1). The temperature of the end plates is controlled to an accuracy of $\pm$ 0.01^{o}C with a thermoelectric cooling system. Soil pressures and temperatures are monitored with small sensing devices mounted in the walls of the cell. Flow between the reservoirs and the soil is measured by observing the position of meniscii in small capillaries connected to the end reservoirs. (See Figure 2.2). A semi permeable membrane separates the

Figure 2.1

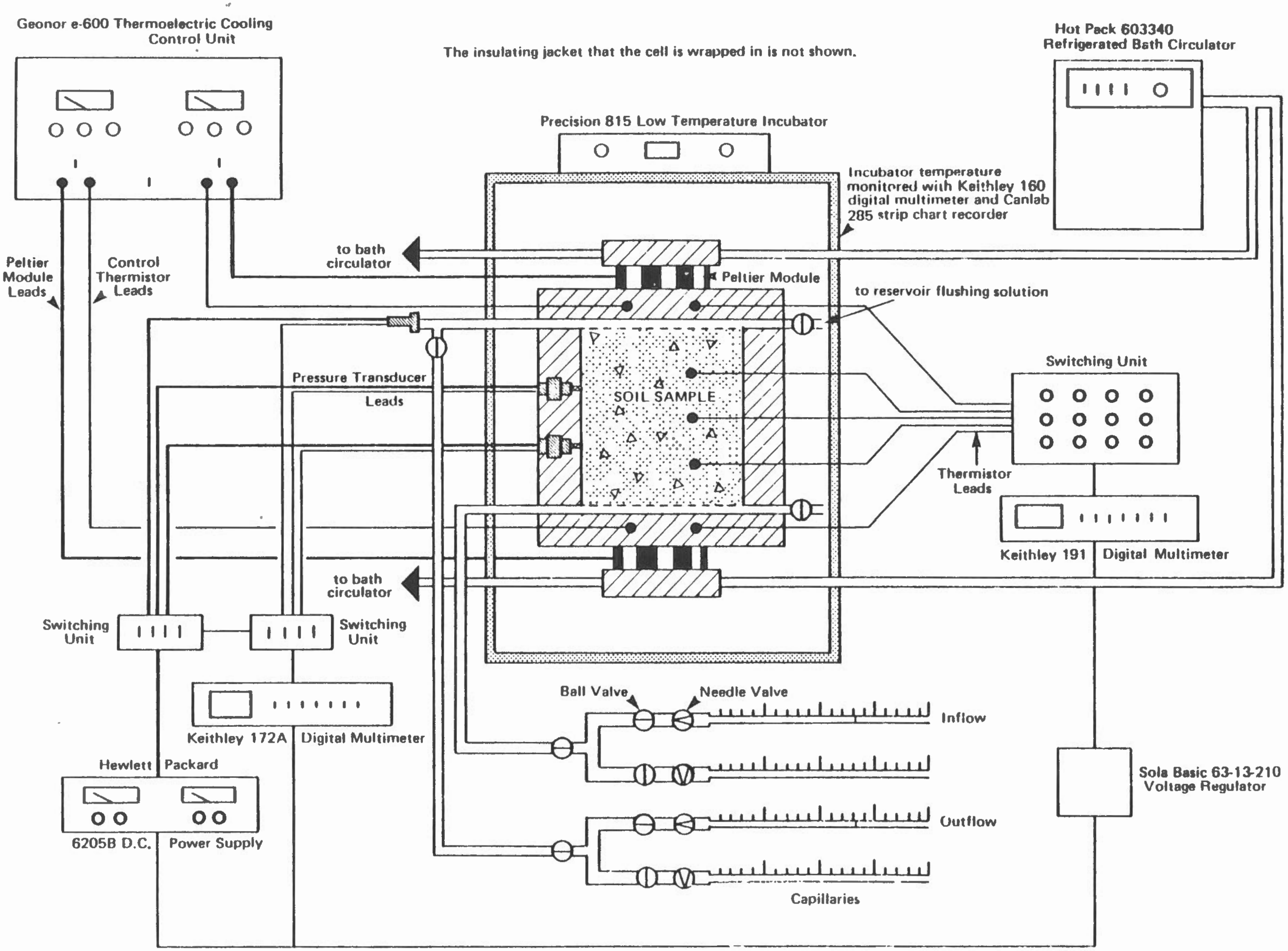
CROSS-SECTION OF THE EXPERIMENTAL APPARATUS



The nylon screws used to hold the apparatus together are not shown.
Brass fittings, and plexiglass retaining nuts are not drawn to scale.

Figure 2.2

SCHEMATIC REPRESENTATION OF THE ENTIRE EXPERIMENTAL ASSEMBLY



reservoirs from the sample permitting water to enter the soil but restricting the entry of lactose.

A detailed description of the experimental procedure as well as the various technical aspects involved in running the experiments is provided in the final report submitted earlier in the year.

2. Use of Lactose

Lactose solution is used in the end reservoirs for two reasons:

(1) to prevent freezing in the reservoirs and (2) to eliminate potential osmotic gradients between the reservoirs and the sample which would otherwise occur if pure water was used. The concentration of the lactose is adjusted so that ideally, in the static situation (that is under no flow conditions), chemical equilibrium exists between the water in each reservoir and the adjacent soil. In theory, at least, if the solute concentration is adjusted precisely, the flow of water between the reservoirs and the soil should be produced entirely by the temperature induced gradients of potential within the soil itself.

In general, the experiment is limited to relatively warm temperatures $> -0.5^{o}C$ since, at this temperature, the concentration of lactose ($83.2\ gl^{-1}$) is near saturation. In addition, there are also significant deviations from ideality at concentrations exceeding this limit.[1]

[1] An ideal solution is one in which the chemical potential of any component increases linearly with the logarithm of the mole fraction of that component with slope RT. (Prigogine and Defay, 1954).

3. Soil Samples

Soil samples were prepared as slurries using deaired, deionized water and frozen rapidly in the sample container prior to assembling the apparatus. Two locally obtained soils were used in the experiments: (1) A colloidal soil, Allendale silty clay, which contains slightly less than 50% clay sized particles, (2) Castor sandy loam, a non-cohesive granular material containing slightly less than 3% clay sized particles. A table listing the physical properties of both soils as well as graphs of their pore composition and hydraulic properties in the frozen slate are provided in the final report by Williams and Wood (1982).

Although both soils have large quantities of silt present, their properties are markedly different due to the presence of large quantities of clay minerals (chiefly illite and chlorite) in the Allendale. When rapidly frozen, the Allendale soil exhibits a dense pattern of randomly oriented ice lenses ranging from hairline thickness up to 0.2 cm thick. In contrast, with the Castor soil, usually no ice lenses are visible, all of the ice apparently existing as pore ice.

III RESULTS AND DISCUSSION

Results from experiment nos. 25 and 26 which are long-term tests on the Allendale and Castor soils are plotted in Figures 3.1 - 3.4. Relevant date obtained from additional experiments conducted during the summer are also listed in tabular form in Appendix I. Although there was some degree of variation in the

Figure 3.1

TEMPERATURE PROFILE OF SOIL SAMPLE DURING APPROACH TO STEADY-STATE HEAT TRANSFER (Experiment Number 25)

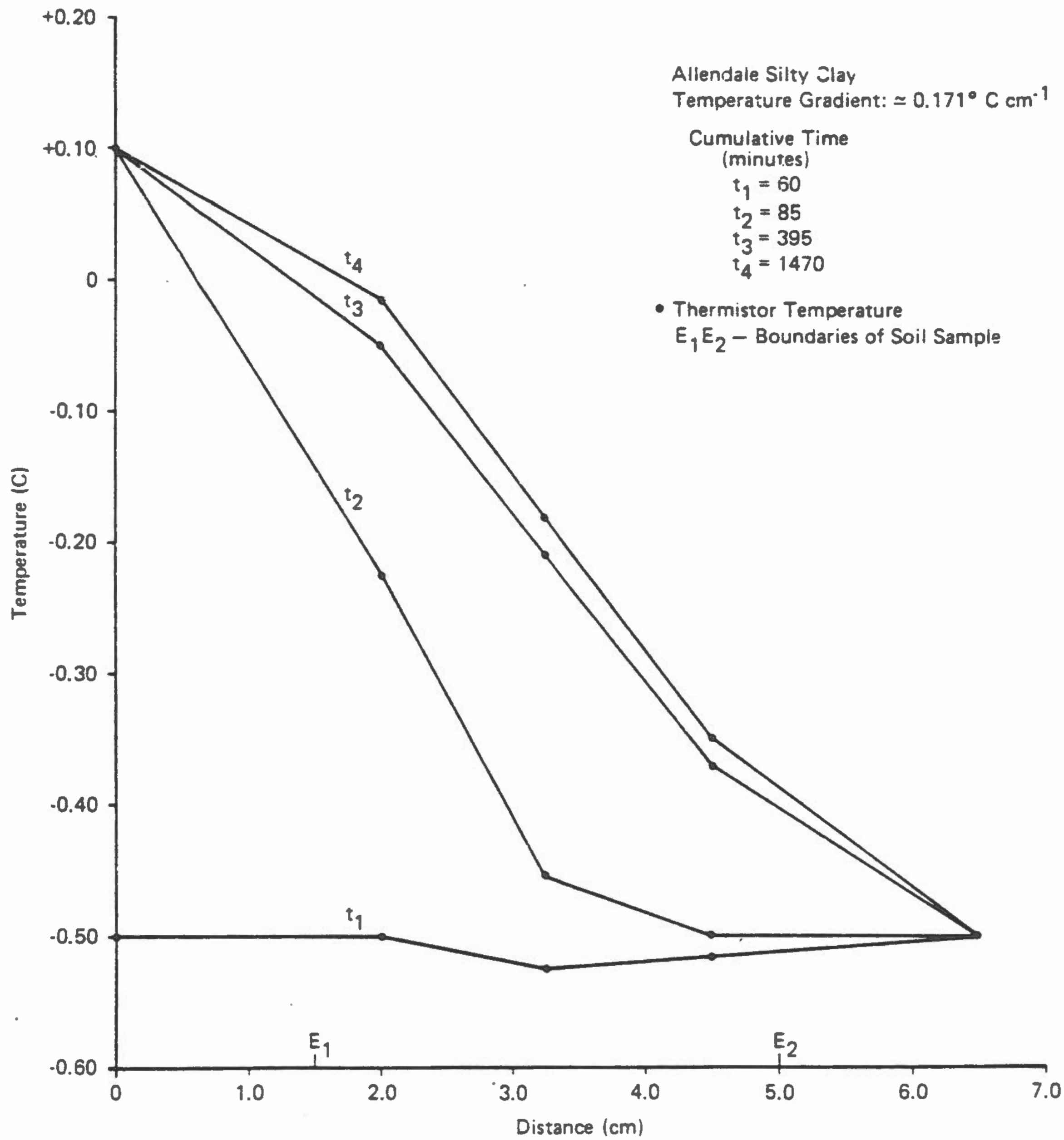


Figure 3.2a

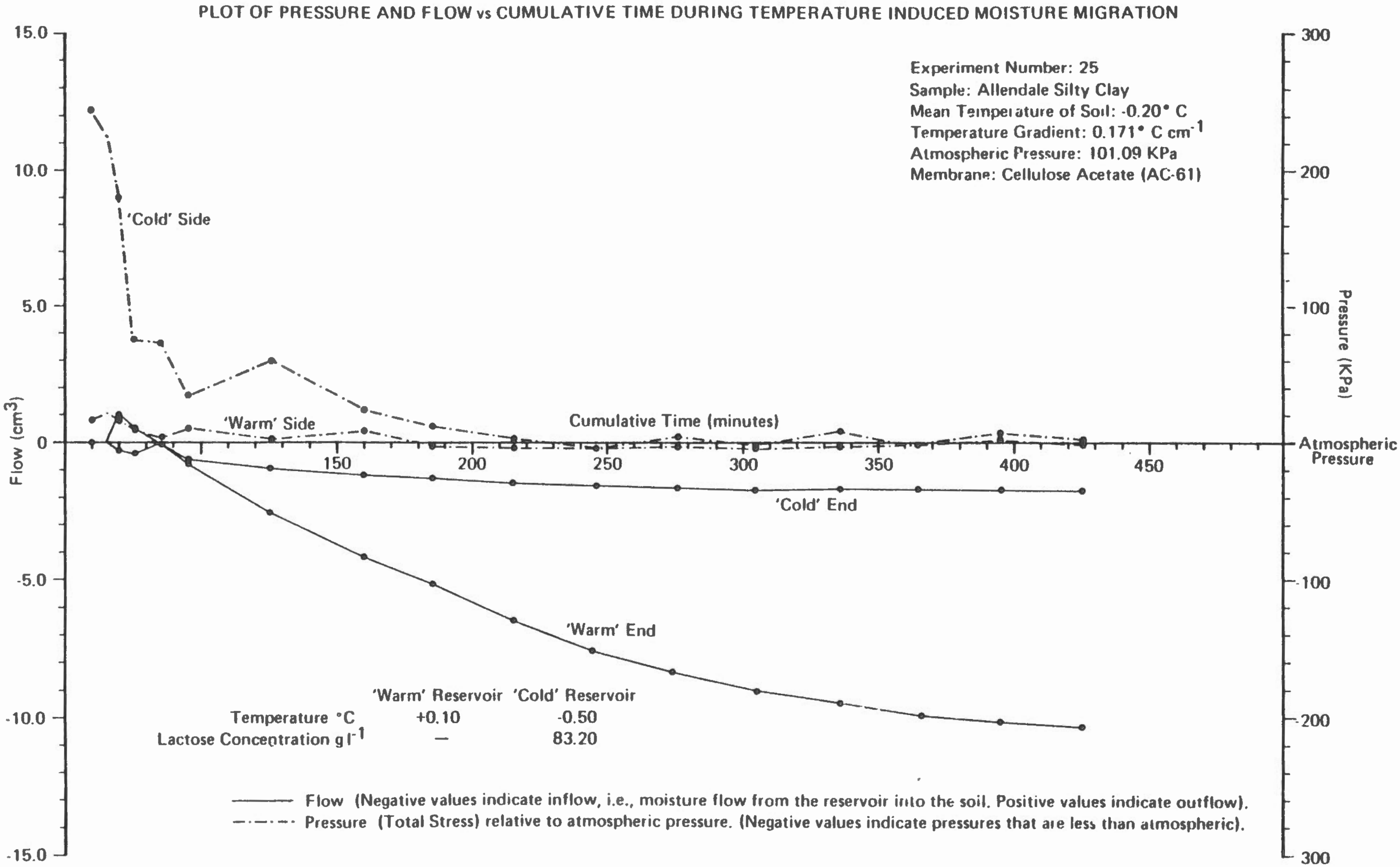
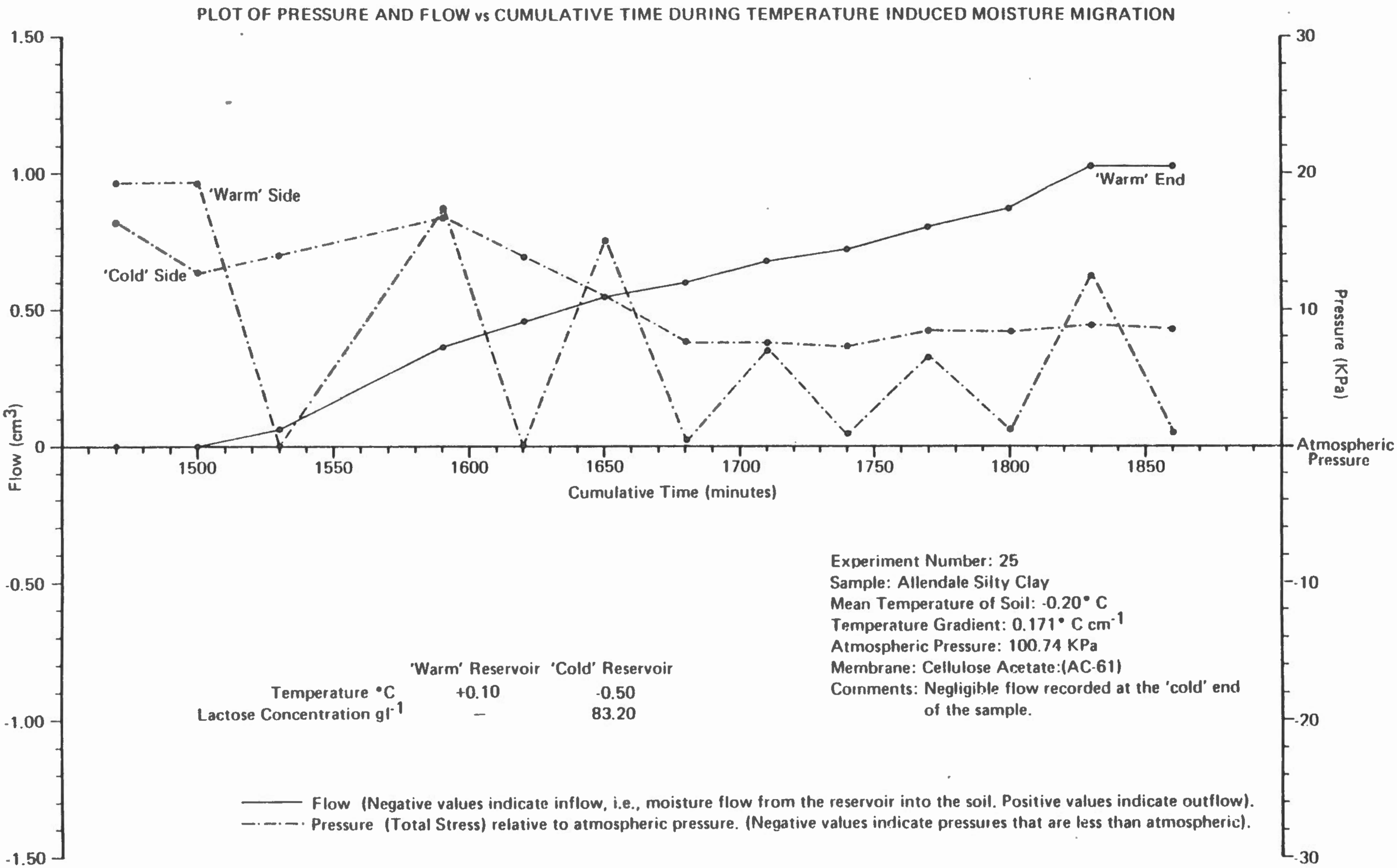

PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION
Experiment Number: 25
Sample: Allendale Silty Clay
Mean Temperature of Soil: -0.20° C
Temperature Gradient: 0.171° C cm-1
Atmospheric Pressure: 101.09 KPa
Membrane: Cellulose Acetate (AC-61)
15.0
10.0
5.0
0
-5.0
-10.0
-15.0
Flow (cm3)
300
200
100
Atmospheric Pressure
100
200
300
Pressure (KPa)
'Cold' Side
'Warm' Side
Cumulative Time (minutes)
150
200
250
300
350
400
450
'Cold' End
'Warm' End
'Warm' Reservoir 'Cold' Reservoir
Temperature °C +0.10 -0.50
Lactose Concentration g l-1 — 83.20
Flow (Negative values indicate inflow, i.e., moisture flow from the reservoir into the soil. Positive values indicate outflow).
Pressure (Total Stress) relative to atmospheric pressure. (Negative values indicate pressures that are less than atmospheric).

Figure 3.2b



PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION
1.50
1.00
0.50
0
-0.50
-1.00
-1.50
Flow (cm3)
30
20
10
-10
-20
-30
Pressure (KPa)
Atmospheric Pressure
1500
1550
1600
1650
1700
1750
1800
1850
Cumulative Time (minutes)
'Warm' Side
'Cold' Side
'Warm' End
Experiment Number: 25
Sample: Allendale Silty Clay
Mean Temperature of Soil: -0.20° C
Temperature Gradient: 0.171° C cm-1
Atmospheric Pressure: 100.74 KPa
Membrane: Cellulose Acetate:(AC-61)
Comments: Negligible flow recorded at the 'cold' end of the sample.
'Warm' Reservoir 'Cold' Reservoir
Temperature °C +0.10 -0.50
Lactose Concentration gl-1 — 83.20
Flow (Negative values indicate inflow, i.e., moisture flow from the reservoir into the soil. Positive values indicate outflow).
Pressure (Total Stress) relative to atmospheric pressure. (Negative values indicate pressures that are less than atmospheric).

Figure 3.2c

PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION

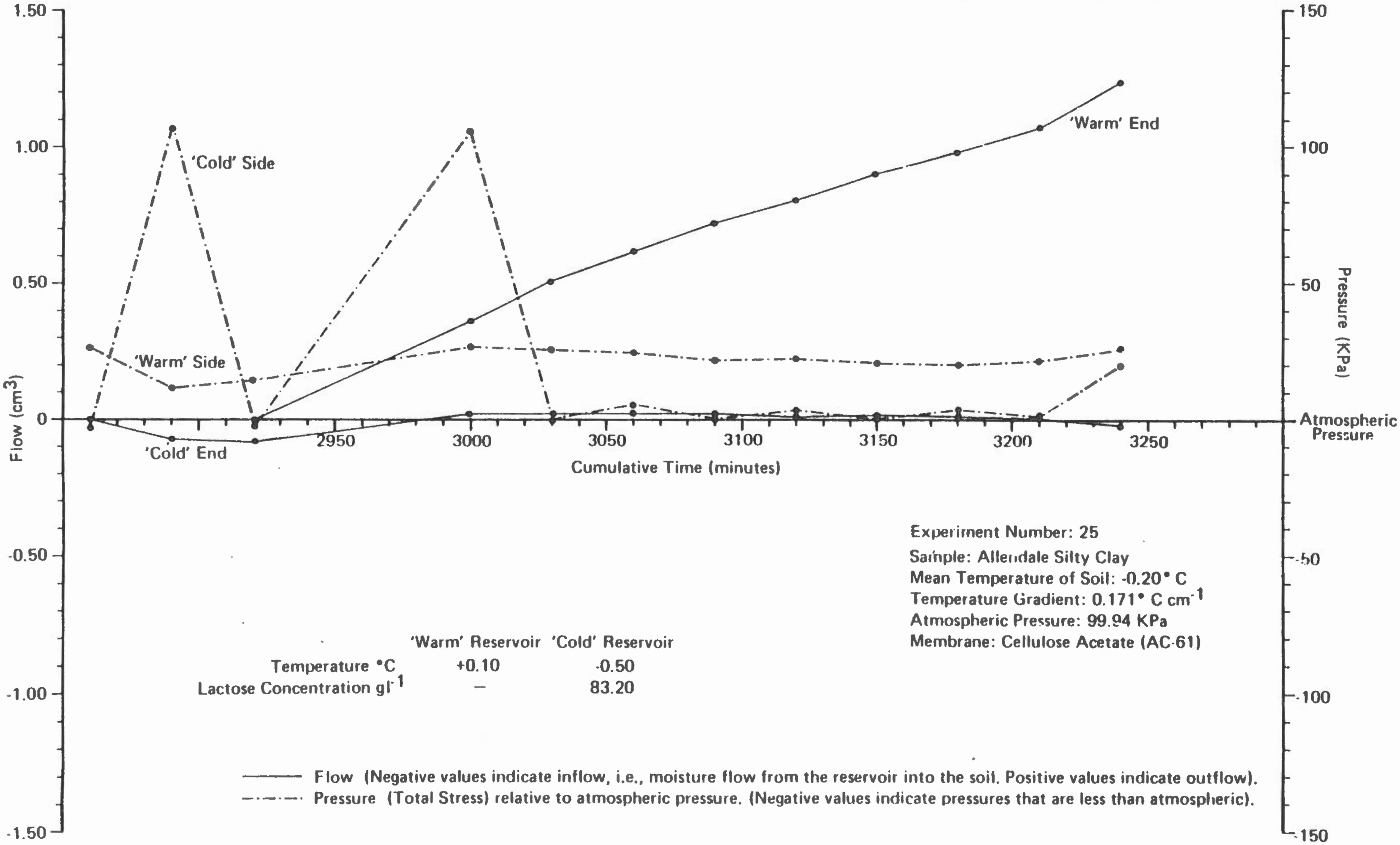


Figure 3.2d

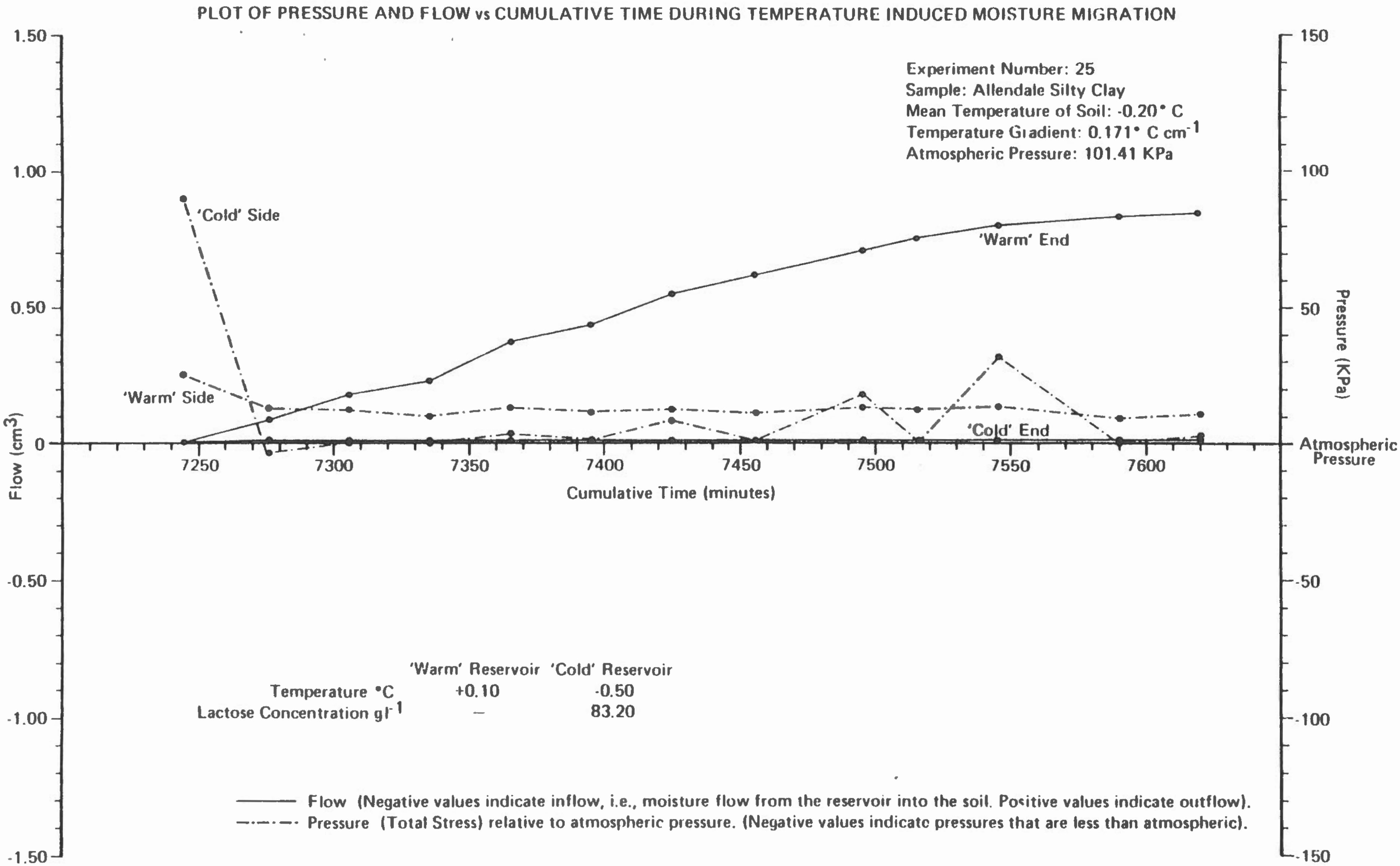

PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION
Experiment Number: 25
Sample: Allendale Silty Clay
Mean Temperature of Soil: -0.20° C
Temperature Gradient: 0.171° C cm-1
Atmospheric Pressure: 101.41 KPa
'Cold' Side
'Warm' Side
'Warm' End
'Cold' End
1.50
1.00
0.50
0
-0.50
-1.00
-1.50
Flow (cm3)
150
100
50
-50
-100
-150
Pressure (KPa)
Atmospheric Pressure
7250
7300
7350
7400
7450
7500
7550
7600
Cumulative Time (minutes)
'Warm' Reservoir 'Cold' Reservoir
Temperature °C +0.10 -0.50
Lactose Concentration gl-1 — 83.20
Flow (Negative values indicate inflow, i.e., moisture flow from the reservoir into the soil. Positive values indicate outflow).
Pressure (Total Stress) relative to atmospheric pressure. (Negative values indicate pressures that are less than atmospheric).

Figure 3.2e

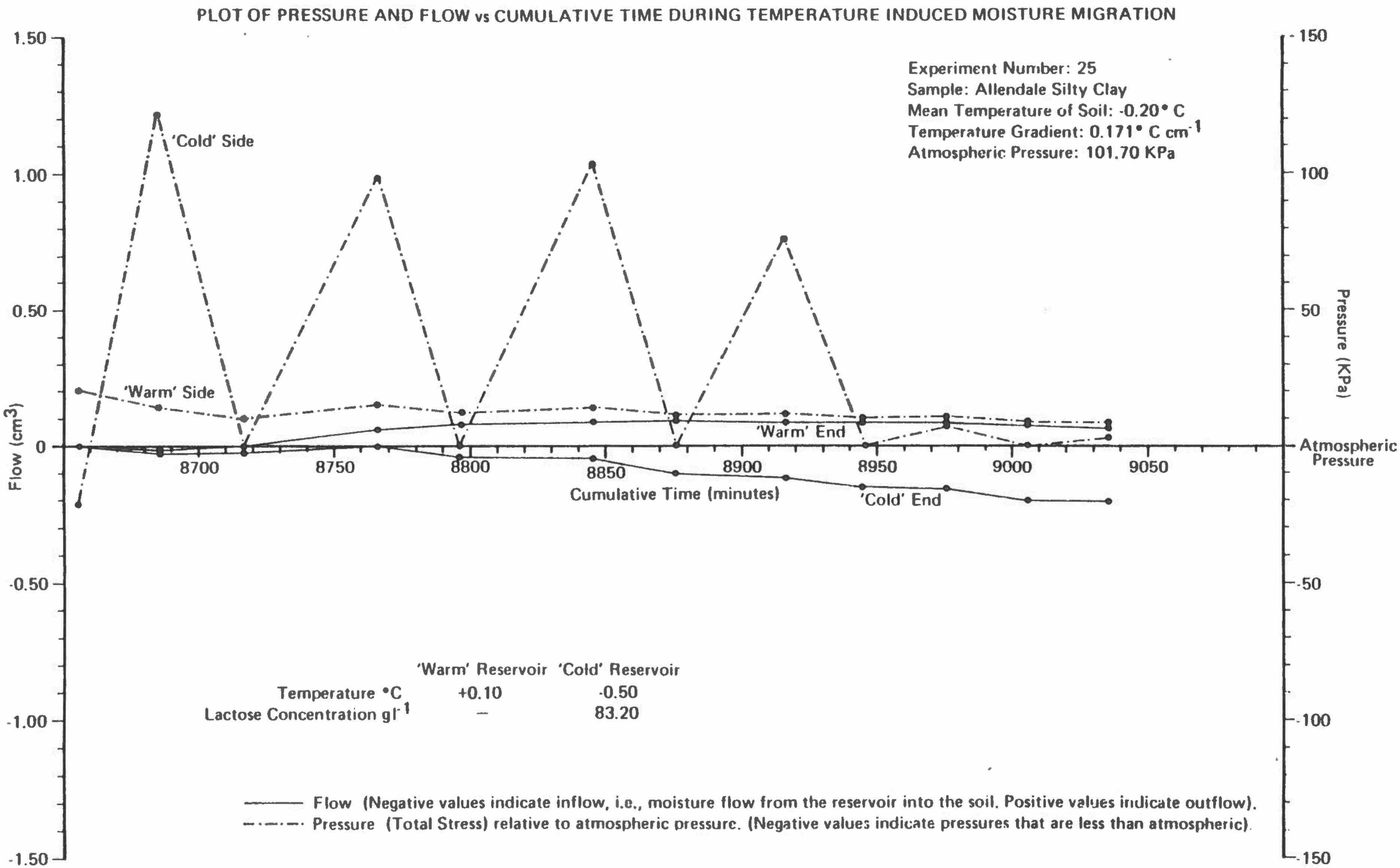

PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION
Experiment Number: 25
Sample: Allendale Silty Clay
Mean Temperature of Soil: -0.20° C
Temperature Gradient: 0.171° C cm-1
Atmospheric Pressure: 101.70 KPa
'Cold' Side
'Warm' Side
'Warm' End
'Cold' End
Flow (cm3)
Pressure (KPa)
Atmospheric Pressure
Cumulative Time (minutes)
1.50
1.00
0.50
0
-0.50
-1.00
-1.50
150
100
50
-50
-100
-150
8700
8750
8800
8850
8900
8950
9000
9050
'Warm' Reservoir 'Cold' Reservoir
Temperature °C +0.10 -0.50
Lactose Concentration gl-1 — 83.20
Flow (Negative values indicate inflow, i.e., moisture flow from the reservoir into the soil. Positive values indicate outflow).
Pressure (Total Stress) relative to atmospheric pressure. (Negative values indicate pressures that are less than atmospheric).

Figure 3.2f

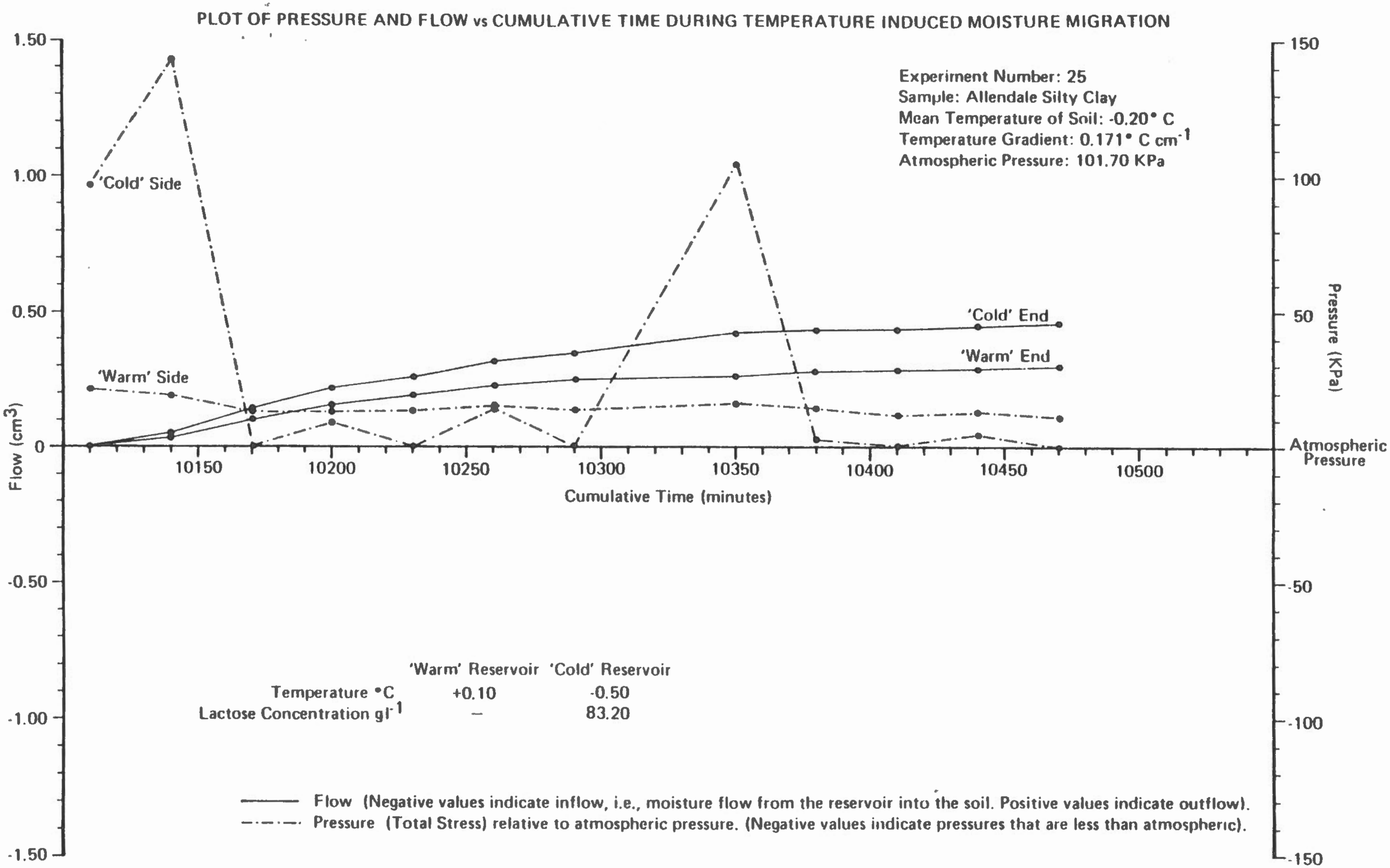

PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION
Experiment Number: 25
Sample: Allendale Silty Clay
Mean Temperature of Soil: -0.20° C
Temperature Gradient: 0.171° C cm-1
Atmospheric Pressure: 101.70 KPa
'Cold' Side
'Warm' Side
'Cold' End
'Warm' End
Flow (cm3)
Pressure (KPa)
Atmospheric Pressure
Cumulative Time (minutes)
1.50
1.00
0.50
0
-0.50
-1.00
-1.50
150
100
50
-50
-100
-150
10150
10200
10250
10300
10350
10400
10450
10500
'Warm' Reservoir 'Cold' Reservoir
Temperature °C +0.10 -0.50
Lactose Concentration gl-1 – 83.20
Flow (Negative values indicate inflow, i.e., moisture flow from the reservoir into the soil. Positive values indicate outflow).
Pressure (Total Stress) relative to atmospheric pressure. (Negative values indicate pressures that are less than atmospheric).

Figure 3.2g

PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION

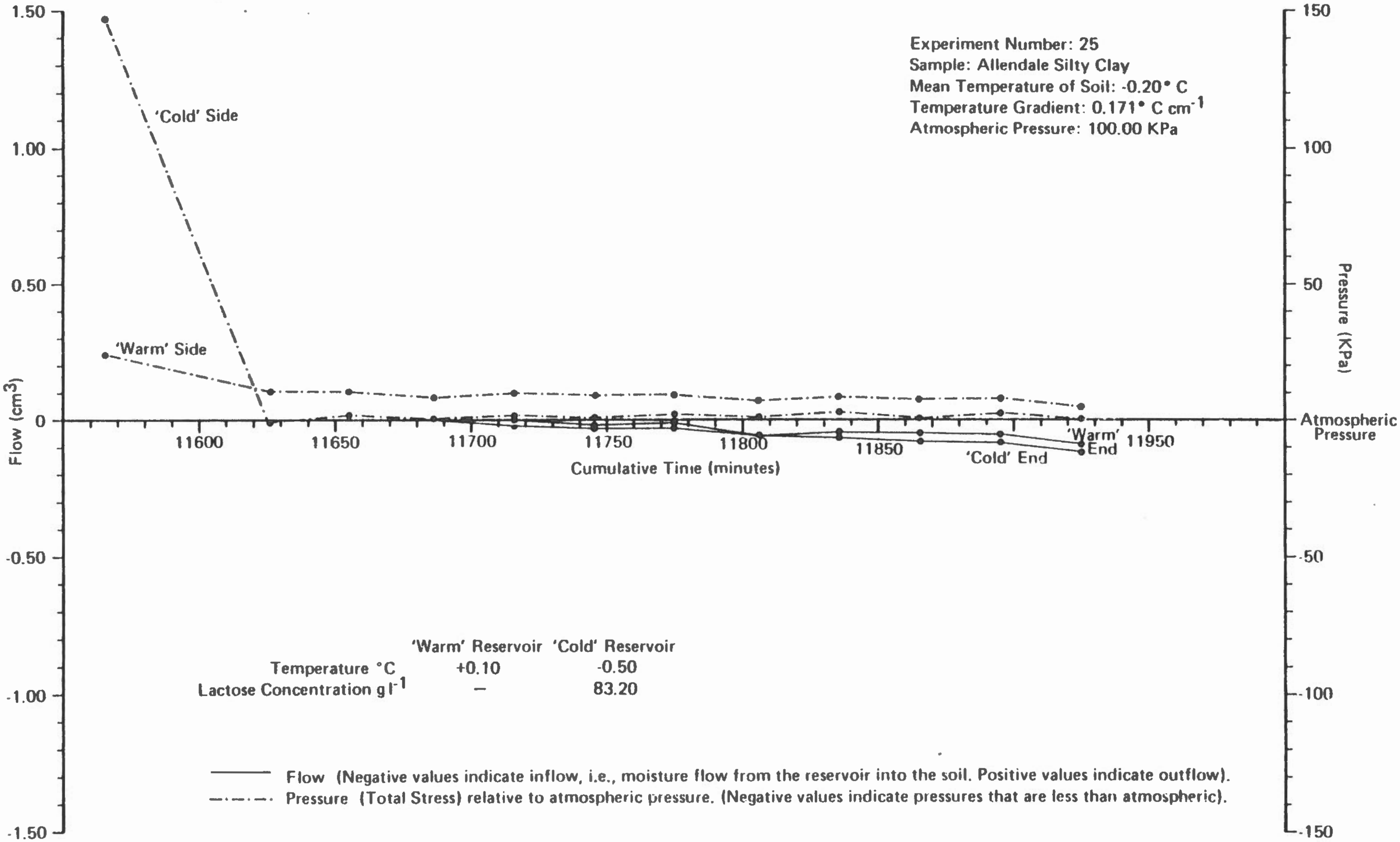


Figure 3.3

TEMPERATURE PROFILE OF SOIL SAMPLE DURING APPROACH TO STEADY-STATE HEAT TRANSFER (Experiment Number 26)

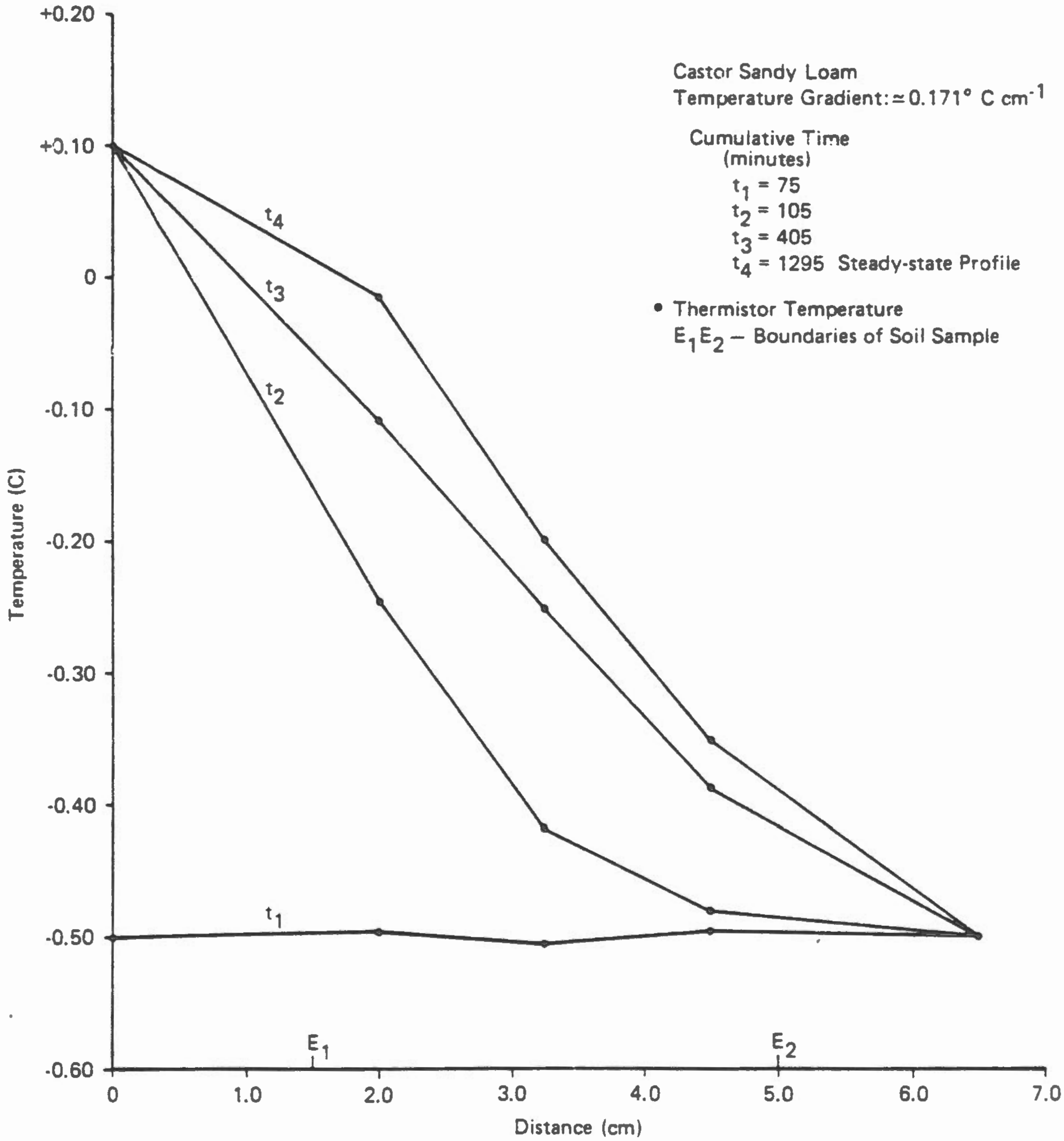


Figure 3.4a

PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION

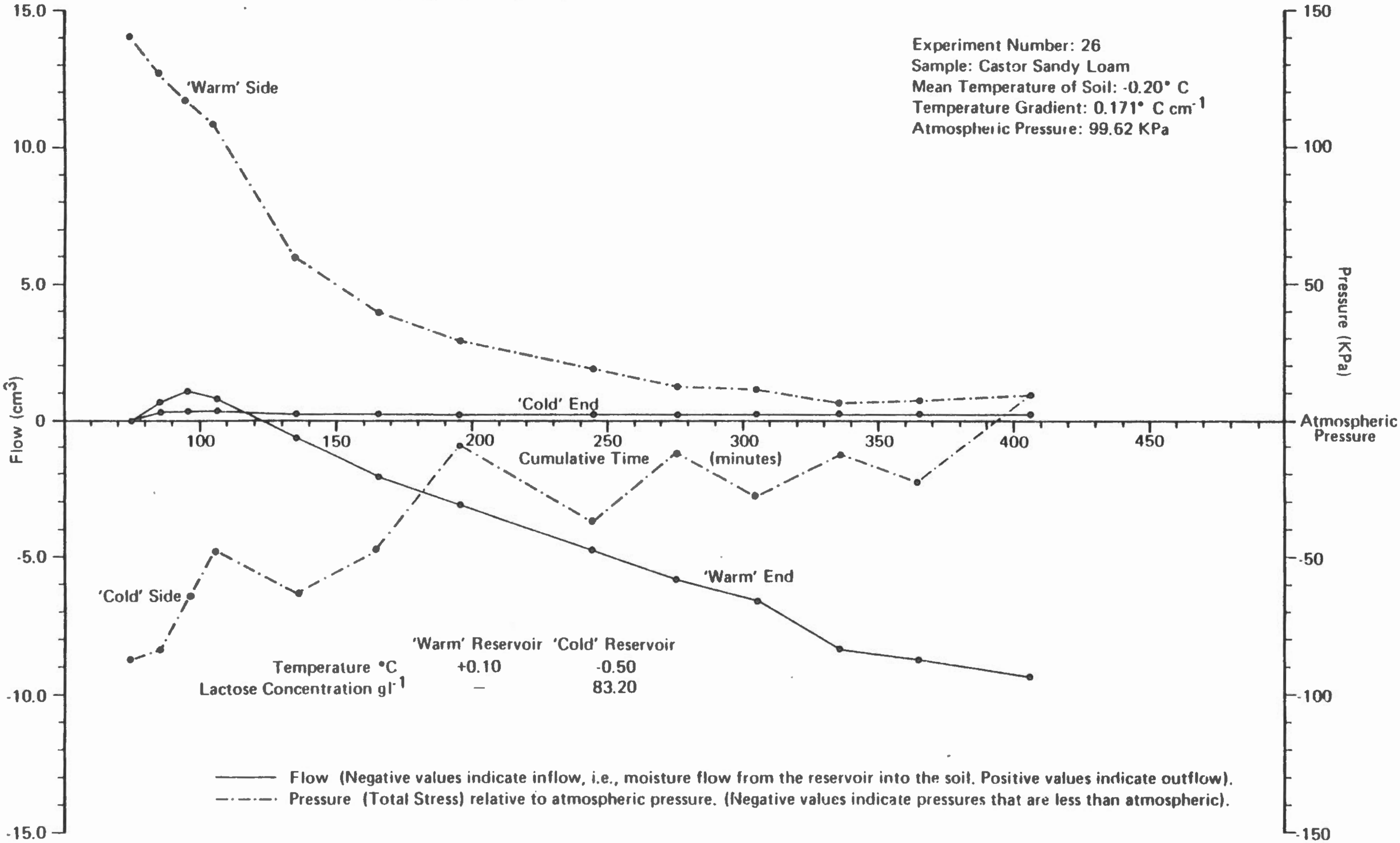


Figure 3.4b

PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION

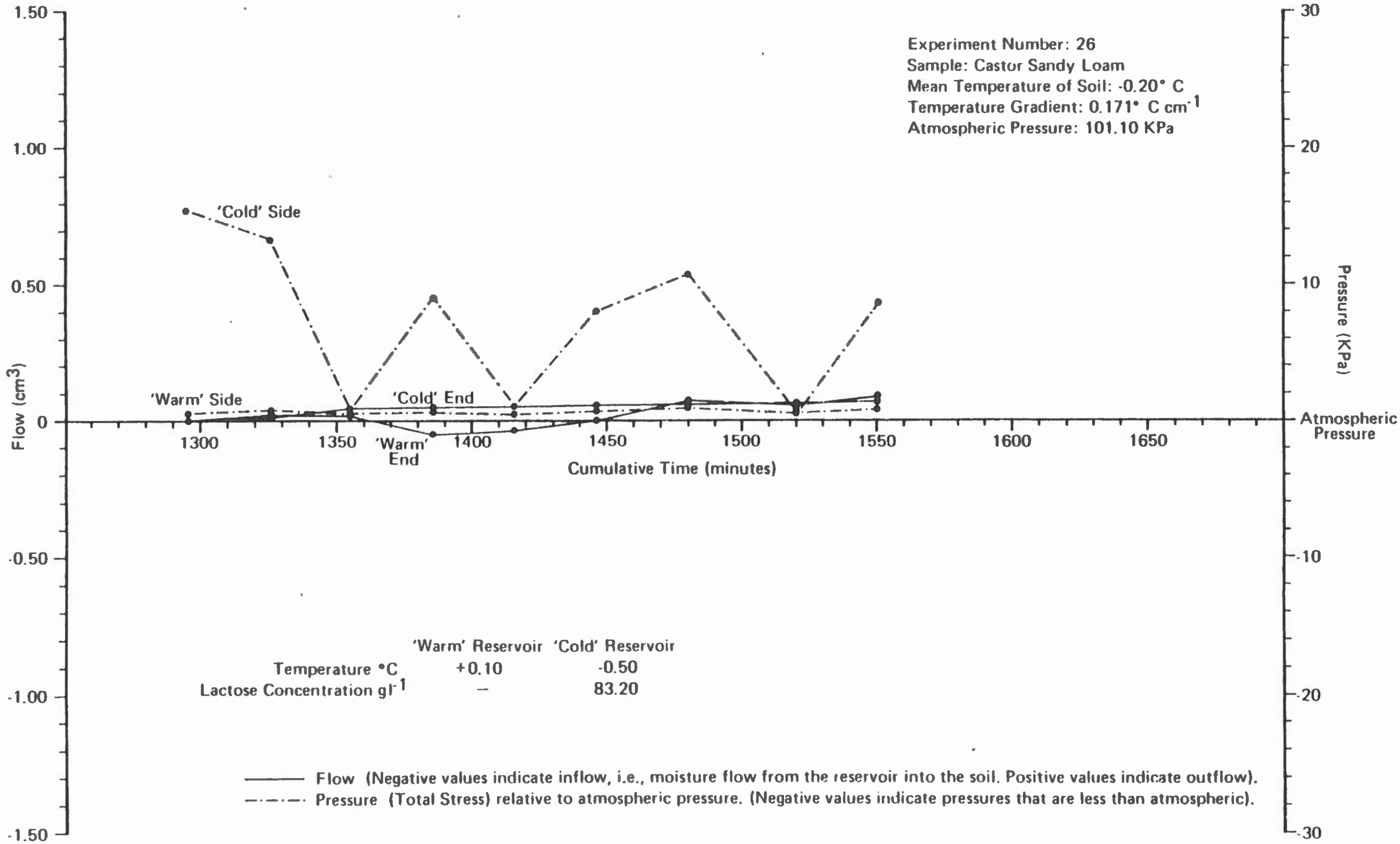
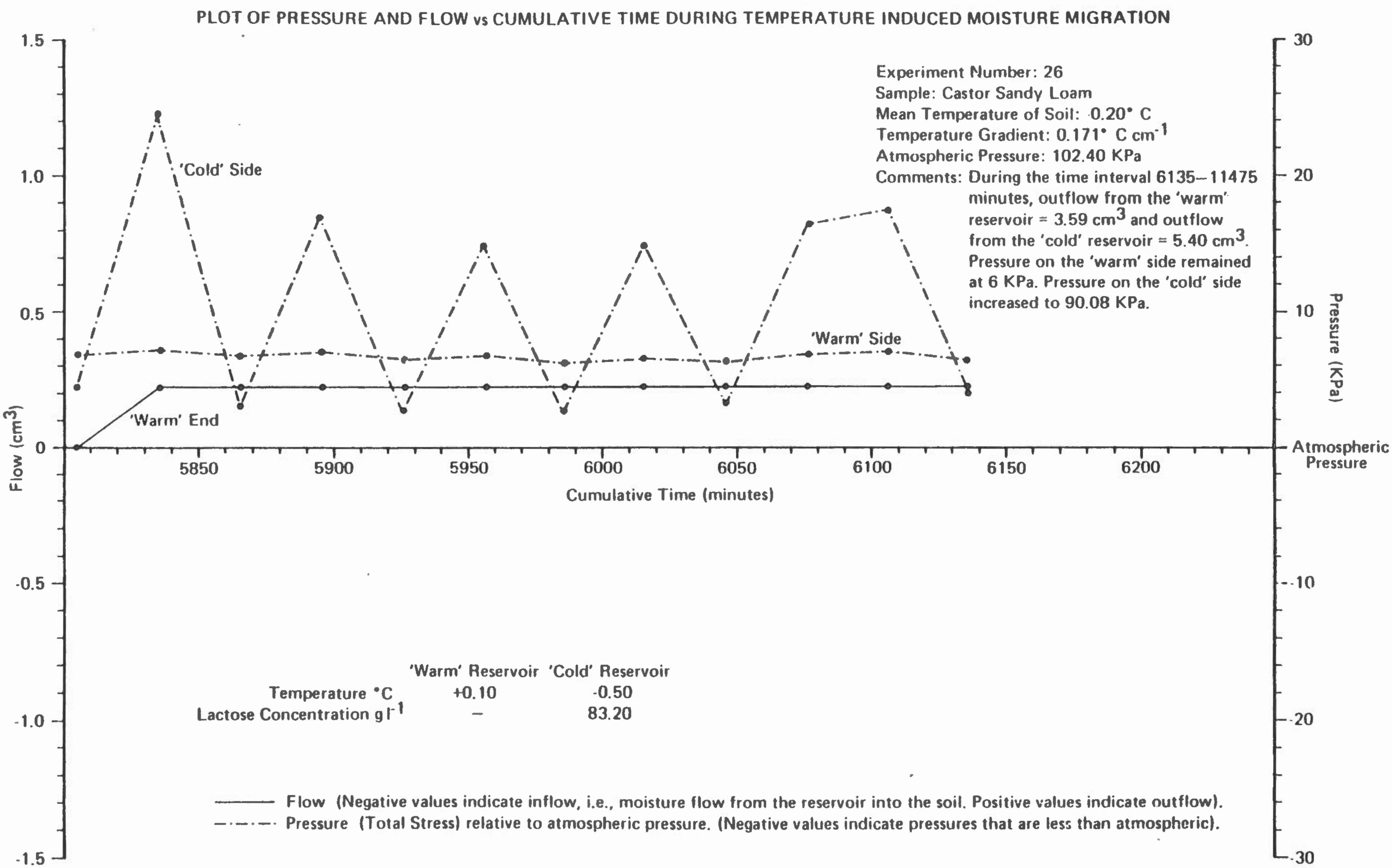


Figure 3.4c



PLOT OF PRESSURE AND FLOW vs CUMULATIVE TIME DURING TEMPERATURE INDUCED MOISTURE MIGRATION
Experiment Number: 26
Sample: Castor Sandy Loam
Mean Temperature of Soil: -0.20° C
Temperature Gradient: 0.171° C cm-1
Atmospheric Pressure: 102.40 KPa
Comments: During the time interval 6135–11475 minutes, outflow from the 'warm' reservoir = 3.59 cm3 and outflow from the 'cold' reservoir = 5.40 cm3. Pressure on the 'warm' side remained at 6 KPa. Pressure on the 'cold' side increased to 90.08 KPa.
'Cold' Side
'Warm' Side
'Warm' End
Flow (cm3)
Pressure (KPa)
Atmospheric Pressure
Cumulative Time (minutes)
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
30
20
10
-10
-20
-30
5850
5900
5950
6000
6050
6100
6150
6200
'Warm' Reservoir 'Cold' Reservoir
Temperature °C +0.10 -0.50
Lactose Concentration g l-1 – 83.20
Flow (Negative values indicate inflow, i.e., moisture flow from the reservoir into the soil. Positive values indicate outflow).
Pressure (Total Stress) relative to atmospheric pressure. (Negative values indicate pressures that are less than atmospheric).

results obtained from one experiment to the next, certain trends are also apparent. These are described along with a preliminary analysis of the results in sections 1 - 4 below.

1. Moisture Movements and Temperature Changes

After assembly the soil was brought up to an approximately uniform temperature and allowed to equilibriate with the reservoirs before establishing a temperature gradient. Following this, the temperature at one end of the sample was raised a fraction of a degree and the 'warm' reservoir was flushed with the appropriate concentration of lactose. (Pure water was used when the 'warm' end was above $0^{o}C$). In most instances, a nearly linear temperature gradient was established within the soil in a period of about 1 hour, although a true steady-state profile did not occur until about 12 - 18 hours after the temperature change was initiated. (See Figure 3.1)

The establishment of a temperature gradient across the soil results initially in a large influx of water at the 'warm' end of the sample, the rate of flow diminishing during the approach to a linear temperature gradient. In many of the experiments, a small amount of outflow was observed at the 'cold' end of the sample although in some instances, the direction reversed and inflow occurred. (See Figure 3.2a).

In general, there did not appear to be a significant difference in the total influx between the two soils, under the same temperature gradient. However, the rate of flow was dramatically influenced by the temperature of the soil at the 'warm' end. In cases where the 'warm' end temperature was below

freezing (−0.1°C), the total magnitude of the inflow during the approach to steady-state thermal conditions was about 0.8 to 1.0 cm^3. In contrast, when the 'warm' end was above freezing (+0.1°C), the total influx was approximately 1 order of magnitude greater (10.0 to 12.0 cm^3). This can be attributed, at least to a large degree, on the greater permeability of the soil in the unfrozen layer at the 'warm' end of the sample. (This is 6 orders of magnitude greater at +0.1°C then at −0.1°C).
In addition, compressive strain rates, which are much greater in unfrozen than in frozen soils (that is under constant stress), may also be a significant contributing factor enabling ice lenses to grow much more rapidly. (See Section 4 for discussion).

Contrary to expectations, water was expelled from both ends of the soil sample for a number of days after the initial influx. Flow reversal on the 'warm' reservoir (that is a change from inflow to outflow coincided roughly with the time that a steady-state temperature profile was fully established. In about one-half of the tests, the outflow at the 'warm' end of the sample exceeded that at the 'cold' end. Usually the rate of moisture expulsion declined to a very low level over a number of days and in some cases ceased after about a week.

2. Problem of Lactose Diffusion

Barring the possibility of equipment failure, experiments are generally limited in duration by the slow diffusion of lactose molecules through the membranes. Because of this, long-term migration of water could not be determined owing to the gradual thawing of the sample. However, the problem has been greatly reduced by the use of a new type of membrane permitting experiments of a week or more to be carried out. In general, the rate of thawing is related to the temperature and the mineral composition of the soil both of which determine its permeability and thus, the diffusion coefficient for lactose. With the Allendale soil a thawed layer 0.1 cm. thick was observed at the 'cold' end of the sample (-0.5°C) after about 5 days (0.2 cm with the Castor). Usually the thickness was about twice this value at -0.1°C after the same time period.

The presence of a small thawed layer at the outer boundary of the soil sample probably does not have a significant effect on the flow conditions within the soil since the chemical potential of the pore contents in the thawed zone should be approximately the same as those in the adjacent frozen zone and in the reservoir. However, the effect of a thawed layer on the stresses generated by the soil are not known. Since the compressive yield strength is much lower in unfrozen than in frozen soils, it seems likely that thawing of the sample would result in greater rates of strain as well as a slower rise in stress, occurring within the sample. It is desirable that these potential effects be kept to a minimum, and so experiments are generally run for no longer than 10 days.

There is a possibility that lactose penetration may be further reduced by heat treating the membranes, enabling longer experiments to be run. According to Sourirajan (1982), immersing the membranes in water at temperatures near the boiling point causes a reduction in pore size, the amount depending upon the temperature and duration of exposure. However, preliminary tests with heat treated membranes are not encouraging since no significant reduction in lactose penetration was observed. The matter will continue to be investigated in the next phase of experimentation.

3. Stresses Generated by the Soil

In general, stresses tended to be much greater towards the 'cold' end of the cell. This follows as a result of the increase in pressure with colder temperatures as indicated by the Clapeyron equation. According to the Clapeyron equation, the ice pressure increases by 1123.7 KPa C^{-1} (above atmospheric pressure), assuming that the pore water pressure remains constant and equal to atmospheric pressure.

In most of the experiments the stress on the 'warm' side of the sample remained fairly stable, within about 10 KPa of atmospheric pressure, throughout the experiment.[2] A characteristic feature of all of the tests is that the stress on the 'cold' side of cell showed a marked periodicity, each full cycle lasting about 1 - 2 hours. (see examples Figure 3.2 and 3.4). With the Castor soil, peak stresses generally varied between about 20 and 50 KPa, whereas with the Allendale, the peaks were much greater, frequently exceeding 100 KPa. Overall, there

---

2 In two of the tests there was a tendency for the stress on the 'warm' side of the cell to rise on the second or third day of the experiment to about 30 - 40 KPa above atmospheric pressure. (see experiment nos. 15 and 22). This was followed by a gradual decline back towards atmospheric pressure during the remainder of the experiment.

was a tendency for the stresses on the 'cold' side of the cell to decline towards atmospheric pressure with time, the peaks in stress becoming less frequent after a week or so.

4. Analysis of Results

There appears to be a close correspondence between the magnitude of the peak stresses occurring within the soil and the long-term tensile strength $\sigma^t_{\ell t}$ of similar materials at approximately the same temperature. Values of $\sigma^t_{\ell t}$ = 30 KPa for a silty heavy sandy loam, which is similar to the Castor, at -0.2°C to -0.4°C and $\sigma^t_{\ell t}$ = 100 - 200 KPa for clayey silt (similar to the Allendale) at -0.5°C, are listed in Tsytovitch (1975) and Johnson (1981). The following explanation is proposed.

Establishment of a temperature gradient across the soil, generates a segregation potential at some point behind the 0°C isotherm, the ice pressure at that point slowly rising toward its equilibrium value which is specified by the Clapeyron equation. However, ice lenses will not form until the ice pressure exceeds the long-term tensile of the frozen soil. Once this condition has been met, the soil then yields and the stress falls off. As heaving progresses, additional compressive yielding also occurs in the areas adjacent to the growing ice lens. However, the heaving stress continues to fall since the strain rate in compression is rapid at the 'warm' end of the sample particularly when the temperature is above freezing.

The maximum possible heaving pressure that can be generated by the soil is dependent upon the temperature at which the ice lenses form. This relationship is indicated by the

Clapeyron equation, which, expressed in finite form, is given as:

$$P_i - P_w = \frac{L \, \Delta T}{v_w T} \qquad (3-1)$$

where P_i and P_w = the ice and water pressure,

L = the latent heat of fusion of water,

v_w = the specific volume of water,

T = the absolute temperature of the system,

ΔT = the difference between the normal freezing temperature of water (absolute) and the actual temperature of the system.

The Clapeyron equation indicates a theoretical limit of 1123.7 KPa C^{-1} However, this limit is probably never attained due to yielding of the soil.

Deformation of the soil is manifested at least to some degree by the stress induced melting of existing segregation ice in the areas adjacent to the actively forming ice lenses. This accounts for the continual expulsion of water from both ends of the sample, the rise and fall in pressure on the 'cold' side acting as a kind of pump sustaining the movement. One would expect that yielding would tend to be much greater towards the 'warm' end of the sample since the compressive strength there, is much lower there than at the 'cold' end.[3] It seems curious that ice lens growth continues to occur within the sample even though moisture is being expelled from both ends, implying dessication of the soil rather than heaving. The only acceptable explanation for this seemingly apparent contradiction is that, once a steady-state temperature profile has been attained, further growth of segregation ice occurs as a result of internal redistributions of water and ice within the soil. (i.e. water and pore ice moving from warmer toward colder regions within the soil). In other words, moisture expulsion from the reservoirs implies yielding towards the extremities of the sample particularly at the 'warm' end. Evidence for this conclusion is that, in the majority of tests, outflow is much greater at the 'warm' end of the sample than at the 'cold' end.

IV FUTURE RESEARCH

1. Uncertainty remains over whether, the soil eventually stabilizes towards a static (no flow) situation, or whether moisture expulsion from the warm reservoir eventually reverses direction and a slow steady flow of water proceeds in the direction of colder temperatures, as predicted by theory. Tests of 10 days duration or more should be conducted to determine the ultimate flow situation as well as the resulting stresses within the soil.

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[3] According to Tsytovitch (1975), the long-term compressive strength of frozen soils, $\sigma^{c}_{\ell t}$ is related to the temperature T by: $\sigma^{c}_{\ell t} = a + bT$

where a and b are parameters.

2. It is assumed that the value which is recorded by the pressure transducers represents the total stress at that location within the column. The total stress at any point is defined as the sum of the intergranular stresses between the soil particles as well as the neutral stresses generated by the pore contents of the soil. There is, however, a possibility that there may be some arching effects within the soil around the small orifices in the walls of the cell. If arching does, in fact, occur then this would tend to reduce the magnitude of the stress which is transmitted to the pressure transducers.

Improvements to the existing system of pressure measurement could be accomplished by attaching a small copper tube to the end of each transducer, the tube extending some distance into the sample. A bulb shaped rubber membrane filled with oil or grease fitted over the open end of the tube would act as the pressure sensitive area. Not only would this arrangement avoid potential arching effects but it would also enable measurement of isotropic stresses generated by the soil. (Axial stresses are not measured with the present arrangement).

3. It is also recommended that strength testing be carried out at a future date, to determine $\sigma^{t}_{\ell t}$ for both soils. Although values for similar soils are listed in Tsytovitch (1975) and Johnson (1981), additional corroborating evidence is not readily available since most strength testing has been done at relatively cold temperatures (less than -1°C). Testing of the Allendale and Castor soils would involve measuring the strain rate at constant stress over a long time interval at various increments in temperature between 0°C and -0.5°C.

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APPENDIX I

A RECORD OF THE EXPERIMENTAL RESULTS

NOMENCLATURE

Cumulative Time: Total time elapsed (in minutes) since temperature control was first established in the soil sample (1440 minutes=24 hours)

Pressure: Total stress in KPa indicated by each transducer, relative to current atmospheric pressure. (+) values indicate pressures that are greater than atmospheric and (-) values pressure that are less than atmospheric. Atmospheric pressure is recorded at each reading from a mercury in glass barometer mounted on the wall of the laboratory.

Flow: Total flow in cm^3 since the start of each reading session. (-) values indicate inflow, that is moisture flow from the reservoir into the soil. (+) values indicate outflow.

Thermistor code: T_1 - Temperature of 'warm' plate

T_2 - Temperature of soil 1.985 cm from T_1 (0.5 cm from B_1)

T_3 - Temperature of soil 3.235 cm from T_1 (1.75 cm from B_1 and B_2)

T_4 - Temperature of soil 4.485 cm from T_1

(0.5 cm from B_2)

T_5 - Temperature of 'cold' plate 6.470 cm from

T_1

B_1 - Boundary of 'warm' end of soil sample

B_2 - Boundary of 'cold' end of soil sample

Pressure

Transducer Code: P_1 - Total stress 2.635 cm from T_1

(1.15 cm from B_1)

P_2 - Total stress 3.835 cm from T_1

(1.15 cm from B_2)

Reservoir Code: R_1 - 'warm' end reservoir

R_2 - 'cold' end reservoir

The following values were determined after each experiment was dismantled:

L_f - Length of frozen section of sample, cm

W - Water content of sample, % dry weight

ρ_B - Bulk density of sample, gm cm^{-3}

NOTE: Readings were taken at 10 or 15 minute intervals for the first hour of each experiment and then at half hour intervals for the remainder of the test. Approximately 6 hours of readings were taken each day. The total flow between each reading session was also recorded with a large diameter capillary attached to each reservoir. This is indicated by an asterisk * beside the time. The symbol indicates that the flow exceeded the volume of the capillary.

EXPERIMENT NO. 22

Allendale Silty Clay

Temperature Gradient = 0.171 $^{o}C\ cm^{-1}$

L_f = 2.20 cm

W = 55.72%

P_B = 1.03 gm cm^{-3}

	'Warm' Reservoir	'Cold' Reservoir
Temperature ^{o}C	+0.10	-0.50
Lactose Concentration gl^{-1}	0	83.20

EXPERIMENT NO. 22

ALLENDALE SILTY CLAY

Cumulative Time Minutes	Thermistor Temperature °C					Pressure KPa		Flow cm^3	
	T_1	T_2	T_3	T_4	T_5	P_1	P_2	R_1	R_2
95	-0.505	-0.470	-0.495	-0.500	-0.500	36.73	150.12	0	0
105	-0.505	-0.290	-0.465	-0.500	-0.500	9.12	70.94	- 79.89	- 43.07
115	+0.100	-0.225	-0.425	-0.495	-0.500	82.80	88.24	-157.69	- 54.18
125	+0.100	-0.190	-0.400	-0.475	-0.500	50.69	100.42	-238.69	- 54.18
135	+0.100	-0.165	-0.370	-0.460	-0.495	-0.16	38.11	-323.43	- 54.18
165	+0.100	-0.135	-0.320	-0.435	-0.500	25.83	32.55	-537.38	- 54.18
195	+0.100	-0.115	-0.300	-0.420	-0.500	-2.68	10.57	-663.14	- 54.18
225	+0.100	-0.100	-0.265	-0.405	-0.500	-1.92	-25.27	-812.90	- 54.18
255	+0.100	-0.090	-0.250	-0.400	-0.500	-0.16	1.29	-919.94	- 54.18
285	+0.100	-0.080	-0.245	-0.395	-0.500	-0.38	-10.87	-1018.67	- 54.18
315	+0.100	-0.075	-0.230	-0.385	-0.500	-0.45	-1.81	-1112.11	- 54.18
345	+0.100	-0.070	-0.230	-0.380	-0.500	-0.61	-1.52	-1162.06	- 54.18
375	+0.100	-0.065	-0.230	-0.380	-0.500	-1.44	-1.51	-1210.25	- 54.18
405	+0.100	-0.060	-0.215	-0.380	-0.505	-1.74	-1.74	-1247.86	- 54.18
410	+0.100	-0.060	-0.215	-0.380	-0.505	-0.91	-0.60	0	0
1380*	+0.100	-0.020	-0.200	-0.370	-0.505	29.53	30.15	>294.0	11.81

EXPERIMENT NO. 22

ALLENDALE SILTY CLAY

Cumulative Time Minutes	Thermistor Temperature °C T_1	T_2	T_3	T_4	T_5	Pressure KPa P_1	P_2	Flow cm^3 R_1	R_2
1380	+0.110	-0.020	-0.185	-0.355	-0.490	30.68	23.76	0	0
1410	+0.100	-0.015	-0.180	-0.355	-0.500	22.97	22.42	7.29	22.05
1440	+0.100	-0.015	-0.190	-0.360	-0.500	24.50	-1.89	11.46	48.27
1470	+0.090	-0.015	-0.180	-0.360	-0.500	27.40	49.18	20.66	64.26
1500	+0.090	-0.015	-0.180	-0.360	-0.500	30.31	0.48	27.08	72.58
1530	+0.090	-0.015	-0.180	-0.360	-0.500	33.35	89.97	43.40	85.08
1590	+0.090	-0.015	-0.180	-0.360	-0.500	46.62	90.73	70.14	96.02
1620	+0.090	-0.015	-0.180	-0.360	-0.500	45.17	-3.10	75.70	97.93
1650	+0.090	-0.015	-0.180	-0.360	-0.500	31.54	0.27	79.17	100.01
1680	+0.090	-0.015	-0.180	-0.360	-0.500	42.99	64.59	94.10	104.53
1710	+0.090	-0.015	-0.180	-0.360	-0.500	46.76	109.75	98.61	106.96
1740	+0.100	-0.015	-0.180	-0.360	-0.500	44.38	1.21	102.08	108.00
1745	+0.100	-0.055	-0.180	-0.360	-0.500	39.50	2.12	0	0
2860*	+0.100	-0.015	-0.180	-0.370	-0.510	52.77	119.93	>174.0	25.01

EXPERIMENT NO. 22

ALLENDALE SILTY CLAY

Cumulative Time Minutes	Thermistor Temperature °C					Pressure KPa		Flow cm^3	
	T_1	T_2	T_3	T_4	T_5	P_1	P_2	R_1	R_2
2865	+0.110	-0.010	-0.185	-0.345	-0.480	47.51	91.77	0	0
2900	+0.100	-0.010	-0.180	-0.350	-0.500	19.82	-1.08	0	28.13
2925	+0.100	-0.005	-0.180	-0.350	-0.500	3.12	-0.92	0	28.13
2985	+0.100	0.000	-0.175	-0.350	-0.500	6.55	20.46	17.02	66.68
3015	+0.100	+0.005	-0.175	-0.350	-0.500	11.88	0.36	17.02	72.24
3045	+0.100	+0.005	-0.175	-0.355	-0.500	15.51	24.75	18.76	77.80
3075	+0.100	+0.005	-0.175	-0.355	-0.500	17.03	1.39	22.58	80.93
3105	+0.100	+0.005	-0.175	-0.355	-0.500	18.38	29.53	29.01	84.06
3135	+0.100	+0.005	-0.175	-0.355	-0.500	19.54	1.38	33.00	85.08
3165	+0.100	+0.005	-0.175	-0.355	-0.500	22.15	62.28	42.90	88.23
3195	+0.100	+0.005	-0.175	-0.355	-0.500	23.74	1.84	45.68	88.75
3225	+0.100	+0.005	-0.175	-0.355	-0.500	23.57	56.09	52.11	88.92
3230	+0.100	+0.000	-0.175	-0.355	-0.485	21.14	10.88	0	0
4305*	+0.110	+0.020	-0.185	-0.350	-0.500	7.82	105.51	116.70	0.35

EXPERIMENT NO. 22

ALLENDALE SILTY CLAY

Cumulative Time Minutes	Thermistor Temperature °C					Pressure KPa		Flow cm^3	
	T_1	T_2	T_3	T_4	T_5	P_1	P_2	R_1	R_2
4305	+0.110	+0.045	-0.145	-0.315	-0.455	1.03	-29.03	0	0
4335	+0.110	+0.040	-0.125	-0.315	-0.500	0.53	-0.38	0	1.39
4365	+0.110	+0.035	-0.125	-0.325	-0.500	1.14	1.14	-1.04	15.98
4395	+0.110	+0.030	-0.130	-0.325	-0.500	-2.67	-42.85	9.03	25.53
4425	+0.110	+0.030	-0.130	-0.330	-0.500	-2.45	-17.66	11.11	27.27
4455	+0.090	+0.030	-0.130	-0.330	-0.500	-2.90	-21.32	17.71	28.49
4485	+0.110	+0.030	-0.130	-0.330	-0.500	-2.45	-17.43	19.62	28.84
4515	+0.105	+0.030	-0.130	-0.330	-0.500	-2.89	-18.64	20.32	28.84
4545	+0.100	+0.030	-0.130	-0.330	-0.500	-2.36	-17.35	21.71	28.84
4575	+0.100	+0.030	-0.130	-0.330	-0.500	-2.82	-18.57	21.71	28.84
4605	+0.100	+0.030	-0.130	-0.330	-0.500	-2.28	-17.42	22.23	28.84
4635	+0.100	+0.030	-0.130	-0.330	-0.500	-2.80	-18.85	22.23	28.84
4665	+0.105	+0.030	-0.130	-0.330	-0.500	-2.17	-17.39	22.23	28.84

EXPERIMENT NO. 23

Allendale Silty Clay

Temperature Gradient = 0.171 $^{o}C\ cm^{-1}$

Comments: Experiment dismantled on third day due to incubator failure

	'Warm' Reservoir	'Cold' Reservoir
Temperature ^{o}C	+0.10	-0.50
Lactose Concentration gl^{-1}	0	83.20

EXPERIMENT NO. 23

ALLENDALE SILTY CLAY

Cumulative Time Minutes	Thermistor Temperature °C					Pressure KPa		Flow cm^3	
	T_1	T_2	T_3	T_4	T_5	P_1	P_2	R_1	R_2
80	-0.500	-0.535	-0.580	-0.550	-0.500	29.75	104.41	0	0
85	+0.100	-0.390	-0.570	-0.540	-0.500	32.03	84.78	75.81	-3.82
95	+0.110	-0.275	-0.510	-0.520	-0.500	39.44	44.38	61.12	-9.03
105	+0.100	-0.220	-0.465	-0.495	-0.500	37.99	21.77	-13.51	-15.46
115	+0.100	-0.185	-0.415	-0.470	-0.500	35.17	18.73	-69.34	-15.98
145	+0.100	-0.135	-0.330	-0.425	-0.500	13.22	6.80	-249.16	-27.44
175	+0.100	-0.105	-0.290	-0.410	-0.500	9.81	13.67	-409.01	-35.77
205	+0.100	-0.090	-0.260	-0.395	-0.500	7.01	15.97	-538.29	-43.76
235	+0.100	-0.080	-0.240	-0.385	-0.500	5.73	23.22	-606.75	-50.36
265	+0.100	-0.070	-0.225	-0.375	-0.500	4.68	8.17	-704.60	-58.01
295	+0.100	-0.060	-0.215	-0.370	-0.500	4.59	20.03	-804.55	-61.48
325	+0.100	-0.050	-0.205	-0.365	-0.500	4.97	7.47	-875.02	-66.34
385	+0.100	-0.040	-0.200	-0.365	-0.500	5.01	24.82	-968.16	-72.24
415	+0.100	-0.035	-0.195	-0.360	-0.500	5.22	7.79	-1017.23	-78.49
445	+0.100	-0.035	-0.190	-0.360	-0.500	6.82	13.20	-1037.21	-81.96
470	+0.100	-0.030	-0.180	-0.365	-0.500	4.76	0.64	0	0
1335 ^	+0.110	+0.010	-0.170	-0.365	-0.500	21.86	12.68	> 294.0	8.52

EXPERIMENT NO. 23

ALLENDALE SILTY CLAY

Cumulative Time Minutes	Thermistor Temperature °C					Pressure KPa		Flow cm^3	
	T_1	T_2	T_3	T_4	T_5	P_1	P_2	R_1	R_2
1340	+0.120	-0.015	-0.170	-0.335	-0.485	15.22	13.59	0	0
1370	+0.100	-0.010	-0.160	-0.345	-0.495	9.60	11.86	4.51	-6.95
1520	+0.100	-0.005	-0.160	-0.345	-0.500	6.25	0.91	42.37	-32.30
1550	+0.100	-0.005	-0.160	-0.345	-0.500	6.99	2.56	62.34	-43.07
1580	+0.100	-0.005	-0.160	-0.345	-0.500	7.07	1.73	76.06	-56.10
1610	+0.100	-0.005	-0.160	-0.345	-0.500	9.20	5.06	76.41	-64.61
1640	+0.100	-0.005	-0.160	-0.345	-0.500	10.09	4.59	78.67	-67.56
1670	+0.100	-0.005	-0.160	-0.345	-0.500	10.35	8.04	92.91	-77.98
1700	+0.100	-0.005	-0.160	-0.345	-0.500	10.49	4.68	108.89	-88.75
1730	+0.100	-0.005	-0.160	-0.345	-0.500	10.67	7.61	121.74	-95.70
1735	+0.100	-0.005	-0.160	-0.345	-0.500	8.23	3.72	0	0
2815 *	+0.160	+0.050	-0.090	-0.290	-0.495	2.11	15.04	> 238.0	> -147.0

EXPERIMENT NO. 24

Castor Sandy Loam

Temperature Gradient = 0.061 $^{o}C\ cm^{-1}$

L_f = 2.20 cm.

W = 22.92%

P_B = 1.64 gm cm^{-3}

	'Warm Reservoir	'Cold' Reservoir
Temperature ^{o}C	-0.085	-0.30
Lactose Concentration gl^{-1}	15.24	52.91

EXPERIMENT NO. 24

CASTOR SANDY LOAM

Cumulative Time Minutes	Thermistor Temperature °C					Pressure KPa		Flow cm^3	
	T_1	T_2	T_3	T_4	T_5	P_1	P_2	R_1	R_2
135	-0.300	-0.270	-0.265	-0.260	-0.300	9.80	13.66	0	0
145	-0.100	-0.265	-0.270	-0.260	-0.300	10.50	13.75	0	0
160	-0.100	-0.215	-0.255	-0.255	-0.300	11.70	13.12	-120.87	-0.17
175	-0.100	-0.195	-0.245	-0.255	-0.300	11.26	12.00	-151.26	-0.34
205	-0.100	-0.170	-0.225	-0.255	-0.300	11.00	13.41	-187.38	-0.86
235	-0.100	-0.160	-0.215	-0.245	-0.300	10.38	12.15	-224.54	-6.59
265	-0.105	-0.150	-0.205	-0.240	-0.300	10.53	9.52	-246.94	-8.15
295	-0.100	-0.150	-0.200	-0.235	-0.300	11.40	1.41	-266.91	-9.71
325	-0.100	-0.145	-0.195	-0.235	-0.300	11.64	8.95	-303.38	-12.14
355	-0.100	-0.140	-0.190	-0.235	-0.300	11.59	9.44	-315.88	-11.79
385	-0.110	-0.140	-0.190	-0.235	-0.300	11.75	9.59	-323.87	-11.79
415	-0.100	-0.140	-0.185	-0.235	-0.300	11.71	9.48	-329.77	-11.79
445	-0.100	-0.140	-0.185	-0.235	-0.300	12.01	9.93	-333.59	-11.44
475	-0.095	-0.135	-0.185	-0.235	-0.300	11.81	9.50	-339.15	-11.44
505	-0.095	-0.135	-0.185	-0.235	-0.300	11.76	9.30	-357.15	-11.44
525	-0.095	-0.130	-0.185	-0.230	-0.300	11.39	3.44	0	0
1320 *	-0.085	-0.120	-0.170	-0.225	-0.295	10.70	8.24	-73.45	2.08

EXPERIMENT NO. 24

CASTOR SANDY LOAM

Cumulative Time Minutes	Thermistor Temperature °C					Pressure KPa		Flow cm^3	
	T_1	T_2	T_3	T_4	T_5	P_1	P_2	R_1	R_2
1380	-0.110	-0.115	-0.165	-0.215	-0.295	11.66	9.05	0	0
1410	-0.100	-0.120	-0.170	-0.215	-0.300	13.04	9.43	0.17	2.78
1440	-0.090	-0.125	-0.170	-0.225	-0.300	12.67	4.04	0.17	12.85
1470	-0.090	-0.125	-0.170	-0.225	-0.300	13.01	8.42	0.17	15.80
1500	-0.090	-0.120	-0.175	-0.225	-0.300	12.51	2.21	0.17	15.97
1530	-0.095	-0.120	-0.175	-0.230	-0.300	12.43	5.56	0	17.01
1560	-0.085	-0.120	-0.175	-0.230	-0.300	12.08	1.71	0	19.27
1590	-0.090	-0.120	-0.175	-0.230	-0.300	12.06	4.34	0	19.79
1620	-0.090	-0.120	-0.175	-0.230	-0.300	11.83	1.61	0	21.53
1650	-0.085	-0.115	-0.175	-0.230	-0.300	11.81	5.63	0	21.70
1680	-0.085	-0.115	-0.175	-0.230	-0.300	11.68	1.54	-0.17	21.70
1710	-0.085	-0.115	-0.175	-0.230	-0.300	11.72	5.08	-0.17	21.70
1740	-0.085	-0.115	-0.175	-0.230	-0.300	11.60	1.53	-0.34	21.70
1770	-0.085	-0.115	-0.175	-0.230	-0.300	11.58	4.26	-0.34	21.70
1800	-0.085	-0.115	-0.175	-0.230	-0.300	11.15	0.47	-0.34	21.70
1850	-0.090	-0.085	-0.140	-0.205	-0.300	10.32	3.45	0	0
2745 *	-0.090	-0.115	-0.170	-0.225	-0.305	9.32	7.85	-49.07	-8.22

EXPERIMENT NO. 24

CASTOR SANDY LOAM

Cumulative Time Minutes	Thermistor Temperature °C					Pressure KPa		Flow cm^3	
	T_1	T_2	T_3	T_4	T_5	P_1	P_2	R_1	R_2
2760	-0.085	-0.105	-0.170	-0.215	-0.300	7.77	6.01	0	0
2790	-0.085	-0.105	-0.170	-0.220	-0.300	8.50	0.56	-20.15	37.86
2820	-0.085	-0.105	-0.170	-0.220	-0.300	8.50	2.24	-23.97	53.32
2850	-0.085	-0.110	-0.170	-0.225	-0.300	8.65	1.17	-29.01	57.84
2880	-0.085	-0.110	-0.170	-0.220	-0.300	8.78	2.75	-29.01	69.47
2910	-0.085	-0.110	-0.165	-0.225	-0.300	8.54	0.61	-36.13	71.55
2940	-0.085	-0.110	-0.165	-0.220	-0.300	8.68	1.82	-38.04	71.90
2970	-0.085	-0.110	-0.165	-0.225	-0.300	8.56	0.85	-42.03	73.12
3000	-0.085	-0.110	-0.165	-0.225	-0.300	8.64	2.00	-44.11	73.12
3030	-0.085	-0.110	-0.165	-0.220	-0.300	8.53	0.82	-47.23	73.12
3060	-0.085	-0.110	-0.165	-0.220	-0.300	8.61	1.66	-47.23	73.12
3090	-0.085	-0.110	-0.165	-0.220	-0.300	8.47	0.77	-52.61	73.12
3120	-0.085	-0.110	-0.165	-0.220	-0.300	8.52	1.88	-56.43	73.12
3150	-0.085	-0.110	-0.165	-0.220	-0.300	8.49	1.62	-61.47	72.95