Canada-France
Pipeline - Ground Freezing Experiment:
Frozen Transition Experiment

Second Freeze Period

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Report to

Terrain Sciences Division,
Geological Survey of Canada,
Energy, Mines and Resources Canada

and to
ESSO RESOURCES CANADA LIMITED

FOOTHILLS PIPE LINES LTD.

INTERPROVINCIAL PIPE LINE INC.

NOVA CORPORATION OF ALBERTA

TRANSCANADA PIPELINES LIMITED
on behalf of THE POLAR GAS PROJECT

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May 1993

Prof. Dr. Edward Ershov, head of the Department of Geocryology of Moscow State University and Dr. Vlad Rougansky of the same department, visited the controlled-environment facility in May 1992. The Department has 25 research scientists covering topics from pipelines to permafrost on other planets, and graduates some 25 students each year. It is the perhaps best-known centre for permafrost studies in the former Soviet Union.

Vlad Rougansky (right) and Peter Williams consider the apparatus installed for carrying-out of the pipeline pull-out resistance tests.

Foreword

This Report covers the period of operation from March 31, 1992 to March 31, 1993 of the Canada-France pipeline ground freezing project. This was the third and final year of an investigation simulating the behaviour of a pipeline at a boundary between permafrost and unfrozen ground. The study is, in fact, still underway as explained below, and the Report makes brief reference to observations between March 31 and mid-May 1993.

The Project has been financed throughout the three-year program by seven companies and Energy Mines and Resources Canada. It was preceded by studies commenced in 1982, of the behaviour under freezing conditions of a pipeline which traversed two types of soil. The techniques used in the work have become progressively more sophisticated and the investigations more comprehensive. In addition to the annual reports many publications have appeared, covering various aspects. The continuity of the project has given unusual opportunity to confirm and extend many of the findings, enhancing the definitive nature of the publications arising from the project. Much attention has been given to the archival storage of data so that it is available for further use.

The value of the project with respect to Northern pipeline design has by no means been fully exploited. It is particularly unfortunate that a shortfall in funding during the year, consequent upon cutbacks in Canadian government expenditures generally, has delayed and is likely to curtail the programme. This curtailment would involve, notably, the series of tests on the 'pull-out resistance' - the resistance of frozen ground overlying the pipe. Preparations for these tests have proceeded with the purchase of necessary equipment. Strenuous efforts have been made to seek a replacement for the original funding (the sum of approximately $50,000 is required) but it appears unlikely that these will be successful in the short time remaining. The carrying-out of such tests later, after the present experiment had been terminated, would involve setting up a new experiment costing a sum many times greater than the present shortfall.

In a long-term view, it appears likely that controlled environment facilities, comparable to those being used currently but involving many new features, will be used in Canada and elsewhere for a wide range of experiments relating to Northern environmental conditions. A series of meetings have been held with representatives of companies and agencies from Canada and abroad with development of plans for such facilities. Also during the year reported, the project was visited by Prof. Dr. Edward Ershov, the distinguished Head of the Moscow State University Department of Geocryology and Dr. Vladimir Rougansky of the same Department. In a preceding visit to Canada, funded by the Department of Indian and Northern Affairs, they gave graphic accounts of the condition of the

extensive network of gas pipelines in the Russian cold regions. It is clear that their extensive experience would increase the value of a cooperation in which Canadian expertise could also be brought to bear on problems of cold region pipelines. Further information on these matters, which have been brought to the fore largely as a result of interest in the current project, may be obtained from the Geotechnical Science Laboratories.

During the year covered by this report the Proceedings of the seminar held in Paris and Caen in late 1991 were published and there have been several invitations to describe the work to major conferences (Williams 1992, Williams et al. 1992, Riseborough et al. 1993).

The Canadian participants in the project remain as always, indebted to their French colleagues. M. Dupas, M. Dumoulin especially, continue to provide outstanding skilled help. Mlle Marie-Christine Delhomme and Mr. Les White have been the able site managers for the French and Canadian teams respectively. Members of the staff of the CNRS Centre de Geomorpholigie have also provided valued assistance. This report has been prepared by Dan Riseborough who has been the very effective manager for a number of years, based in Ottawa, of the Canadian involvement in the project as a whole.

P. J. Williams, Principal Investigator.

Liaison with the seven sponsoring companies:

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has been maintained through John Ellwood of Foothills. Liaison with Energy Mines and Resources Canada is through Dr. Alan Judge. The help of all these is appreciated. The project is supervised by a Scientific Committee whose members are listed below.

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1 Introduction

This report covers the third year of a three year project investigating the behaviour of a gas pipeline buried in frost susceptible soil. The results for July 1 1992 - March 31 1993 are discussed here, representing the period of the second freeze of the current so-called "thermal-transition" experiment. Results for the first freeze cycle and pipe relaxation experiment are discussed in Geotechnical Science Laboratories (1992).

In earlier experiments at Caen, the buried pipeline crossed a "textural" transition from a non-frost-susceptible sand to a highly frost susceptible silt. In the new experiment the pipe crosses a transition from initially unfrozen soil to already frozen soil, simulating the forces that would be exerted on a buried gas pipeline crossing a boundary between permafrost and unfrozen, frost-susceptible ground. Crossing a thermal interface of this type is expected to be a more severe frost heave design scenario for gas pipelines buried at high latitudes.

Table I Significant dates in the experiment

Event	Date	Days elapsed from 26-Jun-91
Soil all placed in trough	28-Sep-90	-271
Thermal separation wall placed	24-Oct-90	-245
Pre-freezing Starts @ -3	01-Nov-90	-237
Pre-freezing @ -8	12-Nov-90	-226
Pre-freezing @ -15	08-Dec-90	-200
Pre-freezing @ -18	15-Jan-91	-162
Ditch excavation	06-Feb-91	-140
Pipe placement	02-Apr-91	-85
Backfill ditch cold side	26-Apr-91	-61
Pre-freezing @ -8	26-Apr-91	-61
Backfill ditch warm side	29-May-91	-28
Pre-freezing @ -4	12-Jun-91	-14
Freezing experiment starts	26-Jun-91	0
Pipe temperature lowered to -8.5	27-Jan-92	215
Pipe relaxation begins	09-Mar-92	257
Relaxation ends: transition begins	22-Mar-92	270
Soil columns all installed	11-Jun-92	351
Transition ends; 2nd freeze starts	01-Jul-92	371

Table II Pipe specifications

273 mm diameter steel pipe 7 mm wall thickness +/-12.3% rupture resistance 4.13 x 10^5 kPa grade B steel elastic limit 2.41 x10^5 kPa
Sand/silt transition (previous) experiment: 3 welded sections; 12 m centre, 3 m ends no exterior protective coating
Frozen transition (current) experiment: two 8 m welded sections
exterior protective coating 3.8 mm thick made from 3 layers of machine wrapped polyethylene (water resistant to 8600 kPa)

During the first freezing period of the current experiment, the behaviour of the soil and the pipe was dominated by frost heave on the initially unfrozen side of the experiment, and by thawing at the base and subsequent settlement of the pre-frozen side. The temperature in the pipe was lowered to about -8.5°C for the end of that freeze, halting thaw settlement beneath the pipe on the prefrozen side. Following this, pipe circulation temperature was increased to +5°C, while surface temperature was maintained at -0.75°C. This allowed thaw to occur around the pipe while otherwise maintaining freezing conditions in the ground, as an experiment in pipe relaxation. During the relaxation period, pipe stresses were reduced significantly as the thawing annulus of soil lost strength. The pipe lost much of its curvature, although it remained significantly tilted from its initial position.

On March 22 1992, pipe circulation was shut down and the insulating wall (described in the next section) separating the prefrozen and initially unfrozen sides of the experiment was closed (the wall had been partially reconstructed during the pipe relaxation period). The temperatures in the facility were subsequently maintained at +5°C on the initially unfrozen side (to initiate thaw), and at -5°C on the prefrozen side (to reestablish deeper frost). This phase of the experiment has been designated the transitional phase.

The second freezing cycle was initiated July 1 1992. During the second freeze cycle, pipe temperatures are being maintained at -6°C while surface air temperature is -4°C.

In addition to the execution of the experiment, work undertaken in this year of the experiment included preparation for a test to determine the soil's resistance to pipe uplift (brought about by differential frost heave). These preparations are discussed in a separate section of this report.

Background: installation of the experiment

The experiment was set up in 1990 in a controlled environment provided by an 8-m by 18-m hall with a soil-filled basin. The facility is located at the CNRS Centre de Geomorphologie, Caen,

Table III Instrumentation used in the experiment

Thermal regime:	- thermistor strings (in soil) - thermistors (on pipe surface) - thermistors (air temperature)
Hydrological regime:	- monitoring of water inputs - piezometer wells to monitor water table
Pressure measurements:	- EPC total earth pressure cells - modified Petur/RST total pressure cells - Glotzl total pressure cells
Soil movement/expansion:	- optical surface surveying - magnet heave measurement system - Bison soil strain gauges - hydrostatic profiler (for soil movement beneath pipe)
Pipe movement:	- optical survey of pipe survey rods
Pipe deformation:	- strain gauges
Pipe- soil interaction:	- "LVDT" longitudinal pipe-soil shear device - flexible steel strip soil shear device. - wooden disc vertical shear columns.

France. The basin was filled to a depth of 2.3 m with Caen silt, a frost susceptible soil (Table I provides a timetable for implementation and execution of the two freezing cycles of the frozen transition experiment). The soil was placed in lifts of approximately 300 mm, with an average dry bulk density of 1560 kg m^{-3}. Modifications (relative to the earlier sand-silt experiments) were made to allow soil to be placed to 0.63 m above the top of the basin, by extending an impermeable membrane to this height and by the placement of cribbing around the entrances to the cold room.

The frozen-unfrozen soil interface was established by the construction of a temporary insulated wall across the midpoint of the cold room from the soil surface to the ceiling, dividing the facility into two sections whose temperature could be controlled independently. This wall was constructed from honeycombed polystyrene blocks, originally developed as lightweight fill for embankments. After the wall was assembled, joints between blocks were filled with foam-in-place insulation, and plastic sheets hung

on the cold side to limit vapour loss. The ground in the cold ("permafrost") half of the room was then frozen from the surface downwards by circulating cold air above the soil surface for 237 days, with air temperatures ranging from -3°C to -18°C.

The pipe was not placed until after freezing had been underway for some time in the "prefrozen" or permafrost section. The pipe ditch was excavated once the frost line extended below 0.8 m. This was done with a backhoe in the unfrozen section. In the frozen material, slit trenches approximately 150 mm wide were first cut along the edges of the ditch, with the soil between then removed using a backhoe. The excavated material was placed on plastic sheets on the soil surface. The ditch was excavated to 0.8 m (0.2 m below the base of the pipe).

An instrumented, 16-m length of 273-mm-diameter pipeline was placed in the trench using a truck mounted crane. Specifications for the pipe used in the experiment (including differences from the pipe used in the sand-silt transition experiments) are given in Table II. Following pipe placement, the ditch was backfilled using different procedures for the frozen and unfrozen trench sections. In the cold section, frozen spoil material was placed in 150 mm lifts to which about 50 mm of water was added. In the warm section, the soil was mixed to 2-4% wetter than the Proctor optimum water content and placed in 80 mm lifts. The final water content in the ditch material was about 18%. By the commencement of the first freezing experiment, the prefrozen end of the ditch was frozen, and the frost depth in that section extended below the deepest temperature sensors (1.85 m below the surface). Extrapolations from thermistor cables indicate that the soil was frozen to depths ranging from 2 m (beneath the ditch spoil) to that of the base of the installed soil.

Prior to the start of the second freeze, three columns of frost susceptible soil were installed adjacent to the pipe (0.5 m from the pipe), in order to investigate the frost heave behaviour of different soil types: Two columns contain new soils (one of which is a mixture of Caen silt and clay); the third column contains Caen silt, to allow comparison of soil contained within a column to soil The columns are 300 mm in diameter and 1.2 m deep, and are separated from the surrounding Caen silt by polyethylene sheet material. Each is instrumented with 50 mm diameter bison cells (with thermistors attached by epoxy resin to each cell), and with magnet rings. Soil micromorphological studies will be undertaken on these soils at the conclusion of the freeze.

Pipe temperature and air circulation are controlled by a fan and compressor system mounted inside the cold room. The system incorporates a mechanism to reverse the direction of air flow in the pipe, since the difference in temperature between air entering and leaving the pipe is about 2C°. The direction of circulation is reversed every six hours to maintain a uniform daily average pipe temperature.

Instrumentation

The measurement requirements of a frost heave experiment are to monitor thermal and hydrological regimes, internal soil pressures, and soil movement and expansion. In the current experiment, measurements of pipe movement, pipe deformation and pipe/soil interaction are also required. Table III is a list of the devices and techniques used in the frozen transition experiment to fulfil these requirements. A detailed description of the devices and techniques is provided in the first report for the frozen transition experiment (Geotechnical Science Laboratories, 1991). Figure 1 shows a plan view of the experiment, with sensor locations keyed to Table IV.

Table IV Sensor locations

Device	Site Label	Distance Off Axis (m)	Axial Distance (m)
Bison Cells	B1	-2.00	-3.50
	B2	-2.00	-1.00
	B3	-2.00	1.00
	B4	-2.00	3.00
	B5	0.00	-3.25
	B6	0.00	-2.40
Magnet Rings	A1	-1.00	-4.50
	A2	-2.00	-3.00
	A3	-1.00	-3.00
	A4	-1.00	-2.00
	A5	-1.00	-1.10
Petur Total Pressure Cells	1P	0.00	1.00
	2P	0.00	-1.00
	3P	0.00	-4.50
	4P	0.00	-2.75
	5P	0.00	-6.00
Glotzl Cells	1G	0.00	-3.63
	2G	0.00	4.50
	3G	0.00	0.00
Earth Pressure Cells (EPC's)	EPC1	0.00	-4.50
	EPC14	0.00	4.50
Thermistor cable sites	T1	-0.25	-7.00
	T2	-0.25	-4.50
	T3	-1.00	-4.50
	T4	-2.00	-4.50
	T5	-3.00	-4.50
	T6	-0.25	-2.50
	T7	-0.25	-1.00
	T8	-1.00	-1.00
	T9	-3.00	-1.00
	T10	-0.25	1.00
	T11	-1.00	1.00
	T12	-3.00	1.00
	T13	-0.25	2.50
	T14	-0.25	4.50
	T15	-1.00	4.50
	T16	-2.00	4.50
	T17	-3.00	4.50
	T18	-0.25	7.00
Wood columns (horizontal shear)	C1	-0.30	-5.00
	C2	-0.60	-5.00
	C3	-1.00	-5.00
Piezometer wells	P1	2.00	-5.50
	P2	-2.00	-5.50
	P3	2.00	-0.50
	P4	-2.00	-0.50
	P5	2.00	5.50

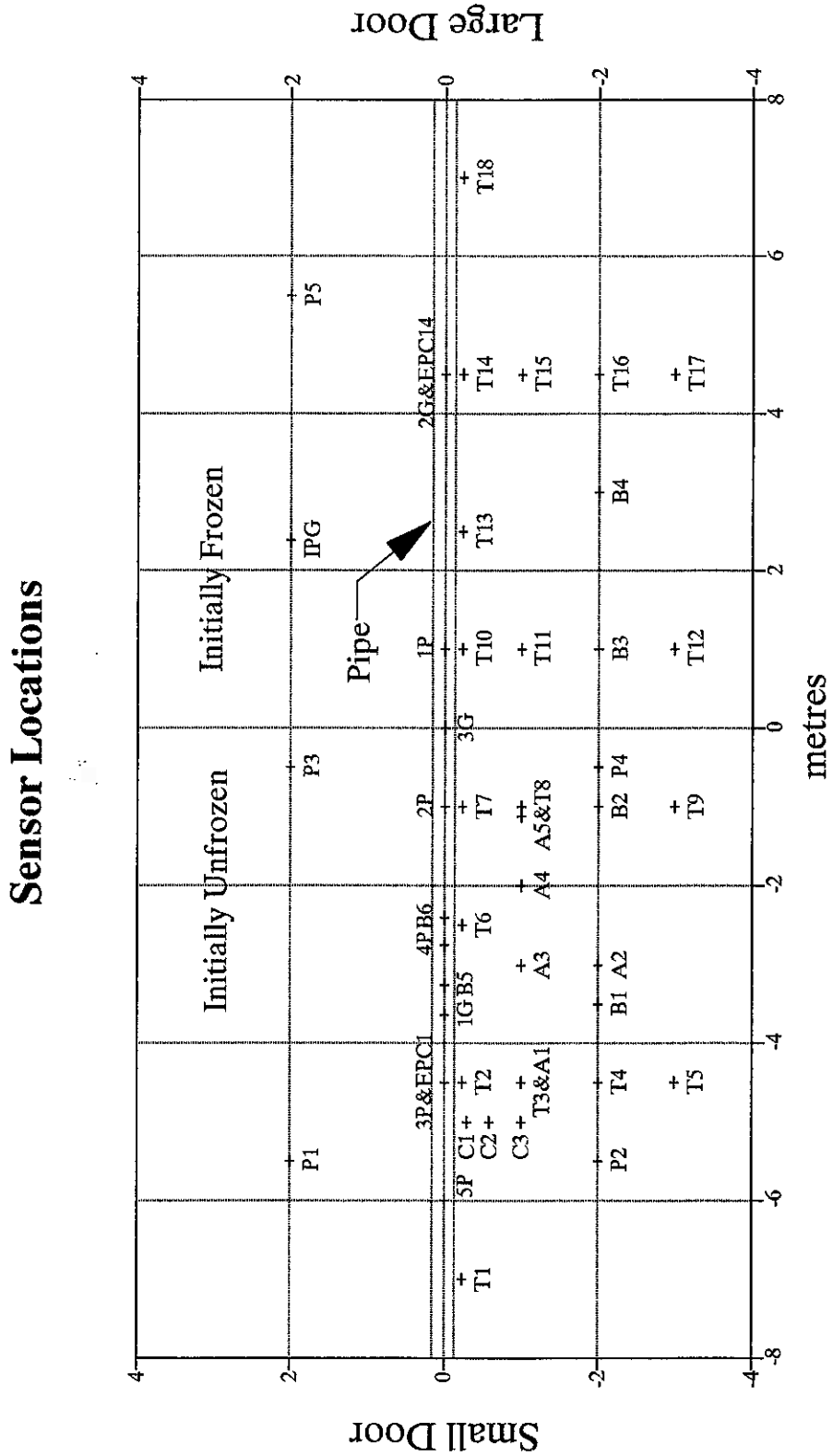


Figure 1 Plan of experiment, showing sensor locations. Refer to Table IV for key to symbols.

2 Results

Overall behaviour
Pipe and soil behaviour in the second freeze of the thermal interface experiment is dominated by much colder operating temperatures, to prevent thaw settlement in the prefrozen material (as experienced in the first freeze). Proximity to the pipe is less significant in determining the thermal regime of the soil than in previous freezes, producing relatively uniform heave over the soil surface transverse to the pipe axis.

Colder temperatures, while eliminating thaw settlement and producing more rapid frost penetration compared to the first freeze, have led to a condition in which the frost penetration on the initially unfrozen side rapidly approached that on the prefrozen side. As a result, there was little *differential* frost heave in the soil after the first 100 days of the second freeze.

The behaviour of the pipe (from optical survey and strain gauge data) suggest progressive yielding of the prefrozen soil above the pipe throughout the freeze cycle.

Hydrological Regime
The water table was maintained at approximately the same depth (m) below the soil surface throughout the second freeze. This required daily monitoring of the standing water level in 4 piezometer wells. (One additional well was continually frozen.) Water was supplied as necessary via pipes embedded in sand underlying the Caen silt. Figure 2 shows the recorded average water height from the wells over the course of the second freeze. Figure 3 shows the cumulative addition of water to the soil during the freeze. Ongoing frost heave continuously drew water to the freezing front as well as elevating the soil surface. Over the course of the freeze, water was added at an average rate of approximately 100 litres per day, equivalent to a depth of approximately 0.7 mm per day over the entire area of the experiment. However, not all of this water became segregation ice: the total change in volume of the soil during the experiment was approximately 12 m^3, as estimated from the optical survey data. This represents approximately half of the total water added. The discrepancy between the figures can be partially accounted for by evaporative loss through the soil surface, as well as possible leakage through the foundation.

Thermal regime
Figure 4 shows operating temperature conditions in the pipe and in the air circulating in the facility during the freeze. Figure 5 shows interior and exterior pipe temperatures. Interior (air circulation) temperatures are averaged while exterior (pipe surface) temperatures are instantaneous in Figure 5. Pipe interior temperatures are instantaneous values in Figure 4. Measurements are every 6 hours in both figures. Exterior surface attenuation of the interior temperature cycle is significantly greater in the initially

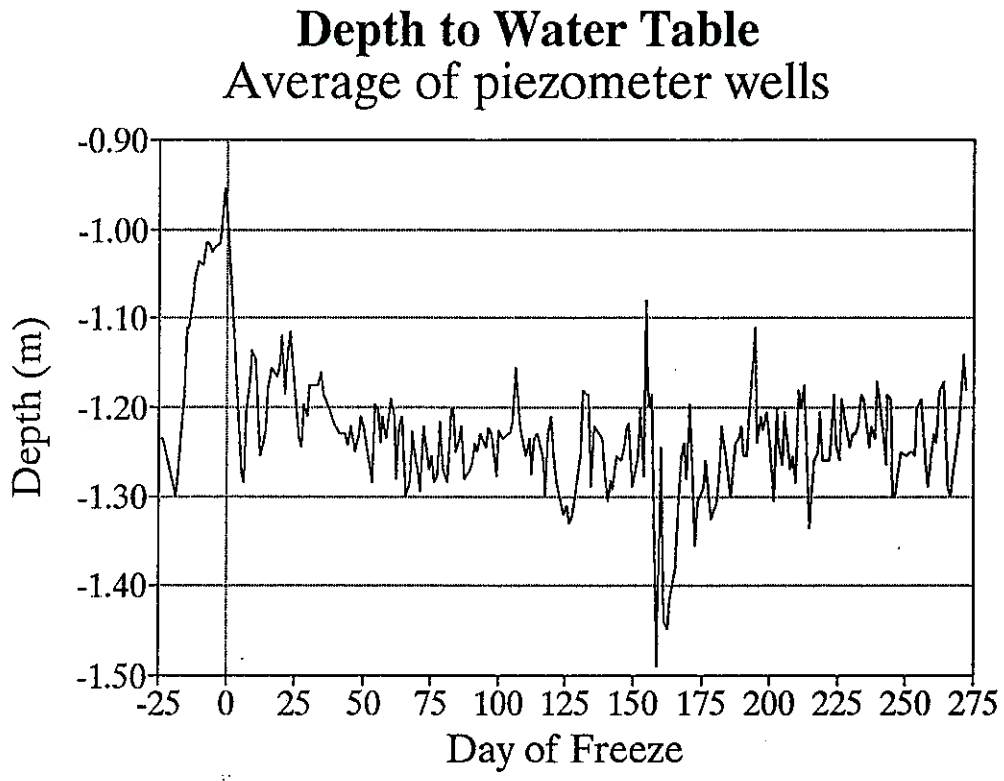


Figure 2

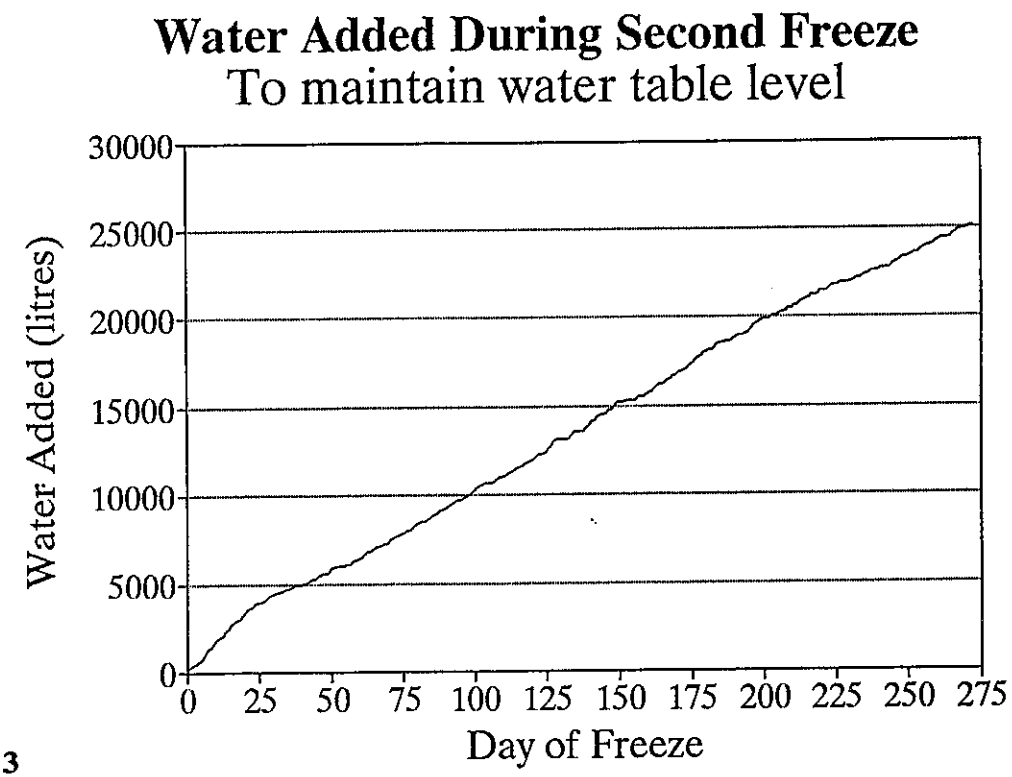


Figure 3

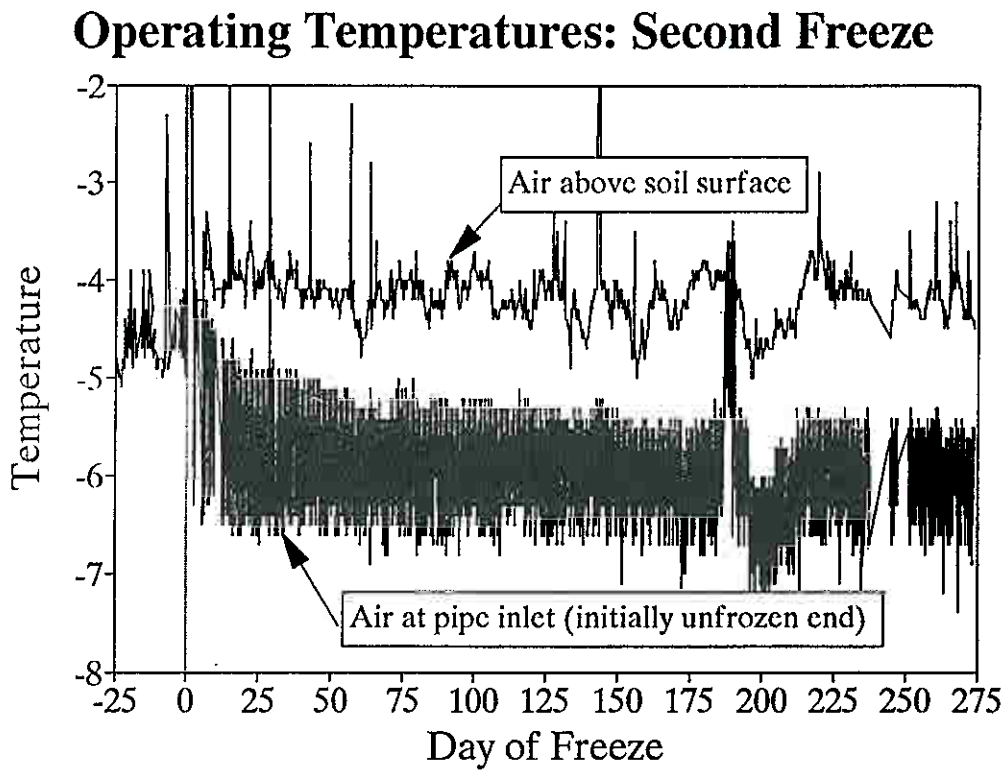


Figure 4

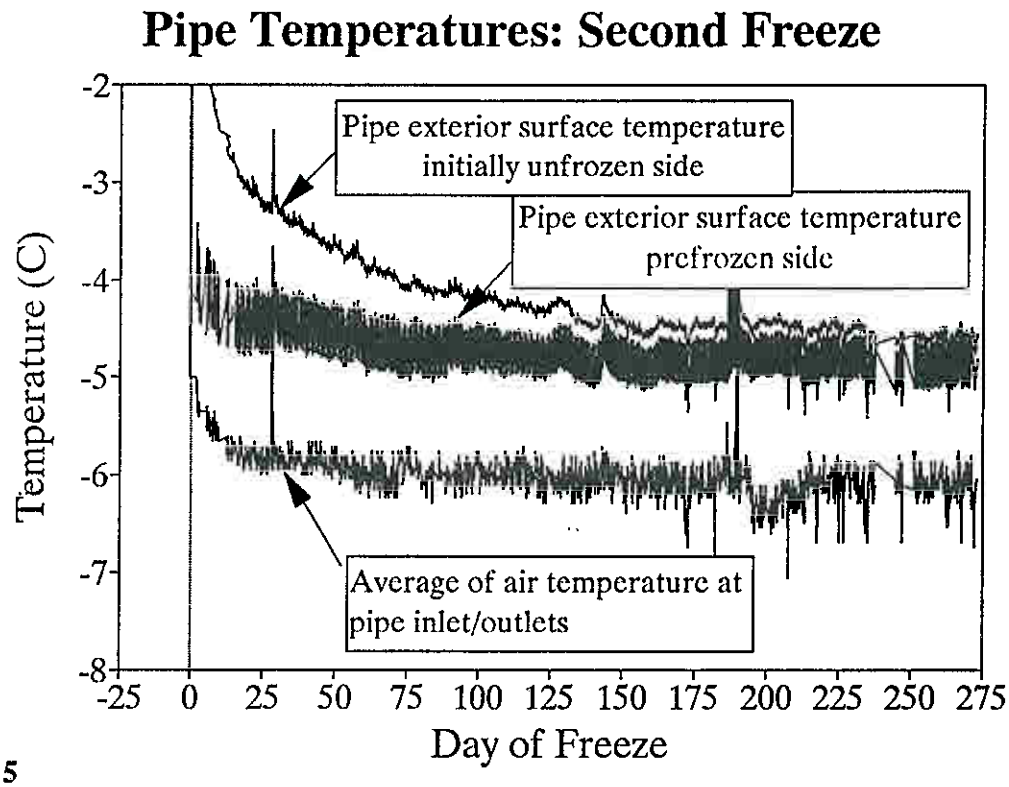


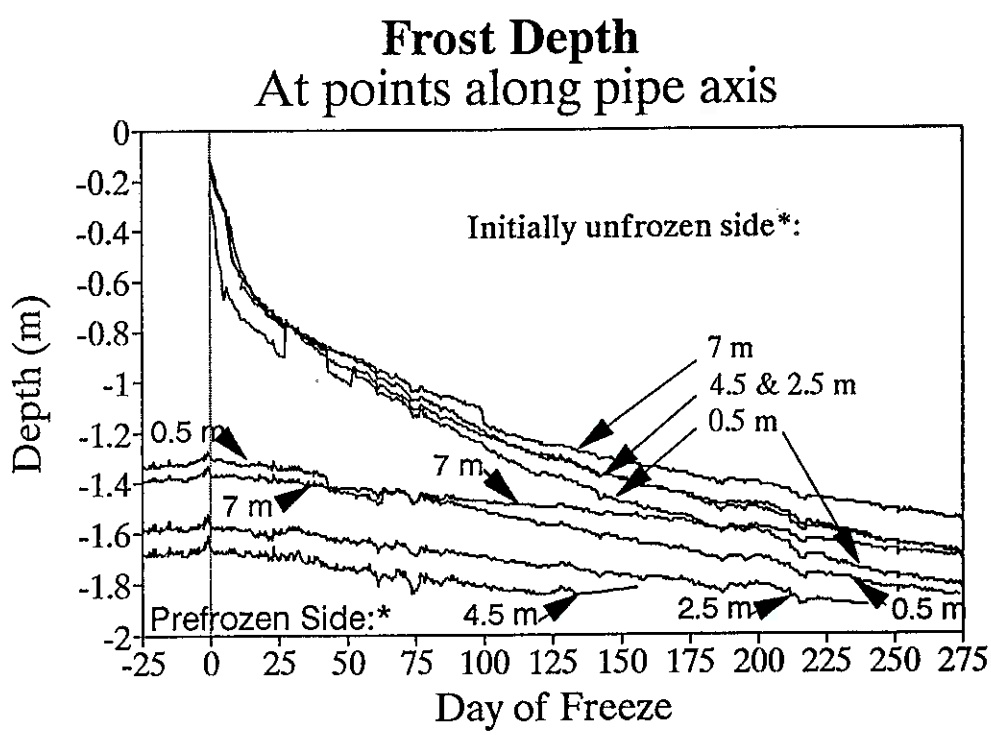
Figure 5

unfrozen material than in the prefrozen material. This may be due to the proximity of the freezing front in the initially unfrozen material, or simply to poorer contact with the pipe (thereby increasing contact resistance). Given that the effect does not change as freezing deepens with time, the latter explanation appears more likely.

Figure 6 shows frost line progression determined from thermistor strings adjacent to the pipe. Thermistors extend to a depth of 1.85 to 1.90 m (depending on the cable configuration): the 0°C isotherm could not be followed below this depth. The frost line penetrated quickly on the initially unfrozen side of the experiment, while on the prefrozen side the depth of the prefrozen material exhibited slower but continuing frost penetration. Over the course of the freeze, frost depth on the prefrozen side of the experiment increased by 0.2 to 0.4 m along the pipe axis.

Figure 7 shows the freezing front along the pipe axis for selected dates. By day 150, freezing on the initially unfrozen side near the transition extended below the freezing front in the prefrozen material where it was shallowest.

Figure 8 compares the depth of frost transverse to the pipe in the initially unfrozen material in the two freezes of the thermal transition experiment. Figure 9 shows the depth of frost at each of the thermistor cable cross sections on day 274 of the current freeze. This shows the more uniform frost depth both transverse to the pipe, as well as along the pipe axis



* numbers indicate distance from trasition; font indicates: prefrozen, init. unfrozen

Figure 6

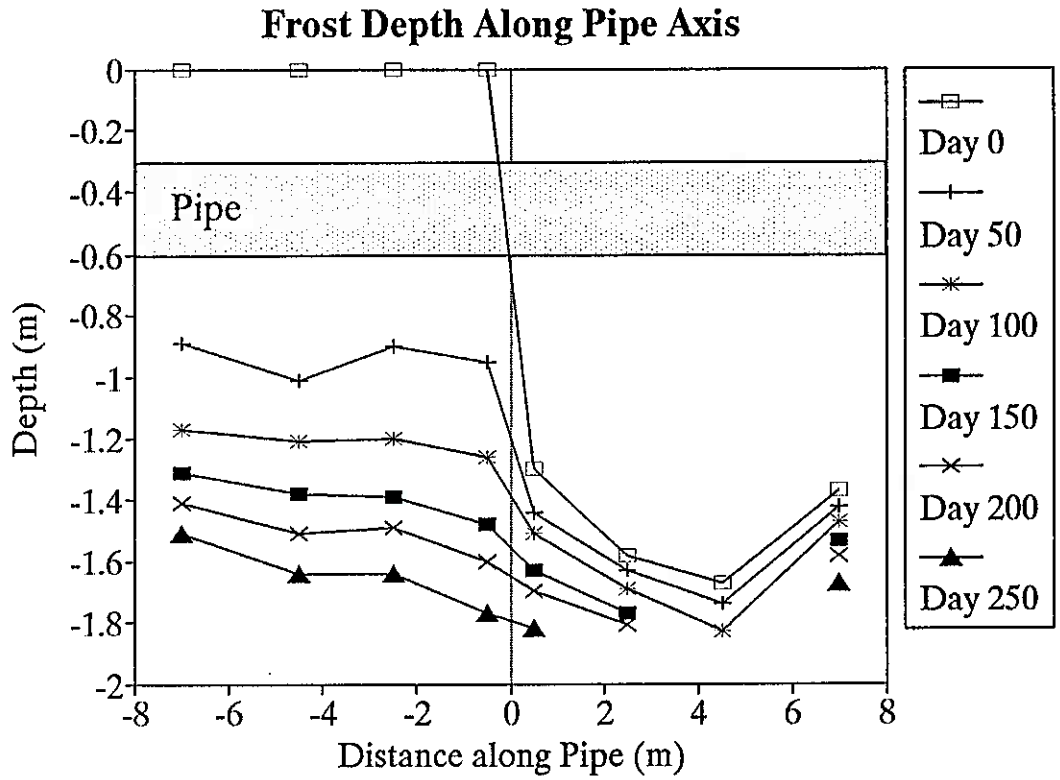


Figure 7

on either side of the frozen transition.

By day 274 of the second freeze, a sharp transition between the initially unfrozen and prefrozen material no longer existed.

Pressure measurements

All pressure sensors used in the experiment operate on the same principle: compression of an oil filled vessel forces displacement of a diaphragm within the sensor. Back-pressure is applied to the opposite side of the diaphragm to return it to its neutral position: measured back-pressure is thus equal to the pressure on the sensor.

The EPC and Glotzl cells are designed specifically for earth pressure measurements: both consist of flat steel plates welded at the periphery, with oil in between. The Petur cells are "general purpose piezometers", modified to measure total pressure. All pressure transducers are read using the same measurement instrument, designed originally for the Glotzl cells.

Some pressure sensors behave inconsistently or appear to have failed during the experiment (eg 1.43 m deep sensor, Figure 17). Such behaviour may be due to separation of the sensing surface from the soil.

All of the pressure sensors used in the thermal transition experiment are aligned along the pipe axis: this makes it difficult to interpret measured pressures as being

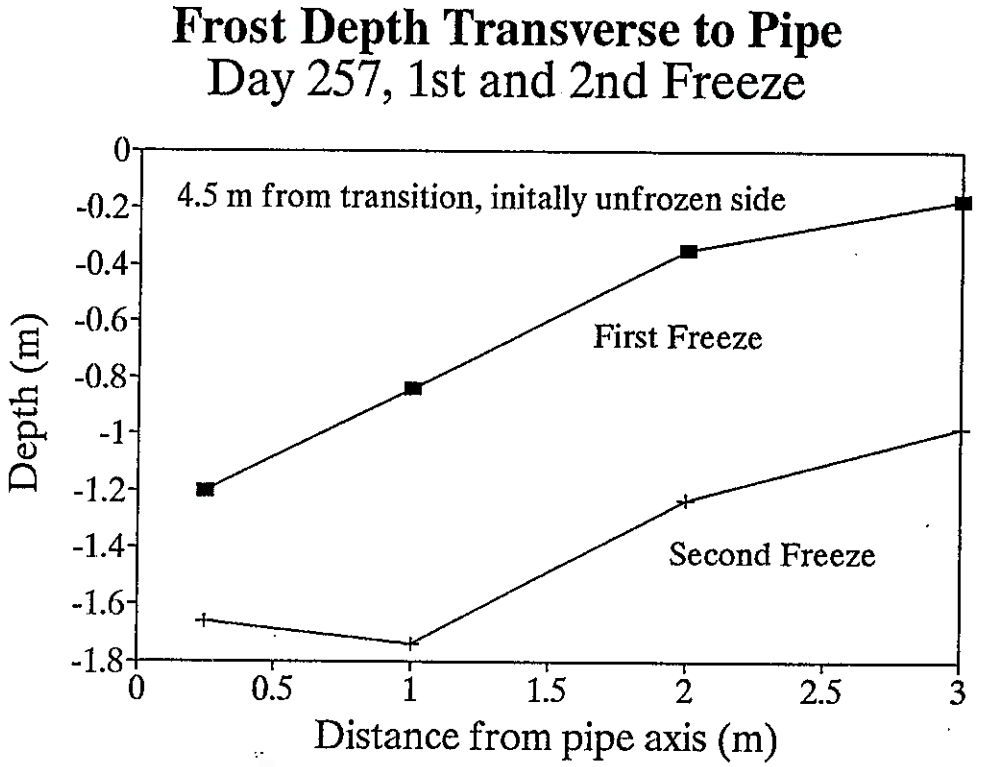


Figure 8

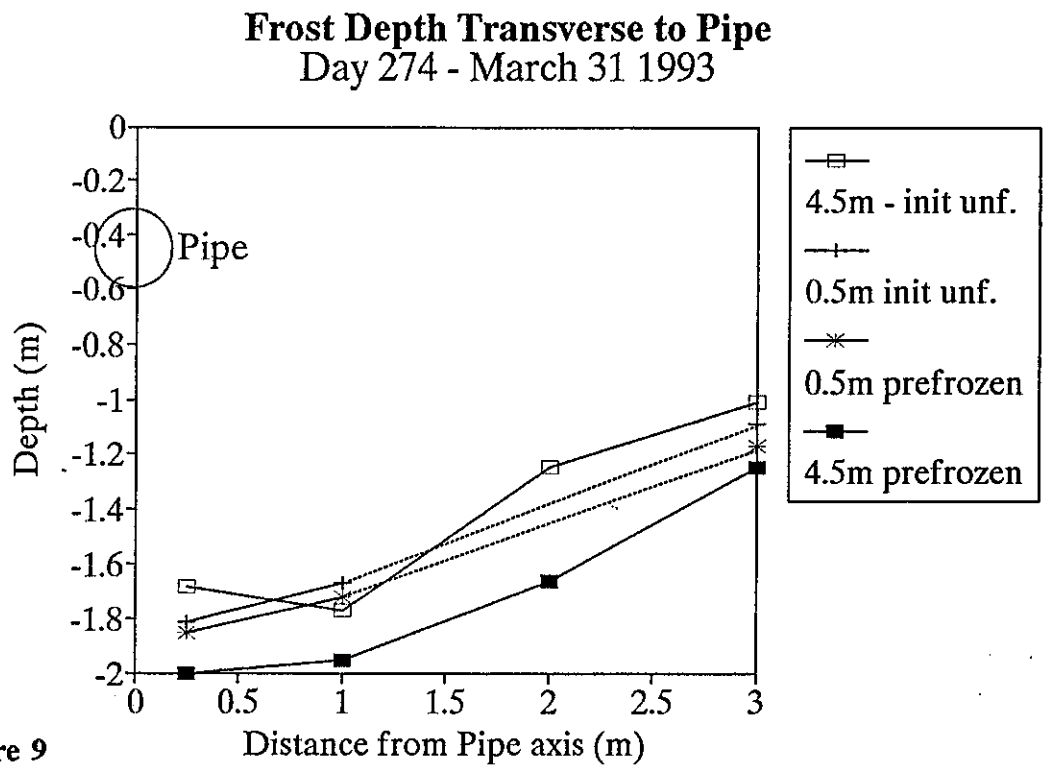


Figure 9

due to thermally induced soil pressures or pipe related mechanical pressures.

Earth Pressure Cells (EPCs)
The Roctest EPC-6 is designed to measure total pressure acting on a plane surface within the soil or at soil boundaries. Twelve EPC's are installed on seating plates attached to the pipe: six on top in the prefrozen section and six on the bottom in the unfrozen section, at 0, 0.5, 1.0, 1.5, 2.5, and 3.5 m from the transition (note there are 2 EPC's at the transition). Two additional EPCs are buried at 150 mm depth in the soil above the pipe: these are on the prefrozen and initially unfrozen sides of the experiment, 4.5 m from the transition. Results for these transducers are shown in Figures 10 to 12.

Measurements taken with the EPCs attached to the pipe indicate that the cells are probably not in good contact with the soil; cell pressures hover near their initial values (Figure 11). This is similar to their behaviour in the first freeze, when only one cell experienced a large pressure increase as the freeze progressed. In addition to contact problems which may be expected with any rigid pressure sensor buried in freezing/frozen soil, the differential heaving of the pipe could result in localized arching of the pipe, thereby separating the sensors from the soil.

Petur cells
Petur (RST Instruments) model P-100 piezometers are designed to measure pore water pressure. As delivered they

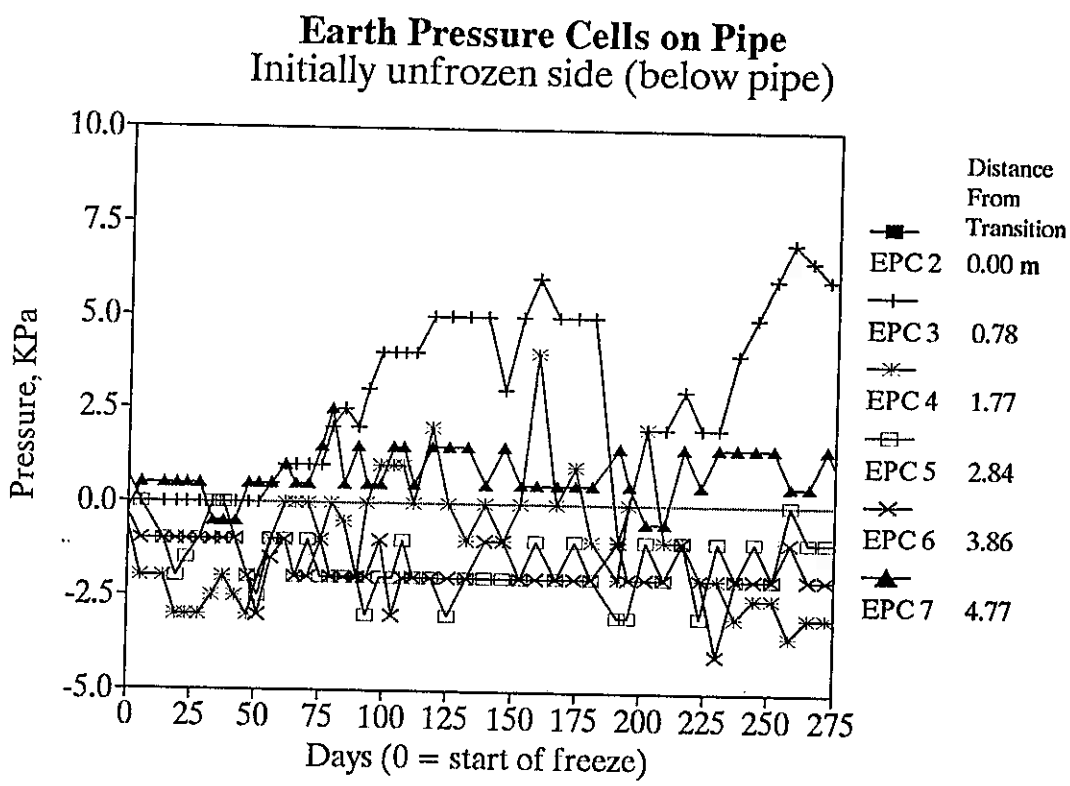


Figure 10

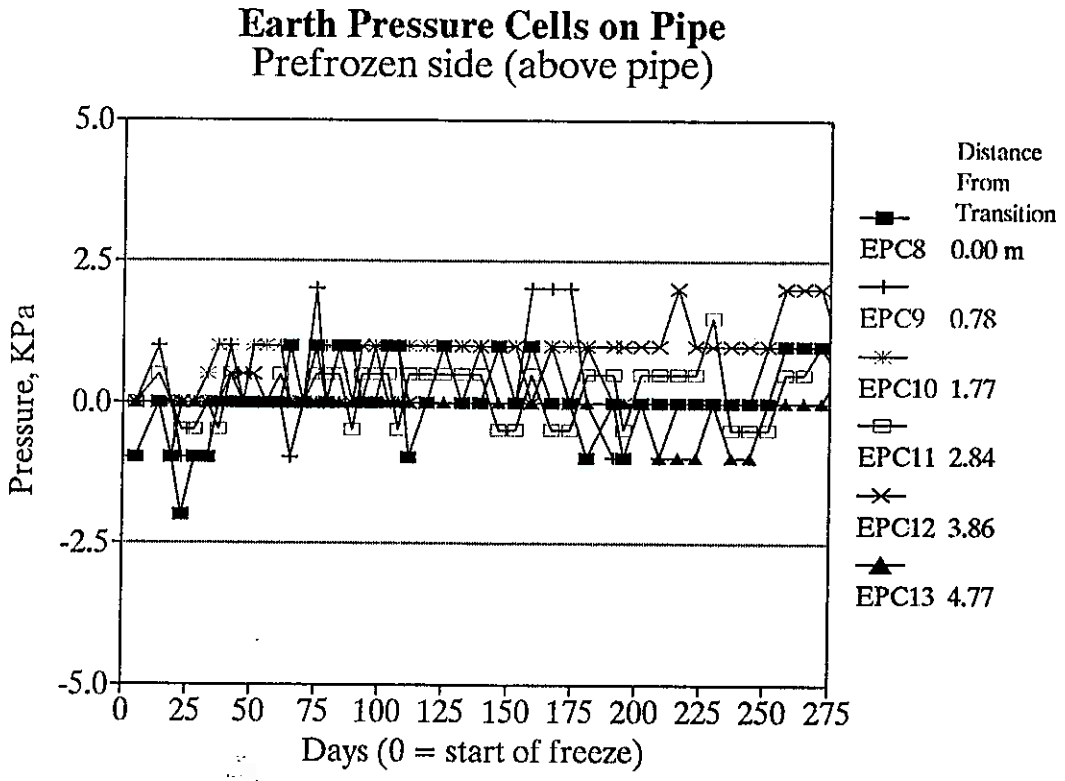


Figure 11

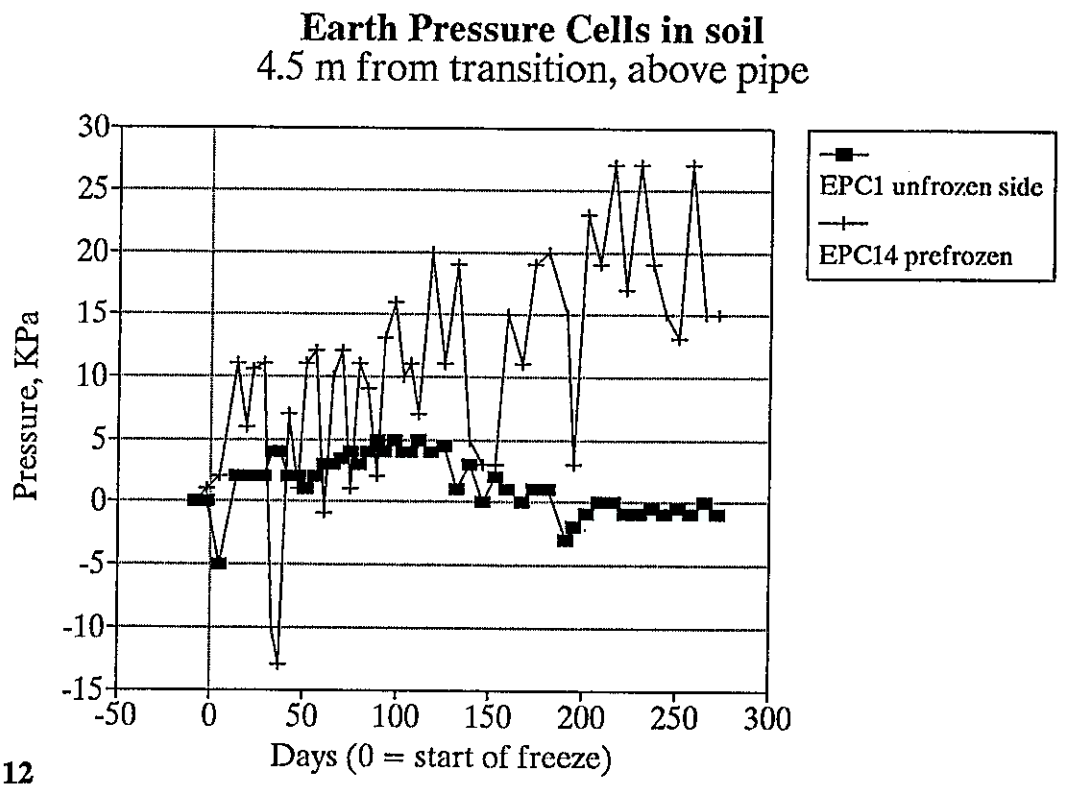


Figure 12

are small diameter cylindrical devices (16 mm O.D. x 63 mm long), with a non-metallic filter at one end and air lines to the readout device at the other. To measure total pressure within the soil, an oil filled latex rubber bulb was placed over the filtered end, and secured using a hose clamp, taking care to exclude air from the bulb. There are five arrays of five petur cells each, all installed below the pipe, along the axis. The readings for these are shown in Figures 13 to 17, where the values shown represent the change from an initial reading obtained prior to the initiation of freezing.

Behaviour of the Petur cells was similar in both the first and current freezing periods. On the initially unfrozen side of the experiment, the cells respond to the passage of the frost line with an increased pressure reading, which continues to increase at a declining rate until the onset of thawing. The peak pressure measured at each array declines with distance from the transition. (In the array nearest the transition on the initially unfrozen side, the cells which would be expected to show the highest pressures failed before reaching a peak value.)

The deepest sensors (1.63 m below the surface) in the arrays show declining pressure over the course of the freeze. Those farthest from the transition register the greatest decline. In the current freeze, the Petur array in the prefrozen material had the only deep sensor which maintained its initial pressure reading throughout the freeze.

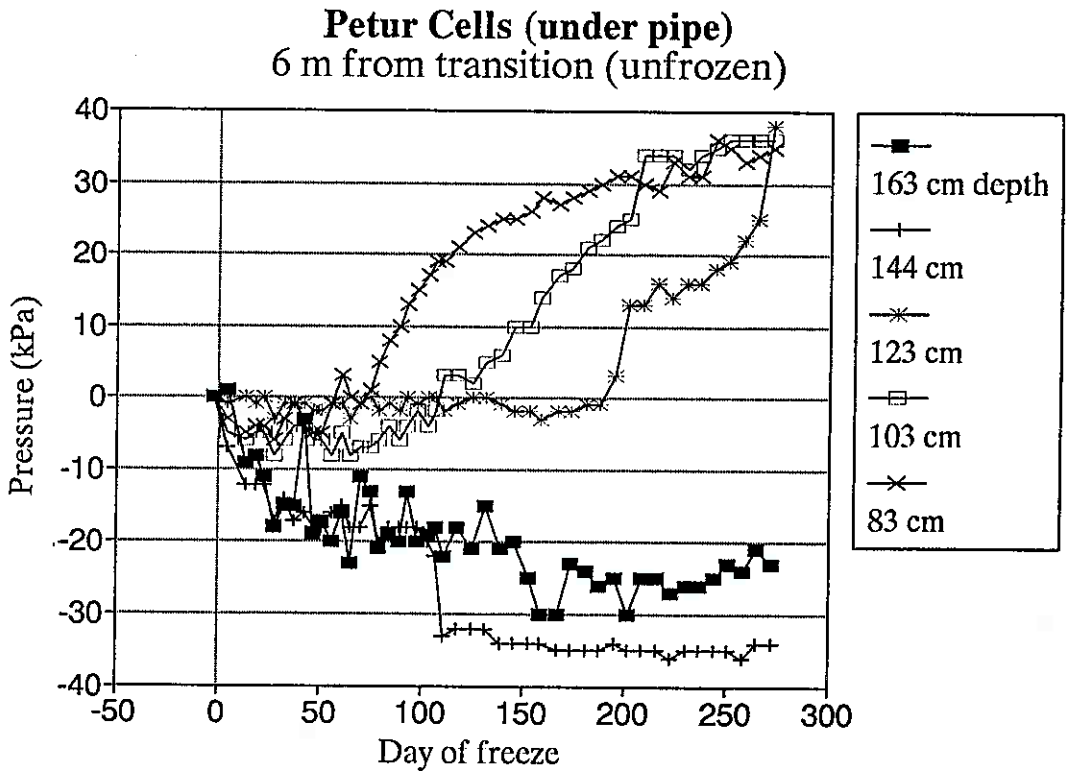


Figure 13

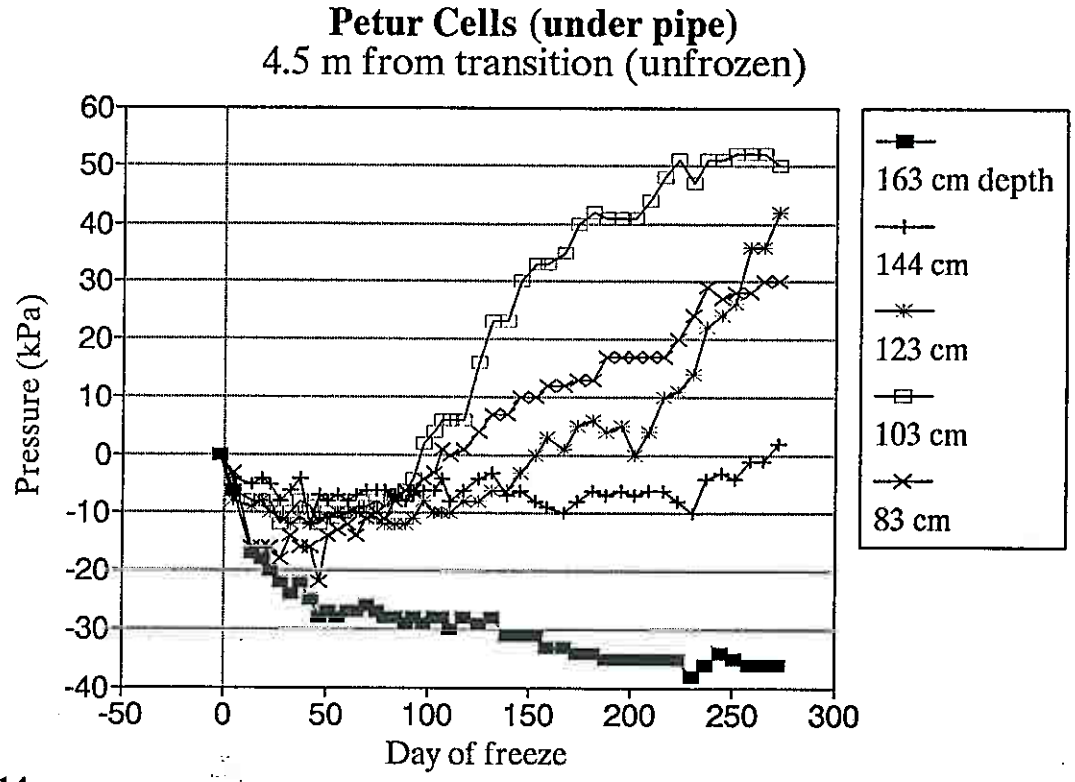


Figure 14

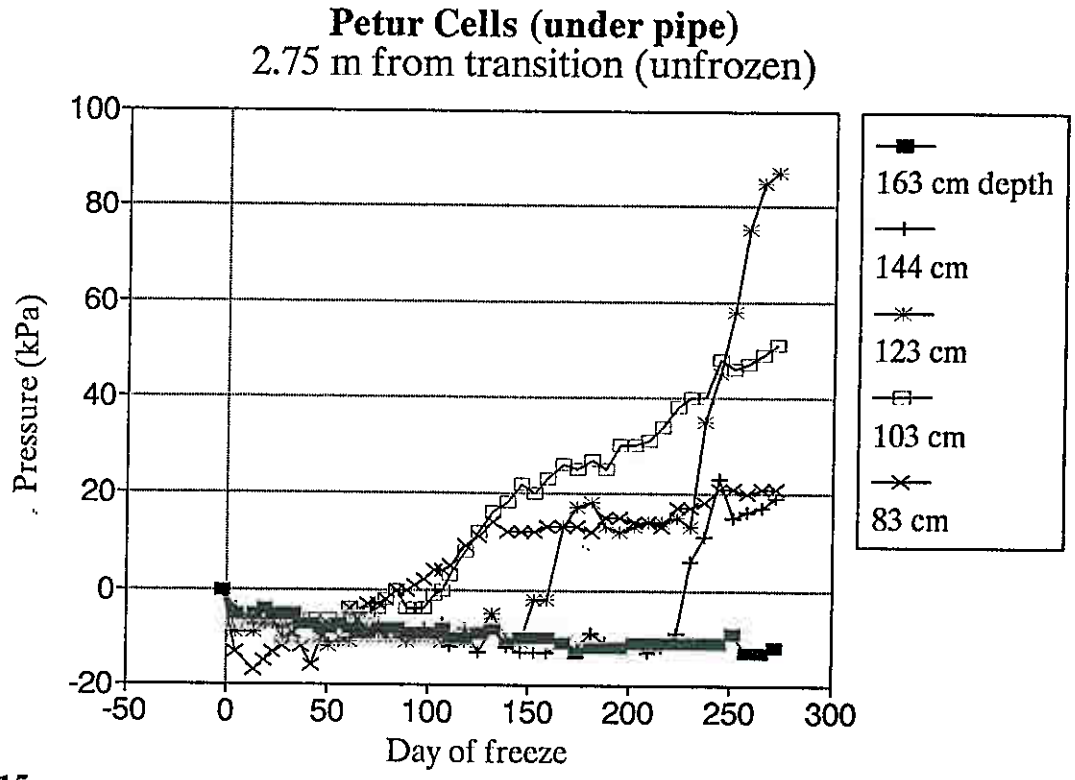


Figure 15

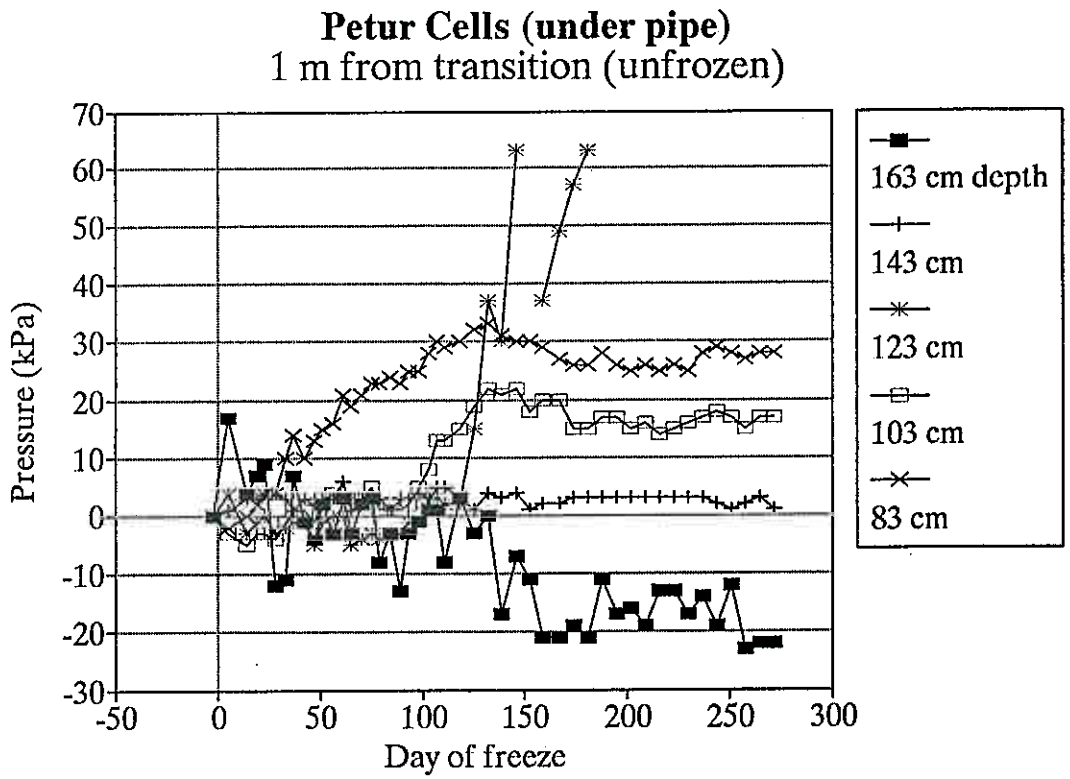


Figure 16

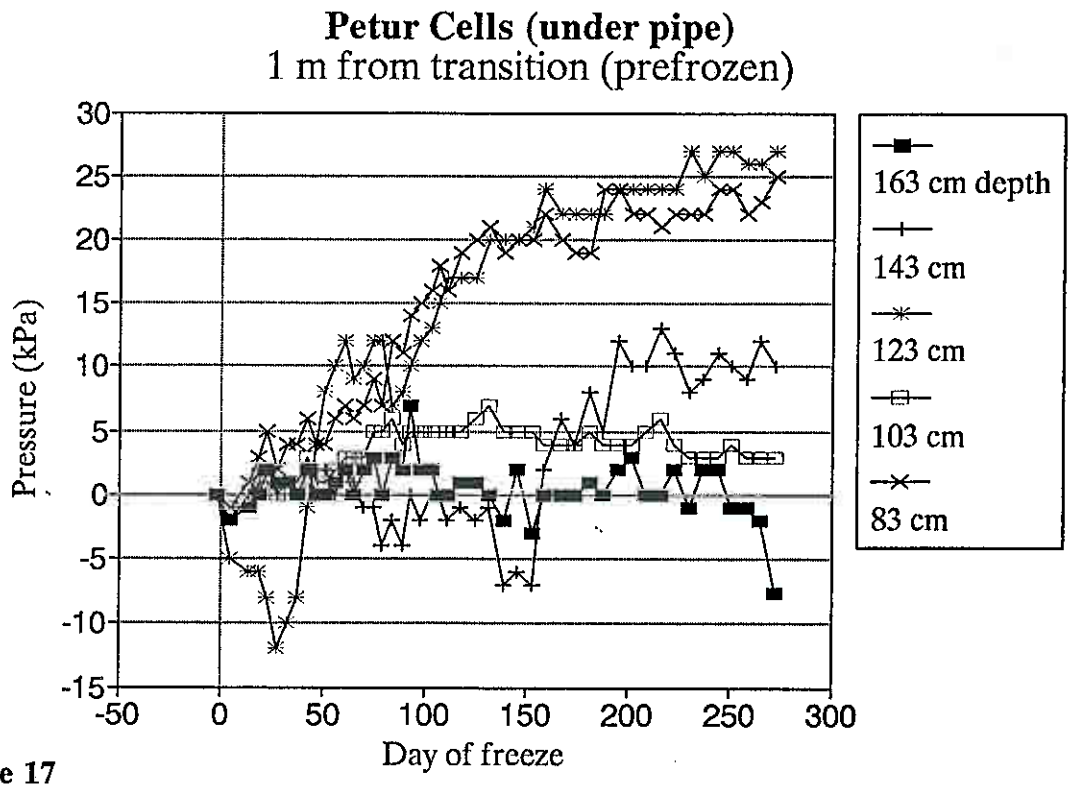


Figure 17

The depth of these sensors is approximately the limit of frost penetration along the pipe axis: the depth indicated is the depth at which the sensors were initially installed, while freezing depths indicated in the section above represent the depth below a heaving surface.

Glotzl cells

Figures 18 to 20 show results from the three Glotzl cell arrays, all of which are buried beneath the pipe. On the initially unfrozen side of the experiment (Figure 18), behaviour is broadly similar to that of the adjacent Petur cell arrays (Figures 14 and 15).

On the prefrozen side (Figure 19) the cells react to t he onset of the experiment rather than to the passage of the freezing front, since they were frozen into the soil prior to the initiation of the freeze. In the first freeze, the Glotzl cell arrays in the unfrozen material and at the transition both show a rapid increase in pressure with the onset of colder temperatures for the end of that freeze. This temperature sensitivity in the cells, resulting from differences in the thermal expansion coefficients of oil within the cell and the steel of the cell walls, is probably responsible for the behaviour of the Glotzl cells on the prefrozen side of the experiment in the current freeze.

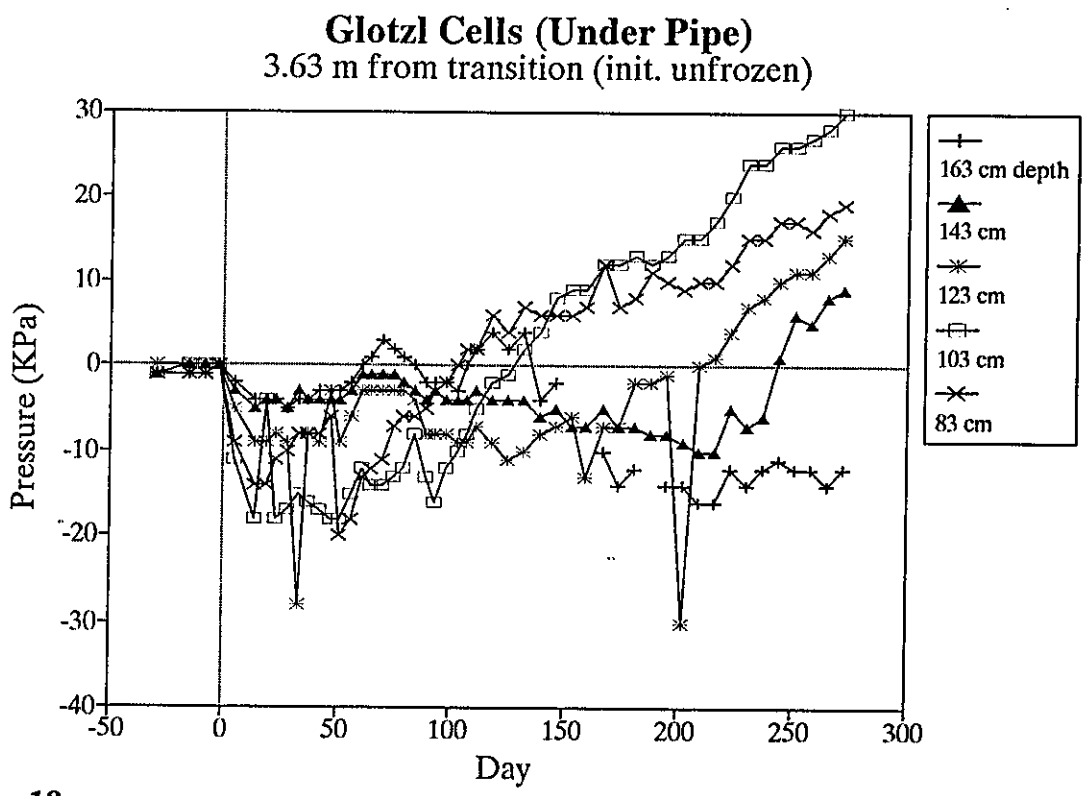


Figure 18

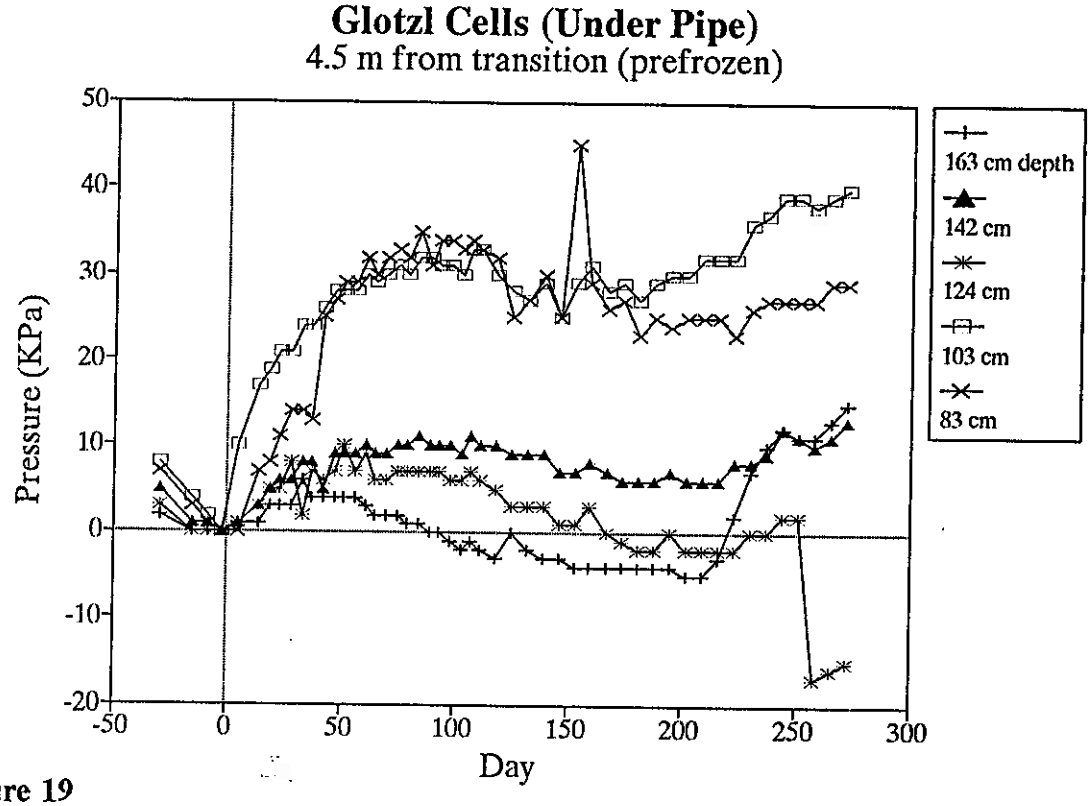


Figure 19

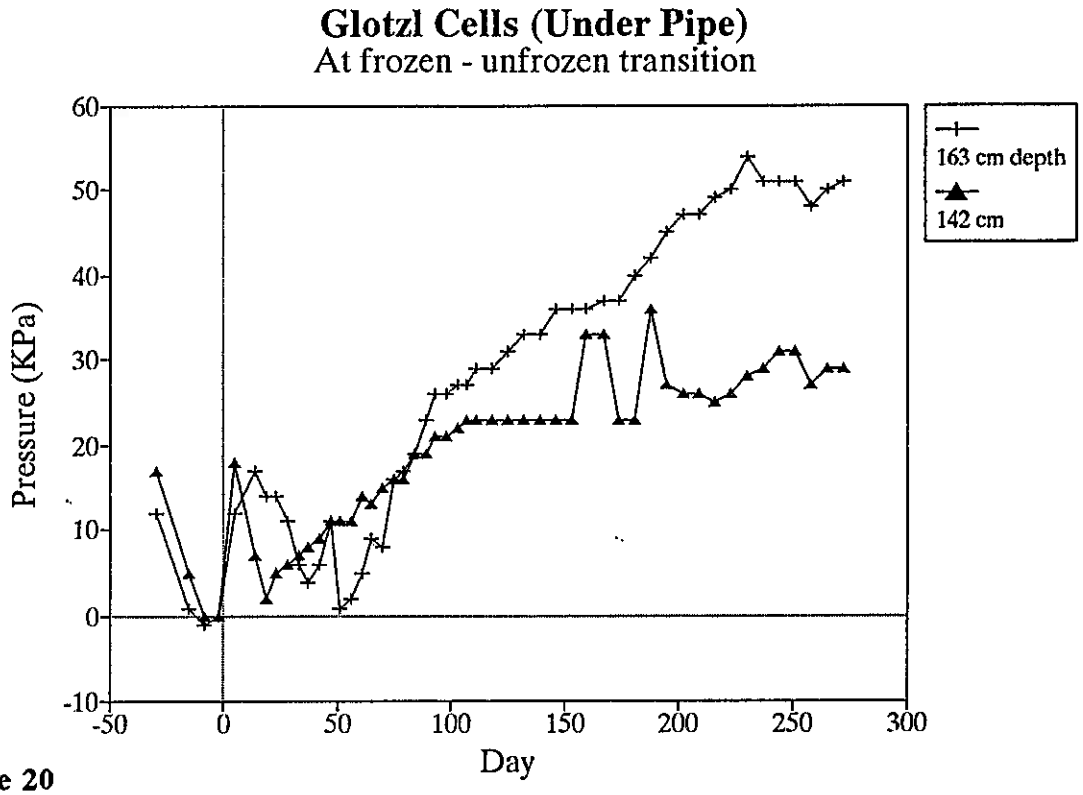


Figure 20

Soil Movement and Expansion

Bison cells

Bison soil strain gauges (Bison "cells") consist of resin covered discs containing induction coils. The cells are buried co-axially, at spacings of 1 to 4 times their diameter. The measurement device sends a sinusoidal signal through one cell, which is received by a second cell. The ratio of emitted to received amplitudes is calibrated to cell spacing. A series of cells arranged in an array permits monitoring of soil strain over several depths: cells are used alternately as emitters and receivers as measurements are taken.

Figures 21 to 26 reveal the progressive passage of the freezing front past successive cells at each of the Bison cell sites. The rate of frost heave (i.e. the slope of the displacement versus time relationship) declines with time, as the frost penetration rate declines with depth.

Thermistors were attached to Bison cells prior to installation in the soil. This combination of movement and temperature sensors allows monitoring of the thermal condition of the soil at the same location where frost heave is measured. Figures 27 to 35 shows the same soil expansion data as in Figures 21 to 26 above, but plotted against Bison cell temperature. In Figures 27 to 30, expansion is plotted against the temperature of the colder cell of the pair (that is, the cell which undergoes were incomplete, and are not fully represented in these figures.) Data for all cells suggest that freezing is initiated at approximately -0.2°C. Figures 31 to 35 show expansion plotted against the temperature of the warm Bison cell, and shows expansion begins to decline at a temperature near -0.3°C, and has diminished significantly by -0.5°C. Temperature gradients measured across the Bison cells in this freeze vary from 1 to 10 $C°m^{-1}$. With a temperature range of 0.3C° over which frost heave processes are most active, these gradients imply a zone of ice segregation from 30 to 300 mm in width. These gradients are much steeper than in the first freeze, due to the colder pipe and ground surface conditions.

Figures 36 to 41 plot the frost heave rate determined from the Bison cell measurements against the temperature gradient measured across the zone experiencing heave. The points plotted include only those where the temperature of the cell on the warm side was above -0.4°C *and* the temperature of the cell on the cold side was below -0.2°C: this limits the measurements to those in which the zone of primary frost heave is entirely within a single pair of Bison cells. The data are plotted with identical axes, to allow comparison of the results for different sites. While the data for all sites fall roughly along the same line, only sites 5 and 6 (directly beneath the pipe) experienced a sufficient range of conditions for a clear pattern to emerge from the scatter in the results.

Figure 42 shows the data for sites 5 and 6 together. A linear relationship between the temperature gradient and the frost heave rate is apparent, with scatter increasing at larger gradients. The two points significantly above the linear relationship are the initial measurements

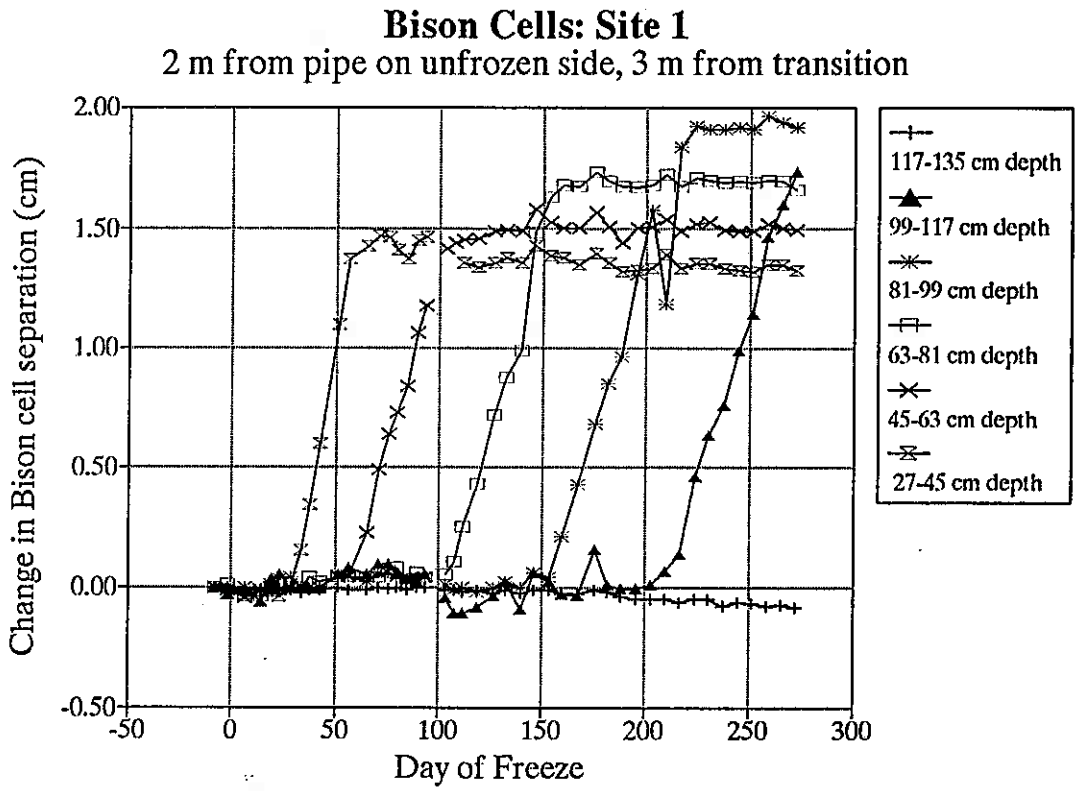
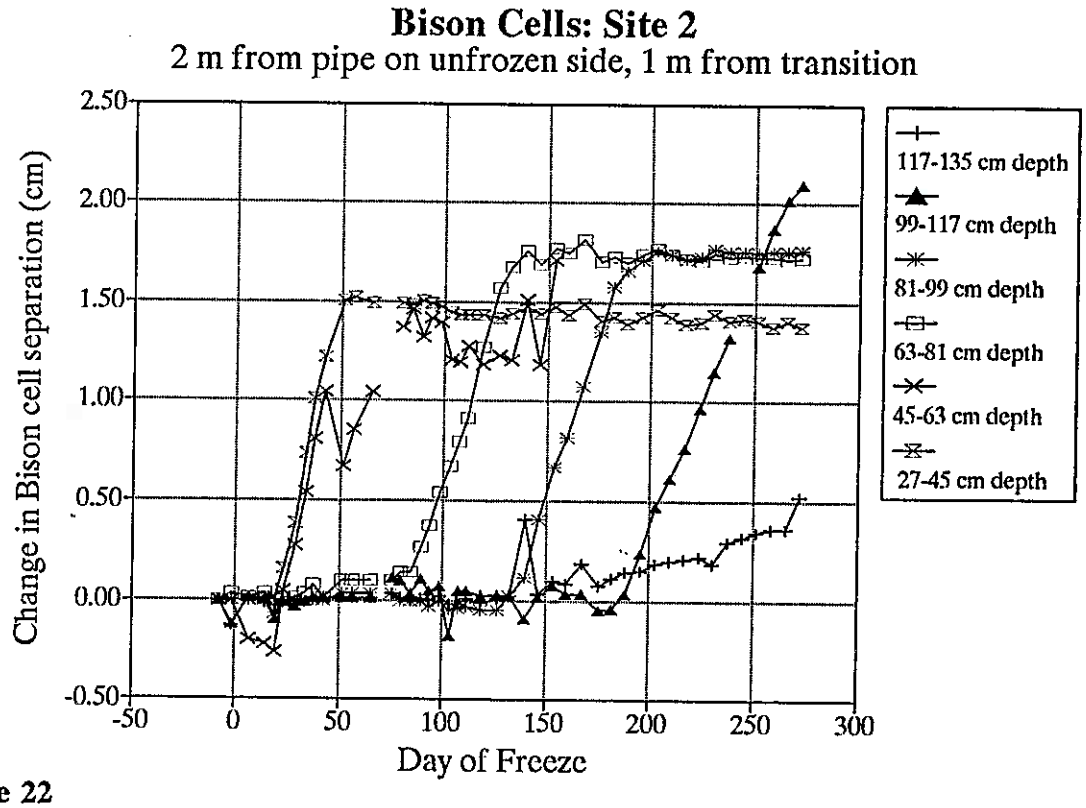


Figure 21



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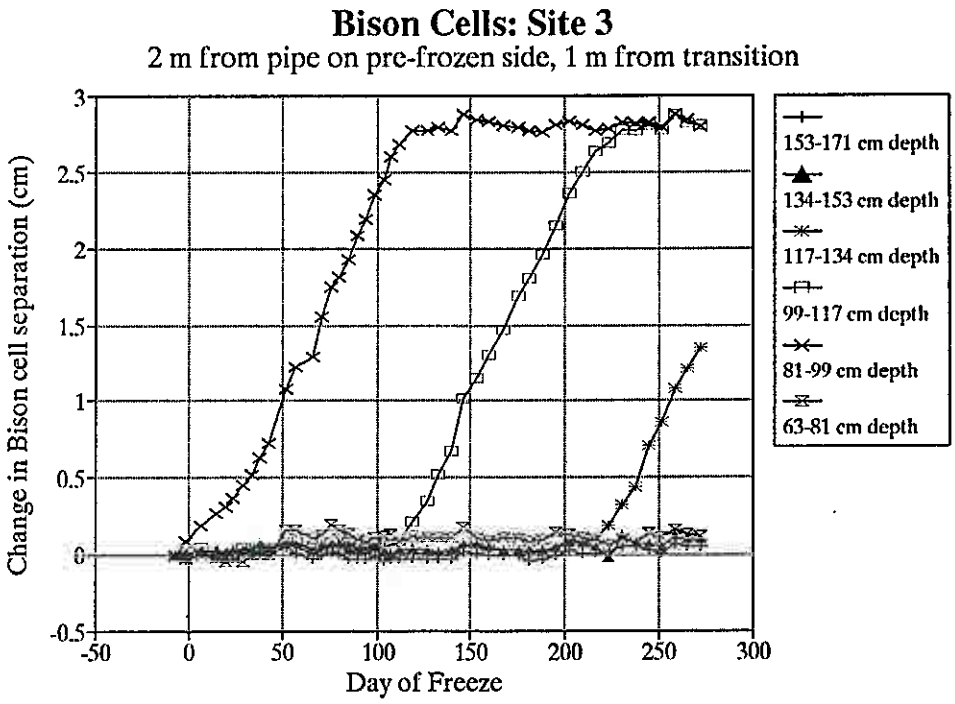

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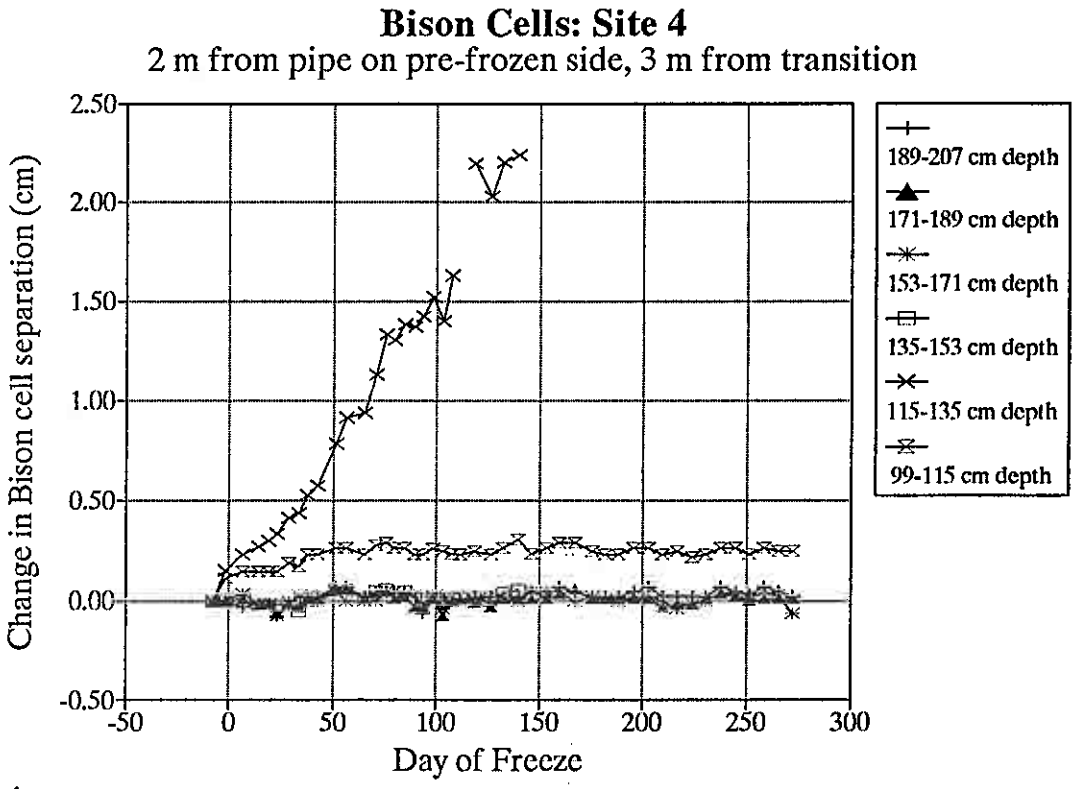


Figure 24

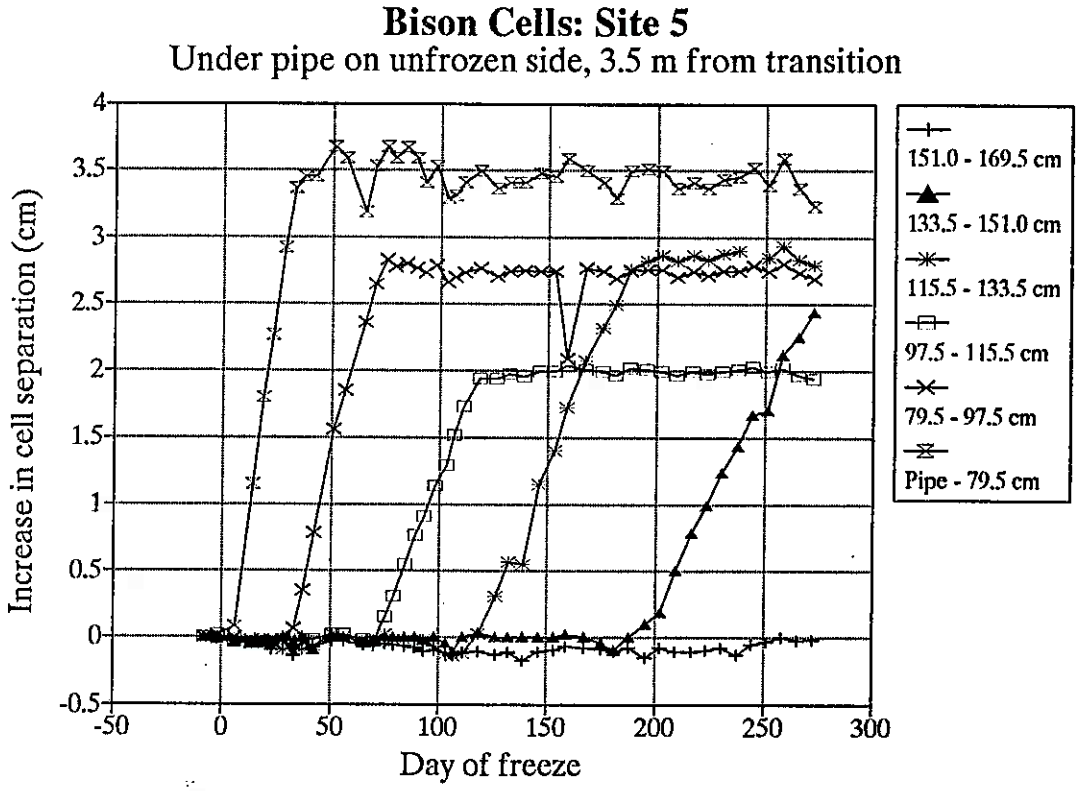


Figure 25

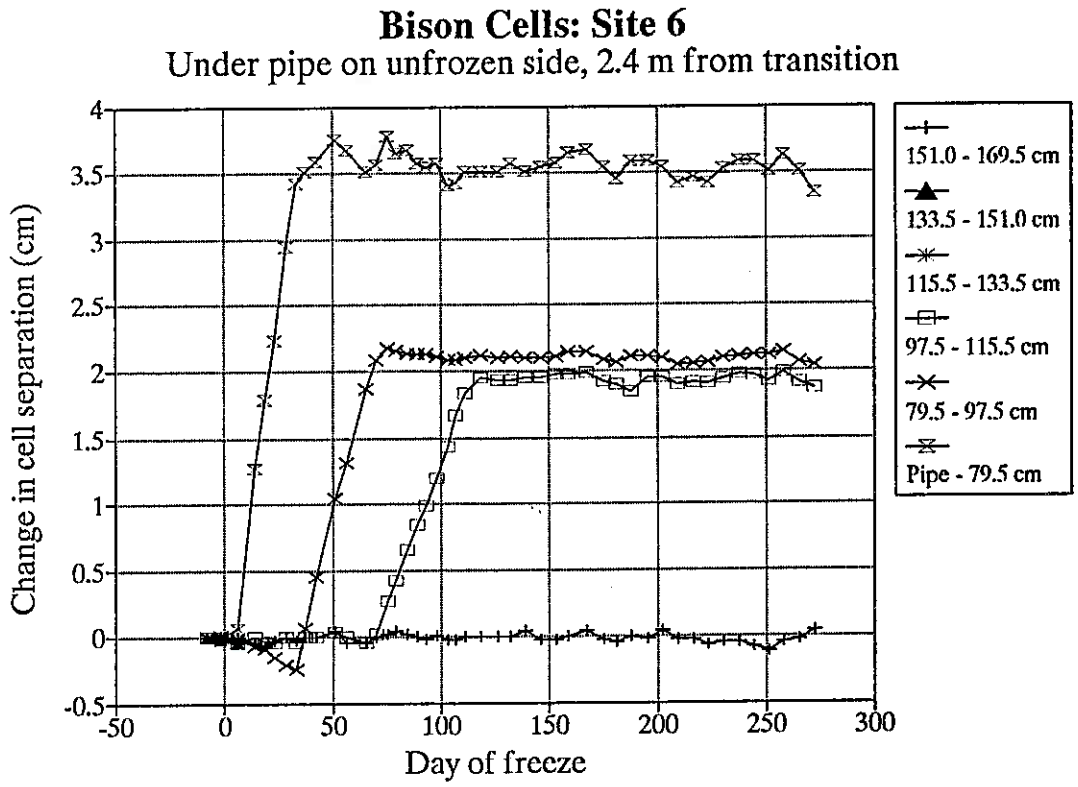


Figure 26

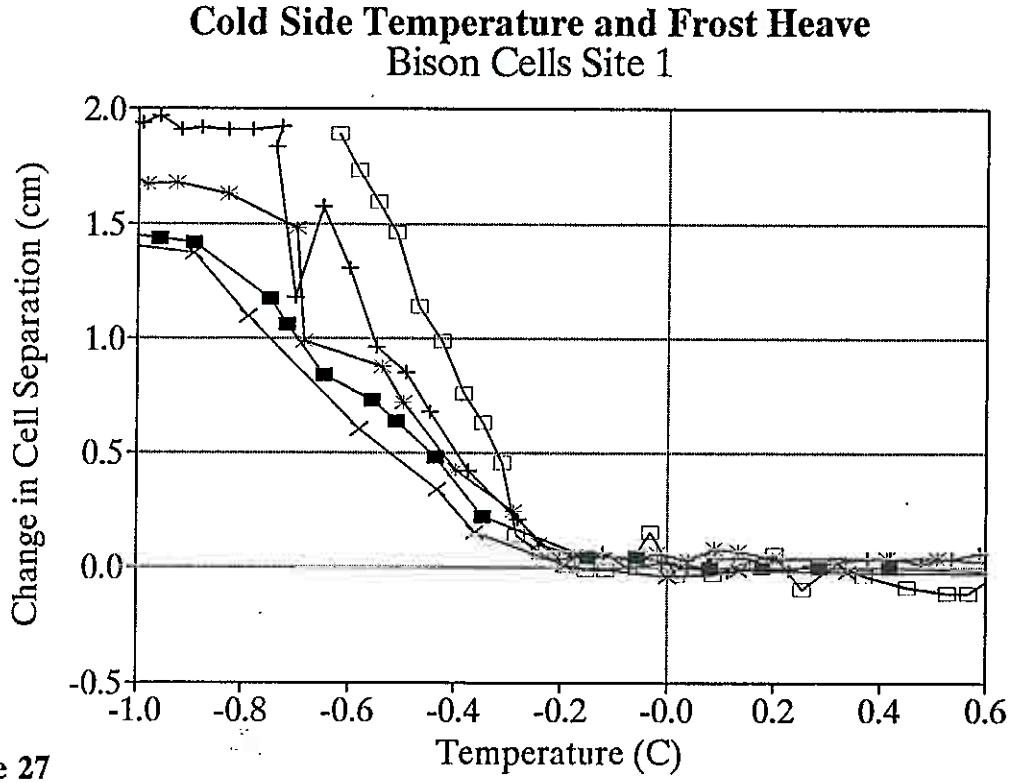
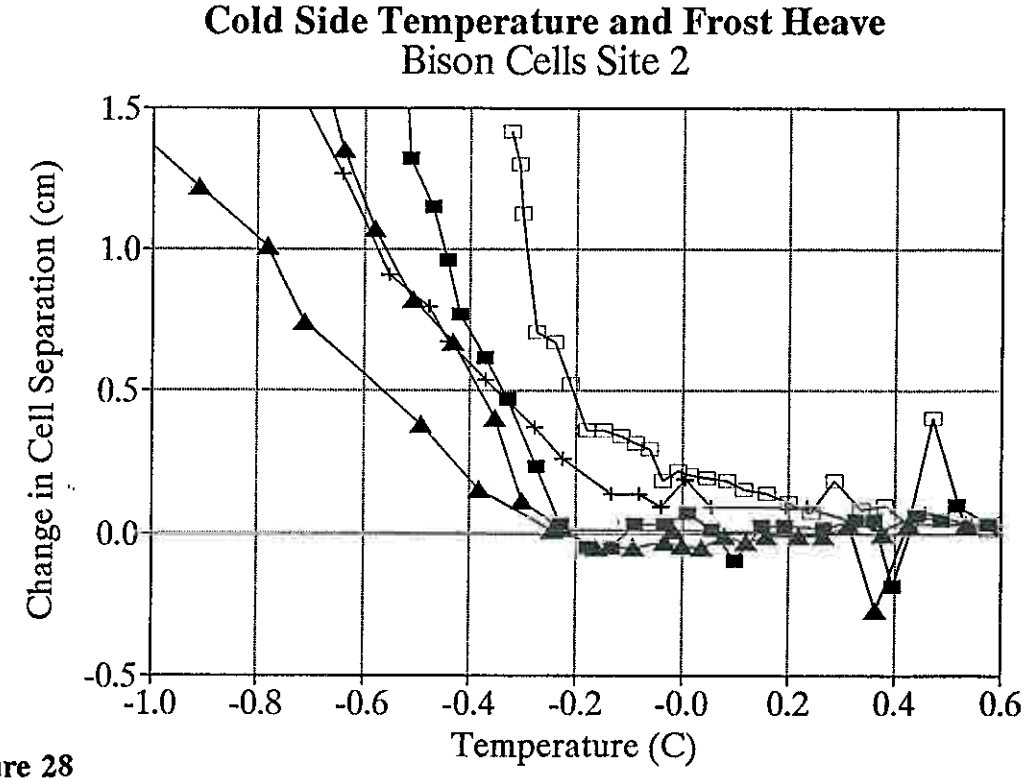


Figure 27



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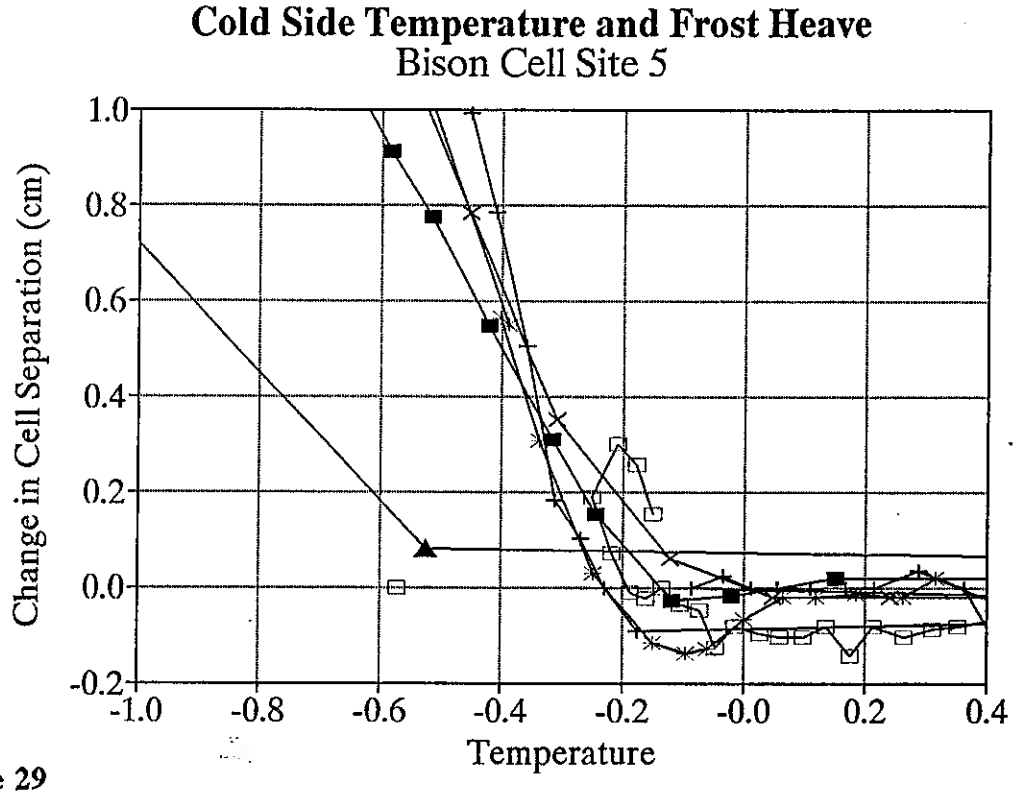

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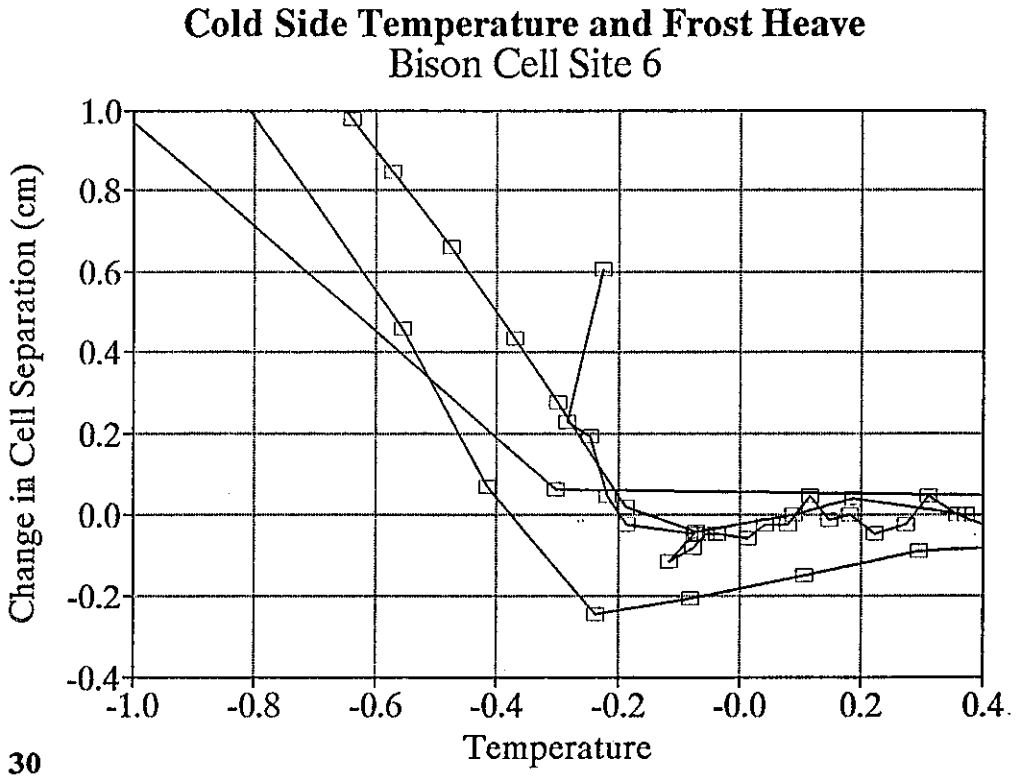


Figure 30

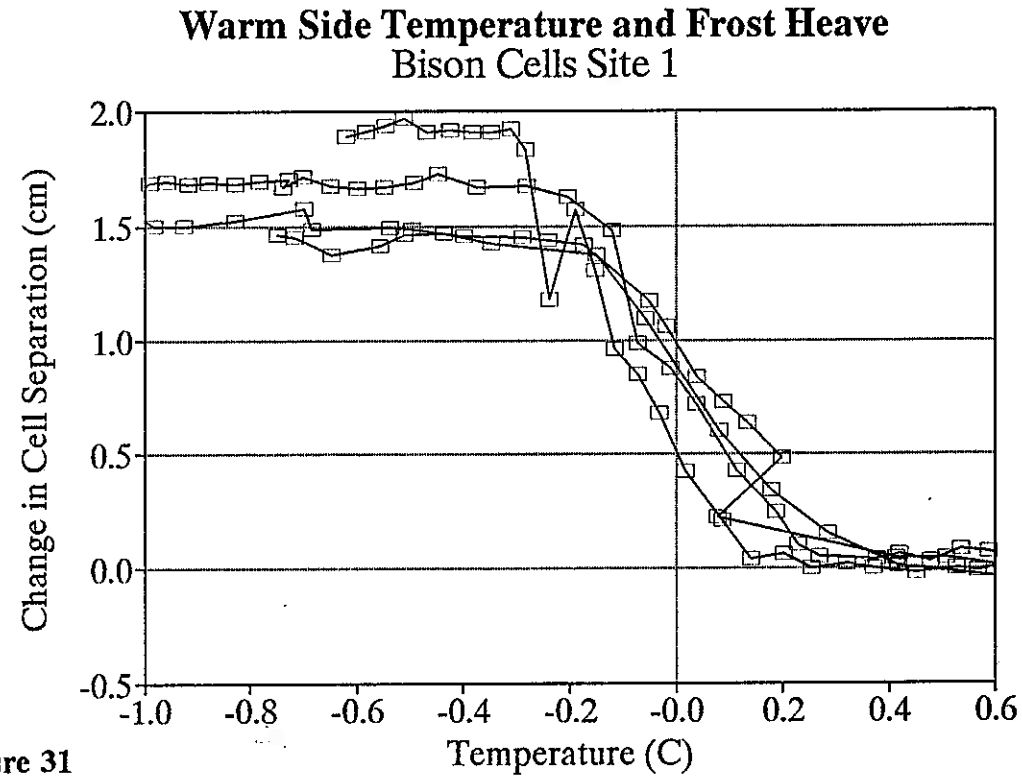


Figure 31

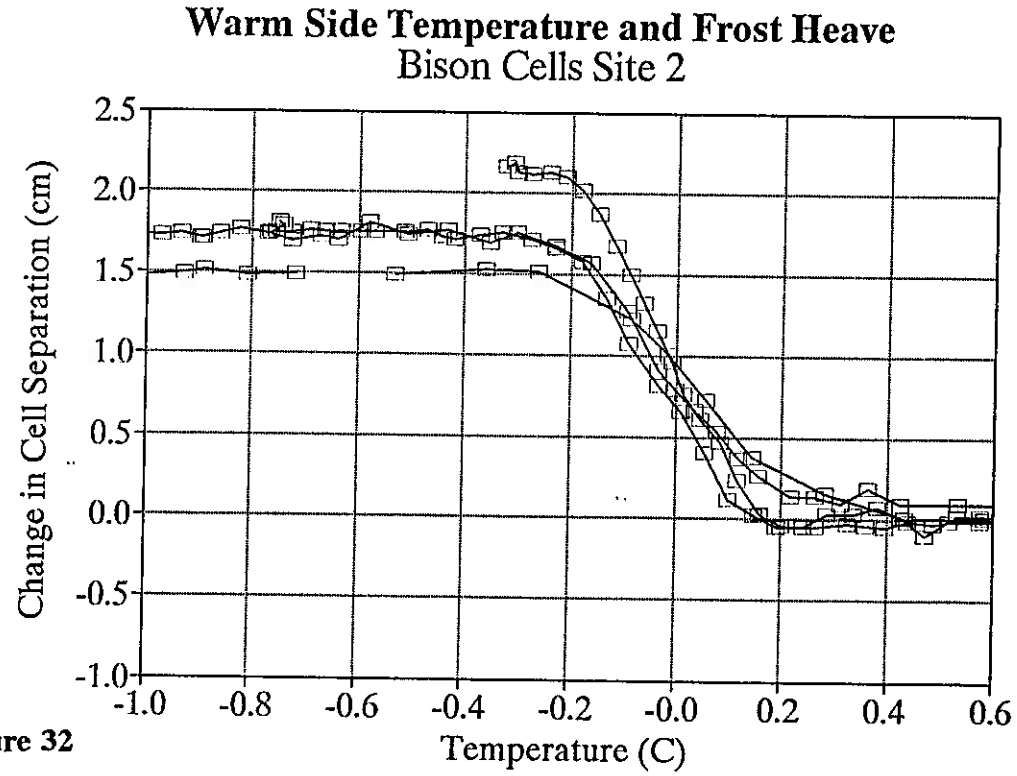


Figure 32

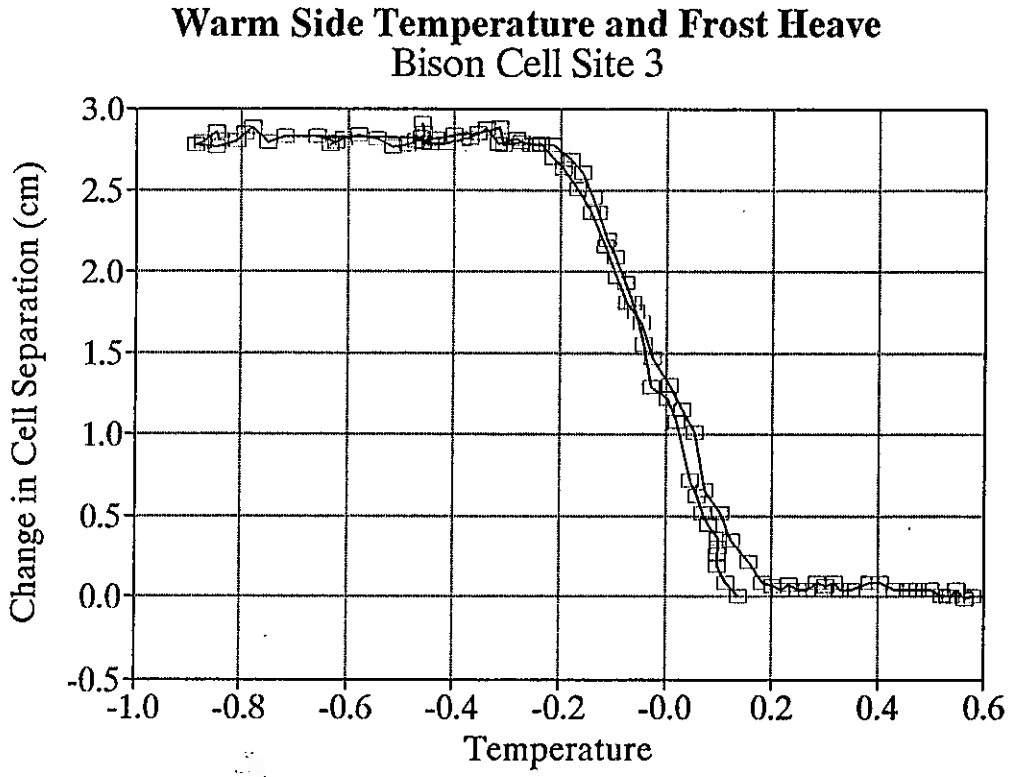


Figure 33

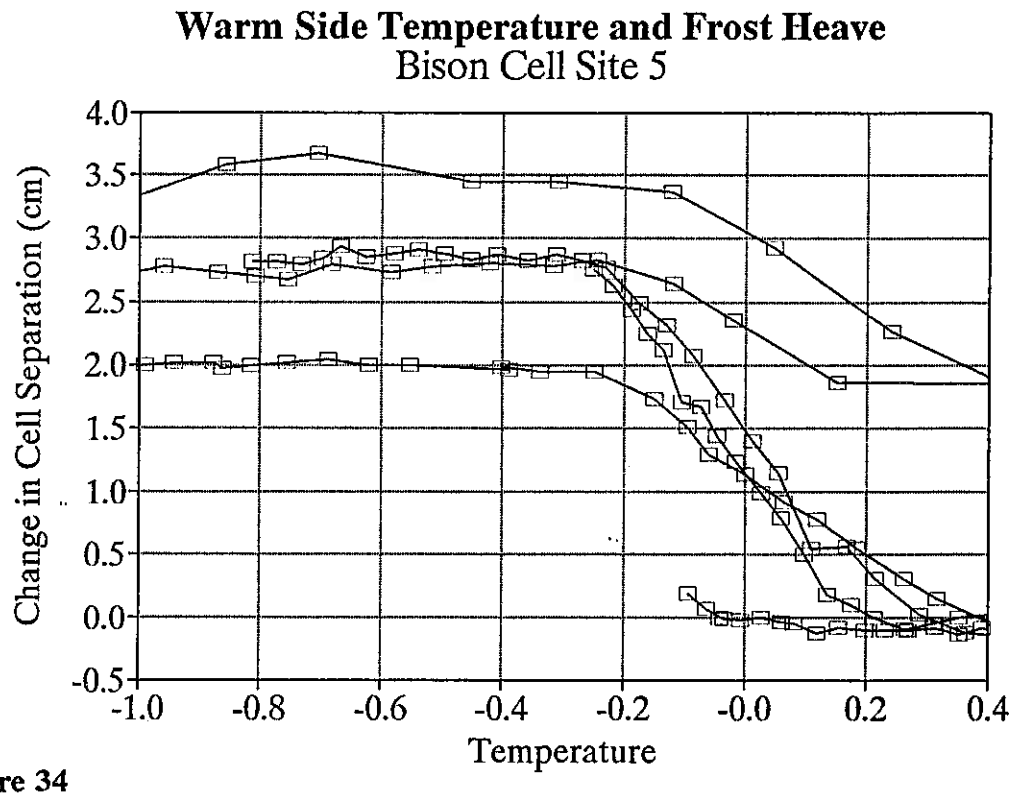
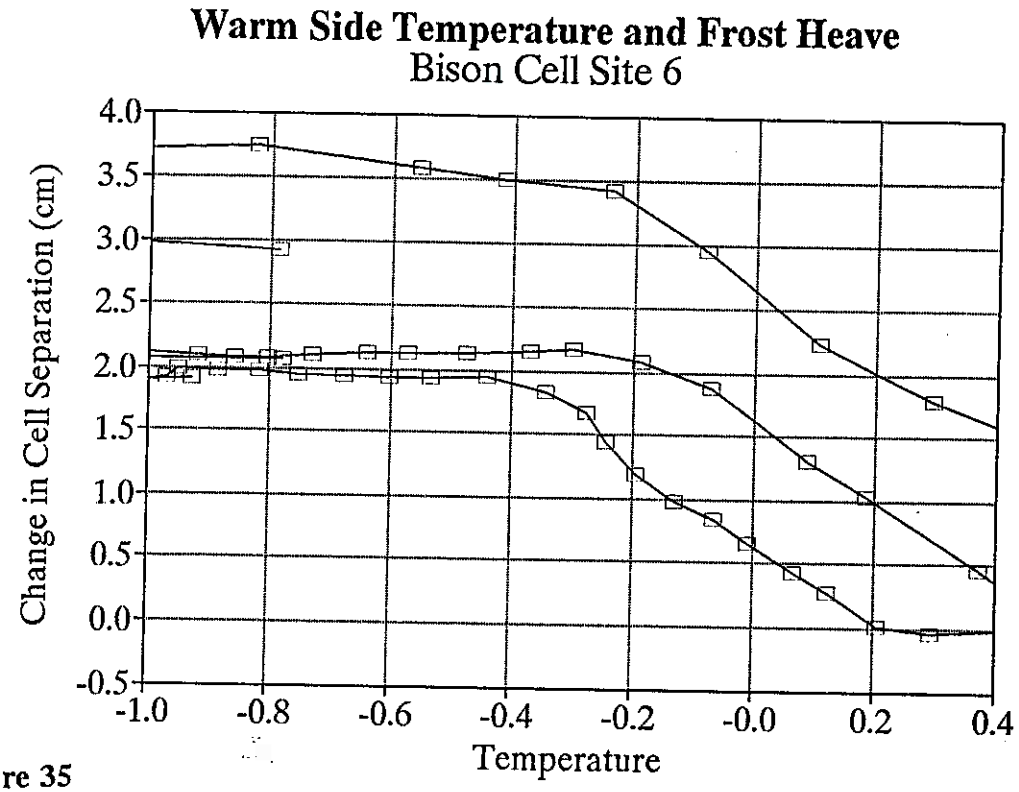


Figure 34



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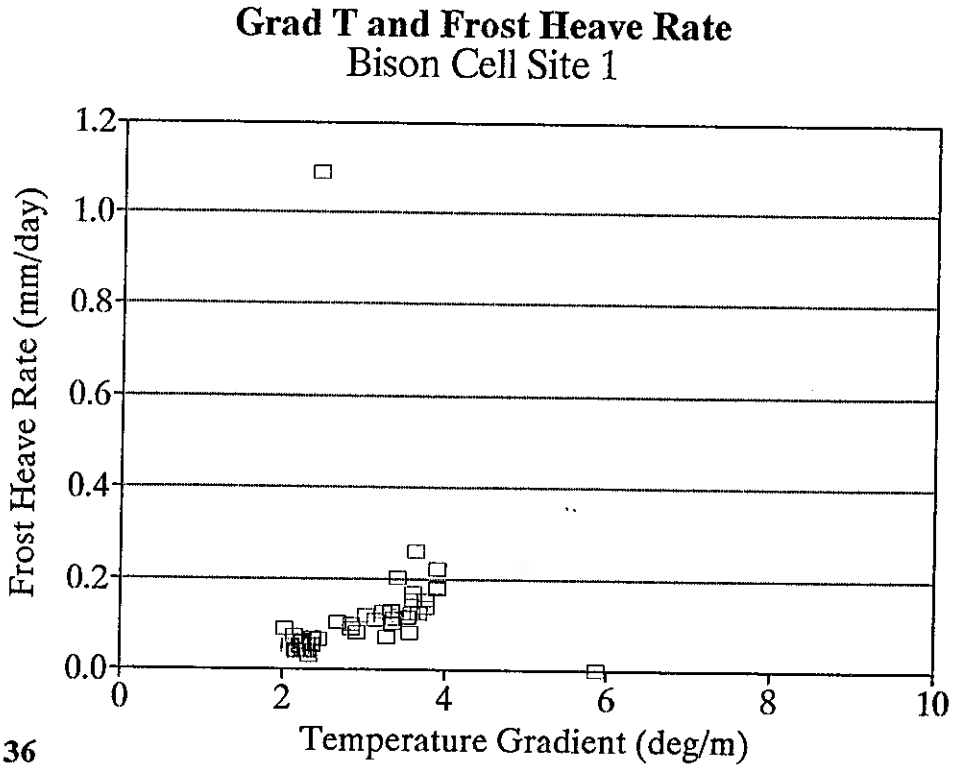
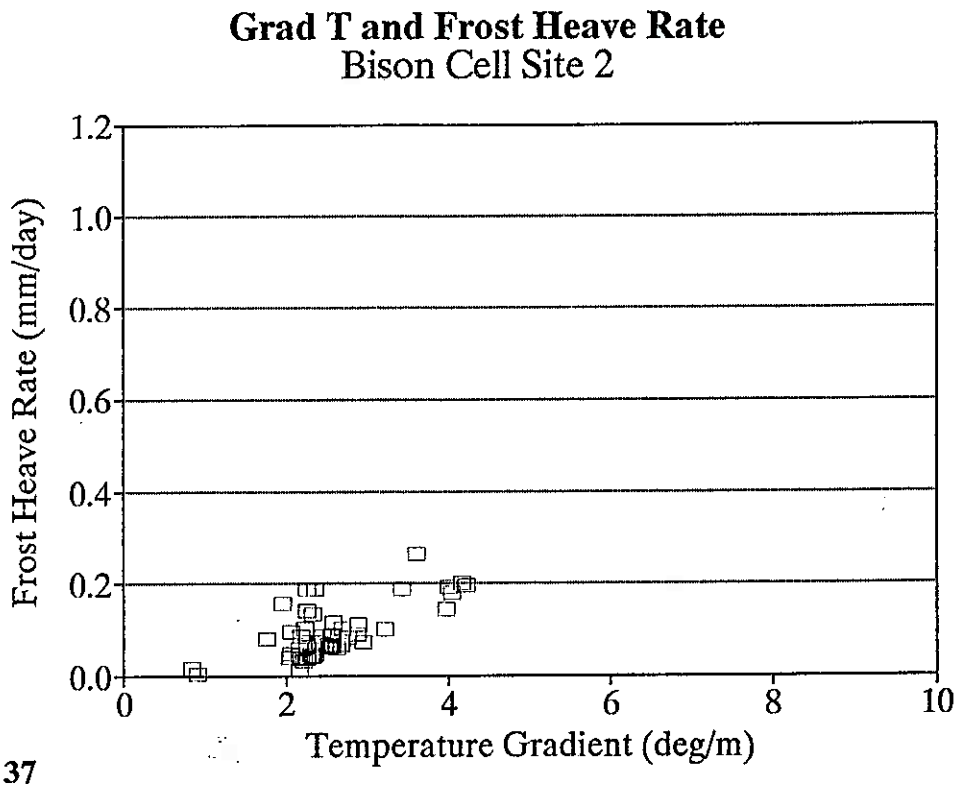


Figure 36



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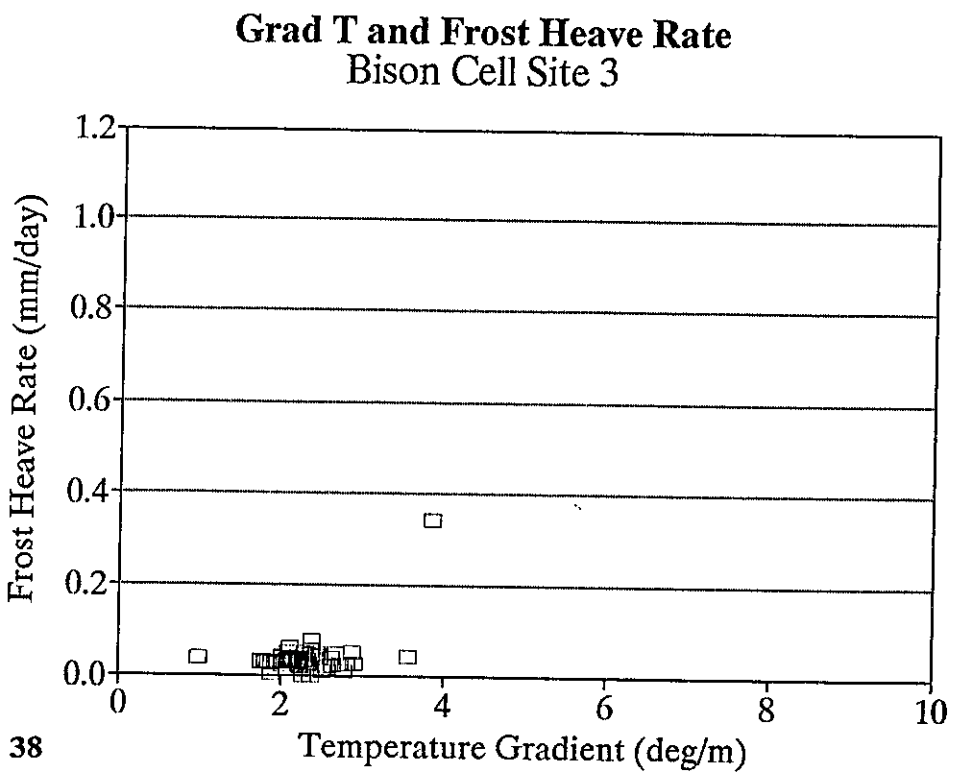
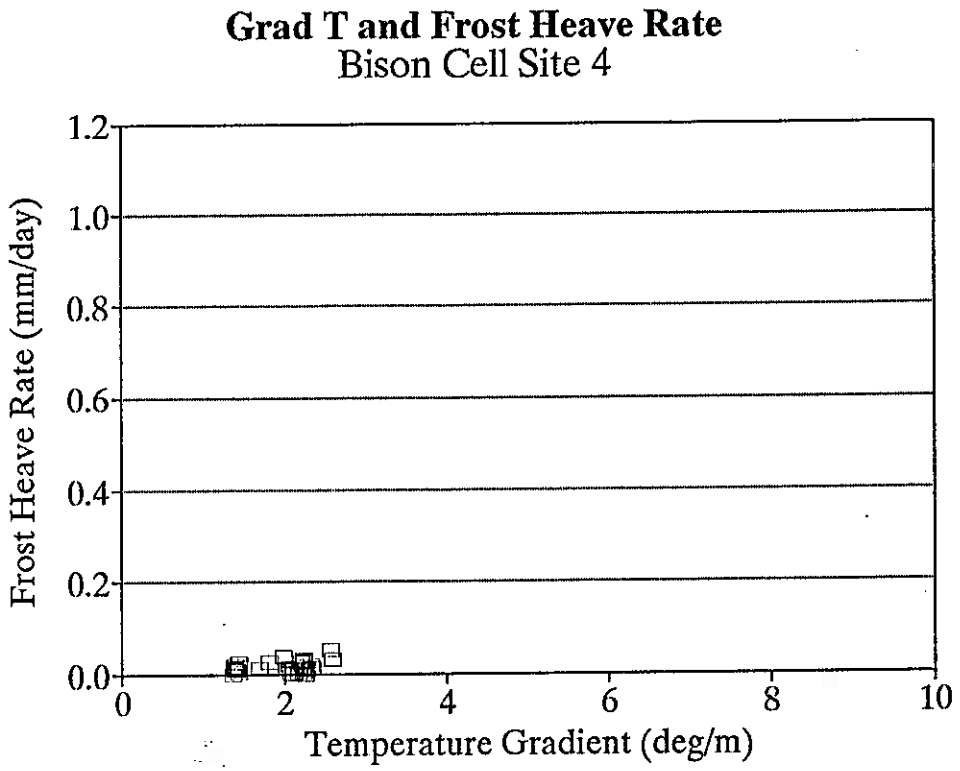


Figure 38



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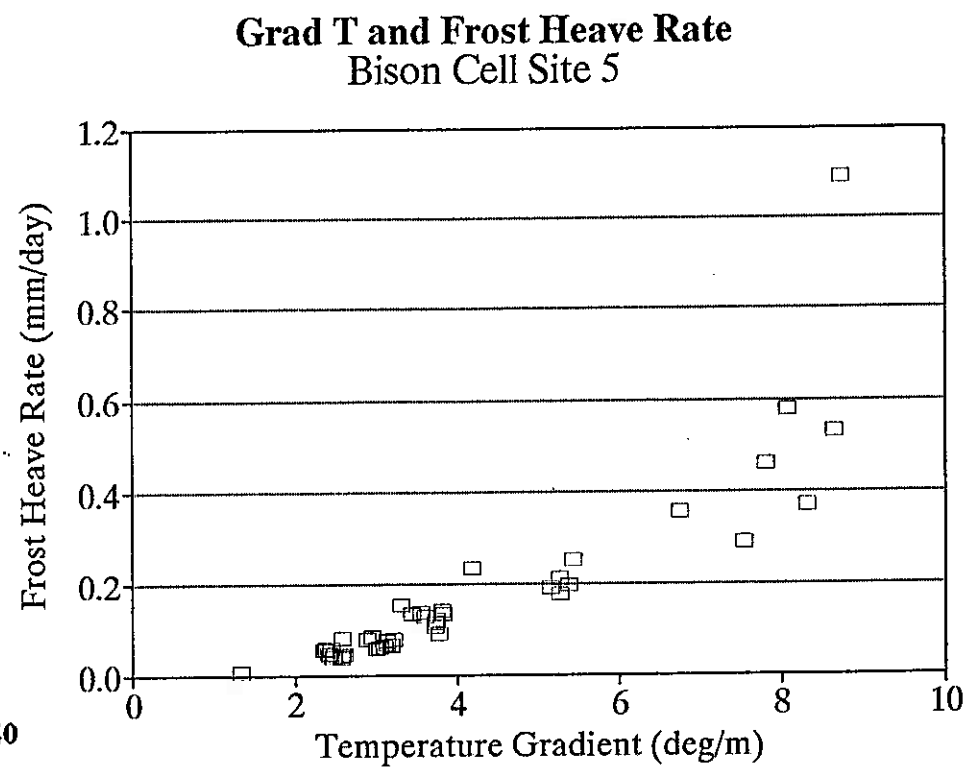

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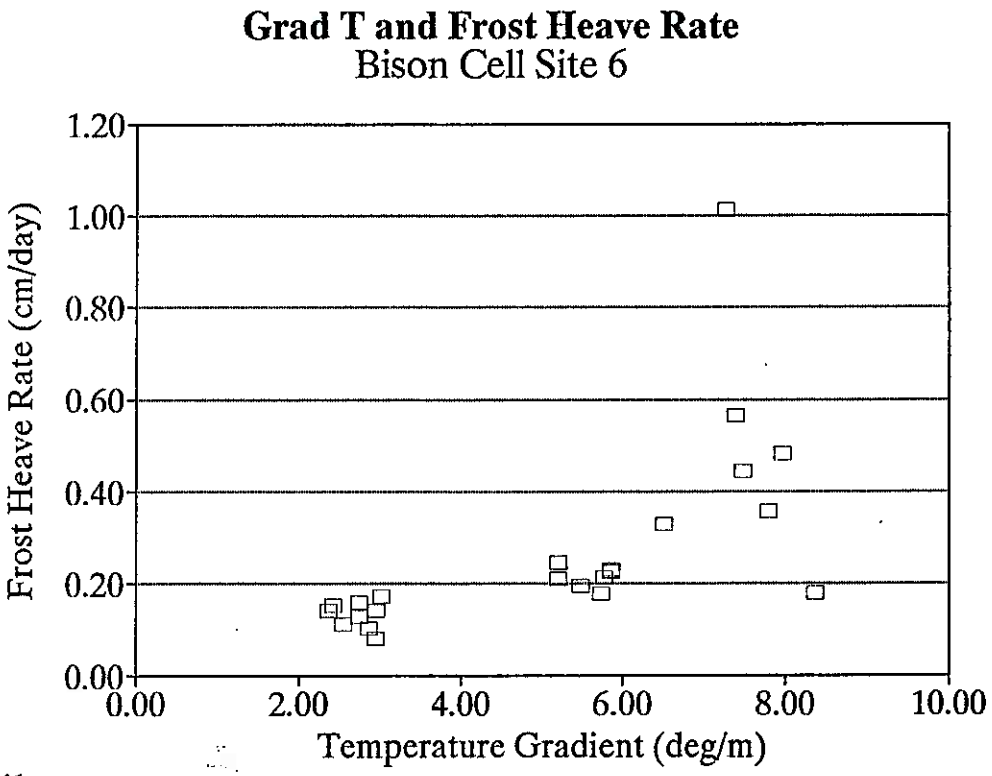

Figure 41

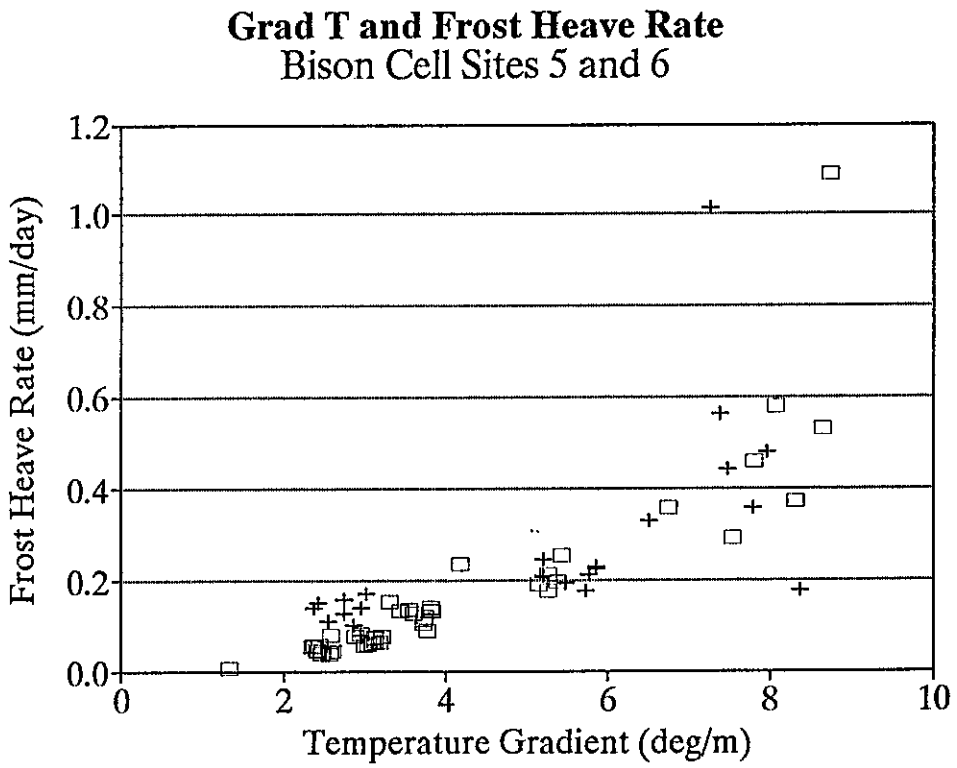

Figure 42

taken at each of these sites. These measurements were taken in the first week after freezing was initiated in the pipe. The departure from the relationship apparent for other measurements may be due to the rapidly changing temperatures in the first week: the temperature gradients used for comparison are those found at the end of measurement period, and thus will underestimate (for the start of freezing especially) the average gradient present at the time that the soil was heaved.

Excluding the two points mentioned above, regression provides a slope to the relationship of 0.0636, which converted to units of SP (segregation potential) gives 73.6 x $10^{-5}mm^2s^{-1}C^{-1}$. Adjusting this to account for the expansion of migrating as well as *in situ* water upon freezing, provides an approximate value for SP of 7 x $10^{-4}mm^2s^{-1}C^{-1}$, which falls within the range of SP values compiled for the Caen silt by Dallimore (1985).

The data for all sites also show that the frost heave rate intercepts the temperature gradient axis near a gradient of about 2 $°Cm^{-1}$. Measurements with gradients significantly closer to zero, if experienced by actively freezing soil between Bison cells, would have been excluded from the relationship because the entire zone of heave could not be confined to the zone between a pair of cells (which are typically about 170 mm apart). In this situation, the heave occurring in the zone of active heave would be spread over more than a single pair of Bison cells.

Soil Surface Survey

The soil surface is surveyed optically using a level mounted in the frame of the small door to the cold room. The reference point for all level measurements is an iron bar embedded in the concrete of a retaining wall just outside the facility. Survey points are laid out in a grid of nails embedded in the soil surface. There are 11 survey lines axial to the pipe, each having 30 marker nails at 0.5 m spacing. The soil surface was surveyed approximately monthly throughout the experiment. The initial and "final" configurations of the soil surface are shown in Figure 42. The pattern of frost heave is not readily apparent from the raw survey data, due to the uneven initial surface, and to the frost heave which occurred on the prefrozen side during the period of freezing which preceded the start of the experiment. Manipulation of the raw survey data can reveal features of the spatial and temporal variation of the soil behaviour during the experiment. In this section, results for two simple analyses of the surface heave data are presented:

- total change in elevation from the start of freezing, and
- the changing spatial distribution of the rate of heave and settlement over time.

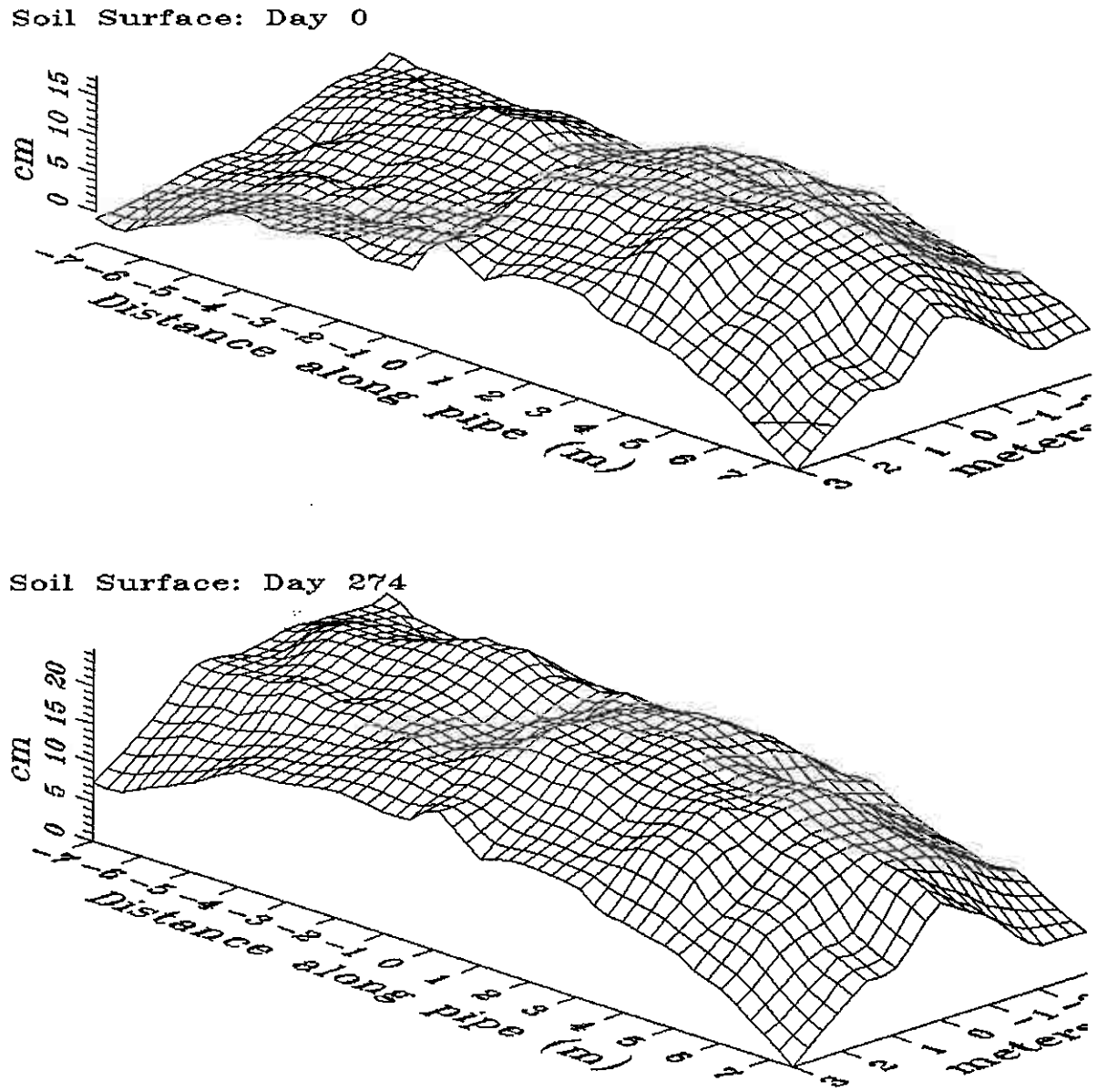

Figure 43 Surveyed soil surface at start of freeze (top) and at day 274 of freeze (April 1 1993).

Elevation change

The change in elevation of the soil surface was extracted from the surface survey data (Figure 43), by subtracting, at each point on the surface, the surveyed elevation at the start of the freeze from its elevation measured during the freeze. The dominant features of the series are:

- On the initially unfrozen side of the experiment, heave is greater adjacent to the pipe than directly beneath it for some distance from the transition.

- Frost heave over the ground surface is only weakly related to distance from the pipe axis. This is in contrast to the first freeze and to the earlier experiments at Caen, and is due to the much colder surface freezing temperature (-4.0°C) which is closer to the pipe circulation temperature than any earlier freeze at Caen.

- Frost heave is evident over the entire surface on the prefrozen side of the experiment. Heave increases with proximity to the thermal interface at the midpoint. Because frost depth was initially greater (at the outset of the freeze) near the centre of the prefrozen material, the subsequent rate of frost penetration was slower there than near the transition.

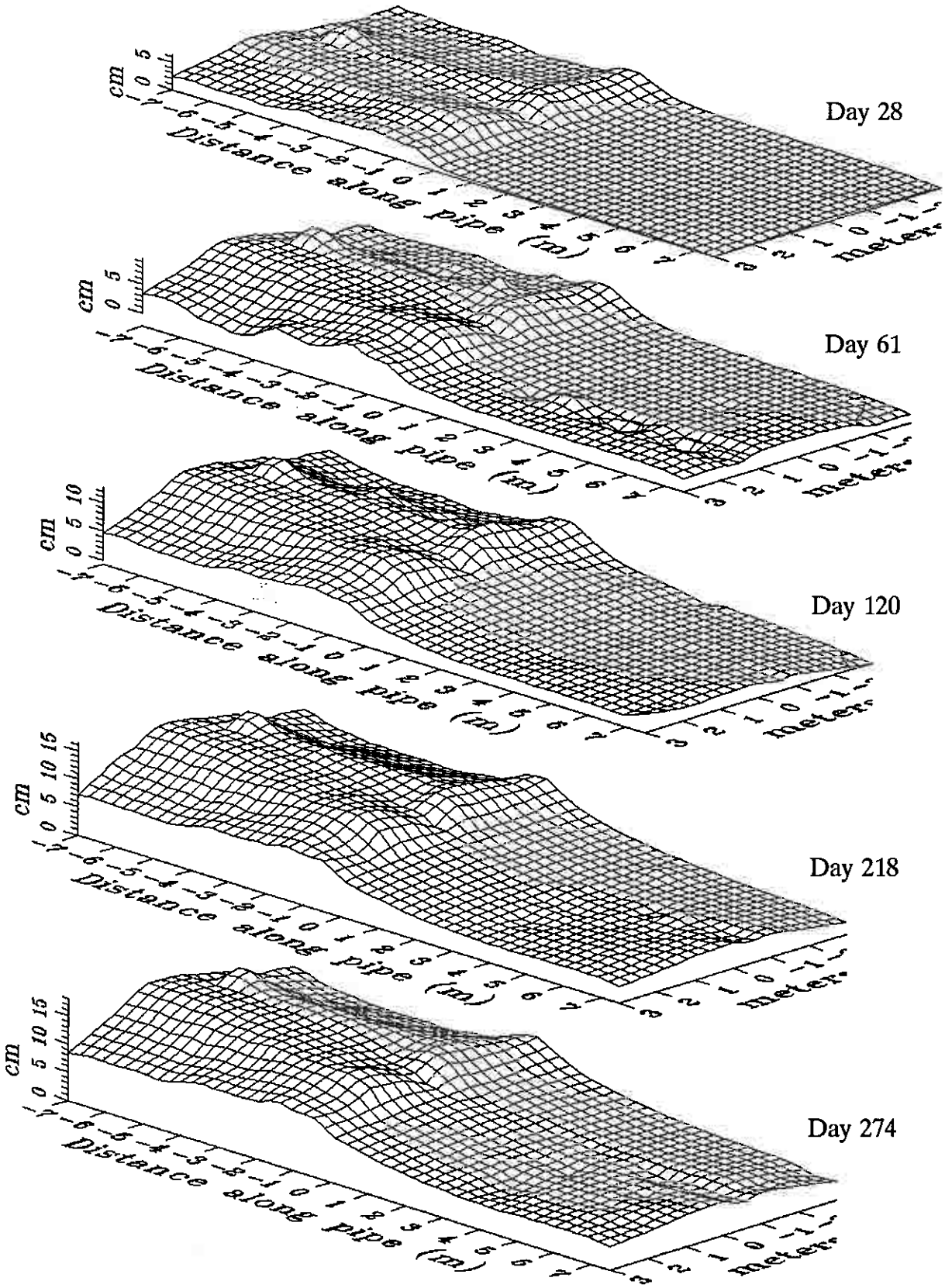

Figure 44 Surface elevation change during freeze. Calculated as the difference between surface elevation on date specified and elevation at initiation of freeze (July 1 1992).

Heave and settlement rates over time
The changing spatial distribution of the rate of elevation change over time was calculated from the elevation changes between dates within the survey record. Figure 44 shows the spatial variation in heave rate calculated for different periods of the freeze. In these figures, the relatively subtle variations in the calculated rates of elevation change amplify minor errors in the original data, apparent as localized peaks and hollows.

The dominant features are:

- A marked contrast in heave rates between the initially unfrozen and prefrozen halves of the experiment is evident in the first 28 days of the experiment only. In the period following this the rate of heave is somewhat higher in a zone along the pipe axis in the initially unfrozen section. Thereafter, the heave rate was distributed relatively uniformly over the entire soil surface. On the prefrozen side of the experiment, the heave rate was distributed relatively uniformly throughout the period of the second freeze.

- Heave rates generally decrease as the freeze cycle progresses.

- The depression immediately above the pipe axis near the transition develops in the first month of the freeze. In the first freeze, this feature developed over the first 71 days of the freeze.

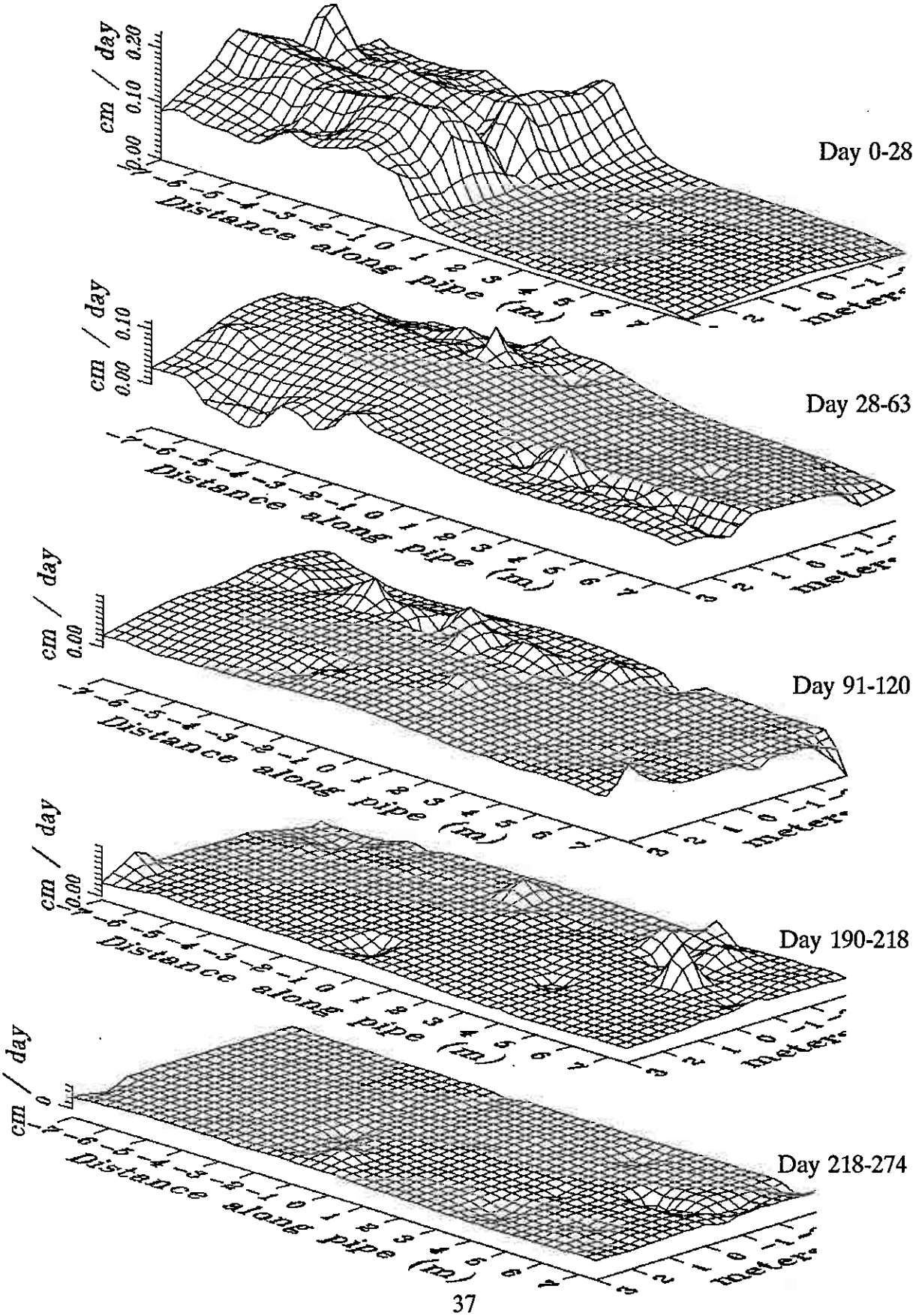

Figure 45 Surface variation in frost heave rate, calculated from elevation change between surface surveys.

Pipe Instrumentation

Optical Survey of Pipe

Vertical survey rods are attached to the pipe at 0.66 m intervals along its full length, for a total of 24 rods. A loose plastic sleeve was placed around each rod prior to backfilling, to permit their free movement as the pipe is deformed and lifted by the heaving soil.

The shape of the pipe on certain dates throughout the second freeze is shown in Figure 46.

The change in pipe shape from the start of the experiment to the end of the first freeze is shown in Figure 47. In the earliest stages of freezing, the greatest curvature in the pipe was at the transition. This gradually gave way to the sigmoid curvature which was observed in the earlier Caen experiments. Migration of the point of inflection of pipe curvature into the prefrozen material is apparent.

Figure 48 shows the disposition of the uplift rate along the pipe for selected dates. On the initially unfrozen side of the experiment, the pipe uplift rate declines approximately asymptotically with time toward that on the prefrozen side (which remained constant throughout the freeze at about 0.2 mm day^{-1}). While the differential frost heave rate (greatest uplift minus least uplift along the pipe) was as much as 1.4 mm day^{-1} during the early part of the freeze, the difference by day 274 was about 0.1 mm day^{-1}.

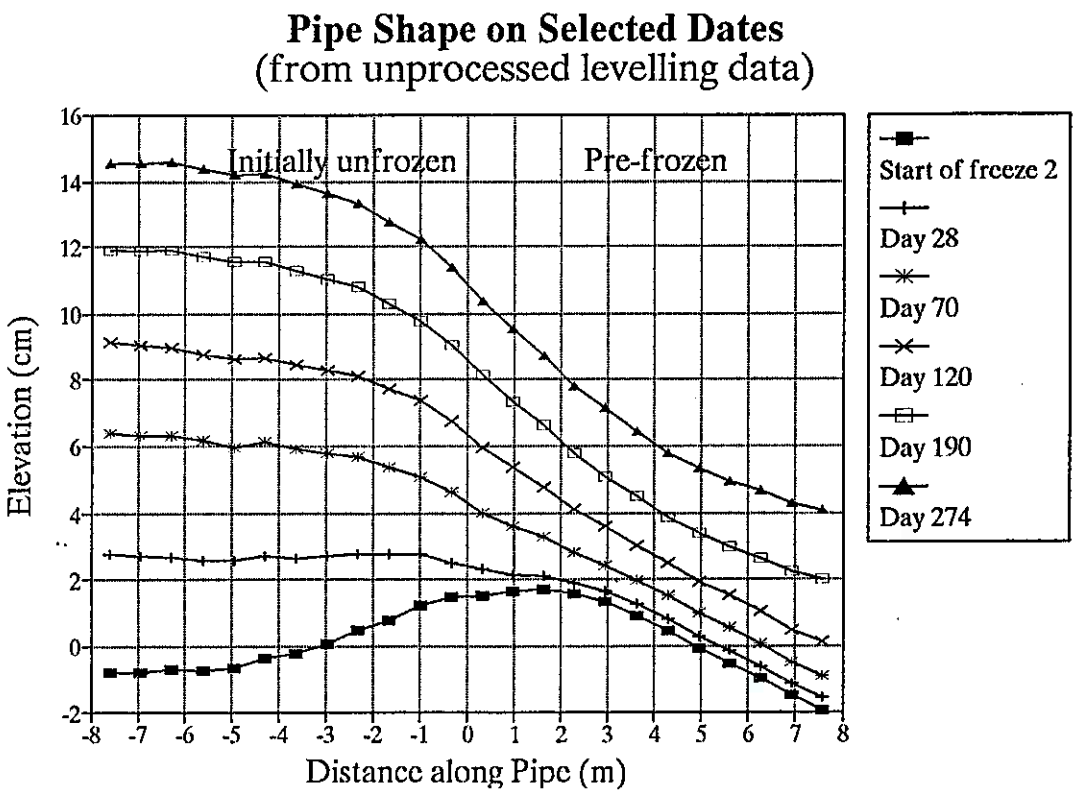

Figure 46

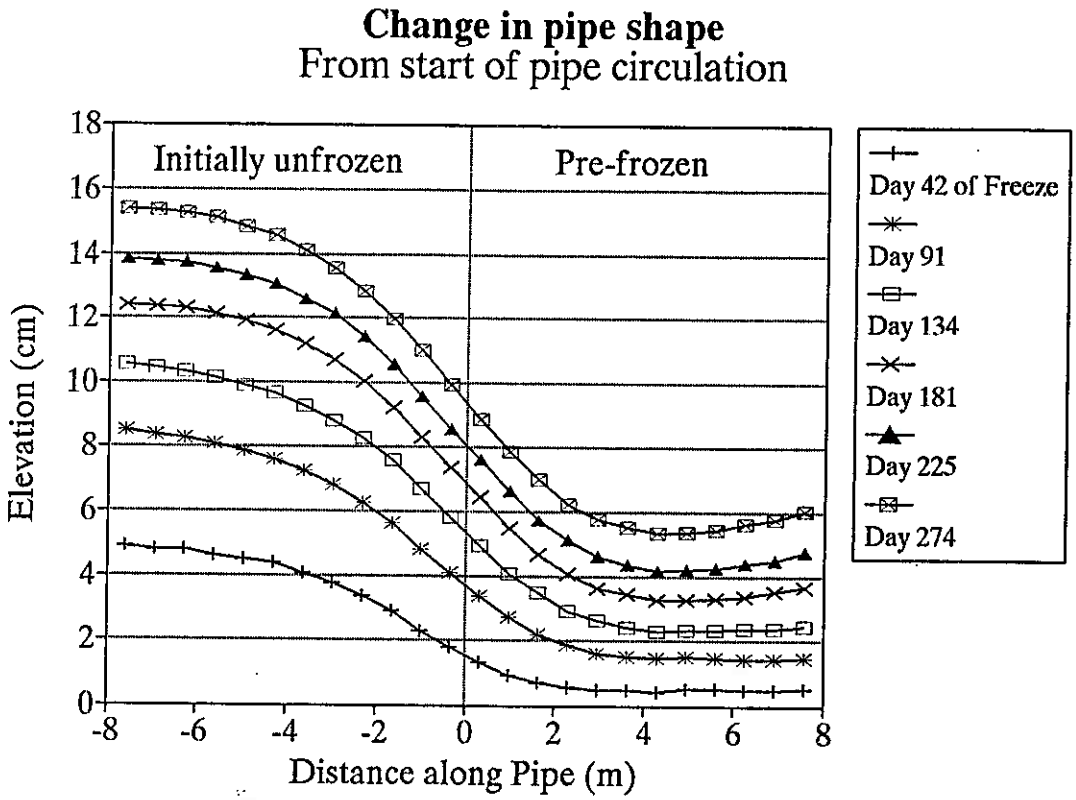

Figure 47

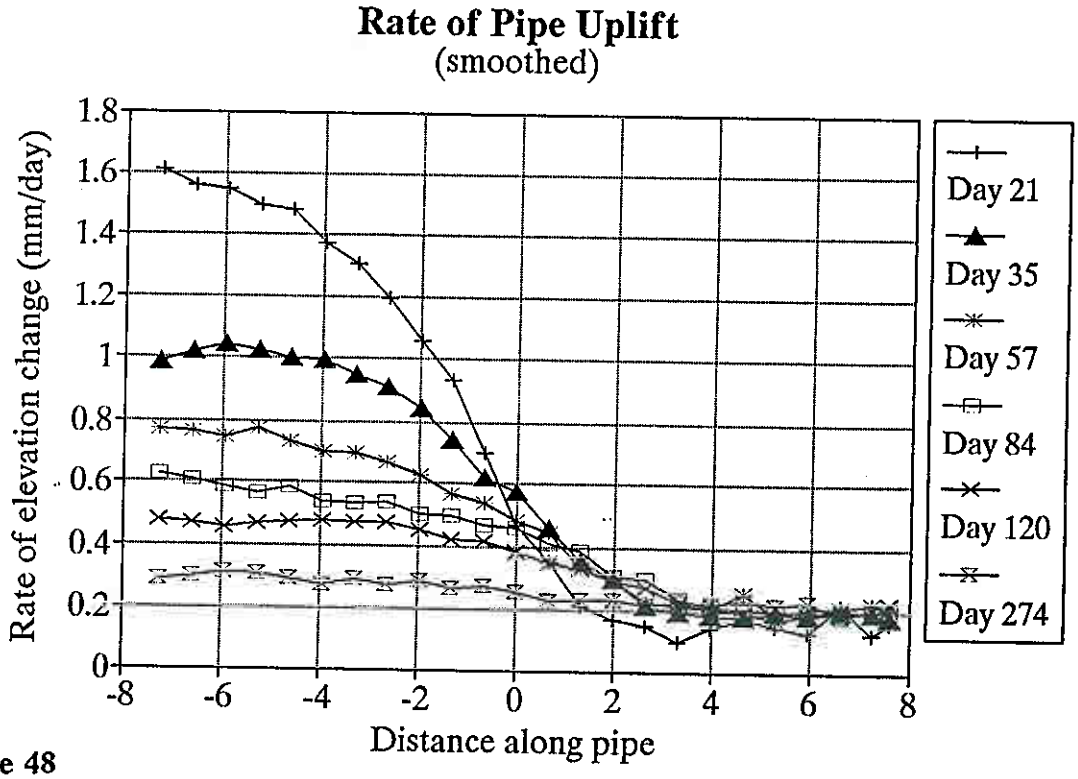

Figure 48

Strain Gauges
Data for individual strain gauges are included in the appendix to this report.

Figure 49 shows the development of strain along the pipe axis during the new freeze. Problems with the data acquisition system resulted in the loss of strain data between days 5 and 33. On the initially unfrozen side of the experiment, the peak pipe strain was about 2 metres from the transition throughout the freeze. In contrast, the point of maximum strain on the prefrozen side of the experiment has migrated into the prefrozen material, and appears now to be about 2.5 m from the transition. Figure 50 shows the behaviour of each gauge separately, and shows the approximate dates at which gauges successively farther from the transition exhibited the peak strain value. This behaviour can be explained by the progressive failure of the soil above the pipe on the pre-frozen soil, resulting in gradual movement of the pipe bending inflection point away from the transition. Figure 51 shows the behaviour of the gauges near the transition on the initially unfrozen side: migration of the point of peak strain is not apparent on this side of the transition.

Direct comparison with the strain behaviour of the pipe during the first freeze is not possible, due to the problems experienced with the data acquisition system at that time. As described in the annual report on the first freeze cycle however, strain in the pipe near the transition was examined for the first freeze by using the optical

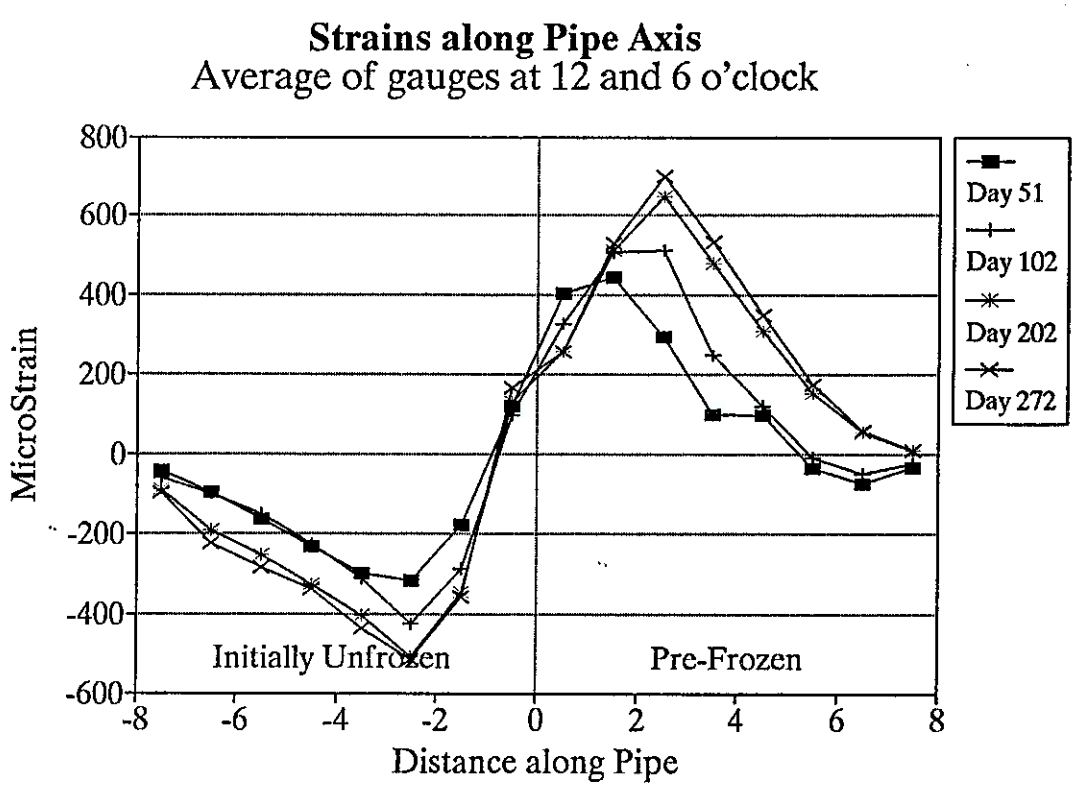

Figure 49

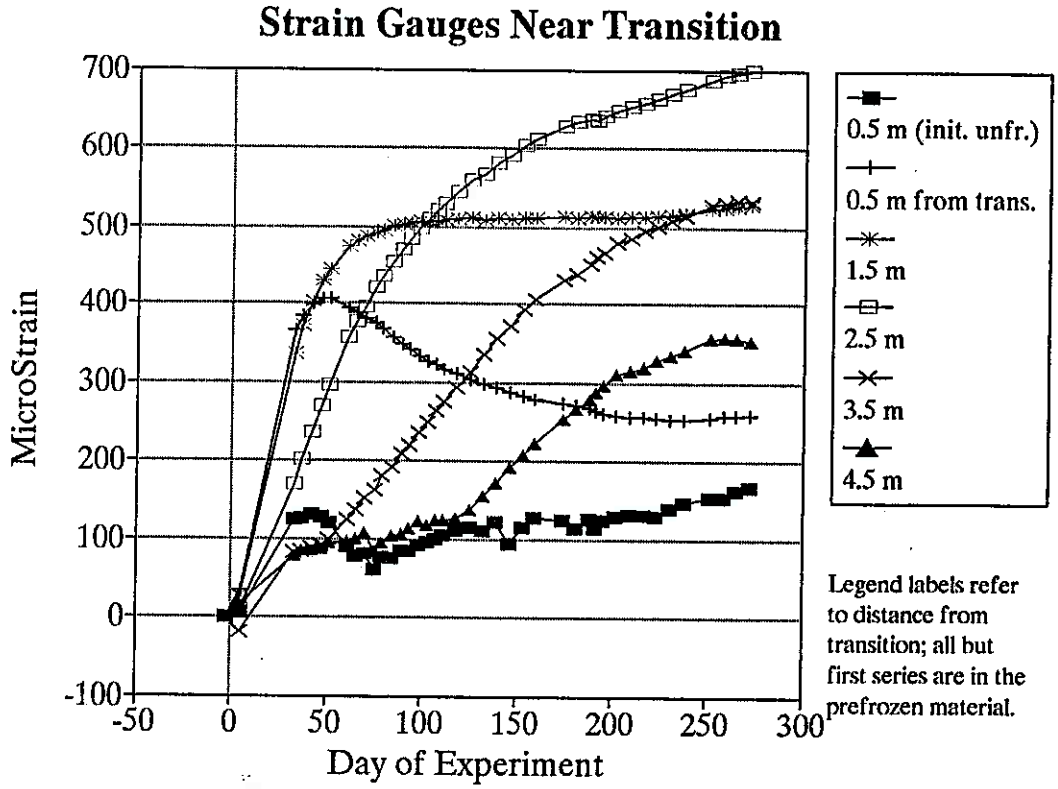

Figure 50

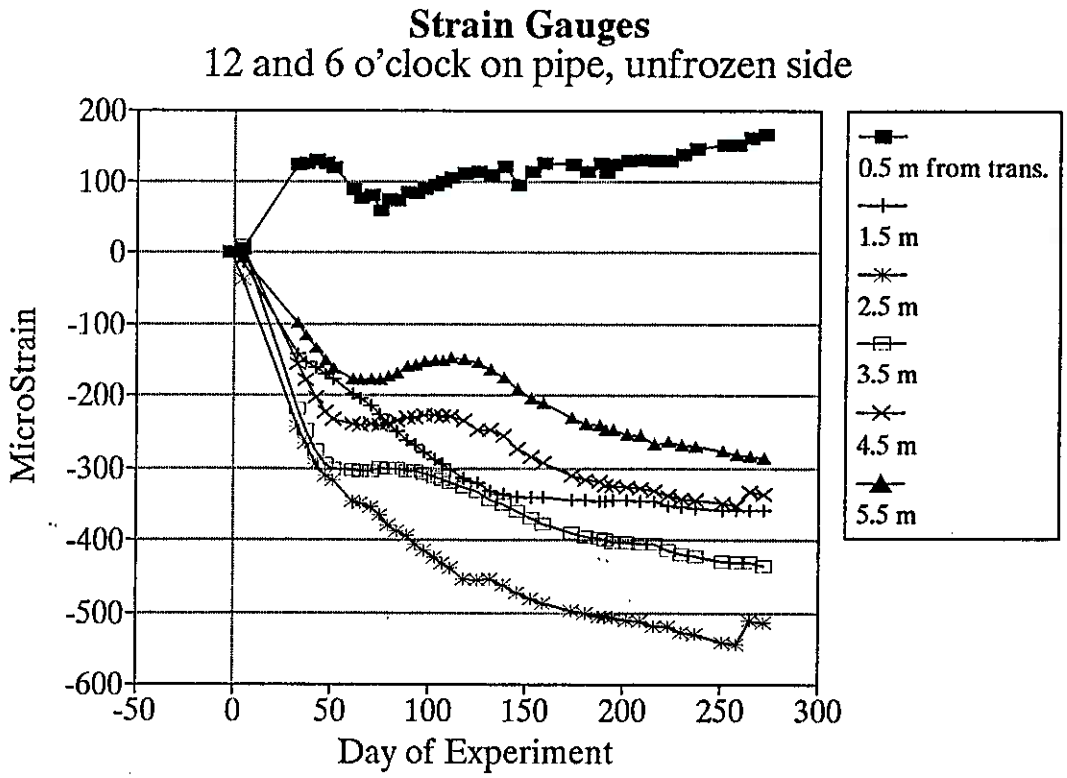

Figure 51

survey data for the pipe and making use of the relationship between strain and curvature. Pipe shape on selected dates was modelled with a polynomial curve fitted to the levelling data: curvature was then estimated from the second derivative of the polynomial.

Figure 52 shows pipe curvatures estimated for the first freeze for points corresponding to the positions of the strain gauges shown in Figure 50 (i.e. the current freeze). The pattern of behaviour of the pipe in the two freeze cycles is similar, except that the shift of peak strain (curvature) away from the transition occurred more slowly in the first freeze. In addition to the limitations of the curvature analysis, two differences in the freezing conditions between the two cycles could account for this:

- Frost penetration was much slower in the first freeze. The strains at the point 1.5 m from the transition were first exceeded by those at that 2.5 m at about day 190 in the first freeze (with the frost line at approximately 1 m). In the second freeze this took place at about day 100 (with the frost line at 1.2 m).

- Thaw settlement at the base of the prefrozen section in the first experiment resulted in the longitudinal rotation of the pipe throughout that cycle, effectively reducing the strain on the pipe from uplift on the initially unfrozen side of the experiment.

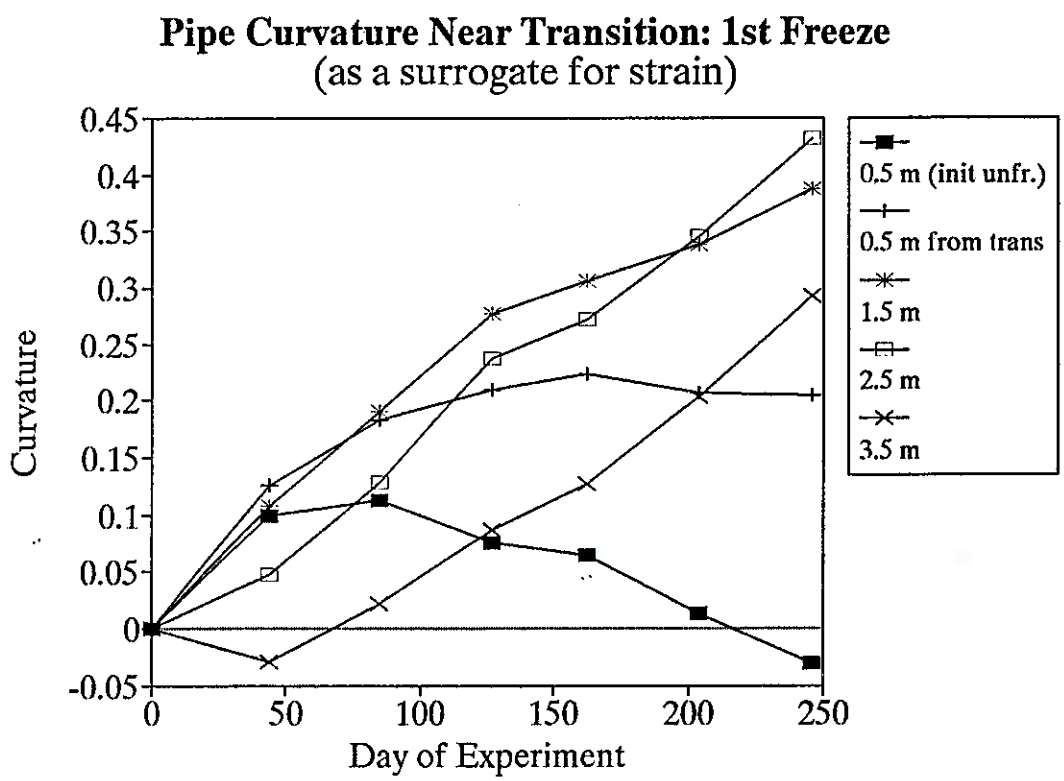

Figure 52

"LVDT" device
This device consists of a linear potentiometer attached to two "fixed" points: one on the pipe and the other in the soil some distance from the pipe. The linear potentiometer consists of a piston and sleeve with universal joints on both parts for attachment. At one end, the universal joint attaches to a steel strap connected rigidly to the pipe. At the other end the potentiometer attaches to a soil anchor, consisting of a pair of crossed aluminum plates 20 cm square and 1 cm thick. Figure 53 shows the extension of the LVDT device. The device has registered a change in its extension over the second freeze of 3 mm, mostly confined to the initial freezing in place and thaw settlement of the soil. After the initial freezing in of the device, movement of about 0.2 mm was recorded. This behaviour and magnitude of movement is similar to that in the first freeze.

Problems with instruments
Some of the devices used in the course of the experiment have not performed as hoped:

- The SINCO hydrostatic profiler was intended to measure soil displacements immediately below the pipe. SINCO in the United Kingdom (now Brainard-Kilman Ltd.) have determined the source of persistent problems with the stability of elevation readings to be improper pressure regulation. This finding has come too late for any potential modifications to the

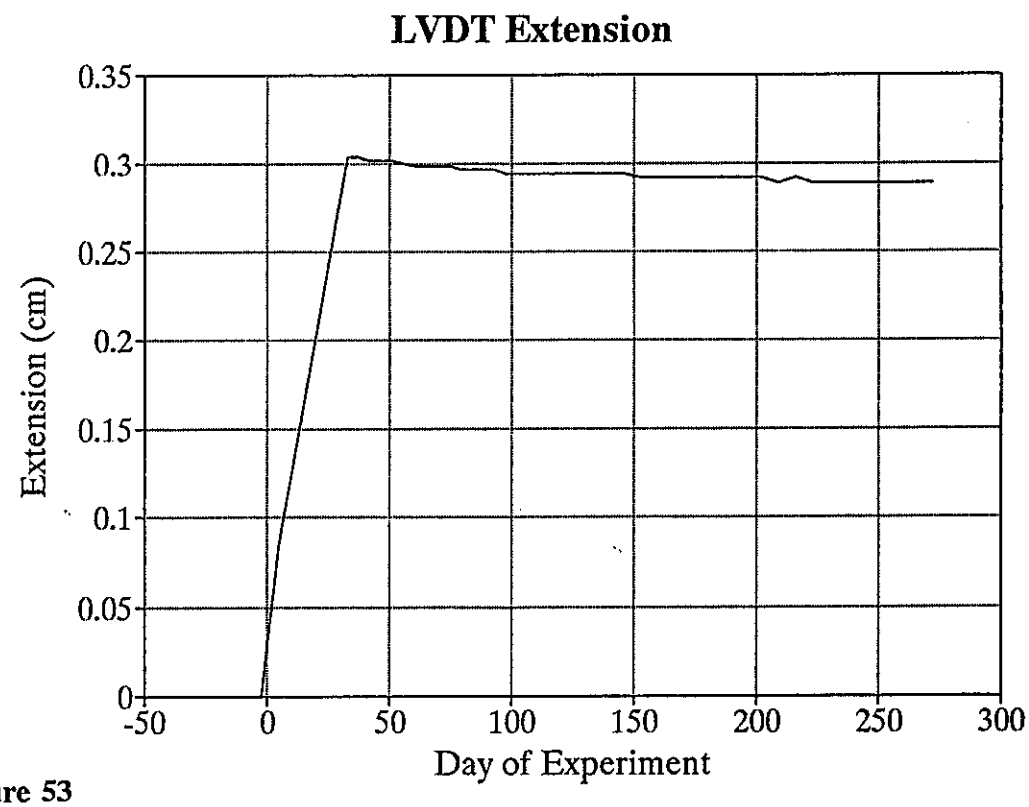

Figure 53

system to provide results for the present experiment.

- The steel strip device, installed horizontally radial to the pipe, was intended to measure shear within the soil adjacent to the pipe. Results from the strain gauges attached to this device have not provided useful results: two of the gauge pairs failed in the first freeze cycle, with one other gauge pair giving erratic results. Results for the remaining strain gauges (Figure 54) suggest that deformation of the strip is dominated by radially differential frost heave rather than the longitudinal shear between the pipe and the soil.

- The magnet ring soil strain system was out of operation for extended periods in the first freeze cycle, due to damage caused to its rack and pinion adjustment when the measurement access tubes became deformed by radial frost heave near the pipe. The system was modified for the second freeze. Unfortunately, the new method of keeping the rack and pinion engaged introduced excessive play in the system, increasing the overall uncertainty in the measurements to the extent that the subtle displacements due to continuing frost heave could no longer be measured with sufficient precision.

- Bison cells in the three soil

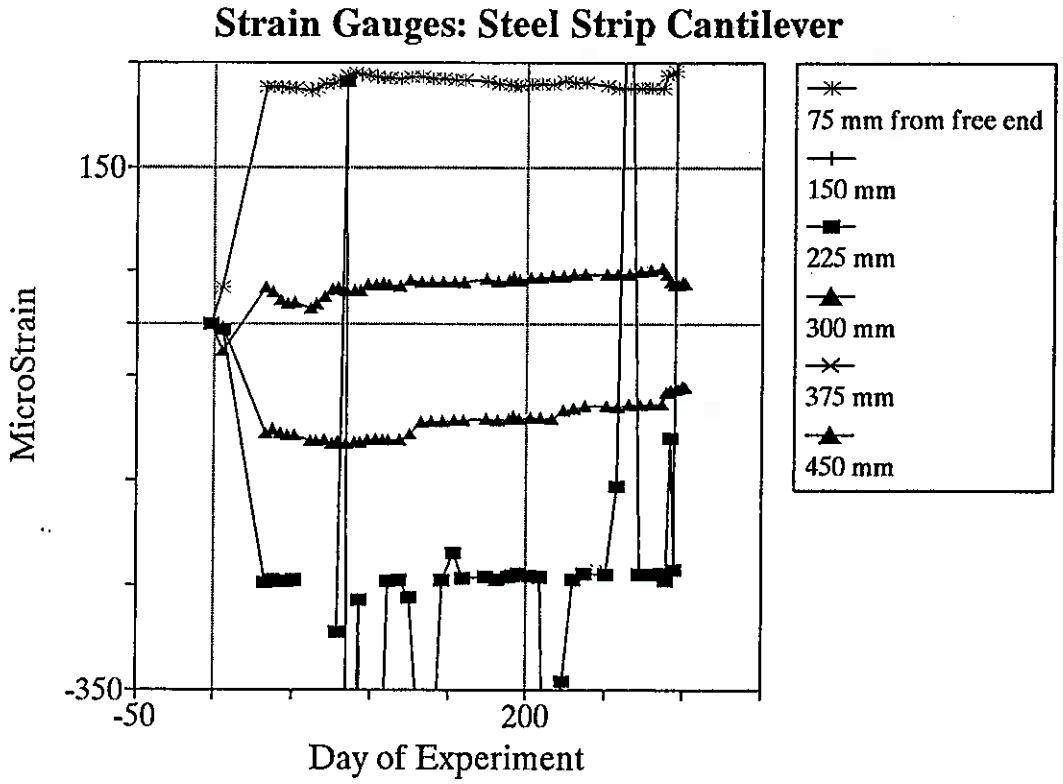

Figure 54

columns installed adjacent to the pipe had thermistors attached in the same manner as the Bison cells originally installed. Analysis of results from these cells showed that cell separation started to increase before the temperature on the cold side had fallen below 0°C. This indicated that the cells were being pulled through the soil as their connecting electrical leads were frozen into the heaving soil. This had been avoided with the original installation by coiling the leads as the columns of cells were being backfilled.

3 Comparison with Earlier Experiments

The material which follows is an excerpt from a paper to be presented to the Offshore Mechanics and Arctic Engineering Conference, to be held in Glasgow, Scotland June 20-24 1993. To simplify language in the paper, the current experiment was designated "UP" (i.e. Unfrozen-Permafrost transition experiment), with the earlier experiment designates "SS" (Sand-Silt transition experiment). This paper will be the first published which discusses results from the Frozen Transition experiment. The data presented for the current freeze extends to about day 200, corresponding to January 16 1993.

Results and discussion

Detailed discussions of various aspects of the SS experiments have been reported elsewhere (Geotechnical Science Labs 1992, Williams 1992, Williams et. al. 1992, Smith and Onysko 1990, Smith and Williams 1990, Smith and Patterson 1989). Discussion here is limited to a comparison of pipe behaviour and pipe-soil interaction in the two situations. Comparisons are limited to the first 200 days of each of the frost cycles examined, since this is the limit of data available for the latest freeze, which is still in progress.

The overall behaviour of the pipe and soil was broadly similar in each of the four freeze cycles of the SS experiments, with incremental changes in the pipe and soil due to irreversible deformations. The intent in establishing the operating temperatures for the first freeze of the UP arrangement had been to replicate the boundary conditions used in the SS arrangement, to allow a direct comparison of the relative severity of stresses imposed on the pipe in the two cases. Two factors mitigated against such a simple comparison. First, similar operating temperatures produced considerably slower frost penetration in the UP experiments compared to the SS experiments (Figure 55), due to the insulation provided by the plastic wrapping on the pipe (absent in the SS experiments). Second and principally, unanticipated thaw at the base of the prefrozen material in the first freeze of the UP experiments (Figure 56) produced conditions in which the pipe was not simply anchored in the frozen material, but moving with it as it settled at the base. These conditions were eliminated in the second of the UP freeze cycles by operating at lower pipe and air temperatures. This eliminated thaw settlement at the base of the prefrozen section and produced more rapid frost penetration compared to the first freeze. However, this rapid frost penetration allowed the frost depth on the initially unfrozen side of the experiment to approach that on the prefrozen side, producing conditions which limit the amount of *differential* frost heave in the soil and the subsequent stresses in the pipe.

Optical survey of pipe

Figure 57 shows the longitudinal displacement profile of the pipe shape during each of the experiments. The

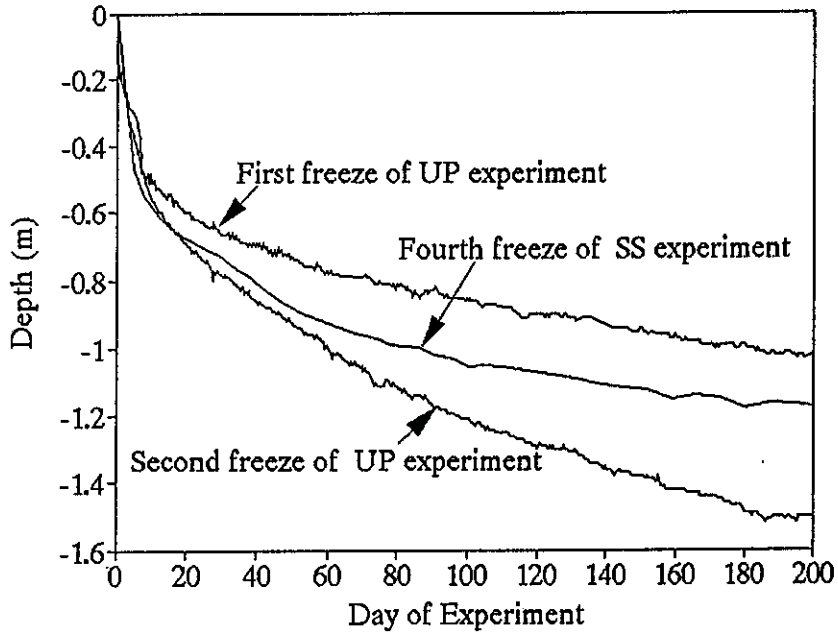

Figure 55 Evolution of frost depth adjacent to pipe, centre of "heaving" section of experiment (silt section in sand-silt or "SS" experiment, initially unfrozen material in frozen-unfrozen transition or "UP" experiment.

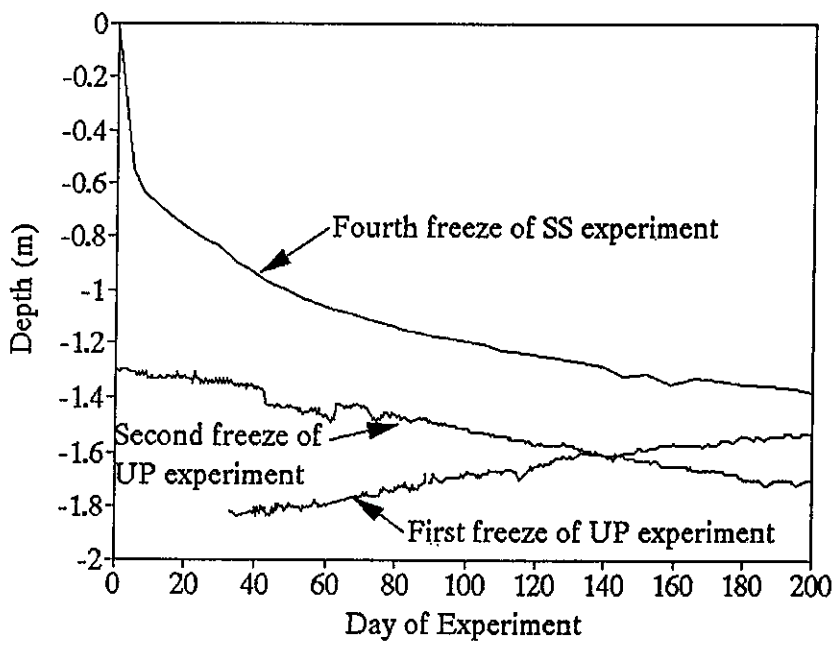

Figure 56 Evolution of frost depth adjacent to pipe, near transition in "anchoring" material (sand-silt transition in SS experiment, frozen-unfrozen transition in UP experiment.

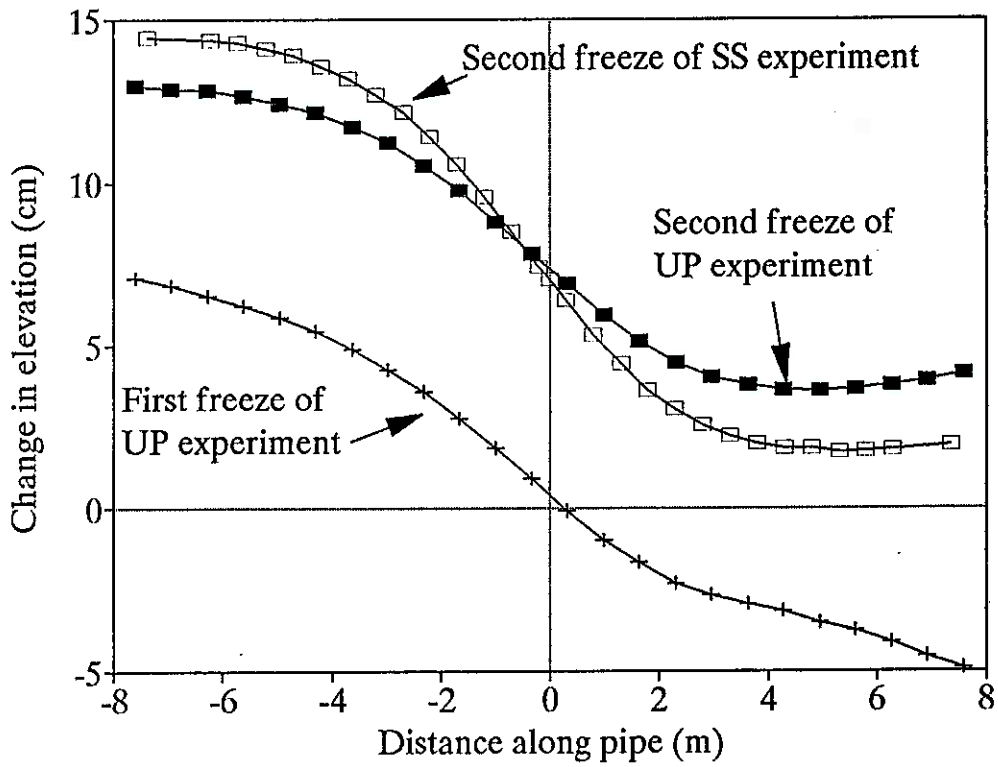

Figure 57 Displacement and deformation of pipe on day 200, second cycle of freeze in sand-silt or (SS) experiment and first/second freezes of frozen-unfrozen transition (UP) experiment.

maximum heave at the end of the pipe is about 10% higher in the SS experiment than in the second freeze of the UP arrangement, and twice as much as in the first freeze of the frozen transition. Movements on the "anchored" (right-hand) side of the experiment (sand in the SS experiment; prefrozen material in the UP arrangement) have a significant impact on the *differential* movement of the pipe (i.e. the difference in elevation of the ends of the pipe). Thaw at the base of the prefrozen section combined with heave in the initially unfrozen material during the first UP experiment resulted in differential movement of the pipe about 95% as great as in the SS experiment. In the second freeze of the UP experiment, the ongoing heave at the base of the prefrozen material offset the heave on the initially unfrozen side, with the result that differential heave of the pipe is only about 70% of that in the sand-silt experiment.

Pipe strain

Figures 58 and 59 show the development of strain along the pipe axis during the second freeze cycle of the SS and UP arrangements. In both experiments the

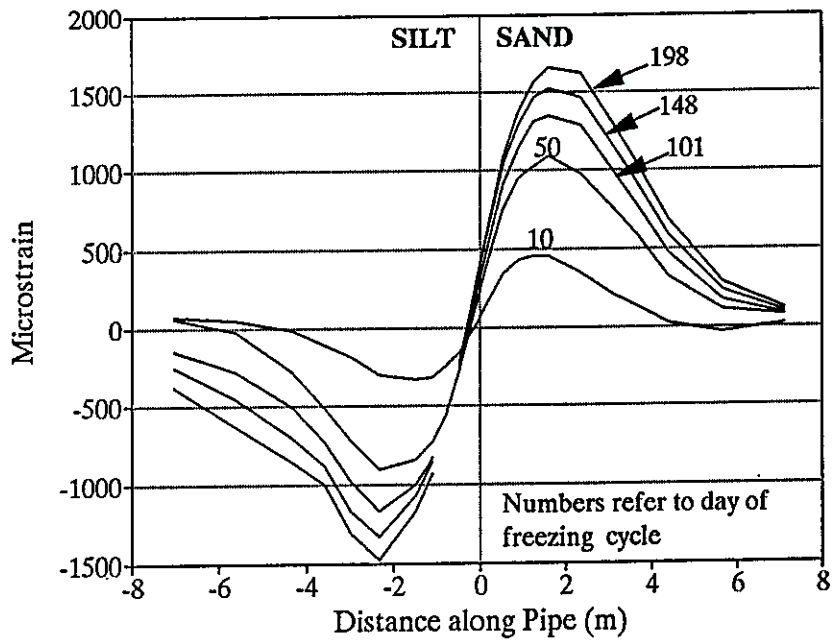

Figure 58 Longitudinal strains in pipe measured by strain gauges, second freeze cycle sand-silt transition (SS) experiment

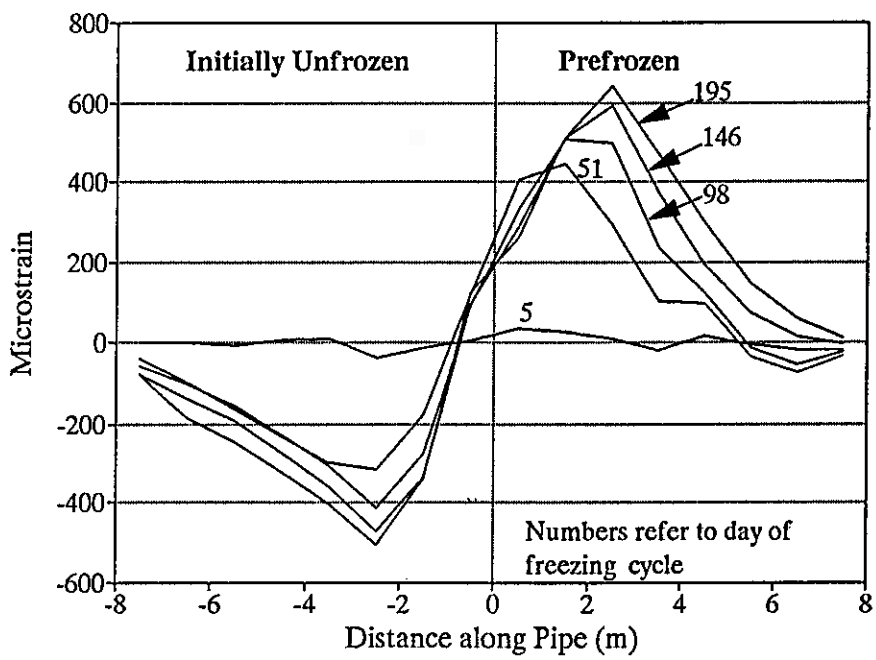

Figure 59 Longitudinal strains in pipe measured by strain gauges, second freeze cycle frozen-unfrozen transition (UP) experiment

strain is disposed approximately symmetrically about an inflection point near the transition, with the peak strain occurring between 2 and 2.5 m from the transition. In both cases the peak strain is somewhat higher on the "anchoring" side of the transition (sand in SS experiment; prefrozen material in UP experiment) Peak strains experienced by the pipe in the UP experiment are much less (about half) than were experienced at the same time in the SS experiment. An analysis of the curvature of the pipe (Geotechnical Science Laboratories 1992b) suggested a similar magnitude of pipe strain in the first and second freezes of the UP arrangement. The smaller differential movement of the pipe can explain the lesser strain in the second freeze of the UP experiment. In the first freeze of the UP arrangement, the pattern of thaw at the base of the prefrozen section was such that settlement increased with distance from the transition, due presumably to more rapid thaw at the margins of the basin. This pattern of thaw allowed the pipe to rotate about the transition, thereby reducing pipe stresses.

Figures 60 and 61 show the development of strain with time for strain gauges near the transition during the second freeze of the SS and UP experiments respectively. On the prefrozen side of the UP experiment (Figure 61), the point of maximum strain gradually moved away from the transition throughout the freeze. Up to about day 40, the gauge 0.5 m from the transition showed the greatest strain. From day 40 to day 100 the greatest strain was measured 1.5 m from the transition, with the gauge 2.5 m from the transition showing the greatest strain thereafter. This behaviour can be explained by the progressive yielding of the soil above the pipe on the pre-frozen side, resulting in gradual displacement of the pipe bending inflection point away from the transition. In contrast, the point of peak strain in the pipe established at the initiation of freezing does not migrate during the SS experiment (Figure 60).

Soil deformation

While measurements taken directly from the pipe reveal the magnitude of the forces acting on it, the change in elevation of the soil surface provides insights into the nature of the pipe-soil interaction. The total elevation change over the soil surface from the initiation of the experiment to approximately day 200 is shown in Figures 62a to 62c for the fourth freeze of the SS experiment, and for the first and second freezes of the UP experiment. The line on the surface which does not form a part of the grid in Figures 62a and 62b represents the position of zero change in elevation over the course of the experiment. Note that Figure 62 shows elevation *changes*, positive and negative, from the initial state (i.e., in 61b, *after* one half of the pit was prefrozen).

The differences in thermal and soil conditions in each experiment account for the greatest differences in the surfaces: In the SS experiment (Figure 62a), the surface is dominated by heave in the silt, predominantly along the pipe axis, whereas in the first freeze of the UP experiment (Figure 62b), the dominant feature is the division between frost heave and the thaw settlement

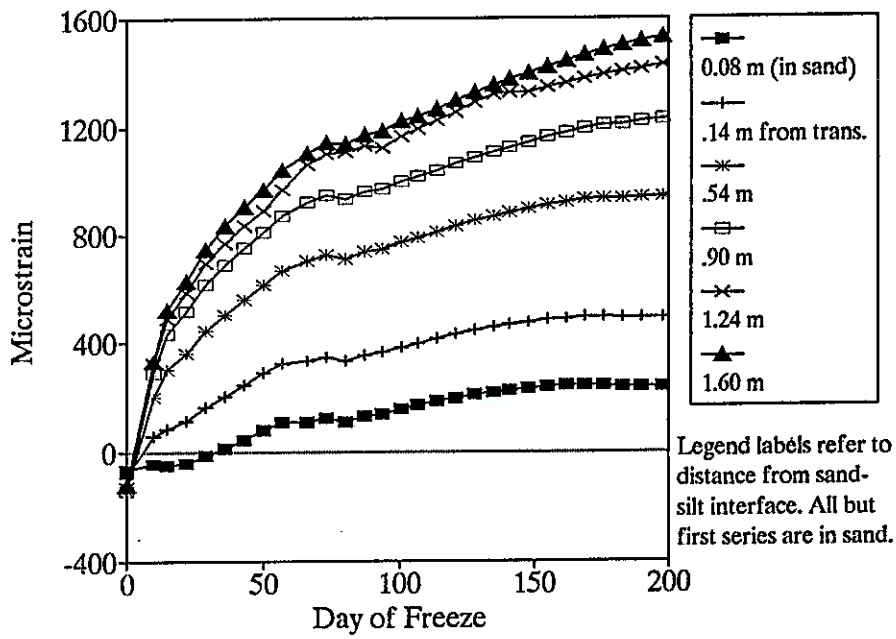

Figure 60 Evolution of pipe strains near transition, second freeze cycle sand-silt transition (SS) experiment

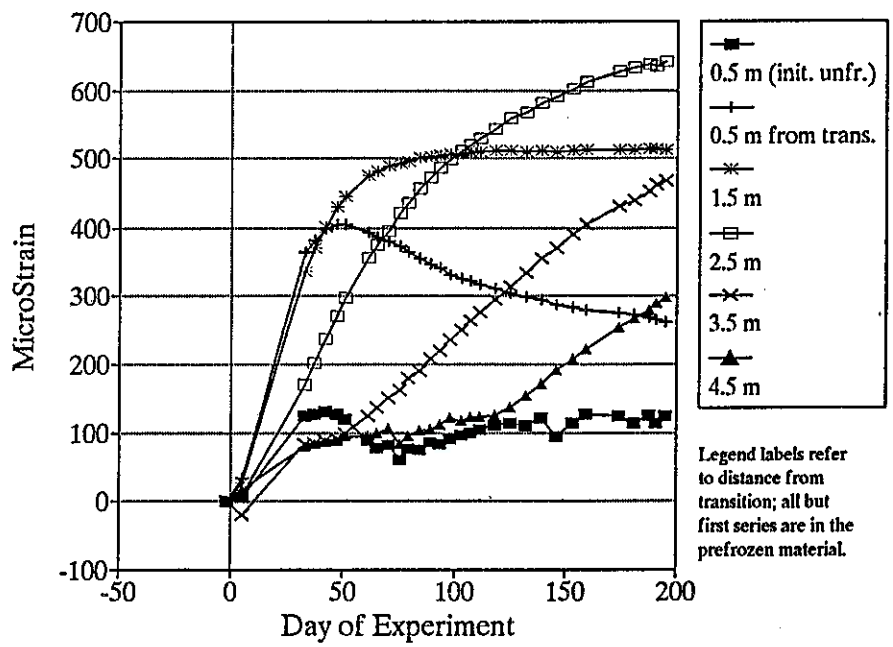

Figure 61 Evolution of pipe strains near transition, second freeze cycle frozen-unfrozen transition (UP) experiment

(negative values in the prefrozen section)due to basal thaw, as noted above. The dominance of frost heave adjacent to the pipe in the initially unfrozen soil is similar to that in 62a. In the second freeze of the UP experiment, surface temperatures closer to the pipe temperature produced heave in the initially unfrozen material which was more uniformly distributed over the surface. Heave is significantly less in the prefrozen material, although the transition is not as sharply defined as in 62b. In all cases, frost heave is augmented adjacent to the transition, due to either deeper frost penetration or (in the case of the SS experiment) the greater availability of moisture there.

Examining the figures more closely reveals significant differences in the interaction between the pipe and the soil:

- In the SS experiment, surface uplift due to the pipe extends well into the sand, despite the limited heave experienced by the sand. In contrast, surface uplift *due to the pipe uplift* in the initially unfrozen material in the UP experiment, does not extend into the prefrozen section.

- Near the transition in both UP experiments, heave is greater *adjacent* to the pipe than directly above for some distance from the interface. In the SS experiment however, the pipe axis is the line of greatest elevation along its entire length.

The void in the soil due to the presence of the pipe should result in less frost heave along the pipe axis than adjacent to it, since the pipe replaces soil which would otherwise undergo heave upon freezing. That this is not the case in the sand-silt experiments is consistent with the observation that uplift due to the pipe extends into the sand, and that the shifting position of the point of peak strain in the pipe in the UP experiment (noted above) is not evident in the SS experiment: the weakness of the developing annulus of soil in the SS experiment (relative to the prefrozen mass of material in the UP experiment) allows the pipe to acquire a gradual curvature at the transition before freezing arrests further change in shape. In contrast, in the UP experiment the frozen material holds the pipe in place at the transition until uplift of the pipe by frost heave exceeds the creep strength of the soil.

Conclusions

Nixon et al. (1990) suggest that an initially frozen-unfrozen (UP) transition should provide a more extreme design case than a soil texture (SS) transition, since the frozen side of the transition provides a stiffer restraint to upward pipe movement. The evidence presented here demonstrates this greater restraint of the pipe in the frozen material. However, with either the same duration of freezing (first freeze of UP) or the same depth of freezing (second freeze of UP), pipe strain was found to be significantly lower than in the SS experiments. This apparent contradiction is due to the details of the UP experiments, which lead to behaviour in the prefrozen material which

contributed to reduced pipe strain. In the first UP experiment, frost heave was about half of that experienced in the SS experiments, and thaw settlement on the prefrozen side allowed the pipe to tilt rather than bend. In the second UP experiment, frost penetration on the initially unfrozen side of the experiment rapidly approached the depth on the prefrozen side, reducing differential frost heave along the pipe.

For the UP experiment to provide a true comparison with the SS experiments, thermal conditions which would produce negligible frost heave or thaw settlement in the pre-frozen soil mass will be necessary. This would be relatively straightforward with a frozen soil mass several times thicker, whose thermal response time would be slower due to the distance between the surface boundary and the frost front. Achieving this condition with the relatively limited depth of the test basin in the present facility will require a delicate thermal balance which may be difficult to achieve.

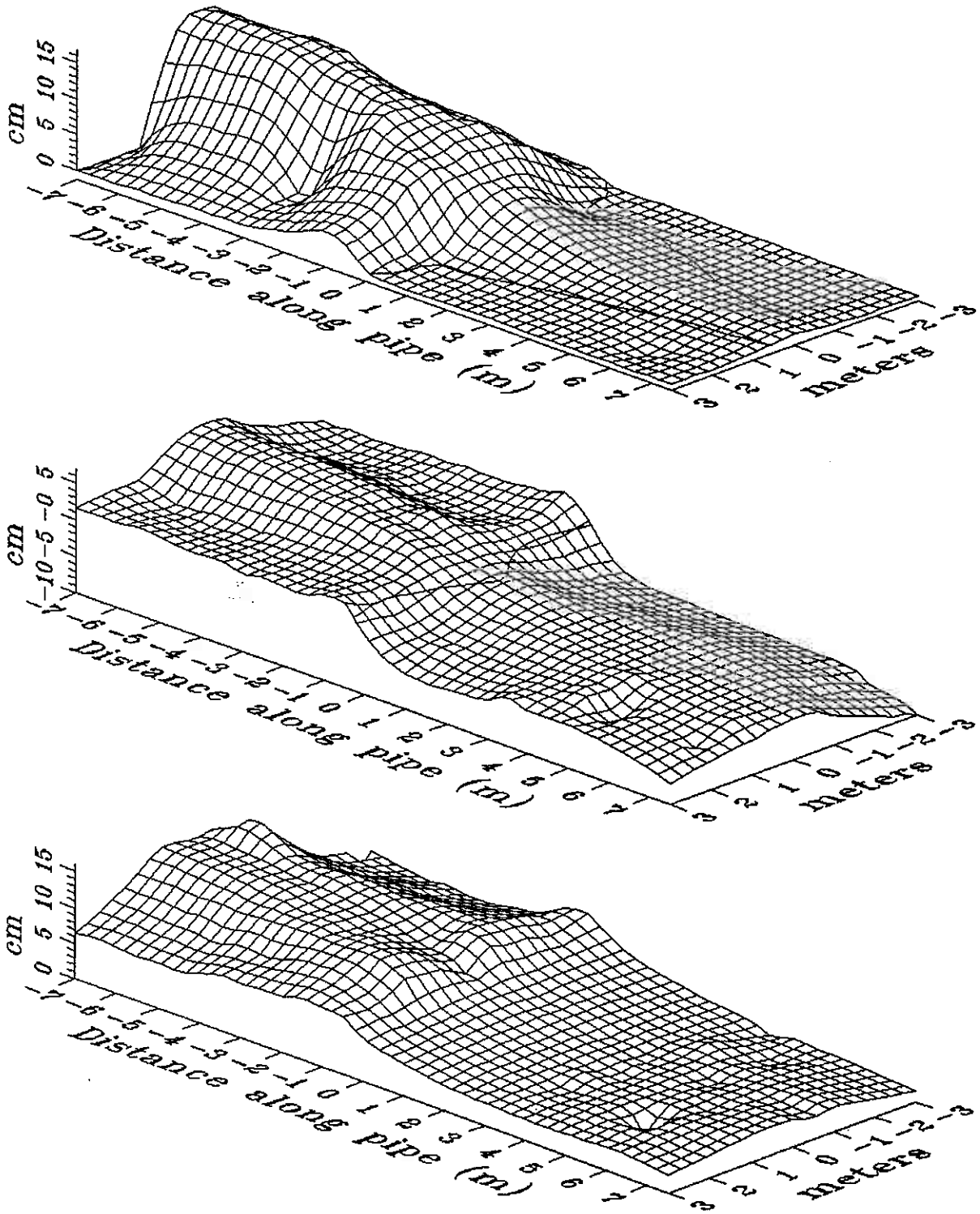

Figure 62 Soil surface elevation change from initiation to approx. day 200: Top(a): 4th freeze of SS expt.; Middle(b): 1st freeze of UP expt.; Bottom(c): 2nd freeze of UP expt. The line not part of the grid represents the line of zero elevation change.

4 Soil Microfabric Studies

The study of the microstructure of soils and the changes that occur in association with freezing and thawing have received rather little attention in the Western world. In Russia there has been considerable investigation by soil scientists. In the present project, experience is being gained in the techniques for such studies and the results obtained are being correlated with the changes in geotechnical properties which are evidenced in the successive cycles of freezing and thawing around the pipe.

Electron microscopy

In the past year, scanning electron microscopy using a cryological stage, enabled images to be obtained at sub-freezing temperatures of soil samples having various freeze-thaw histories. It is believed this is the first time that images of frozen samples have been obtained in Canada. Techniques of coating with aluminum and gold-sputter were also used to enhance the images.

The work was carried out by an Honours student, Ms. Christine Morgan, who was awarded a Natural Sciences and Engineering Research Council Summer Bursary for the purpose. She prepared an extensive report on her work, which included a survey of the literature and many striking illustrations of the images of the frozen soil. Scanning electron microscopy is a complex subject and her work demonstrated its potential for the study of freezing effects on soils. It is hoped that the experience she gained and the techniques consequently now available, can be applied to a detailed study correlating changes at the smallest observable scale with changes in soil engineering behaviour. This will bring the study of the soil part of the pipe-soil system to a similar level to that of the metallurgy of pipes - where electron microscopy is a long-established tool.

Soil microfabric

Striking differences in microstructure, clearly visible in slides examined by microscope, were found in samples taken from the Caen silt prior to the commencement of the current program. These samples, which had experienced up to four freeze-thaw cycles, thus provided a baseline for comparison with never-frozen material, or samples exposed to a single freeze-thaw cycle. The main forms observed have been described in a paper to the 1991 France-Canada Seminar (Williams, 1993) and recently to the International Permafrost Conference 1993 (the paper will be published in the Conference Proceedings). These results were also described in the Masters thesis (1992) of Les White (currently field project manager), where he also reported on the techniques that can be used and reviewed the literature on the subject.

During the year covered by the present report, White has carried out a comparison of the microstructure of specimens obtained during summer 1992,

and thus exposed to the first freeze-thaw cycle, with their geotechnical properties and field behaviour. This has included numerous determinations of hydraulic conductivity. With the assistance of French colleagues digital image analysis has been used to examine porosity. This new technique was also applied to specimens of the Caen silt with the kind assistance of Agriculture Canada who provided specialised laboratory and equipment facilities for studies carried out in Ottawa.

Studies of microfabric appear a most promising approach to a proper understanding of soil behaviour. It should allow more accurate prediction of soil behaviour not least in respect to stresses and deformations around sensitive structures such as pipelines. Fortunately the current NSERC funding provides for White to continue his Ph. d. studies on certain aspects of these matters.

5 Pipe Pullout Test

The two important geotechnical factors which control the stresses imposed on buried pipelines crossing a soil thermal or textural transition are the rate of frost heave uplift and the resistance of the frozen soil to pipe uplift (Nixon et al. 1990). During the installation of the heave experiment at Caen, provision was made to perform uplift tests with a buried section of pipe and a buried steel plate, both of which have been maintained in the frozen soil for over two years. These tests would measure directly the uplift resistance of the Caen silt for the particular conditions of the Caen experiment, thus providing an important parameter required in modelling of the pipe behaviour and determining the stresses which develop during the experiment. While no such test can provide generally applicable results, the test is needed in order to calibrate theoretical models of the soil's resistance to pipe uplift. This resistance of the soil to frost heave uplift is considered to be one of the governing criteria in gas pipeline design under frost heave conditions.

A constant rate pullout test is preferable to a constant load test, since the results will yield both the peak and the residual pullout resistance of the soil. The time dependent creep properties of the frozen soil produce an uplift resistance which is somewhat dependent on the uplift rate. The present test has been designed to produce a constant pipe uplift rate of 1 mm per day, which is within the range experienced by the pipe in the course of a freezing cycle.

The test is to be done on a section of pipe identical to the pipe used in the main experiment. The trench was backfilled in the same manner and connected to the circulation system in series with the main pipe. Soil conditions should thus closely match those of the main experiment. The pipe section is 1.5 m in length, providing a ratio of length to diameter which reduces end effects to an acceptable level. It was reinforced with a 120° section of pipe added to the underside of the test specimen (fitting between the test section and the pipe cradles), effectively doubling the thickness of the pipe where it bears on the pullout cradles.

The steel plate was buried adjacent to the short pipe, at the depth of the pipe axis. Results of this test will provide an indication of the degree to which pullout plate tests can be substituted for results for actual pipe tests, which though more realistic are more difficult to execute.

The requirements of the pullout test are that the pipe be pulled through the soil at a constant rate of displacement of 1 mm day^{-1}, for a total of 30 days (30 mm). This is estimated to require a total force not exceeding 400 KN.

An early prototype for the pullout apparatus consisted of a rigid frame bearing on the soil surface, with the uplift rate controlled by an electric motor connected through a reduction

gear actuator. This system was rejected primarily due to uncertainties about the uniformity and rate of creep of the soil beneath the footings (frost thickness is not uniform). In addition, it was felt that a rigid frame would store strain energy transferred by the actuating system, releasing it in short bursts as the stored energy surpassed the uplift resistance. Further, the cost of the actuating system alone was expected to exceed the cost of the entire system as finally designed.

Pullout apparatus

All components of the pullout apparatus have been purchased or are under construction.

The system uses two pneumatic cushions which underlie the ends of a frame (two steel I-beams bolted together). The frame connects to the buried pipe via the rods attached to the pipe cradles, the rods passing between the beams (Figures 63 and 64). The I-beam assembly and pipe are forced upwards as the cushions inflate. The rate of pipe uplift is controlled by feedback between the displacement sensors and valves controlling pressure in the pneumatic cushions. Because uplift is controlled by the displacement of the pipe (and not displacement of the cushions themselves), the system automatically compensates for creep of the frozen soil

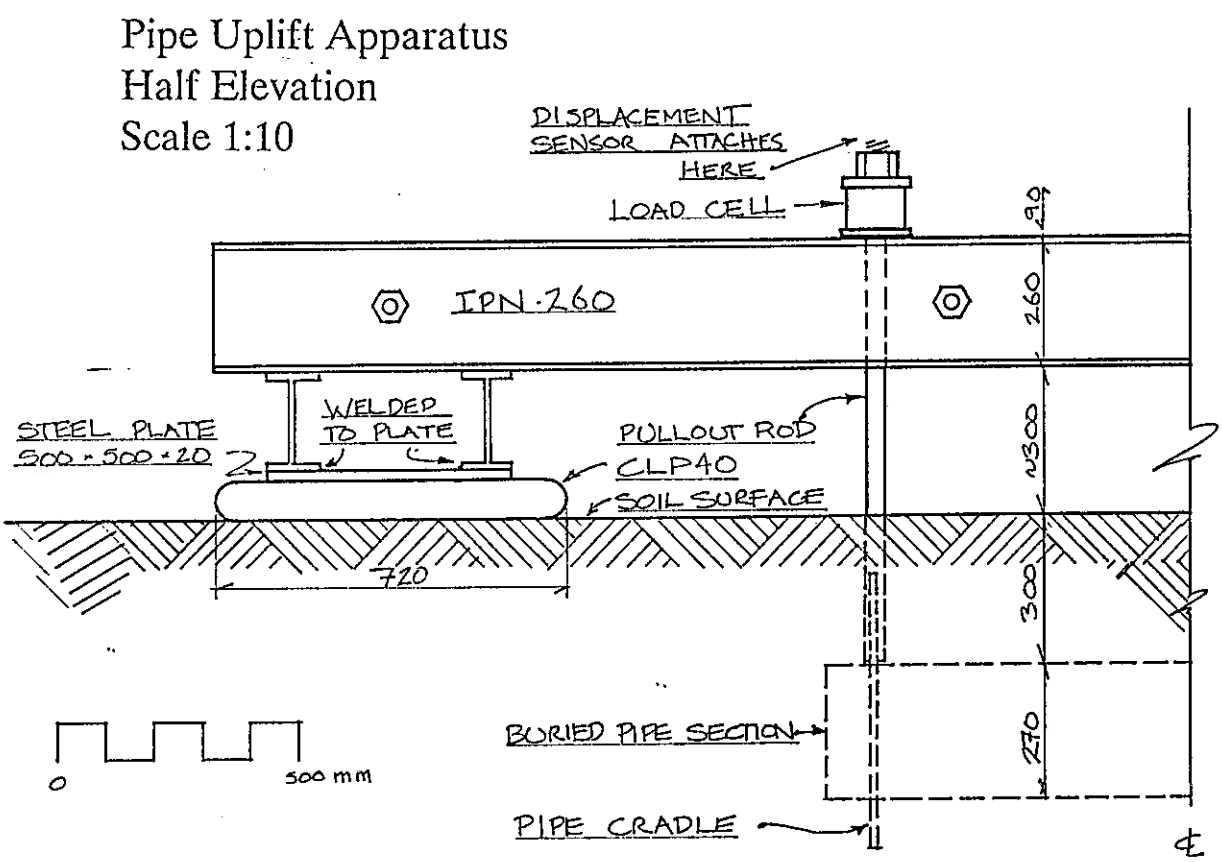

Figure 63

Pipe Uplift Apparatus
Half Plan
Scale 1:10

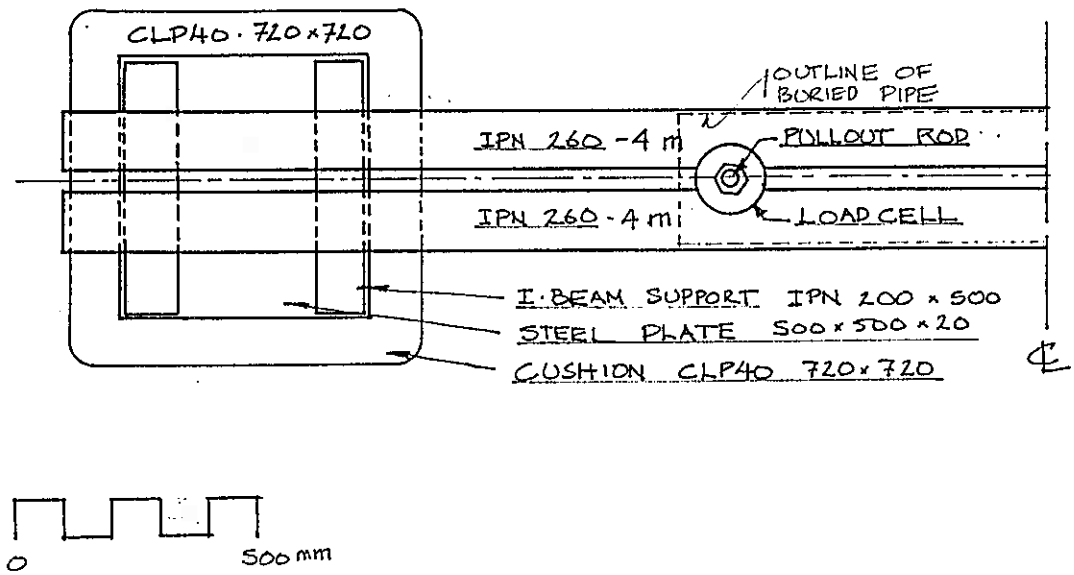

Figure 64

where the cushions bear on the surface.

Mechanical

The overall height of the pullout frame is controlled by the height of the rods connected to the pipe cradles. 200 mm of clearance is also required beneath the I-beam assembly, to allow passage of the sleeves connecting the small pipe to the air circulation system. This clearance is provided by short I-beam sections welded to a 20 mm thick steel plate which bears on the pneumatic cushions. The I-beam assembly consists of 260 mm high I-beams, bolted together and resting on top of the short I-beam sections mentioned above. Bolts are preferable to welding, to simplify assembly in place. The rods attached to the pipe pass between the I-beams. A wooden pad will be placed between the soil and one of the pneumatic cushions in order to level the I-beam assembly at the outset of the test.

Pneumatic

Uplift force will be provided using fibre reinforced elastomer pneumatic cushions (specifications included in appendix). Pressure is supplied using bottled nitrogen, supplied to the cushions through a simple system of valves. The pneumatic cushions chosen are 720 mm square, and can

provide up to 400 KN of uplift each. There is a non-linear relationship between maximum displacement and total load, with the model chosen providing up to 130 mm of lift for a 200 KN load (the anticipated maximum load on each cushion) when the system operates at 8 atmospheres pressure. The extra displacement capacity will permit automatic compensation for soil creep beneath the cushions.

Control of uplift rate

The rate of pipe uplift will be controlled using the pipe displacement sensors in a feedback loop. The output from a comparison potentiometer will be made to change at about 24 mV per day, matched to the change of output from the displacement sensors when the displacement rate equals 1 mm day^{-1}.

The control circuit will compare independently the outputs from the displacement sensors and the comparison potentiometer to decide whether to open or close the valves for the cushions. Each cushion will be controlled separately, using the displacement sensor nearest each cushion for feedback control. If the potentiometer output exceeds that of the displacement sensor (indicating that the displacement is less than required) then the cushion valve remains open. If the displacement sensor output exceeds that of the potentiometer (indicating that the displacement exceeds that expected) then the cushion valve will be closed.

To prevent runaway displacement when the soil's peak uplift resistance has been exceeded, the system will incorporate a small leak between the valve and the cushion. This will ensure that the uplift force provided by the cushions can be reduced when the uplift resistance declines.

Measurement

Displacement sensors and load cells will be connected at the point of attachment between the pullout frame and the rods connected to the pipe cradles. Load cells will be positioned between washers under the nut which connects the pullout frame to the pipe rod. Displacement sensors will be attached to a rigid frame mounted on the wall, then connected to the pipe pullout rods.

Load cell and displacement measurements will be made using the datalogger which is currently in use for strain measurements on the principal pipe experiment. The software controlling this datalogger allows real-time monitoring of the data stream, which is stored on disk automatically.

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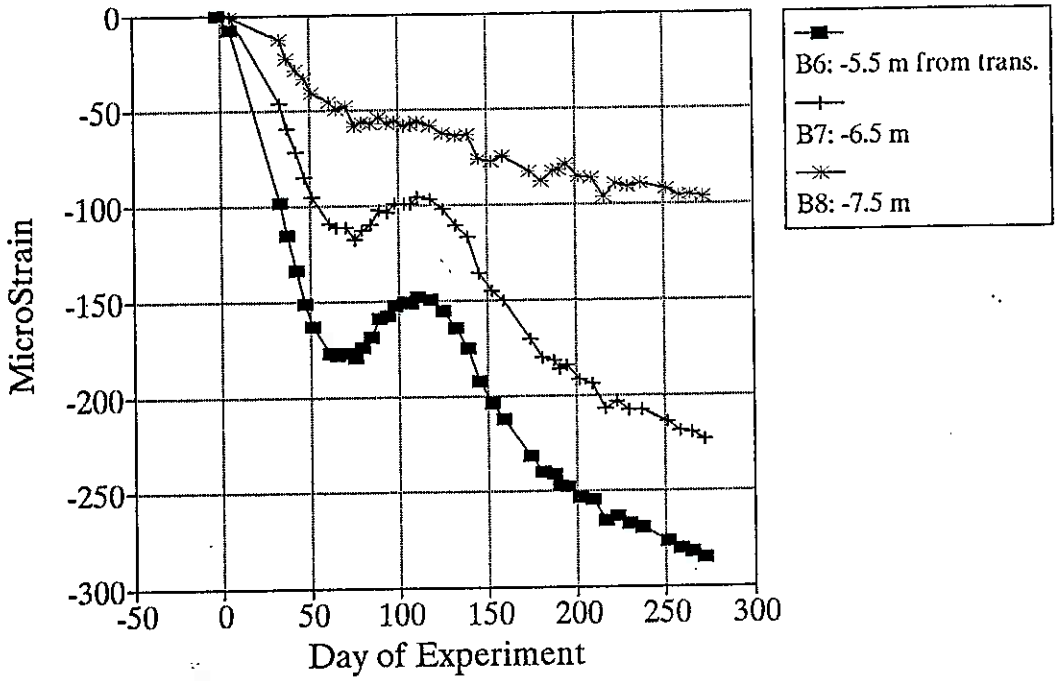
Appendix

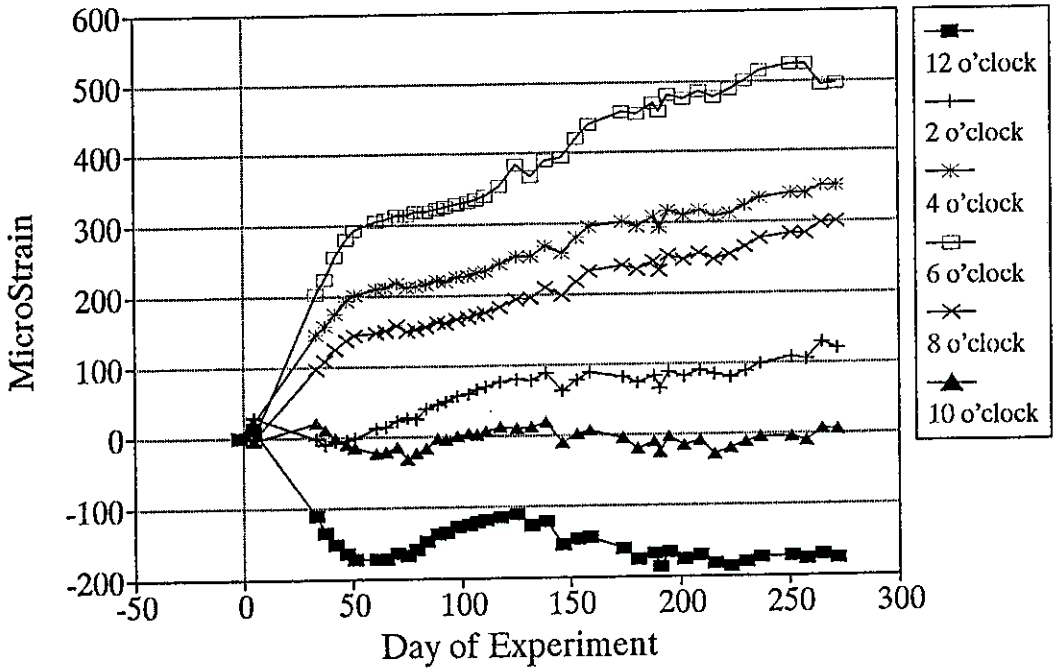
Graphs of data for individual strain measurements

Specifications for pneumatic cushions

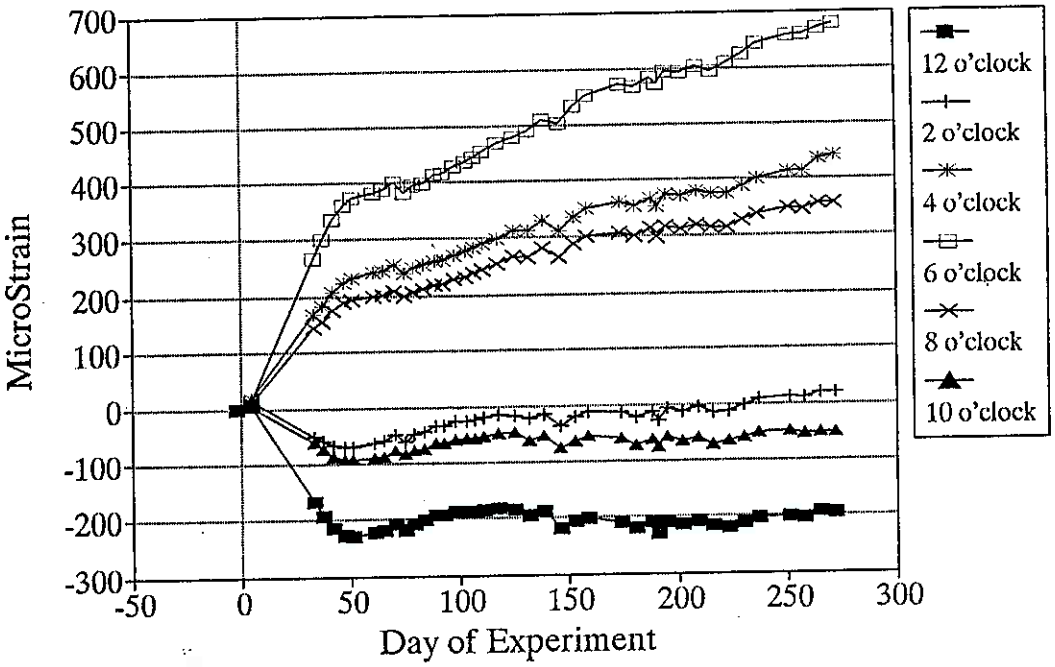
Strain Gauges: Half Bridge
On Initially Unfrozen Side



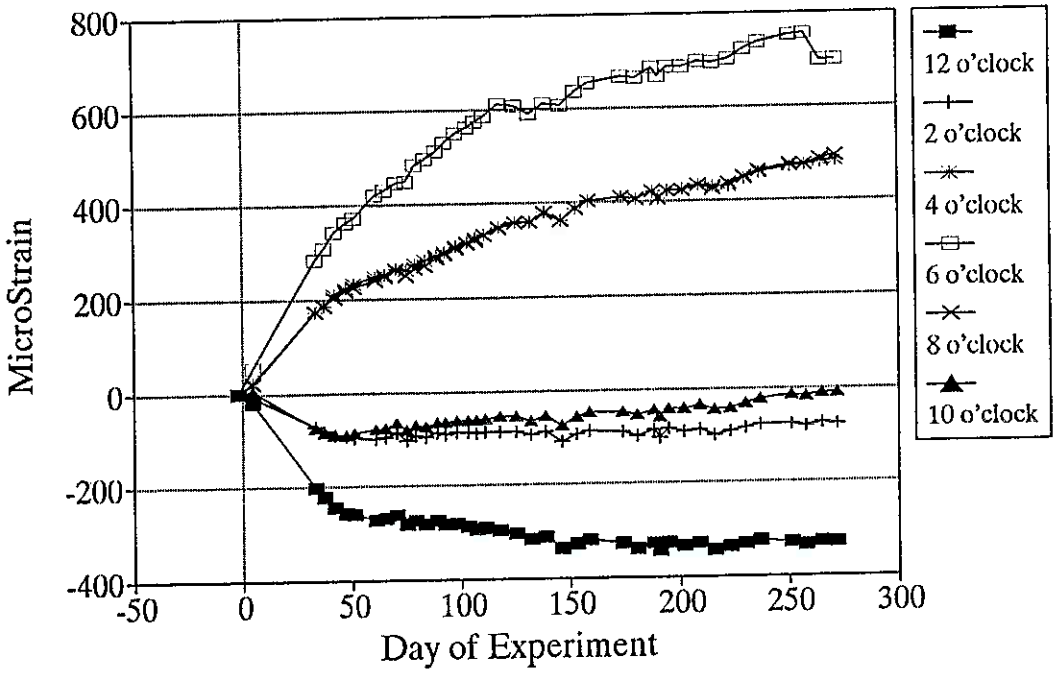
Radial Strain Gauge Array
B5: 4.5 m from trans., unfrozen side



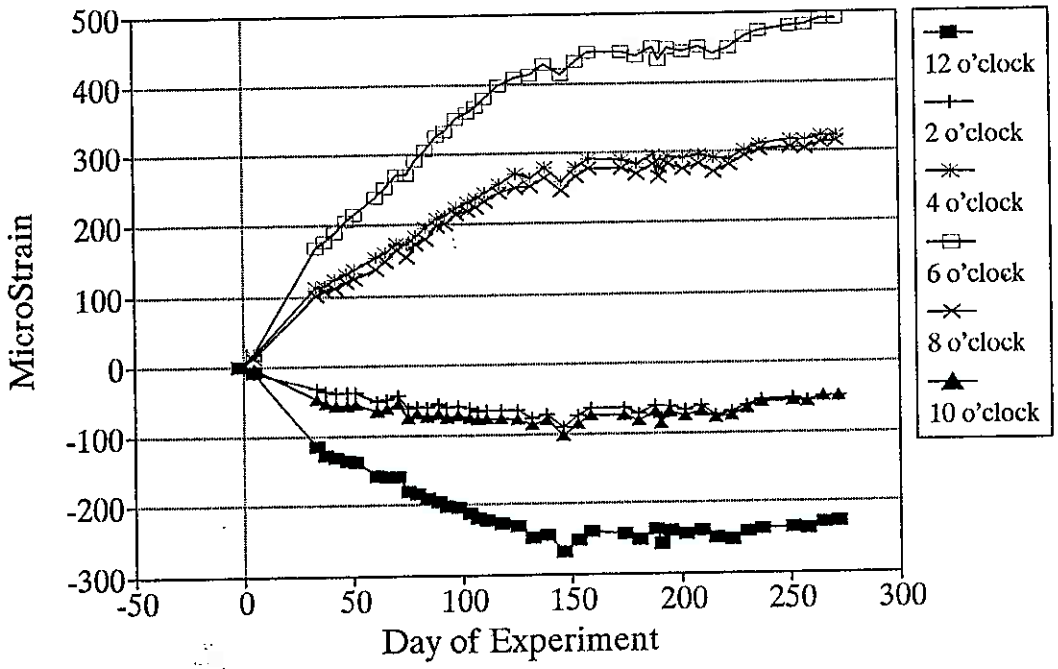
Radial Strain Gauge Array
B4: 3.5 m from trans., unfrozen side



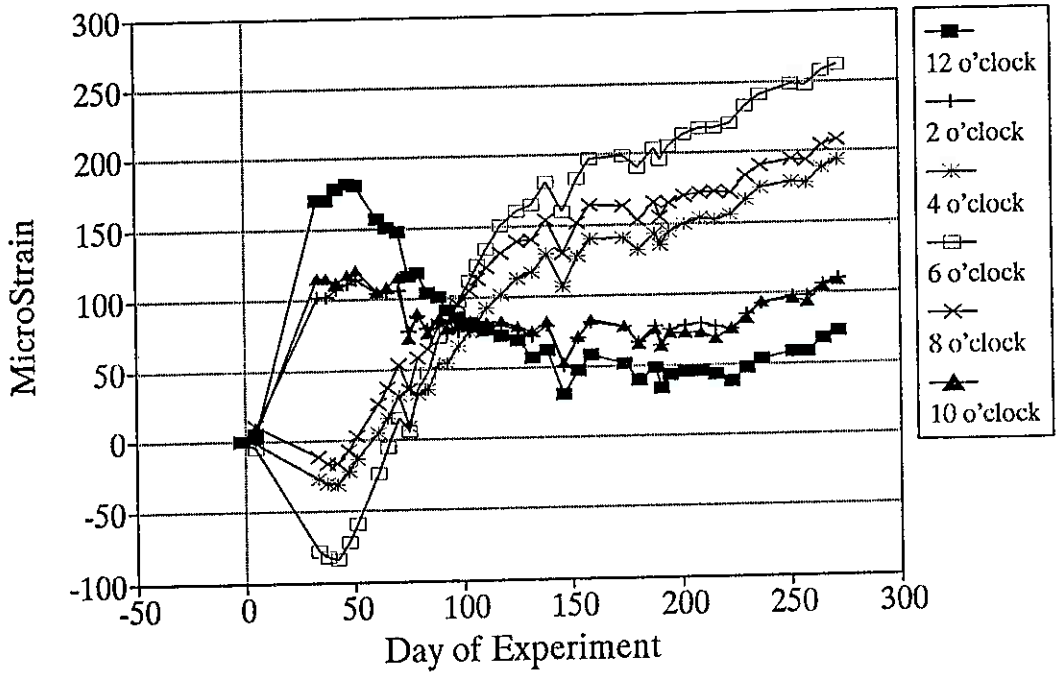
Radial Strain Gauge Array
B3: 2.5 m from trans., unfrozen side



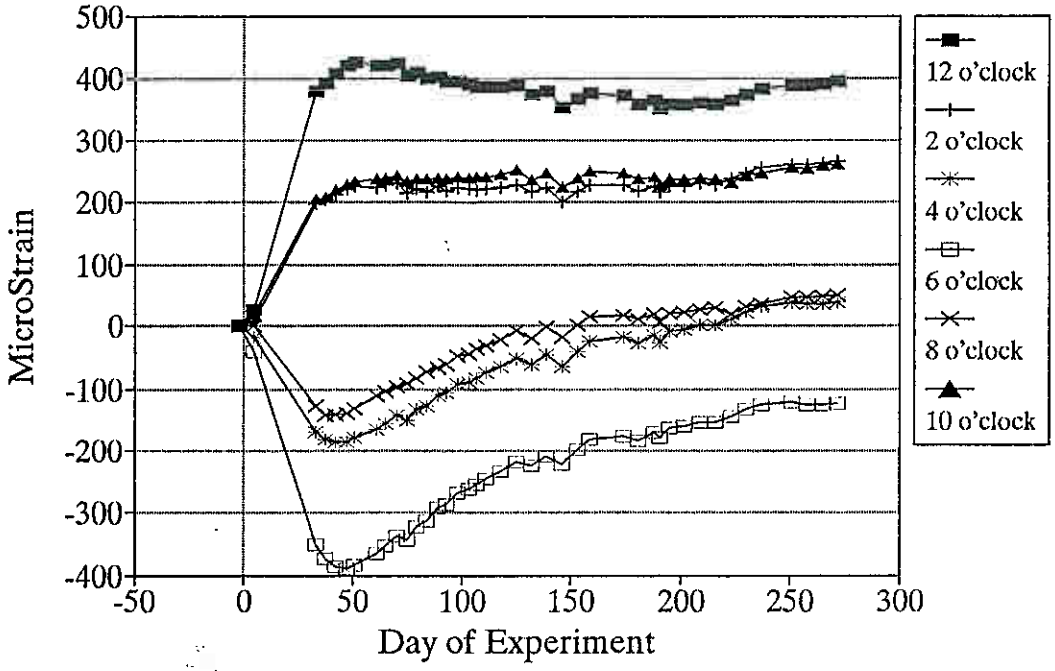
Radial Strain Gauge Array
B2: 1.5 m from trans., unfrozen side



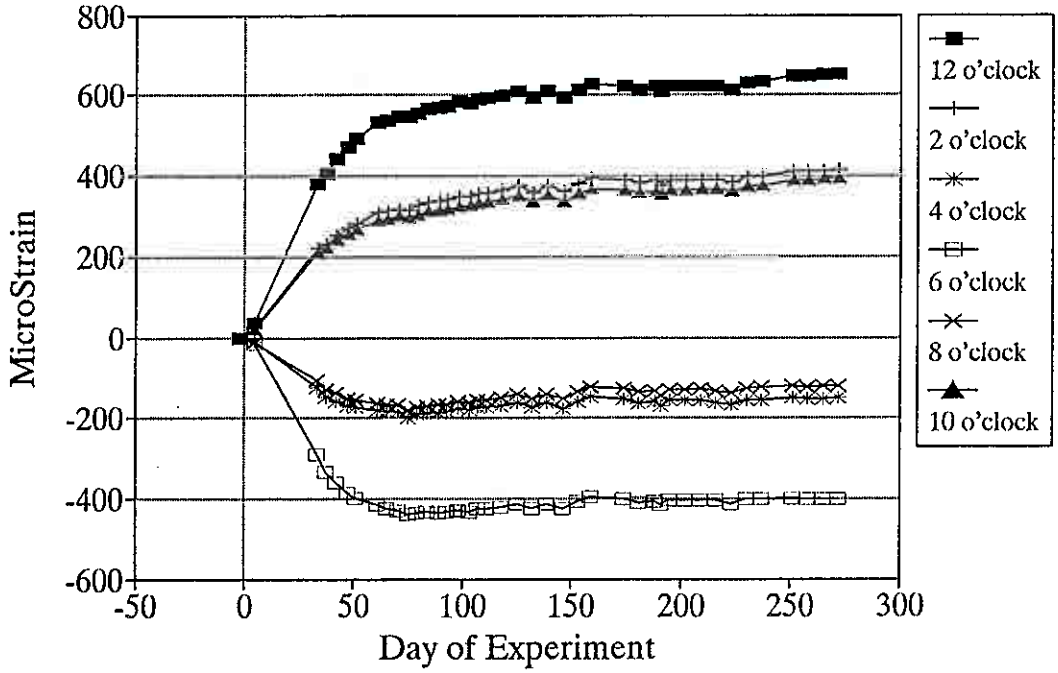
Radial Strain Gauge Array
B1: 0.5 m from trans., unfrozen side



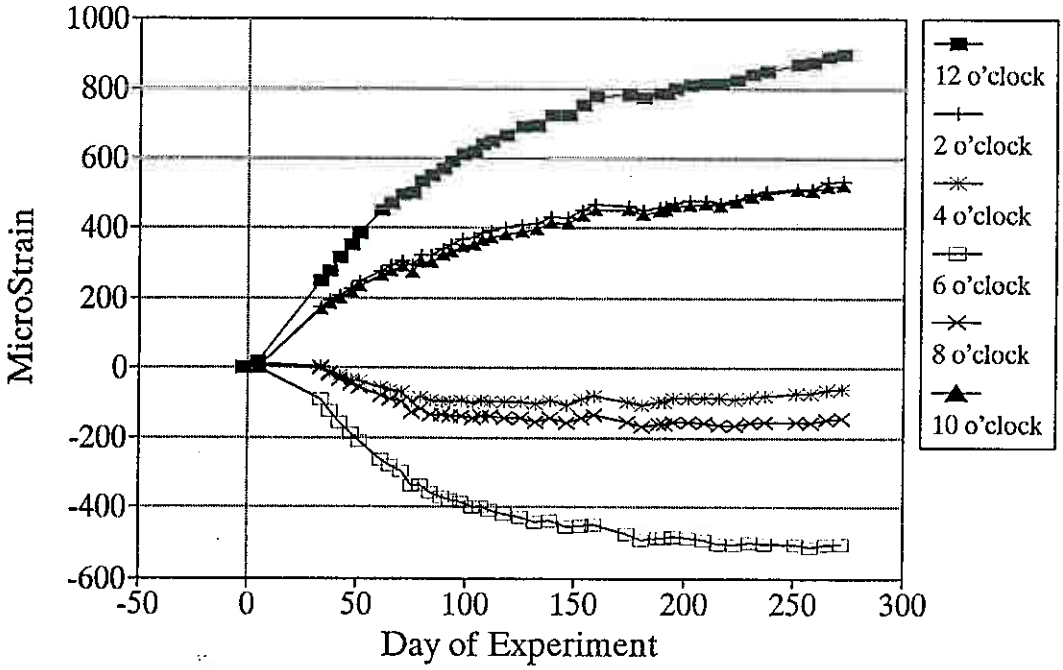
Radial Strain Gauge Array
A1: 0.5 m from trans., prefrozen side



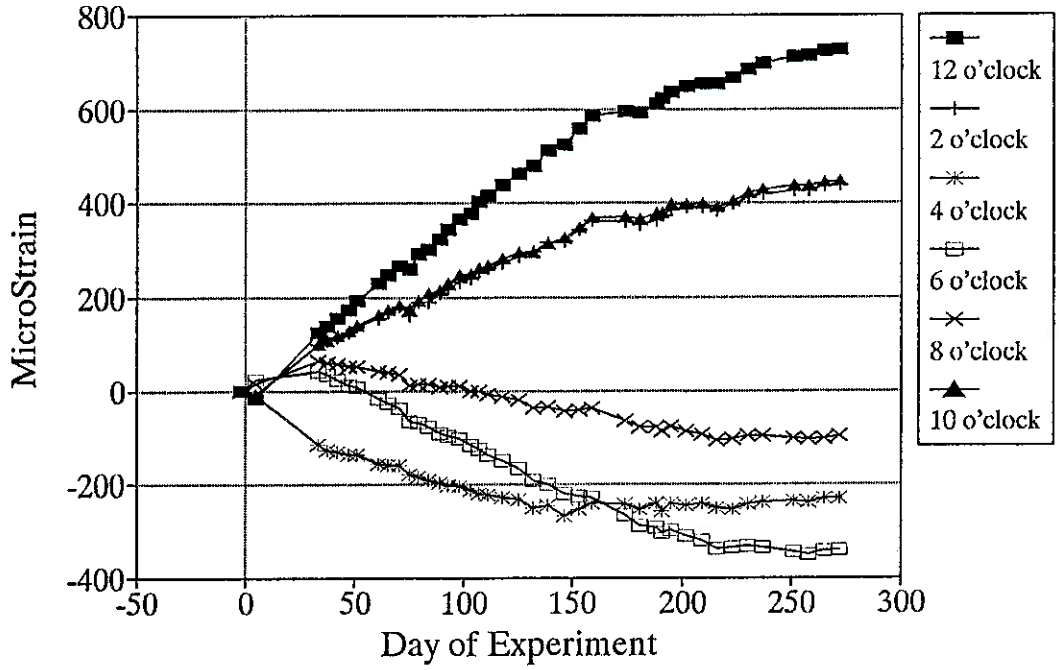
Radial Strain Gauge Array
A2: 1.5 m from trans., prefrozen side

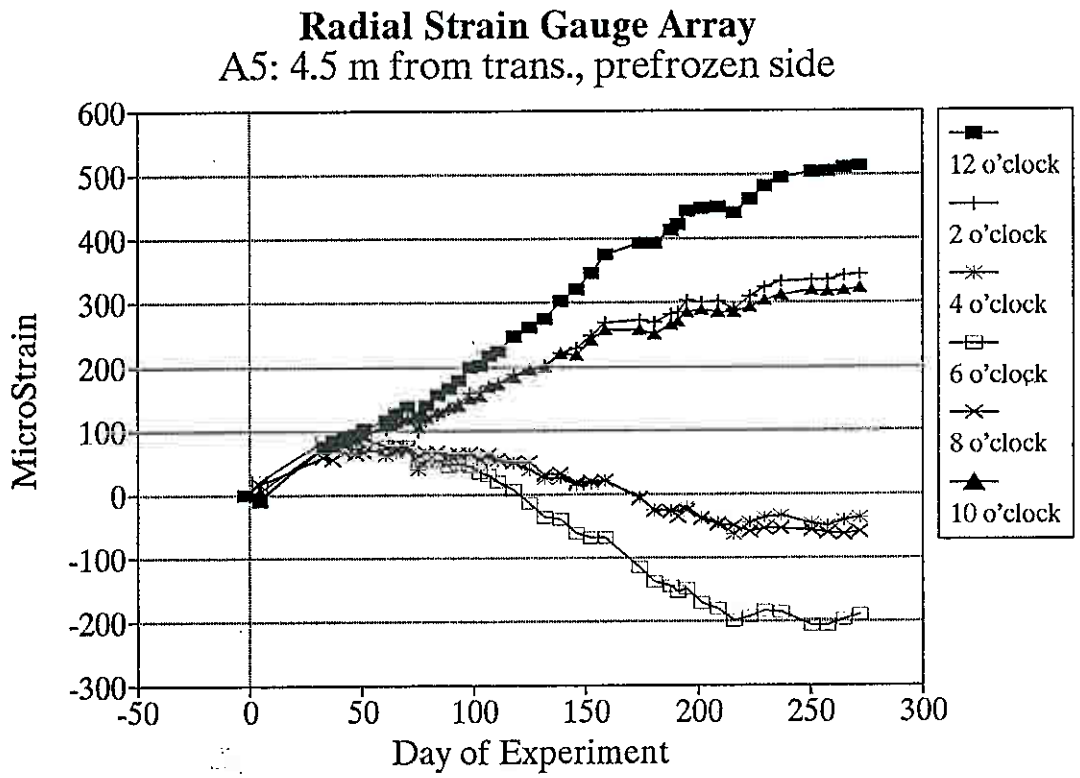


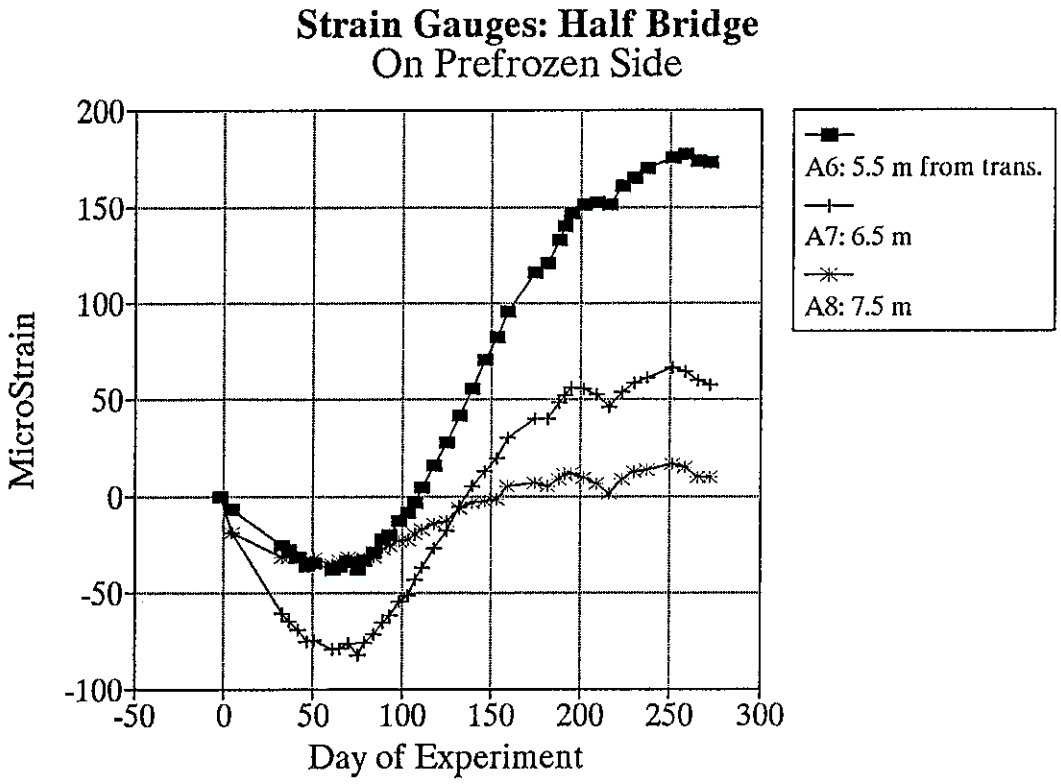
Radial Strain Gauge Array
A3: 2.5 m from trans., prefrozen side



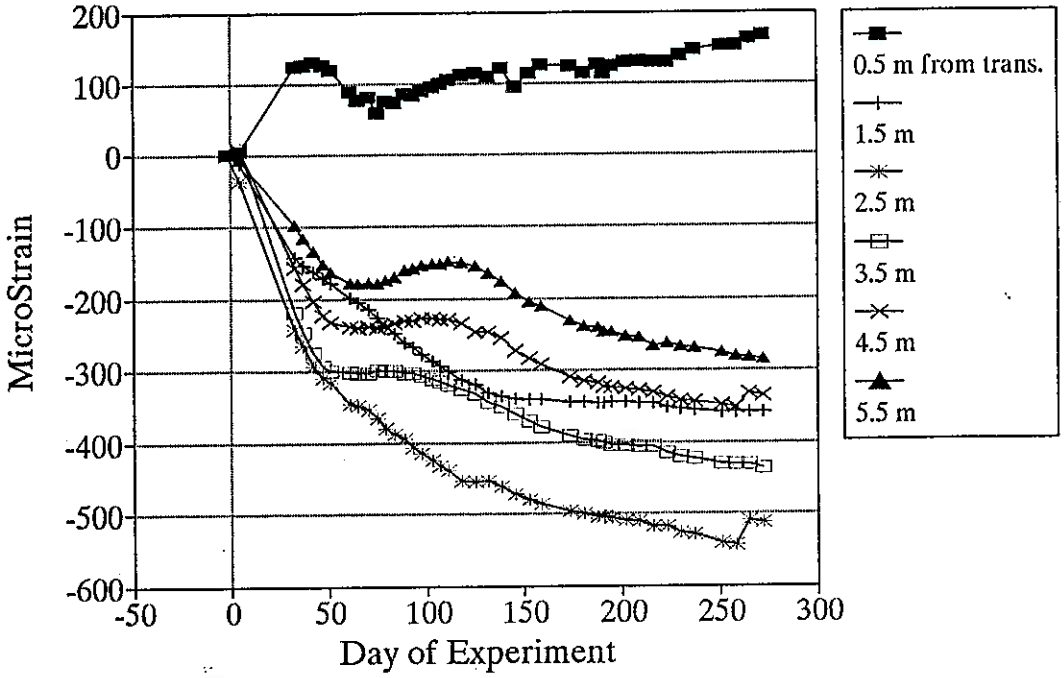
Radial Strain Gauge Array
A4: 3.5 m from trans., prefrozen side



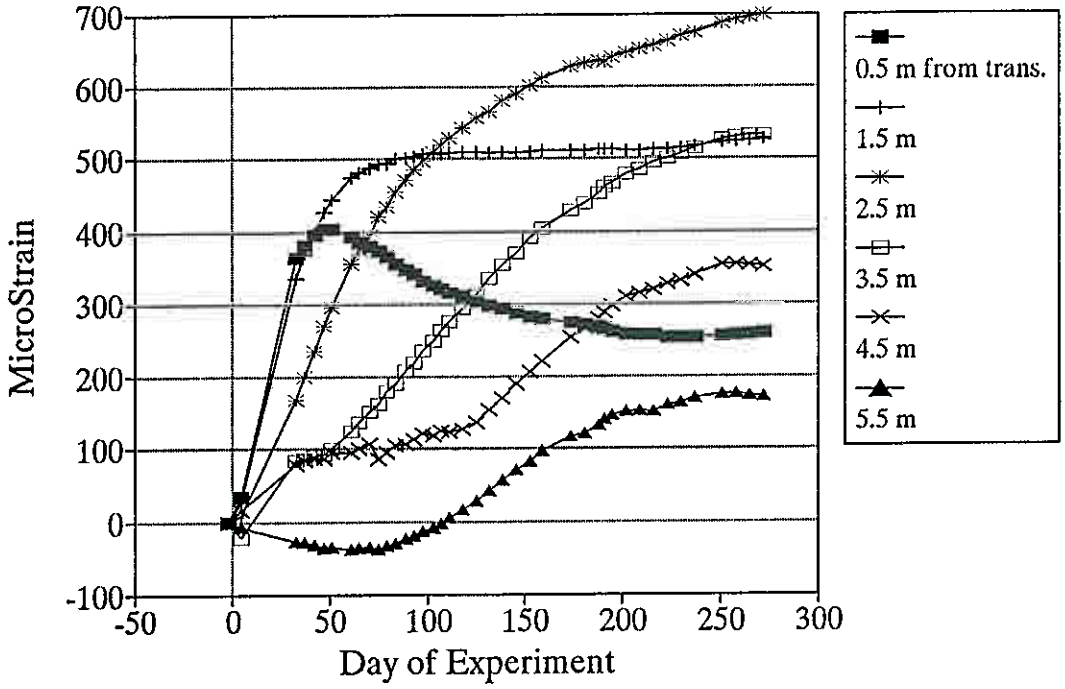

Radial Strain Gauge Array
A5: 4.5 m from trans., prefrozen side
MicroStrain
600
500
400
300
200
100
0
-100
-200
-300
-50
0
50
100
150
200
250
300
Day of Experiment
12 o'clock
2 o'clock
4 o'clock
6 o'clock
8 o'clock
10 o'clock


Strain Gauges: Half Bridge
On Prefrozen Side
MicroStrain
200
150
100
50
0
-50
-100
-50
0
50
100
150
200
250
300
Day of Experiment
A6: 5.5 m from trans.
A7: 6.5 m
A8: 7.5 m

Strain Gauges
12 and 6 o'clock on pipe, unfrozen side



Strain Gauges
12 and 6 oclock on pipe, prefrozen side



Pipe Uplift Apparatus

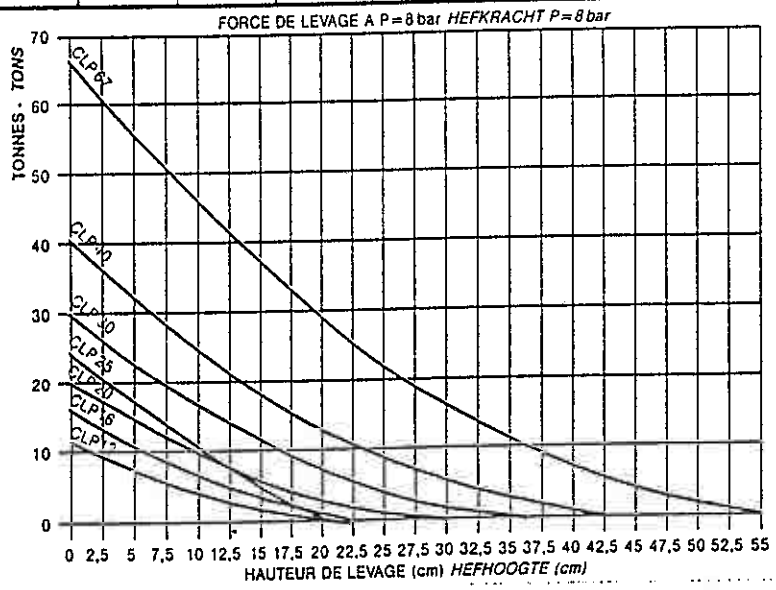
Uplift Characteristics of "Pronair" Lifting Cushions

CARACTERISTIQUES TECHNIQUES DES COUSSINS DE LEVAGE PRONAIR®

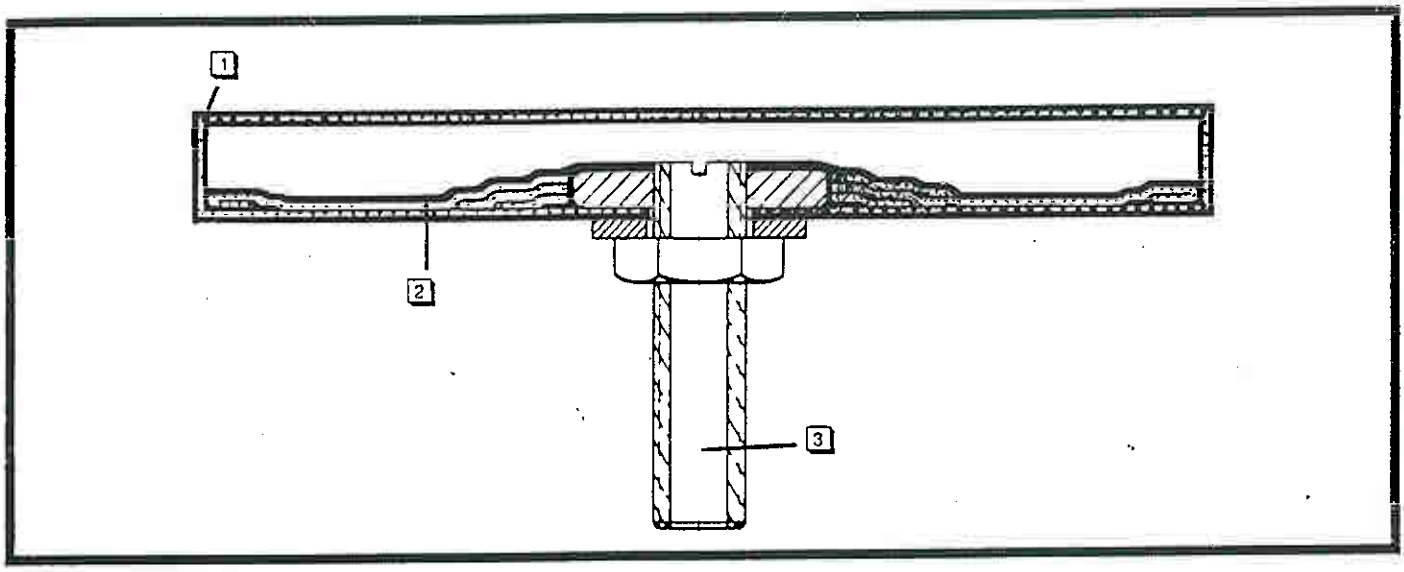
TECHNISCHE KARAKTERISTIEKEN VAN DE PRONAIR® HEFKUSSENE

REFERENCE / *KODE*	CLP 12	CLP 16	CLP 20	CLP 25	CLP 30	CLP 40	CLP 67
DIMENSIONS - MM / *AFMETINGEN - MM*	390 x 390	540 x 390	510 x 510	1000 x 320	620 x 620	720 x 720	920 x 920
EPAISSEUR A VIDE - MM / DIKTE (LEEG) - MM	25	25	25	25	25	25	25
MASSE - KG / GEWICHT - KG	3	5	7	8	12	17	25
FORCE DE LEVAGE - TONNE / HEFKRACHT - TON	12,17	16,9	20,8	25,6	30,6	41,4	67,7
PRESSION DE SERVICE - BAR / WERKDRUK - BAR	8	8	8	8	8	8	8
PRESSION D'ECLATEMENT - BAR / BARSTDRUK - BAR	51	51	37	59	30	26	20
PRESSION D'EPREUVE - BAR / BEPROEVINGSDRUK - BAR	12	12	12	12	12	12	12
COURSE MAXI - MM / MAX. HEFHOOGTE - MM	231	231	324	203	394	458	585
CAPACITE D'AIR - L / LUCHTINHOUD - L	90	130	211	205	405	650	1332

FORCE DE LEVAGE
KEFKRACHT



Principle of Lifting Cushion Operation



Le vérin souple PRONAIR est constitué de trois éléments principaux :
1 Le corps du vérin souple en tissu de fibres synthétiques haute résistance enduit, sur chaque face, d'élastomère.
2 La chambre, en élastomère non toilé, destinée à réaliser l'étanchéité du vérin souple PRONAIR vis-à-vis du fluide de gonflage choisi.
3 La tubulure servant à la fois à l'alimentation en fluide de gonflage et à la fixation par rondelle et écrou.

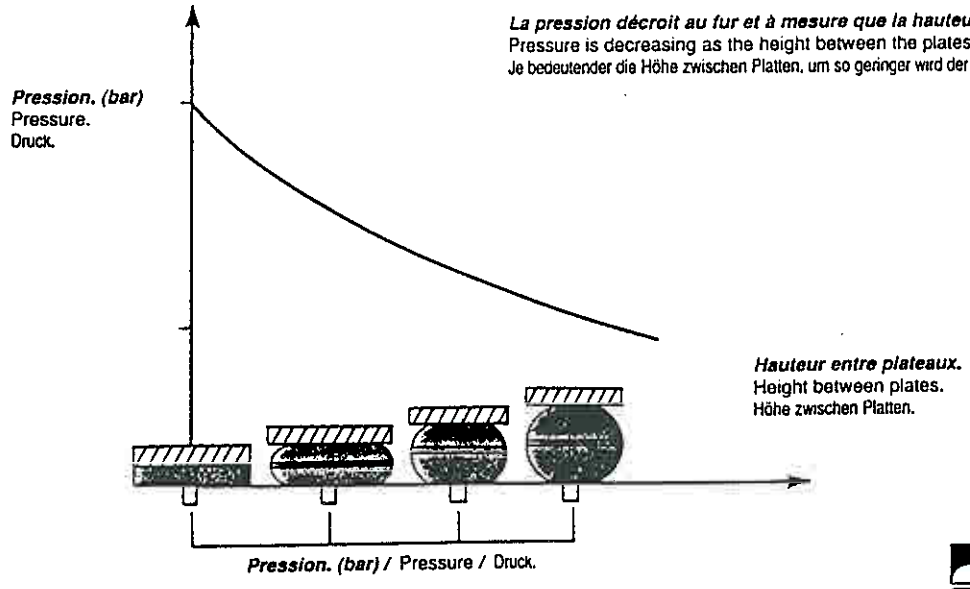
The PRONAIR lifting bag is made up of three main parts :
1 The body of the lifting bag is made of high strength synthetic fibre coated on each side with elastomer.
2 The chamber, made of non reinforced elastomer, is designed to be leakfree, irrespective of the inflating fluid, and to have a high degree of flexibility with a long life expectancy.
3 The stem acting both as a means of introducing the inflating fluid and a means of attachment together with a washer and nut.

Das PRONAIR-Druckluftkissen besteht hauptsächlich aus drei Elementen :
1 Der Körper ist aus sehr widerstandfähigem, beiderseits mit Elastomer beschichtetem synthetischen Fiberstoff.
2 Die Kammer aus unverstärktem Elastomer dient zum Abdichten des Druckluftkissens gegen Füllflüssigkeit.
3 Das Ventil dient sowohl zum Auffüllen mit einer Flüssigkeit, als auch zum Befestigen mit Scheibe und Mutter.

Principe de fonctionnement des vérins souples PRONAIR

Operating principle of PRONAIR lifting bags

Arbeitsprinzip der PRONAIR-Druckluftkissen



PRONAL
L'Ingénierie de l'Elastomère