FOOTHILLS PIPE LINES (YUKON) LTD.

PERFORMANCE ANALYSIS
OF
CALGARY FROST HEAVE TEST FACILITY

RECEIVED
FEB 25 1980
State of Alaska
Office of
Pipeline Coordinator

SEPTEMBER 1, 1979

EBA Engineering Consultants Ltd.

FOOTHILLS PIPE LINES (YUKON) LTD

PERFORMANCE ANALYSIS

of

CALGARY FROST HEAVE TEST FACILITY

September 1, 1979

EBA Engineering Consultants Ltd.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I INTRODUCTION

The operation of a chilled gas pipeline in the unfrozen ground over continuous and discontinuous permafrost terrains will result in the formation of a frost bulb around the pipe. For fine grained soils, freezing may cause volumetric expansion of in-situ pore water and water migrating to the frost front. This volumetric expansion, resulting in uplift of the pipe, is called frost heave. Frost heave thus presents some unique problems to the proposed Alaska Highway Gas pipeline project, for which no previous pipelining experience is available.

Extensive engineering studies required for final design decisions have been undertaken by the sponsors of the project. These studies include the various field investigations to delineate the extent of the problem, the development of a numerical model to predict frost action on pipelines, structural analysis of a pipeline subject to differential frost heave, and the development of potential mitigative design measures.

In addition to theoretical and laboratory studies undertaken to understand the frost heave phenomenon and to develop a model to predict the frost heave magnitude over the design life of the pipeline, the sponsors of the Alaska Highway Gas pipeline project are operating two full scale frost heave testing facilities (Figure 1.1). One, which is located in Calgary, is operated by Foothills Pipe Lines (Yukon) Ltd., while the other, near Fairbanks, Alaska, is operated by Northwest Alaskan Pipeline Co. Both test sites utilize full scale 48-inch diameter pipe sections and circulate chilled air. The growth of the frost bulb and the movement of pipe sections are monitored, as they are integrated components of the frost heave phenomenon.

The objectives of the large scale test facilities are as follows:

(i) to obtain a better understanding and appreciation of the frost heave mechanism;

(ii) to provide input, substantiate and improve the frost heave predictive mathematical model;

(iii) to test the effectiveness of mitigative design measures; and

(iv) to provide input, substantiate and improve pipeline structural analysis models.

This report presents detailed analyses of the performance to date of the Calgary Test facility, which has been in operation since March 21, 1974. Not only has the data regarding the ground temperatures and frost heave measurements been compared with laboratory testing results and model predictions, detailed field drilling programs have also been conducted to investigate the characteristics of the segregated ice formed within the frozen zone.

Ground freezing and associated frost heave from a chilled pipeline is of decay nature. The data obtained at the test site over the last 5 years should provide the major portion of the frost heave to be encountered, thus presenting an understanding and appreciation of the frost heave problem.

This work was authorized in June, 1978 by Dr. Francis Yip of Foothills Pipe Lines (Yukon) Ltd.

II DESCRIPTION OF TEST FACILITY

2.1 Site Selection

The main criteria for the selection of a frost heave test site are as follows:

(i) Soil conditions at the test site should possess many of the troublesome conditions likely to be encountered along the pipeline route.

(ii) As the size of the frost bulb, around the pipe, to be considered is about 7 metres, a sufficient depth of frost susceptible soil is necessary to ensure that the frost front will be maintained within that material over the test duration.

(iii) Clayey silts are traditionally the more frost susceptible soils. These soils posess the ability to attract water during freezing and at the same time have a high enough permeability to permit the passage of water migrating through the soil to the freezing front.

(iv) The soil strata should be as uniform as possible so that the interpretation of the test results can be made in a definitive manner with a minimum of uncertain factors.

(v) The presence of a high water table provides a ready supply of water to the freezing front. The availability of water is a priority requirement for frost heaving.

(vi) Easy access of service systems such as electricity, water and sewer, is a favorable economic consideration.

2.2 Geology and Subsurface Soil Properties

The site is located at the University of Calgary Research Park, as shown in Figure 2.1. The site is relatively flat. The overburden at the site consists of lacustrine sediments deposited in Glacial Lake Calgary in late glacial times. The sediments in this area have a thickness of about 25 metres (85 feet).

The generalized soil stratigraphy, obtained from detailed soil investigations (Ref. 1,2 and 3), consists of sandy silt to a depth of about 5 metres (15 feet), underlain by clayey silt (till) with traces of sand, coal and fine gravel. Figure 2.2 shows representative grain-size distribution of the soils at the test site, compared with those of Fairbanks silt and Mackenzie Valley soils. The moisture content varied between 18% and 20%. The plastic limit of the soil varied between 14% and 18%, with a liquid limit of 24% to 31%.

The range of permeability for the soils, determined from laboratory tests, is compared with that of field in-situ test results in Figure 2.3. It is generally the case that the values determined from field in-situ tests are always greater than those determined from laboratory tests. Visual inspection of undisturbed shelby tube samples indicated that a number of fissures, which were likely responsible for the higher permeability values obtained in-situ, were present in the soil.

2.3 Groundwater Table

The depth to the groundwater table was found to be between 2.3 to 2.6 metres (7.5 to 8.5 feet) below the original ground surface. During the construction of the pipe sections, some surface stripping and site levelling was made. This involved the removal of between 0.3 to 1.2 metres (1 to 4 feet) of soil cover. Figure 2.4 shows the depth of groundwater table below nominal ground surface after construction, as monitored in open standpipes over the last 5 years.

2.4 Layout of Test Sections

The test facility (Figure 2.5) was comprised of four pipe sections 12.2 metres (40 feet) long and 1.2 metres (48 inches) in diameter. Refrigerated air at atmospheric pressure was circulated through the pipes at a temperature of about -12°C (10°F) since March 20, 1974. Configurations of the test sections (Figure 2.6) are as follows:

2.4.1 Control Section

At this section, the pipe was buried 0.8 metres (2.5 feet) below the nominal ground surface and a berm 0.5 metre (1.5 feet) high was added. Operation of this section was discontinued at the end of September, 1977.

2.4.2 Restrained Section

The pipe configuration of the Restrained Section is the same as that of the control section. A load restraint is provided with hydraulic jacks. The pipe section is restrained by two beams, located 1.5 metres (5 feet) from each end of the pipe, anchored with concrete reaction piles.

2.4.3 Gravel Section

The pipe was buried under the same condition as for the control section; however, 0.9 metres (3 feet) of gravel was used as bedding material under the pipe.

2.4.4 Deep Burial Section

At this test section, the pipe was buried 1.7 metres (5.5 feet) below the nominal ground surface and a berm, 0.5 metres (1.5 feet) high, was added, prior to the start of operation. On June 3, 1975, the berm was raised by 1.5 metres (5 feet).

2.5 Instrumentation

2.5.1 Thermistors

Vertical strings of thermistors were installed for measurements of ground temperatures and location of the 0°C (32°F) isotherm. Location of the thermistors, for all four sections, are shown in Figures 2.7 and 2.8.

The thermistors used were the Atkins PR-99-3 type, which, accoring to the manufacturer, are suited to measuring temperatures in the range of -20°C to 29.5°C (-4°F to 85°F) with an accuracy range of ± 0.3°C (± 0.5°F). The cables from the thermistor probes are led to the instrument trailer, at the test site, where they are connected to a switching box. Using an Atkins meter, the thermistors are read directly in degrees Fahrenheit. In addition, thermistors are also used to monitor temperatures of the chilled air into and out of the pipe sections, and leaving and returning to the refrigeration system.

2.5.2 Heat Flux Transducers

Five heat flux transducers were installed on the inside surface of the Control Section. They were obtained from Hy-Cal Engineering, California (Model No. B1-6 and B1-7), and are read with a Biddle potentiometer used as a millivoltmeter.

2.5.3 Heave Guages

The main purpose of the test facility is to observe vertical displacement of the chilled pipeline and the surrounding soil; consequently, several heave guages were installed at each section of the test facility. Their locations are shown on Figures 2.9 and 2.10. Each guage consisted of a horizontal plate, 3 inch in diameter, attached to a vertical steel rod. The rod was encased in a plastic pipe with the annular space between the rod and the pipe filled with grease.

A 12.2 metre (40 foot) deep bench mark was installed on site for measurements of the changes in elevation of the heave guages with an accuracy level of ± 1 millimetre.

In order to observe the vertical displacement of each pipe section, 19 millimetre (3/4 inch) diameter vertical steel rods were welded to the pipe at the positions shown on Figure 2.11. These rods protruded above the ground suface permitting surveying of their elevation at regular intervals.

2.5.4 Piezometers

During the process of frost heaving, water is attracted to migrate towards the freezing front resulting in the growth of ice lenses. According to Darcy's law, excess pore water gradient must exist in the unfrozen zone so that the water will flow from a region of high pore pressure to one of low pressure.

In order to obtain quantitative data on the magnitude of excess pore water pressure, about 50 "Terra Tec" (Model P-1022) pneumatic piezometers which were read individually using a Terra Tec control unit (Gauge C-6300), were installed at different depths beneath the pipe sections. The accuracy of the piezometers was rated at approximately ± 0.7 kilopascals (± 0.1 psi), which is equivalent of ± 75 millimetres (± 3 inches) of water column. In addition, the pizeometers were equipped with a preload, enabling the measurements of pore water pressures in the range of -80 kilopascal to 120 kilopascals (-12 to +17 psi), which is equivalent of -8 metres to 11 metres (-25 to +35 feet) of water. Two open standpipe piezometers were also installed at the site to monitor the position of the free groundwater table. Figures 2.12 and 2.13 shows the piezometer locations.

2.5.5 Extensometers and Others

Extensometers were installed inside the pipe on the control and restrained sections to measure the possible change in pipe diameter due to freezing of the surrounding soil. Each extensometer consisted of a Houston Scientific Position Transducer (Model 1800-02A) fixed to one side of the pipe; a change in pipe diameter results in a change of the voltage signal.

Other types of equipment consisted of electrical transducer piezometers, at the control section, and electrical resistance frost gauges placed in the Control, Gravel and Deep Burial sections.

III THE FROST HEAVE PREDICTIVE MODEL

3.1 General

The operation of a chilled gas pipeline in unfrozen ground is without precedent; as such, there is no experience pertaining to frost heave action on pipelines. Although research studies into the mechanisms of frost heaving have been conducted for the last century, a comprehensive predictive theory was still not at hand when the problem was first investigated by Foothills and Northwest in 1975.

Freezing of soils around a chilled pipeline is a long-term continuous process. The "heave rate" method originally developed by CRREL (Ref. 4) only for relative frost susceptibility classification of soils (Figure 3.1), was considered for the frost heave of a chilled pipeline (Ref.5). Based on the present status of the method, the following difficulties were encountered in applying this method for frost heave prediction:

(1) Variation of heave rate with time

The heave rate, $\overset{\frac{\partial h}{\partial t}}{\frac{dh}{dt}}$, is defined as the rate of change of frost heave with respect to time. For a freezing condition due to constant prescribed temperature such as the chilling of a gas pipeline, or the laboratory small sample tests, the relationship between frost heave and time is always a curve. The slope of the curve, at any time, is, by definition, the heave rate. Unless the curve is a straight line, it becomes difficult to determine the heave rate which will be relevant for the long-term pipeline frost heave prediction, the total frost heave being

$$h \text{ (heave)} = \int_0^{t \text{ (say 30 years)}} \frac{dh}{dt} \,.\, dt = \int_0^t \frac{\partial h}{\partial t} \partial t$$

Where $\overset{\frac{\partial h}{\partial t}}{\frac{dh}{dt}}$ = a function of soil type, pressure, temperature, geometry of the thermal domain and time.

(2) Variation of Heave Rate for a Given Soil

For a given testing condition, the large variation of heave rate for a given soil, as determined from laboratory testing (Figure 3.1), makes it very difficult to apply the method for quantitative evaluation of frost heave, as noted by the large variation of heave rate in logarithmic scale.

In order to understand various factors affecting frost heave, such as loading pressures and soil types, a phenomenological (macroscopic) model study was undertaken (Ref. 6,7,8 and 9). Although the microscopic behaviour of the frost heaving mechanism is recognized, the fact that the many complex parameters affecting the frost heave behaviour of soils are still poorly understood, makes the microscopic model prohibitively complicated for practical pipeline work.

3.2 Theoretical Approach

3.2.1 Phenomenological Description

A general phenomenological description of the soil deformation in a frost heave process is as follows:

(a) Equilibrium condition of forces to be satisfied in both frozen and unfrozen zones.

(b) Stress-strain relationships to be satisfied for frozen and unfrozen soil behaviour,

(c) Consolidation within the unfrozen soil with water movement following Darcy's law, as a result of,

(d) Development of pore water pressure at the freezing front or fringe in conjunction with the capillary suction stress at the ice water interface and the rate of movement of the freezing front, and

(e) Heat balance at the freezing front so that the rate of heat extraction equals ~~to~~ the rate of ice segregation. ?

The frost heave mechanism can be described in the following two processes:

1. Mass Transfer - Continuity of Water Flow

Vapor movement - - important?

During the process of freezing, by nature of the energy balance at the ice-water interface, a suction occurs, similar to the concept of the capillary model, which draws water toward the freezing front to form segregated ice lenses. The amount of water drawn to form ice lenses, under a fully saturated soil system, should be proportional to the permeability of an unfrozen soil and its hydraulic gradient (Darcy's Law).

2. Heat Transfer - Heat Extraction at the Freezing Point

As the water is being drawn to form ice lenses, heat extraction must occur in order to freeze the in-situ water in the soil and the water migrating to the frost front, ~~into ice~~. The amount of heat extraction is equal to the amount of heat flux into the frozen zone minus the incoming heat flux from the unfrozen zone.

Detailed descriptions of the two coupled processes and their quantitative evaluations have been presented in other reports (Ref. 6,7,8 and 9). Figure 3.2 presents the configuration of the two-dimensional model.

← Get!

The model enables one to evaluate the lower and upper bounds of the ice segregation mechanism.

1. Lower Bound Ice Segregation - One dimensional freezing

For a frost susceptible soil, the availability of water is the most important input parameter for the occurance of frost heave. Without the availability of water, both within the pores of the soil and by the process of migration towards the freezing front, there will be no frost heave under any freezing condition. When water is restricted to migrate only vertically to the freezing front from a free source remote from the freezing front, the least amount of heave will occur. This is the lower bound value of frost heave. It has been found (Ref. 6) that under such conditions, the magnitude of segregation heave can only be as large as the in situ heave of the soil. In other words, total heave can only be as large as twice the volume increase of the in situ water due to freezing. In terms of heave strain or ice segregation ratio, which was defined as heave per unit volume of frozen soil, the lower bound value is about 8% for a typical soil with dry density of 1.6 Mg/m^3 (100 lbs./cu.ft.) and water content of 25%.

2. Upper Bound Ice Segregation

Irrespective of its properties, the soil will draw as much water as the pipe is capable of freezing into ice. This is the freezing condition of upper bound ice segregation. Thus the upper bound value for frost heave below a chilled pipeline is equal to the thickness of the ice wedge or layer which can be formed below the pipe (Figure 3.3). In terms of heave strain or ice segregation ratio, the upper bound value is equal to 1.0 for the pure ice condition.

In reality, the value of ice segregation ratio for frost susceptible soils will vary between the upper and the lower bound values. Figure 3.4 illustrates the various conditions of frost heave and frost depth. The corresponding frost heave for various ice segregations are presented in Figure 3.5 for pipeline conditions.

3.2.2 Methodology of Theoretical Approach

The phenomenological model describes the frost heave mechanism into two coupled processes: one being the mass transfer process which is to evaluate the amount of water migrating though the unfrozen zone towards the frost front to form segregated ice lenses; the other being the heat transfer process which evaluates the heat flux both in the frozen and the unfrozen zones, and the movement of the freezing front (Ref. 7,8 and 9). Thus the input parameters required are as follows:

1) Mass Transfer process

(a) Capillary suction of soil during freezing, Ps
(b) Soil permeability, k, and
(c) Coefficient of consolidation or expansion, Cv

2) Heat Transfer process

(a) Thermal properties of soils (frozen and unfrozen) such as thermal conductivity, specific heat and latent heat
(b) The above properties will vary during the freezing process, as the moisture content of the soil is changing due to moisture migration evaluated from the mass transfer process.
(c) Geometry and temperature boundary conditions of the thermal domain including pipe diameter and pipe operating temperatures.

3.2.3 Model Prediction of Calgary Test Site - Theoretical Approach

This section presents model prediction of the Deep Burial Section so as to appreciate the range of quantitative variation of various input parameters. Since the accuracy of any prediction by a theoretical model is a function of the accuracy of all its input parameters, the applicability of the theoretical approach for pipeline frost heave design will be examined.

(A) Soil Stratigraphy

Based on the grain size distribution, two soil layers are defined in the material generally called Calgary Silt (Figure 3.6): one is the soil to a depth of about 1 metre (3 feet) below the pipe, which is classified as sandy clayey silt. Beyond this depth, the soil is silty clay. Figure 3.7 shows the two grain size distributions.

(B) k and C_v

The range of k at the test site is shown in Figure 3.8, varying from 1×10^{-6} to 6×10^{-5} cm/sec. The range of C_v, as shown in Figure 3.9, varies from 0.03 to 0.5 cm^2/sec. Such a wide range of variation reflects the nature of the soil and the difficulty in determining quantitative parametric values. For prediction purposes, the laboratory determined average values of k and C_v are applicable to both soils, k of 3×10^{-5} cm/sec and C_v of 0.3 cm^2/sec (Figures 3.8 and 3.9).

(C) Capillary Suction Pressure

Typical values of Ps, the capillary suction pressure, can only be determined from a range of values as presented in Table 1.

Since the capillary suction varies with the fines content of the soil, such a variation of soil properties will be taken into acccount in the model prediction presented herein. The capillary suction pressure will be considered in the following manner in order to take into account the difference in the clay and silt contents of the soils:

TABLE 1

TYPICAL VALUES OF Ps = $\left(\frac{2\sigma_{iw}}{\gamma_c}\right)$ *

GENERAL SOIL TYPE	$\frac{2\sigma_{iw}}{\gamma_c}$ (psf)	$\frac{2\sigma_{iw}}{\gamma_c}$ (kg/cm^2)
Coarse sands, or coarser material only	0	0
Medium and fine sands, or coarse silty sands	0-150	0-0.075
Medium silts, or mixed soils with small amounts < 0.006 mm particle diameter	150-300	0.075-0.15
Largely fine silts, or silts with some clays	300-1000	0.15-0.5
Silty clays	1000-4100	0.5-2.0
Clays	> 4100	> 2.0

* From Williams, P.J., 1967. Properties and Behaviour of Freezing Soils: Norwegian Geotechnical Institute Publication No. 72.

(a) Linear variation of Ps from the sandy clayey silt to silty clay.

$Ps = 1.0 + 2.4\ (kg/cm^2)$ for $X \leq 1$ metre (3 feet)
$Ps = 3.4\ (kg/cm^2)$ for $X > 1$ metre

X = frost depth (metres), 1.0 kg/cm^2 = 2000 psf,
3.4 kg/cm^2 = 7000 psf

(b) Constant Ps

$Ps = 2.4\ kg/cm^2$ (5000 psf)

(c) Constant Ps

$Ps = 3.4\ kg/cm^2$ (7000 psf)

3.2.4 Prediction Versus Performance

The predicted curves for (a) frost heave, (b) frost depth and (c) segregated ice content in the frost bulb, are presented in Figures 3.10 and 3.11, respectively. The segregated ice contents were obtained from drilling results in June, 1978 (Ref. 3), after the pipe had been operating for about 5 years.

As can be seen, the predictions compare satisfactorily with the observed data.

3.3 Practical Limitations of the Theoretical Approach

In previous subsections, the frost heave model has been shown to be consistent with observations of the segregated ice content variation with depth: the frost depth and the frost heave of the deep burial section at the Calgary Test Site. It should be recognized, however, that the accuracy of any prediction by a theoretical model is a function of the accuracy of all its input parameters.

Unfortunately, due to the complexity exhibited by the nature of soils and the difficulty in accurately determining the soil parameters required for the theoretical prediction, practical limitations should be recognized:

1. During the process of freezing, the magnitude of the capillary suction pressure may vary depending on the thermal properties of the soil, the rate at which heat is being removed from the freezing zone and other factors. The nature of such variations is not yet well understood. Moreover, the magnitude of the suction pressure, as shown in Table I, can only be assessed within a range of values for a soil type.

2. The permeability and the coefficient of consolidation for a given soil may vary by about one order of magnitude. This, unfortunately, is the generally accepted accuracy level for determination of these parameters. Such a variation will undoubtedly affect the magnitude of the predicted frost heave. Moreover, in most field conditions along a pipeline route, complicated soil conditions such as an interbedded soil stratigraphy and embedded sand layers favouring the supply of water may be encountered, further complicating matters.

3. The coupled effect of these soil parameters is not well understood.

It is therefore concluded that the accuracy of the theoretical approach is not satisfactory for the practical requirements of a pipeline design. Consequently, a semi-empirical approach is proposed.

3.4 Semi-Empirical Design Approach

3.4.1 General

The limitations of applying the frost heave model using a theoretical approach have been discussed in previous sections. Due to the complexity exhibited by the nature of soils and the difficulty in accurately determining the soil parameters required as input to the approach, the accuracy of a theoretical frost heave prediction is considered to be unsatisfactory for the practical requirement of a pipeline design. A semi-empirical design approach is therefore proposed for the frost heave design.

3.4.2 Rationale

The rationale of the semi-empirical approach is as follows:

1. The heat transfer aspect of the frost heave model is maintained, which involves the consideration of heat transfer mechanisms in both the frozen and unfrozen zones of the soil domain, and the growth of the frost bulb.

2. The mass transfer aspect of the frost heave model, which evaluates the heave strain or ice segregation ratio, will be determined by laboratory frost heave testing rather than evaluated using the soil parameters of capillary suction pressure, hydraulic permeability and the coefficient of consolidation or expansion of the soil. Since the heave strain is a cumulative function of these coupled parameters, a laboratory determined heave strain method should eliminate the quantitative uncertainty inherent in the theoretical appr

In summary, the semi-empirical approach transforms the complicated heat and mass transfer aspects of the frost heave mechanism into a conventional thermal problem, with the heave strain defined (which is heave per unit frost penetration) as another input parameter determined by laboratory testing techniques.

As the frost heave of a chilled pipeline is mainly a result of ice segregation of the soil column below the pipe, the one-dimensional (vertical direction) behaviour of the soil column below the pipe center line is to be considered for the semi-empirical approach. This is a result of symmetry with respect to the thermal and hydraulic (water access) boundary conditions. The frost heave of a pipeline "h" is:

$$h = \int_0^X \frac{dh}{dx} \cdot dX = \int_0^X \frac{\partial h}{\partial x} \, dx$$

where

$$\frac{\partial h}{\partial x} \simeq \frac{dh}{dX} = \text{heave strain which is heave per unit frost depth}$$

and

X = frost depth

The frost depth X is a function of

(a) Thermal properties of soils (thermal conductivity, specific heat and volumetric latent heat);

(b) Thermal boundary conditions such as geometry, pipe and ground temperatures, and

(c) Time.

The evaluation of X (frost depth at any time) is a conventional thermal problem whose method of anlaysis, analytical or numerical, has been well established (Ref. 10 and 11). This is the heat transfer portion of the theoretical frost heave model.

-Geot

The infinitesmal heave strain or ice segregation ratio, by definition, is:

$$\frac{dh}{dX} = \lim_{\Delta X \to 0} \frac{\Delta h}{\Delta X}$$

This can be approximated by a soil element with finite length of ε (say a few inches) so that:

$$\frac{dh}{dX} = \lim_{\Delta X \to \varepsilon} \frac{\Delta h}{\Delta X} = l_s^i = \text{elemental heave strain or ice segregation ratio}$$

Where l_s^i = Heave strain or ice segregation ratio of soil elements i which can be of the same or different soil type from its adjacent soil element $i \pm 1$.

let $\varepsilon = X_i$ (finite frost depth increment) then the total frost depth X becomes

$$X = \sum_{i=1}^{n} X_i$$

and the total heave becomes a summation of elemental heaves such as

$$h = \sum_{i=1}^{n} l_s^i X_i$$

Figure 3.12 describes schematically the above definition.

When pure ice formation is considered, $I_s^i = 1.0$, the frost heave becomes the frost depth such as

$$h = \sum_{i=1}^{n} X_i = X$$

This condition is illustrated in Figure 3.3, the upper bound frost heave condition.

A laboratory testing technique has been set up (Ref. 12) to determine the elemental heave strain or ice segregation ratio I_s^i. The laboratory testing procedure was set up to simulate the field boundary conditions during ground freezing. Since some of the conditions can not be properly simulated in laboratory testing, more severe boundary conditions were utilized for a conservative (safe) consideration.

In setting up the testing procedure, the following considerations are essential:

(a) Soil sample size
(b) Hydraulic condition - access of water
(c) Temperature and heat flux
(d) Soil pressure, and
(e) Testing duration

(A) Soil Sample Size

The soil sample size should be large enough so that the particle size of the solid grain would not affect the overall result. Experience in geotechnical practice, regarding the determination of soil shear strength, indicates that a sample having about 100 millimetres in both diameter and length are adequate for both sandy and fine-grained (silt and clay) materials. Where gravels are involved, larger sample size may be required. Since gravel and coarse sand are both frost stable, the 4 inch sampler can still be used by replacing the gravel content in the soil with sand.

(B) Hydraulic Condition - Access of Water

The one-dimensional laboratory testing of a small finite length (about 100 millimetres) sample was found to always provide greater water accessibility than the two dimensional water flow condition towards the freezing front beneath a chilled pipeline (Ref. 12). This provides a conservative factor in the semi-empirical approach with respect to hydraulic conditions of freezing phenomena.

Along a pipeline route, complicated soil conditions such as interbedded soil stratigraphy and embedded sand layers favoring supply of water may be encountered. However, those adverse conditions have now been inherently considered in the laboratory test because the supply of free water automatically simulates the sand layer with respect to hydraulic condition.

(C) Temperature and Heat Flux

The temperature and heat flux of a soil element below a chilled pipeline is a function of its position relative to the chilled pipe and time duration of the pipeline operation. Since frost heaving occurs mainly around the fringe of the 0°C (32°F) isotherm, the prescribed cold side temperature should be maintained as close to 0°C (32°F) as the controlling accuracy of testing equipment allows, and the warm side temperature maintained at ground temperature to simulate the field condition. The cold side temperature for most frost heave tests are maintained at about -1°C (30°F), and the warm side temperatures at 0.6 and 1.7°C (33 and 35°F). In general, the heat flux, over the duration of the laboratory freezing porcess under such prescribed temperature boundary conditions, varies from about 95 to 0.03 watts/m^2 (30 to 0.01 BTU/hr/ft^2), which is about the range for a pipeline field condition (Ref. 13).

(D) Soil Pressure

The frost bulb diameter? for a bare pipeline over its design life may be about 9 metres (30 feet). The overburden pressure that the soil is subjected to during formation of such a frost bulb has an insignificant effect on the frost heave for fine-grained soils (Ref. 7). For dirty, coarse-grained material, the magnitude of stress exerted by the overburden material may have a significant effect. Since laboratory testing will be conducted under the in-situ overburden pressure, the effect of pressure on the frost heave behaviour of the soil is inherently considered.

(E) Duration of Frost Heave Testing

Ground freezing by a chilled pipeline is a slow transient thermal balance. Over the lifetime of a pipeline, the thermal state of the ground may or may not reach its ultimate state - the steady state condition. A soil element below the pipe, depending on its relative location with respect to the chilled pipe and the time duration of the pipeline operation, may or may not reach its thermal steady-state equilibrium. Since the ultimate ice segregation is reached at the steady-state condition, the use of laboratory determined heave strain or ice segregation ratio after steady-state is reached should result in conservative (safe) designs.

3.4.3 Methodology of the Semi-Empirical Approach

The rationale of the semi-empirical approach for frost heave design has been described in previous sections. The approach is summarized as follows:

1. Primarily based upon the soil type and its grain size distribution, the soil domain is divided into representative stratigraphy.

2. Laboratory frost heave tests will be perfromed to determine the heave strain or ice segregation ratio for re~~x~~presentative soils under its in-situ overburden pressure. The soil sample has a finite length of about 100 millimetres with free access of water. The cold side temperature will be prescribed at about -1°C (30°F), the warm side temperature will be prescribed at about 0.6 to 1.7°C (33°F to 35°F), depending on the mean average ground temperature. The frost heave test will run until the steady-state thermal equilibrium is reached. The heave strain or ice segregation ratio will be defined as:

$$I_s = \frac{h_{max}}{X_{max}}$$

where h_{max}, X_{max} are the frsot heave and the frost depth at steady-state, respectively.

3. Once the heave strain or ice segregation ratio is obtained for each re~~x~~presentative soil layer, it will be applied to the upper bound solution of the two dimensional frost heave model, based upon energy balance, to evaluate the frost heave and frost depth, with time.

IV FROST HEAVE PREDICTION BY SEMI-EMPIRICAL APPROACH

4.1 General

The semi-empirical design approach of the frost heave predictive model transforms the complicated frost heave phenomena into a conventional thermal problem, with the heave strain as another input parameter in addition to the parameters required for thermal analysis. Such an approach enables one to analyse the performance of the Calgary Test site into two isolated components: one is the variation of ground temperatures, the other, the corresponding frost heave. Even though these two components are of coupled nature, being able to isolate them will certainly simplify the design process for pipeline frost heave problems. This will be demonstrated in a later seciton.

4.2 Thermal Domain and Soil Properties

Soil stratigraphy of the test site after construction are presented in two boreholes drilled in July 1978 (Figures 4.1 and 4.2). These two boreholes were located in the unfrozen area (Figure 2.5 shows the borehole locations). Water contents in the soils were compared with previous soil data. It was found that the water contents remained the same between the time prior to construction of the test site in late 1973, to July 1978, when the test site had been operating for about 5 years.

The thermal domain was defined into two soil layers as shown in Figures 4.3 and 4.4 for the Deep Burial and the Gravel sections, respectively, one being sandy clayey silt (Sand 50%, Silt 44% and clay 6%), the other silty clay (Sand 4%, Silt 63% and clay 33%). Curves A and B in Figure 3.7 shows the respresentative grain size curves of the two soil layers. The transitional changes of grain size between the interface of the two soil layers were ignored for simplification purposes of the thermal analysis.

Laboratory one-dimensional frost heave tests on representative soil samples in the two soil layers were performed (Appendix A) to determine the heave strains and ice segregation ratios of the soil. Figure 4.5 shows the sample locations. The frozen soil samples (from boreholes drilled in July, 1978) were thawed and consolidated under the in-situ overburden soil pressures, before the laboratory frost heave tests started. In such a way, the excess ice contents obtained in the laboratory tests can be compared with field conditions as obtained from the drilling results. Table II shows the ice segregation ratio, for each soil type, which was also compared with the drilling results.

Tables III and IV show the thermal properties of the soil layers for the Deep Burial and Gravel Sections of the Calgary Frost Heave Test Site.

TABLE II
HEAVE STRAIN OR ICE SEGREGATION RATIO
CALGARY FROST HEAVE TEST SITE

		DRILLING RESULTS OF EXCESS ICE CONTENT(%)		EXCESS ICE CONTENT (%) ONE-D LABORATORY FROST HEAVE TESTS	DESIGN VALUE OF HEAVE STRAIN(%) (AVERAGE OF EACH SOIL TYPE)
SOIL TYPE	TEST NO.	VISUAL(1)	BACK-CALCULATION(2)		
Sandy Clayey Silt	FH-12(A)	10	8-15	12.5	12
	FH-12(B)	10		10	
Silty Clay	FH-9	30	25-28	57	40
	FH-10	30		30	
	FH-11(A)	35	30-39	32	
	FH-11(B)	35		42	

(1) From photographs taken and visual field estimation

(2) Back-calculated from frozen bulk density and water content of the samples.

TABLE III

SOIL PROPERTIES - DEEP BURIAL SECTION

SOIL TYPE	DEPTH BELOW GROUND SURFACE (metres)	MOISTURE CONTENT(%)		HEAVE STRAIN* or ICE SEGREGATION RATIO(%)	BULK DENSITY (Mg/m^3)		THERMAL CONDUCTIVITY (W/m/^{o}C)		SPECIFIC HEAT (J/g/^{o}C)		LATENT HEAT (kJ/m^3)
		UNFROZEN	FROZEN		UNFROZEN	FROZEN	UNFROZEN	FROZEN	UNFROZEN	FROZEN	
Back Fill and Berm	-	21	29	12	2.07	1.92	1.64	1.97	1.34	1.09	1.26×10^5
Clayey Silt	0-3.7	21	29	12	2.07	1.92	1.64	1.97	1.34	1.09	1.26×10^5
Silty Clay	3.7-24.4	18	53	40	2.08	1.60	1.69	2.06	1.67	1.67	1.72×10^5

* From laboratory one dimensional frost heave tests

Note: 1 Mg/m^3 = 62.43 lbs/ft^3

1 W/m/^{o}C = 0.578 BTU/hr/ft/^{o}F

1 J/g/^{o}C = 1 KJ/kg/^{o}C = 0.239 BTU/lb/^{o}F

1 kJ/m^3 = 2.68×10^{-2} BTU/ft^3

TABLE IV

SOIL PROPERTIES - GRAVEL SECTION

SOIL TYPE	DEPTH BELOW GROUND SURFACE (metres)	MOISTURE CONTENT (%)		HEAVE STRAIN* or ICE SEGREGATION RATIO (%)	BULK DENSITY (Mg/m^3)		THERMAL CONDUCTIVITY ($W/m/^oC$)		SPECIFIC HEAT ($J/g/^oC$)		LATENT HEAT (kJ/m^3)
		UNFROZEN	FROZEN		UNFROZEN	FROZEN	UNFROZEN	FROZEN	UNFROZEN	FROZEN	
Back Fill and Berm	-	21	29	12	2.07	1.92	1.64	1.97	1.34	1.09	1.26×10^5
Gravel	-	15	15	0	2.21	2.21	2.77	3.81	1.17	0.88	0.97×10^5
Clayey Silt	0-3.7	21	29	12	2.07	1.92	1.64	1.97	1.34	1.09	1.26×10^5
Silty Clay	3.7-24.4	18	53	40	2.08	1.60	1.69	2.09	1.67	1.67	1.72×10^5

* From laboratory one dimensional frost heave tests

Note: $1\ Mg/m^3 = 62.43\ lbs/ft^3$

$1\ W/m/^oC = 0.578\ BTU/hr/ft/^oF$

$1\ J/g/^oC = 1\ KJ/kg/^oC = 0.239\ BTU/lb/^oF$

$1\ kJ/m^3 = 2.68 \times 10^{-2}\ BTU/ft^3$

TABLE V
METEOROLOGICAL INPUT DATA
CALGARY TEST SITE ANALYSIS

Date	Ambient Temperature (^{o}F)	Average Wind Velocity (M.P.H.)	Snow Depth (FT.)	Average Solar Radiation (BTU/hr./ft^{2})
Jan. 15	12.3	10.1	0.35	15.8
Feb. 15	18.6	10.0	0.35	29.8
Mar. 15	24.3	10.3	0.22	49.0
April 15	38.0	11.6	0.0	64.8
April 20	39.8	11.6	0.0	66.8
May 15	48.8	11.5	0.0	77.0
June 15	55.7	10.9	0.0	84.7
July 15	61.7	9.4	0.0	90.1
Aug. 15	59.4	9.1	0.0	73.9
Sept. 15	51.2	10.2	0.0	53.9
Oct. 15	42.2	10.6	0.0	33.0
Nov. 5	32.1	10.1	0.0	22.7
Nov. 15	27.3	9.1	0.06	17.8
Dec. 15	18.4	10.0	0.22	11.8

Properties of Snow Cover:	Thermal Conductivity	0.10 BTU/HR./FT./^{o}F)
	Surface Emissivity	0.90
	Surface Absorbtivity	0.40
Properties of Bare Ground:	Surface Emissivity	0.90
	Surface Absorbtivity	0.70
Greenhouse Factor:	0.83	

4.3 Meteorological Data

The meteorological data is required for the thermal analysis when the ground surface heat transfer mechanism is considered. Table V shows the relevant parameters which are (a) air temperatures, (b) solar radiation, (c) wind velocity, (d) surface albedo, emissivity and greenhouse factor, and (e) snow cover and its thermal conductivity.

4.4 Pipe Temperatures

As chilled air is circulated through the pipes, the pipe temperatures are a function of the air temperature, the conductance between the air and the pipe wall, and the pipe - soil contact. The pipe - air conductance is a function of pipe diameter, duct air temperature, pressure and its velocity as well as the film coefficient. In order to avoid uncertainty in prescribing the air temperatures and the pipe - air conductance, the measured pipe - wall temperatures was used as a prescribed temperature boundary conditions for the thermal analysis. Figure 4.6 shows the measured pipe - wall temperatures versus the duct air temperatures at the Control Section. The average value of the pipe wall temperatures is about -9.4°C (15°F), which is about 1.7°C (3°F) higher than the average duct air temperature of about -11.1°C (12°F).

4.5 Predicted Versus Measured Ground Temperatures and Frost Heaves

Based on the input data described in previous subsections, the model was applied to predict the ground temperatures at the test site. The predictions were compared with measured values.

4.5.1 Annual Ground Temperature Variations

Thermistor string RT6 (Figure 2.5) was located in an area about 14 metres (50 feet) away from the test pipe sections. The ground temperature variation can be regarded as seasonal changes, with little influence from the chilled pipes. One dimensional simulation was made by the model to predict the seasonal changes. The simulation assumed a constant bottom boundary temperature of 4.4°C (40°F) at a depth of 34 metres (110 feet). Figure 4.7 shows the predicted and measured ground temperatures at depths of 0.6m (2ft.), 1.5m (5 ft.) and 3m (10 ft.), respectively.

As it can be seen, good predictions were made.

4.5.2 Deep Burial Section

Measured temperatures at typical sensor locations around the Deep Burial Section were presented and compared satisfactorily with the model predictions (Figures 4.8 to 4.15). Thermistor cable DT6 was installed in January 1977 because the frost depth then was deeper than the depths of the other thermistors installed previously.

For temperature sensor locations close to the pipe, more variation between the measured and predicted values were found. This is thought mainly due to the reason that the pipe temperature specified in the model simulation was a mean value of -9.4°C (15°F) rather than the actual fluctuation of the pipe temperature as shown in Figure 4.6. However, as the sensor location is about 1 metre away from the pipe, the use of mean pipe temperature presents good predictions.

The frost depth ($0^{o}C$ isotherm) below the pipe and frost heave of the pipe are presented in Figure 4.16; they compare very favourably with the observed performance from the temperature sensor readings and from a drilling result (Ref. 3). Compared with most deformation predictions in the field of geotechnical practice (eg. building settlement), the accuracy of the semi-empirical approach for frost heave prediction should be regarded as excellent.

4.5.3 Gravel Section

Similar to the Deep Burial section, the comparison between the predicted and measured ground temperatures around the Gravel Section is satisfactory as shown in Figures 4.17 to 4.21, inclusive. The predicted frost heave of the pipe and the frost depth below the pipe compared favourably with the observed performance of the pipe section (Figure 4.22).

4.6 Discussion on Model Predictions

Frost heave and frost depth are integrated parts of the freezing phenomena when a chilled pipeline is operating in a frost susceptible soil. The semi-empirical approach of the frost heave model has transformed the complicated frost heave problem into the conventional geothermal problem whose design procedure has been well established and applied to many engineering projects. In this section, the performance of the Deep Burial and Gravel Sections in terms of frost heave and frost depth have been analysed and compared satisfactorily with model predictions.

The satisfactory results of ground temperature predictions are to be expected, since the geothermal aspect of the model has already been verified, with the performance of the Norman Wells Test Facility, Canada Artic Gas Pipeline Ltd. (Ref. 11), for a warm gas pipeline on permafrost. As far as thermal results of a gas pipeline are concerned, freezing of a chilled pipeline in unfrozen soils is similar to the thawing of a warm pipeline in permafrost soils.

The predicted results of frost heave for both pipe sections compare very favorably with the observed performance. The over-prediction by the semi-empirical approach of the observed frost heave data is to be expected. As described in Section 3.4, the laboratory testing aspect of the semi-empirical method seeks to simulate the ice segreagation mechanism in the soil element in the field. Since the thermal and hydraulic conditons in the field cannot exactly be duplicated in the laboratory, more severe boundary conditions than those occuring in the field are applied to the soil samples. As the range of heat flux conditions applied to the soil samples during the laboratory testing are about the same as that of field condition, the following factors may be the main contributors to the over-prediction:

(1) As described in subsection 3.4, the one-dimensional laboratory testing of a small finite length soil sample with free access of water at one end of the sample always provides greater water accessibility than the field condition of a chilled pipeline. This provides a safety factor in the semi-empirical approach with respect to the hydraulic conditions of ground freezing phenomena.

(2) The heave strain or ice segregation ratio determined in the laboratory is at the steady-state condition, which is the ultimate condition of soil freezing. A soil element below the pipe, depending on its relative location with respect to the chilled pipe and the time duration of the pipeline operation, may or may not reach its thermal steady-state equilibrium. Thus, the ice segregation ratio determined at the steady-state results in the over prediction of the semi-empirical approach.

(3) The fact that the microscopic behaviour of frost heaving is not well understood based on the present state of the art, the provision of using ultimate boundary conditions (free access of water and steady-state thermal equilibrium) in determining ice segregation ratio is warranted.

(4) The results have also been compared with the conditions of pure ice and 50% excess ice content (Figure 4.23). If pure ice is formed below the deep burial section, the heave of the pipe to date should be about 9 feet instead of 2 feet as observed. If 50% excess ice is formed, the frost heave should be about 5 feet.

(5) It is, therefore believed that the semi-empirical approach of the two-dimensional frost heave model is the most adequate design tool based on the present state of the art on frost heave problems.

Model predictions were not made for the Control and the Restrained Sections. It is believed that similar results as those of the Deep Burial and Gravel Sections will be obtained. Figures 4.24 and 4.25 show the observed data for frost heave and frost depth at the Control and Restrained Sections.

V OTHER OBSERVATIONS

5.1 Porewater Pressure

Poor choice of piezometers!

The 50 piezometers installed around the pipe sections were to measure the excess porewater presssures in the unfrozen zones, from which the hydraulic gradients might be estimated. It was found that the excess porewater pressure around the frost bulb was too small to be recorded by the piezometers and that the piezometer results reflected mainly the change in the free water table, as recorded in the open standpipe shown in Figure 2.4.

It is interesting to note that the theoretical predictions by the frost heave model (Ref. 7 and 8) has indicated that the excess porewater pressure around the frost bulb was less than the accuracy level of the piezometer of 14 psf, or 3 inches of water.

5.2 Heat Flux

The average pipe heat flux was measured at the Control Section for the first year (Figure 5.1). As no computer simulation was made on the Control Section, the measured heat flux was compared with that of the Gravel Section. As both test sections have the same configuration except for the gravel bedding, the average pipe heat flux for the Gravel section is felt to be representative for the Control Section. It is seen that the measured value is ~~about~~ slightly higher than the computer simulation, but the agreement between the two is reasonable.

5.3 Heave Profile Along Pipes

As shown in Figure 2.11, vertical rods welded on the pipe were to measure, through level survey, the vertical movement of the pipe due to frost heaving. Figures 5.2 to 5.5 show the heave profiles of each test section.

Observation of tilting of each section may provide information to evaluate possible differential frost heave along the pipe resulting in pipe-bending.

The tilting of a pipe section may be caused by:

(a) Variation of ice segregation and thus frost heave longitudinally along the pipe section, even though the soil properties and pipe temperature are generally uniform.

(b) End restraint due to duct connections or other restraint at the end of the pipe.

(c) End effect of thermal regime due to temperature boundary conditions at each end of the pipe.

The tilting or differential heave of the restrained section (Figure 5.5) was probably mainly due to the end restraints applied by te restraining collars and restraining loads at the extremities of the pipe section.

The tilting of the control section was felt to be caused by the duct connections to the chiller, as it has more heave towards the free end of the pipe.

Minor tilting, until the end of September 1978, was observed at the Gravel section (Figures 5.3). The differential heave between both ends of the pipe, and the mid-section was about 10% of the heave observed at the mid section ((1.5 ft. - 1.37 ft.)/1.37 ft.). The reason for this is not clear and may be the cu~~m~~mulative result of the above three causes.

May be??

The heave profile of the Deep Burial Section (Figure 5.2) was thought to be most representative of the field condition of a pipeline. In the field, because of the great length of the pipeline in comparison with its crossectional dimension, the temperature regime is uniform longutudinally.

} why?

In the deep burial section, because of the 3.7 metre cover (12 foot) over the pipe, the effect of ground surface variation becomes insignificant. This makes the thermal regime uniform along the pipe section, similar to the field condition. The overburden soil pressure also makes the possible end restraints due to duct connections insignificant. Thus, the deep burial section is under as uniform a freezing condition as can be simulated for the field. It is interesting to observe that under this condition there is no differential heave along the deep burial section (Figure 5.2).

It is therefore concluded that under a field conditions where the soil is uniform, there will be insignificant differential heave longitudinally over the same soil terrain.

5.4 Frost Heave in Frozen Soils

The heave gauges installed at each test sections (Figures 2.9 and 2.10) were to monitor vertical movements at various points in the soil near the chilled pipes. The relative movement of a pair of gauges will indicate the heave strain of the soil element between the two gauges. When the frost bulb passes the upper of the two gauges, the upper gauge commences to heave, and the lower one remains relatively stationary. When the frost bulb reaches the lower gauges, it will commence to move upwards. Up to this point, the frost heave behaviour is generally called primary frost heaving, which is the frost heave occuring from the unfrozen state to frozen state. When the frost bulb passes both gauges, the relative movement between the two gauges will indicate frost heaving in the frozen soil, which is generally called secondary frost heaving.

Several gauge pairs from the Deep Burial and Gravel Sections were selected for analysis in evaluating the relative magnitude between the primary and secondary frost heaves.

Gauge pair 20-22 of the Deep Burial Section (Figure 5.6) was under consideration. As the frost front approaches the upper gauge (Gauge 20), a small negative relative heave occured. This is the result of the consolidation of the unfrozen soil beneath the advancing frost front. Once the frost front passed the upper gauge, the soil layer between the gauge pair commences to heave, and continue to do so until the frost bulb has engulfed both gauges. After that, the relative heave between the gauge pair remained constant, indicating practically no secondary frost heaving between mid 1975 until the end of 1978, when the soil was frozen for over 3.5 years.

Although the observation data only covers the duration of 5 years, its trend does suggest that for practical purposes, the magnitude of secondary frost heaving is insignificant in comparison with that of primary frost heaving. This is illustrated in Figures 5.6 to 5.9 for other gauge pairs beneath the Deep Burial and Gravel Sections. For the last 3.5 years when the soils were frozen, relative heave between each gauge pair has been insignificant.

VI FIELD VERIFICATION - DRILLING RESULTS

6.1 General

Observation data on the Calgary Test Site presented in the previous sections were exterior results of frost heaving - namely the change of ground temperatures and the resulting frost heave of the pipe sections. The purpose of the drilling program was to obtain the soil samples beneath the pipe sections after they had been frozen from initially an unfrozen state, and to investigate the characteristics of ice segregation. The drilling work at the Control Section was done in September, 1977 prior to its removal.

The Restrained, Deep Burial and the Gravel sections were drilled in June and July, 1978. Holes were located as close to the midpoint of these test sections as possible. All vertical holes were drilled utilizing a helicopter portable, skid mounted Arctic Auger rig. A truck mounted, B-40L, auger rig was used for all the inclined holes. The frozen soil was continuously cored; a 10.2 centimetre (4 inch) I.D. core barrel was used at the Control Section, and a 7.6 centimetre (3inch) I.D. core barrel was used at the other test sections. After field classification was made, all samples were transported to the EBA Edmonton laboratory. Prior to transportation, the frozen soil samples were packed with gel freezer packs.

6.2 Borehole Locations

6.2.1 Control Section

Three boreholes were drilled to intercept the frost bulb which had formed around the chilled pipe. The approximate locations of two boreholes are shown in Figure 6.1. The other one which failed to intercept the frost bulb is not shown in the figure.

6.2.2 Restrained Section

The approximate location of boreholes with respect to the pipe and berm is shown on Figure 6.2. Hole R1 was terminated as a result of the permafrost core barrel loss. An alternate core barrel was utilized for the other boreholes.

6.2.3 Gravel Section

A cross-section at the approximte borehole location is shown on Figure 6.3. An unsuccessful attempt (Borehole G2) was made to sample the granular bedding material with the permafrost core barrel. The two other boreholes provided excellent samples of the ice rich frozen zone, particularly at the maximum frost penetration depth below the pipe.

6.2.4 Deep Burial Section

A cross-section showing the approximate location of all boreholes is presented in Figure 6.4. Hole D1 was terminated when it struck the pipe, and hole D1A when a rock was encountered. Boreholes D2 and D3 successfully penetrated the frost bulb.

6.3 Laboratory Testing

Representative soil samples were tested to determine the following engineering properties:

(1) Water content, frozen bulk density, and Atterberg limits.

(2) Grain size distribution.

(3) Consolidtion and thaw strain.

The laboratory testing results are presented in Appendix B.

6.4 Ice Segregation

The estimated percentage volume of segregated ground ice logged during the field program is presented on the borehole logs in appendix B. Core sample photographs allow for visual appreciation of the fractional volume of segregated ice and its distribution with respect to pipe location. The photographs and the locations of these samples are presented in Appendix C.

Estimated segregated ice contents of all samples generally ranges from 0 to 35 percent. However, the ice content approaches about 40 percent for short core intervals near the maximum frost penetration depths, at the Control, Gravel and Deep burial sections (Boreholes C3, D3 and G2A). These estimated segregated ice contents were verified by back calculated results from the total moisture contents obtained from the frozen core, and the moisture content in the soil phase without segregated ice (Table 11).

An attempt was made to investigate the variation of ice content with depth below the pipe at the deep burial section, as it had the most borehole information (Figure 6.4).

Boreholes D-1A and D-2 (Appendix B) indicated that at a depth of about 5.5 metres (18 feet) from the top of the berm, which is about 0.9 metres (3 feet) below the pipe bottom, the soil changes from silt to silty clay. Figures 6.5 shows the difference in grain size distribution with respect to clay content.

It is interesting to observe the following excess ice content distribution:

(a) Within the first metre (3 feet) below the pipe, the soil is sandy clayey silt, the ice content is about 5 to 10% by volume, as one can see form Boreholes D2-2, D2-3, and DIA-2 with photographs of these samples, plates DIA-4, D2-9, D2-10, and D2-11 shown in Appendix C. The ice content distribution in the soil is relatively uniform as it is consistent with the total water content distribution shown in Boreholes DIA and D2 (Appendix B).

(b) The soil beneath becomes silty clay with depth and the ice content increases to 30 to 35 percent. Again, the excess ice content distribution in the soil up to the freezing front is relatively uniform, as can be seen from Plates D2-12 to D2-16, DIA-8 to DIA-10, and D3-12 to D3-15, inclusive. This is consistent with total water content distribution shown in Boreholes DIA, D2 and D3.

(c) The freezing rate or the rate of frost penetration is directly proportional to the net heat flux at the freezing front. Figure 6.6 shows the calculated neat heat flux at the frost front for the deep burial section. Thus, the frost front penetration through the two soil layers is varying with depth, as the heat flux varies about 400%, from 4.7 to 1.3 watts/m^2 (1.5 BTU/hr/ft^2 to 0.4 BTU/hr/ft^2) over a depth from 1.5 to 3 metres (5 to 10 ft.) below pipe.

However, the excess ice content and the total water content in the two soil layers remain realtively uniform. The difference in depth between Samples D2-12 (1 metre below pipe), DIA-10 (2.4m below pipe) and D3-15 (3m below pipe) is aobut 1.8 metres (6 feet), but the drilling results show the ice content to be about the same, even though the freezing rate at these locations are about 400% different. Since the berm height above the Deep Burial Section is approximately 3 metres (10 feet), the soil pressure changes between these depths are insignificant. It is therefore concluded that under the heat flux ranges generated by a chilled pipeline, the variation of the ice segregation ratio is mainly due to the difference in soil types rather than the variation of heat flux or freezing rate.

(d) For the case where the pipe is insulated with 6 inch of styrofoam or equivalent material, the computed net heat flux at the freezing front is shown in Figure 6.7. This is similar to the flux magnitude computed at 3 metres (10 feet) for the Deep Burial Section (Figure 6.6). Thus, it seems reasonable to interpret that the ice segregation ratio of about 35 ± 5% obtained from the drilling results at 3 metre (10 foot) depth at the Calgary Test Site would be representative of the condition when the pipe is insulated.

6.5 Thaw Strain

Thaw strain is defined as the ratio between thaw settlement, under a stress equivalent to the overburden pressure, and the initial height of the sample. The thaw strain of a soil is generally related to its frozen bulk density. In order to compare the frozen soil samples obtained from the Calgary Test site to permafrost soils, thaw settlement tests were taken for the frozen core samples at selected depths from various boreholes to represent a wide range in segregated ice contents. Figure 6.8 shows the relationship between thaw strain and the frozen bulk density.

It can be seen that the average curve of the test data has a slightly higher value than the correlated curve obtained by Speer et al *(1973) (Ref. 13), which represents a wide range of permafrost soils. This may be attributed to the fact that ice lenses created by continuous freezing under a chilled pipeline may be more uniform than under natural freezing conditions.

VII CONCLUSIONS

The report presents detailed analyses of the performance to date of the well instrumented Calgary Test Facility, which has been in operation since March 1974. Not only have the observed data of ground temperatures and pipe heaves been compared favorably with the predictive method, continuous core samples of frozen soils have also been obtained through drilling programs to investigate the characteristics of ice segregation. In doing so, a comprehensive appreciation of the frost heave phenomena induced by a 48-inch chilled pipeline has been made. The following conclusions are drawn from this study:

1. Based on the satisfactory comparison between the predicted and observed data with respect to ground temperatures and frost heaves at various test sections, it is believed that the semi-empirical approach of the two-dimensional frost heave model is the most adequate design tool based on the present state of the art on frost heave problems. The fact that the miscroscopic behaviour of frost heaving is not well understood, the overprediction on frost heave by the model is warranted for practical application. Compared with most deformation predictions in the field of geotechnical practice (eg. building settlement), the accuracy of the semi-empirical approach can be regarded as excellent.

2. Within the range of heat flux generated by a chilled pipeline, the variation of the ice segregation ratio (which can be regarded as volumetric excess ice content) is mainly due to the difference in soil types rather than the variation of heat flux.

3. Over a uniform soil stratigraphy, longitudinal differential heave for a chilled pipeline is insignificant.

4. Based on the observed data over the last 3.5 years, the frost heave occuring in frozen soil (secondary heave) is insignificant in comparison with the magnitude of the frost heave when the soil changes from unfrozen to frozen state (primary heave).

Respectfully submitted,

EBA Engineering Consultants Ltd.

PROFESSIONAL ENGINEER ALBERTA
C. T. HWANG

C.T.Hwang, Ph.D., P. Eng.

PROFESSIONAL ENGINEER ALBERTA
J.M. CHEVALLIER

J-M Chevallier, P. Eng.

CTH/hek

References

1. Northern Engineering Services Co. Ltd. (1975); Interim Reprot on Frost Effects Study; prepared for Canadian Arctic Gas Study Limited.

2. EBA Engineering Consultants Ltd. (1977): Drilling Results, Calgary Frost Heave Test Faciltiy. CAGPL; submitted to Foothills Pipe Lines Ltd.

3. EBA Engineering Consultants Ltd. (1978): Preliminary Report on Stage II Drilling Results of Calgary Frost Heave Test Facility. A report submitted to Foothills Pipe Lines (Yukon) Ltd.

4. Kaplar, C.W. 1974. Freezing Test for Evaluating Relative Frost Susceptibility of Various Soils. U.S. Army CRREL, Hanover, New Hampshire.

5. Penner, E., and Walton, T. 1978. Effects of Temperature and Pressure on Frost Heave. Proceedings, International Symposium of Ground Freezing, Ruhr, Germany.

6. EBA Engineering Consultants Ltd. 1976. Freezing of Saturated Soils, One-Dimensional Model. A report submitted to Foothills Pipe Lines Ltd.

7. EBA Engineering Consultants Ltd. 1976. Interim Report on Frost Heave Study, Two Dimensional Model. A report submitted to Foothills Pipe Lines Ltd.

8. Hwang, C.T. 1977. Frost Heave Design of a Chilled Gas Pipeline. Proceedings, 30th Canadian Geotechnial Conference, Saskatoon, Saskatchewan, Canada.

9. Hwang, C.T. and Yip, F.C. 1977. Advances in Frost Heave Prediction and Mitigative Methods for Pipeline Application. Proceedings, ASME Winter Annual Meeting, Atlanta, Georgia.

10. Hwang, C.T. 1976. Predictions and Observations on the Behaviour of a Warm Gas Pipeline on Permafrost; Can. Geotech. J., 13(4), pp. 452-480.

11. Hwang, C.T. 1977. On Quasi-Static Solutions for Buried Pipes in Permafrost. Can. Geotech. J., 14(2), pp. 180-192.

12. EBA Engineering Consultants Ltd. 1979. Development of An Empirical Frost Heave Design Procedure. A report submitted to Northwest Alaskan Pipeline Co.

13. Speer, T.L., Watson, G.H., and Rowley, R.K. 1973. Effects on Ground-Ice Variability and Resulting Thaw Settlement on Buried Warm Oil Pipelines. Proc. 2nd Int. Permafrost Cong. Yakutsk, U.S.S.R., pp. 746-752.

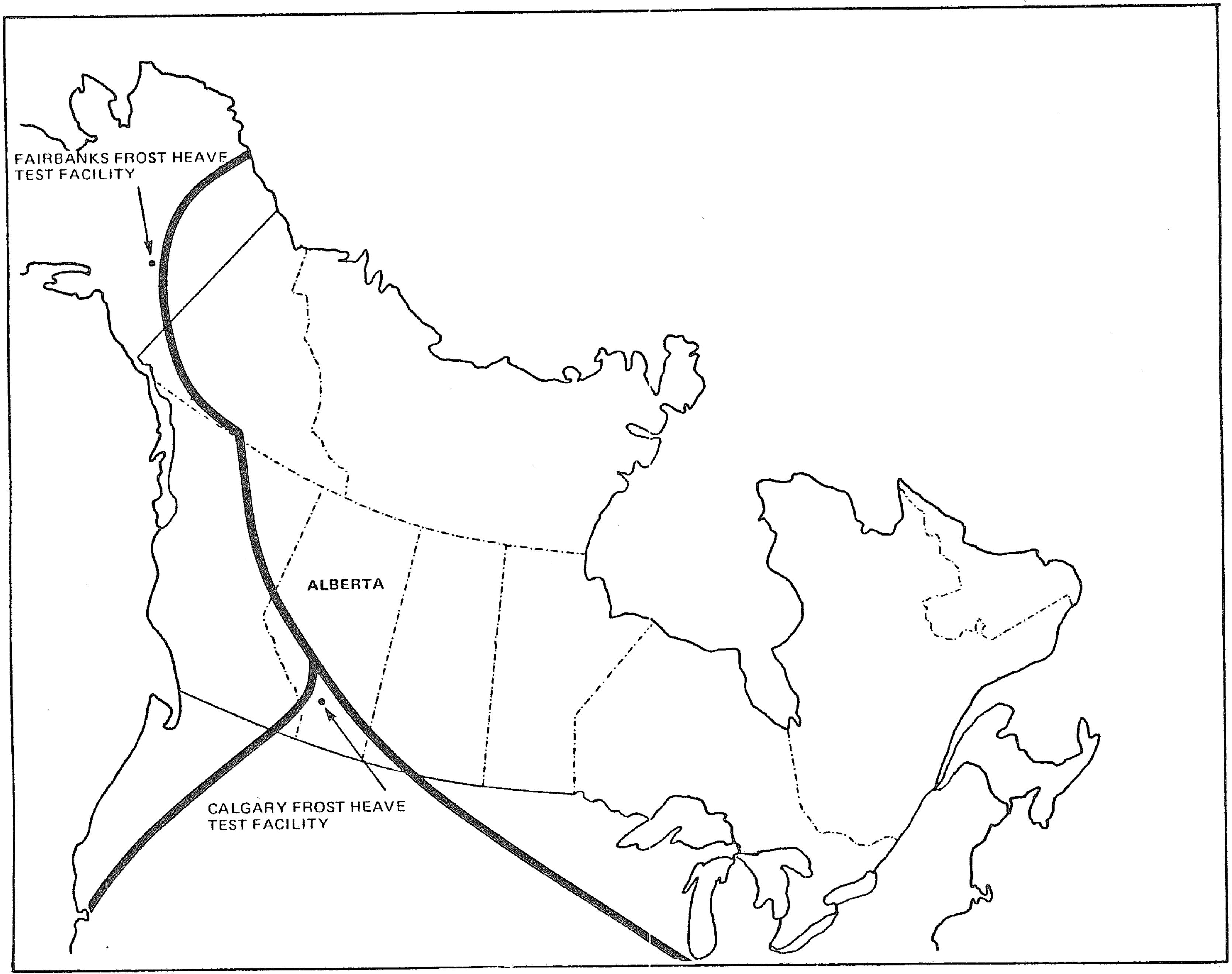


FIGURE 1.1

PIPELINE ROUTE

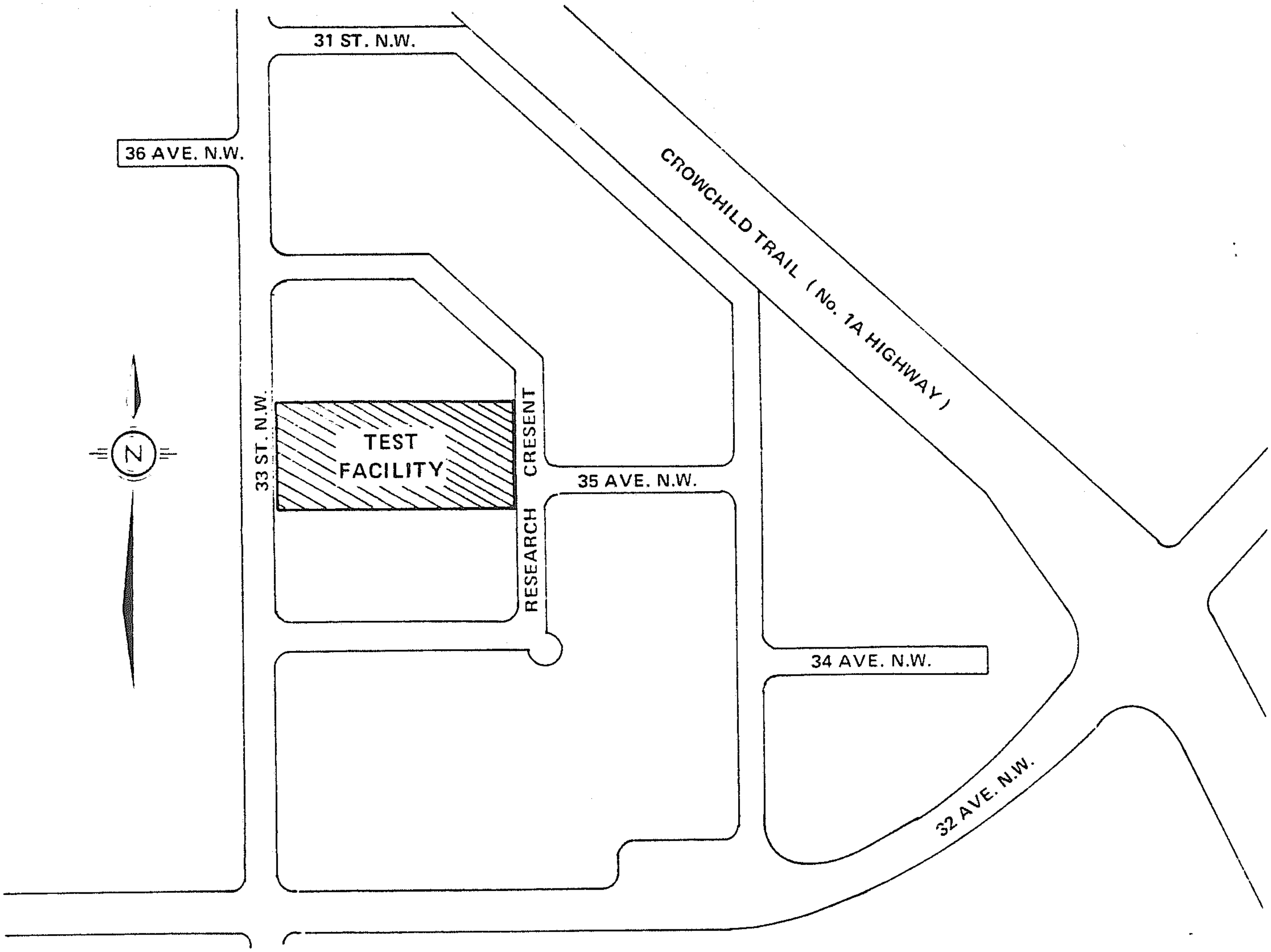
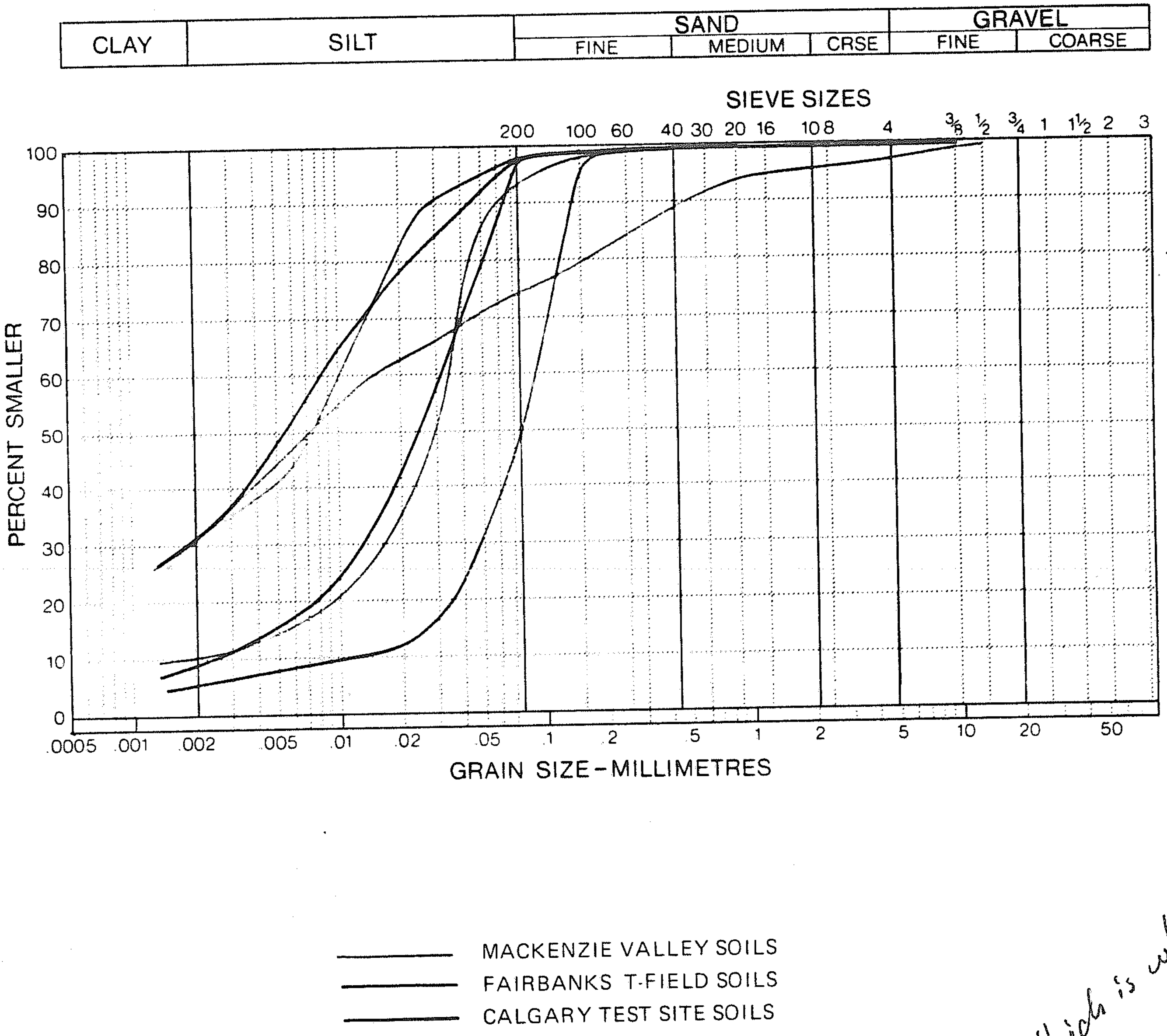


FIGURE 2.1 LOCATION OF TEST FACILITY, UNIVERSITY OF CALGARY, N.W. CALGARY.



Which is which?

FIGURE 2.2

RANGE OF SOILS
GRAIN SIZE DISTRIBUTION

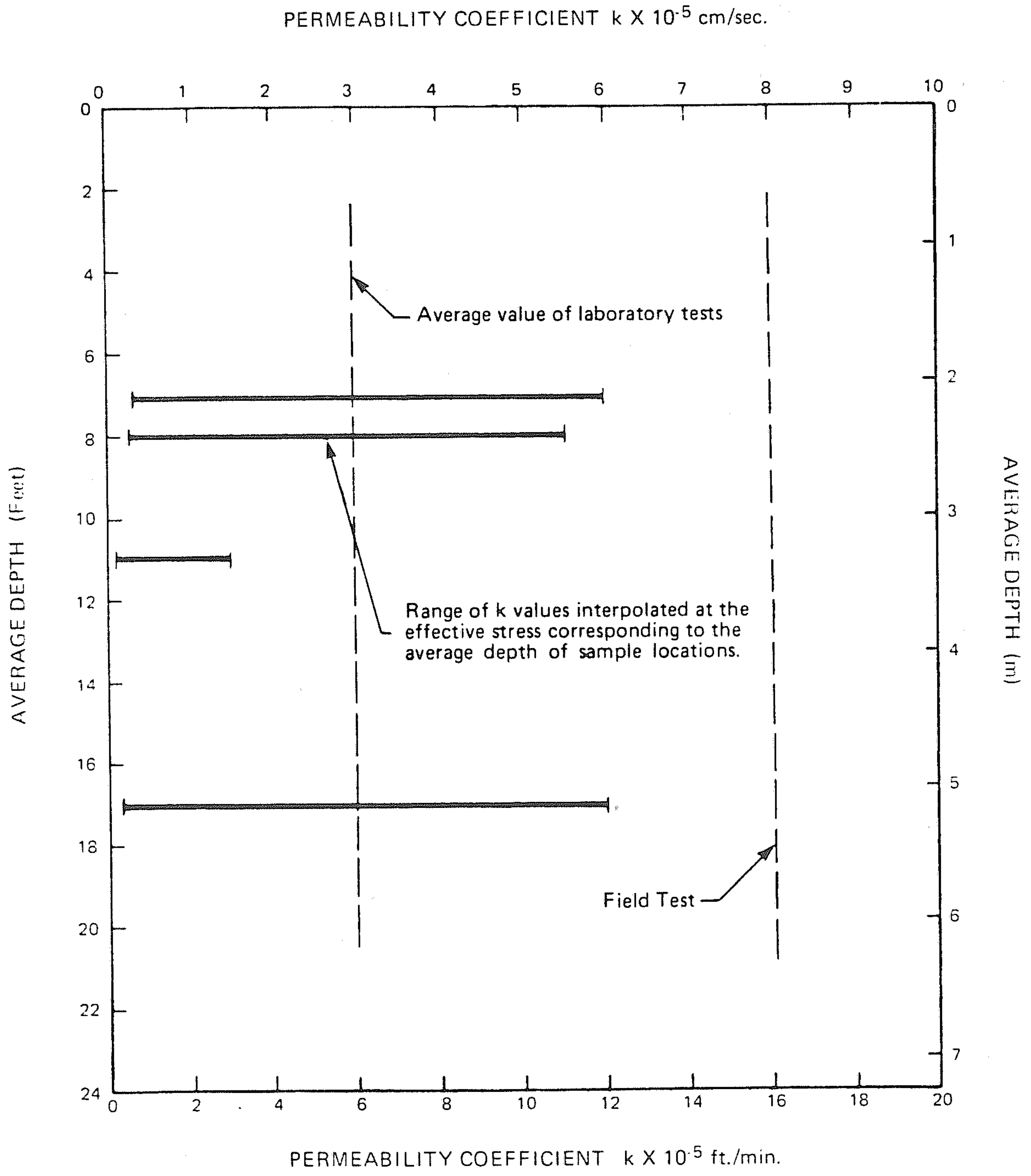


FIGURE 2.3 RANGE OF SOIL PERMEABILITY CALGARY TEST SITE

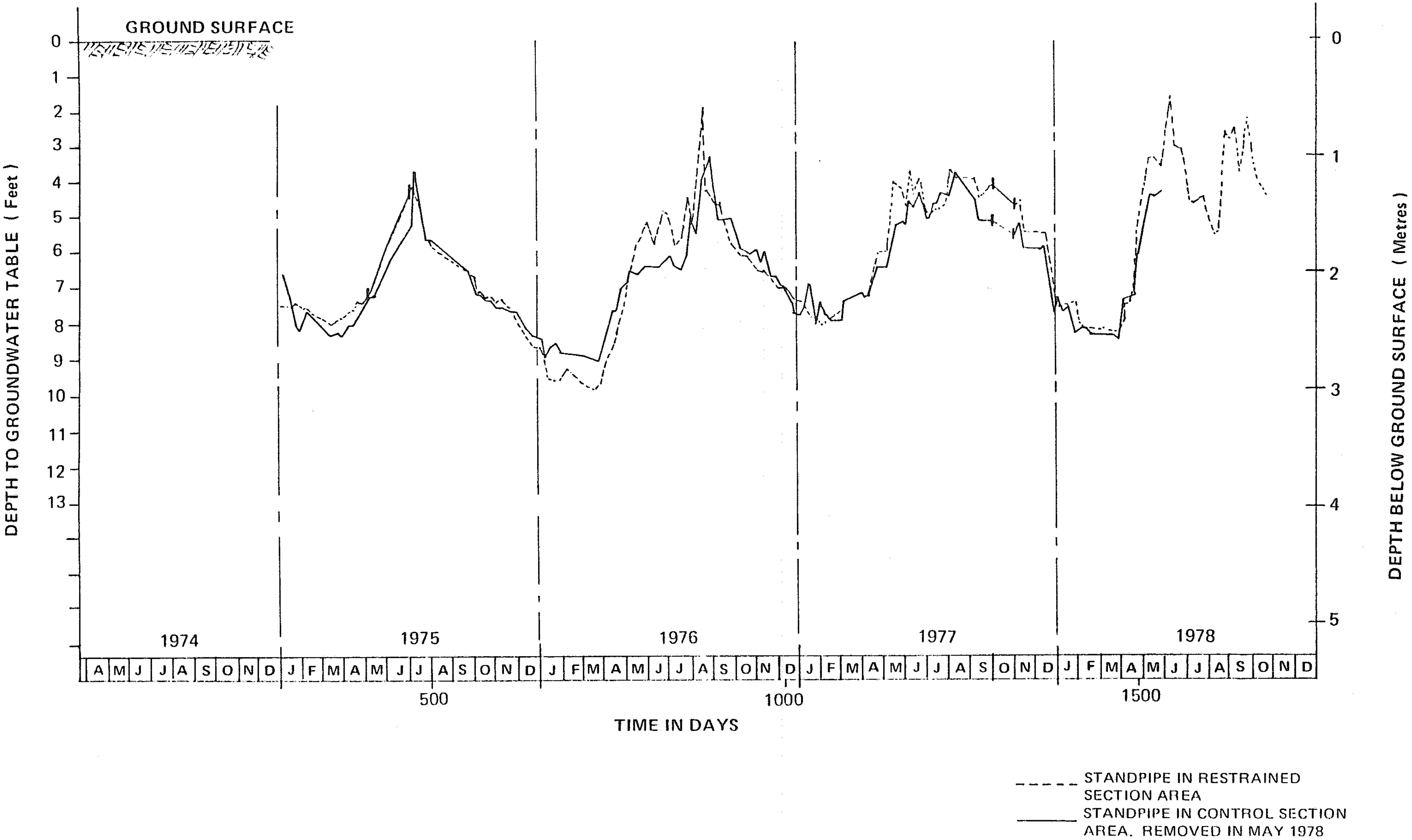
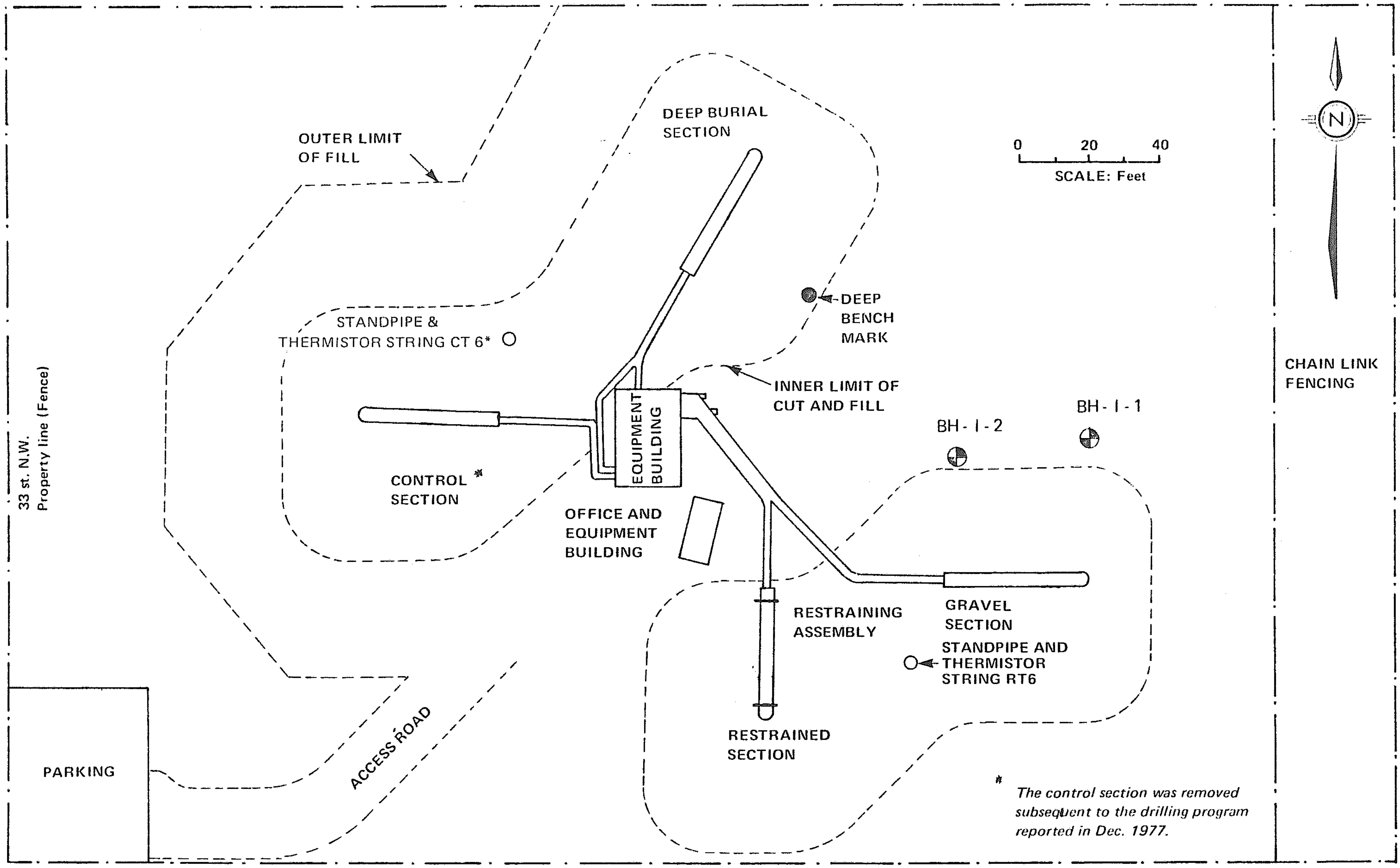


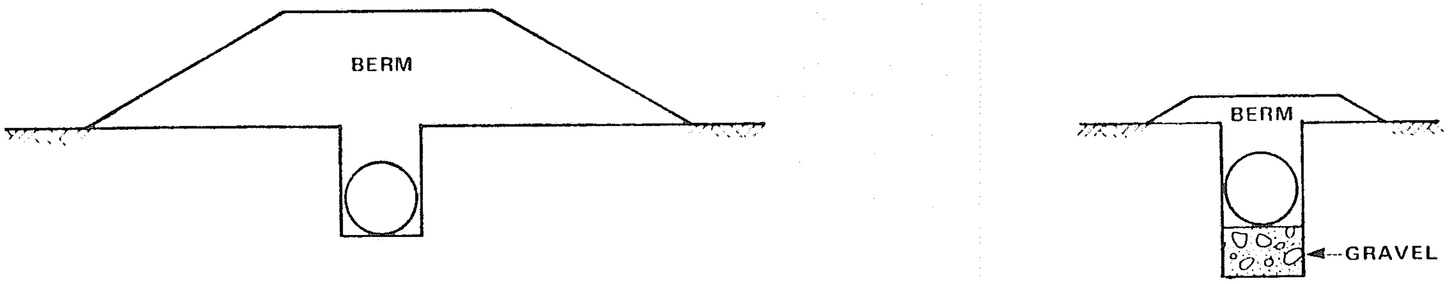
FIGURE 2.4 VARIATION OF GROUNDWATER TABLE CALGARY FROST HEAVE TEST SITE



* *The control section was removed subsequent to the drilling program reported in Dec. 1977.*

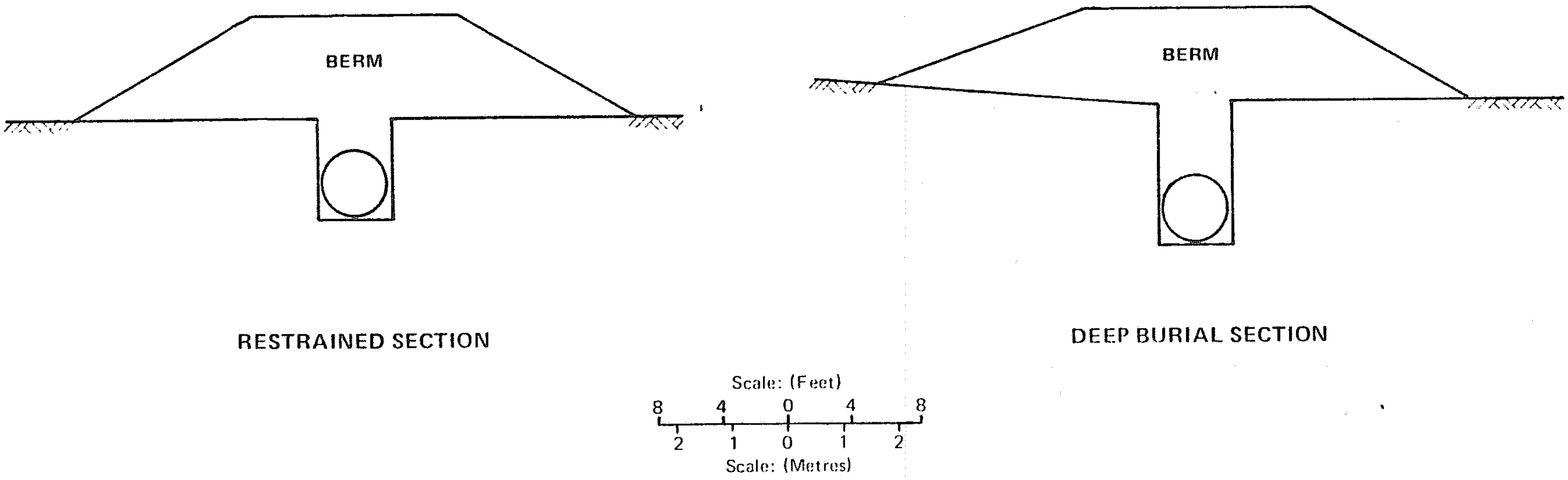
FIGURE 2.5

LAYOUT OF TEST SECTIONS,
CALGARY FROST HEAVE TEST FACILITY



CONTROL SECTION

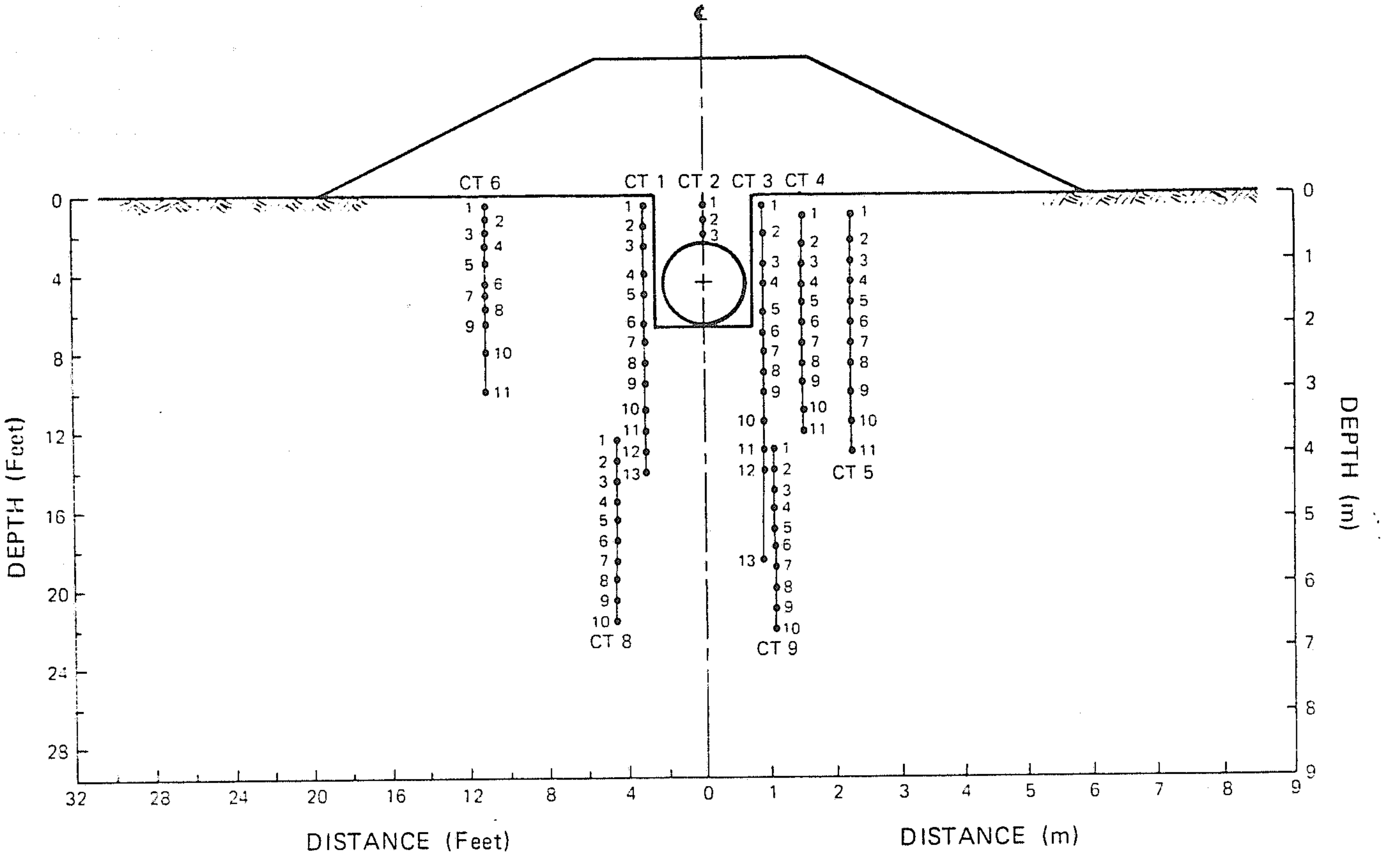
GRAVEL SECTION



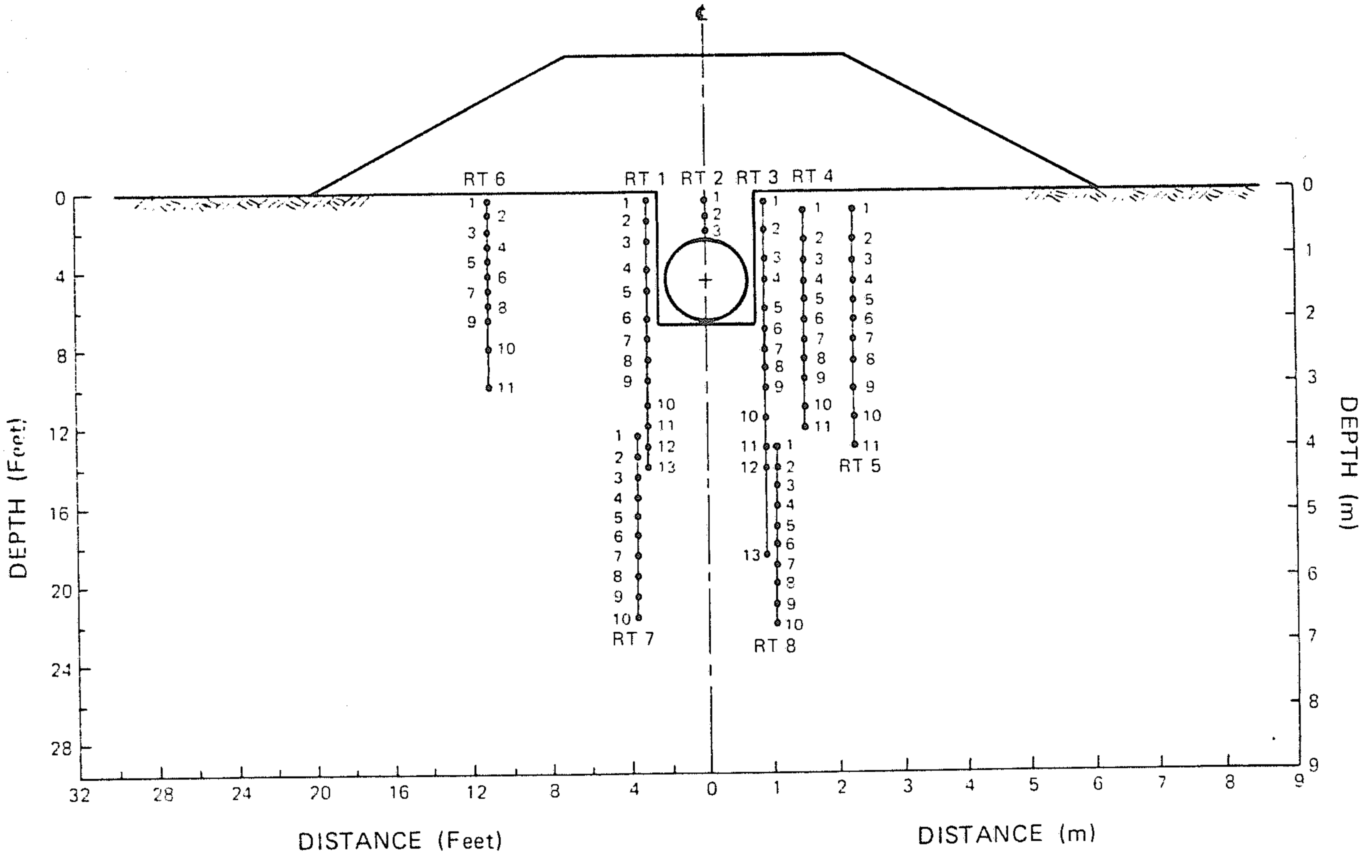
RESTRAINED SECTION

DEEP BURIAL SECTION

FIGURE 2.6 CONFIGURATION OF TEST SECTIONS CALGARY FROST HEAVE TEST FACILITY

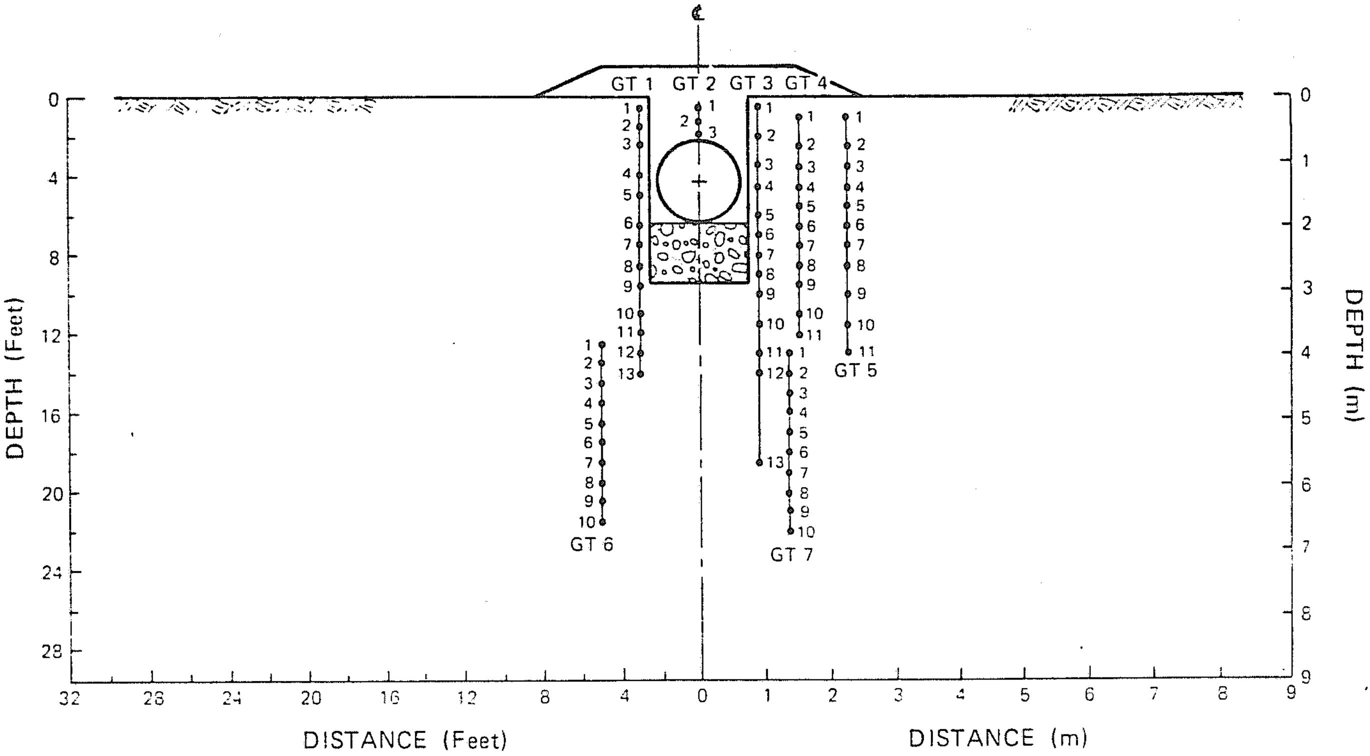


CONTROL SECTION

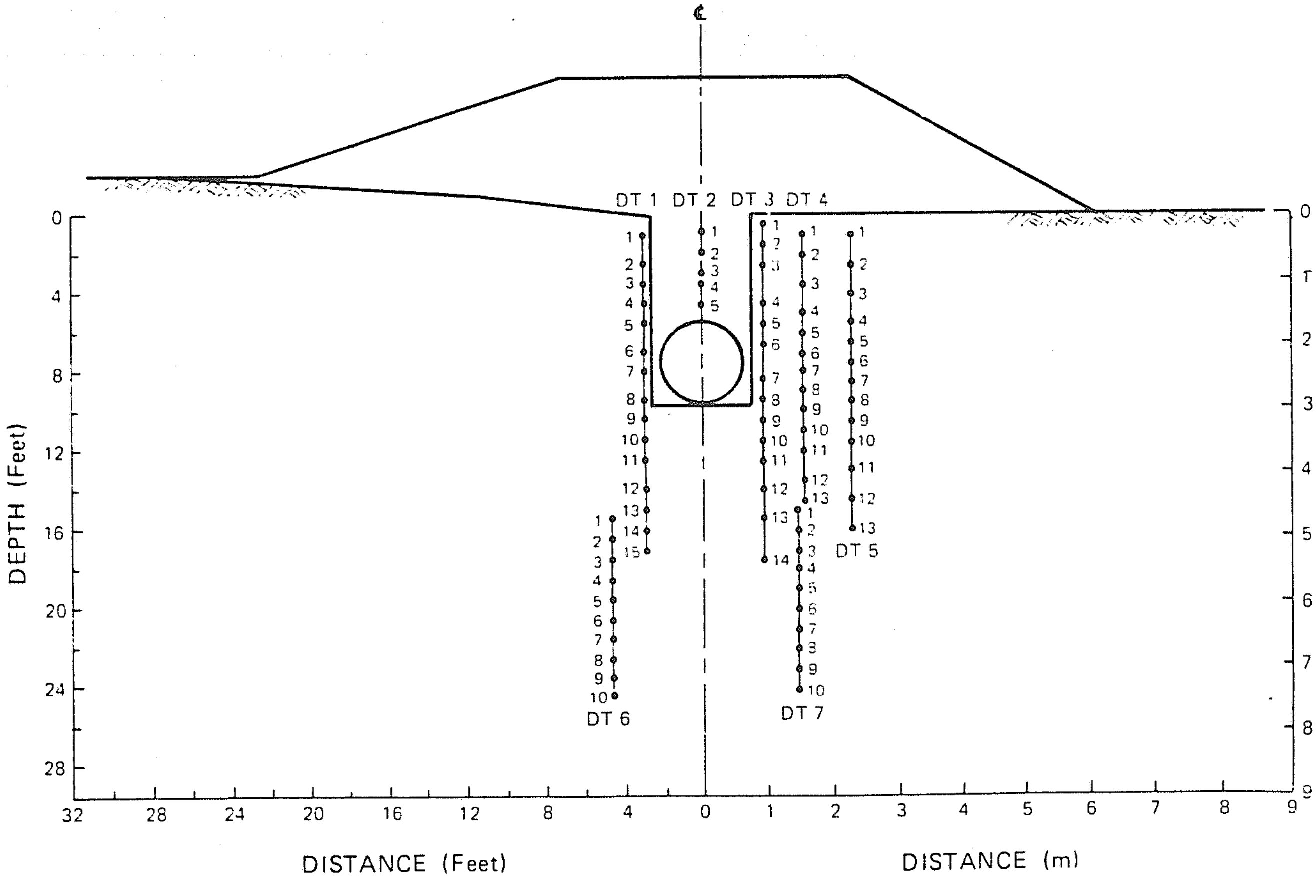


RESTRAINED SECTION

FIGURE 2.7 THERMISTOR LOCATIONS

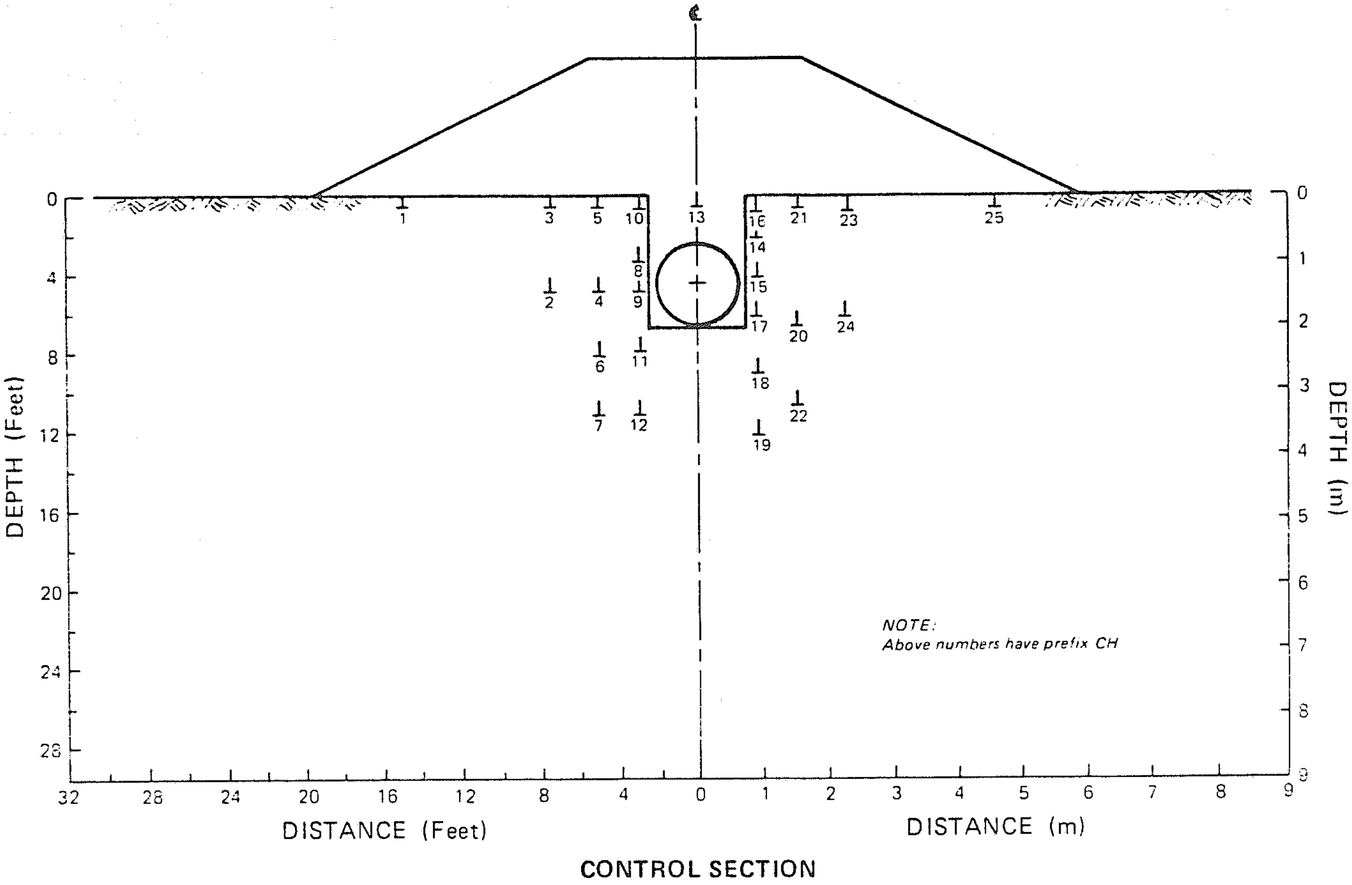


GRAVEL SECTION



DEEP BURIAL SECTION

FIGURE 2.8 THERMISTOR LOCATIONS



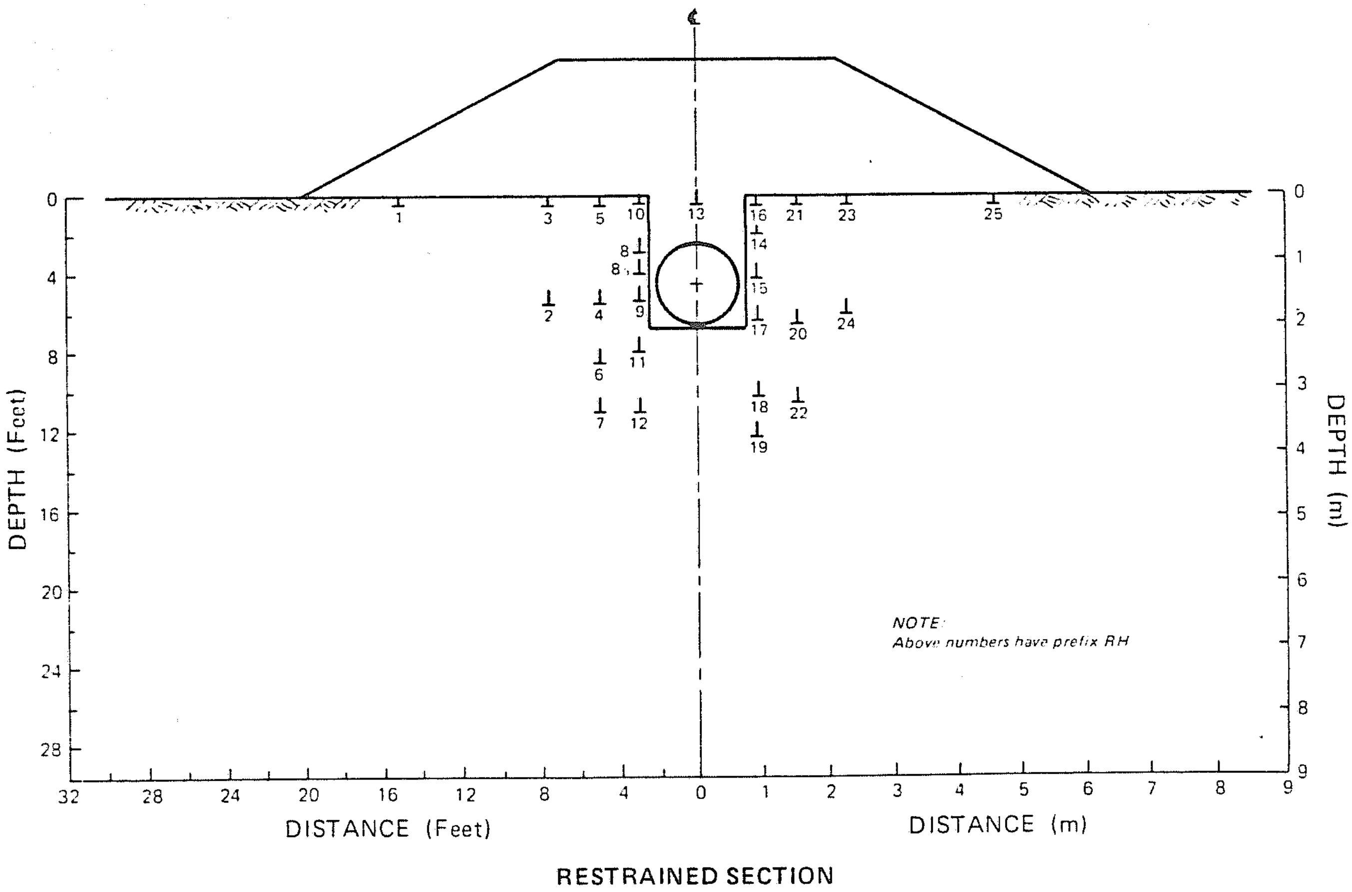
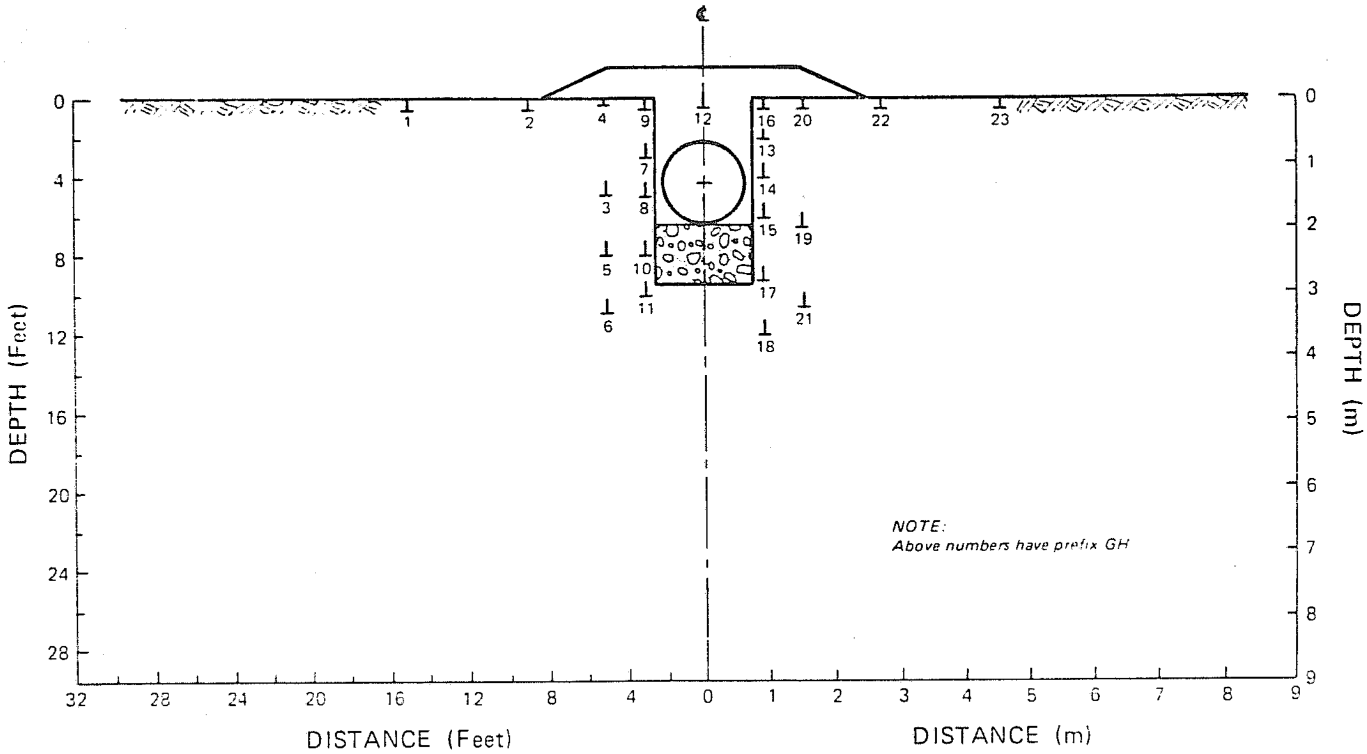
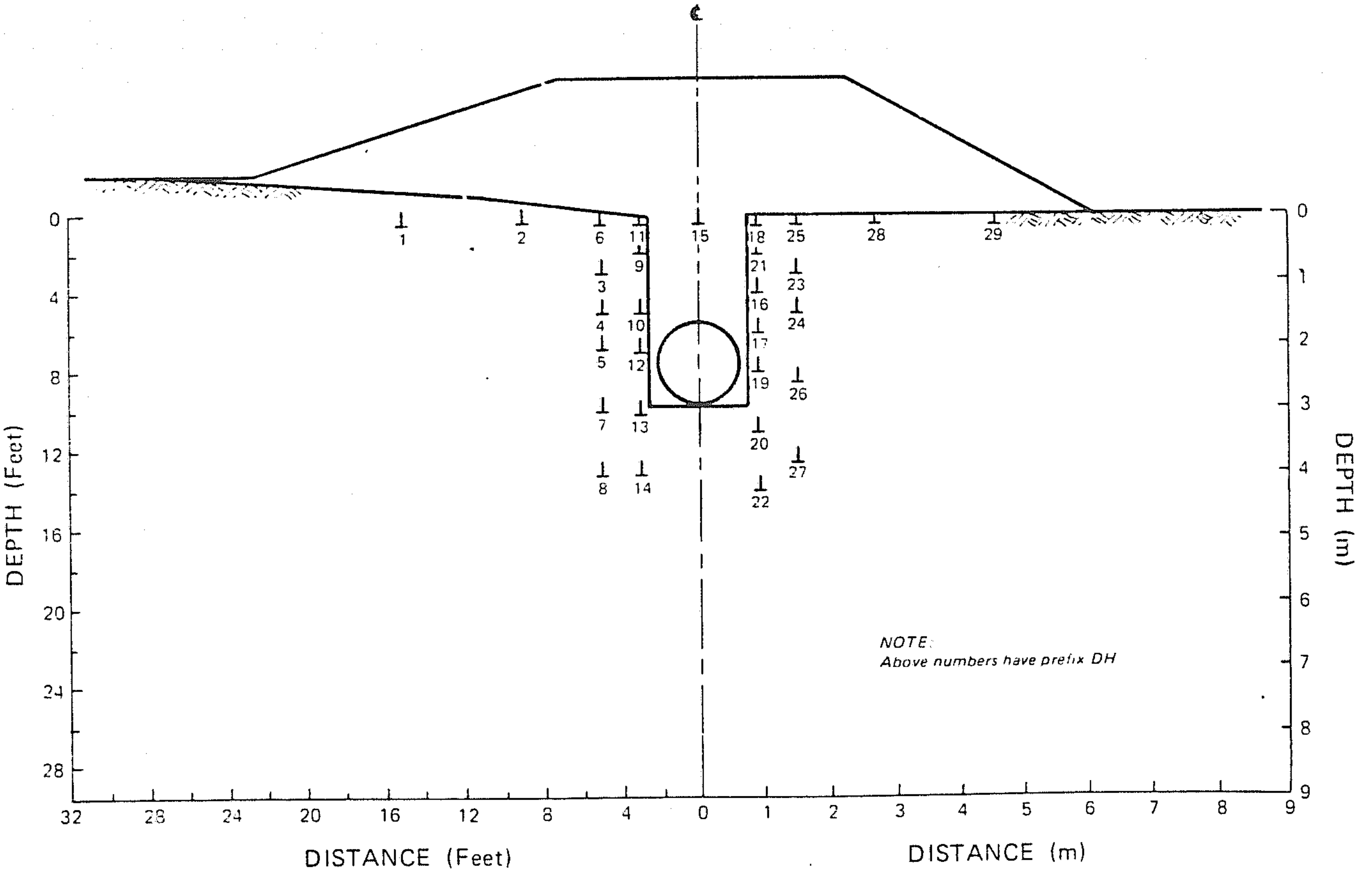


FIGURE 2.9 HEAVE GAUGE LOCATIONS



GRAVEL SECTION



DEEP BURIAL SECTION

FIGURE 2.10 HEAVE GAUGE LOCATIONS

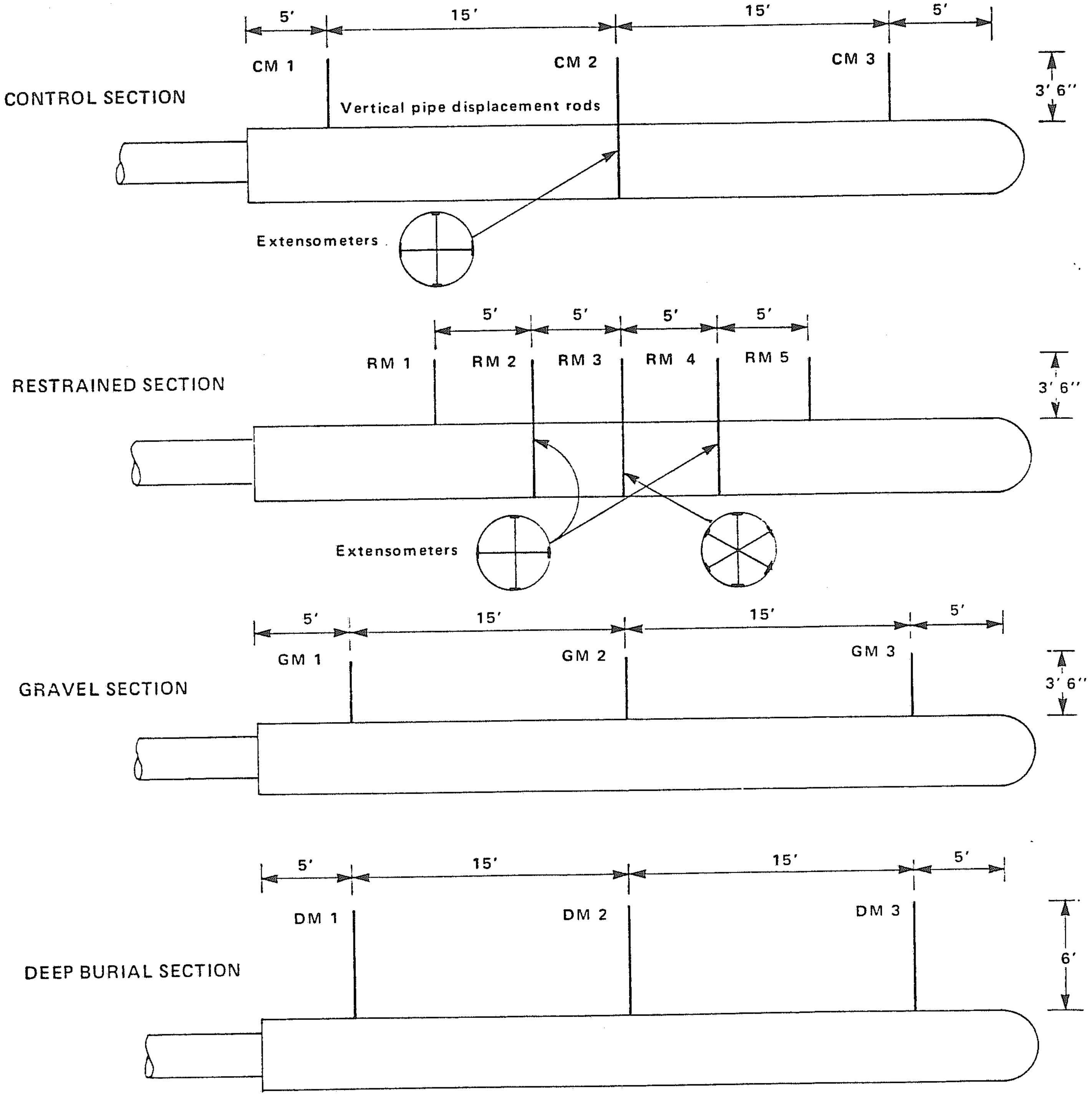
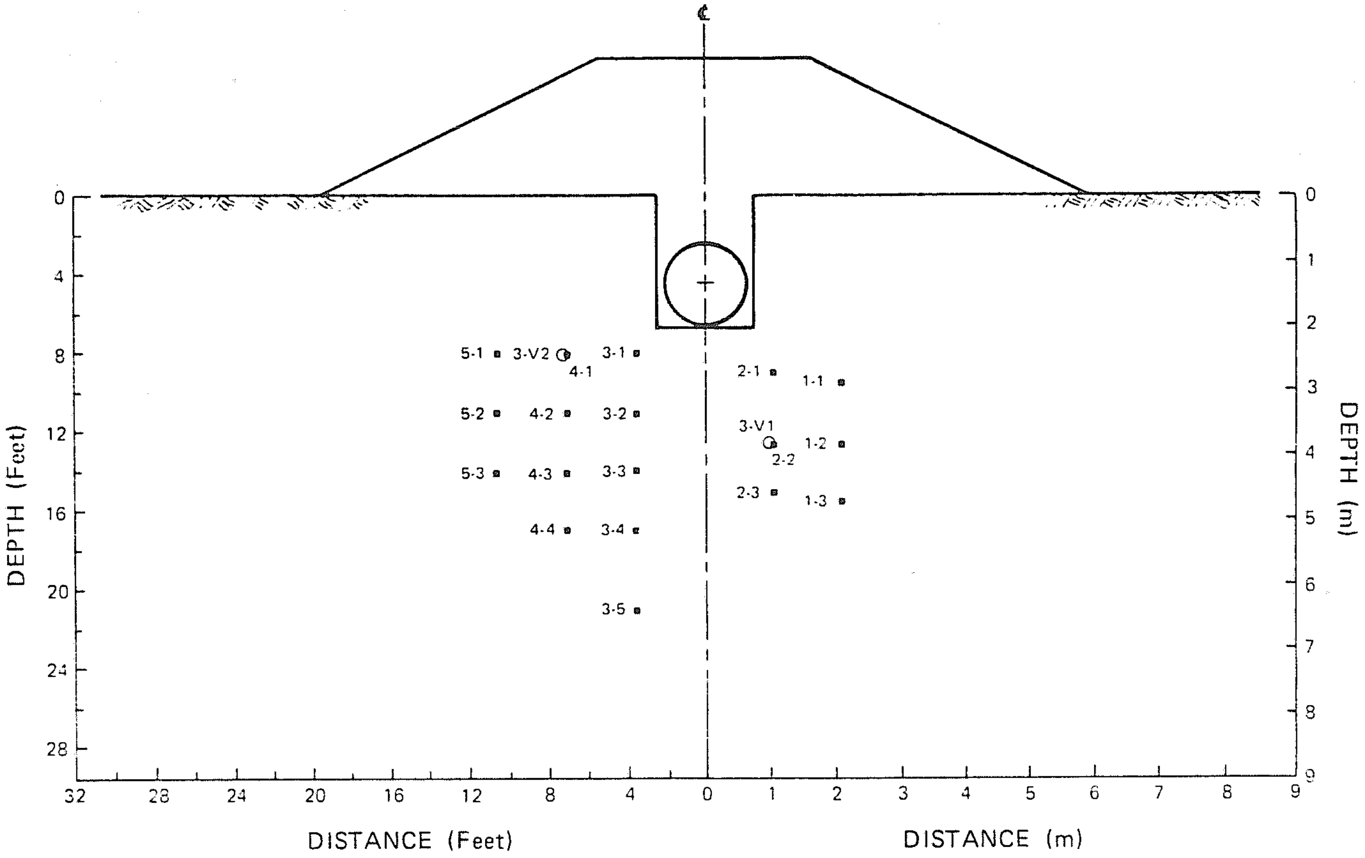
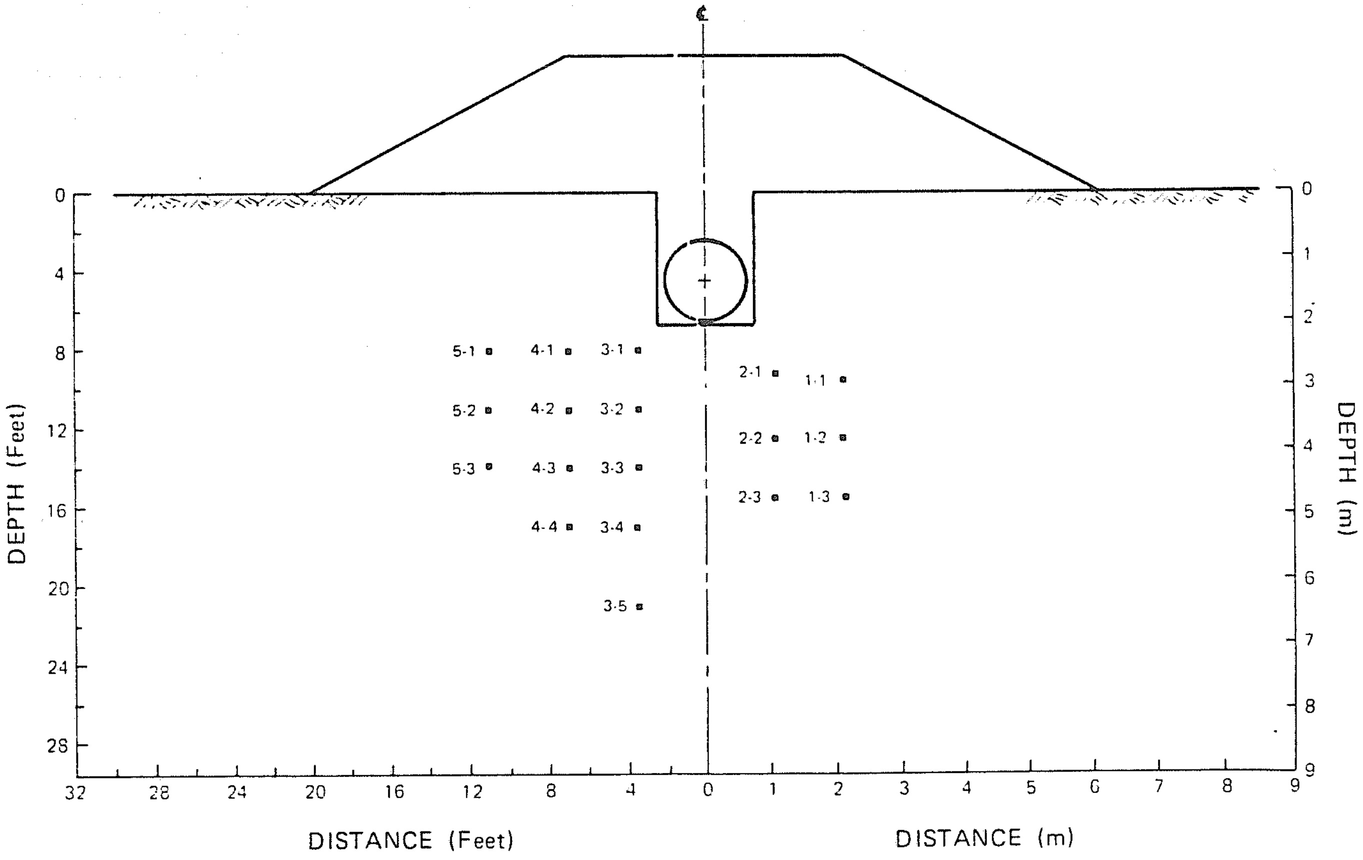


FIGURE 2.11 LOCATIONS OF PIPE HEAVE RODS
CALGARY FROST HEAVE TEST SITE

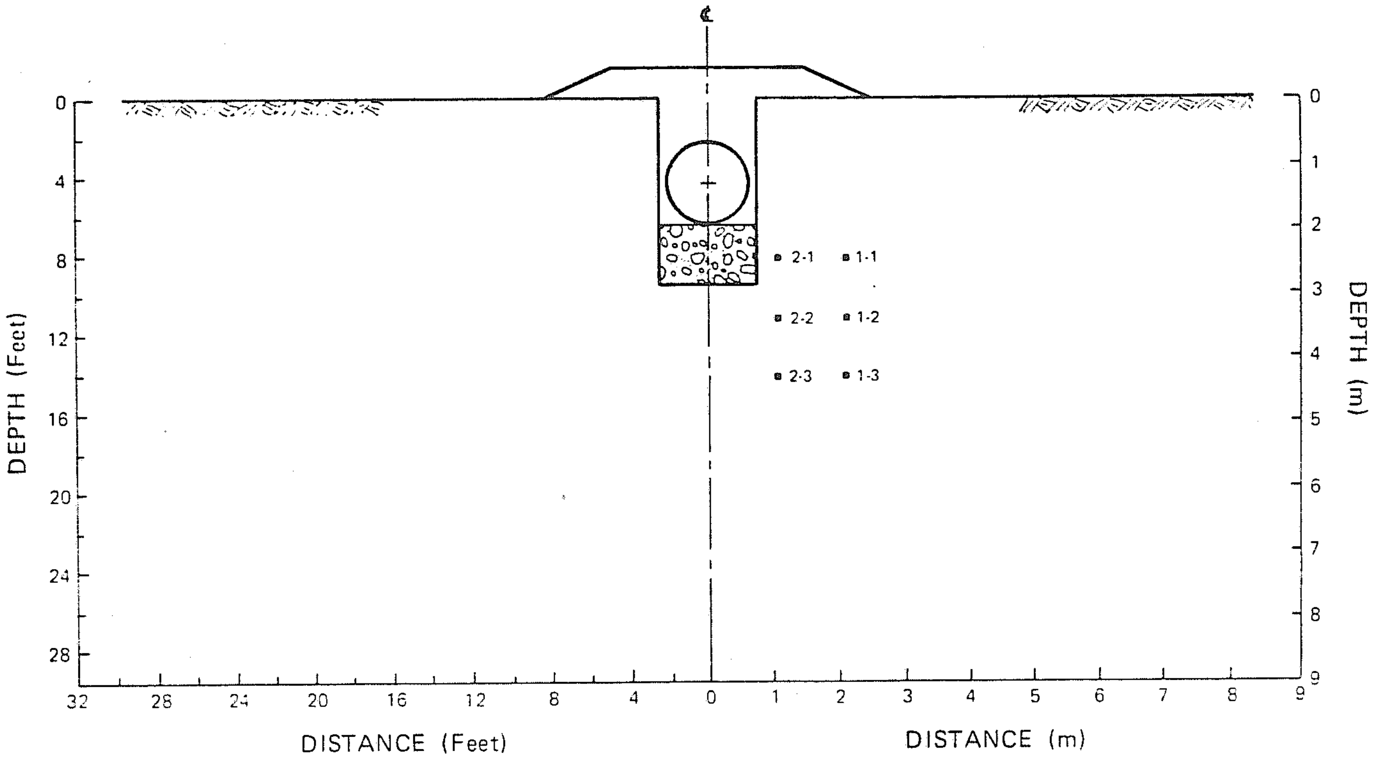


CONTROL SECTION

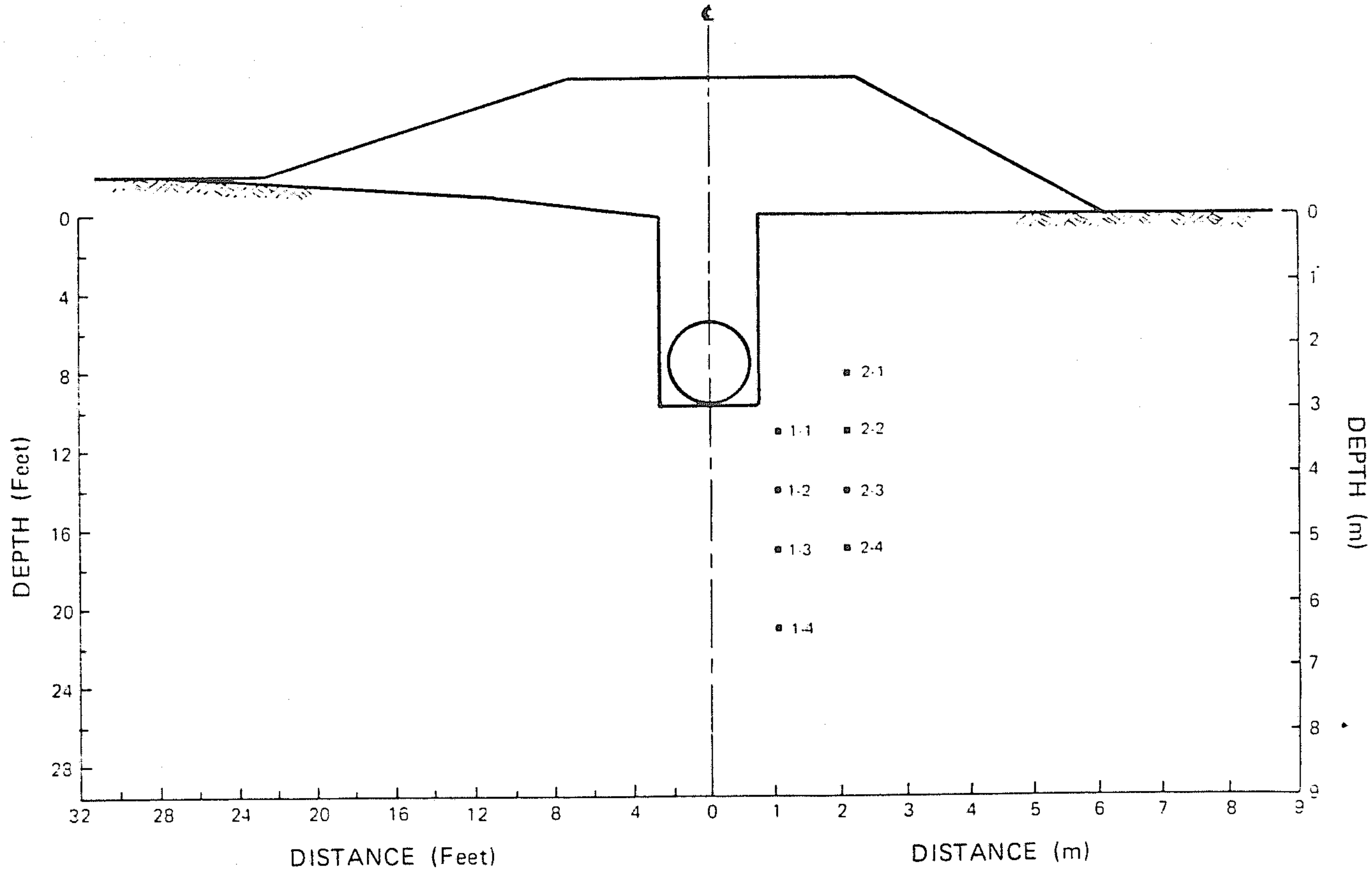


RESTRAINED SECTION

FIGURE 2.12 PIEZOMETER LOCATIONS



GRAVEL SECTION



DEEP BURIAL SECTION

FIGURE 2.13 PIEZOMETER LOCATIONS

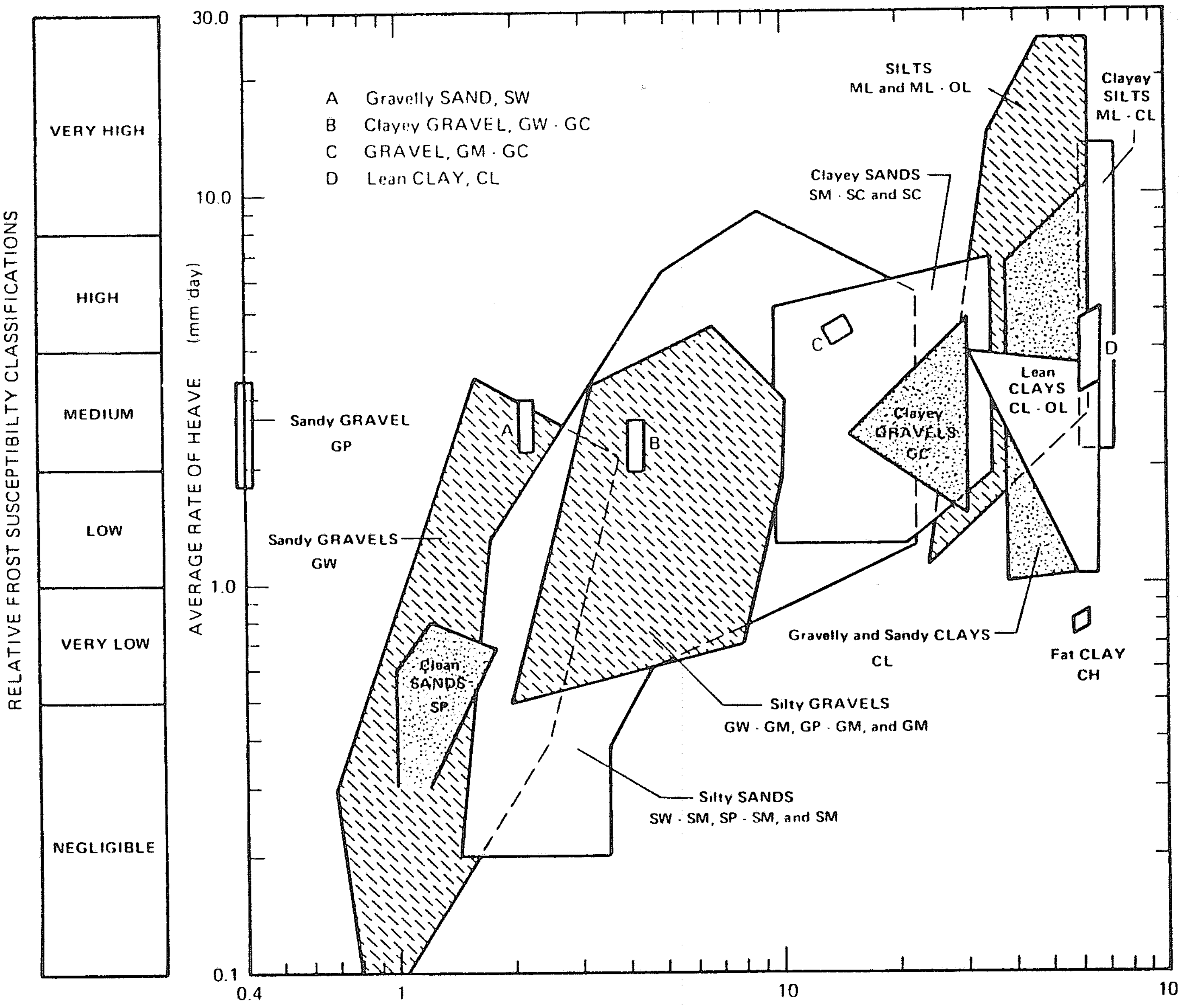


FIGURE 3.1

SUMMARY OF AVERAGE RATE OF HEAVE
vs
PERCENTAGE FINER THAN 0.02 mm SIZE
FOR NATURAL SOIL GRADATION
(From Kaplar, 1974 CRREL)

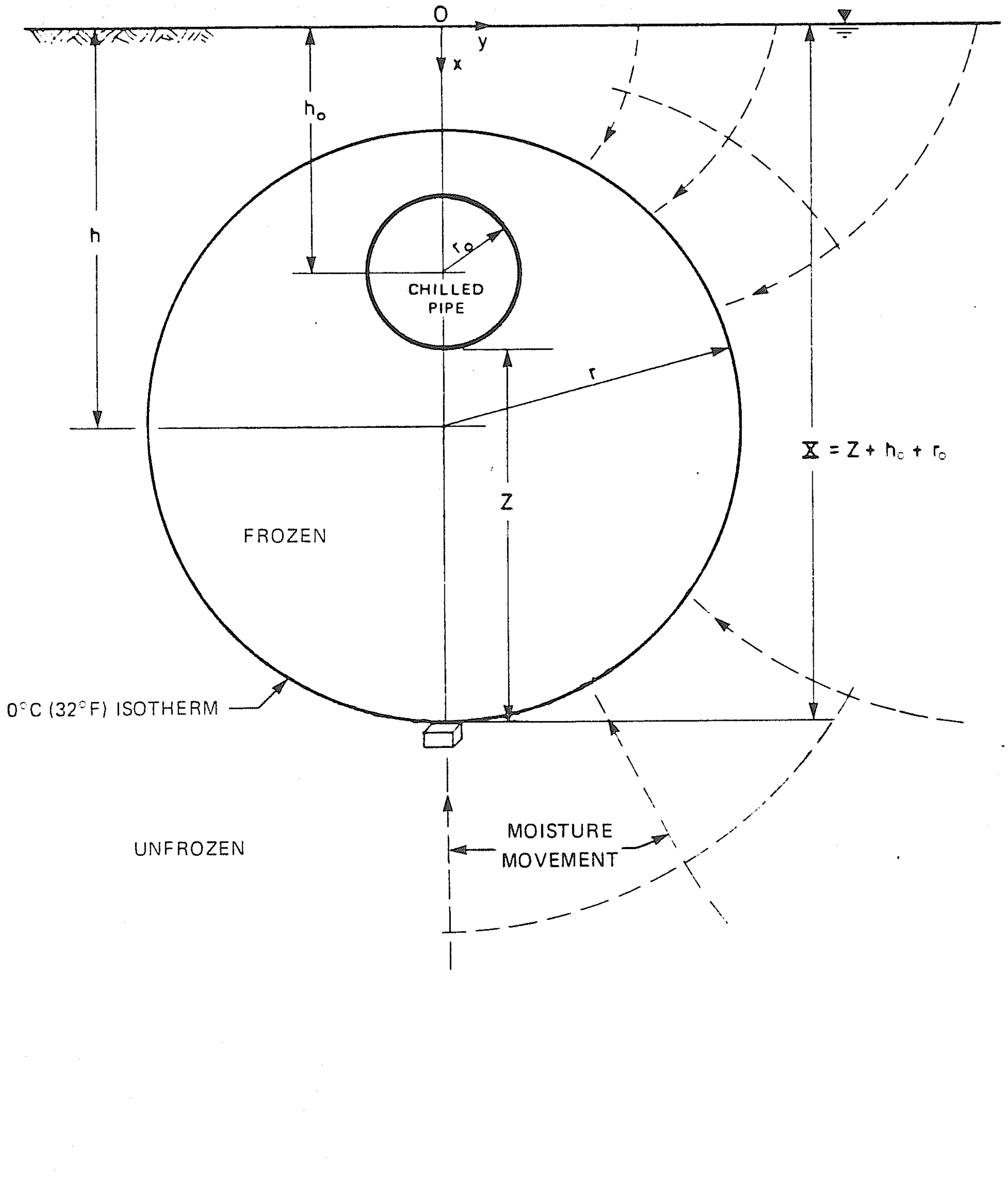


FIGURE 3.2 TWO DIMENSIONAL FROST HEAVE MODEL

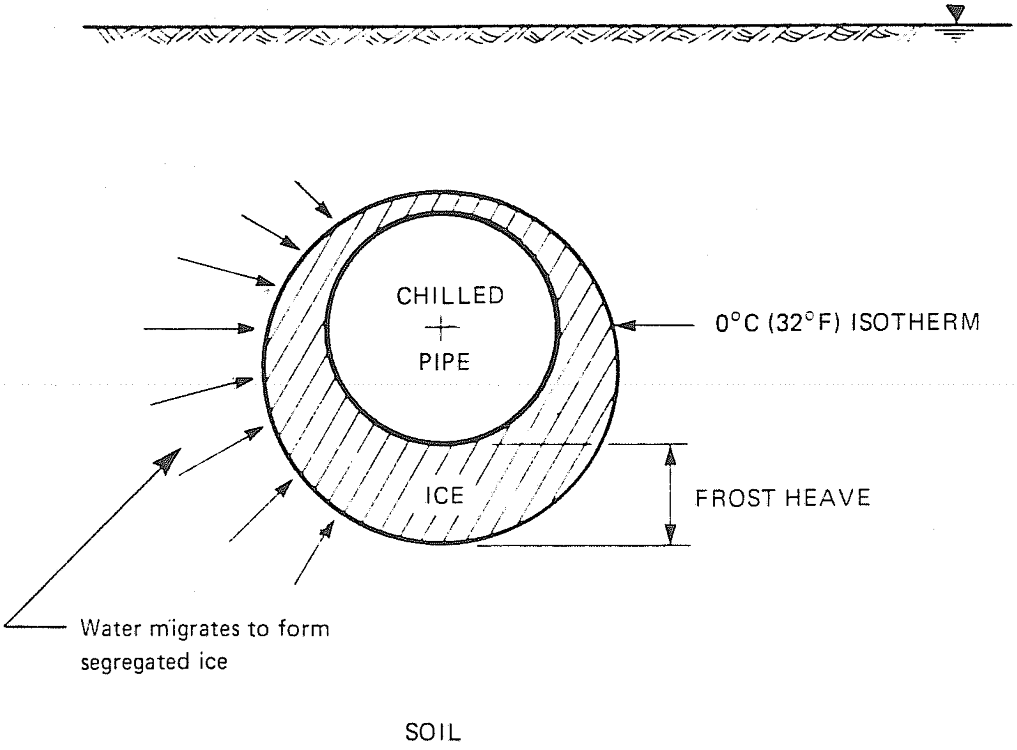


FIGURE 3.3 MODEL FOR EVALUATING MAXIMUM HEAVE BELOW A CHILLED PIPELINE

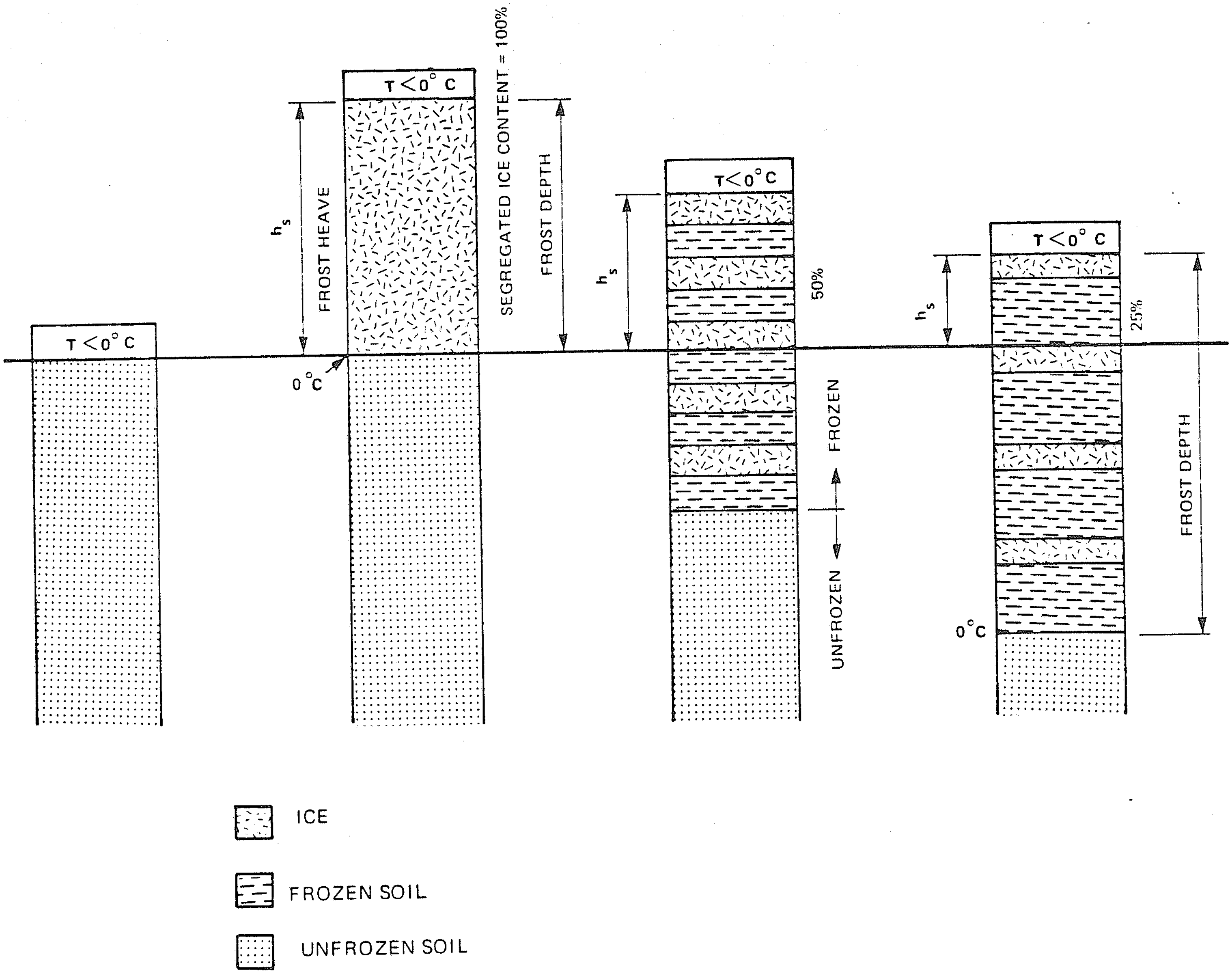


FIGURE 3.4 FROST HEAVE & SEGREGATED ICE CONTENTS

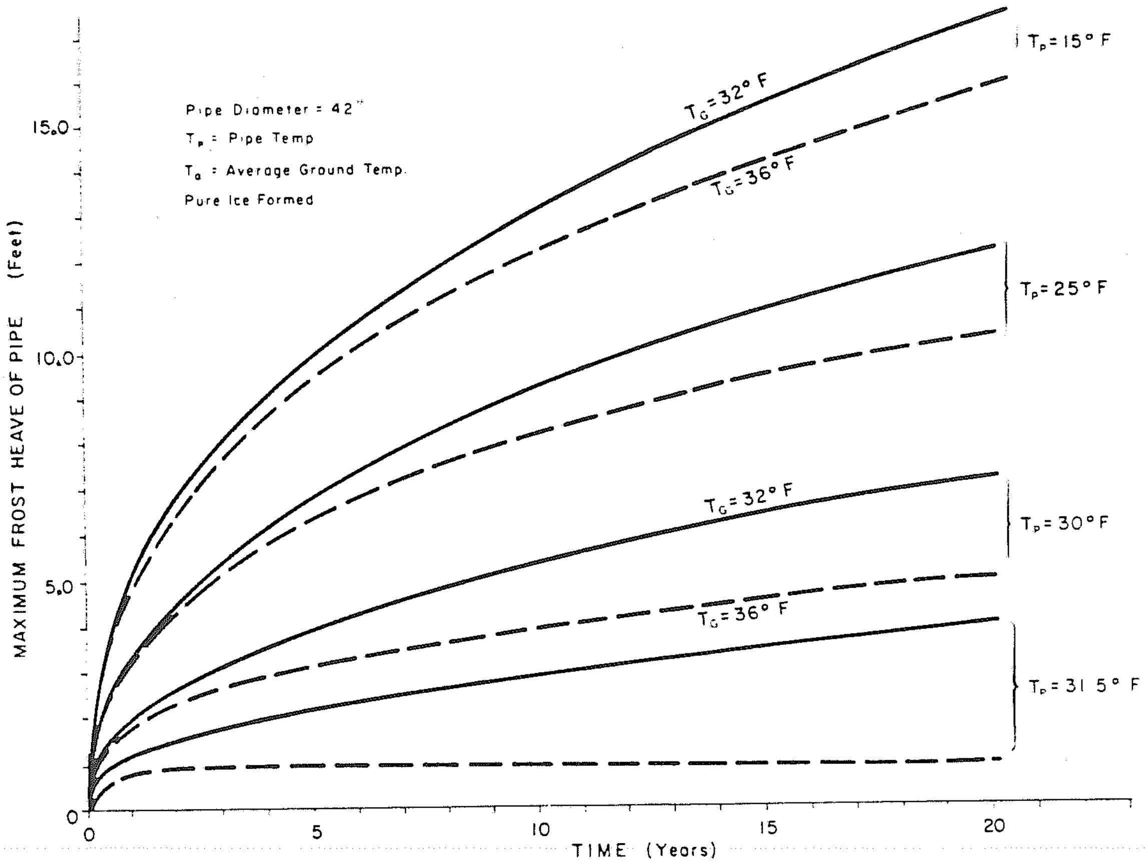


FIGURE 3.5a UPPER BOUND FROST HEAVE OF PIPE

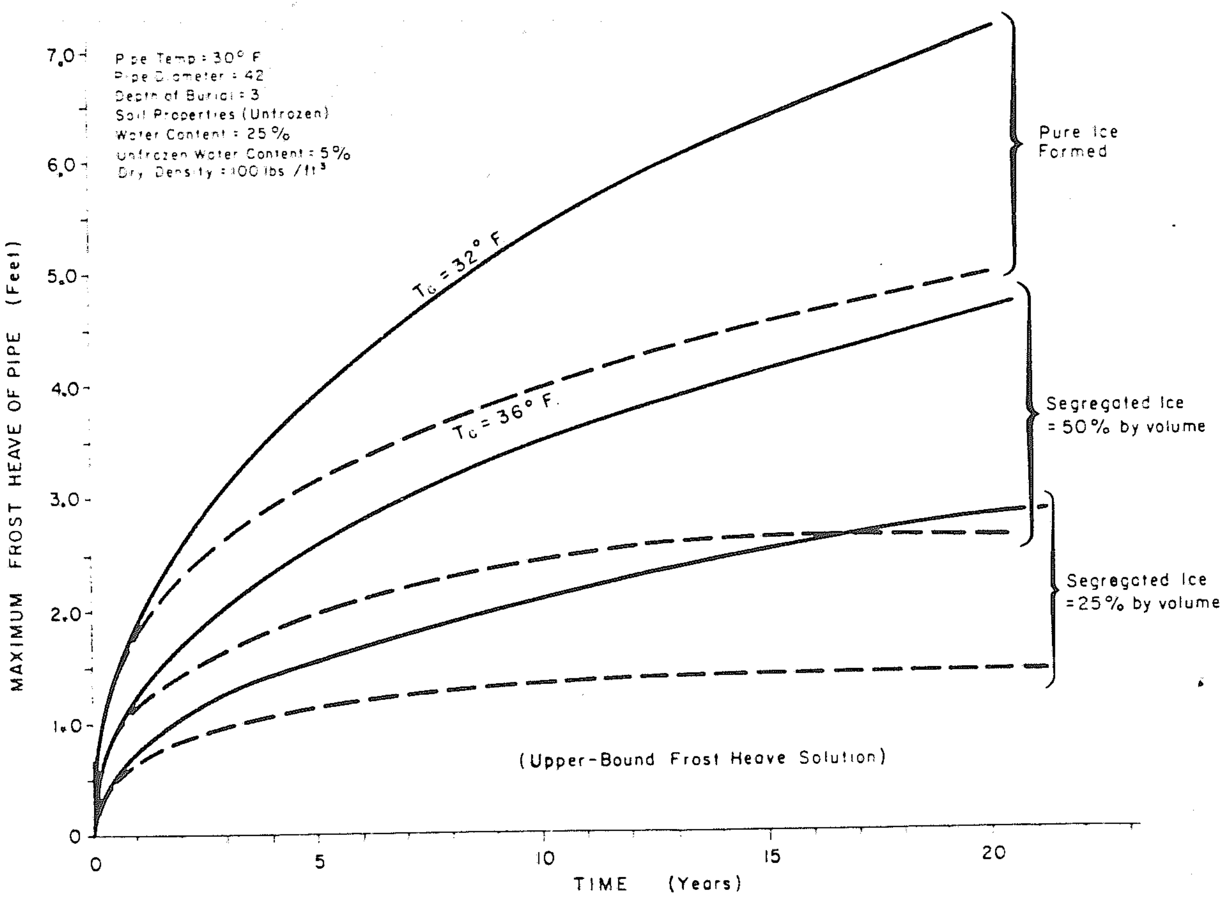


FIGURE 3.5b COMPARISON OF FROST HEAVE FOR DIFFERENT ICE SEGREGATIONS

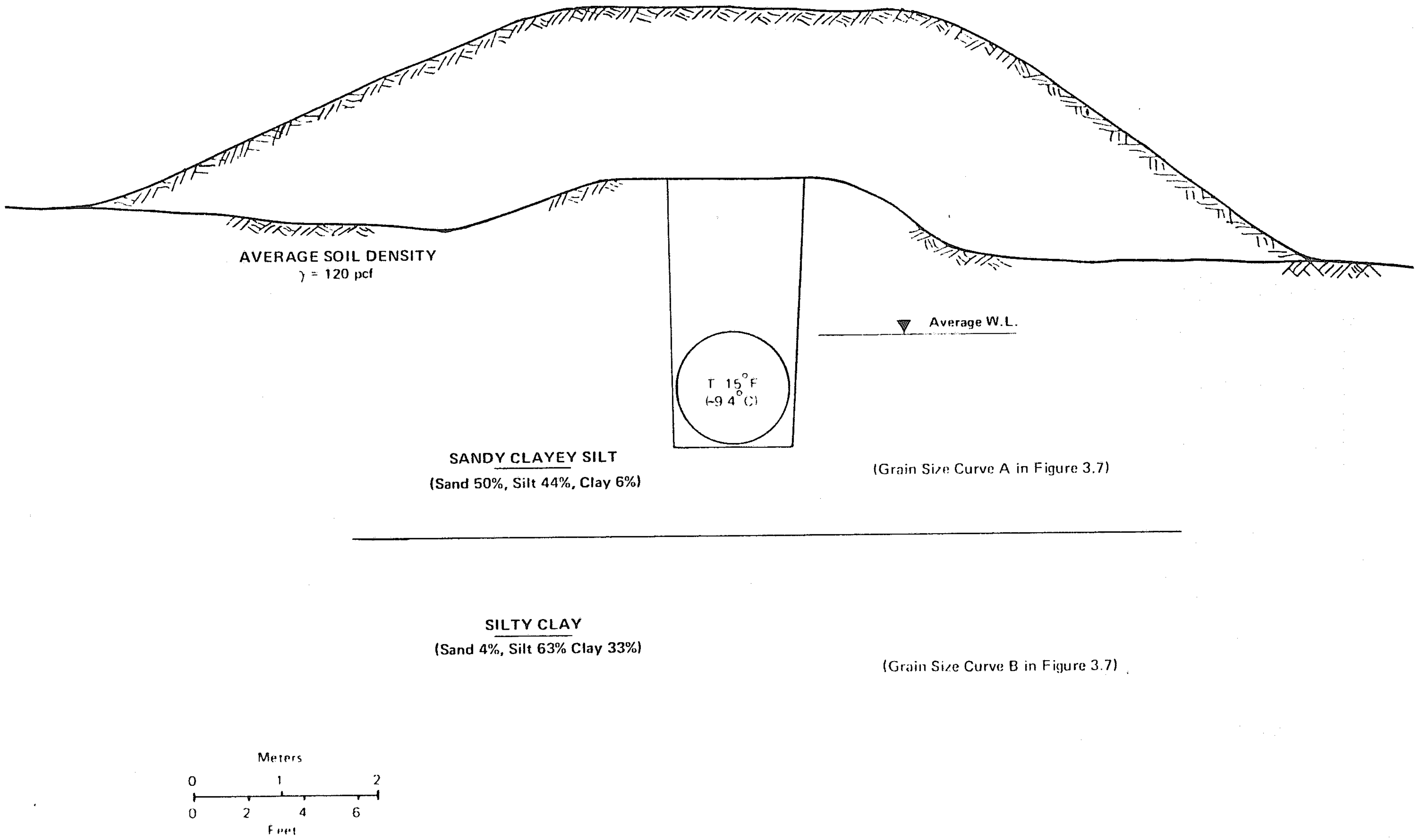


FIGURE 3.6

STRATIGRAPHIC SECTION
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE

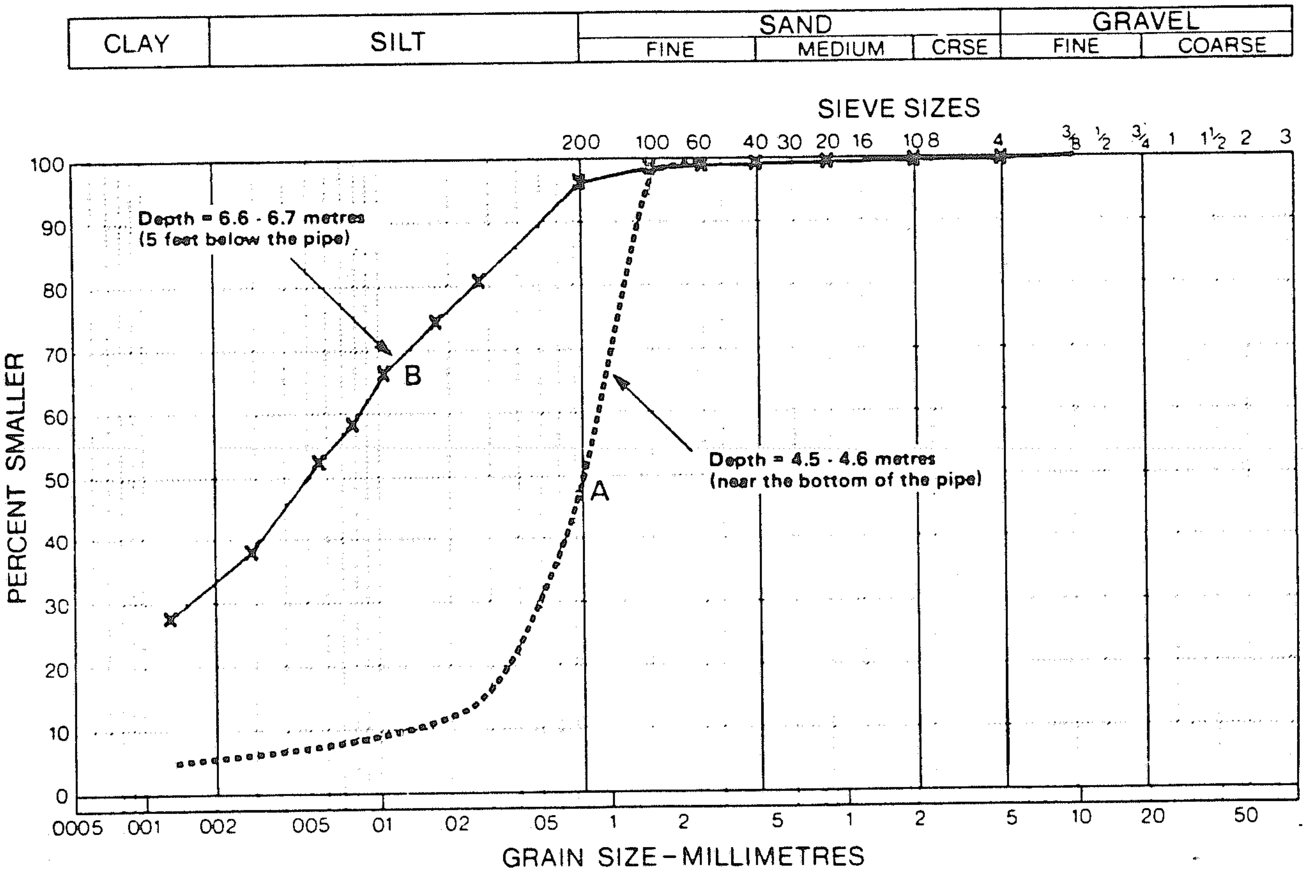


FIGURE 3.7

GRAIN SIZE DISTRIBUTION OF SOILS
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE

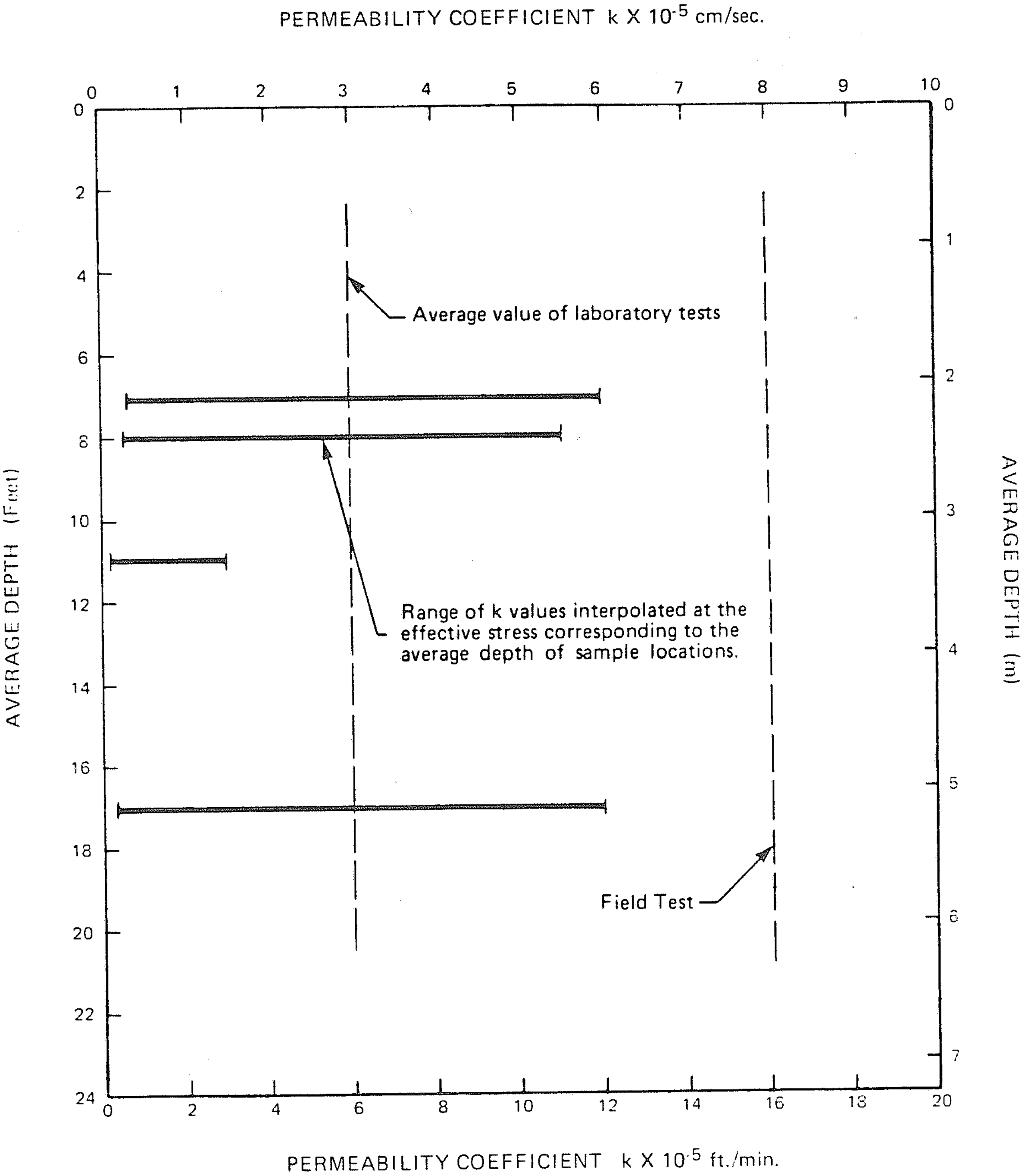


FIGURE 3.8 RANGE OF k VALUES vs DEPTH FROM NESCL LABORATORY TEST DATA CALGARY TEST SITE

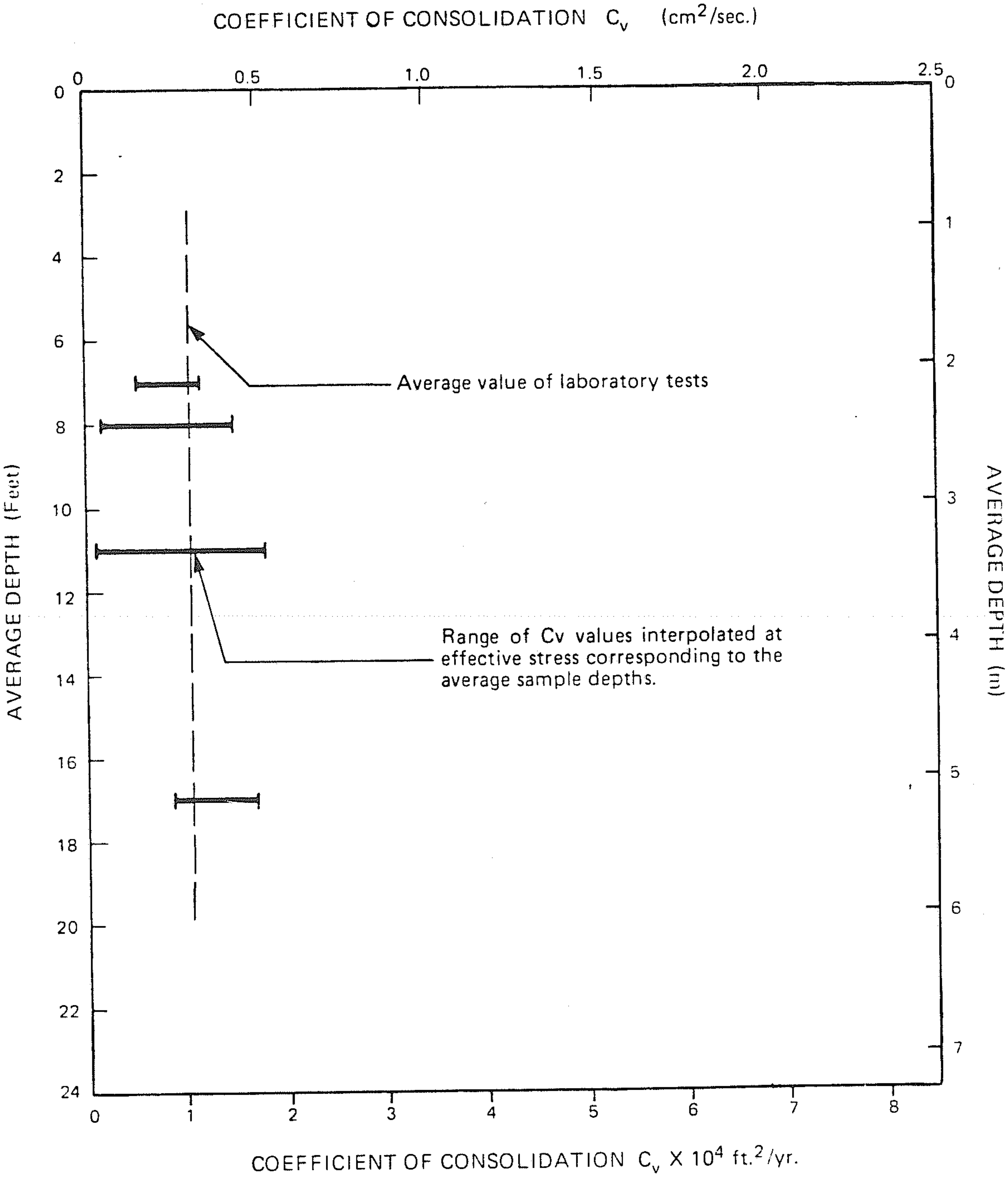


FIGURE 3.9

RANGE OF Cv VALUES vs DEPTH
FROM NESCL LABORATORY TEST DATA
CALGARY TEST SITE

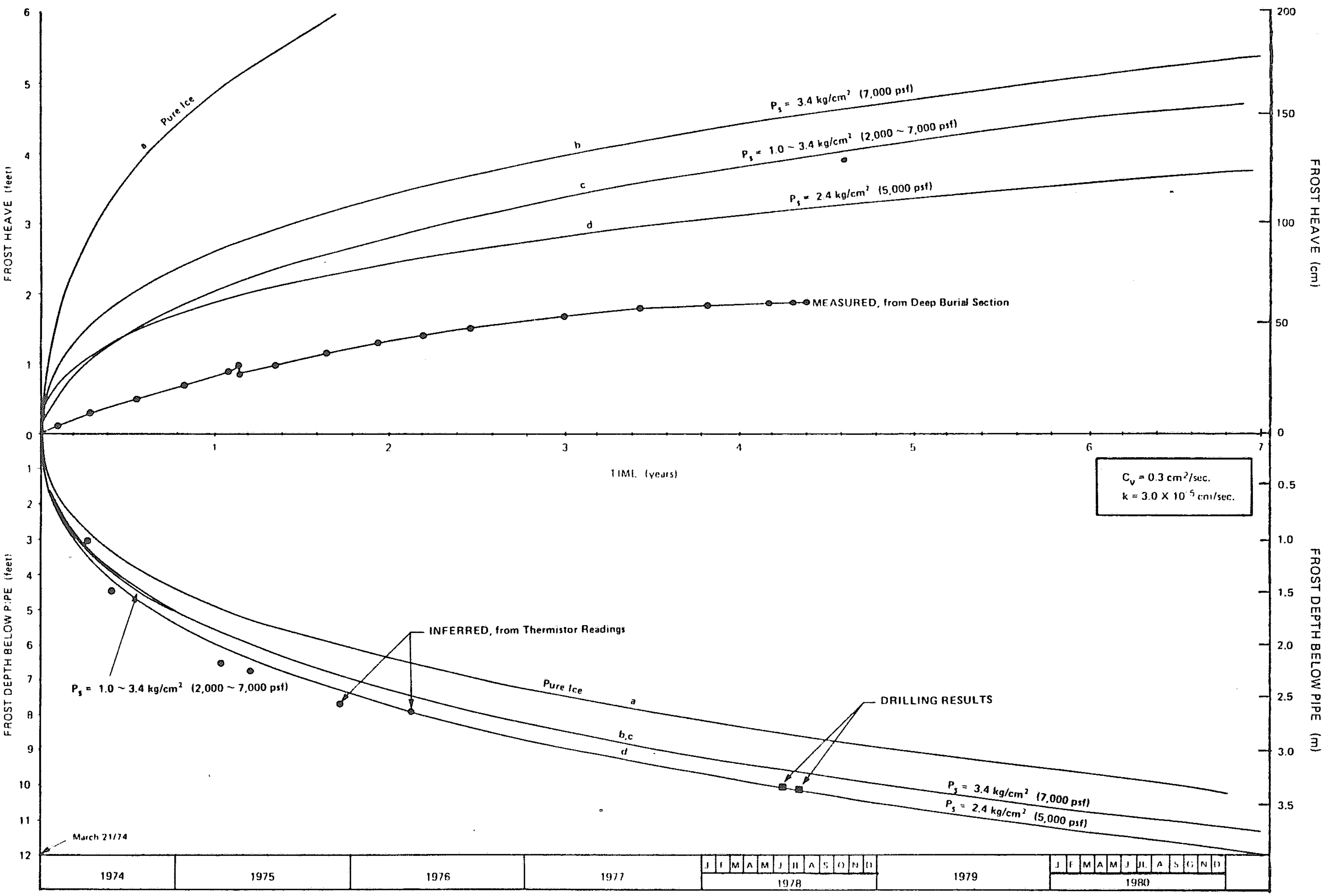


FIGURE 3.10

FROST HEAVE PREDICTIONS
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE

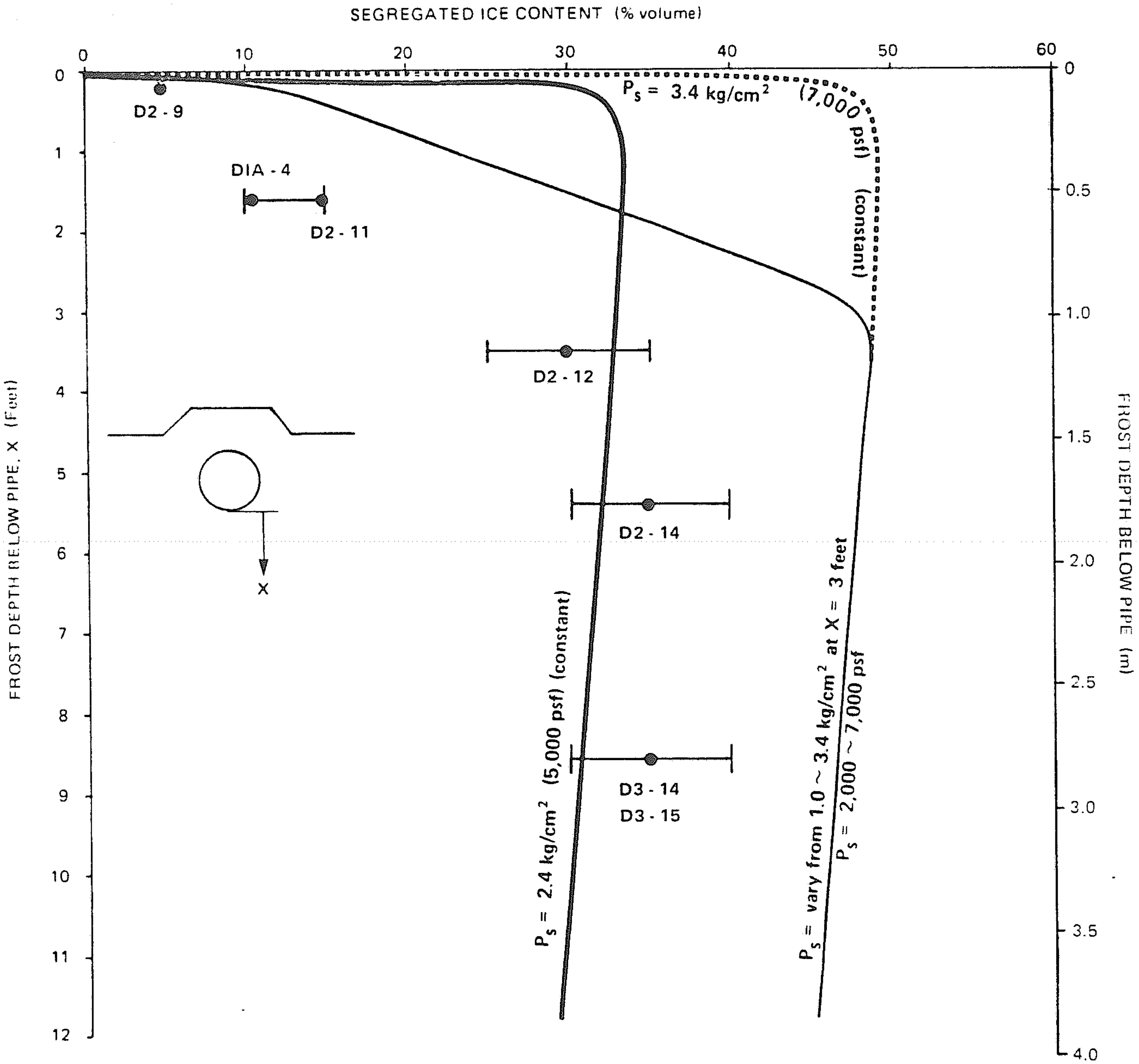


FIGURE 3.11 VARIATION OF SEGREGATED ICE CONTENT WITH DEPTH
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE
(Predicted and Observed)

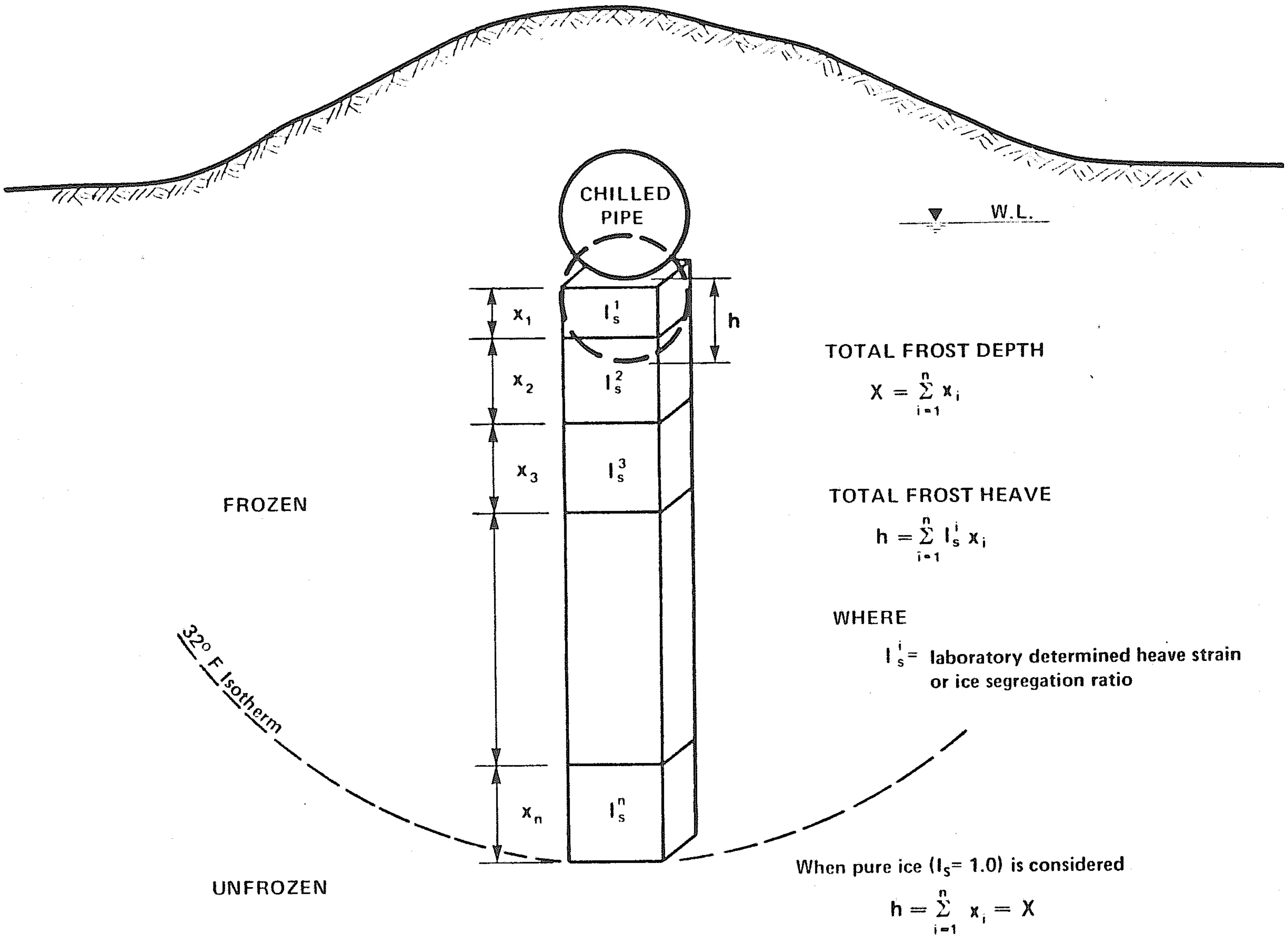


FIGURE 3.12

SUMMATION OF ELEMENTAL HEAVE
TO BECOME TOTAL HEAVE

PROJECT: Calgary Frost Heave Test Facility
HOLE NO.: I-1
PROJECT NO.: 16-2195
LOCATION: Calgary, Alberta
(Research Park, University of Calgary)
SURFACE ELEVATION:
DRILL: B40-L

SAMPLE TYPE: ■ THIN WALLED TUBE ☒ SPLIT SPOON ▤ DISTURBED ⧄ NO RECOVERY ⊞ CORE ☐ OTHER

DEPTH (m.)

SOIL DESCRIPTION

SILT -light to medium brown to grey-brown, sandy (fine grained), non to low plastic

1

2 -light to medium brown, very sandy (fine grained)

Slough : 2.5 Hrs

3 -some clay, low plastic, trace of pebbles to 0.5 cm

-light brown, some clay to clayey, low plastic

4

SILT -light to medium grey-brown, clayey, some (TILL) pebbles to 0.5 cm, low to medium plastic

5 -no pebbles, some coarse sand sizes, stiff to very stiff

-some sub-rounded gravel to 1.0 cm

6 -medium grey brown, more clayey, some black gravel sizes and some coal

7

END OF BOREHOLE .

Water Levels

8 - No water on completion, slough to 6.3 m.

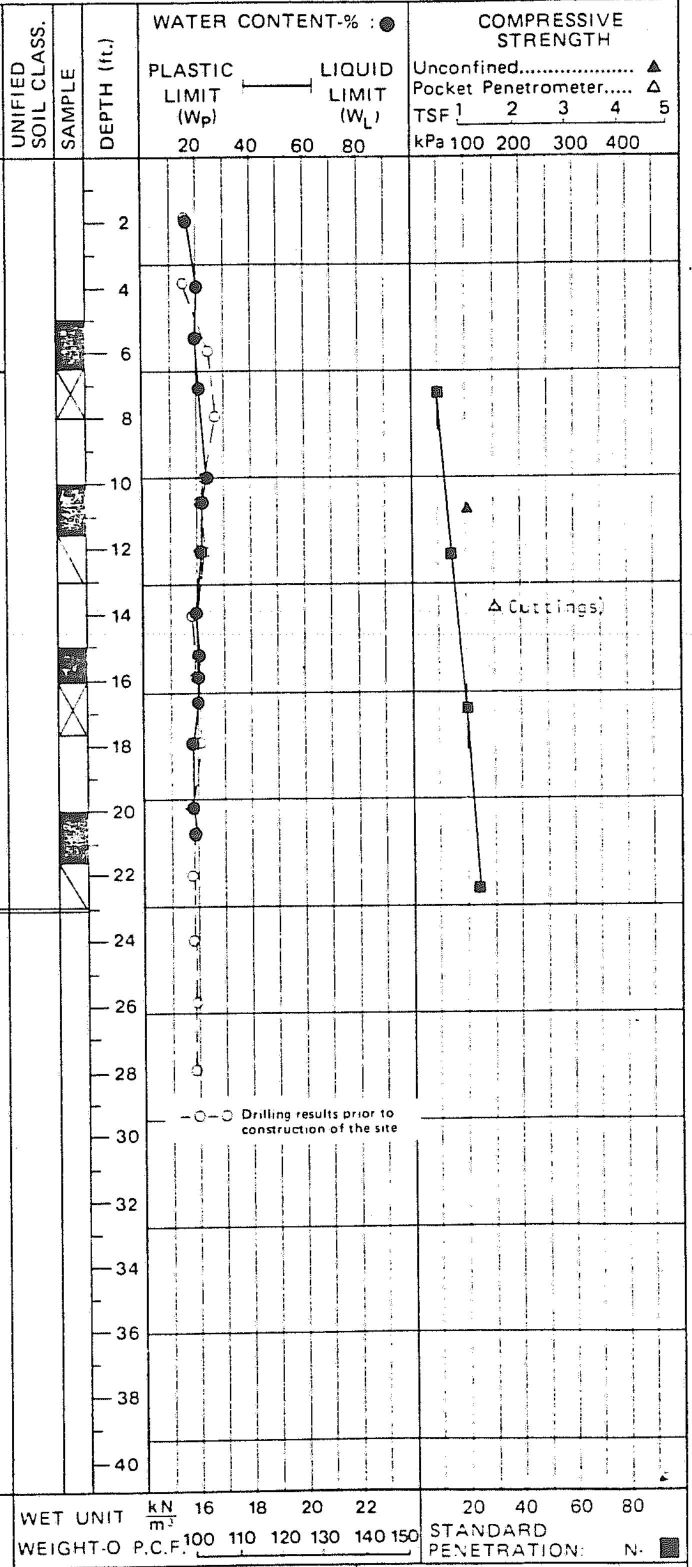
- No water at 2.5 Hrs, slough to 2.0 m

9

10

11

12



DEPTH TO WATER: ⊻
DEPTH TO SLOUGH: —

COMPLETION DEPTH: 7.0 m (23.0 Ft.)
DATE DRILLED: 15/07/78
LOGGED BY: CAG
DRAWING NO. 4.1

PROJECT: Calgary Frost Heave Test Facility	**HOLE NO.:** I-2	**PROJECT NO.:** 16-2195
LOCATION: Calgary, Alberta (Research Park, University of Calgary)	**SURFACE ELEVATION:**	
	DRILL: B40-L	

SAMPLE TYPE: ■ THIN WALLED TUBE ☒ SPLIT SPOON ▤ DISTURBED ⧅ NO RECOVERY ⊞ CORE ☐ OTHER

DEPTH (m.)	SOIL DESCRIPTION
	SILT -medium brown to medium grey-brown, some fine sand, wet and soft to 2.5 m, low to non plastic
1	
2	Sloughed 2 Hrs
3	-light to medium brown, firm, trace of to some clay, low plastic
4	SILT -medium brown to medium grey-brown, some clay (TILL) to clayey, some small sub-rounded pebbles, stiff, low plastic
5	-slightly softer and ligher colour from 5.3 to 5.7 m
6	END OF BOREHOLE
7	Water Levels: -Trace of water at 6 m on completion -Water at 1.95 m (above slough at 2.0 m) . 2 Hrs
8	
9	
10	
11	
12	

UNIFIED SOIL CLASS. | SAMPLE | DEPTH (ft.)

WATER CONTENT-% : ●

PLASTIC LIMIT (W_P) ├──┤ LIQUID LIMIT (W_L)

20 40 60 80

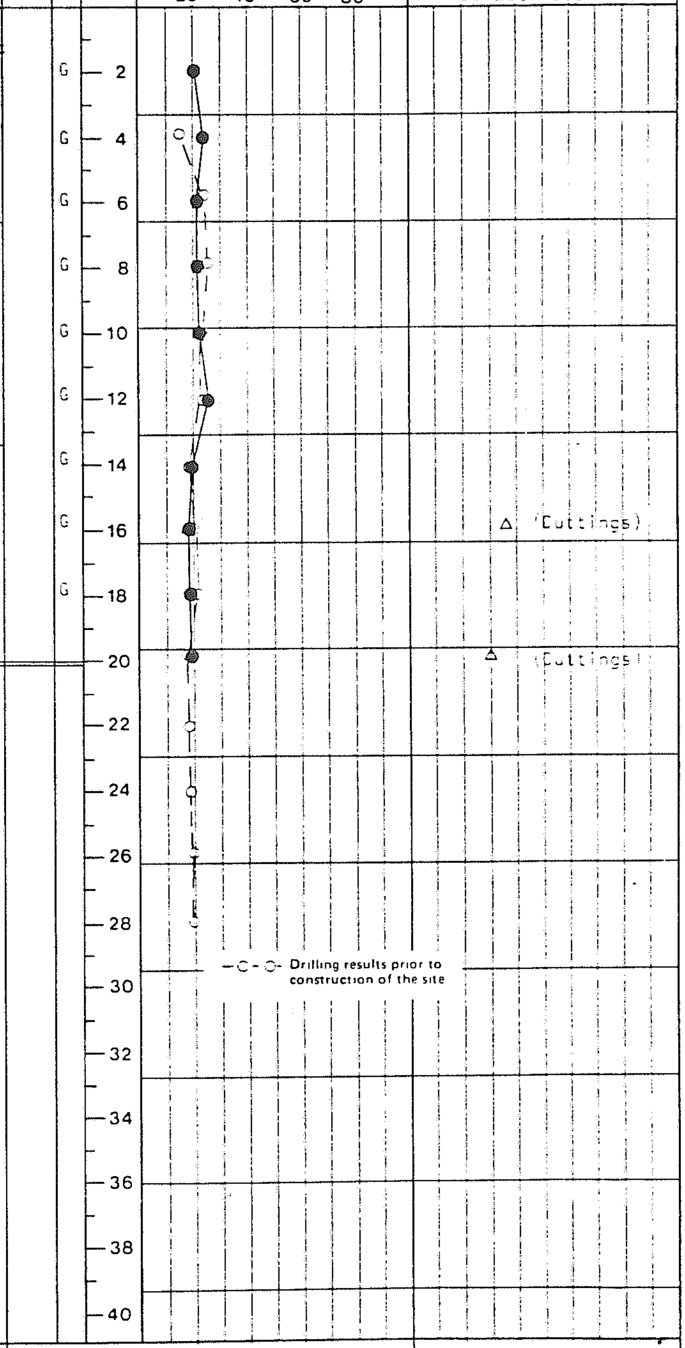
COMPRESSIVE STRENGTH

Unconfined.................. ▲

Pocket Penetrometer..... △

TSF 1 2 3 4 5

kPa 100 200 300 400



WET UNIT WEIGHT-O $\frac{kN}{m^3}$ 16 18 20 22

P.C.F. 100 110 120 130 140 150

STANDARD PENETRATION: N- ■

20 40 60 80

DEPTH TO WATER: ≚

DEPTH TO SLOUGH: —

COMPLETION DEPTH: 6.1 m (20.0 Ft.)	DATE DRILLED: 15/07/78
LOGGED BY: CAG	DRAWING NO. 4.2

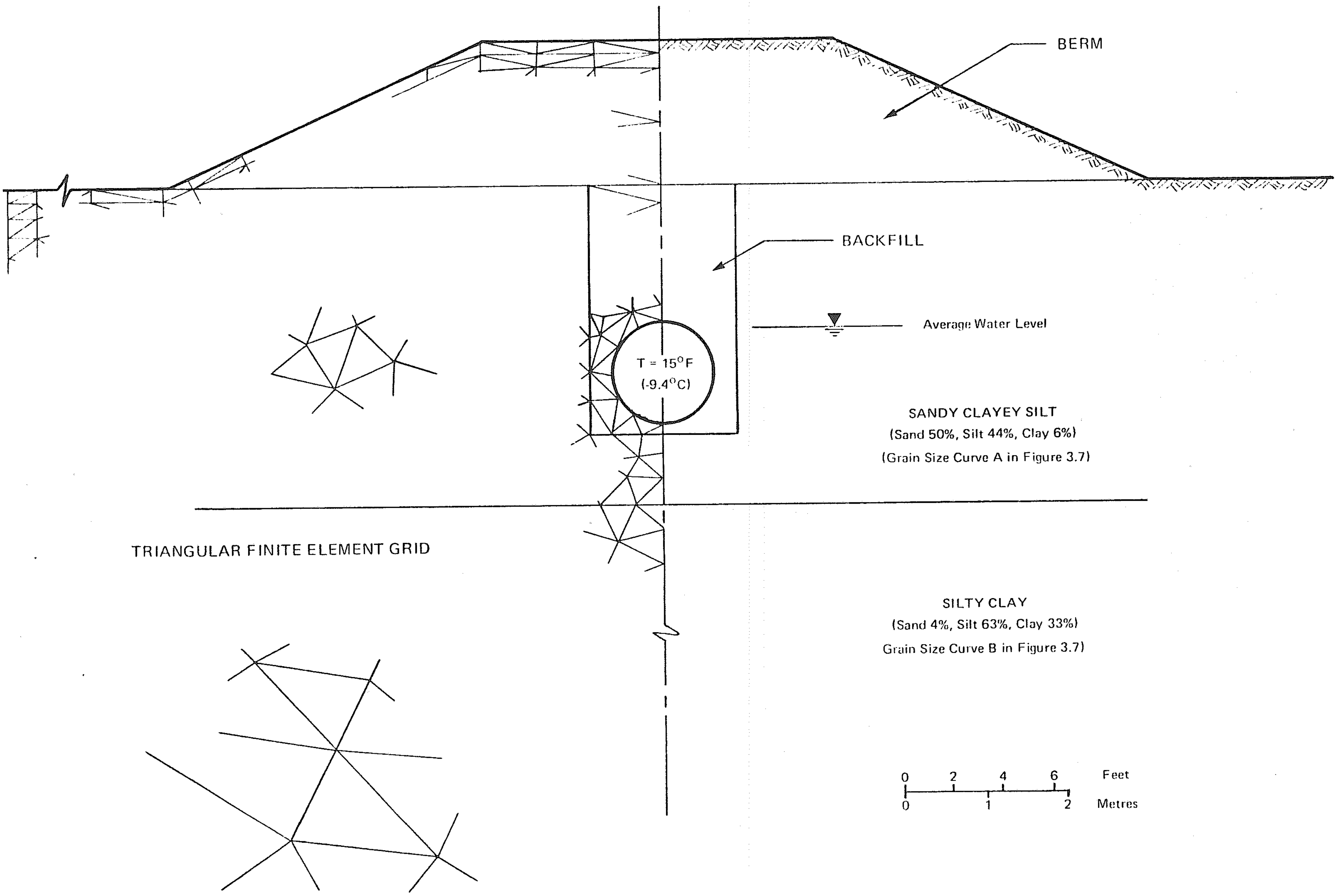


FIGURE 4.3

FINITE ELEMENT CONFIGURATION
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE

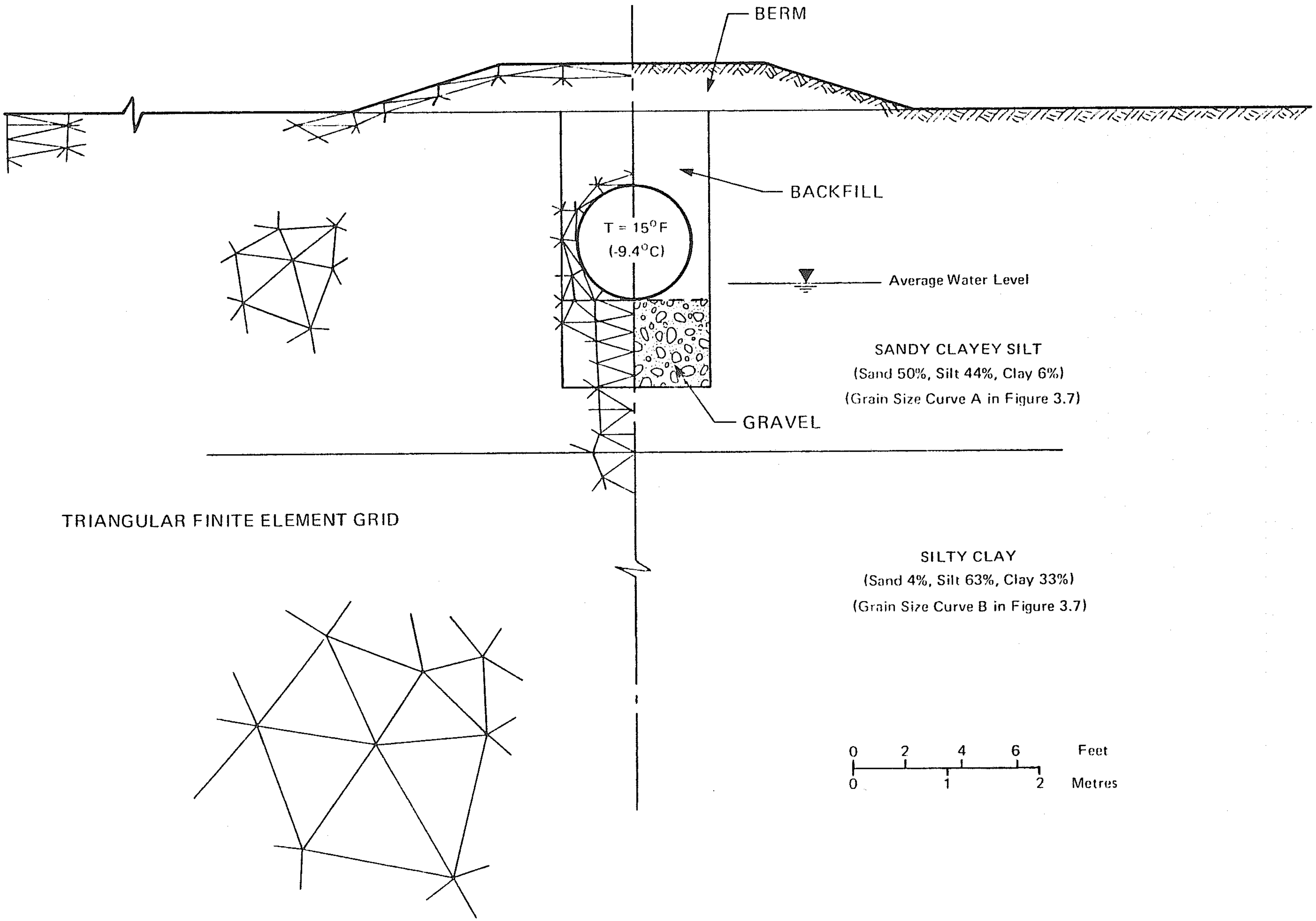


FIGURE 4.4 FINITE ELEMENT CONFIGURATION
GRAVEL SECTION
CALGARY FROST HEAVE TEST SITE

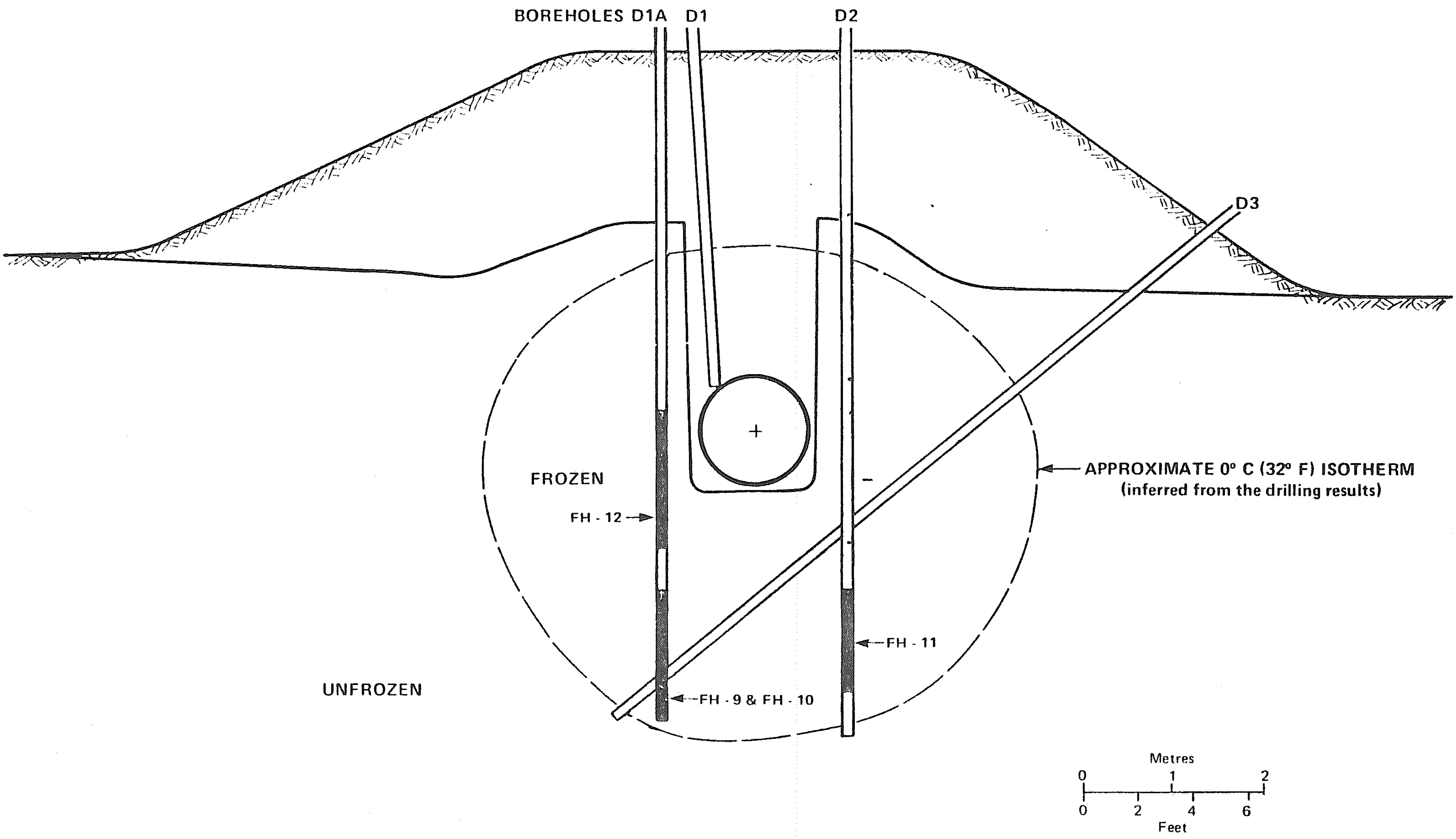


FIGURE 4.5

BOREHOLE AND TEST SAMPLE LOCATIONS
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE

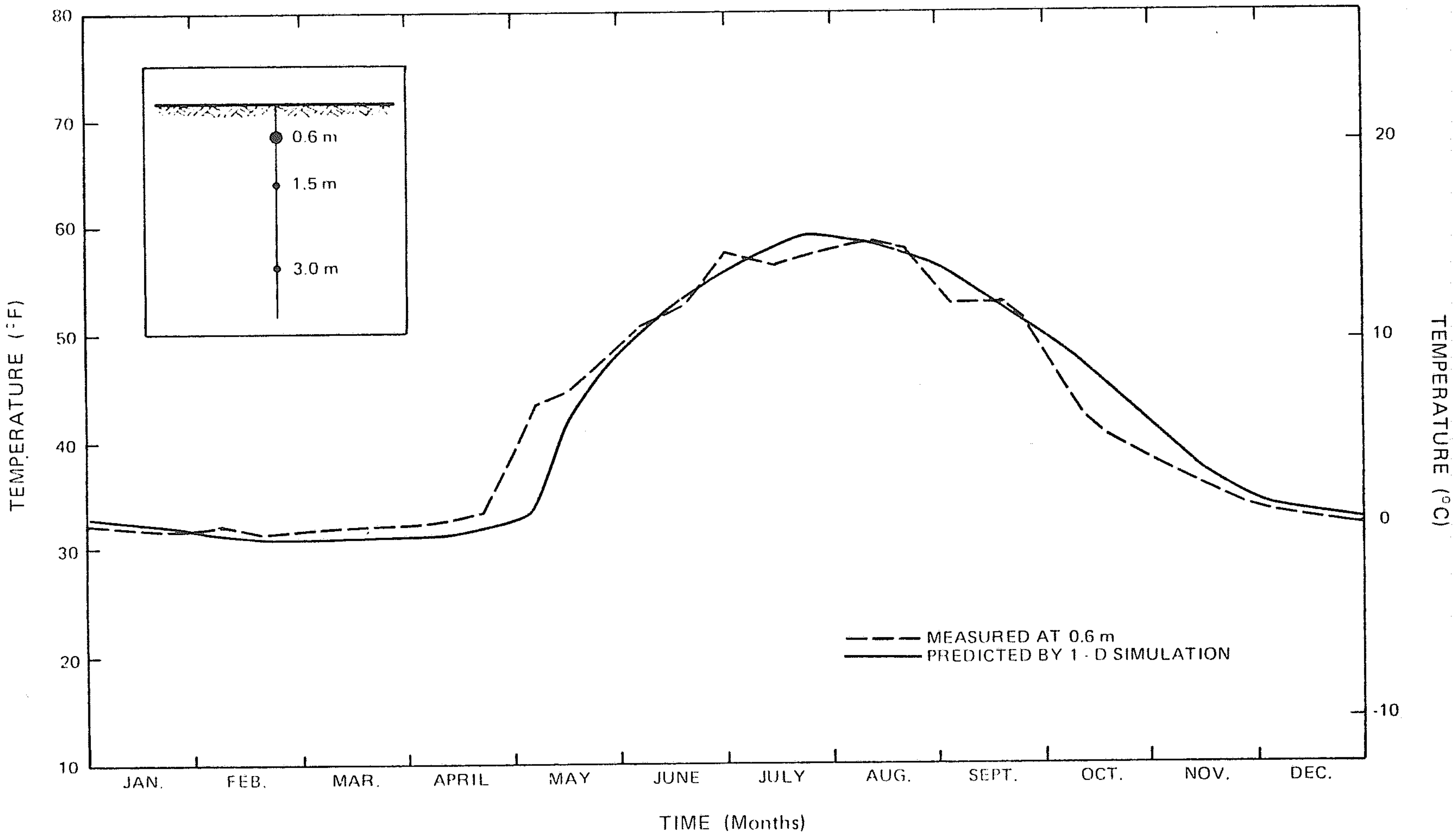


FIGURE 4.7a ANNUAL VARIATION OF GROUND TEMPERATURES
CALGARY TEST SITE
DEPTH = 0.6 m
MEASURED AND PREDICTED VALUES

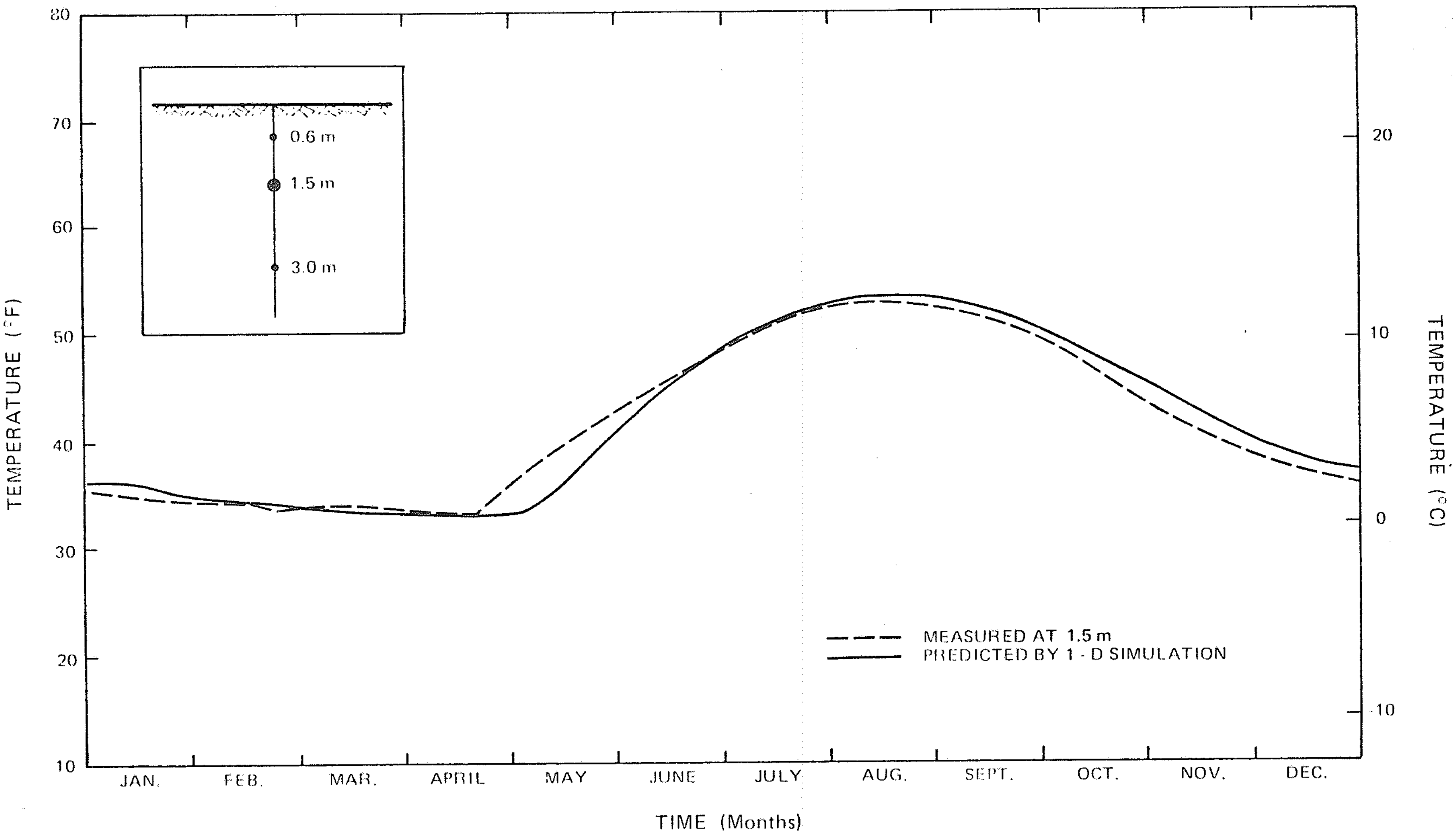


FIGURE 4.7b ANNUAL VARIATION OF GROUND TEMPERATURES
CALGARY TEST SITE
DEPTH = 1.5 m
MEASURED AND PREDICTED VALUES

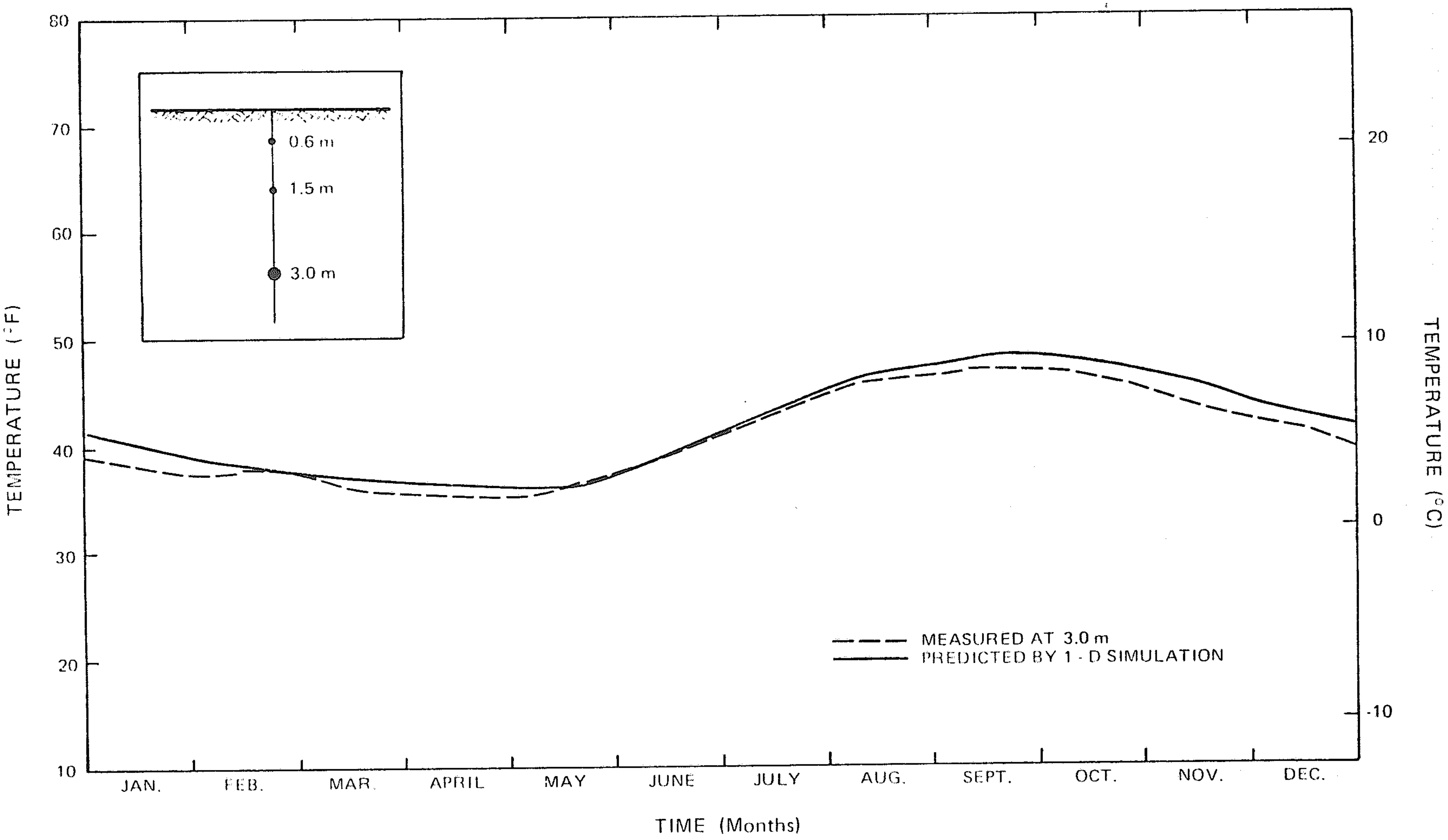


FIGURE 4.7c ANNUAL VARIATION OF GROUND TEMPERATURES
CALGARY TEST SITE
DEPTH = 3.0 m
MEASURED AND PREDICTED VALUES

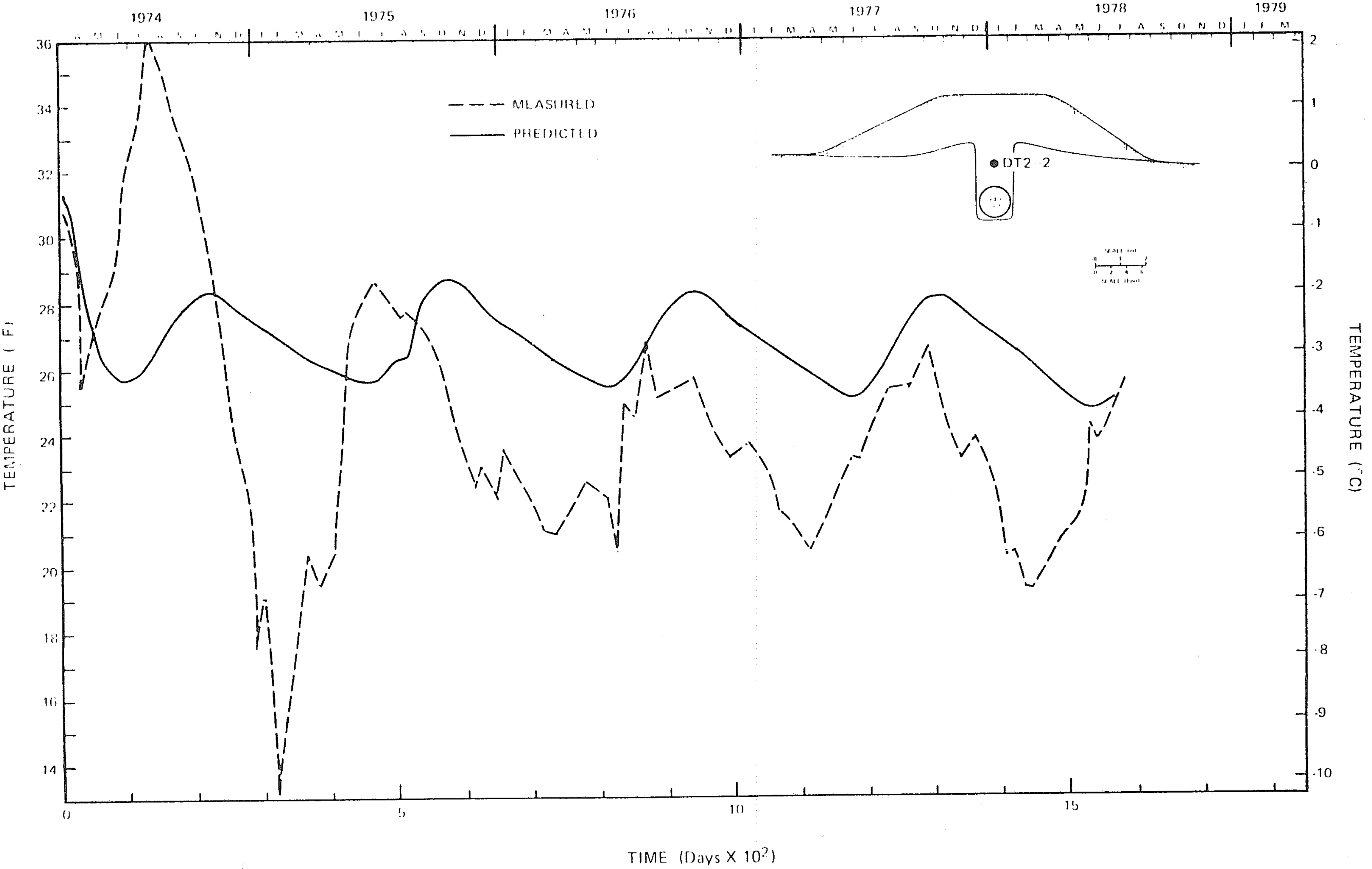


FIGURE 4.8

PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. DT2–2
DEEP BURIAL SECTION

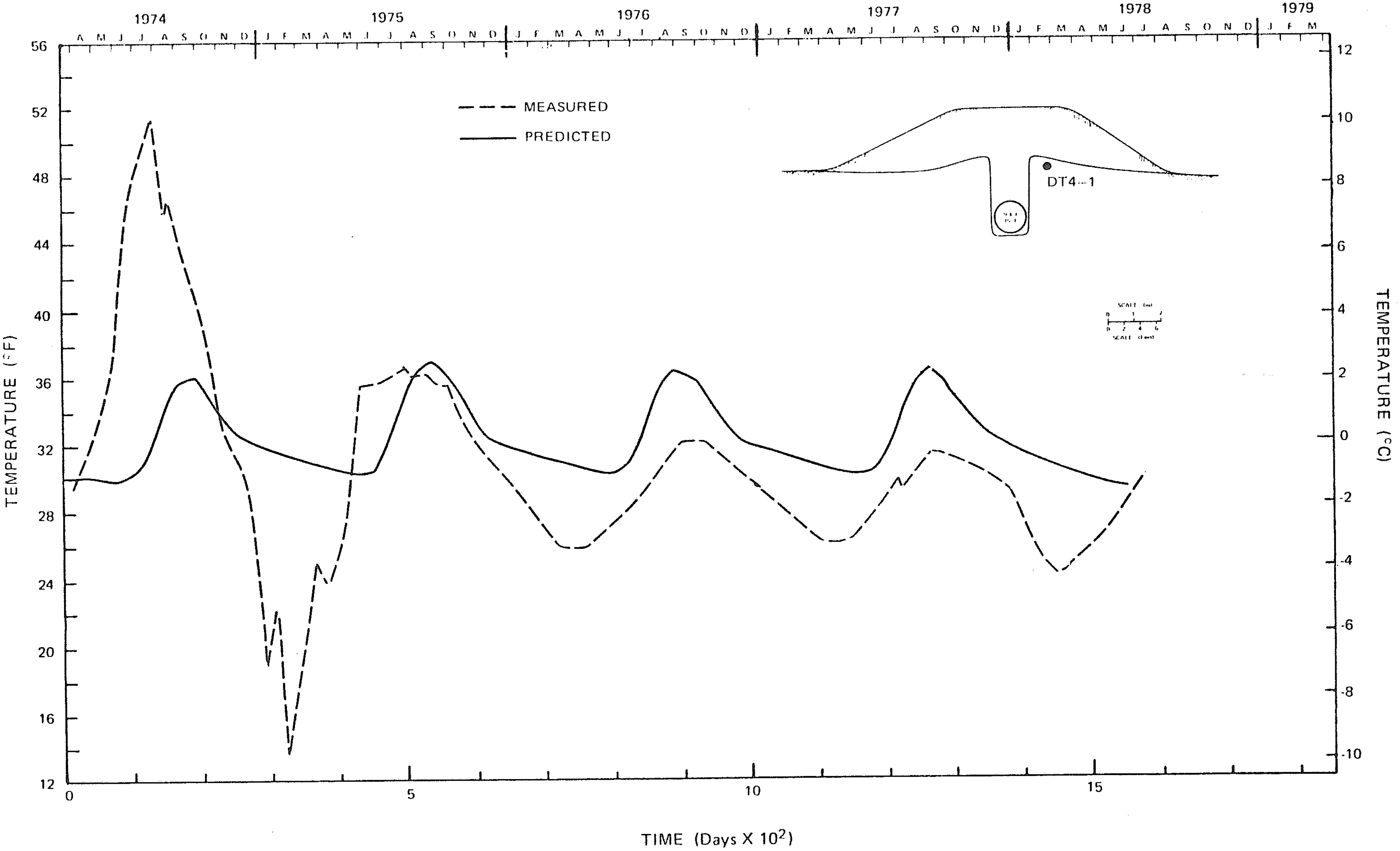


FIGURE 4.9

PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. DT4–1
DEEP BURIAL SECTION

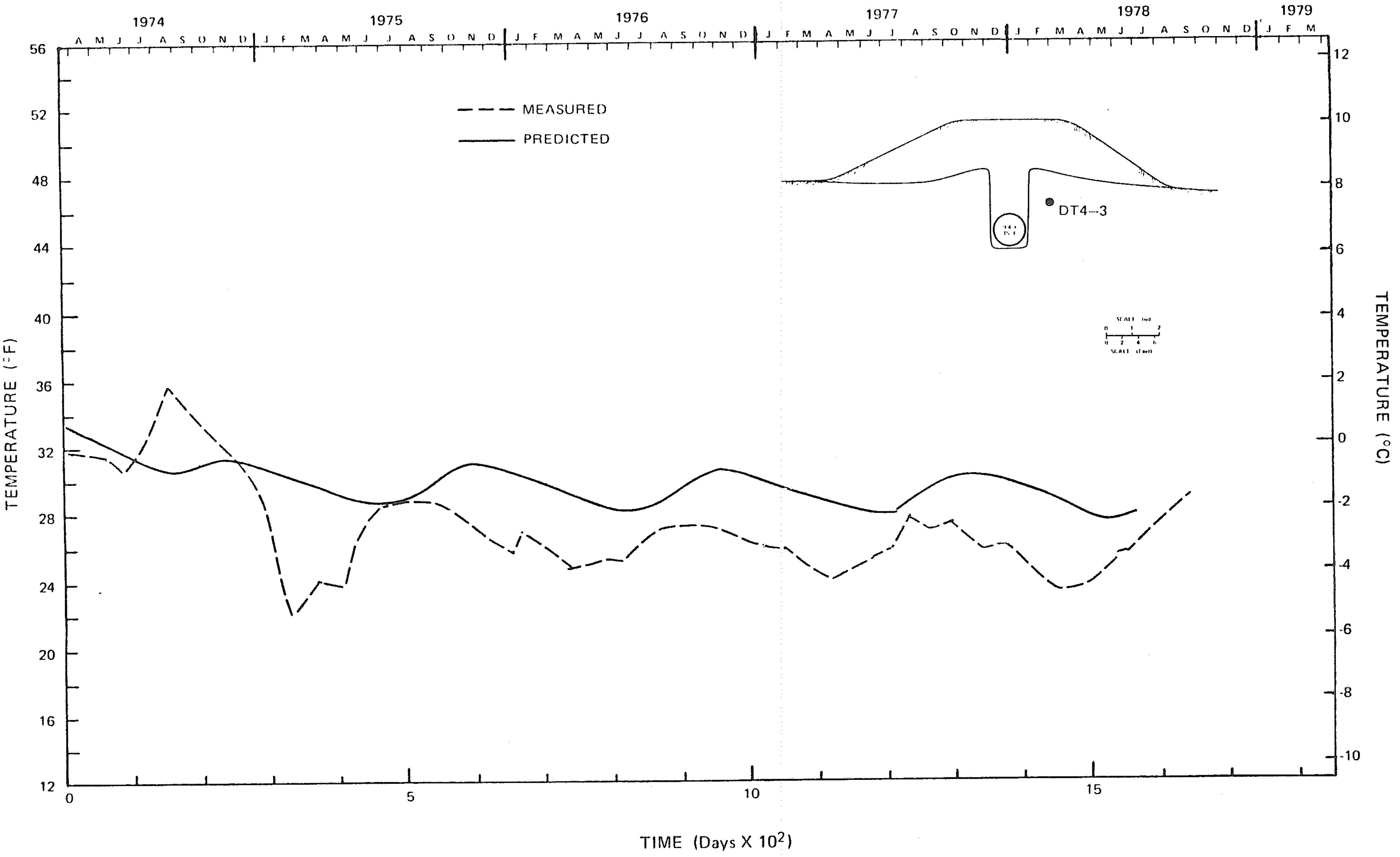


FIGURE 4.10

PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. DT4–3
DEEP BURIAL SECTION

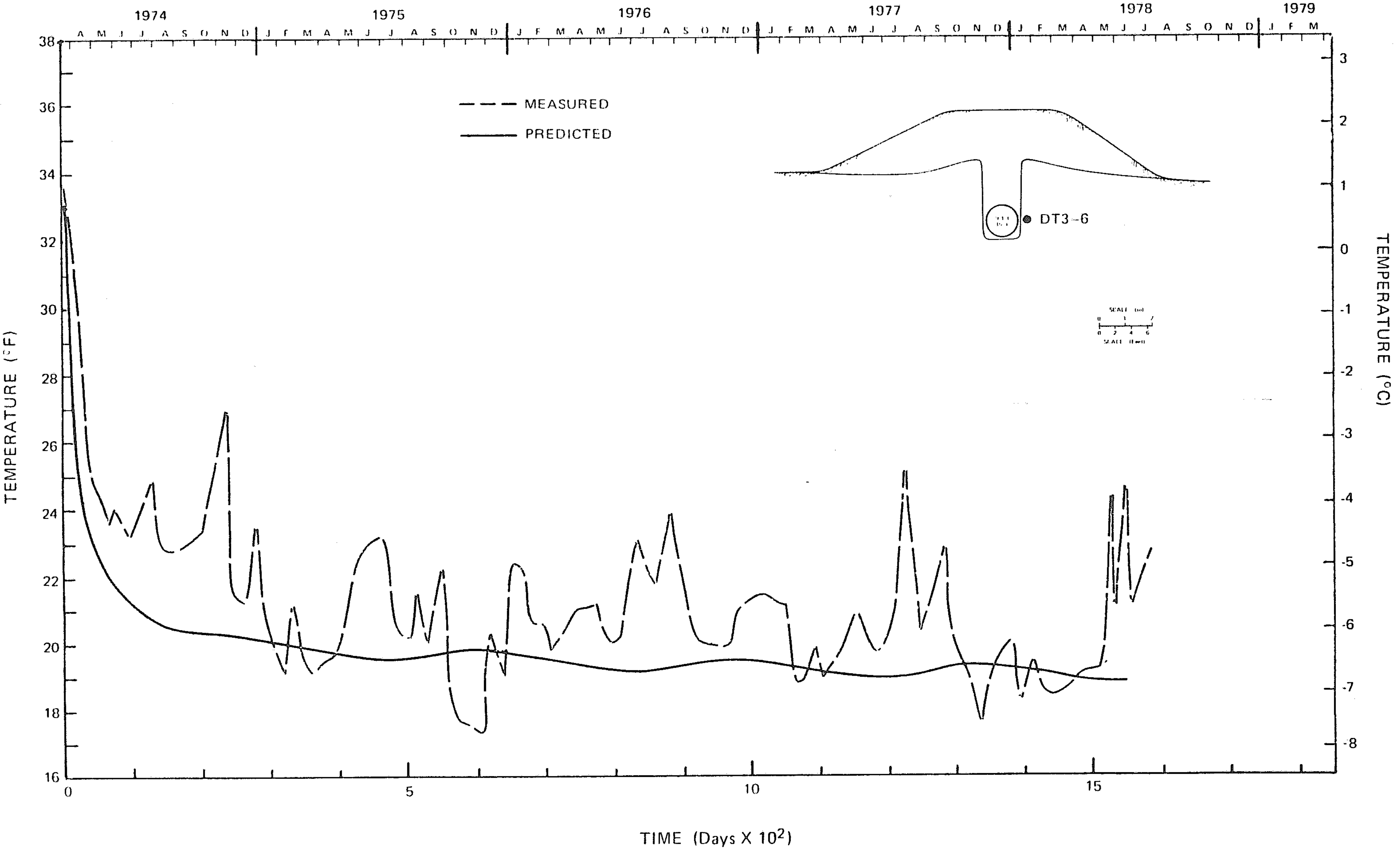


FIGURE 4.11

PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. DT3–6
DEEP BURIAL SECTION

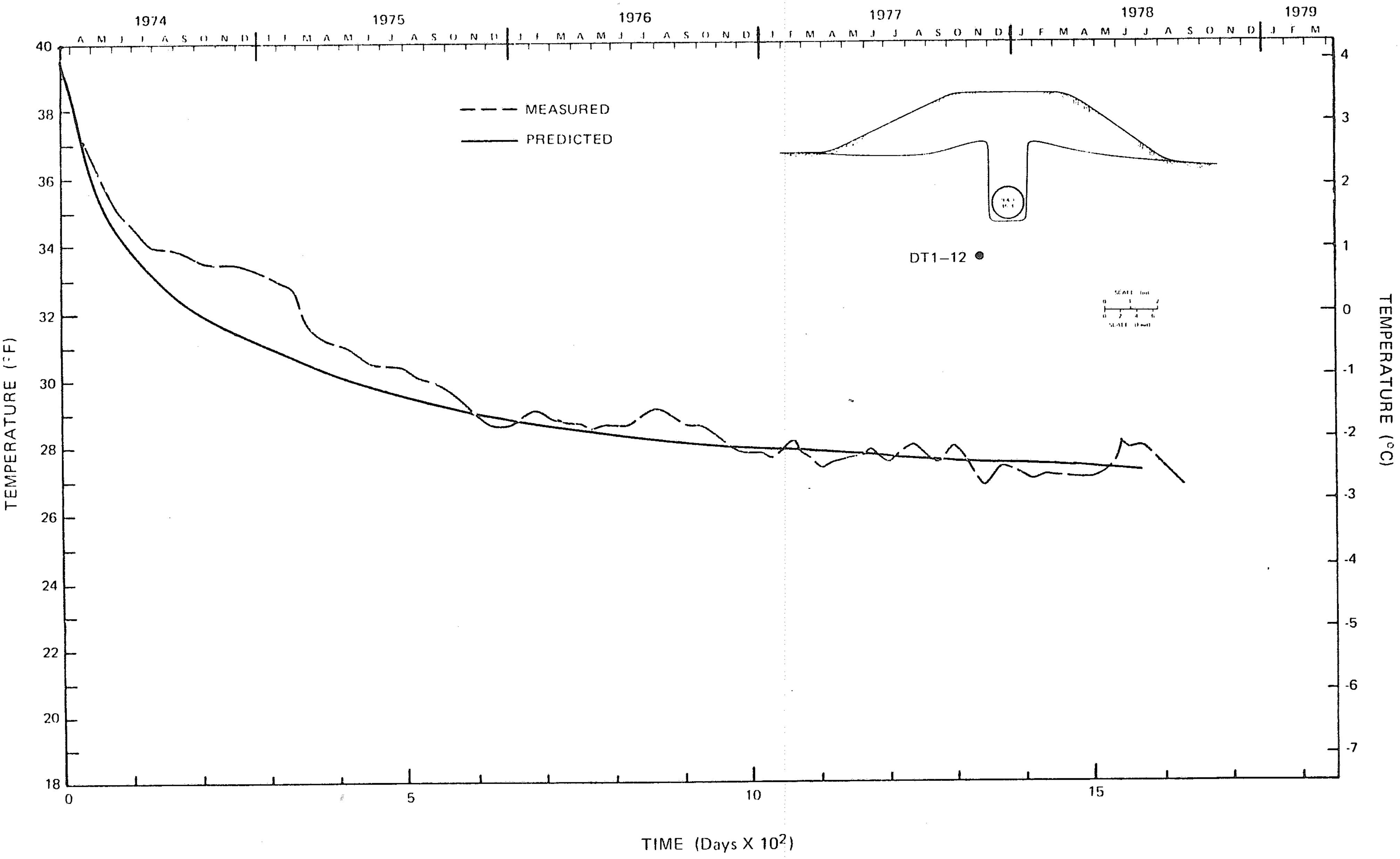


FIGURE 4.12

PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. DT1–12
DEEP BURIAL SECTION

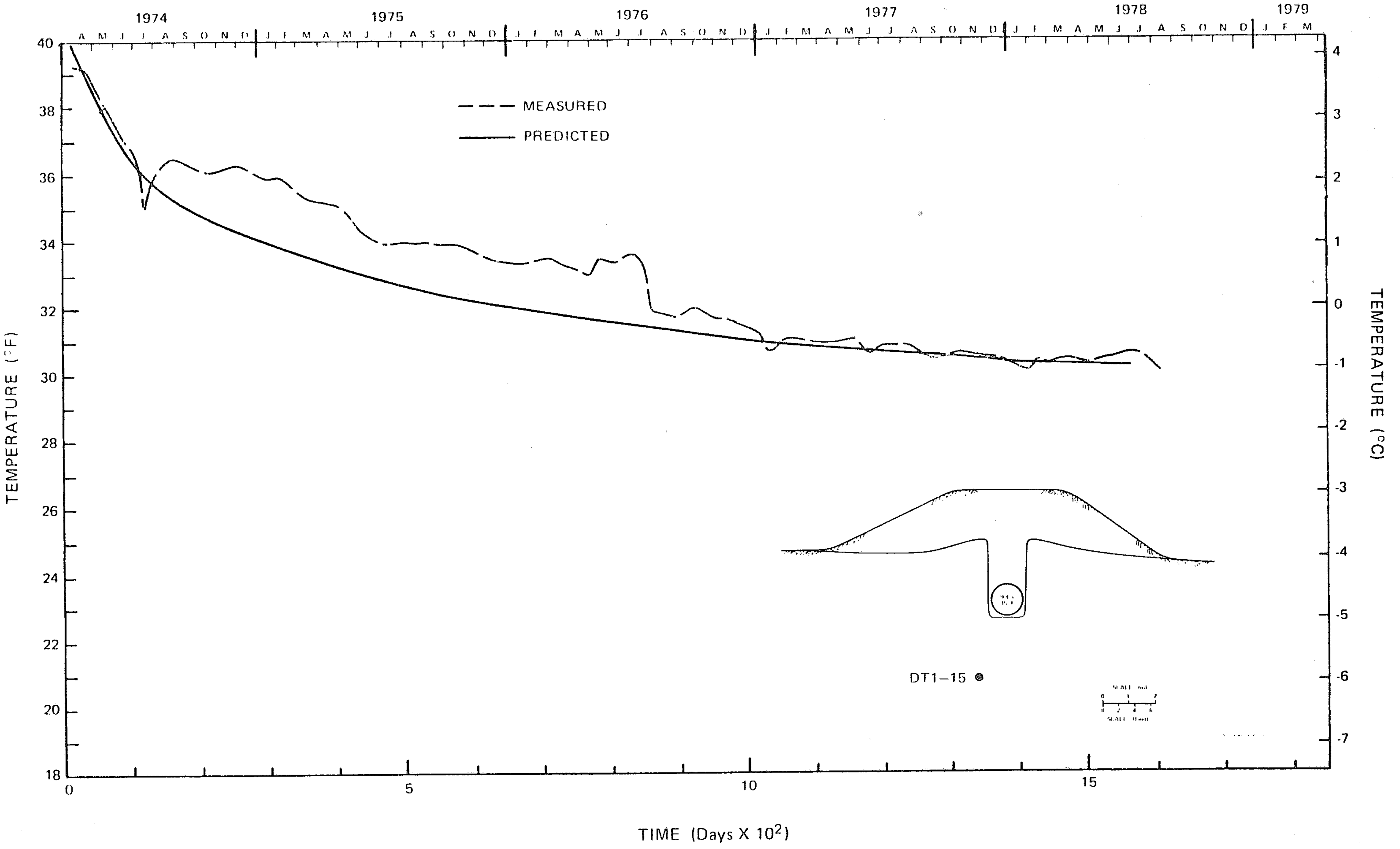


FIGURE 4.13 PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. DT1–15
DEEP BURIAL SECTION

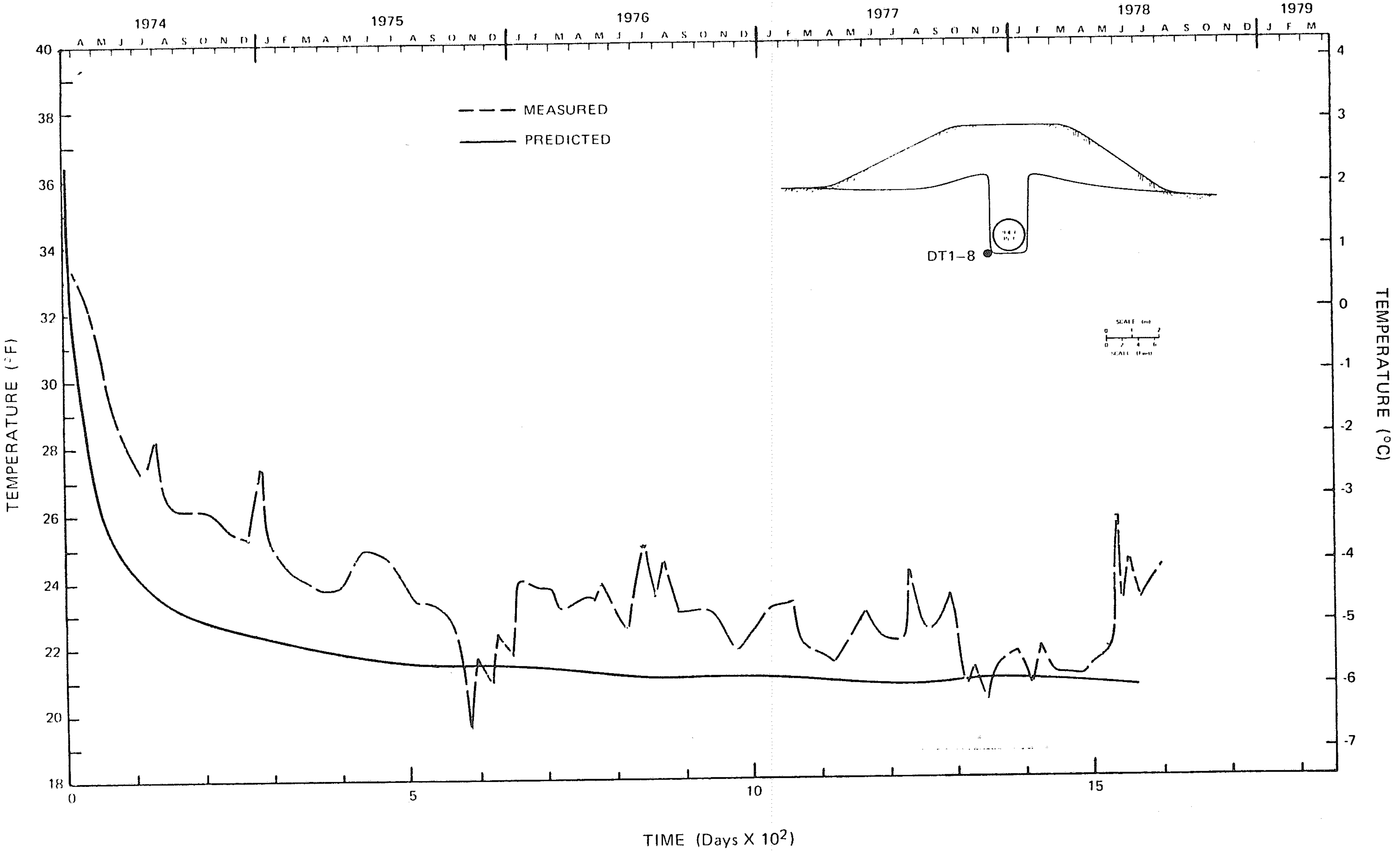


FIGURE 4.14

PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. DT1–8
DEEP BURIAL SECTION

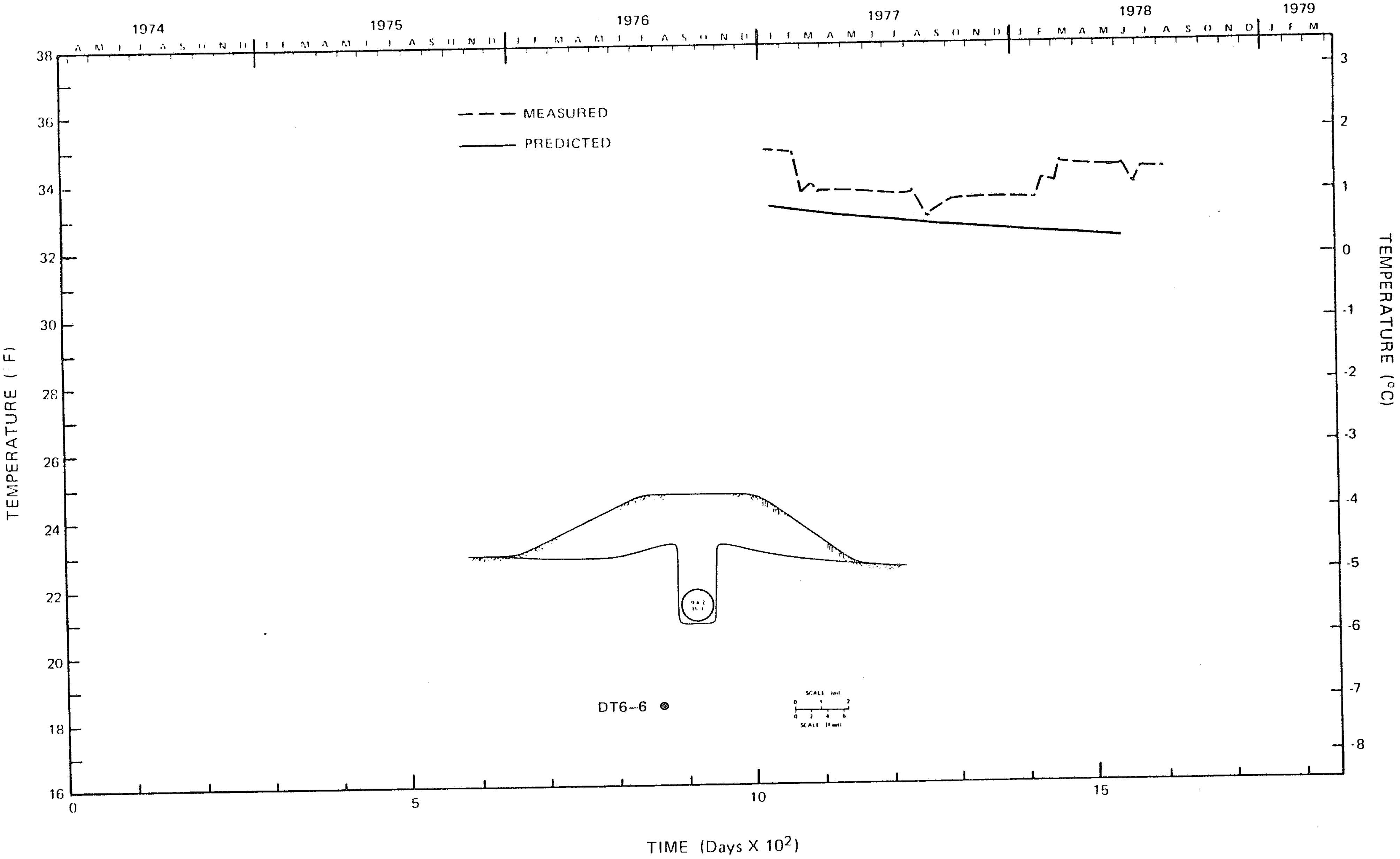


FIGURE 4.15 PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. DT6–6
DEEP BURIAL SECTION

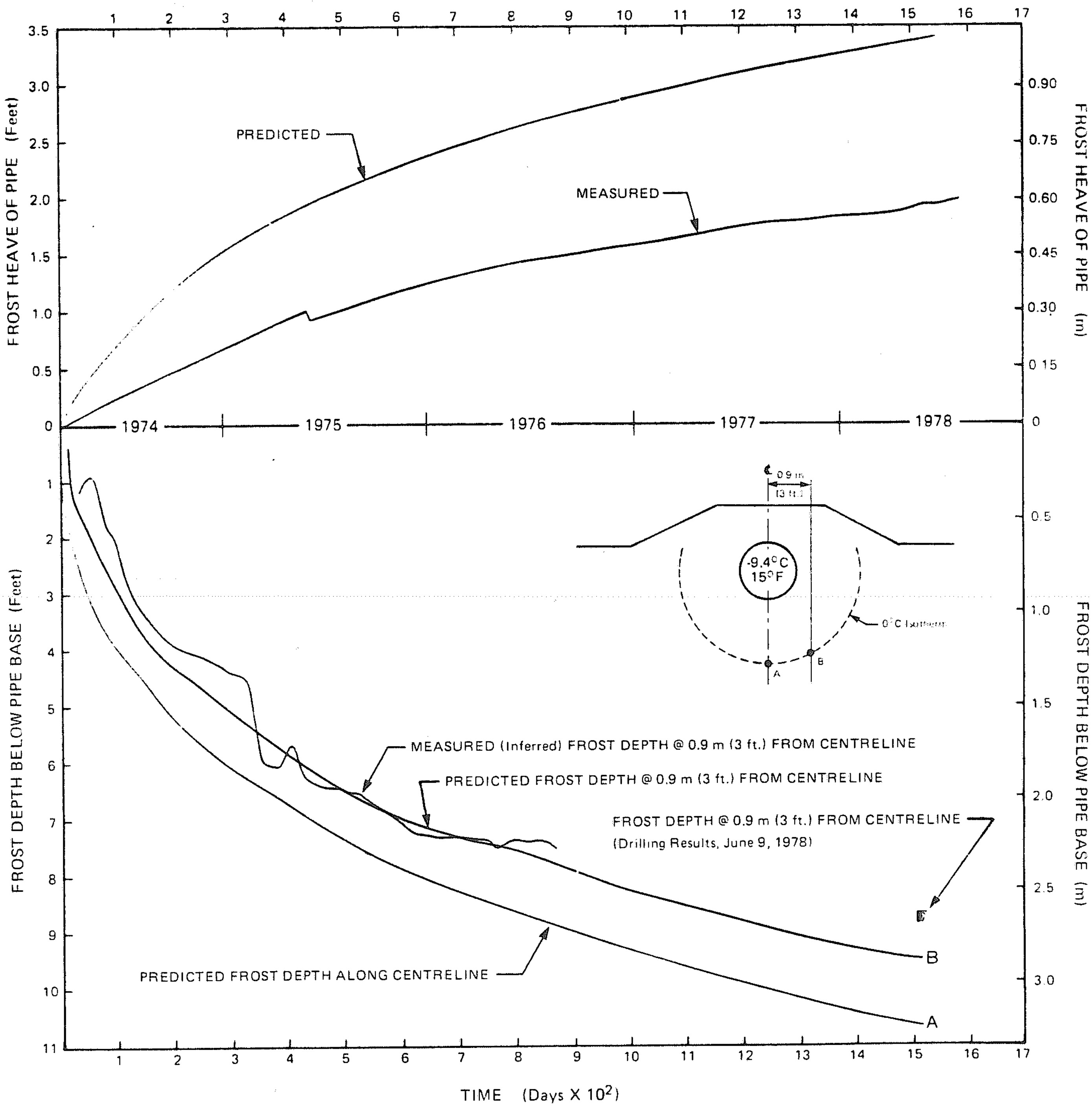


FIGURE 4.16 FROST HEAVE & FROST DEPTH (32°F – 0°C ISOTHERM)
vs.
TIME
DEEP BURIAL SECTION

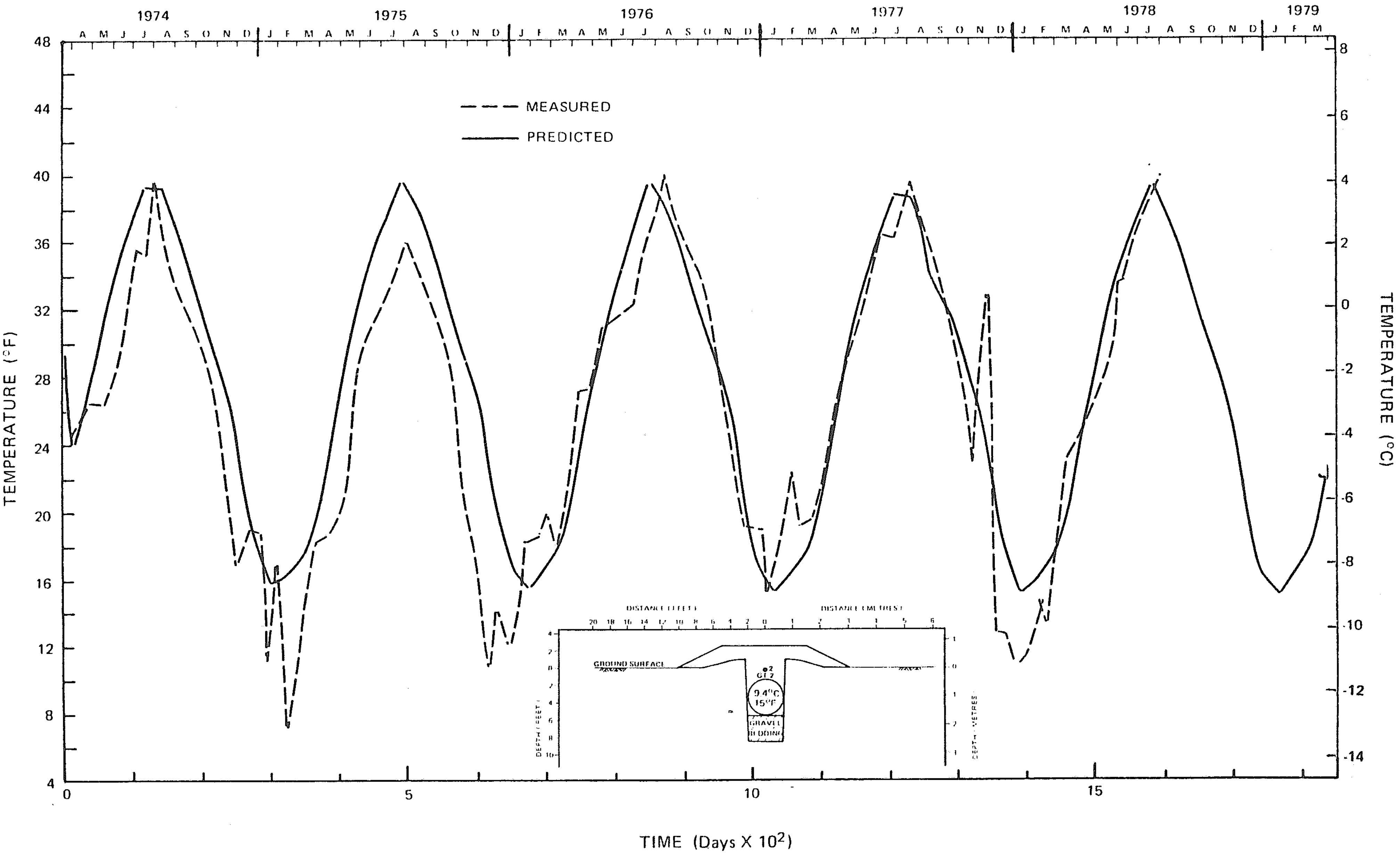


FIGURE 4.17 PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. GT2–2
GRAVEL SECTION

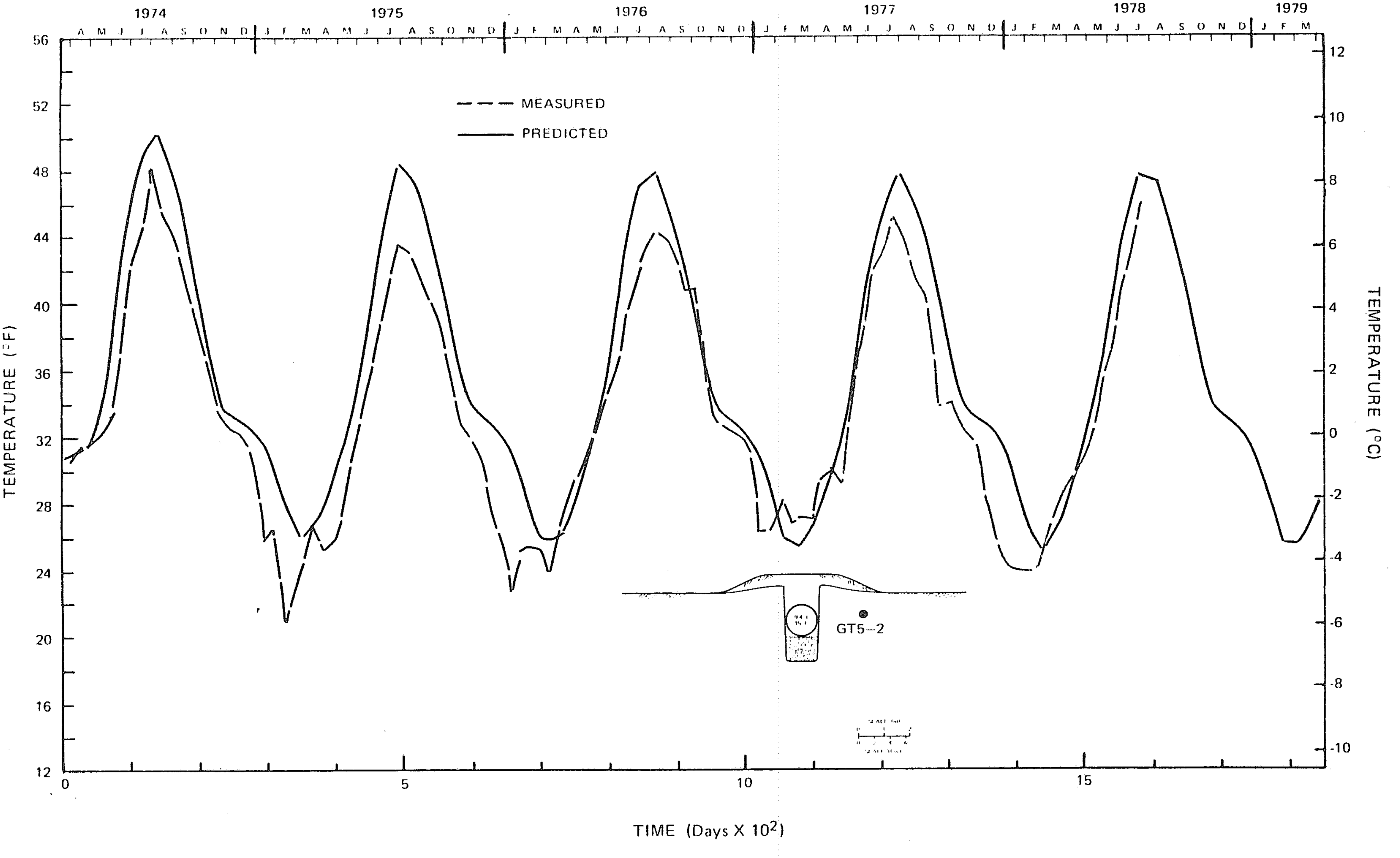


FIGURE 4.18 PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. GT5–2
GRAVEL SECTION

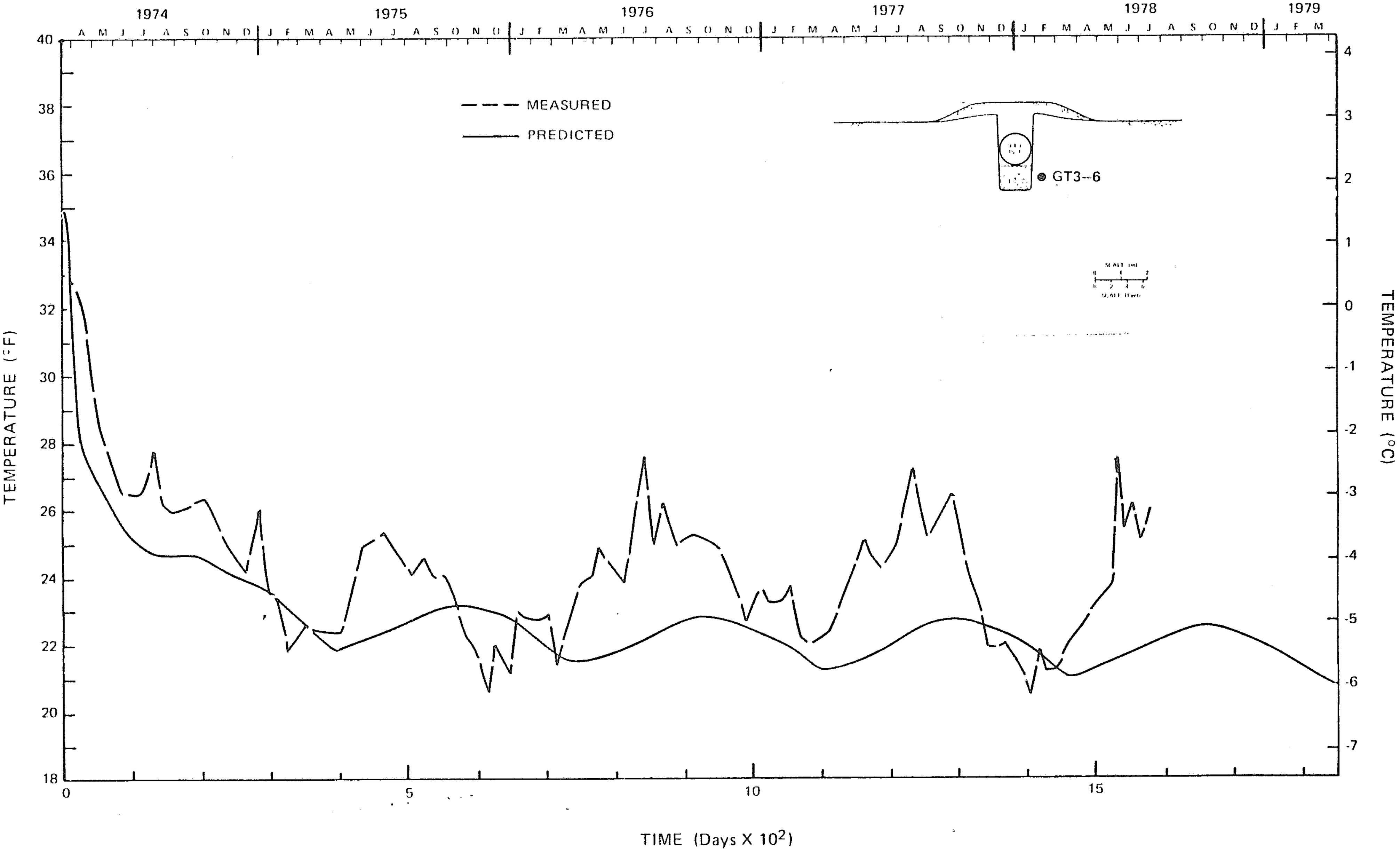


FIGURE 4.19 PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. GT3–6
GRAVEL SECTION

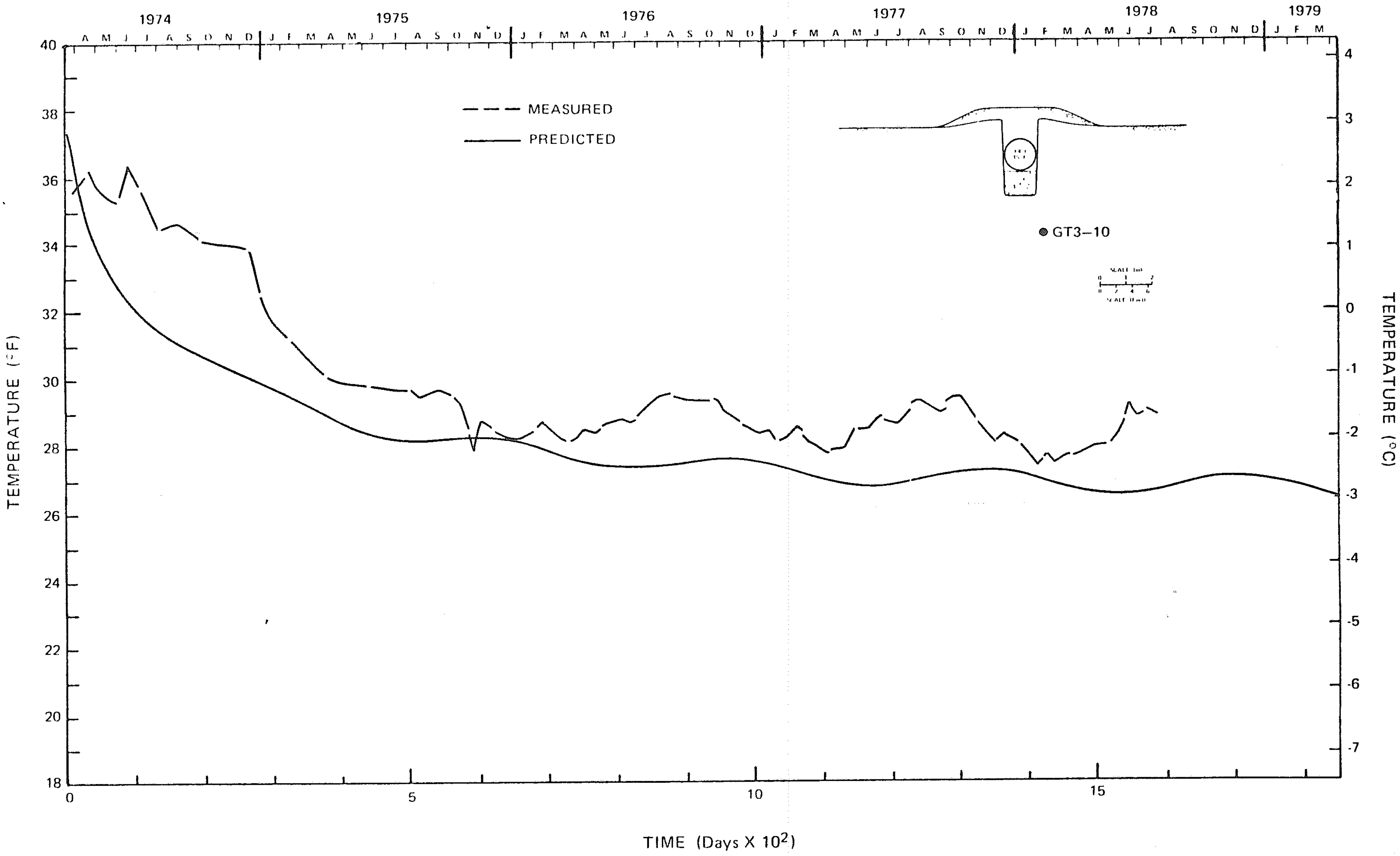


FIGURE 4.20

PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. GT3–10
GRAVEL SECTION

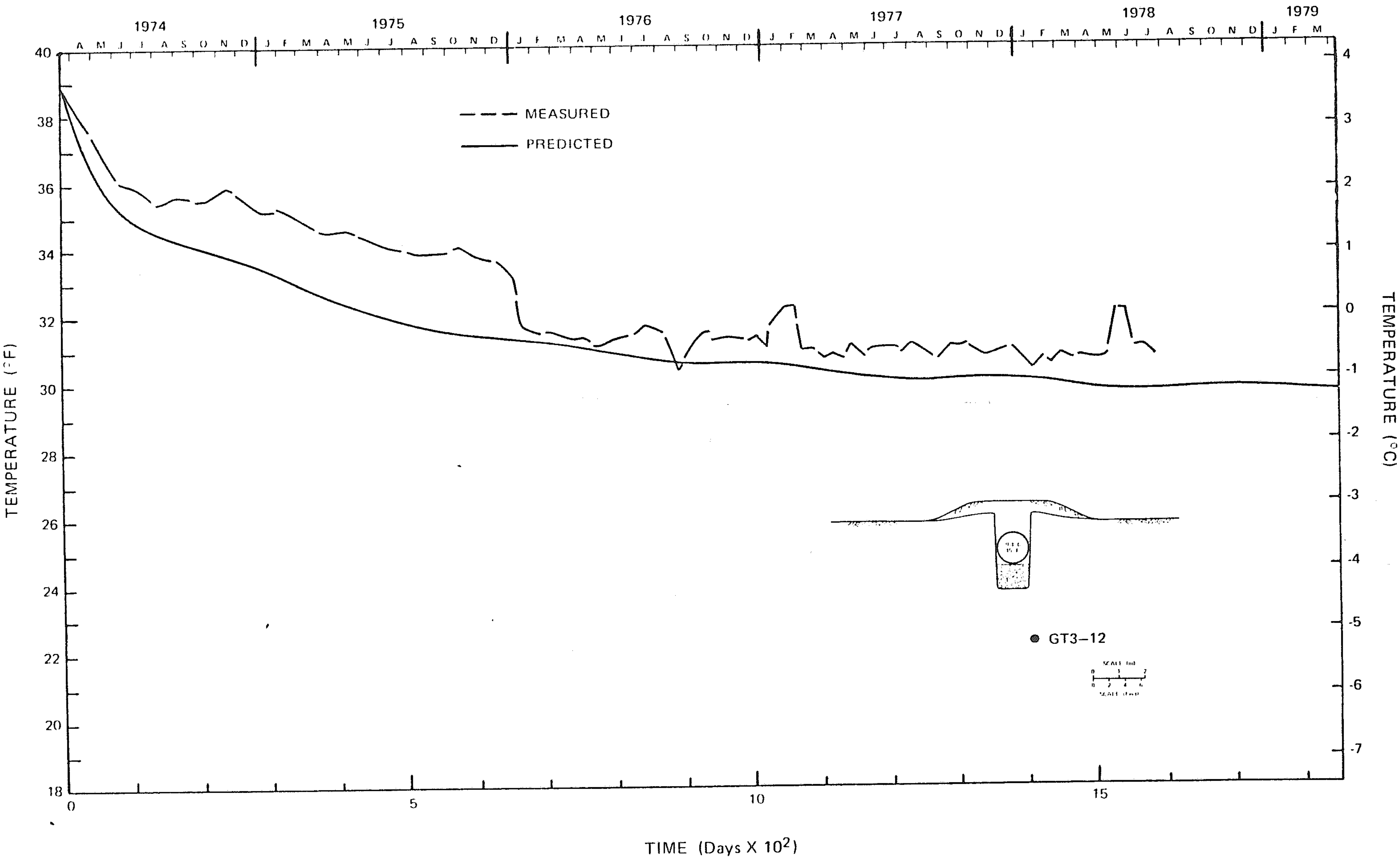


FIGURE 4.21

PREDICTED AND MEASURED TEMPERATURES vs. TIME
THERMISTOR No. GT3–12
GRAVEL SECTION

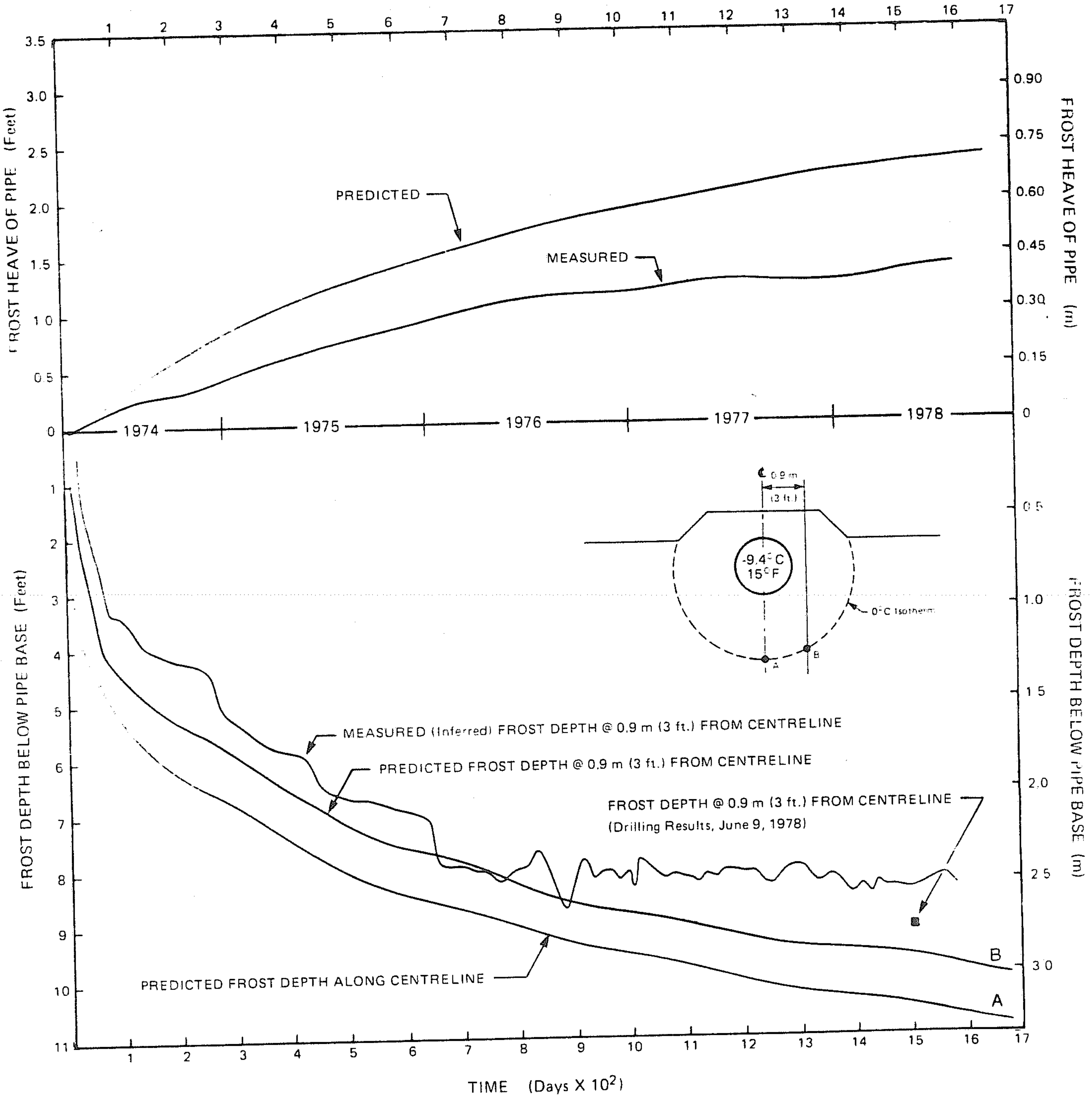


FIGURE 4.22 FROST HEAVE & FROST DEPTH (32°F – 0°C ISOTHERM)
vs.
TIME
GRAVEL SECTION

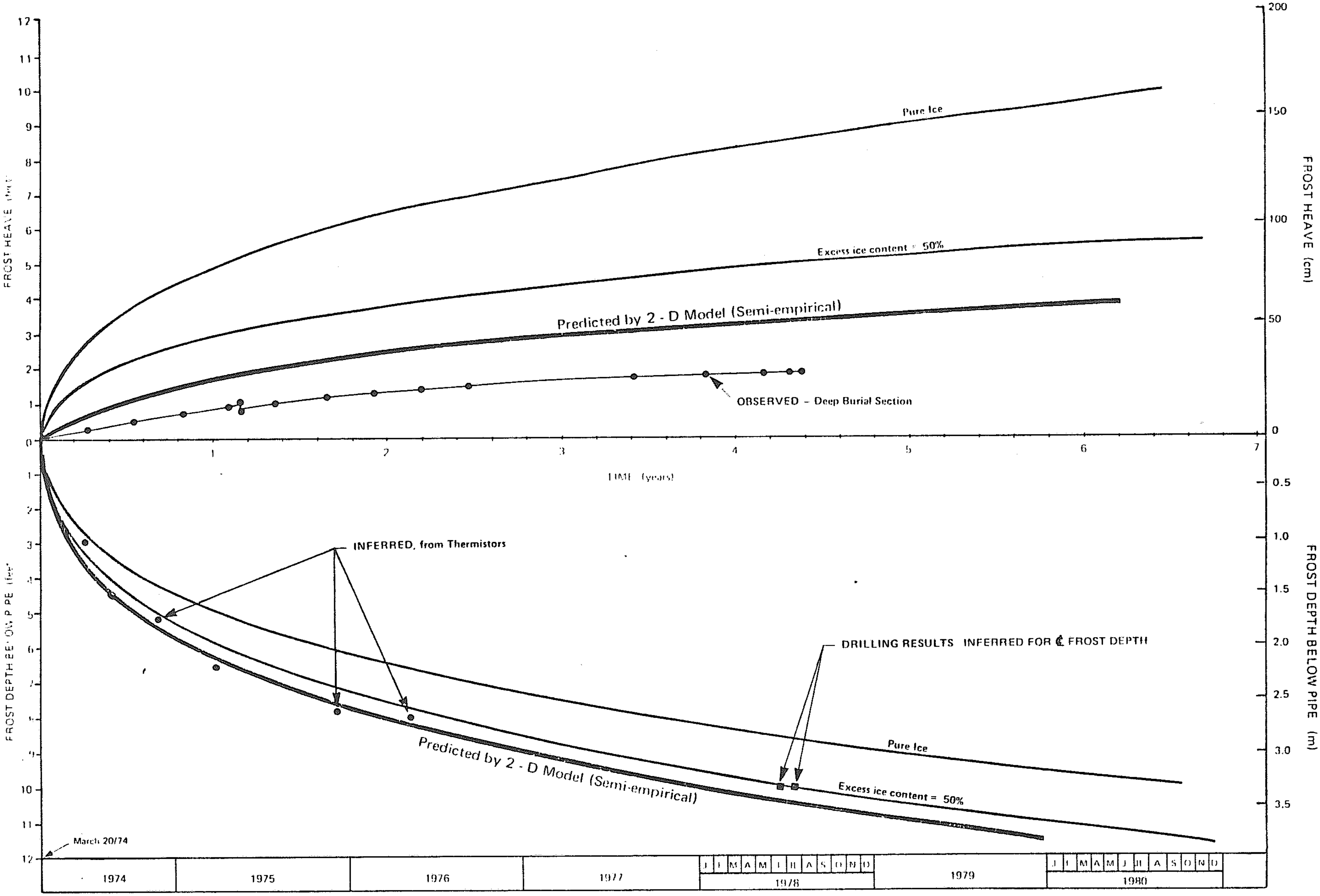


FIGURE 4.23

FROST HEAVE PREDICTION USING
THE SEMI-EMPERICAL METHOD
DEEP BURIAL SECTION
CALGARYFROST HEAVE TEST SITE

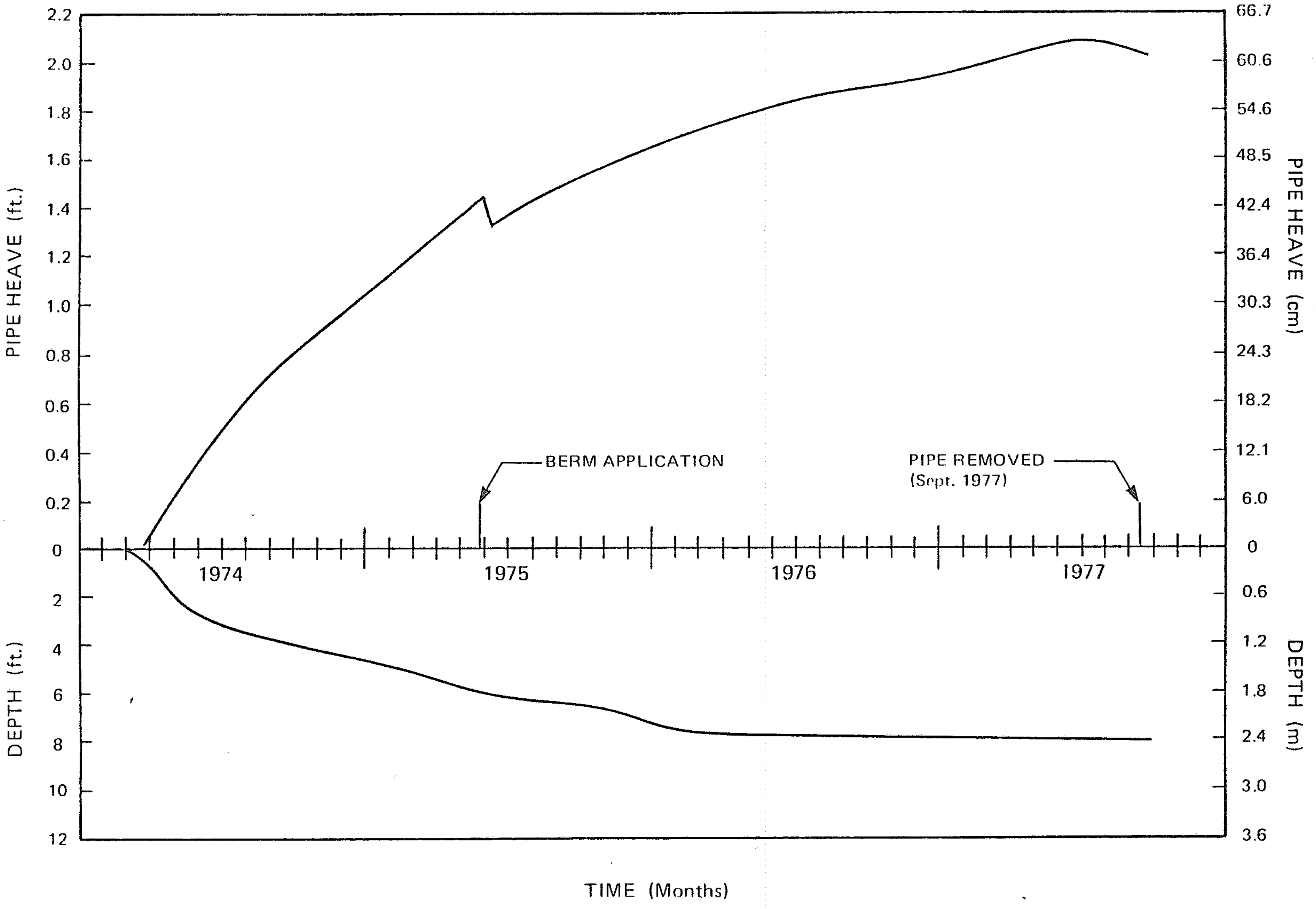


FIGURE 4.24 OBSERVED PIPE HEAVE (Gauge CM 2) & FROST DEPTH BELOW BOTTOM OF PIPE @ 0.9 m FROM CENTRELINE CONTROL SECTION

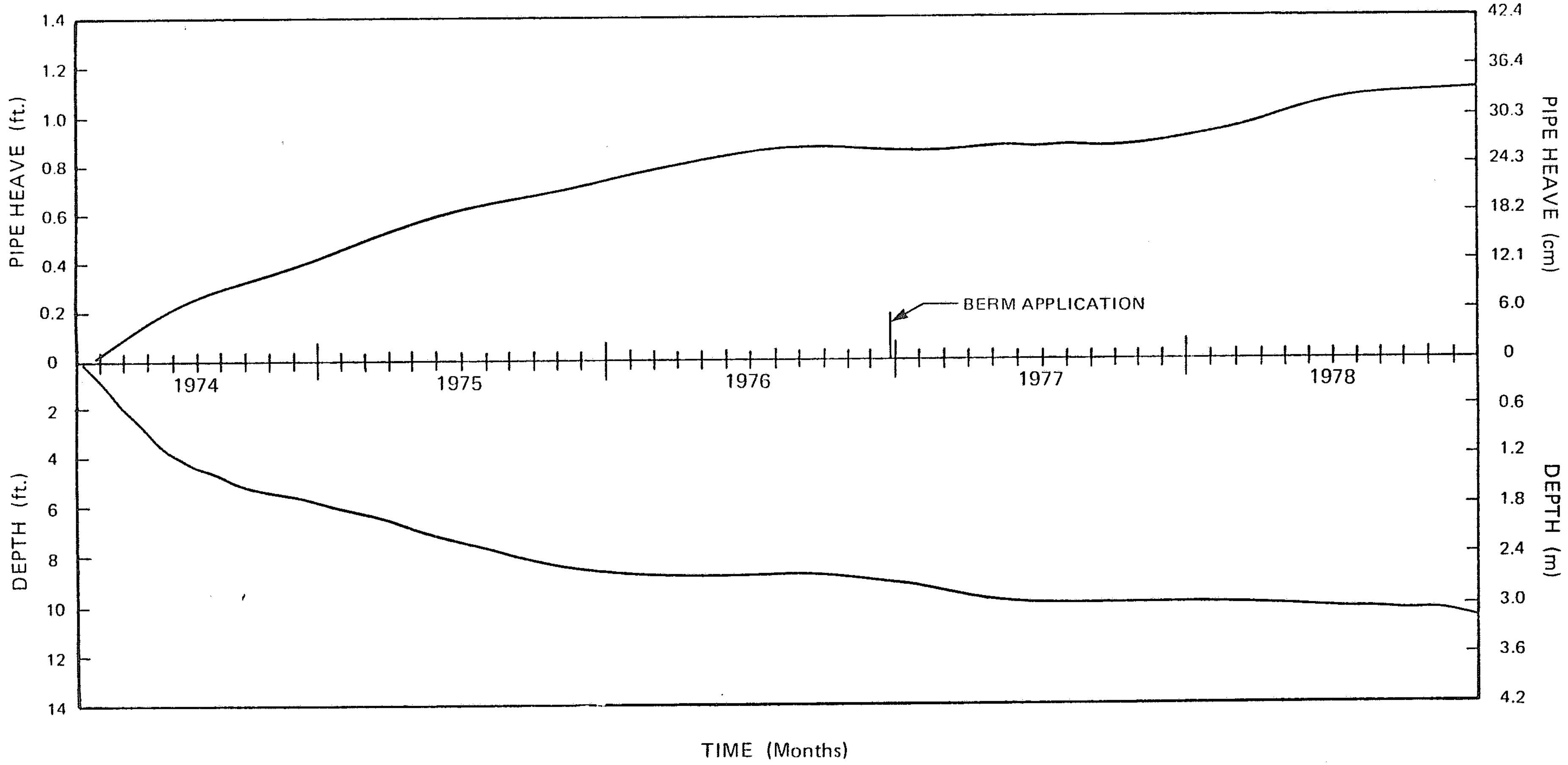


FIGURE 4.25

OBSERVED PIPE HEAVE (Gauge RM 3) & FROST DEPTH
BELOW BOTTOM OF PIPE @ 0.9 m FROM CENTRELINE
RESTRAINED SECTION

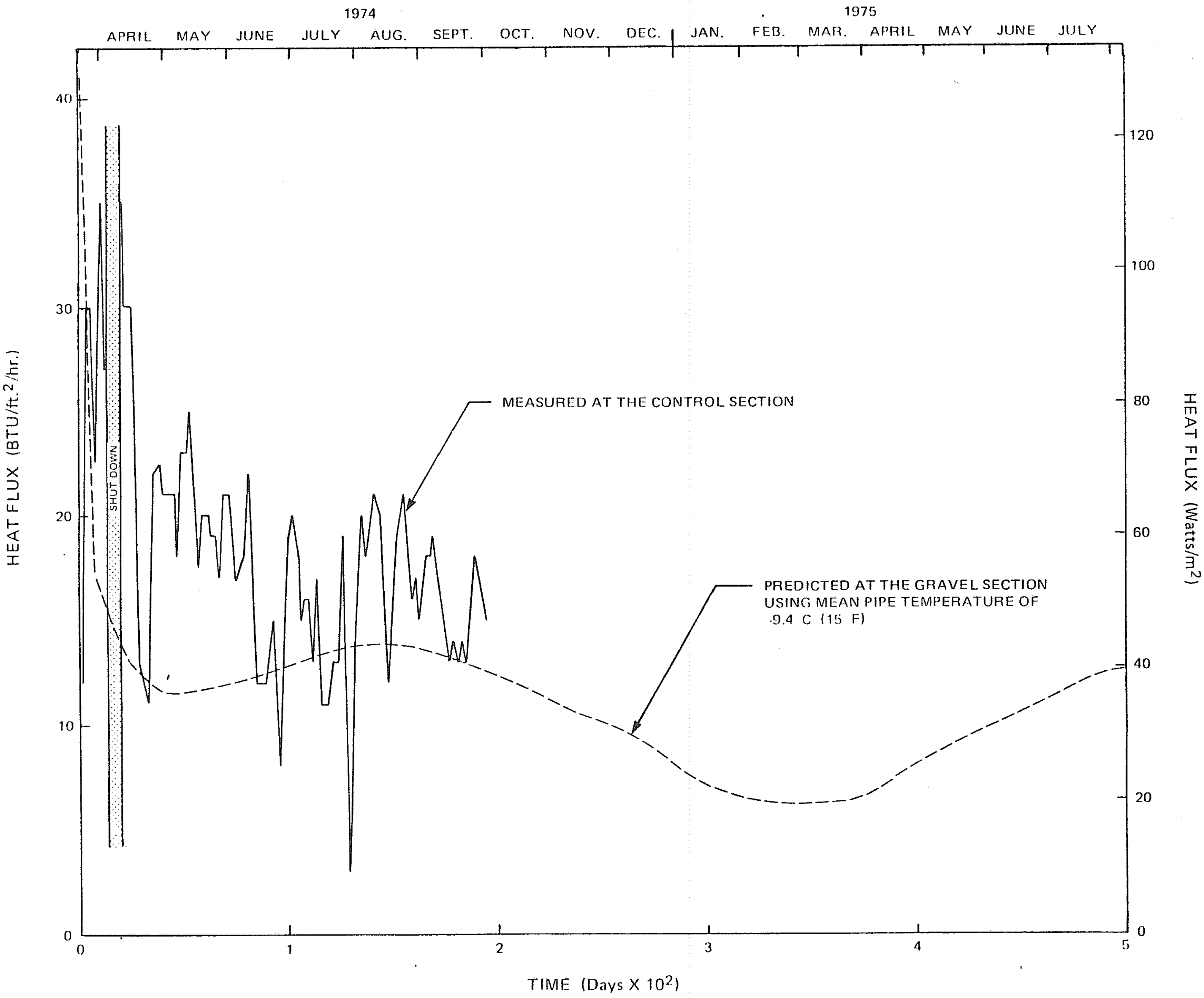


FIGURE 5.1 PREDICTED & MEASURED HEAT FLUX vs. TIME
CALGARY FROST HEAVE TEST SITE

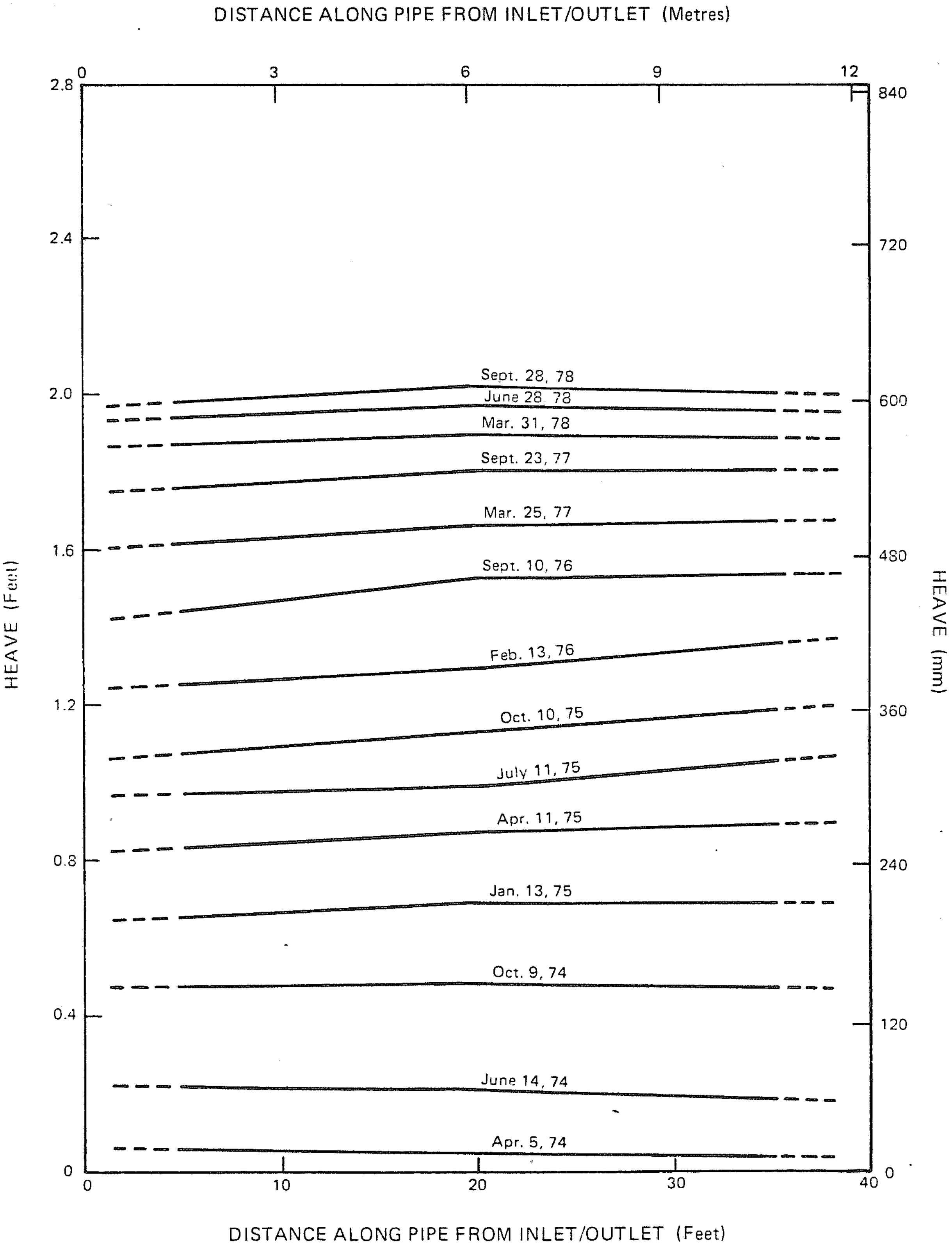


FIGURE 5.2 HEAVE PROFILES ALONG PIPE DEEP BURIAL SECTION

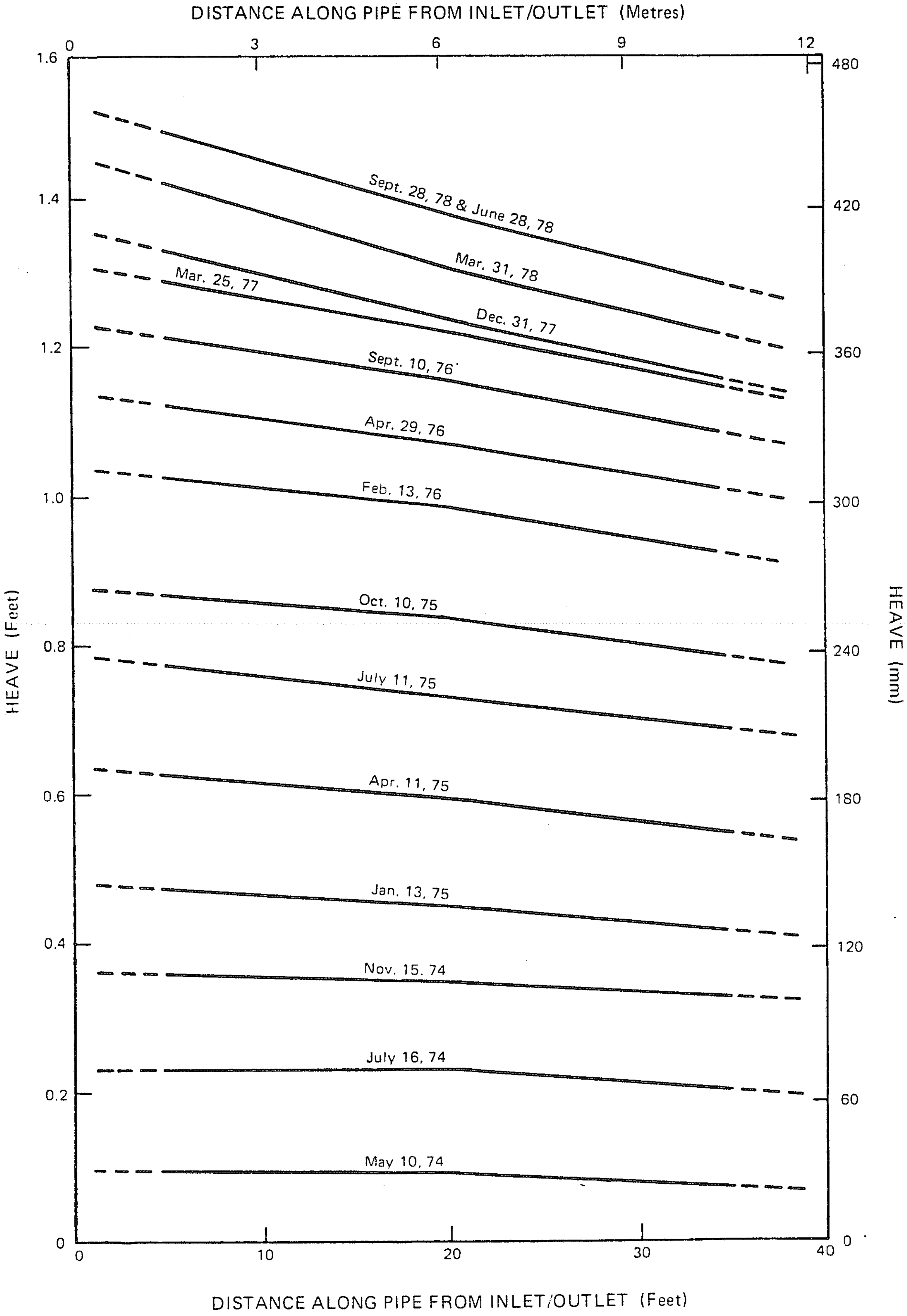


FIGURE 5.3

HEAVE PROFILES ALONG PIPE
GRAVEL SECTION

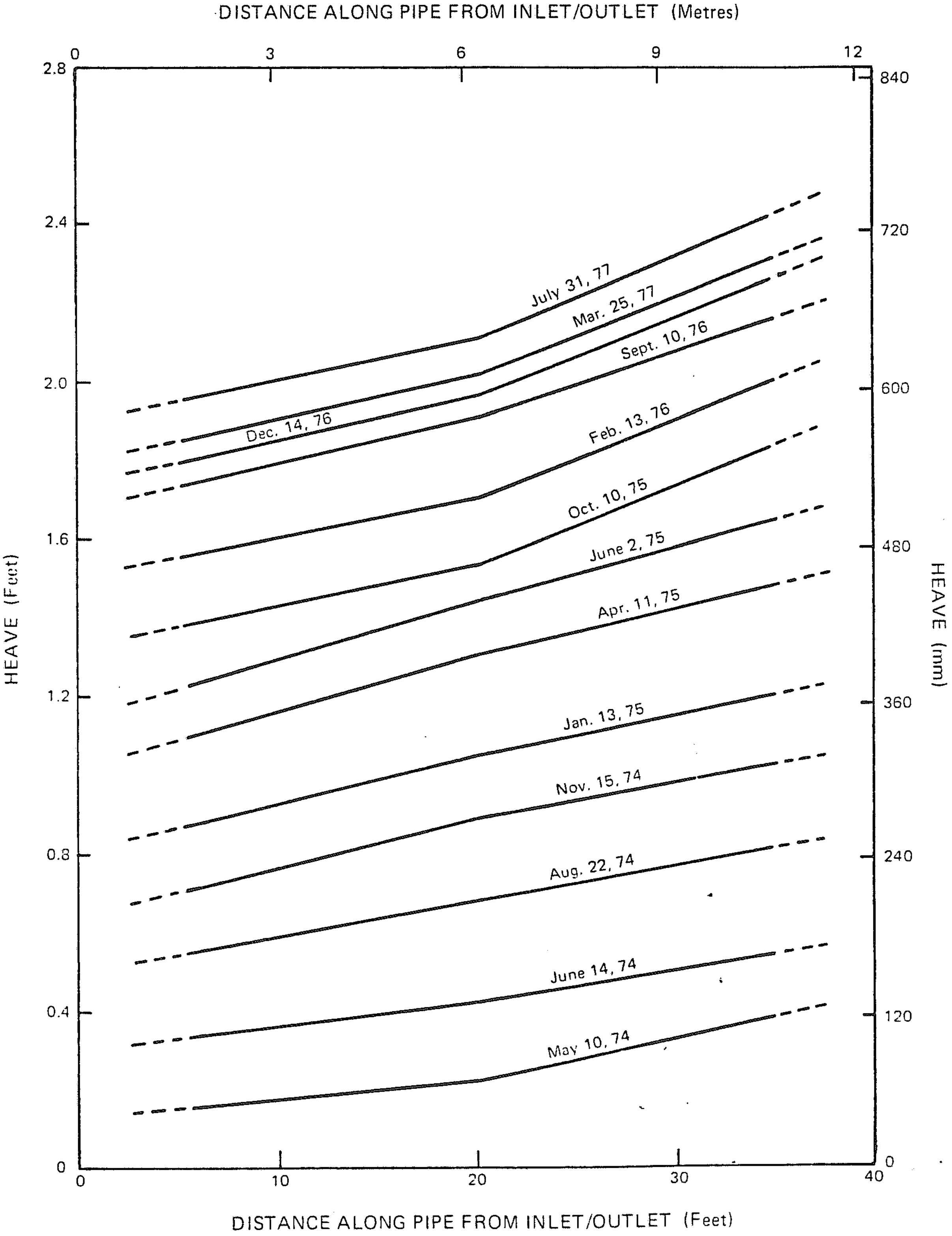


FIGURE 5.4 HEAVE PROFILES ALONG PIPE CONTROL SECTION

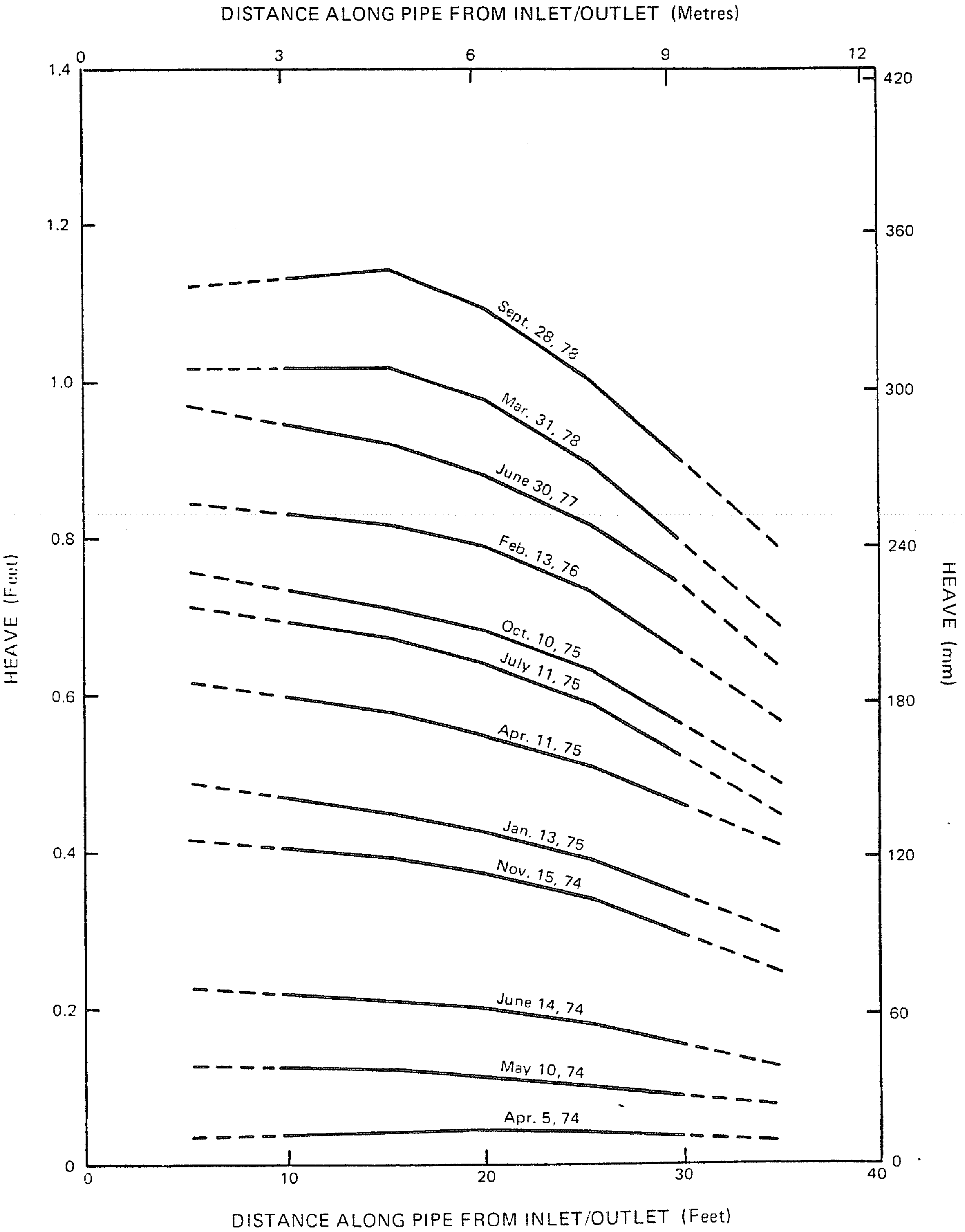


FIGURE 5.5 HEAVE PROFILES ALONG PIPE RESTRAINED SECTION

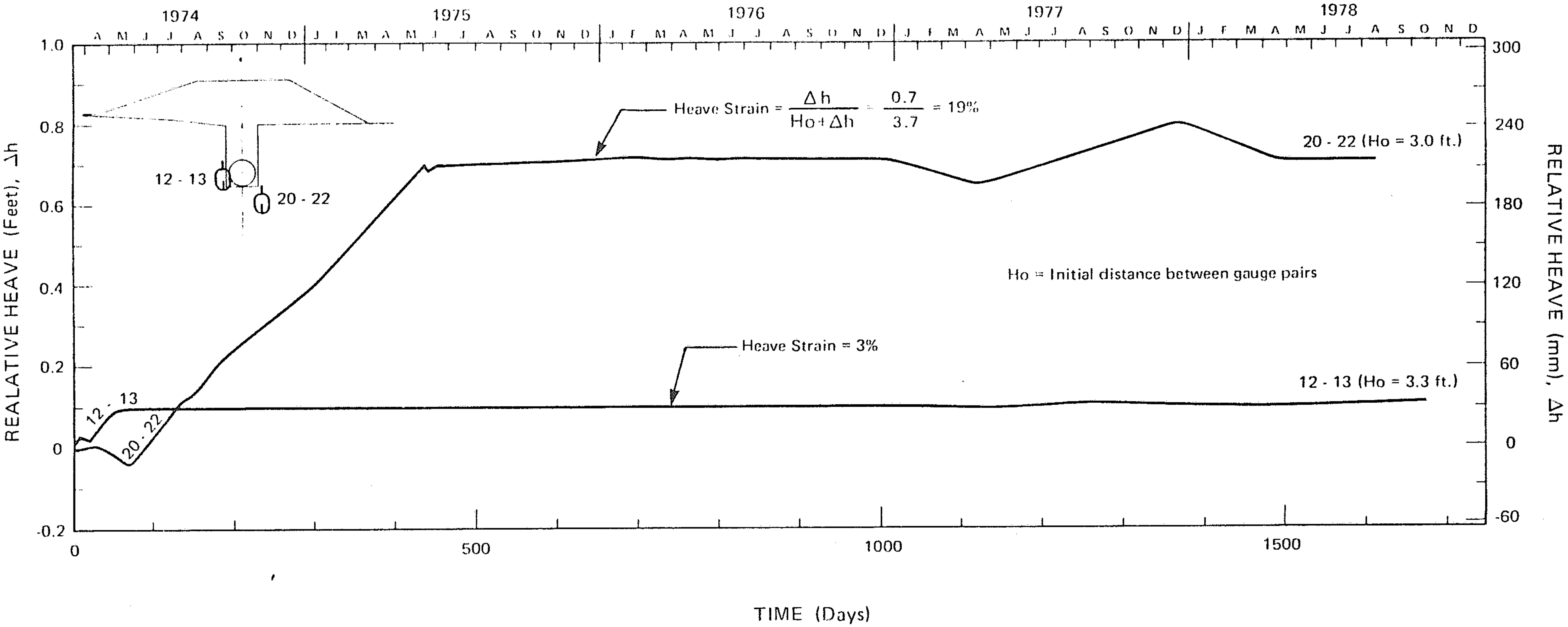


FIGURE 5.6

RELATIVE HEAVE OF HEAVE GAUGES
DEEP BURIAL SECTION

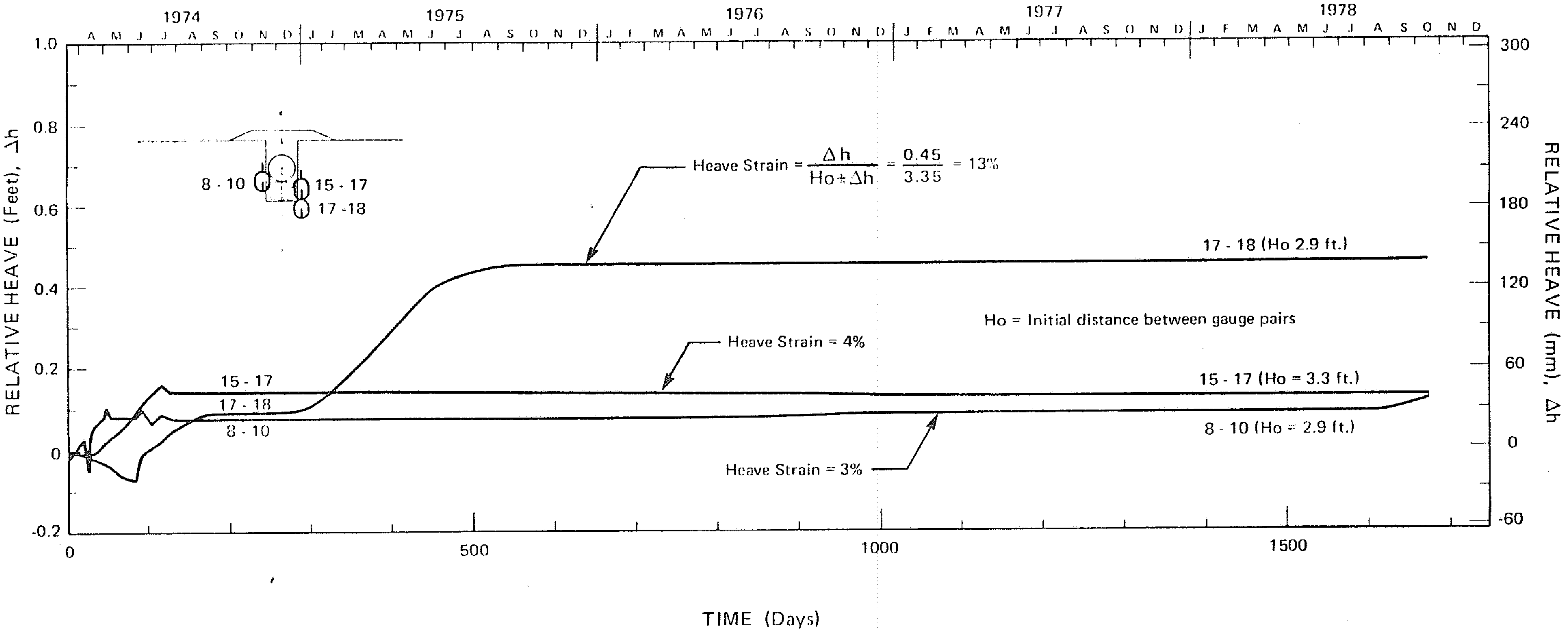


FIGURE 5.7

RELATIVE HEAVE OF HEAVE GAUGES
GRAVEL SECTION

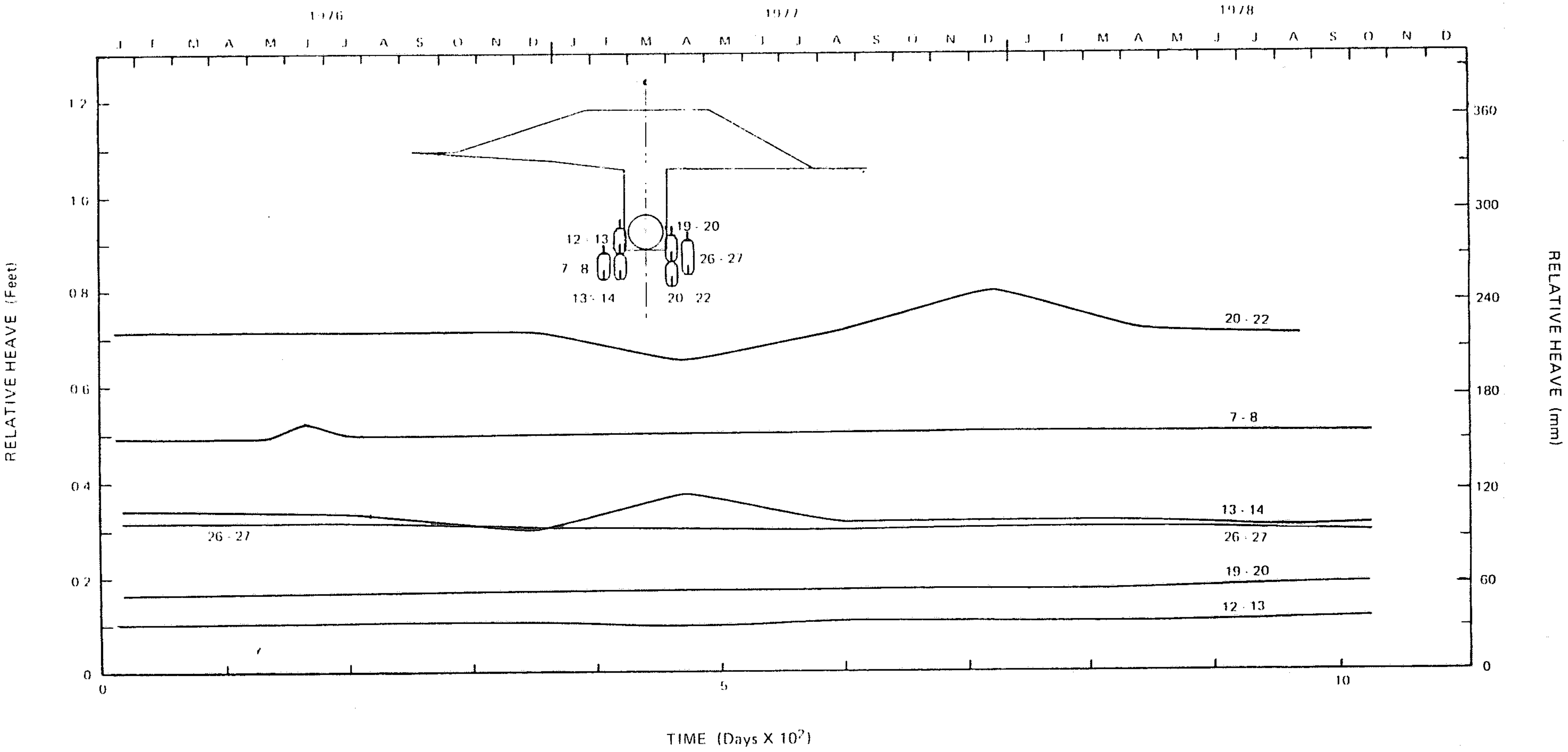


FIGURE 5.8

RELATIVE HEAVE OF HEAVE GAUGES
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE

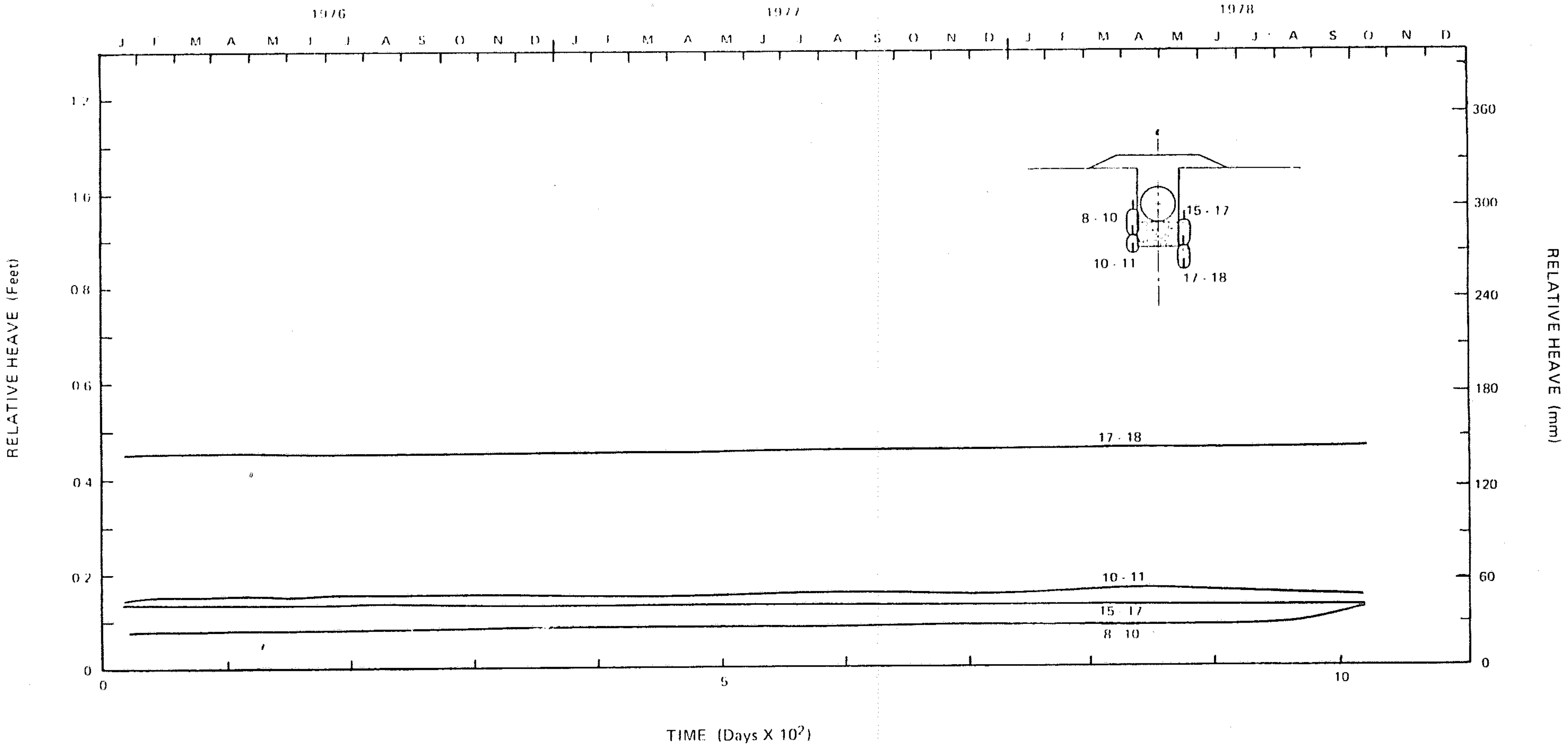


FIGURE 5.9 RELATIVE HEAVE OF HEAVE GAUGES
GRAVEL SECTION
CALGARY FROST HEAVE TEST SITE

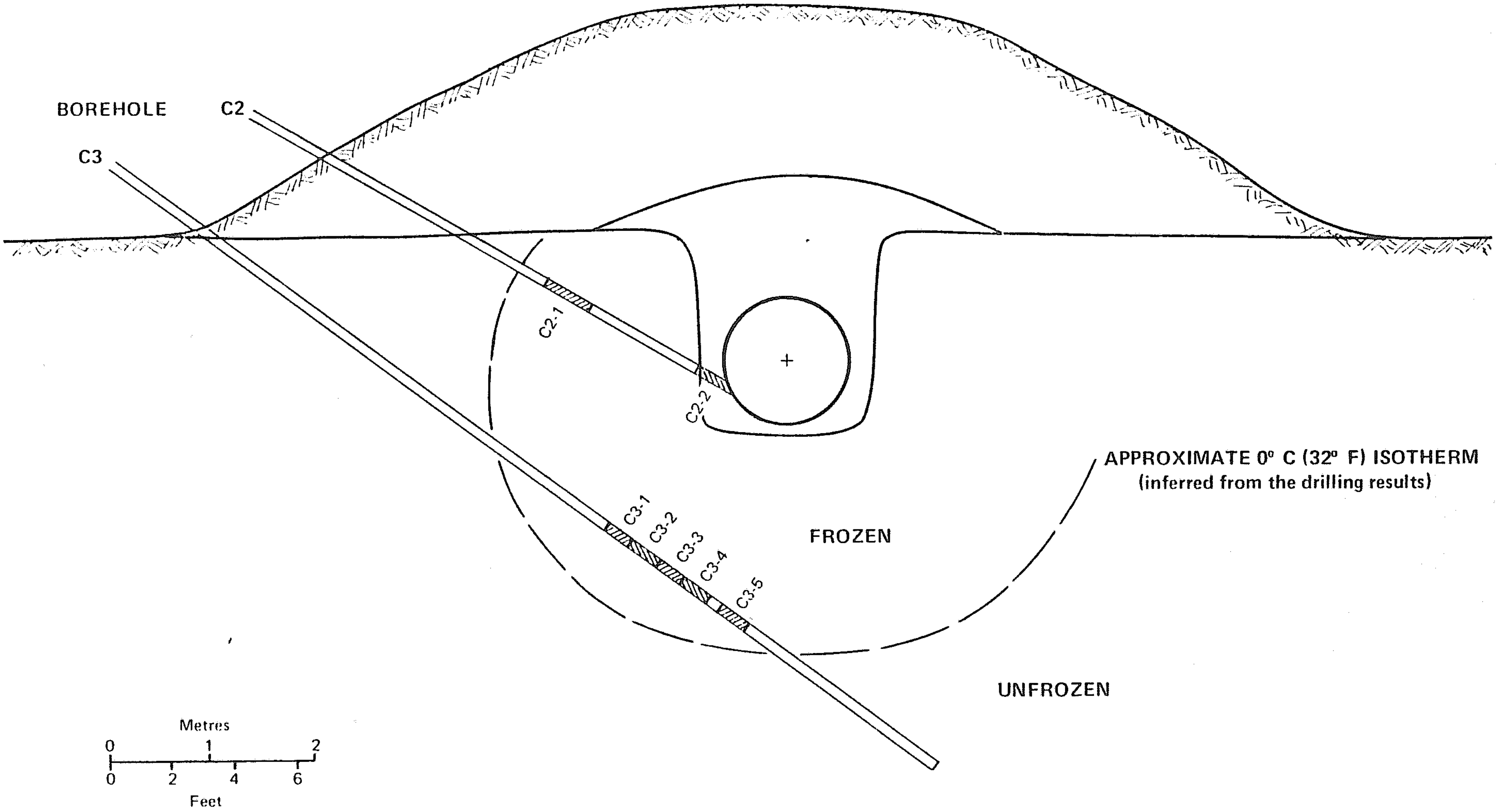


FIGURE 6.1 APPROXIMATE BOREHOLE LOCATIONS CONTROL SECTION CALGARY FROST HEAVE TEST SITE

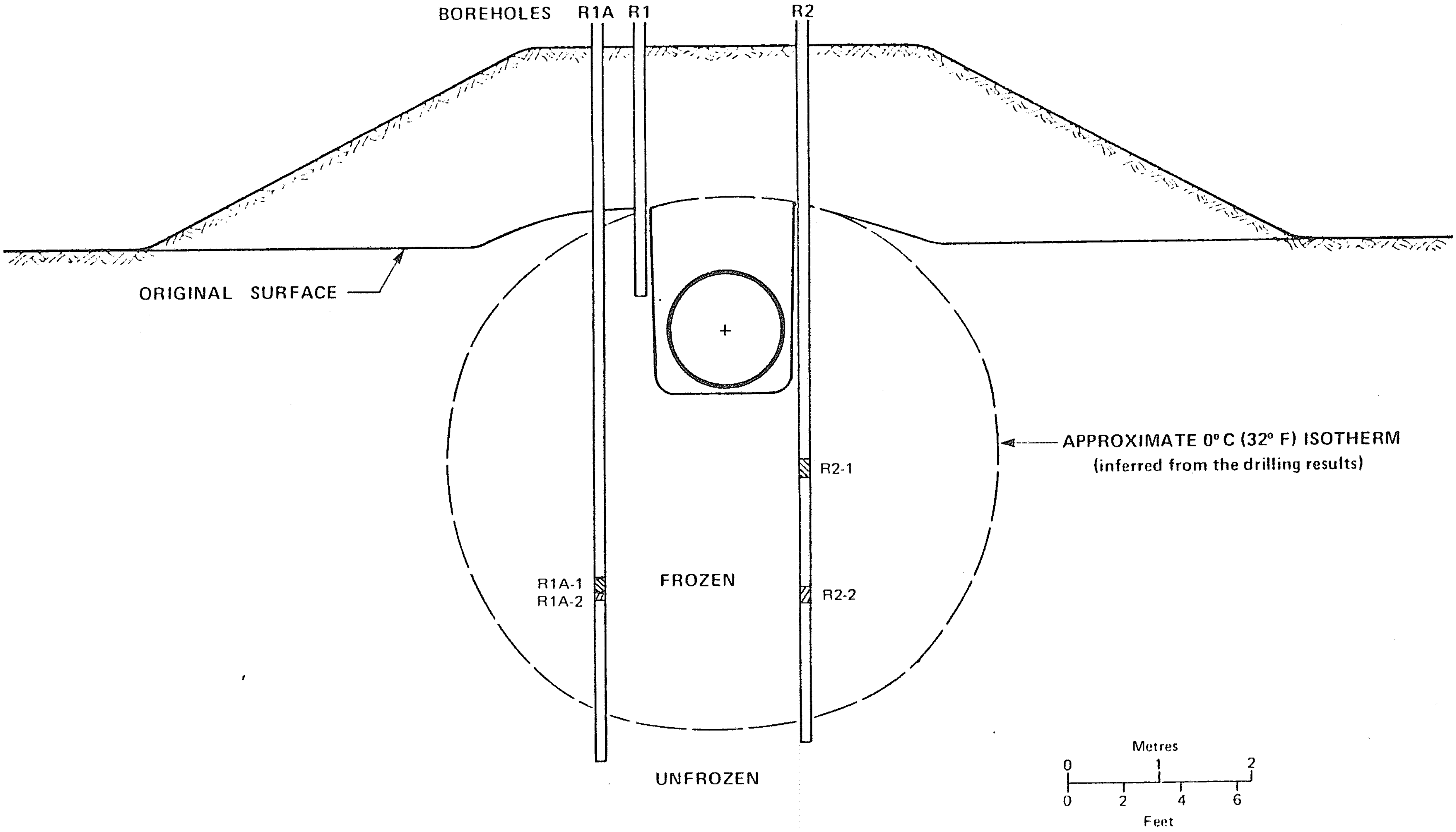


FIGURE 6.2

APPROXIMATE BOREHOLE LOCATIONS
RESTRAINED SECTION
CALGARY FROST HEAVE TEST SITE
(Section viewed facing north)

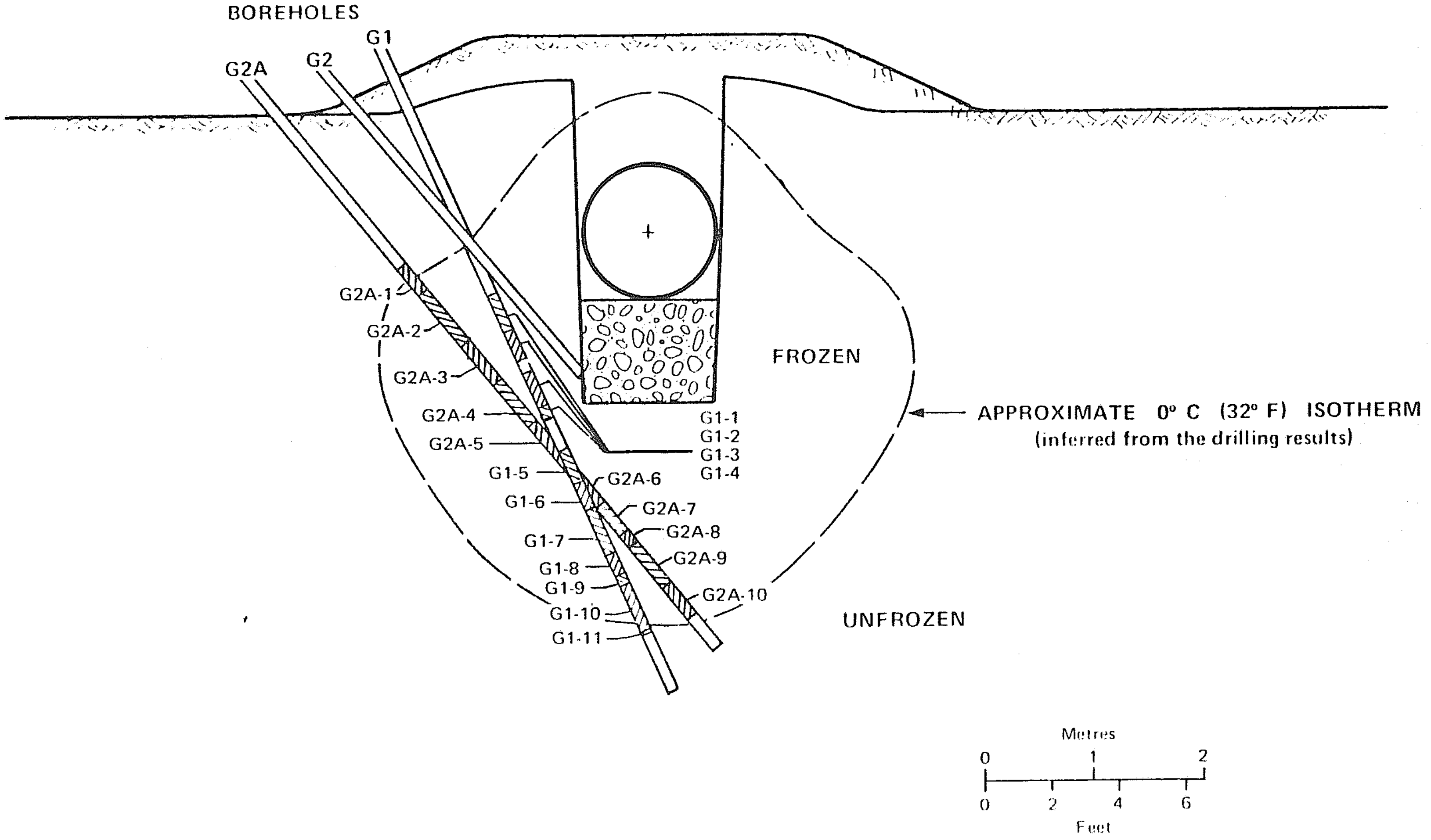


FIGURE 6.3 APPROXIMATE BOREHOLE LOCATIONS
GRAVEL SECTION
CALGARY FROST HEAVE TEST SITE
(Section viewed facing east)

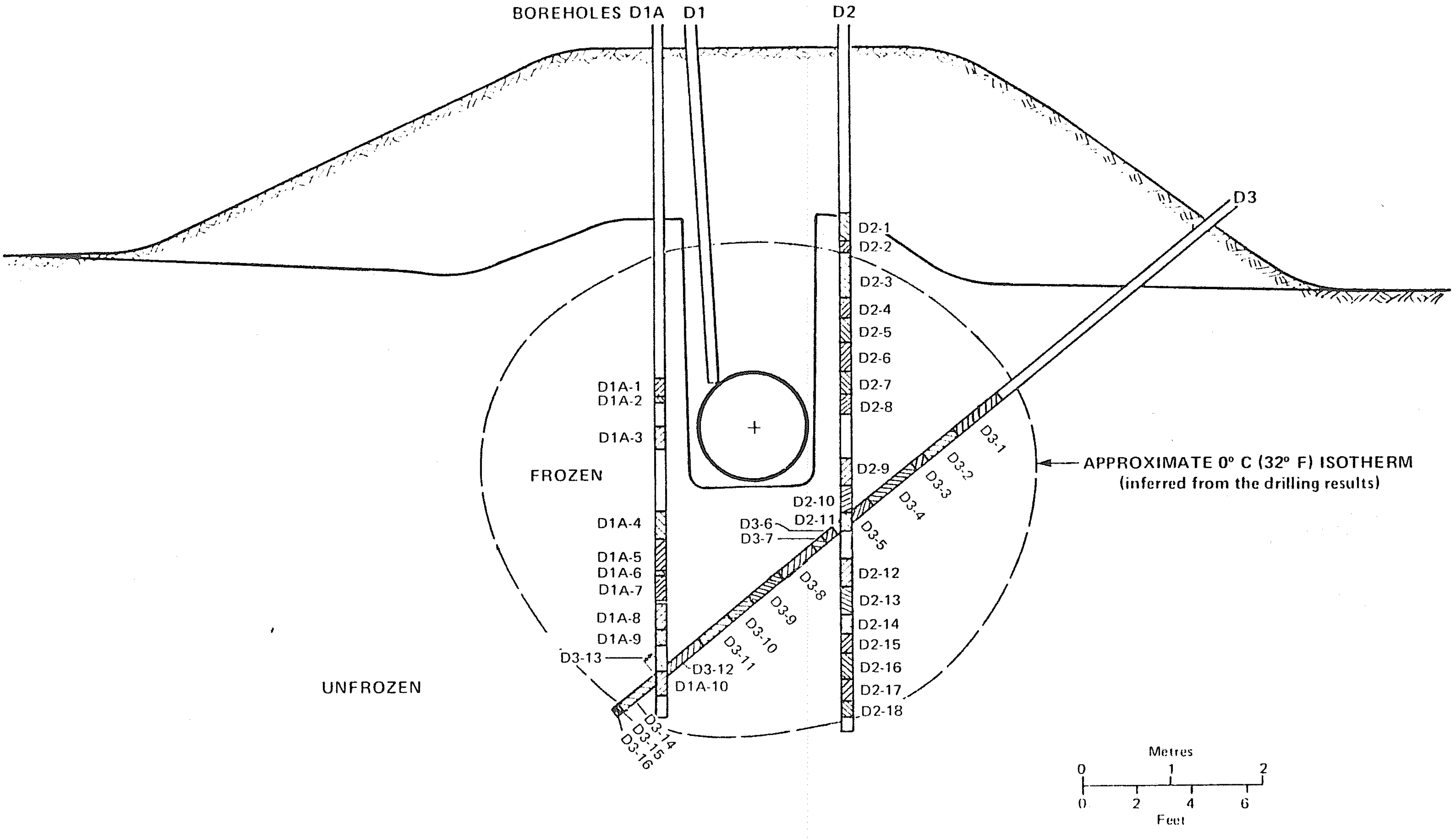


FIGURE 6.4 APPROXIMATE BOREHOLE LOCATIONS
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE
(Section viewed facing north)

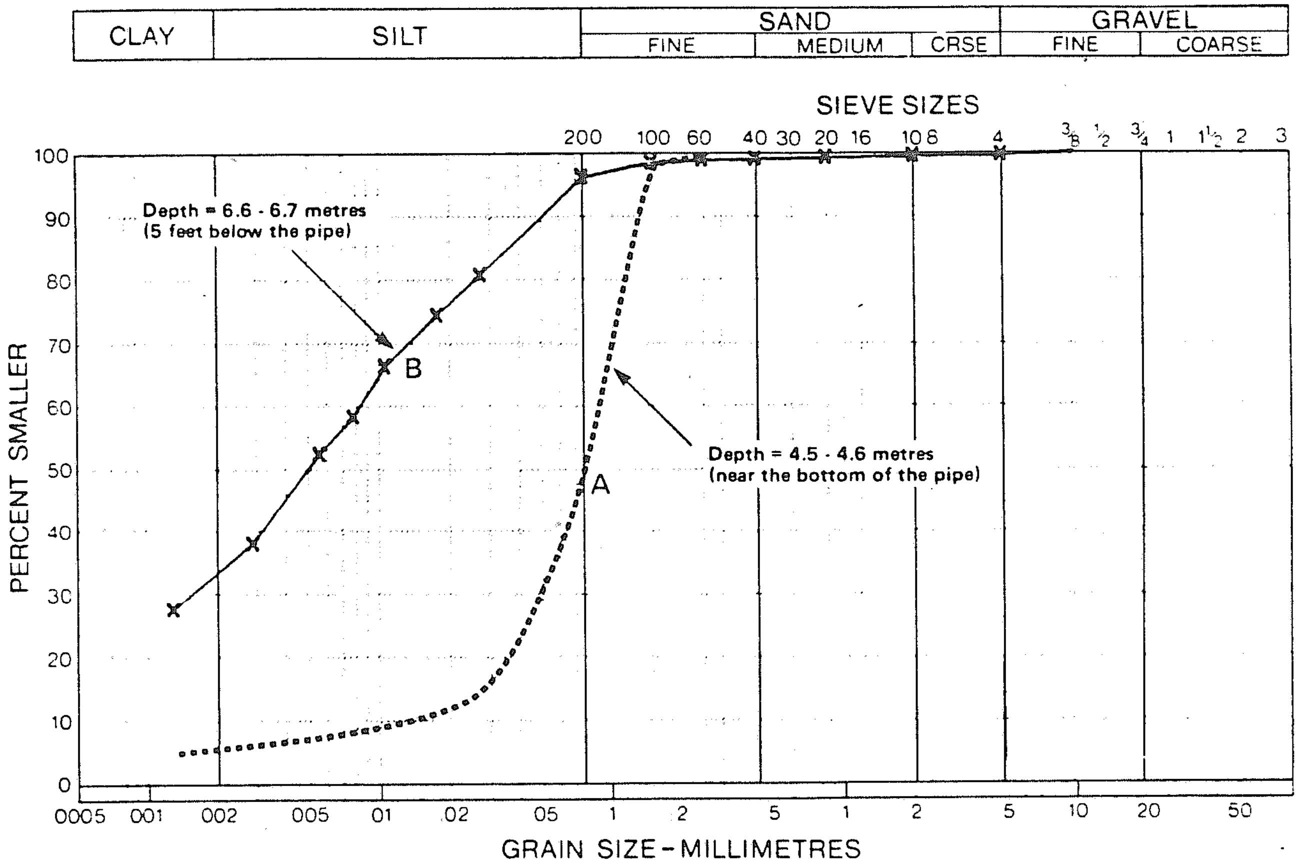


FIGURE 6.5 GRAIN SIZE DISTRIBUTION (Borehole D - 1A)
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE

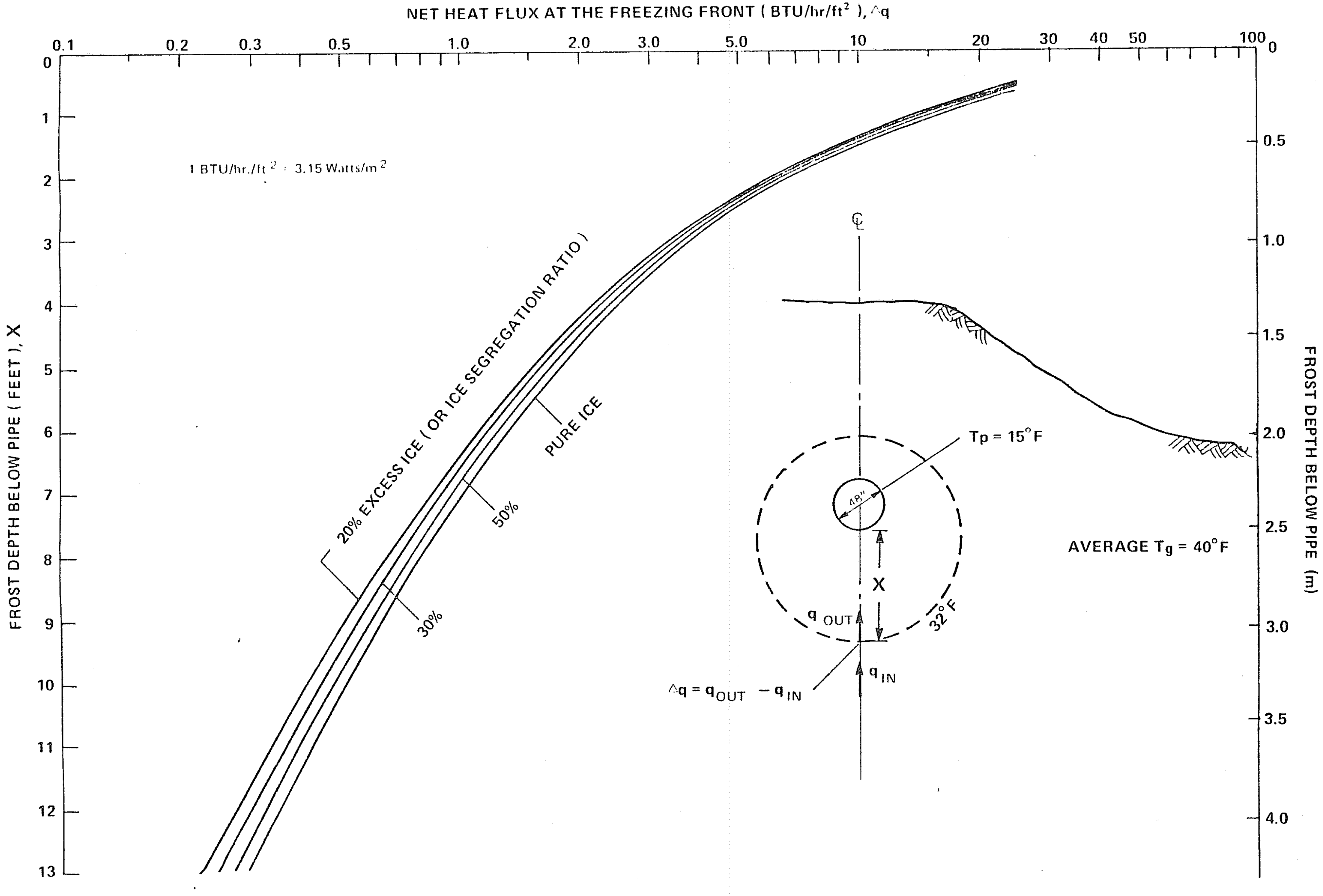


FIGURE 6.6 CALCULATED NET HEAT FLUX AT FREEZING FRONT
DEEP BURIAL SECTION
CALGARY FROST HEAVE TEST SITE

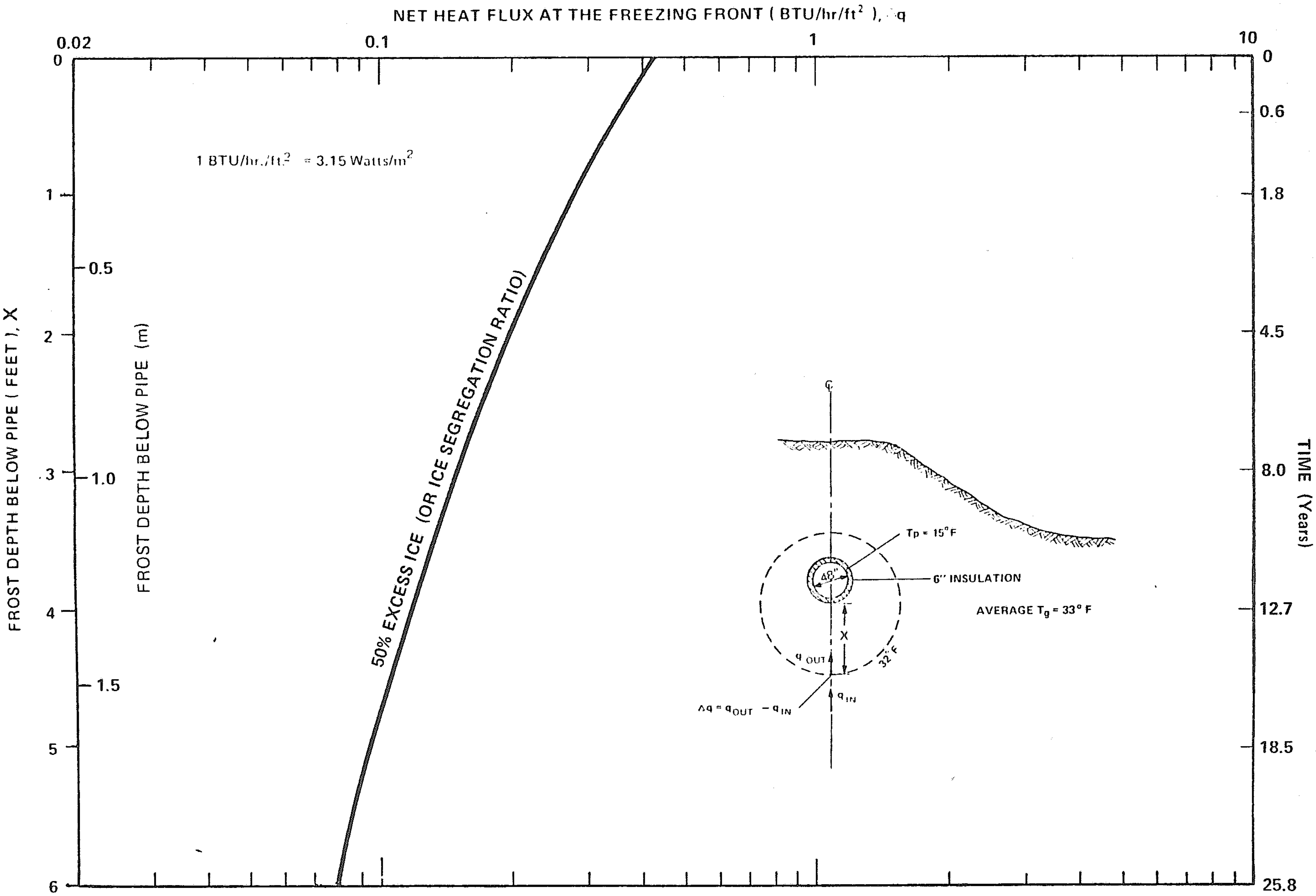


FIGURE 6.7 CALCULATED NET HEAT FLUX AT THE FREEZING FRONT FOR AN INSULATED COLD PIPE IN UNFROZEN GROUND

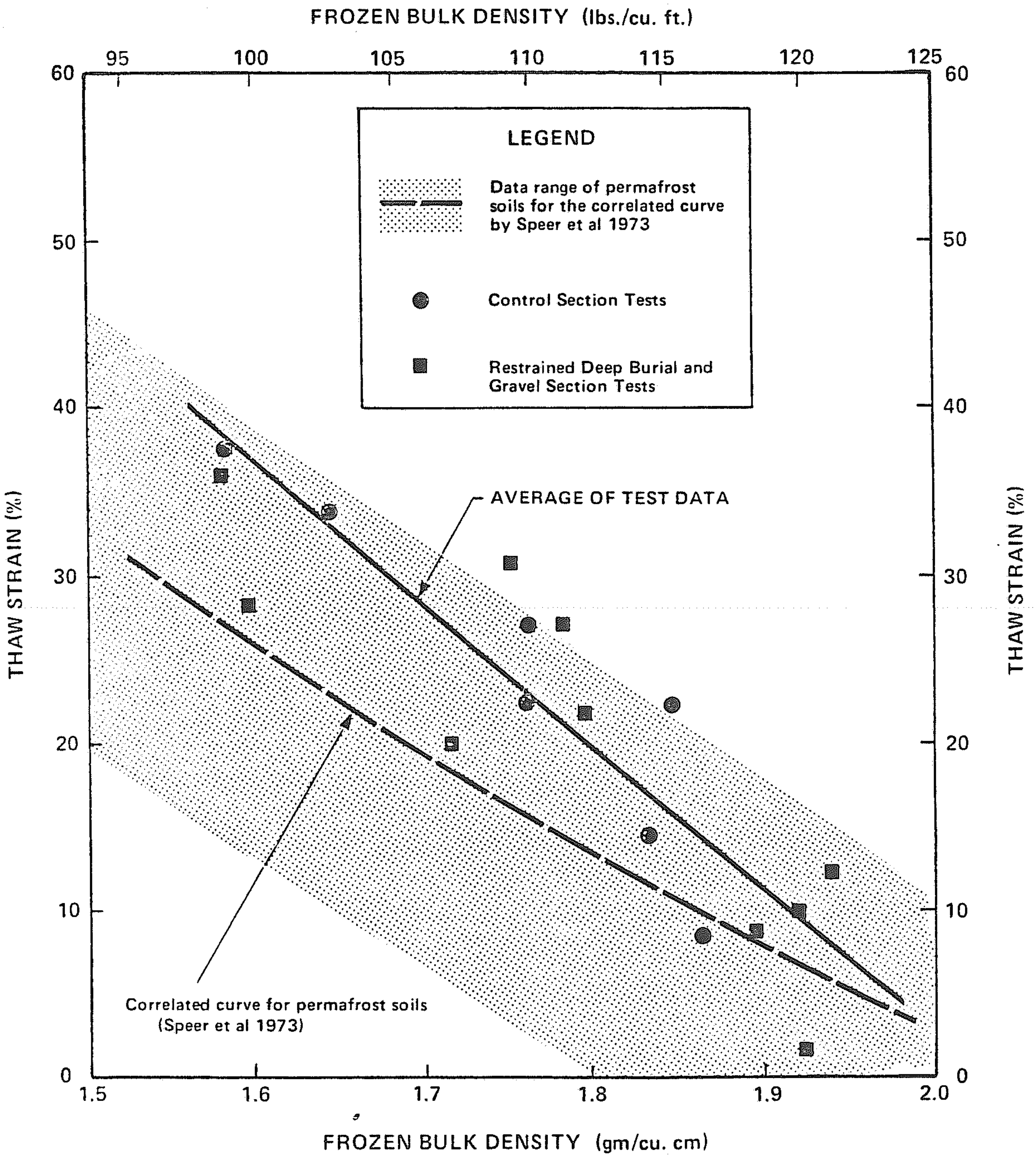


FIGURE 6.8 THAW STRAIN vs. FROZEN BULK DENSITY CALGARY FROST HEAVE TEST SITE

APPENDIX A

LABORATORY FROST HEAVE TESTING

A.1 General

The methodology of the semi-empirical approach have been presented in Section IV. The laboratory test program constitutes an integrated part of the design approach. This section will describe the test equipments and Frost Heave Test results.

A.2 Test Equipment

The purpose of this frost heave testing program is to investigate the heave strain or ice segregation, and frost heave characteristics of specific soil types under one-dimensional freezing of a finite length sample with free access to water. A diagram of the frost heave tests cell that has been developed for Foothills Pipe Lines (Yukon) Ltd. by EBA is shown in Figure A.1. The principal requirements of all test cells are as follows:

1. A sufficiently rigid confining barrel to prevent movement in the radial direction.

2. Insulated cell walls to allow the assumption of a zero heat flux boundary condition at the soil-cell wall contact.

3. Lubrication of the cell walls to allow minimal frictional resistance between the cell wall and the sample confining membrane.

4. A base plate which can be controlled to a fixed cold temperature. This is generally achieved by circulation of a chilled fluid through a galaxy in the base plate.

5. A load cap which can be controlled to a fixed warm temperture. This is generally achieved by circulating a fluid through a galaxy located in the load cap above the pourous stone.

6. A load cap and porous stone assembly coupled with a burrette to allow free access of water to the sample, and accurate measurement of the water intake or expulsion.

7. A water tight seal between the sample's confining membrane, the cold sample base plate and the warm load cap.

8. Temperature measuring thermistors in the base plate, the load cap and embedded into the cell walls provide accurate measurement of both the applied temperature boundary conditions and the thermal response of the soil sample to those applied temperatures.

9. A dial gauge or DCDT to measue the heave and/or settlement of the sample.

10. A hanger system to apply specified vertical loads to the sample through the load cap.

11. Sufficient temperature controlled baths to create sample nucleation and to accurately maintain the specified cold and warm plate temperatures for the entire test duration.

A diagram of the two frost heave test cells developed for Foothills by EBA has been presented as Figure A.1. The cells consist of a split barrel 203mm (8.0 in.) in length and 90mm (3.54 in.) in diameter. Two lines of thermistors are embedded in the cell walls at 12.7mm (0.5 in.) spacings to a height of 133mm (5.25 in.) above the base plate. The exterior of the barrel is coated with 102mm (4 in.) of Polyurethane insulation.

The cold temperature boundary condition may be controlled by a galaxy in the sample base plate, or by a second galaxy in a sub-base plate which is separated from the sample base plate by insulation. The warm temperature boundary condition is achieved by circulation of fluid through a galaxy within the load cap. Thermistors are attached to or embedded in the load cap, the sample base plate and the sub-base plate in order to accurately monitor and control the temperature boundary conditions.

Vertical stress is applied to the sample by a conventional dead weight hanger system. Water is supplied to the sample through the load cap connected by tubing to a burette. The water level in the burette is maintained at approximtely the same level as the top of the sample.

All measurements, with the exception of the burette readings, are automatically read at pre-programmed time intervals using a data acquisition program developed for Foothills by EBA. The Hewlett-Packard data acquisition system and plotter is used to read the approximately 130 thermistors required to monitor the cell walls, the controlled temperature plates, the bath fluid temperatures and the cold room temperature, for the simultaneous testing of four samples. The readings are automatically stored on cassette tape. Each of the thermistor beads has been accurately calibrated. The calibration offsets are stored in the data acquisition program, and are applied to the readings to give the corrected temperatures. For each reading interval, the data acquisition system records the vertical movement of the load cap by an electronic displacement transducer. Plots of frost heave versus time, frost front movement versus time, and cold plate, warm plate or room temperature versus time may be plotted by the Hewlett-Packard directly from the data stored on the cassette tape. The use of the computer for reading data, data reduction, data storage and data plotting significantly reduces both technician/engineering time and the possiblity of data reading or reduction errors.

A.3 Test Procedures and Results

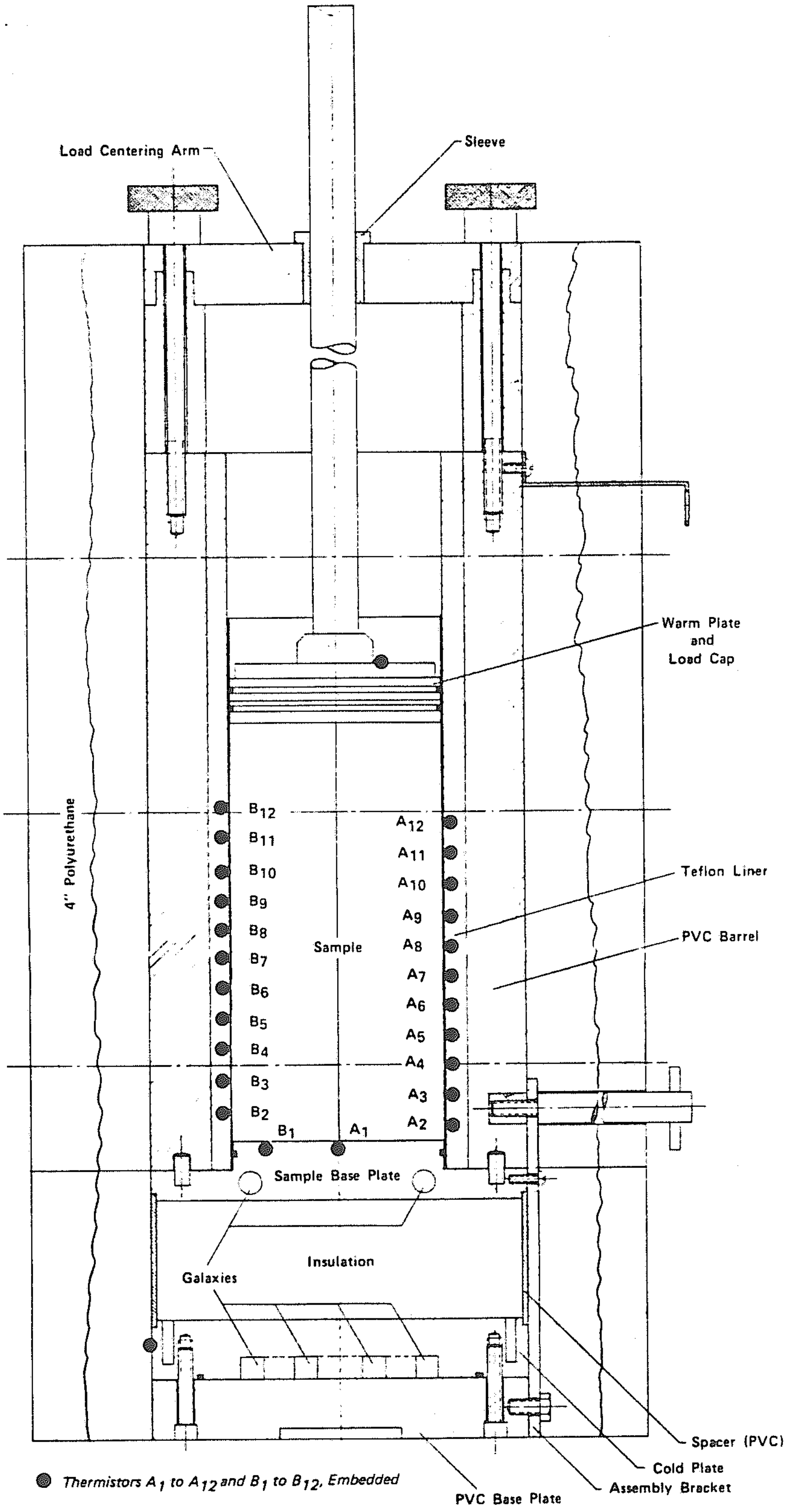
Figure 4.5 shows the soil samples and borehole location. The samples were thawed and reconsolidated under their overburden pressures. The soil sample has a finite length of about 4 inches with free access of water. After nucleation, the cold and warm side temperatures were prescribed and remained constant. The frost heave tests were run until steady-state equilibrium is reached. The heave strain or ice segragation ratio becomes

$$I_s = \frac{h_{max}}{X_{max}}$$

where h_{max}, X_{max} are the frost heave and the frost depth at steady-state, respectively. All the frost heave test were performed in the EBA cold room where the air temperatures were controlled at about $35^{o}F \pm 2^{o}F$.

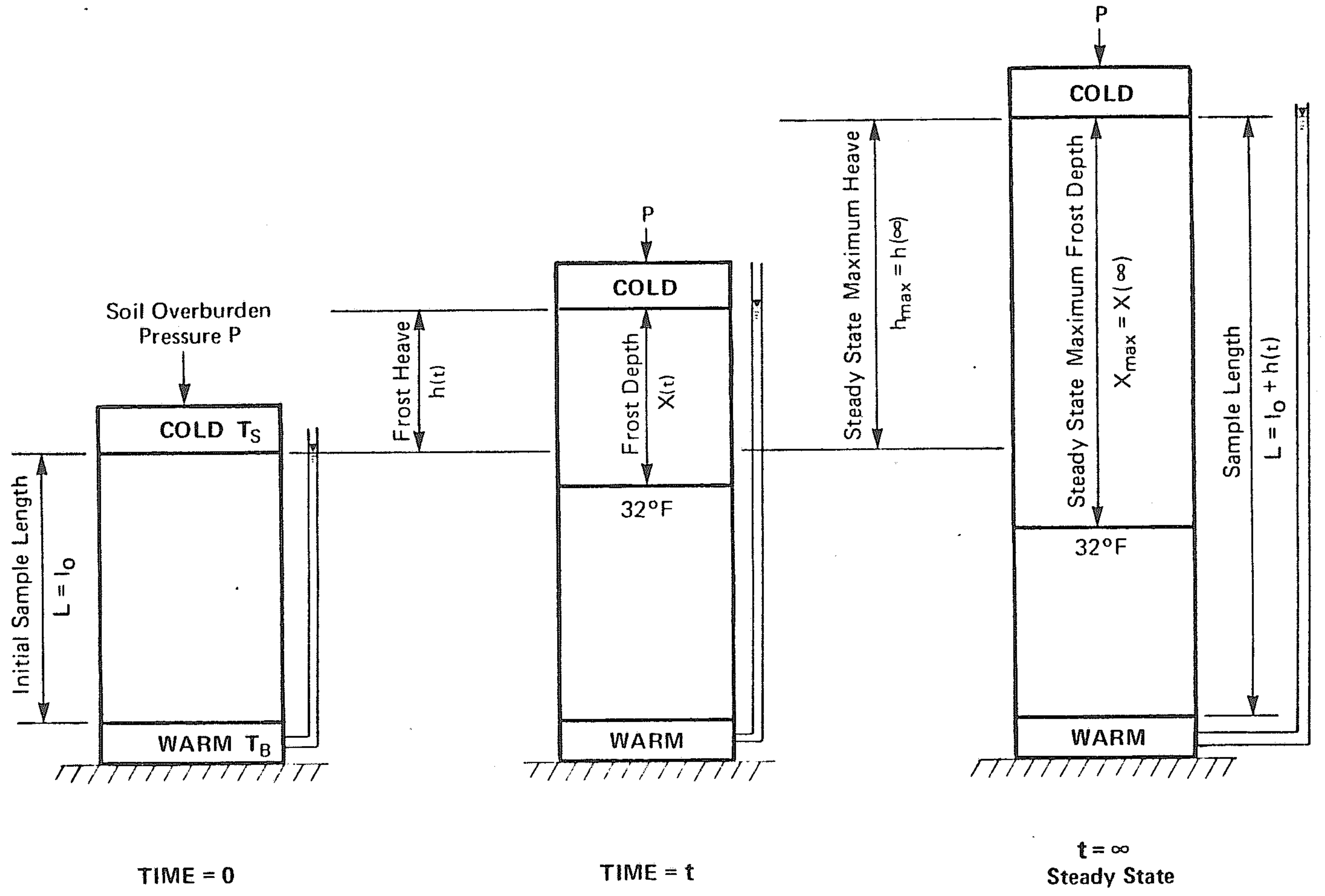
Figure A.2 describes schematicallly the progress of a frost heave test. The test results, as plotted by the Hewlett-Packard data acquisition system for frost heave, frost depth (^{o}C isotherm) and sample boundary temperatures, are presented in Figures A.3 to A.14.

The heave strain or ice segregation ratios for these results are summarized in Table II of Section 4.2



6

FIGURE A-1 FOOTHILLS FROST HEAVE TEST CELL



I = Heave strain or ice segregation ratio
$= h_{max}/X_{max}$

FIGURE A-2 THERMAL CONFIGURATIONS OF A LABORATORY SAMPLE AT THREE STAGES OF THE FROST HEAVE TEST

FOOTHILLS FROST HEAVE

TEST NO. 8
CELL NO. 1

TIME VS FROST PENETRATION

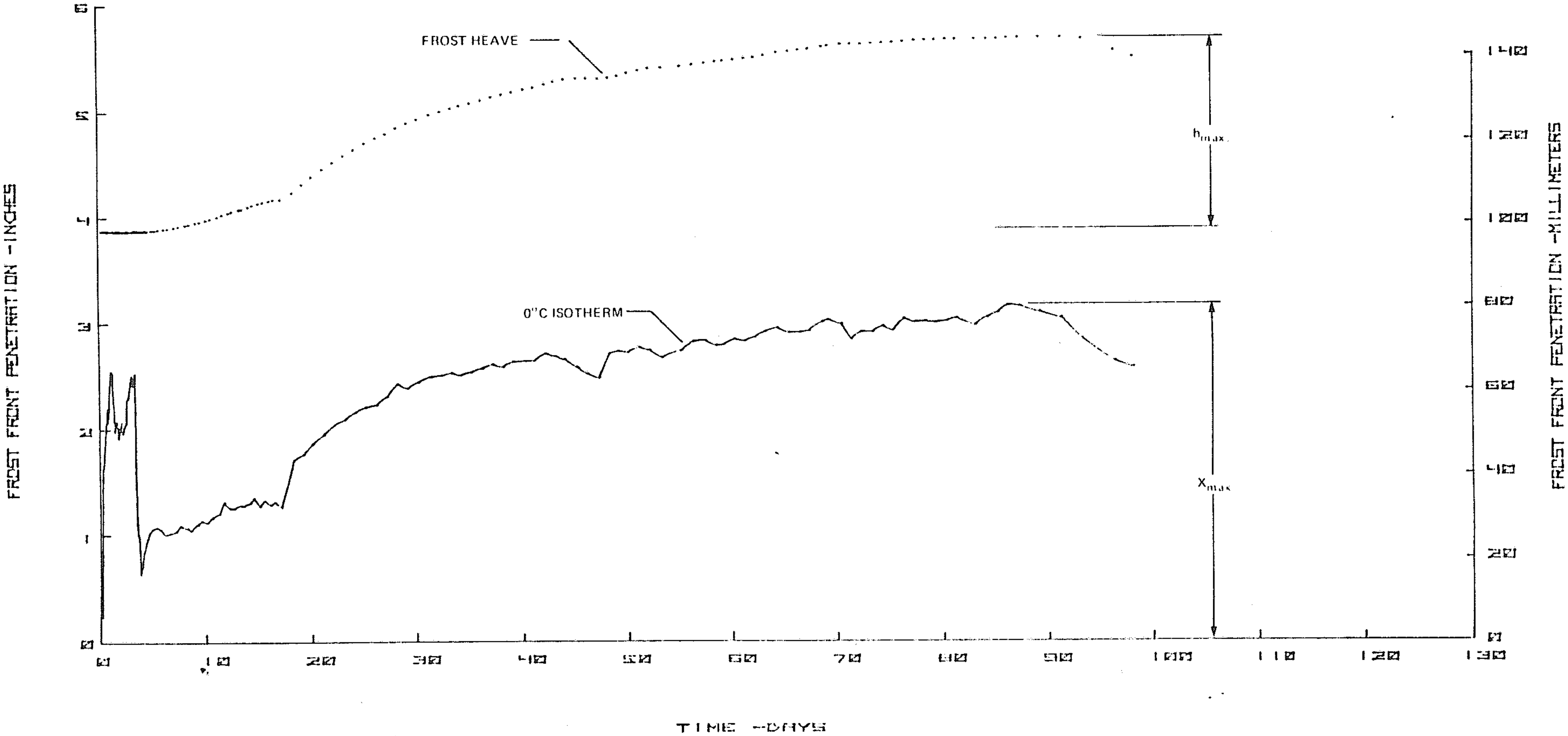


FIGURE A 3

FOOTHILLS FROST HEAVE

TEST NO. 8

CELL NO. 1

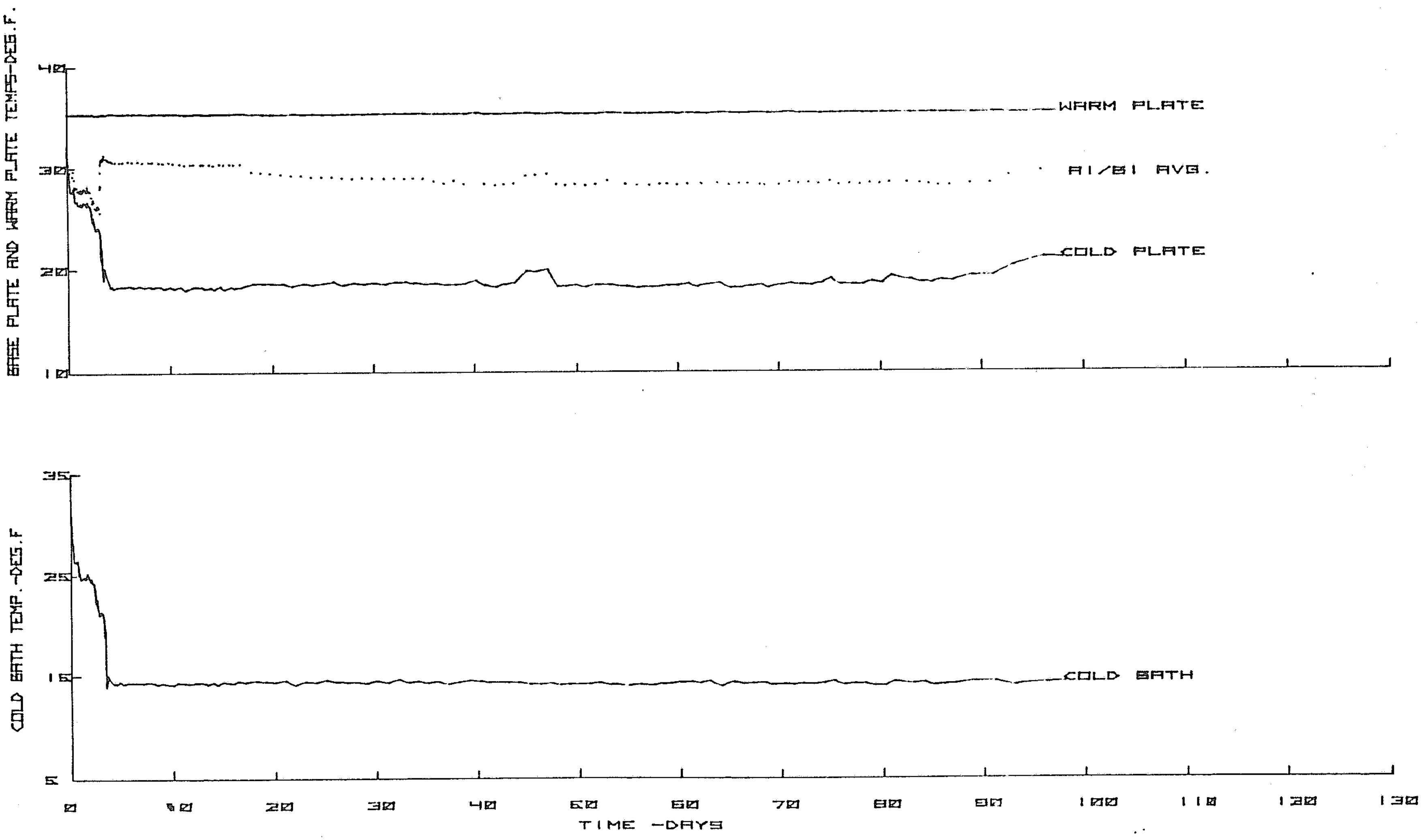


FIGURE A 4

FOOTHILLS FROST HEAVE

TEST NO. 10
CELL NO. 3

TIME VS FROST PENETRATION

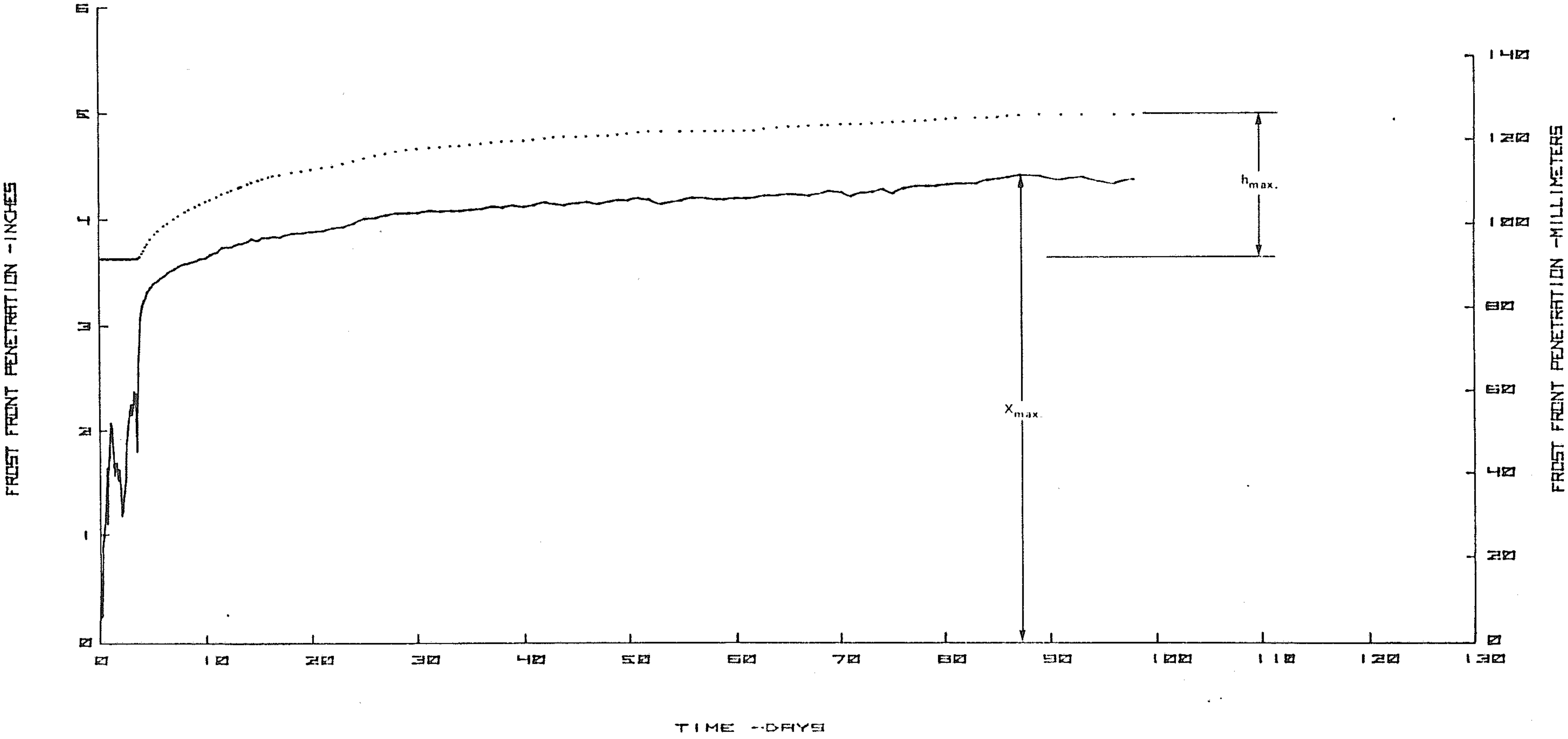


FIGURE A-5

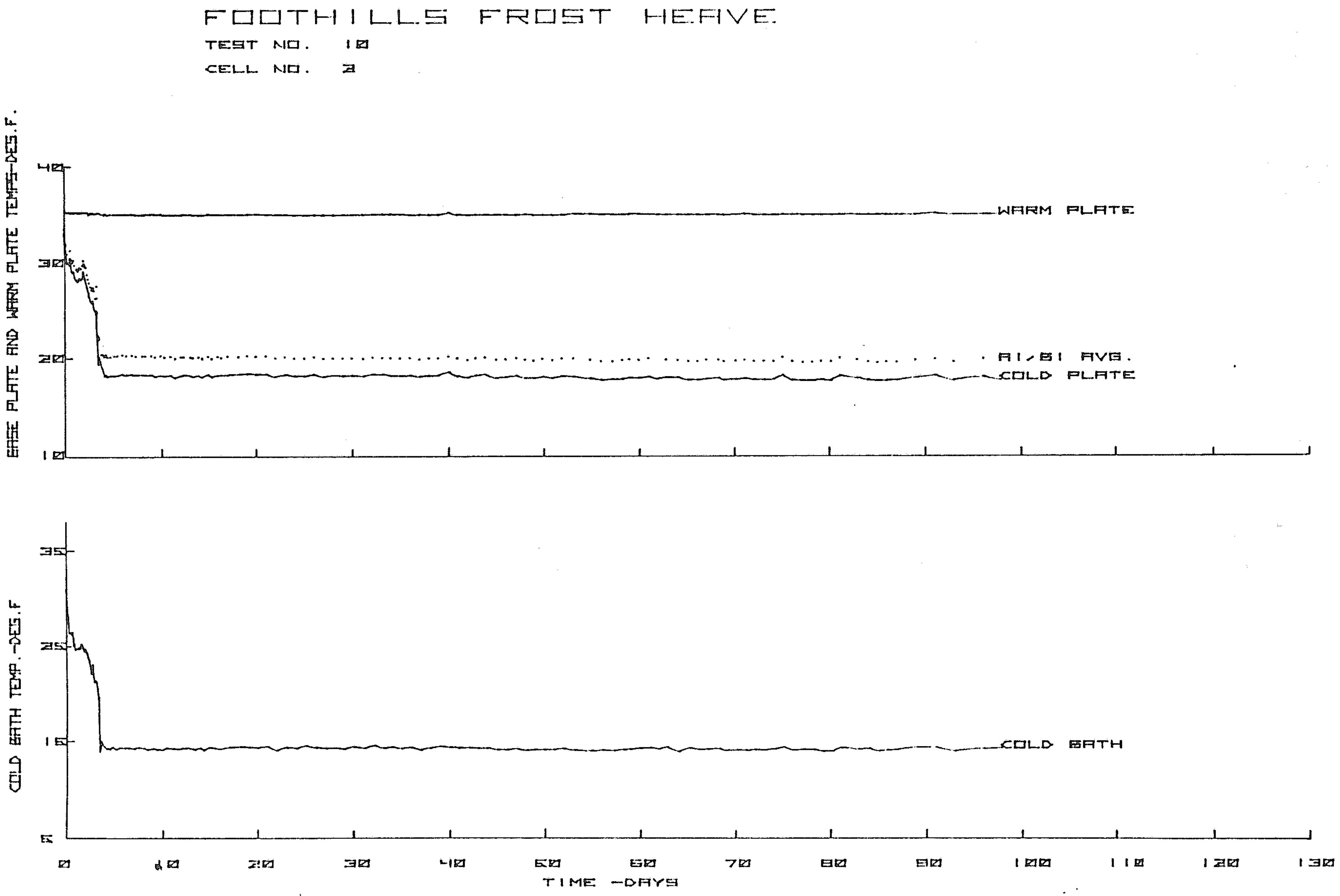

FOOTHILLS FROST HEAVE
TEST NO. 10
CELL NO. 2
BASE PLATE AND WARM PLATE TEMPS-DEG.F.
40
30
20
10
WARM PLATE
A1/B1 AVG.
COLD PLATE
COLD BATH TEMP.-DEG.F
35
25
15
5
COLD BATH
0
10
20
30
40
50
60
70
80
90
100
110
120
130
TIME -DAYS

FIGURE A 6

FOOTHILLS FROST HEAVE

TEST NO. 11 A
CELL NO. 1
√TIME VS FROST PENETRATION

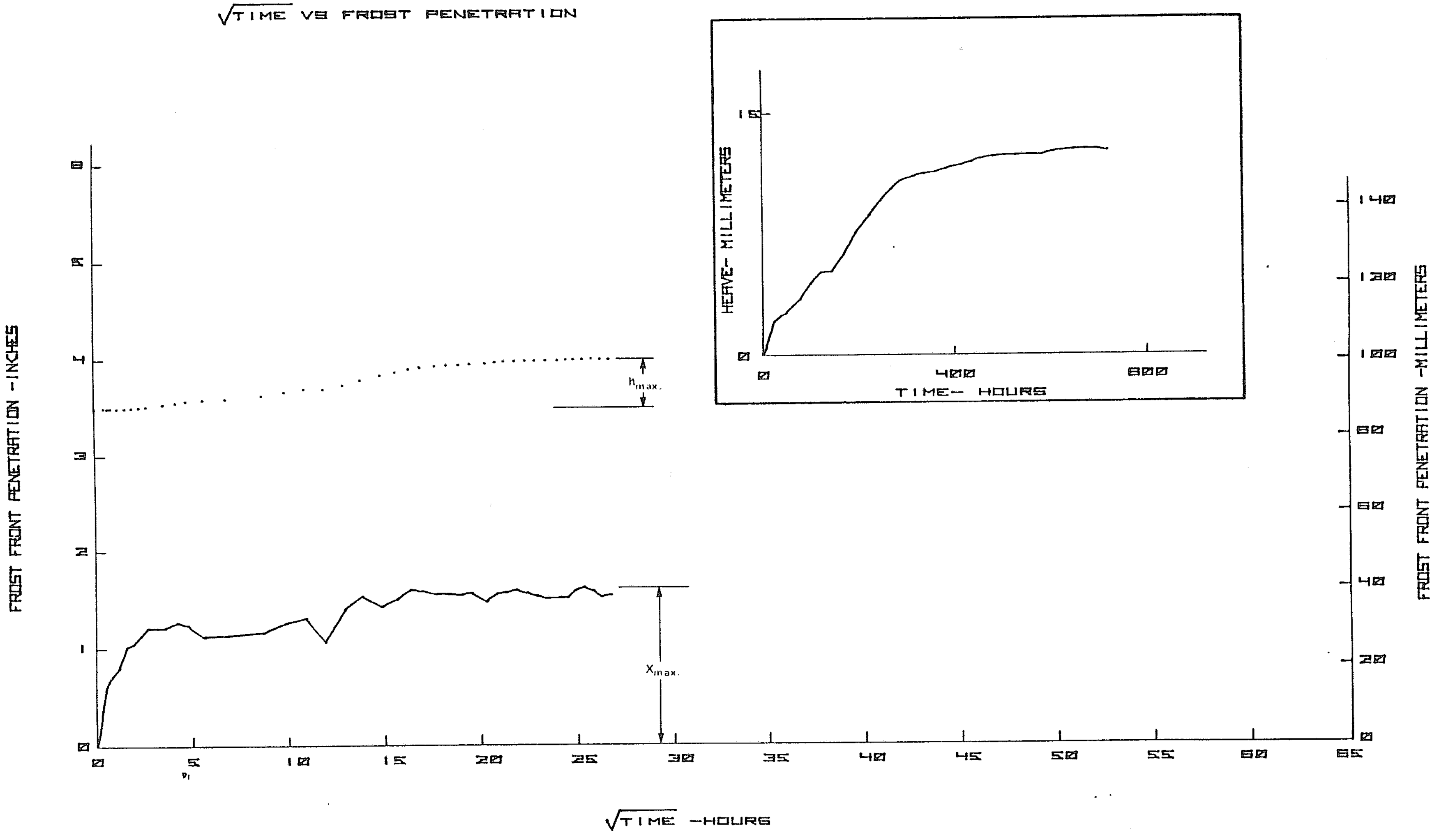


FIGURE A-7

FOOTHILLS FROST HEAVE

TEST NO. 11A
CELL NO. 1

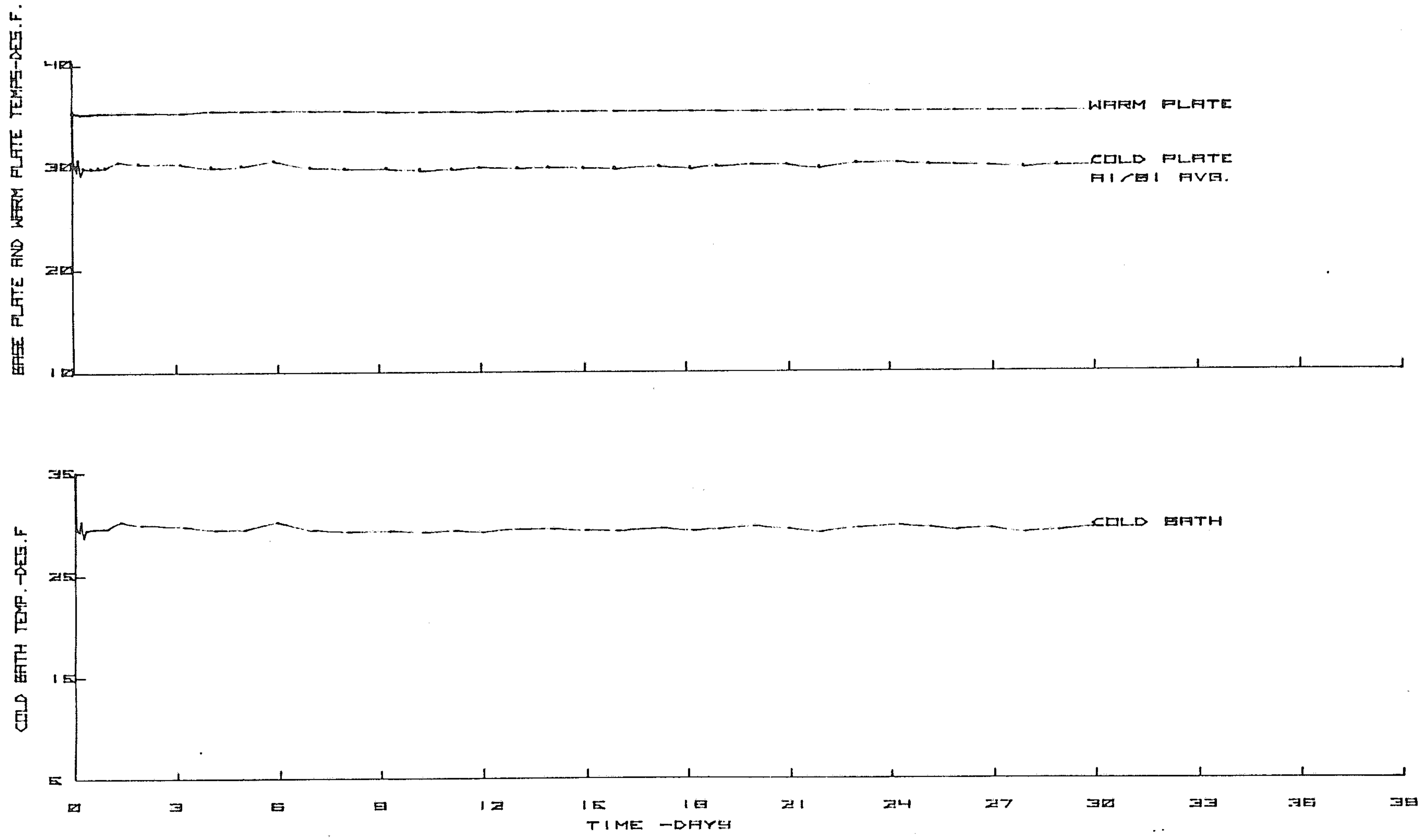


FIGURE A-8

FOOTHILLS FROST HEAVE

TEST NO. 11B
CELL NO. 1
$\sqrt{\text{TIME}}$ VS FROST PENETRATION

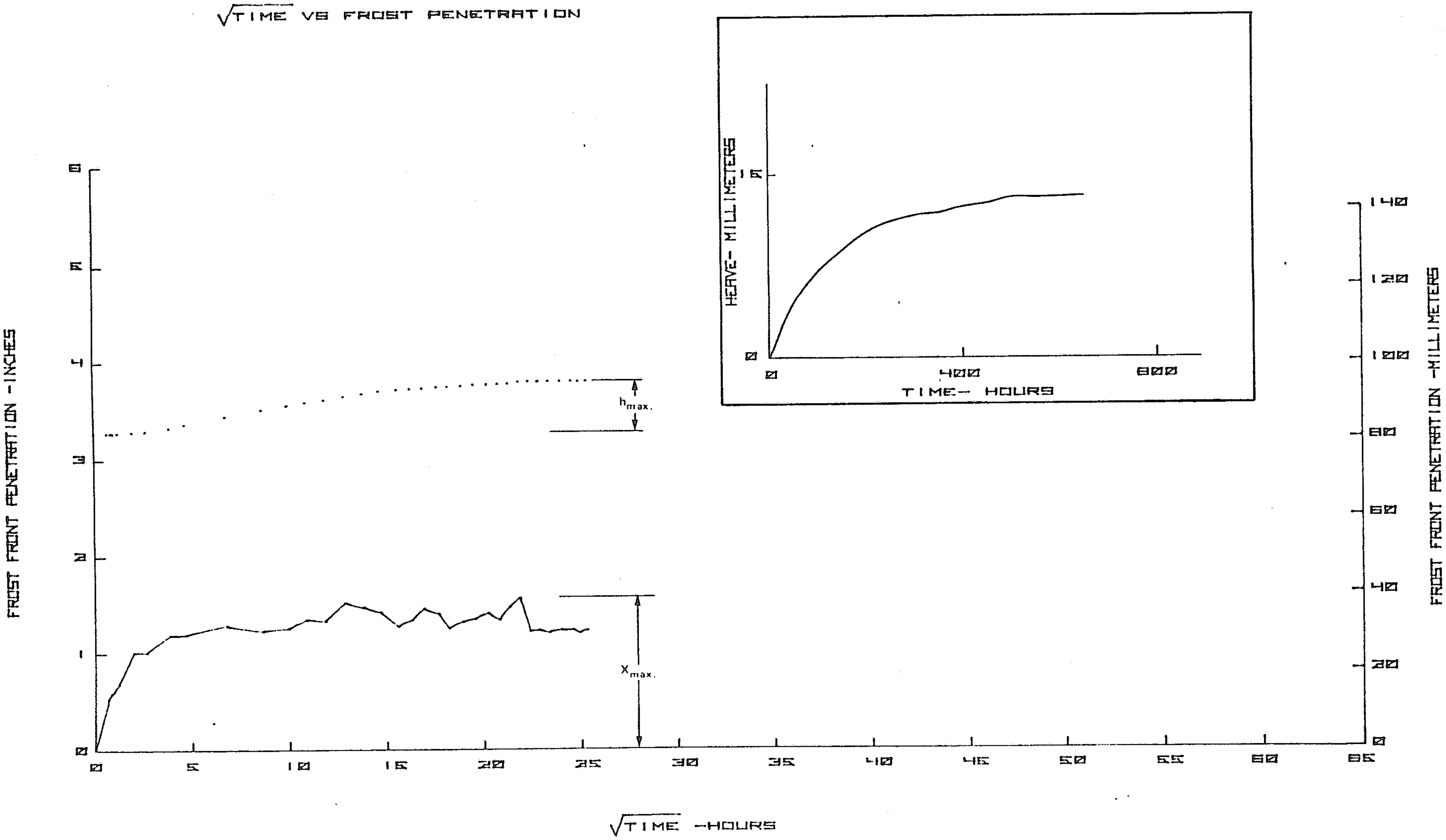


FIGURE A-9

FOOTHILLS FROST HEAVE

TEST NO. 11B

CELL NO. 1

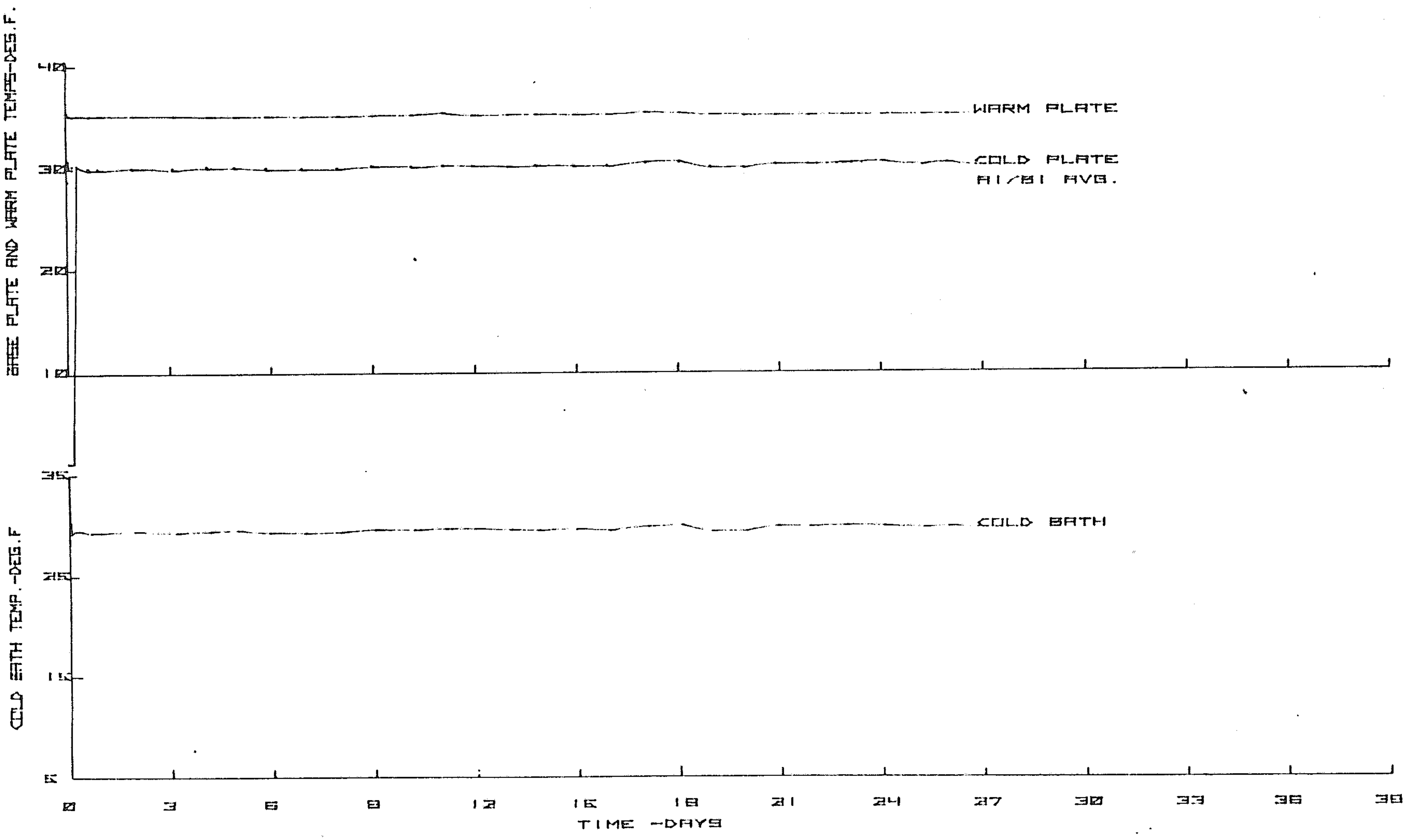


FIGURE A 10

FOOTHILLS FROST HEAVE

TEST NO. 12A
CELL NO. 2
$\sqrt{\text{TIME}}$ VS FROST PENETRATION

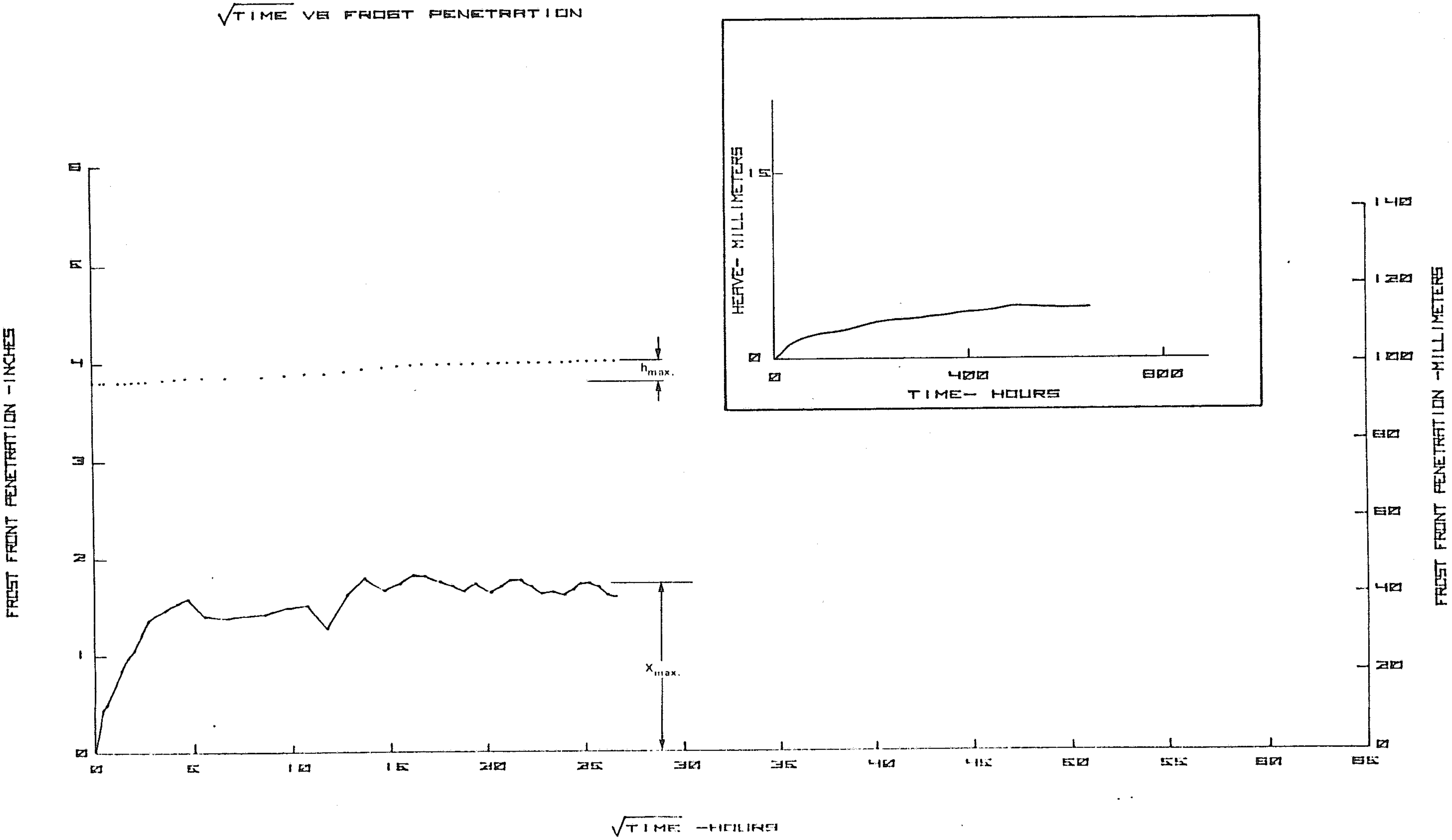


FIGURE A 11

FOOTHILLS FROST HEAVE

TEST NO. 12A

CELL NO. 2

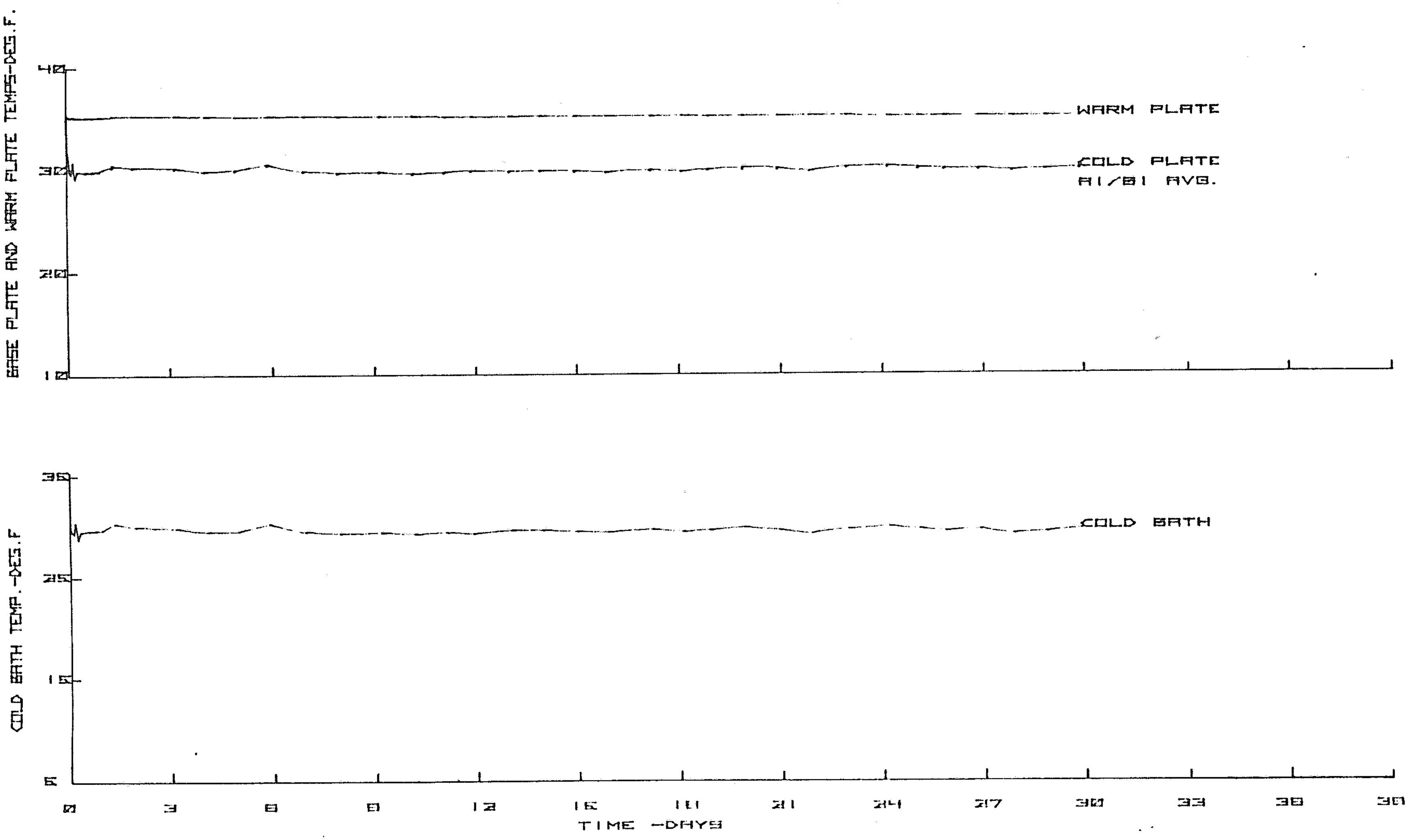


FIGURE A 12

FOOTHILLS FROST HEAVE

TEST NO. 128
CELL NO. 2
$\sqrt{\text{TIME}}$ VS FROST PENETRATION

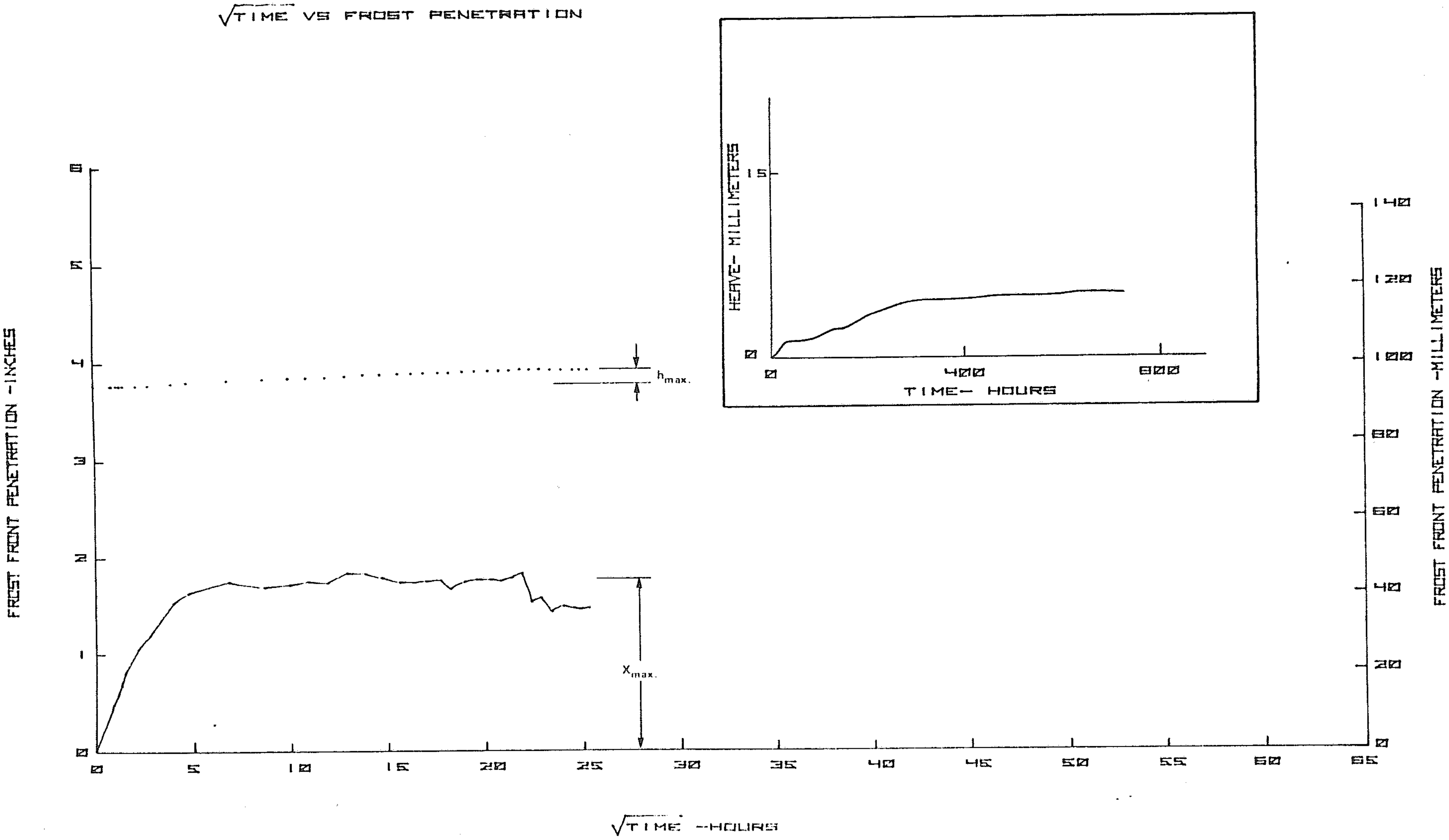
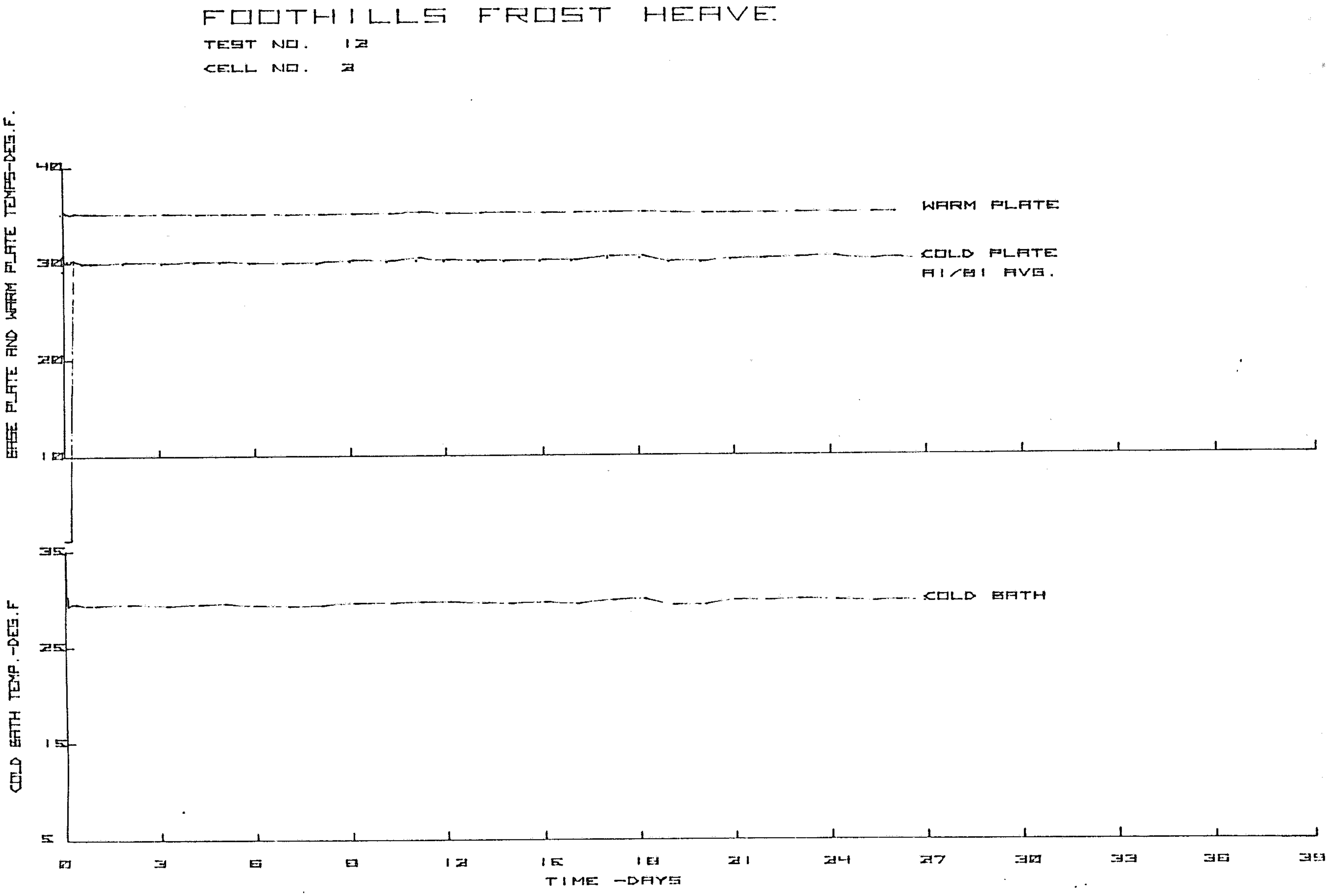


FIGURE A-13



FOOTHILLS FROST HEAVE

TEST NO. 12

CELL NO. 2

FIGURE A.14

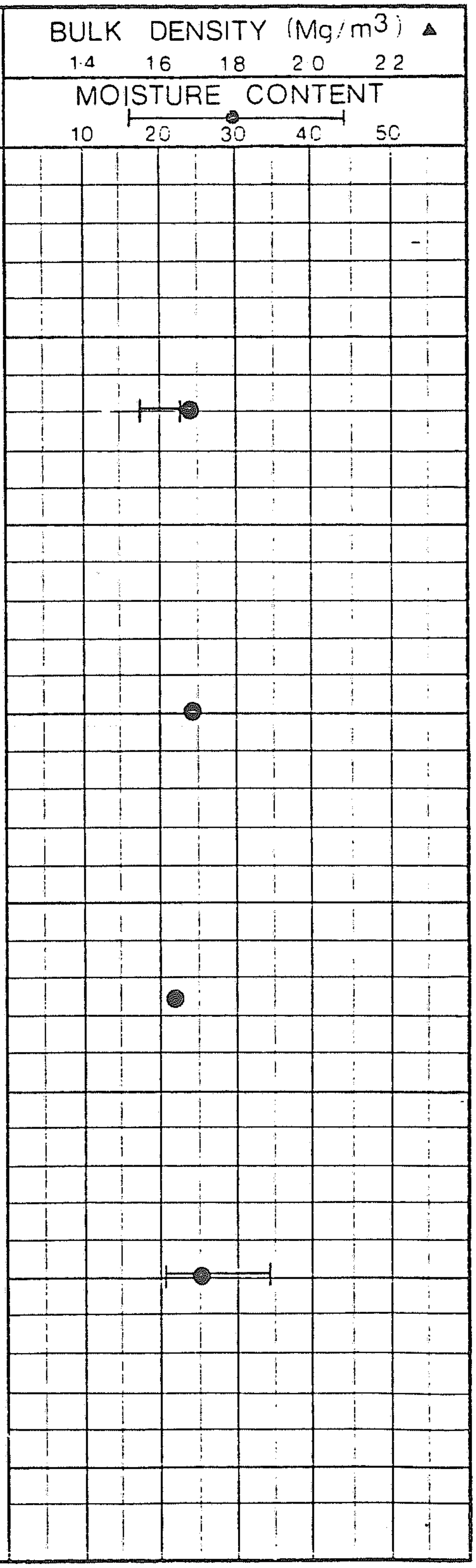
APPENDIX B

BOREHOLE LOGS AND LABORATORY TEST RESULTS

B.1 BOREHOLE LOG

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	CLAY & SILT (CL-ML) -some sand to sandy, unfrozen, grey, moist		UNFROZEN
(3.3') 1			
		G	
(6.6') 2			
(9.8') 3		G	
(13.1') 4	CLAY (CL) (TILL)-silty,some sand, trace of gravel, low plastic, moist, grey	G	UNFROZEN
(16.4') 5			
		G	
(19.7') 6			
(23.0') 7			



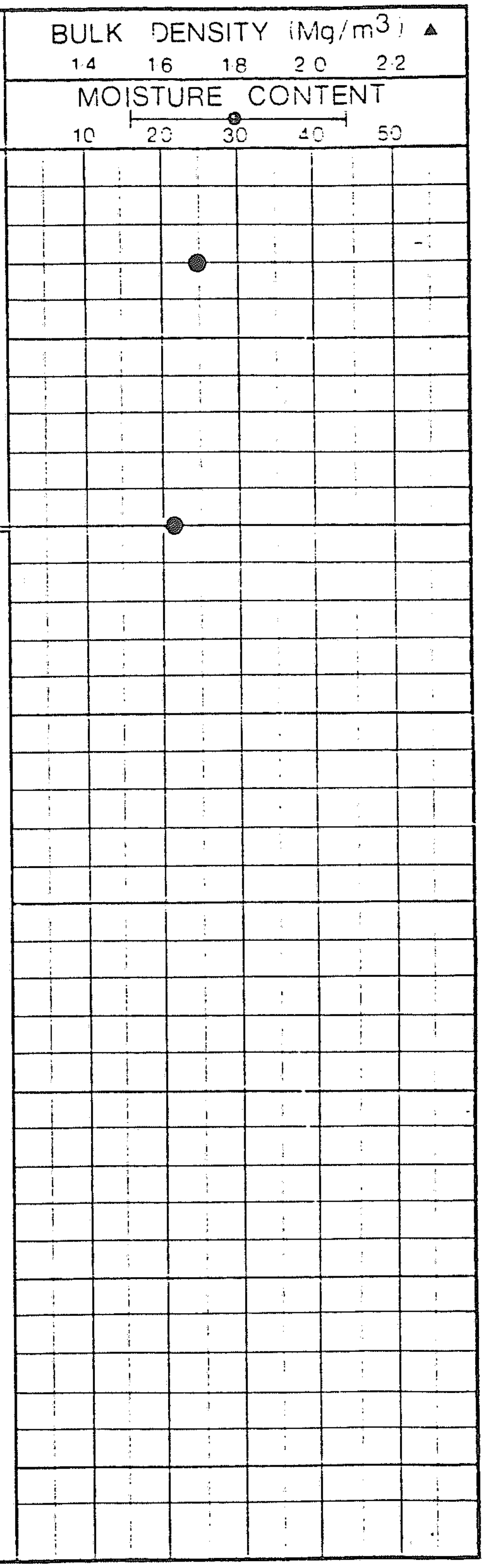
SFC ELEVATION (m)	DATE DRILLED 0/9/77
COMPLETION DEPTH (m) 9.0	LOGGED BY EMF
DRILLING RIG B40	LOCATION Frost Heave Site

BOREHOLE NO.
C-1

PAGE 1 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	CLAY (CL) (TILL) - as above	G	UNFROZEN
(26.2') 8			
(29.5') 9			
	END OF BOREHOLE		
10			
11			
12			
13			
14			

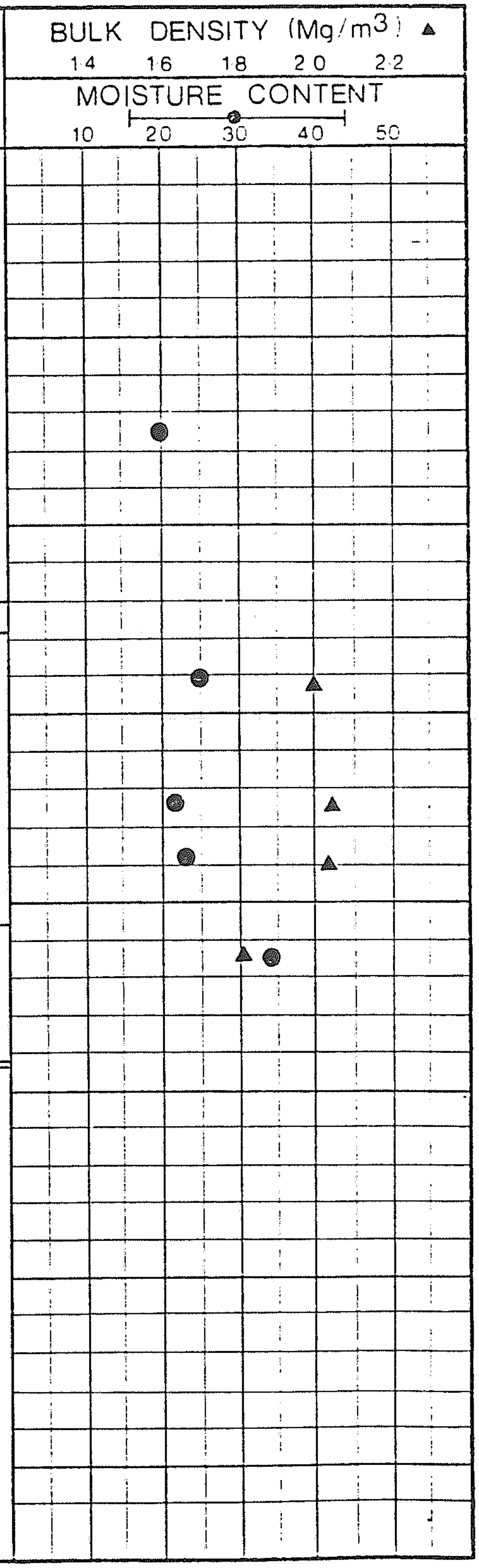


SFC ELEVATION m		DATE DRILLED	20/9/77
COMPLETION DEPTH (m)	9.0	LOGGED BY	EMF
DRILLING RIG	B40	LOCATION	Frost Heave Site

BOREHOLE NO.
C-1
PAGE 2 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	CLAY & SILT (CL-ML) -sandy, uniform, grey		UNFROZEN
(3.3') 1			
		G	
(6.6') 2			
		C	Nbn
		C	Vx + Vr 10%
(9.8') 3			
		C	
		C	
(13.1') 4			
		C	Vr 15%
(16.4') 5	END OF BOREHOLE		
6			
7			



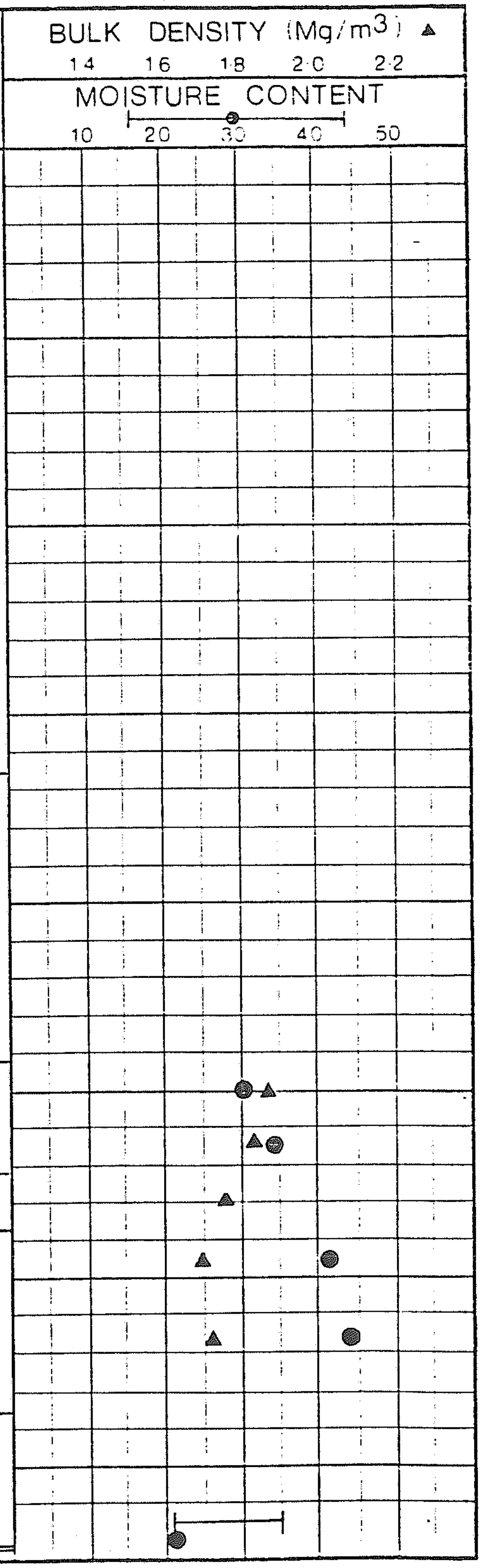
SFC. ELEVATION (m)		DATE DRILLED	26/9/77
COMPLETION DEPTH (m)	4.85	LOGGED BY	EMF
DRILLING RIG	B40	LOCATION	Frost Heave Site

BOREHOLE NO. C-2

PAGE 1 OF 1

BOREHOLE LOG

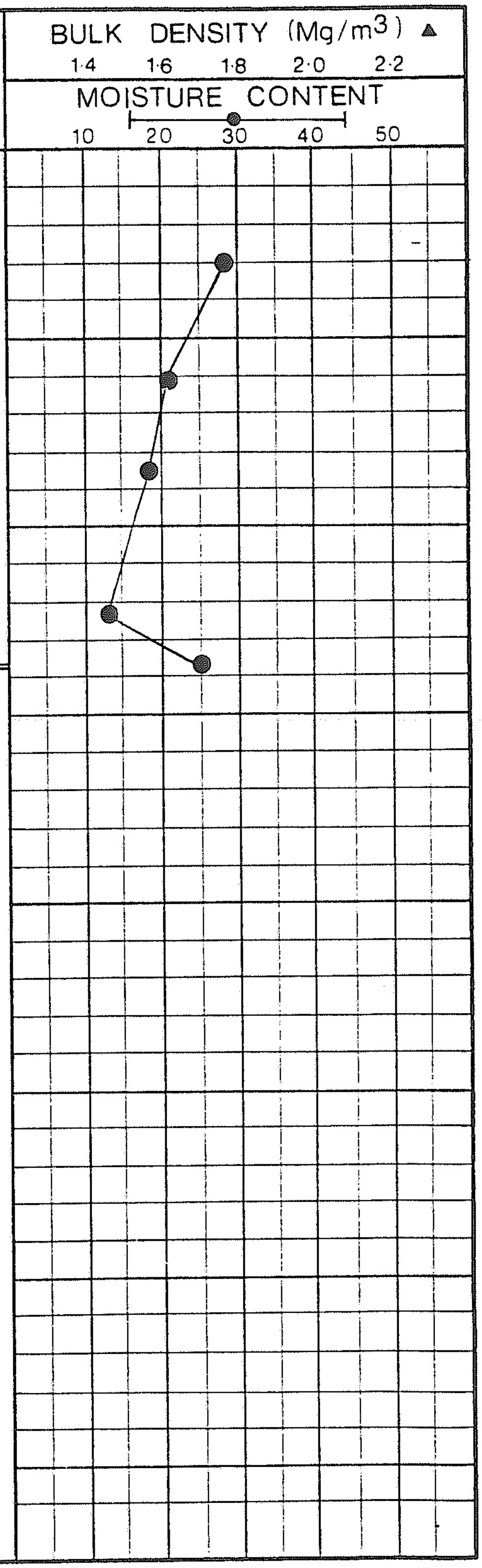
DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	CLAY & SILT (CL-ML)-sandy, uniform, grey, moist		UNFROZEN
(3.3') 1			
(6.6') 2			
(9.8') 3			
			FROZEN -poor recovery
(13.1') 4			
	CLAY (CL) (TILL)-silty, some sand, trace of gravel, low plastic, grey	C	Vs 20%
(16.4') 5		C	
		C	Vs 25%
(19.7') 6		C	Vs 30%
			Vs 35%
			UNFROZEN
(23.0') 7			
	END OF BOREHOLE	G	



SFC ELEVATION m	DATE DRILLED 26/9/77	BOREHOLE NO C-3
COMPLETION DEPTH (m) 7.5	LOGGED BY EMF	
DRILLING RIG B40	LOCATION Frost Heave Site	PAGE 1 OF 1

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-some clay, trace sand and gravel -moist		UNFROZEN
		G	
1	-trace to some fine sand, trace organics -dryer, feels cold	G	
		G	
	-hard drilling		FROZEN (Nf)
2	-very dry -poor recovery		
	-some clay to clayey, trace to some sand, trace gravel	G	
	-laminated organic layers	G	
3	END OF HOLE		
4			
5			
6			
7			



eba

SFC. ELEVATION (m)

DATE DRILLED 7/06/78

COMPLETION DEPTH (m) 2.75

LOGGED BY RJG

DRILLING RIG Arctic Auger

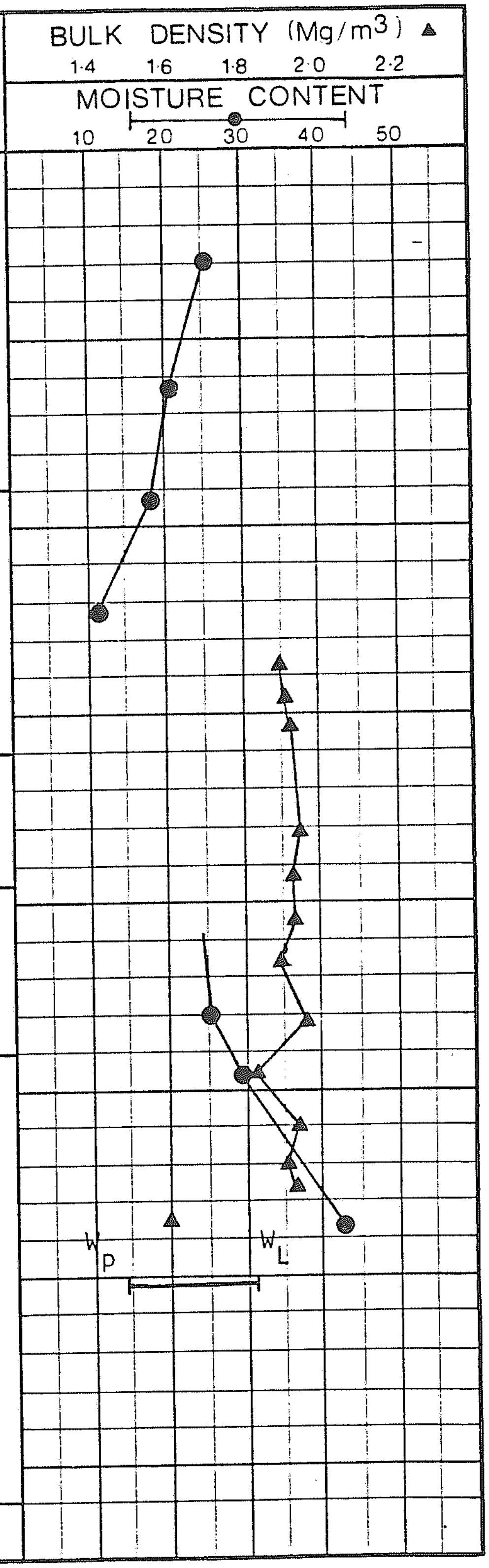
LOCATION W Side of Berm

BOREHOLE NO. R-1

PAGE 1 OF 1

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-some clay, trace sand and gravel -moist		UNFROZEN
		G	
1	-becomes sandier, fine sand -drier		
		G	
	-rock fragments	G	Nbn
2	-few frozen chips in moist silt		
	-some sand, trace clay	G	
3	-trace to some sand and clay	C	
		C	Vs - Vr 5%
		C	
4		C	Nbe - Nbn
		C	
		C	
	-clayey, trace fine sand	C	Vs - Vr 10%
5		C	Vr - Vs 5%
		C	
		C	
	SILT AND CLAY-trace fine sand	C	
6		C	
		C	
7			
			UNFROZEN

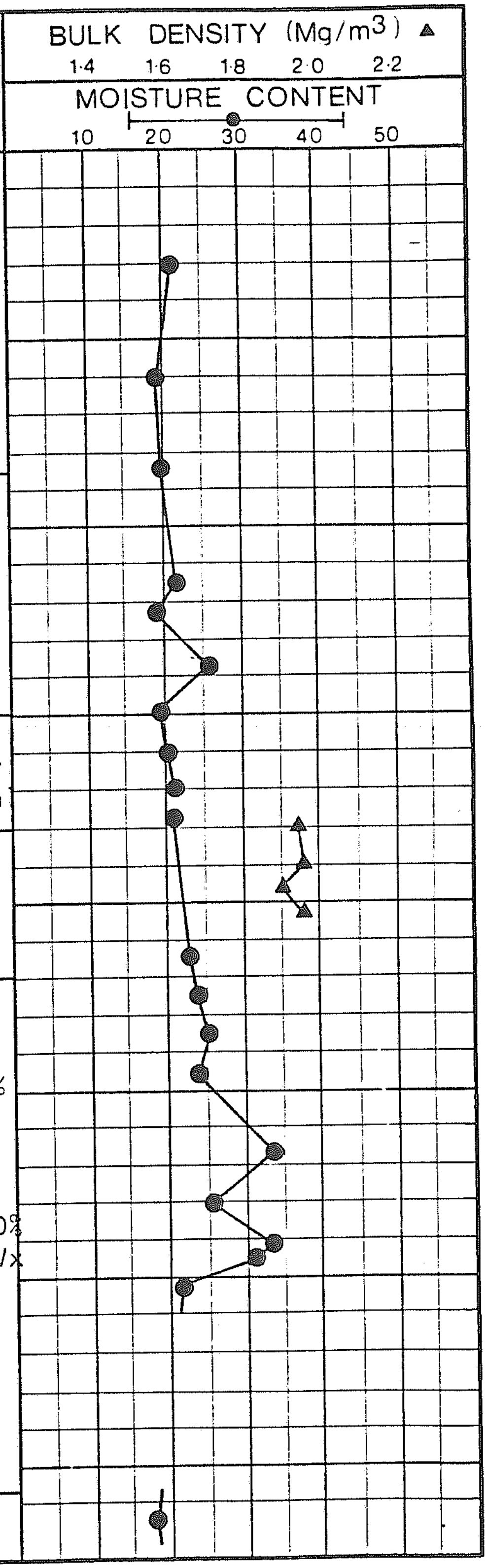


eba

SFC ELEVATION (m
COMPLETION DEPTH (m) 7.60
DRILLING RIG Arctic Auger
DATE DRILLED 8/06/78
LOGGED BY RJG
LOCATION W Side of Berm
BOREHOLE NO. R-1A
PAGE 1 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-trace to some sand and clay, trace gravel -top 0.3m moist, then much dryer	G	UNFROZEN
1	-cold	G	
	-moist		
		G	Nbn
2	-more sandy	G	Nbe
	-some sand, trace clay and organics	C C	
3		C C C C	Vs-Vr-Vx trace locally to 5%,vertica lens
	-some sand to sandy	C	Nbe - Nbn
4		C	
		C	Vx-Vr 5-10%
	-becoming clayey -numerous hairline ice lenses at top of section to lenses up to 3 mm thick at bottom	C C	Vs - Vr 15%
5		C	
	-clayey, trace sand -more ice, lenses 6-10 mm thick	C C C	Vr 20-25% locally to 30% occassional Vx to 3 mm
6		C C	Vs 25-35% lenses to 1 cm
7			UNFROZEN



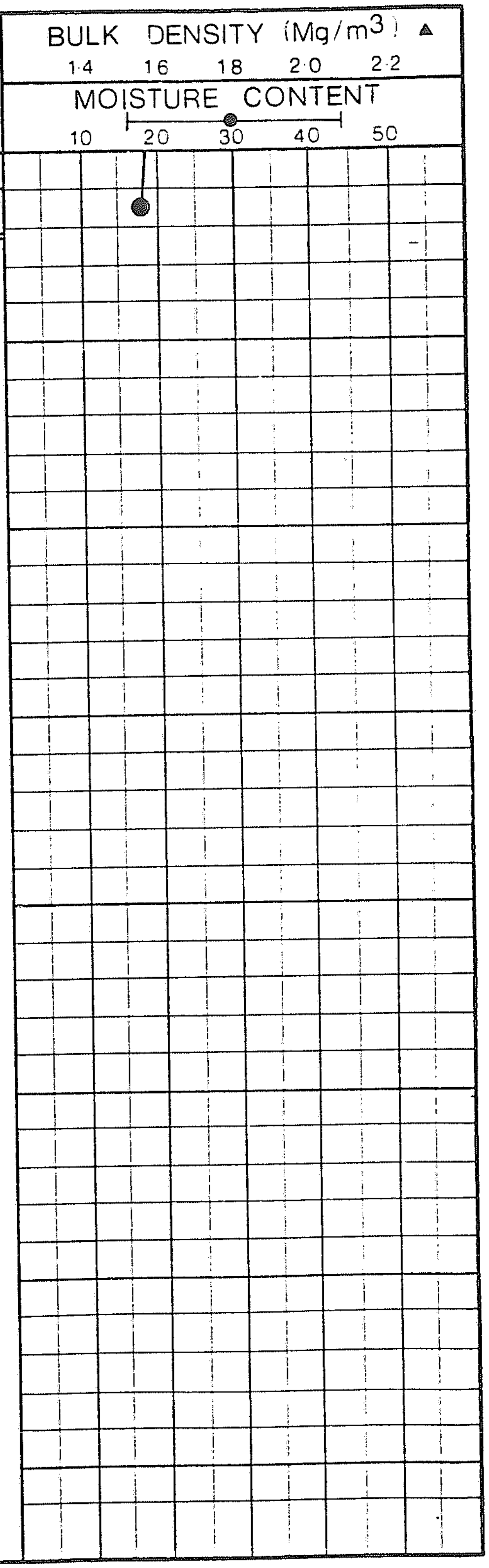
SFC ELEVATION (m)	DATE DRILLED 8/06/78
COMPLETION DEPTH (m) 7.45	LOGGED BY RJG
DRILLING RIG Artic Auger	LOCATION W Side of Berm

BOREHOLE NO. R-2

PAGE 1 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT AS ABOVE		
	CLAY (TILL)-silty,trace sand, some sub-ang.-round gravel to 3/4", poor recovery	G	UNFROZEN
8	END OF HOLE		
9			
10			
11			
12			
13			
14			

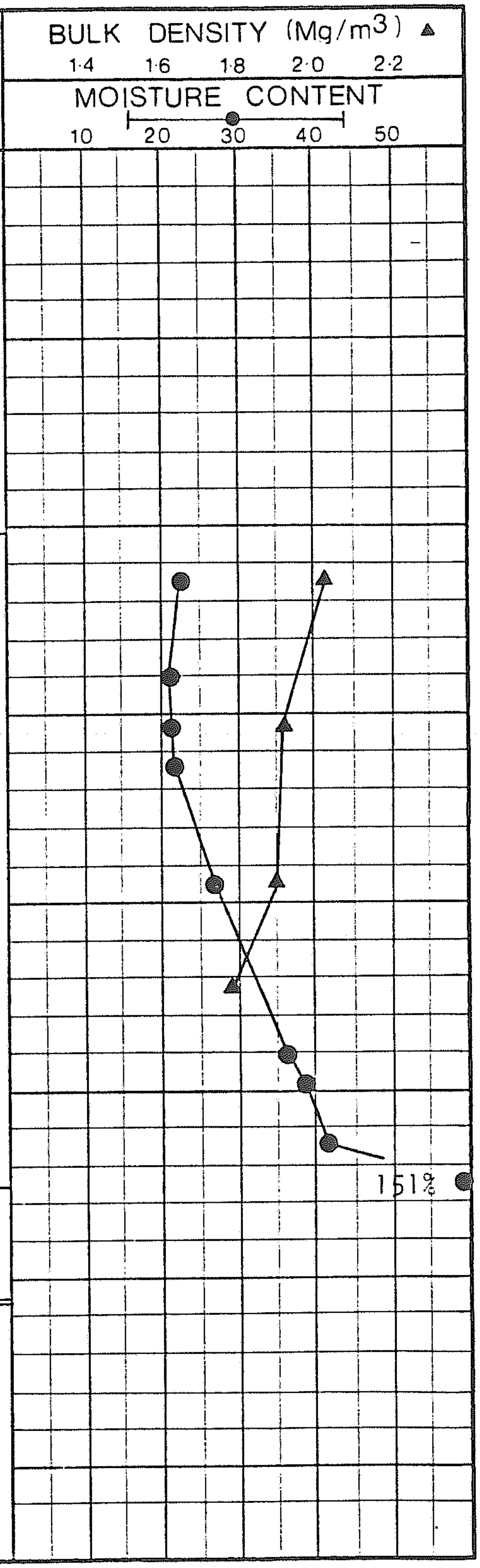


eba

SFC ELEVATION (m)	DATE DRILLED 8/06/78	BOREHOLE NO. R-2
COMPLETION DEPTH (m) 7.45	LOGGED BY RJG	
DRILLING RIG Arctic Auger	LOCATION E Side of Berm	PAGE 2 OF 2

BOREHOLE LOG

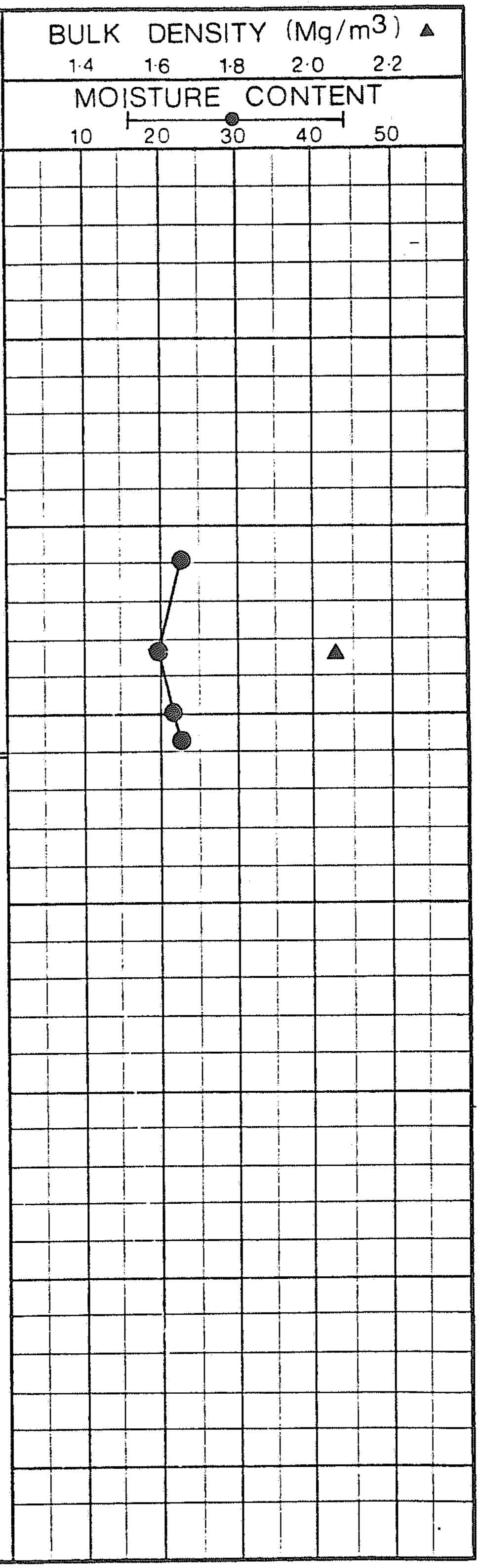
DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-light to medium brown, very sandy (fine grained), non plastic	G	NOT FROZEN
1	-trace of clay	G	
	-moister, colder	G	
2	-some sandy silt with some greyish and blonde colour bands	C C	Nbn to Vs < 5% Nbn to Vs < 3%
3	-some sand, non plastic	C C C	Nbn to Vs < 5%
		C	Vs 15-20%
4		C	Vs 10%
	-slight clayier, trace of sand	C C	Vs 10-12% Vs 30% 3 mm layers
	-clayey silt, medium to light brown, low to medium plastic	C C	Vs 30%, ice up to 25 mm
5		C	30-35% ice ice broken by drilling
	-brownish grey, firm to stiff	G	NOT FROZEN
6	END OF HOLE		
7			



SFC ELEVATION m	DATE DRILLED 14/07/78	BOREHOLE NO. G-1
COMPLETION DEPTH (m) 6.1	LOGGED BY CAG	
DRILLING RIG B40L	LOCATION CALGARY	PAGE 1 OF 1

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-medium to light brown, some fine sand, trace of to no clay		NOT FROZEN
		G	
1			
		G	
	-sandy (fine grained)		
		G	
2		C	Nbn
		C	Nbn
3	-coarse rounded gravel	C	Vr 2%
	END OF HOLE		
4			
5			
6			
7			



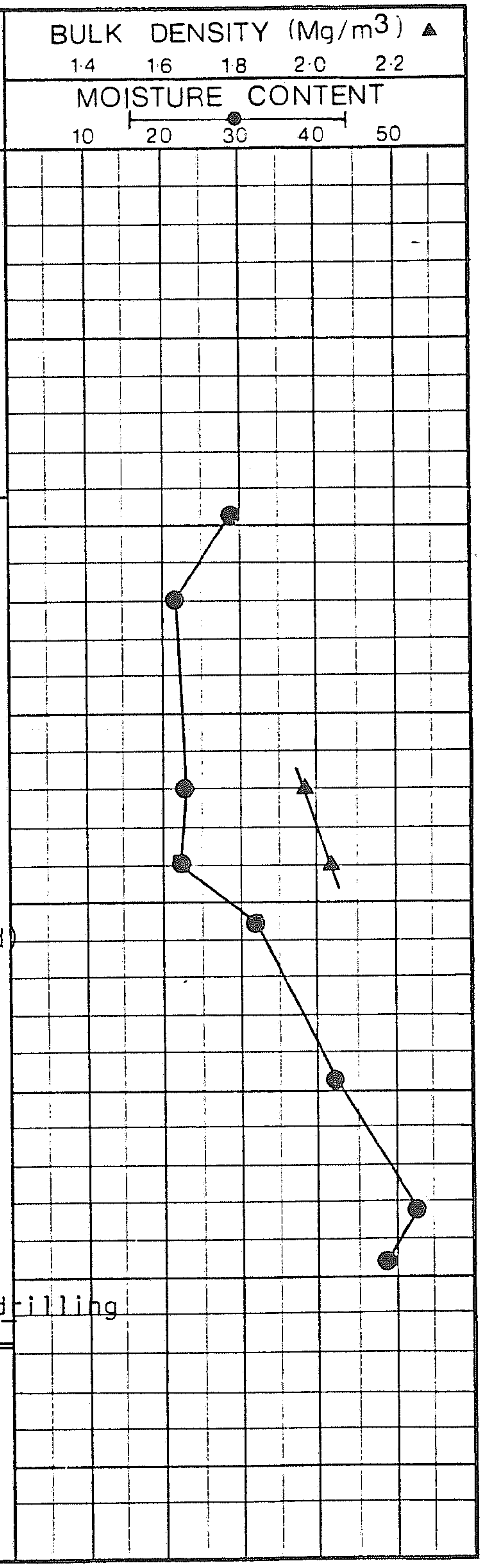
SFC ELEVATION (m)	DATE DRILLED 15/07/78
COMPLETION DEPTH (m) 3.2	LOGGED BY CAG
DRILLING RIG B40L	LOCATION Calgary

BOREHOLE NO. G-2

PAGE 1 OF 1

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-medium to light brown, some fine sand, non plastic		NOT FROZEN
1			
2	-lighter brown, some fine sand	C	Nbn
			Vs 15%
		C	Vs 10-15% (1 - 3 mm)
	-decreasing sand content, trace of clay		
			Vs 5-10%
3		C	
			Vs < 5%
		C	
			Vs 5%
4		C	Vs 10%
		C	15% (crushed)
		C	Vs 10-15%
			Vs 15-20%
		C	
5	-some clay to clayey, low plastic	C	Vs 35%
		C	Vs 30% at 5 m (3-6 mm) to 35% at 5.5 m
		C	Vs 35-40% (to 12 mm)
6		C	40% crushed on drilling
	-clayey	G	NOT FROZEN
	END OF HOLE		
7			



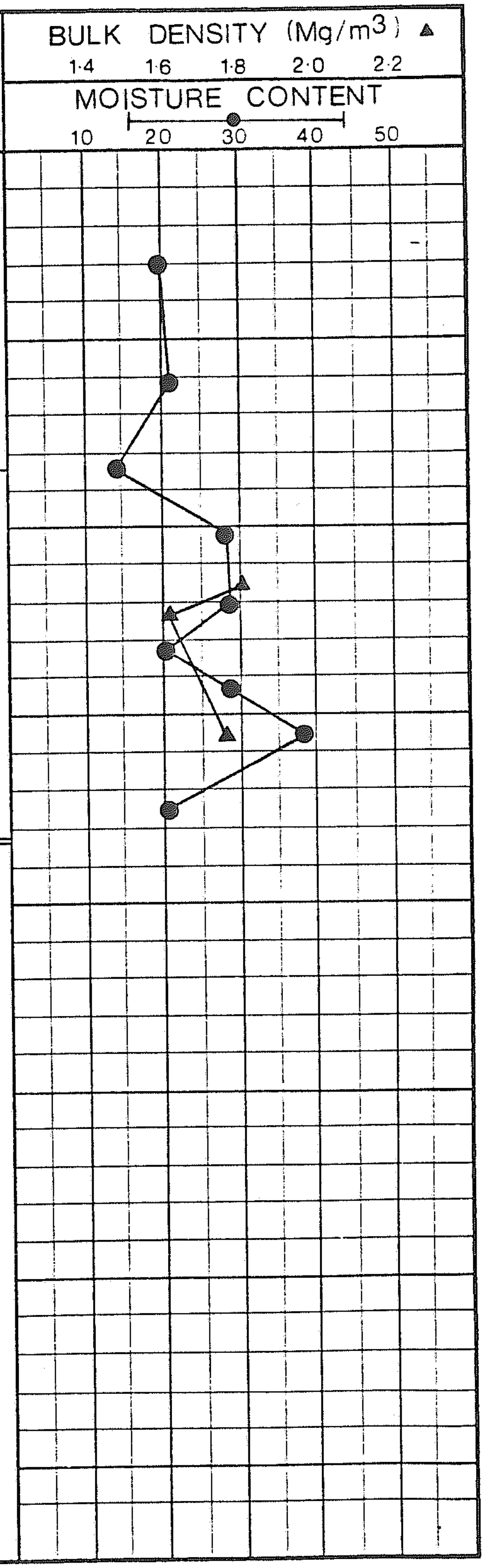
SFC ELEVATION (m)		DATE DRILLED	15/07/78
COMPLETION DEPTH (m)	6.34	LOGGED BY	CAG
DRILLING RIG	B40L	LOCATION	Calgary

BOREHOLE NO.
G2A

PAGE 1 OF 1

BOREHOLE LOG

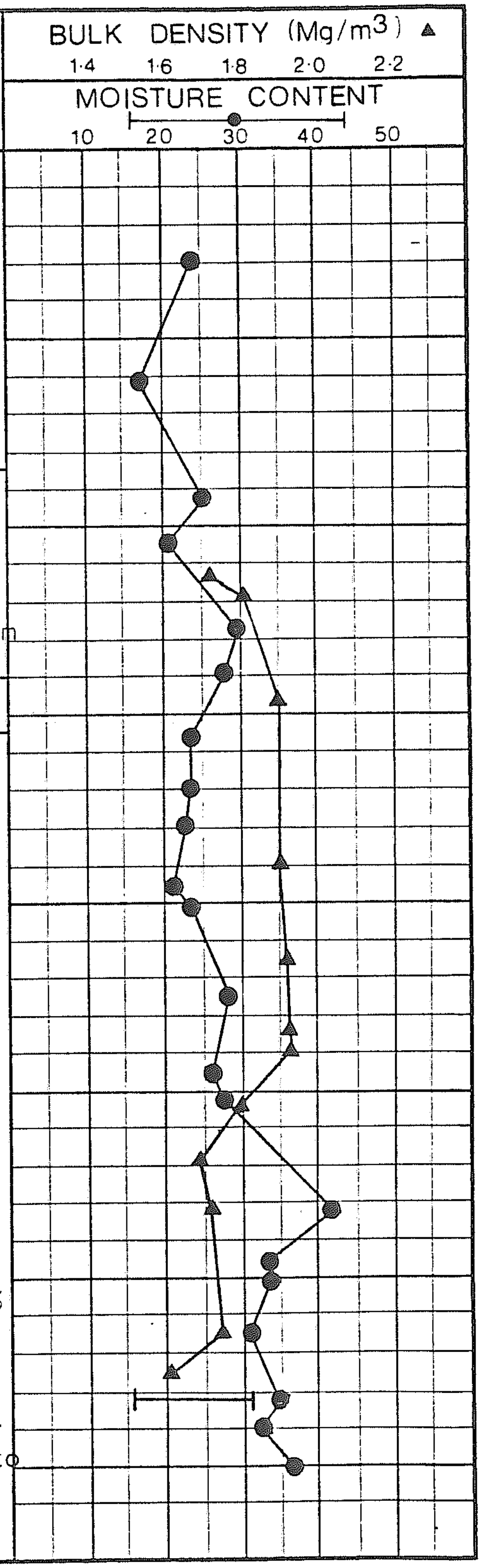
DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-some clay, trace to some sand, trace gravel -top 0.3 metres, moist, drier below	G	UNFROZEN
1	-more sandy, cold	G	
	-very hard drilling	G	
2	-some clay to clayey, trace to some sand	C	Vr-Vx 10-15%
	-trace fine sand	C	Vx-Vr Trace to 5%
		C	
		C	
3	-clayey	C	Vx-Vr 10%
	-core partially melted during extraction	C	
4	END OF HOLE Note: Hit Pipe.		
5			
6			
7			



SFC ELEVATION (m)	DATE DRILLED 8&9/06/78	BOREHOLE NO. D-1
COMPLETION DEPTH (m) 3.65	LOGGED BY RJG	PAGE 1 OF 1
DRILLING RIG Arctic Auger	LOCATION W Side of Berm	

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-clayey, trace of sand and gravel, trace organics -few subangular to subrounded pebbles to about 10 mm		UNFROZEN
		G	
1	-med. to dark brown -moist near surface -more sandy, drier	G	
	-some clay to clayey, trace to some sand	C	Vx-Vr 5-10%
2		C	
	-trace organics	C	Vs-Vr-Vx 10% lenses 2-3 mm thick
		C	
	-stratified silty fine sand, thin silt laminae, trace clay		Nbe
3		C	
		C	Vx trace
	-some sand and clay	C	Vr-Vx 5%
	-stratified silty sand	C	Vx Trace
	-silty clay, some fine sand (lens), trace gravel, shattered shale fragments to 10 mm	C	Vr-Vx 5-10%
4		C	Vs-Vx 5% Vs-Vx trace
	-very sandy, trace of clay	C	
		C	
		C	
5		C	
		C	Vs-Vx 5% Vs-10-20%
		C	8 mm lens Vs 25-30%
6	CLAY (TILL)-silty, trace sand and gravel, angular pebbles	C	Vs-Vx 20-30%
		C	
		C	Vs 25-30%
	-some gravel, light to med. brown, trace iron oxides	C	Vs-Vx-Vr 20-30% lenses to 12 mm
7		C	



SFC ELEVATION (m)

DATE DRILLED 9/06/78

COMPLETION DEPTH (m) 7.40

LOGGED BY RJG

DRILLING RIG Arctic Auger

LOCATION W Side of Berm

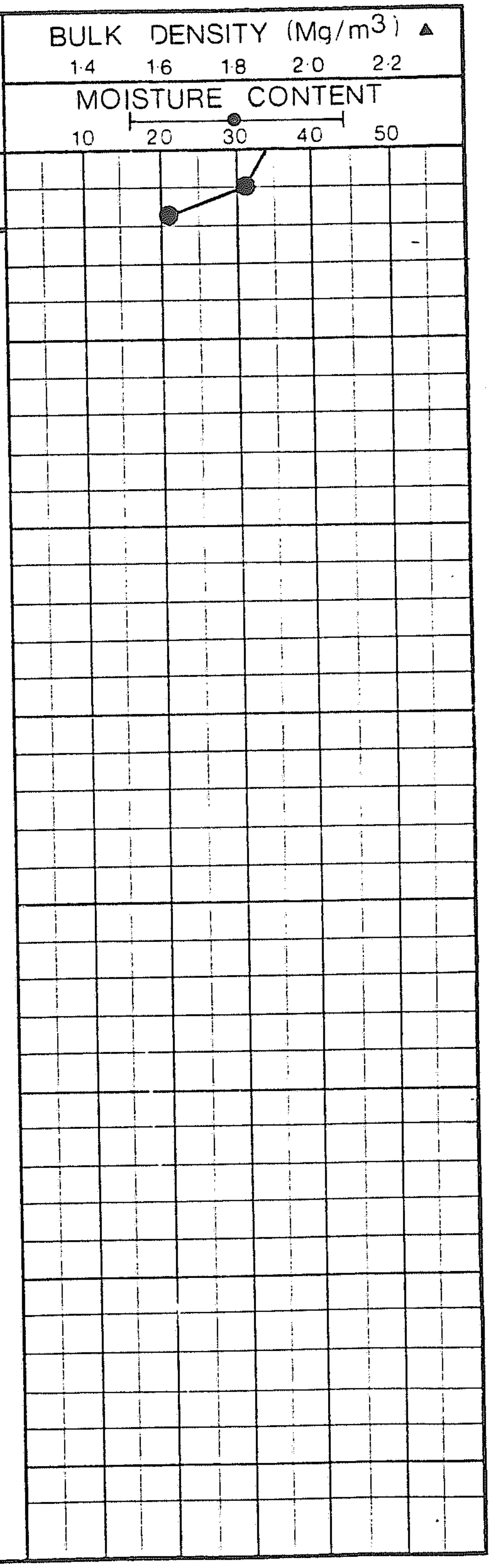
eba

BOREHOLE NO. D-1A

PAGE 1 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	CLAY (TILL)-silty, some gravel, trace sand, low plastic	C C	Vx-Vr-Vs 20-30%(partially melted)
	END OF HOLE Refusal on Rock		
8			
9			
10			
11			
12			
13			
14			



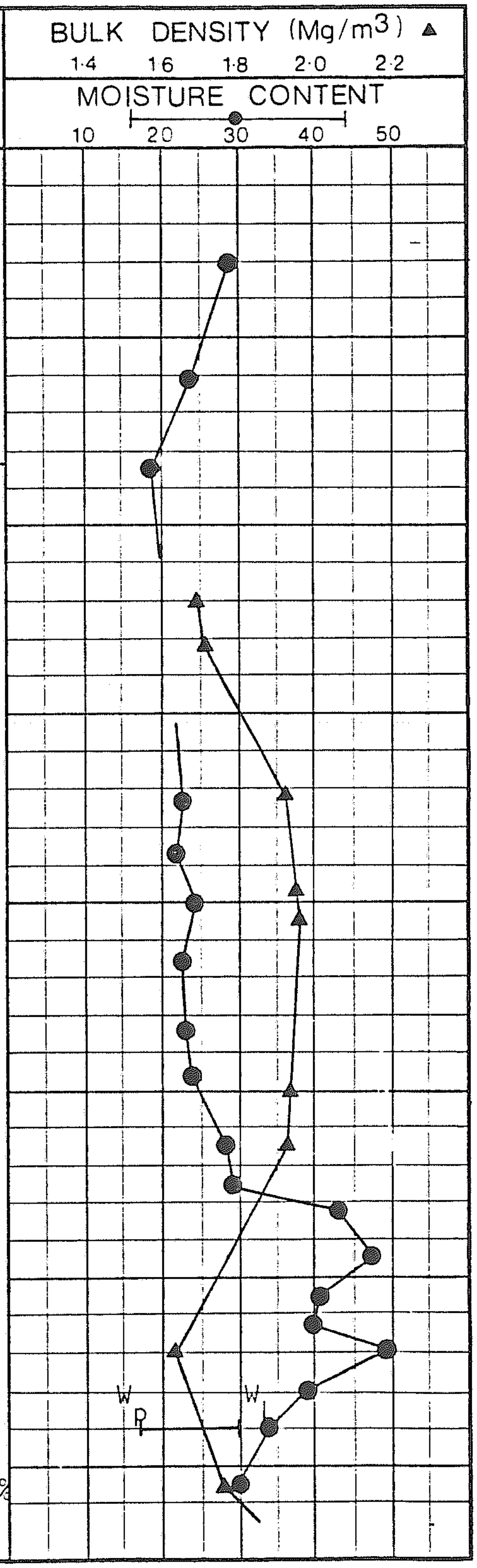
SFC ELEVATION (m)		DATE DRILLED	9/06/78
COMPLETION DEPTH (m)	7.40	LOGGED BY	RJG
DRILLING RIG	Artic Auger	LOCATION	W Side of Berm

BOREHOLE NO. D-1A

PAGE 2 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-clayey, trace sand and gravel, trace organics -subangular to subrounded pebbles, to 18 mm diameter	G	UNFROZEN
1	-some sand, drier	G	
		G	
	-hard drilling, dry, very cold		Vs-Vx 5%
2		C C C	
	-some sand		Vr 5% lenses less than 1 mm
3	-sandy, stratified fine sand, silt lenses	C	
	-more silty, colder	C	Vx trace in sand
	-trace to some clay and sand	C	
	-becoming clayey		Vr-Vx trace to 5%
	-clayey, trace to some sand stratified	C	
4		C	Vr 5%
		C	Vs-Vr trace to 5%
	-clayey to some clay, trace (to some) sand	C	
5			Vc trace
	-trace gravel, sub-rounded, to 18 mm diameter	C	Vs 10-15%
	-clayey, trace fine sand (core partially melted)	C C C	Vs 20-25%
6		C	
			Vs 25-30%
	-melts quickly	C C	
		C	Vs 35%
		C	Vs 30-35 %
7		C	Vs-Vr 25-30 %



eba

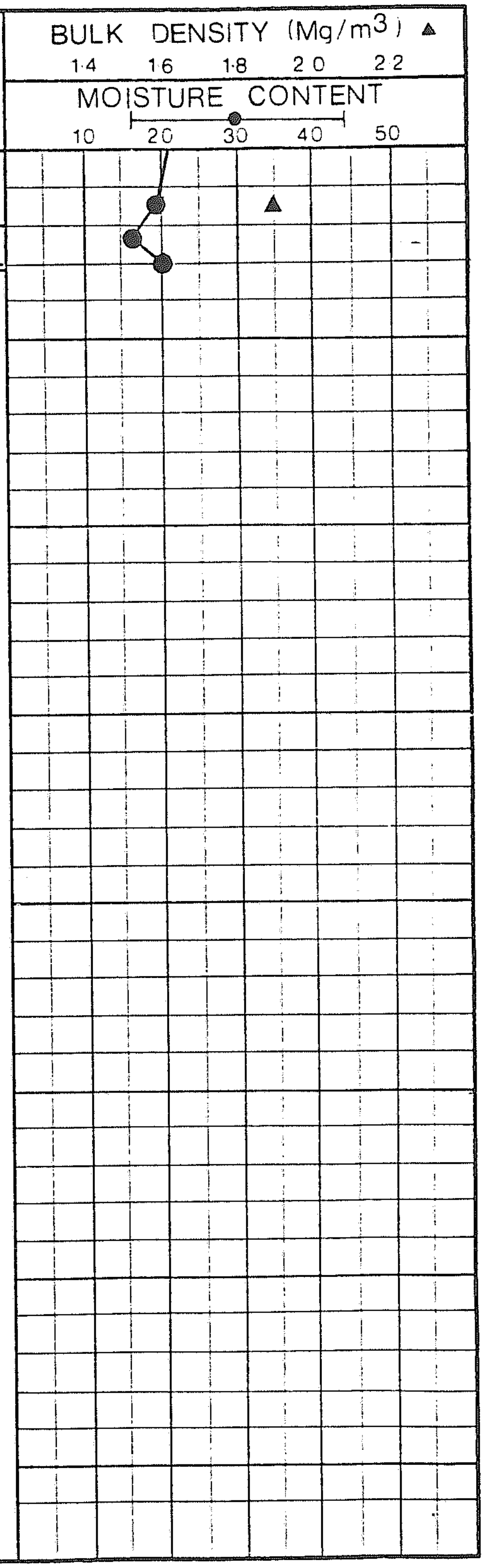
SFC ELEVATION (m)	DATE DRILLED 9/06/78
COMPLETION DEPTH (m) 7.65	LOGGED BY RJG
DRILLING RIG Arctic Auger	LOCATION E Side of Berm

BOREHOLE NO. D-2

PAGE 1 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-as above		
	CLAY AND SILT (TILL)-to silty, trace to some sand, some subrounded to angular gravel	C G	Vx-Vr 20% UNFROZEN
8	END OF HOLE		
9			
10			
11			
12			
13			
14			



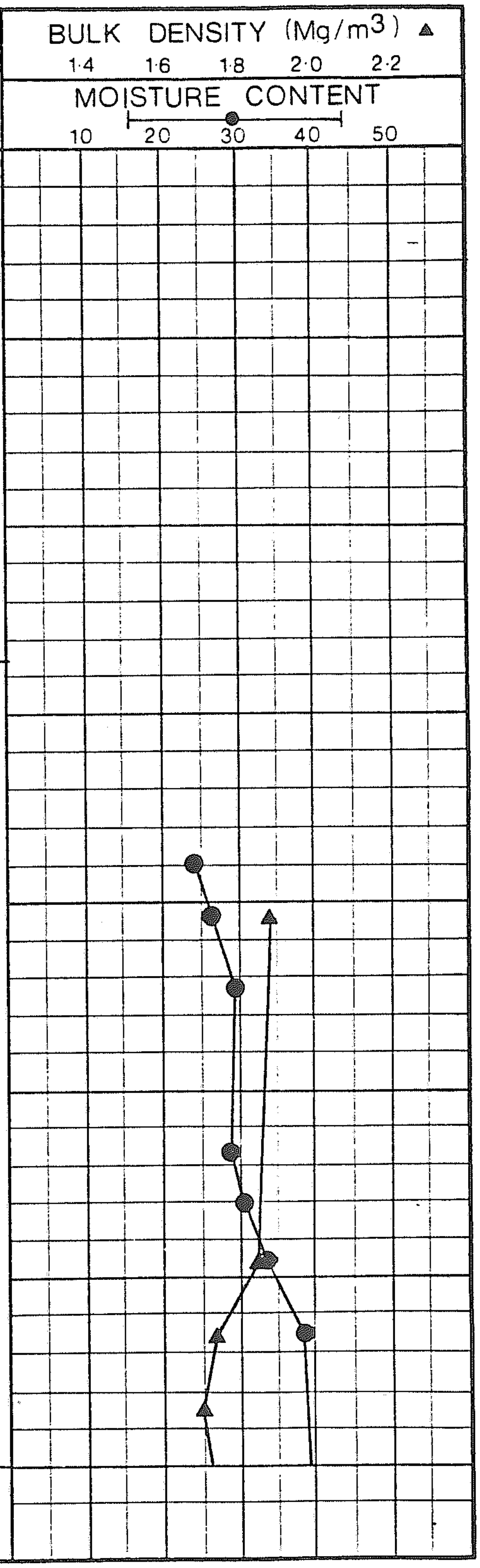
SFC ELEVATION m		DATE DRILLED	9/06/78
COMPLETION DEPTH (m)	7.65	LOGGED BY	RJG
DRILLING RIG	Arctic Auger	LOCATION	E Side of Berm

BOREHOLE NO. D-2

PAGE 2 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-grey-brown, some fine sand, non to very low plastic		NOT FROZEN
		G	
1	(fill) (natural)	G	
	-moister, colder	G	
2		G	
	-medium to light brown, some fine sand, low plastic		Vs 10-15%
3	-very sandy (fine grained)	C	
		C	Vs-Vr 5%
4	-medium brown, very sandy in layers	C	Nbn
	-some yellow organics	C	
	-light to medium brown, trace of clay, trace of to no sand		Vs 15-25%
5		C	Vs 8-10%
		C	Vs < 5%
		C	Vs 25%
6	-some clay, softer, frozen, some light brown sandy pockets, low plastic		Vs 10-15% Vs 25-30% Vs 30%
		C	
		C	Vs 25% Vs 30-35%
7	(continued)	C	



eba

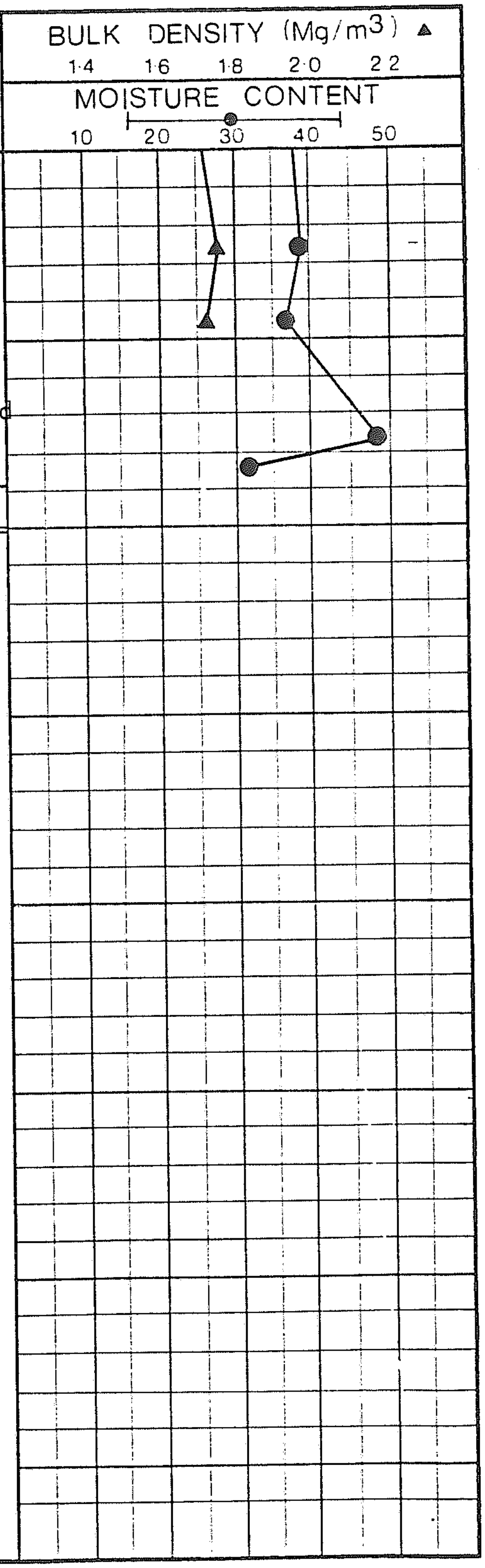
SFC ELEVATION (m)	DATE DRILLED 14/07/78
COMPLETION DEPTH (m) 8.96	LOGGED BY CAG
DRILLING RIG B40L	LOCATION Calgary

BOREHOLE NO. D-3

PAGE 1 OF 2

BOREHOLE LOG

DEPTH (metres)	SOIL DESCRIPTION	SAMPLE	GROUND ICE DESCRIPTION
	SILT-light to medium brown, some clay, some light brown fine sandy pockets	C	Vs 30-35%
		C	Vs 25% to Vs 35%
	-clayey silt to silty clay, medium brown, low plastic	C	Vs 30-35%
8		C	Vs 40% ≈ 40% crushed 35-40%
		G	30%
			NOT FROZEN
9	END OF HOLE		
10			
11			
12			
13			
14			



SFC ELEVATION (m)		DATE DRILLED	14/07/78
COMPLETION DEPTH (m)	8.96	LOGGED BY	CAG
DRILLING RIG	B40L	LOCATION	Calgary

BOREHOLE NO. D-3

PAGE 2 OF 2

B.2 GRAIN SIZE DISTRIBUTION

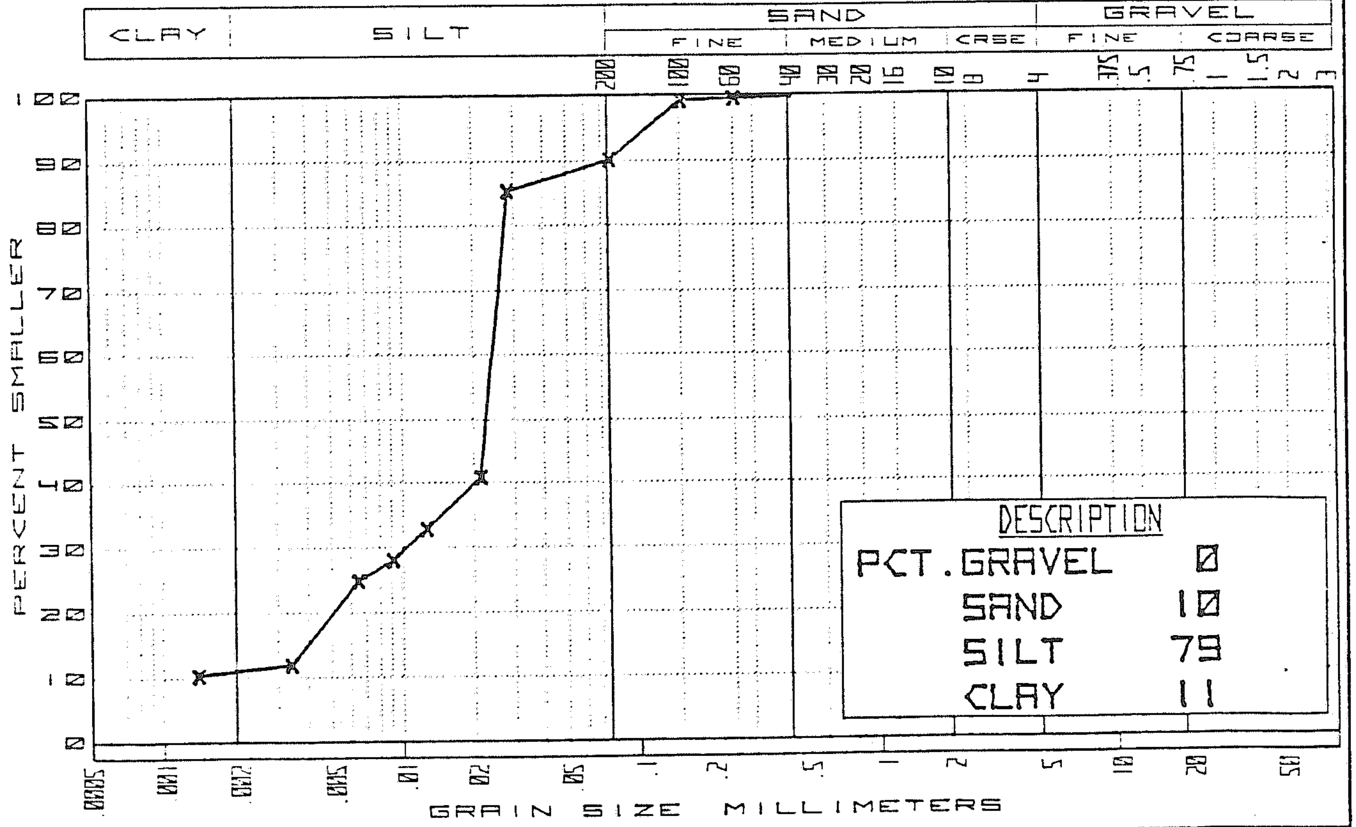
GRAIN SIZE DISTRIBUTION

PROJECT Calgary Frost Heave Test Facility, CAGPL
ADDRESS Calgary, Alberta
JOB NO. 16-1975
DATE TESTED BY
CLIENT
Foothills Pipe Lines Ltd.
ATTENTION

SIEVE	PCT SMALLER
3	
2	
1.5	
1	
.75	
.5	
.375	
4	
8 10	
16 20	
30 40	
50 60	
100	
200	

REVIEWED BY P.ENG.

JOB NO. 16-1975 SITE BH C-2
DATE 28-10-77 BASELINE STATION OFFSET DEPTH 14.0-16.5



DESCRIPTION

PCT. GRAVEL	0
SAND	10
SILT	79
CLAY	11

All tests performed in accordance with ASTM & CSA standards.

GRAIN SIZE DISTRIBUTION

PROJECT Calgary Frost Heave Test Facility, CAGPL

ADDRESS Calgary, Alberta

JOB NO. 16-1975

DATE TESTED ______ BY ______

CLIENT ______

Foothills Pipe Lines Ltd.

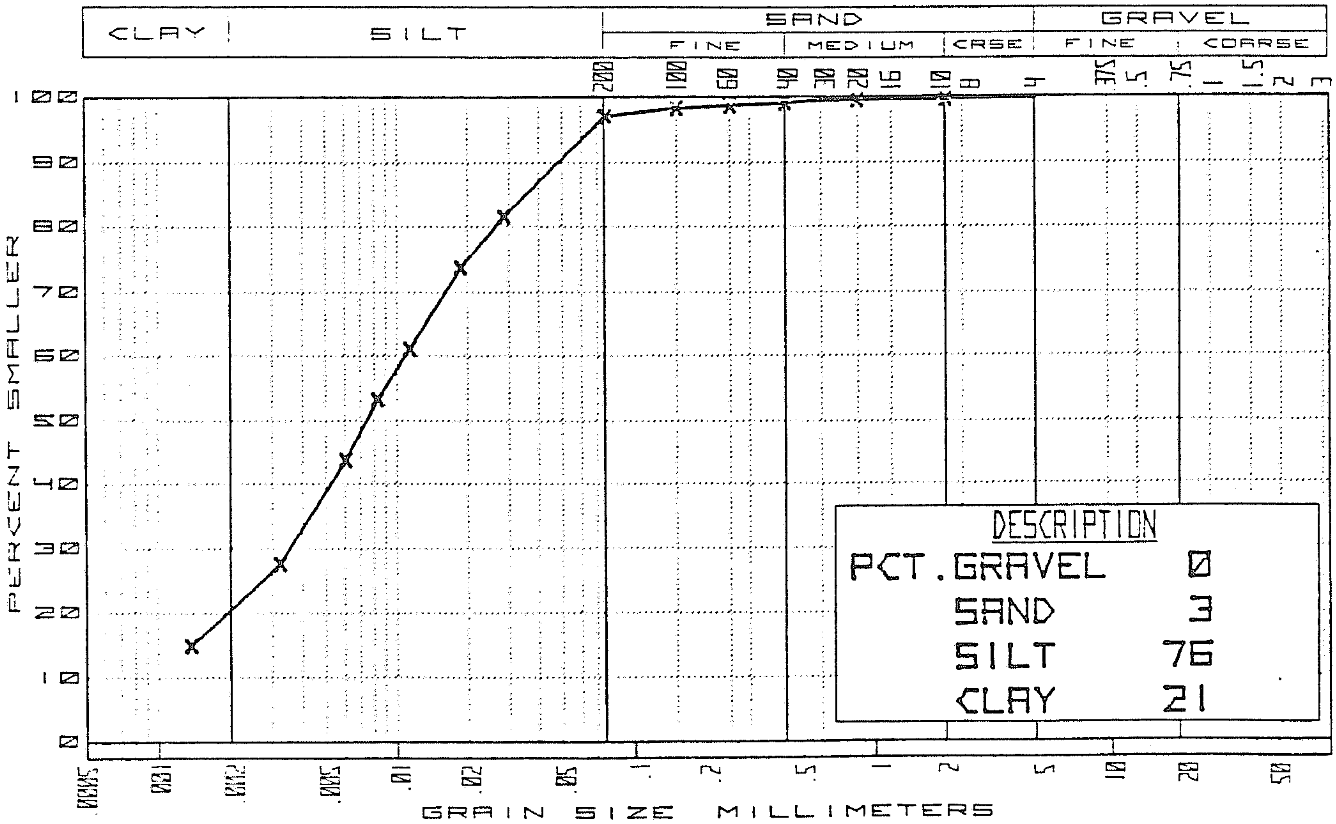
ATTENTION ______

SIEVE	PCT SMALLER
3	
2	
1.5	
1	
.75	
.5	
.375	
4	
8 10	
16 20	
30 40	
50 60	
100	
200	

REVIEWED BY ______ P.ENG.

JOB NO. 16-1975 SITE BH C-3

DATE 28-10-77 BASELINE ______ STATION ______ OFFSET ______ DEPTH 18.0-19.0



DESCRIPTION

PCT. GRAVEL	0
SAND	3
SILT	76
CLAY	21

All tests performed in accordance with ASTM & CSA standards.

GRAIN SIZE DISTRIBUTION

PROJECT Calgary Frost Heave Test Facility, CAGPL

ADDRESS Calgary, Alberta

JOB NO. 16-1975

DATE TESTED ______ BY ______

CLIENT Foothills Pipe Lines Ltd.

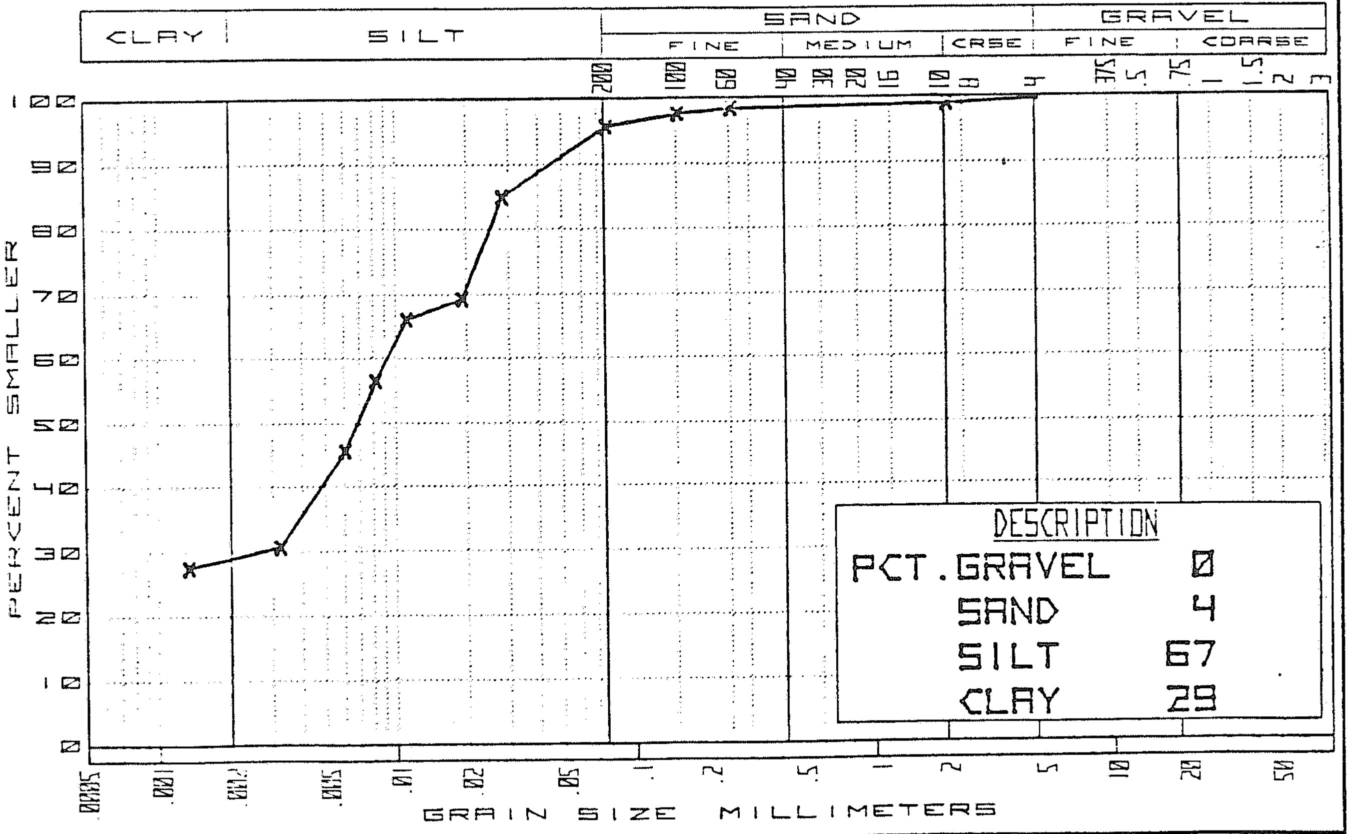
ATTENTION ______

SIEVE	PCT SMALLER
3	
2	
1.5	
1	
.75	
.5	
.375	
4	
8 10	
16 20	
30 40	
50 60	
100	
200	

REVIEWED BY ______ P.ENG.

JOB NO. 16-1975 SITE BH C-3

DATE 28-10-77 BASELINE ______ STATION ______ OFFSET ______ DEPTH 20.5-21.5



DESCRIPTION

PCT. GRAVEL	0
SAND	4
SILT	67
CLAY	29

EBA Engineering Consultants Ltd.

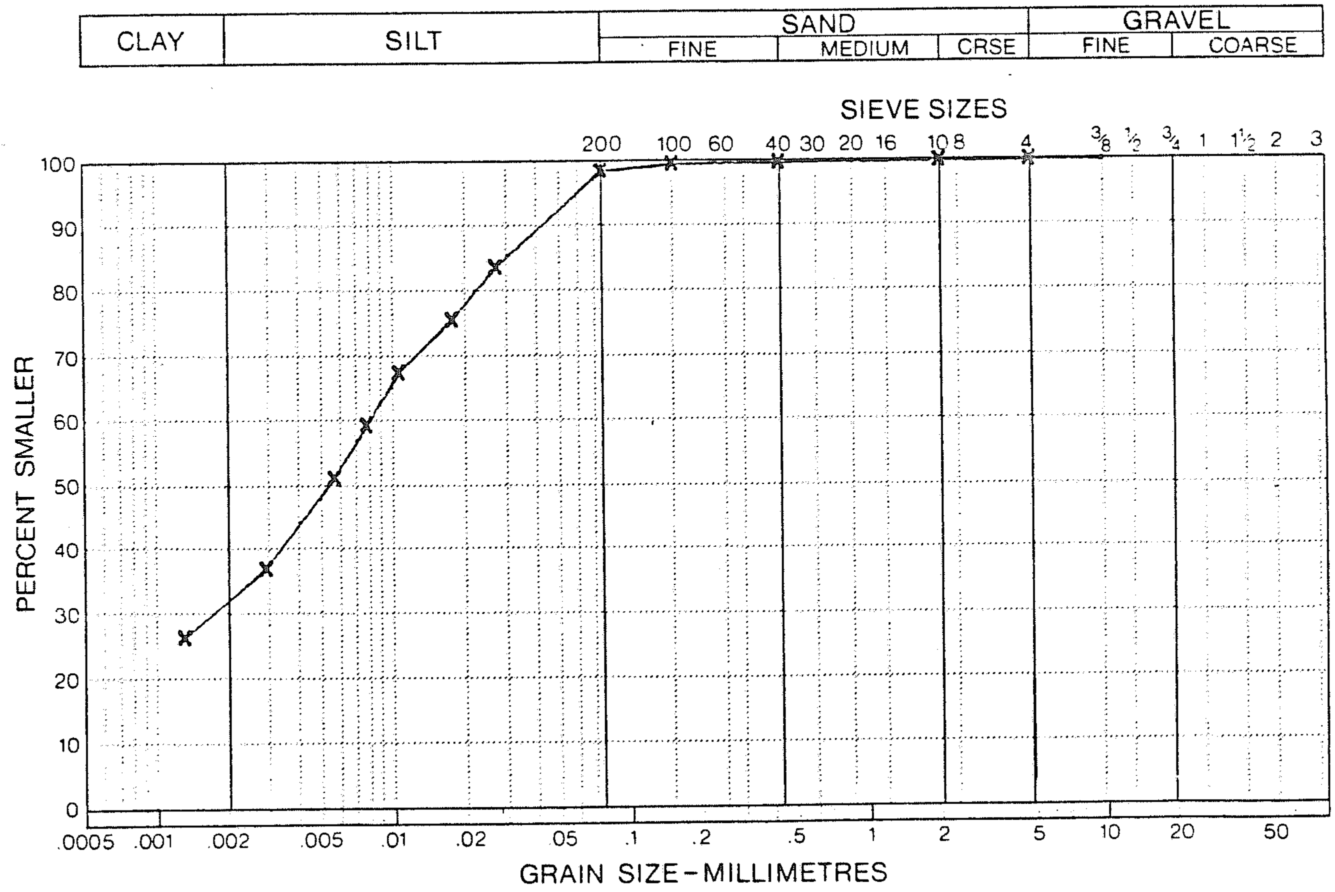
14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

GRAIN SIZE DISTRIBUTION

Project: Stage II Drilling Results
Calgary Frost Heave Test Facility
Project Number: 16-2195
Date Tested: 13-7-78
Remarks:

Test Hole Number: R-1A
Depth: 5.9-6.2 Metres
Sample Description
Gravel: 0
Sand: 2
Silt: 66
Clay: 32



Reviewed By: P. Eng.

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

eba

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

GRAIN SIZE DISTRIBUTION

Project: Stage II Drilling Results
Calgary Frost Heave Test Facility

Project Number: 16-2195

Date Tested: 14-8-78

Remarks:

Test Hole Number: G-1

Depth: 3.7 - 4.1 Metres

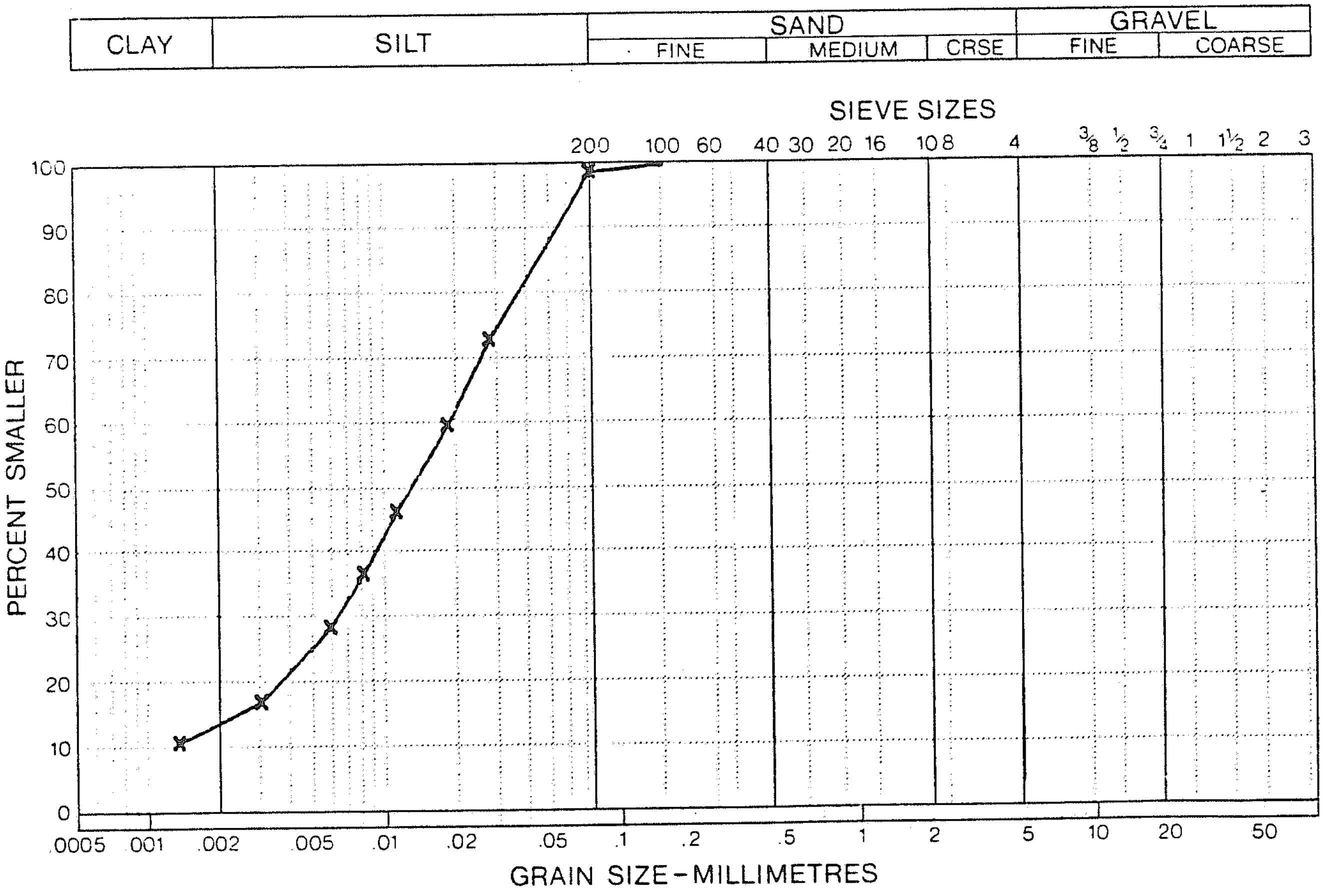
Sample Description

Gravel: 0

Sand: 1

Silt: 85

Clay: 14



Reviewed By: .... P. Eng.

All tests performed in accordance with ASTM and CSA standards unless otherwise noted

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

GRAIN SIZE DISTRIBUTION

Project: Stage II Drilling Results
Calgary Frost Heave Test Facility

Project Number: 16-2195

Date Tested: 14-8-78

Remarks:

Test Hole Number: G-2A

Depth: 5.8 - 6.3 Metres

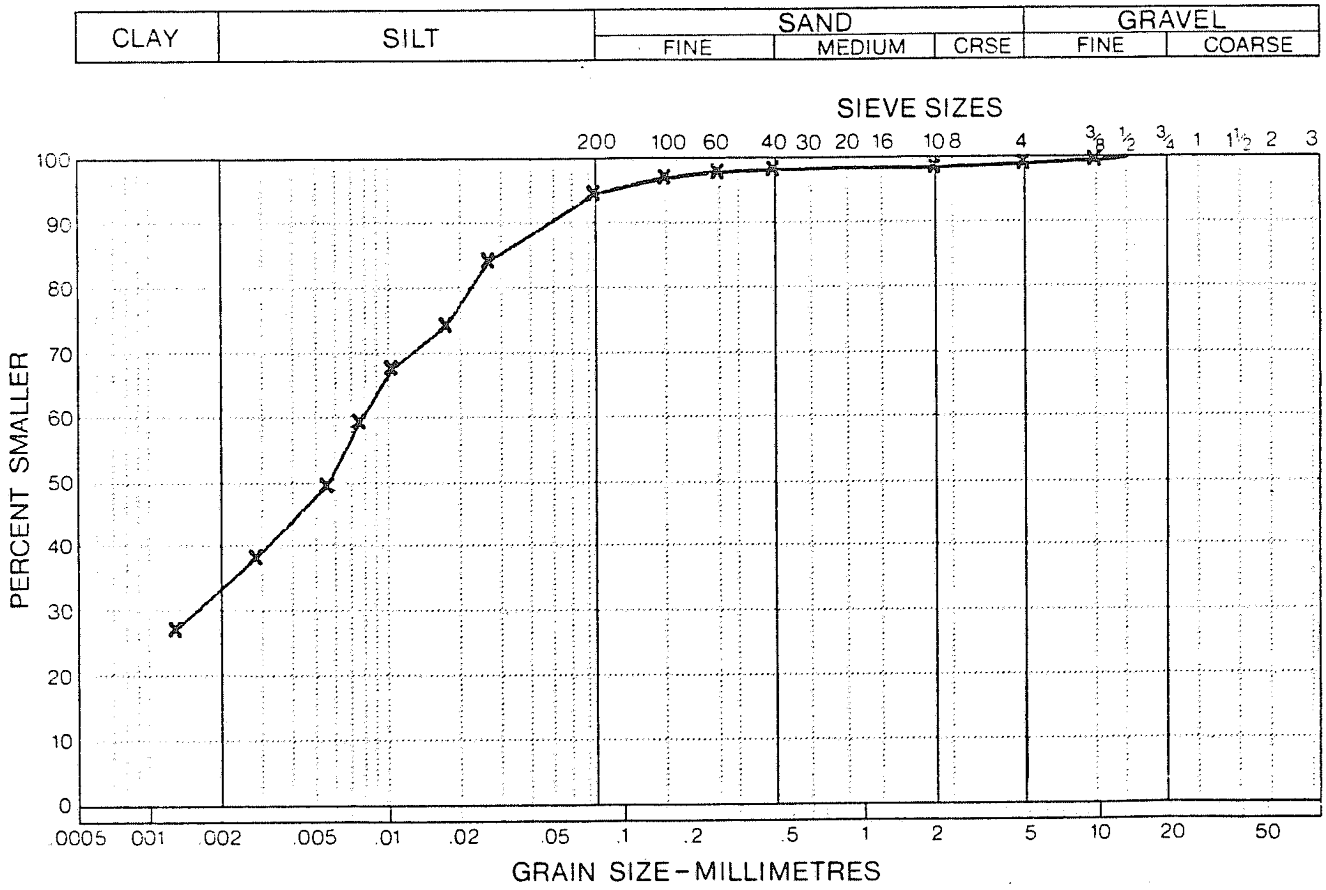
Sample Description

Gravel: 1

Sand: 4

Silt: 61

Clay: 34



Reviewed By: .... P. Eng.

All tests performed in accordance with ASTM and CSA standards unless otherwise noted

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

eba

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

GRAIN SIZE DISTRIBUTION

Project: Stage II Drilling Results
Calgary Frost Heave Test Facility

Project Number: 16-2195

Date Tested: 13-7-78

Remarks:

Test Hole Number: D-1A

Depth: 4.5-4.6 Metres

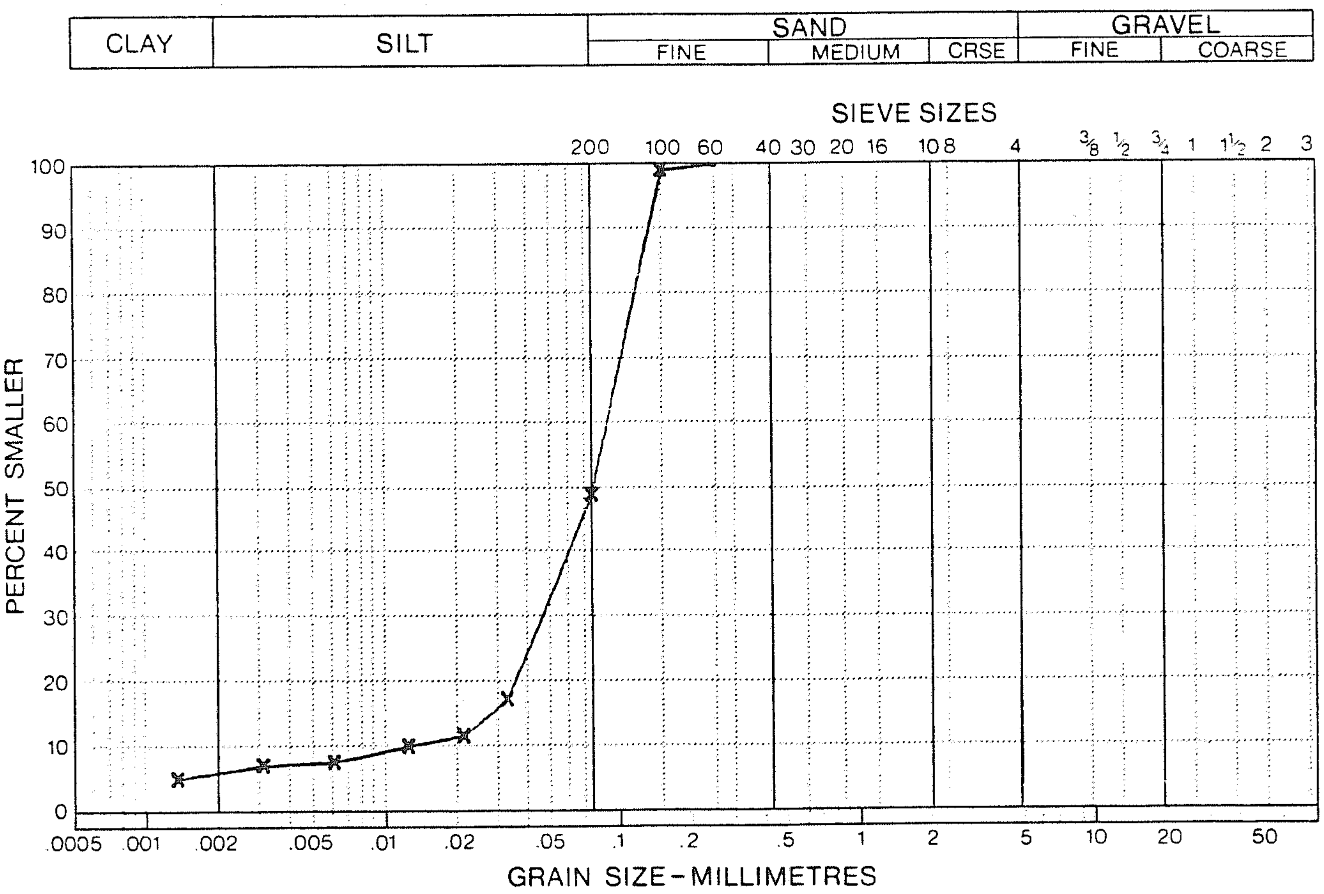
Sample Description

Gravel: 0

Sand: 51

Silt: 43

Clay: 6



Reviewed By: .... P. Eng.

All tests performed in accordance with ASTM and CSA standards unless otherwise noted

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

GRAIN SIZE DISTRIBUTION

Project: Stage II Drilling Results
Calgary Frost Heave Test Facility

Project Number: 16-2195

Date Tested: 13-7-78

Remarks:

Test Hole Number: D-1A

Depth: 6.6-6.7 Metres

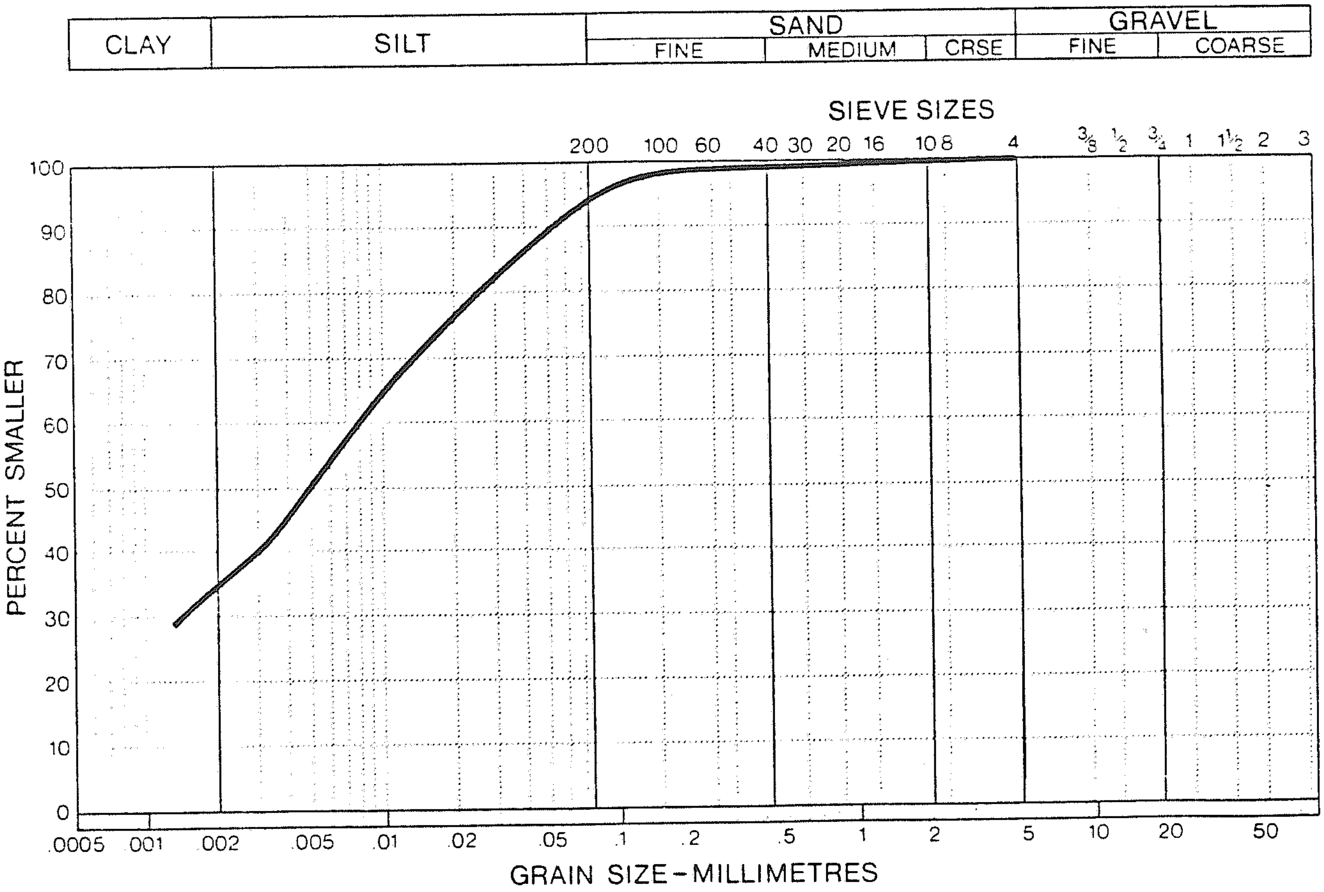
Sample Description

Gravel: 0

Sand: 4

Silt: 62

Clay: 34



Reviewed By: .... P. Eng.

All tests performed in accordance with ASTM and CSA standards unless otherwise noted

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

GRAIN SIZE DISTRIBUTION

Project: Stage II Drilling Results
Calgary Frost Heave Test Facility

Project Number: 16-2195

Date Tested: 14-8-78

Remarks:

Test Hole Number: D-3

Depth: 7.3 - 7.8 Metres

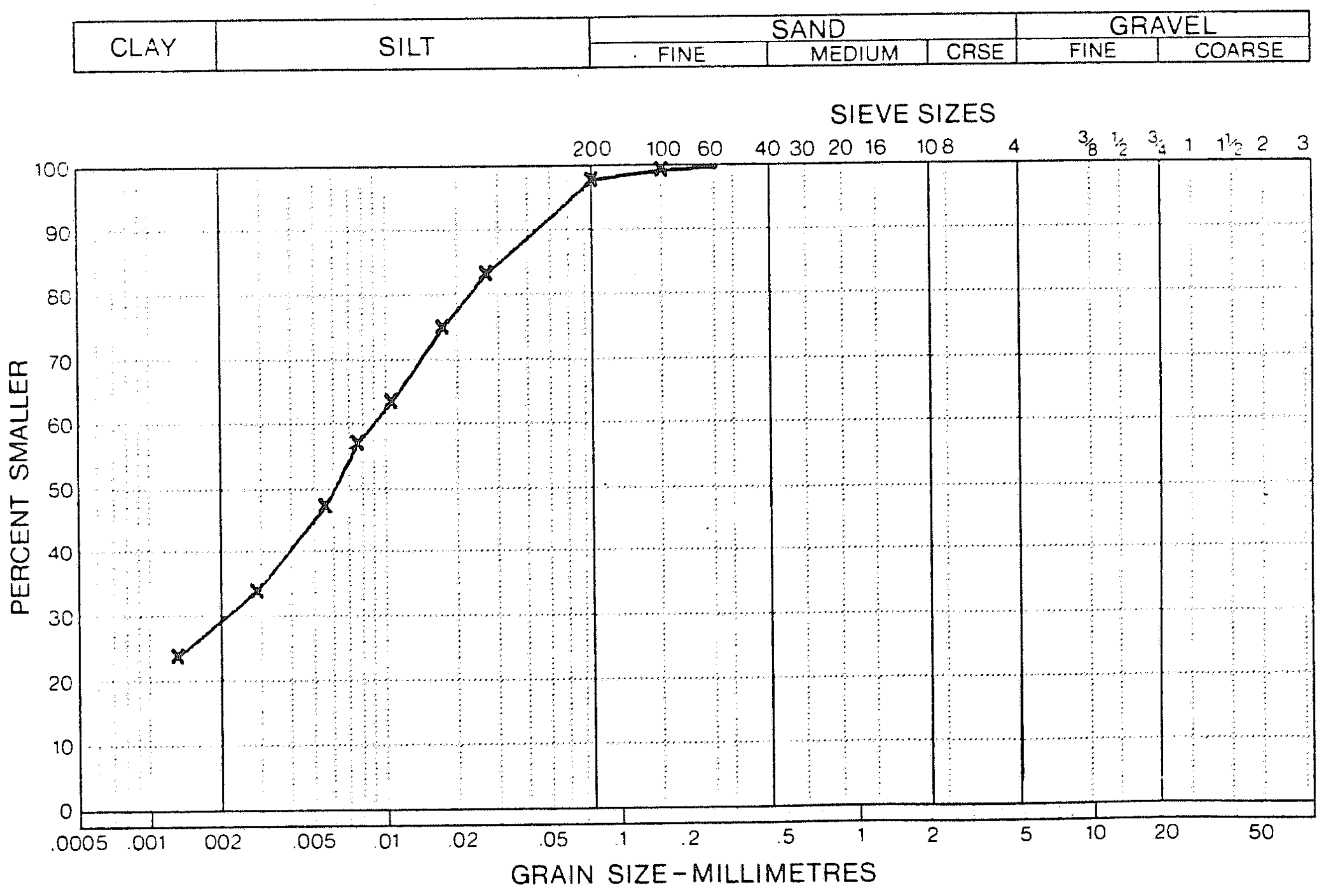
Sample Description

Gravel: 0

Sand: 2

Silt: 68

Clay: 30



Reviewed By: P. Eng.

All tests performed in accordance with ASTM and CSA standards unless otherwise noted

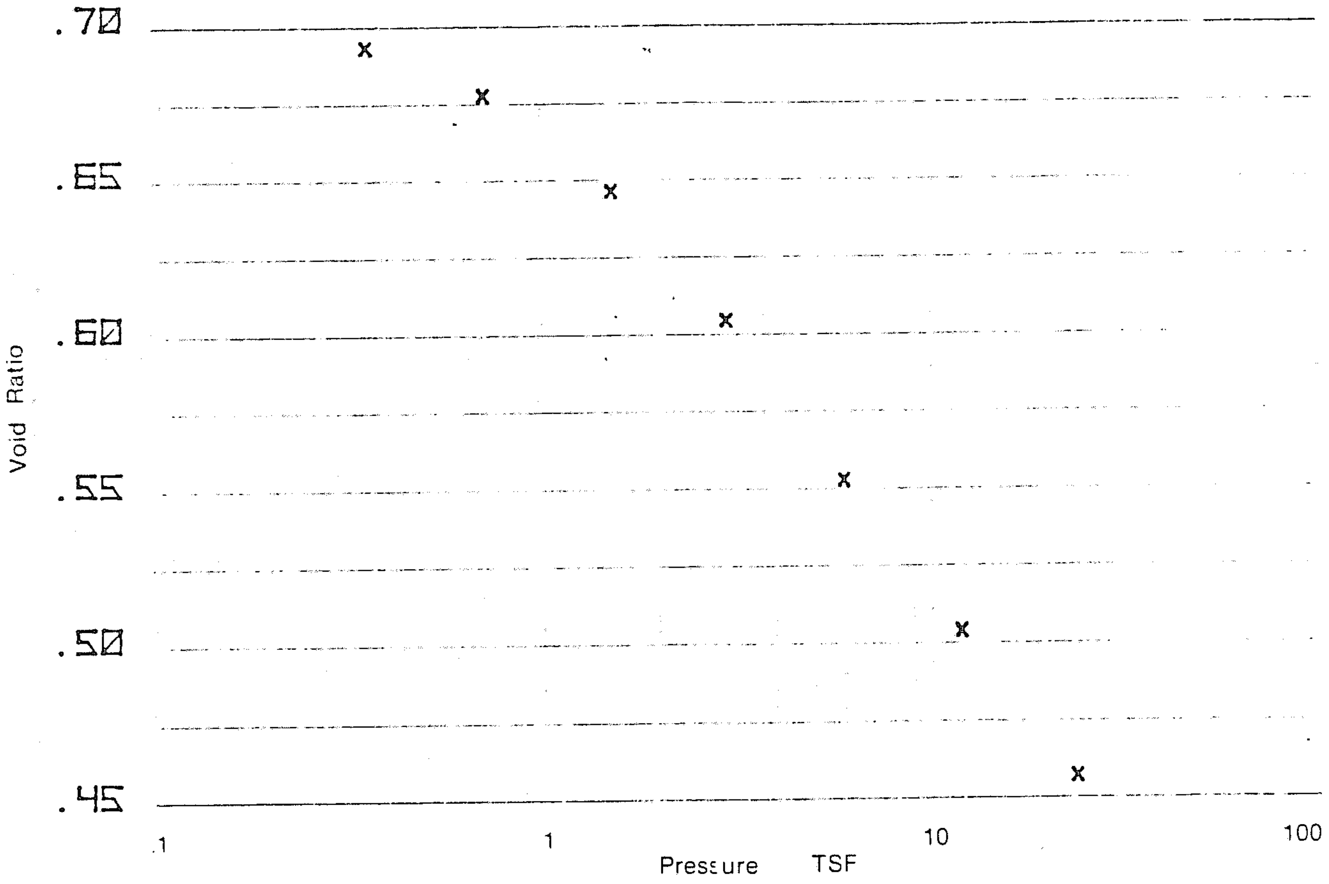
EBA Engineering Consultants Ltd.

14535-118th AVE
EDMONTON, ALBERTA
Phone (403) 453-3041

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

CONSOLIDATION TEST RESULTS

Project:
Address:
Test No.:
Test Hole No.: D-3
Depth Ft.: 10.0-12.0
Job Number: 16-2195
Diameter In.: 2.5
Date Tested 4-10-78 By: S.K.
Assumed Sp. Gravity: 2.68



	INITIAL	FINAL
Height In.	1.0	.85
Water Content %	26.3	17.2
Wet Density PCF	125.6	135.4
Dry Density PCF	99.5	115.5
Void Ratio	.6922	.4589
Saturation %	101.8	100.0

Sample Description: GREYISH BROWN SILTY CLAY, MOIST

Overburden Pressure P_o TSF
Swelling Pressure P_s .4 TSF
Pre-Consolidation Pressure P_c TSF
Compression Index C_c

Reviewed By P.Eng

All tests performed in accordance with A.S.T.M. & A.A.S.H.O. standards.

EBA Engineering Consultants Ltd.

14535-118th AVE
EDMONTON, ALBERTA
Phone (403) 453-3041

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

CONSOLIDATION TEST RESULTS

Project:

Address:

Job Number: 16-2195

Date Tested 10-10-78 By: J.S.

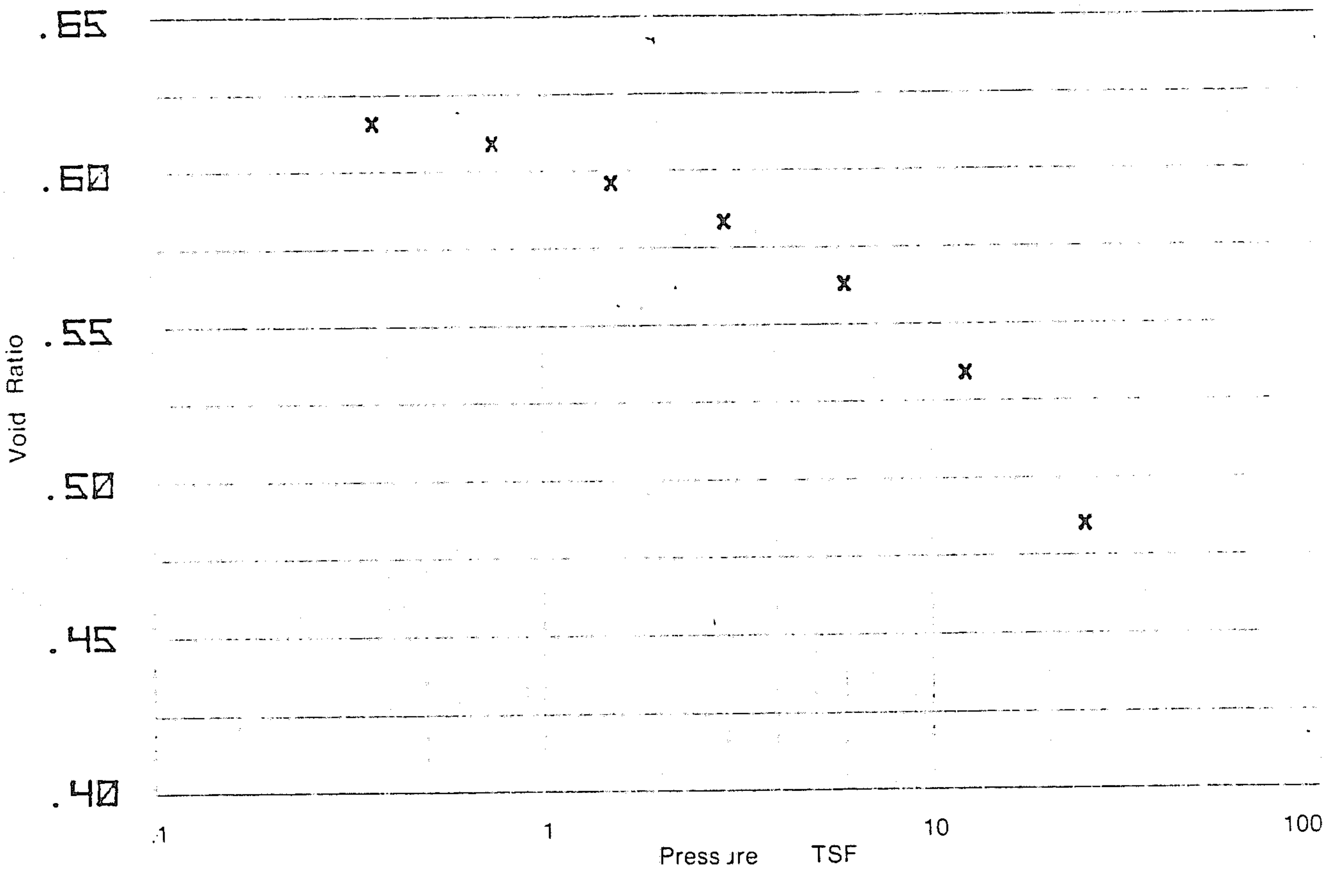
Test No.:

Test Hole No.: D-3

Depth Ft.: 16.0-17.5

Diameter In.: 2.5

Assumed Sp. Gravity: 2.68



	INITIAL	FINAL
Height In.	1.0	.91
Water Content %	24.9	18.1
Wet Density PCF	129.3	133.2
Dry Density PCF	103.5	112.8
Void Ratio	.6179	.4854
Saturation %	108.2	100.0

Sample Description: LIGHT GREYISH BR
SILT

Overburden Pressure P_o TSF

Swelling Pressure P_s .4 TSF

Pre-Consolidation Pressure P_c TSF

Compression Index C_c

Reviewed By P.Eng

All tests performed in accordance with A.S.T.M. & A.A.S.H.O. standards.

EBA Engineering Consultants Ltd.

14535-118th AVE
EDMONTON, ALBERTA
Phone (403) 453-3041

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

CONSOLIDATION TEST RESULTS

Project:

Address:

Job Number: 16-2155

Date Tested: 28-9-78 By: J.S.

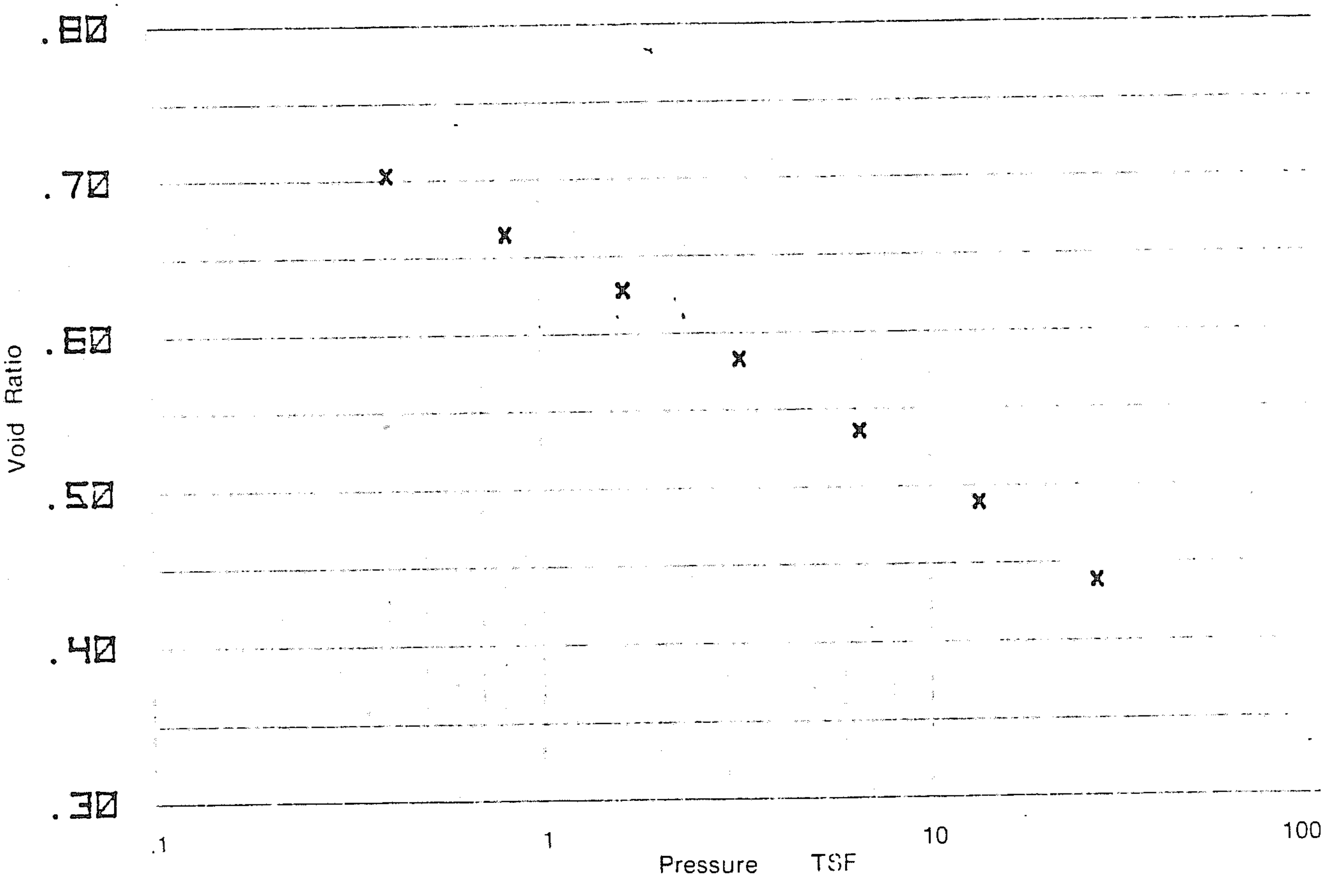
Test No.:

Test Hole No.: D-3

Depth Ft.: 22.6-24.0

Diameter In.: 2.5

Assumed Sp. Gravity: 2.68



	INITIAL	FINAL
Height In.	1.0	.84
Water Content %	24.6	16.5
Wet Density PCF	126.4	140.9
Dry Density PCF	101.5	120.9
Void Ratio	.7062	.4417
Saturation %	93.6	100.0

Sample Description: LIGHT BR. CLAY SOME SILT AND PEBBLES

Overburden Pressure P_o TSF

Swelling Pressure P_s .4 TSF

Pre-Consolidation Pressure P_c TSF

Compression Index C_c

Reviewed By P.Eng

All tests performed in accordance with A.S.T.M. & A.A.S.H.O. standards.

EBA Engineering Consultants Ltd.

14535-118th AVE
EDMONTON, ALBERTA
Phone (403) 453-3041

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

CONSOLIDATION TEST RESULTS

Project:

Address:

Job Number: 16-2195

Date Tested 10-10-78 By: H.R.H.

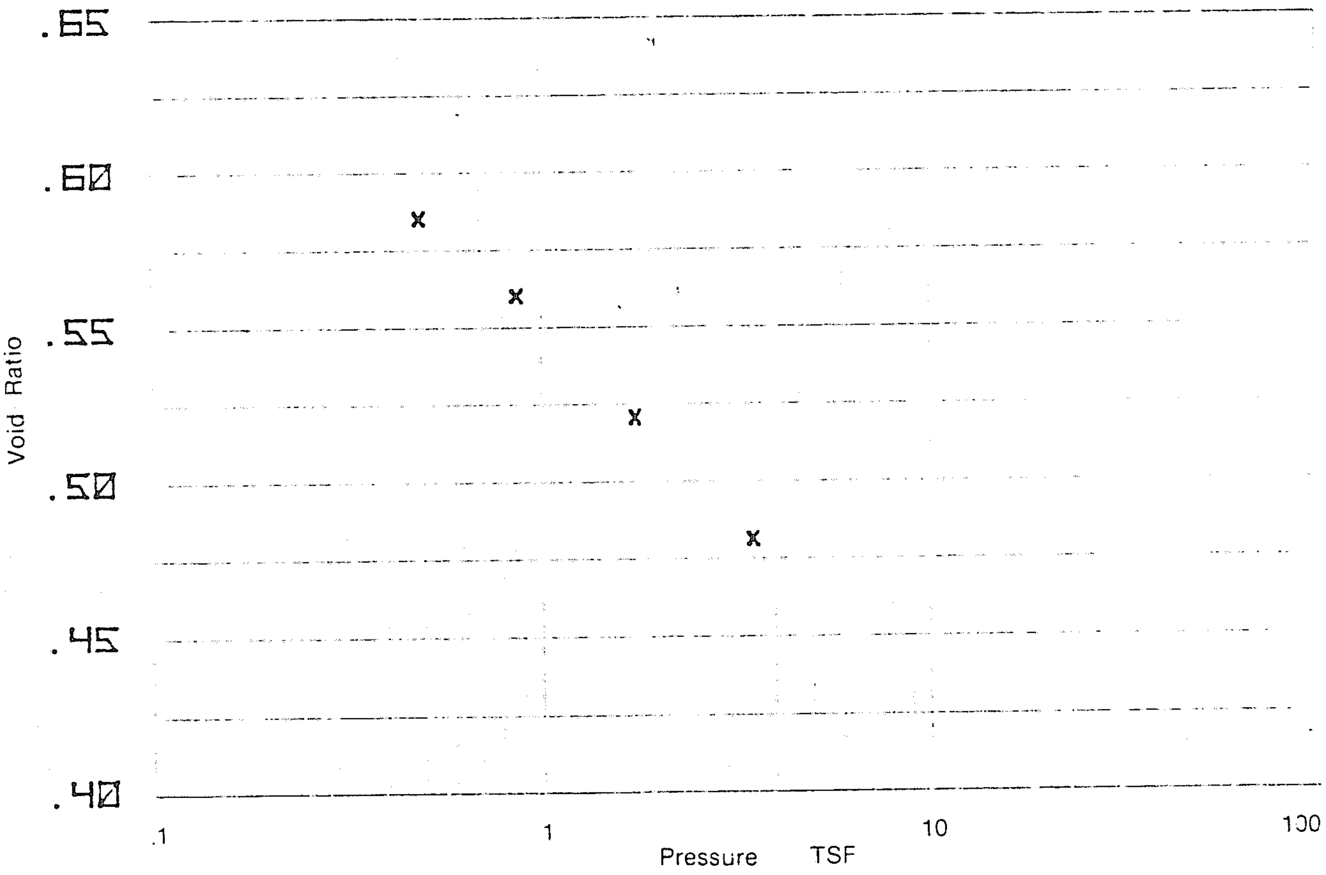
Test No.:

Test Hole No.: D-3

Depth Ft.: 26.1-28.0

Diameter In.: 2.5

Assumed Sp. Gravity: 2.68



	INITIAL	FINAL
Height In.	.9	.88
Water Content %	24.5	18.0
Wet Density PCF	136.6	139.1
Dry Density PCF	109.8	117.9
Void Ratio	.5868	.4820
Saturation %	112.0	100.0

Sample Description: MED BR SANDY SILT-CLAY TR GRAVEL

Overburden Pressure P_o TSF

Swelling Pressure P_s .5 TSF

Pre-Consolidation Pressure P_c TSF

Compression Index C_c

Reviewed By P.Eng.

All tests performed in accordance with A.S.T.M. & A.A.S.H.O. standards.

B.3 THAW SETTLEMENT AND CONSOLIDATION

SUMMARY OF THAW STRAIN TESTING RESULTS

BOREHOLE NUMBER	DEPTH INTERVAL m	DIAM d mm	LENGTH ℓ mm	DENSITY γ Mg/m³	SPECIFIC GRAVITY G_s	MOIST CONT w %	VOID RATIO e	STRESS σ kPa	DEFLECTION δ mm	PERMEABILITY DIRECT k m/s	PERMEABILITY INDIRECT k m/s	COEFF OF COMPRESS m_v kPa^{-1}	COEFFICIENT OF CONSOLIDATION c_v m²/yr	COEFFICIENT OF CONSOLIDATION c_v cm²/s	SAMPLE DESCR USC / ICE	PHOTO
	2.59-	58.3	54.4	1.86F	2.68	31.9	.82								CL-ML	Y
C-2	3.05						.90M		4.6							E
							.66	34	4.6C	3.4E-07					VS+	S
	(8.5'								.2						VR	
							.65	52	4.8C	2.3E-07						
	-10')								.2		4.6E-10	2.0E-04	7.2E-01	2.3E-04		
				1.92		24.0	.64	69	5.0C	1.8E-07						
				1.55D												
	4.27-	88.1	89.9	1.83F	2.68	31.5	.94								CL-ML	Y
C-2	5.03						.93M		13.2							E
							.66	49	13.2C	2.1E-07					VS+	S
									.4		8.1E-10	2.1E-04	1.2E 00	3.8E-04	VR	
	(14'						.65	73	13.6C	2.2E-07						
	-16.5')								.4		4.6E-10	2.1E-04	6.6E-01	2.1E-04		
				2.04		23.9	.64	98	14.0C	2.1E-07						
				1.65D												

JOB No: 16-1975

A - Assumed Spec. Grav.
C - Cumulative Deflection

D - Dry Density
F - Frozen Bulk Density

M - Void Ratio from initial measurements

EBA Engineering Consultants Ltd. eba

SUMMARY OF THAW STRAIN TESTING RESULTS

BOREHOLE NUMBER	DEPTH INTERVAL m	DIAM d mm	LENGTH ℓ mm	DENSITY γ Mg/m³	SPECIFIC GRAVITY G_s	MOIST. CONT w %	VOID RATIO e	STRESS σ kPa	DEFLECTION Δ mm	PERMEABILITY DIRECT k m/s	PERMEABILITY INDIRECT k m/s	COEFF. OF COMPRESS m_v kPa⁻¹	COEFFICIENT OF CONSOLIDATION c_v m²/yr	COEFFICIENT OF CONSOLIDATION c_v cm²/s	SAMPLE DESCR USC / ICE	PHOTO
C-3	5.49-	48.3	53.0	1.76F	2.68	37.7	1.23								CL	Y
	5.79						1.10M		14.6							E
							.65	57	14.6C						VS	S
									.5		3.5E-09	3.9E-04	2.8E 00	8.0E-04		
	(18'						.63	86	15.0C							
	-19')								.4		5.7E-10	3.4E-04	5.3E-01	1.7E-04		
				2.22		22.9	.61	115	15.4C							
				1.80D												
C-3	5.79-	48.7	52.2	1.58F	2.68	48.6	1.66								CL	Y
	6.10						1.52M		19.8							E
							.70	65	19.8C						VS	S
									.4		8.1E-10	3.5E-04	7.2E-01	2.3E-04		
	(19'						.68	98	20.2C							
									.6							
	-20')			2.19		24.4	.65	131	20.7C							
				1.76D												
C-3	6.25-	48.8	61.0	1.64F	2.68	50.1	1.55								CL	Y
	6.55						1.45M		20.8							E
	(20.5'						.71	69	20.8C						VS	S
									.6		2.2E-09	4.1E-04	1.6E 00	5.2E-04		
	-21.5')						.69	103	21.4C							
									.6		6.9E-10	4.0E-04	5.3E-01	1.7E-04		
				2.13		24.9	.67	137	22.0C							
				1.71D												

JOB No 16-1975

A - Assumed Spec Grav
C - Cumulative Deflection

D - Dry Density
F - Frozen Bulk Density

M - Void Ratio from Initial measurements

EBA Engineering Consultants Ltd. eba

SUMMARY OF THAW STRAIN TESTING RESULTS

BOREHOLE NUMBER	DEPTH INTERVAL m	DIAM d mm	LENGTH ℓ mm	DENSITY γ Mg/m³	SPECIFIC GRAVITY G_s	MOIST. CONT w %	VOID RATIO e	STRESS σ kPa	DEFLECTION Δ mm	PERMEABILITY DIRECT k m/s	PERMEABILITY INDIRECT k m/s	COEFF OF COMPRESS m_v kPa^{-1}	COEFFICIENT OF CONSOLIDATION c_v m²/yr	COEFFICIENT OF CONSOLIDATION c_v cm²/s	SAMPLE DESCR. USC / ICE	PHOTO
C-3	4.88-5.18	48.5	53.6	1.84F	2.68	32.2	1.07								CL	YES
							.93M		11.9							
							.64	57	11.9C						VS	
	(16'-17')								.5		3.1E-09	3.7E-04	2.6E 00	8.2E-04		
							.62	86	12.4C							
									.3		3.0E-10	2.5E-04	3.8E-01	1.2E-04		
				2.23		22.8	.61	114	12.7C							
				1.82D												
C-3	5.18-5.49	88.8	92.4	1.76F	2.68	37.8	1.13								CL	YES
							1.09M		21.3							
							.65	57	21.3C	1.8E-09					VS	
	(17'-18')								1.1		7.2E-09	2.6E-04	8.6E 00	2.7E-03		
				2.08		23.3	.62	114	22.4C	1.6E-09						
				1.69D												

JOB No 16-1975

A - Assumed Spec Grav
C - Cumulative Deflection
D - Dry Density
F - Frozen Bulk Density
M - Void Ratio from initial measurements

EBA Engineering Consultants Ltd. eba

SUMMARY OF THAW STRAIN TESTING RESULTS

BOREHOLE NUMBER	DEPTH INTERVAL m	DIAM. d mm	LENGTH ℓ mm	DENSITY γ Mg/m³	SPECIFIC GRAVITY G_s	MOIST. CONT. w %	VOID RATIO e	STRESS σ kPa	DEFLECTION δ mm	THAW STRAIN %	PERMEABILITY DIRECT k m/s	PERMEABILITY INDIRECT k m/s	COEFF OF COMPRESS. m_v kPa^{-1}	COEFFICIENT OF CONSOLIDATION c_v m^2/yr	COEFFICIENT OF CONSOLIDATION c_v cm^2/s	SAMPLE DESCR. USC / ICE	PHOTO
G-2A	9.00-10.50	58.1	64.9	1.99F	2.72A	22.8	.77									ML	YES
							.67M		4.3								
							.66	29	4.3C .4							VS	
							.65	50	4.7C .5	7.2							
				2.18 1.77D		23.5	.64	100	5.2C								
G-2A	14.00-15.00	58.2	64.3	1.96F	2.72A	24.5	.86									CL	YES
							.73M		5.5								
							.71	28	5.5C .1							VS	
							.71	57	5.7C .8	8.9		2.2E-07	2.2E-04	3.1E 02	9.9E-02		
				2.19 1.75D		25.2	.69	113	6.5C								
G-2A	16.50-18.20	58.6	58.7	1.87F	2.72A	30.5	.98									CL	YES
							.90M		2.9								
							.89	30	2.9C .4			4.0E-10	2.5E-04	5.0E-01	1.6E-04	VS	
							.87	61	3.3C 1.2	5.6		4.7E-09	3.5E-04	4.2E 00	1.3E-03		
				2.03 1.55D		30.7	.83	121	4.5C								

JOB No: 16-2195

A - Assumed Spec. Grav.
C - Cumulative Deflection
D - Dry Density
F - Frozen Bulk Density
M - Void Ratio from initial measurements

EBA Engineering Consultants Ltd. eba

2018 x

SUMMARY OF THAW STRAIN TESTING RESULTS

BOREHOLE NUMBER	DEPTH INTERVAL m	DIAM d mm	LENGTH ℓ mm	DENSITY γ Mg/m³	SPECIFIC GRAVITY G_s	MOIST. CONT w %	VOID RATIO e	STRESS σ kPa	DEFLECTION δ mm	THAW STRAIN %	PERMEABILITY DIRECT k m/s	PERMEABILITY INDIRECT k m/s	COEFF OF COMPRESS. m_v kPa⁻¹	COEFFICIENT OF CONSOLIDATION c_v m²/yr	COEFFICIENT OF CONSOLIDATION c_v cm²/s	SAMPLE DESCR. USC / ICE	PHOTO
D-1A	6.15- 6.45	58.1	59.9	1.75F 2.23 1.83D	2.72A	40.1 21.8	1.29 1.18M .63 .62 .59	40 74 159	18.1 18.1C .4 18.4C .7 19.1C	30.8		1.3E-09 2.5E-09	2.5E-04 1.7E-04	1.6E 00 4.5E 00	5.2E-04 1.4E-03	CL VS	YES
D-1A	4.95- 5.15	58.7	57.3	1.78F 2.17 1.78D	2.72A	38.7 22.1	1.19 1.12M .63 .62 .60	37 74 147	15.1 15.1C .3 15.5C .5 16.0C	27.0		4.9E-09 1.0E-08	2.1E-04 1.6E-04	7.3E 00 2.0E 01	2.3E-03 6.5E-03	ML VR VS	YES
G-1	3.35- 3.66	58.6	62.1	1.92F 2.12 1.71D	2.72A	25.2 23.8	.83 .77M .66 .66 .65	28 56 112	5.9 5.9C .3 6.2C .3 6.5C	9.9						ML VS	YES

JOB No. 16-2195

A - Assumed Spec. Grav.
C - Cumulative Deflection

D - Dry Density
F - Frozen Bulk Density

M - Void Ratio from initial measurements

EBA Engineering Consultants Ltd. eba

2018 ×

SUMMARY OF THAW STRAIN TESTING RESULTS

BOREHOLE NUMBER	DEPTH INTERVAL m	DIAM. d mm	LENGTH ℓ mm	DENSITY γ Mg/m³	SPECIFIC GRAVITY G_s	MOIST. CONT w %	VOID RATIO e	STRESS σ kPa	DEFLECTION δ mm	THAW STRAIN %	PERMEABILITY DIRECT k m/s	PERMEABILITY INDIRECT k m/s	COEFF OF COMPRESS. m_v kPa^{-1}	COEFFICIENT OF CONSOLIDATION c_v m²/yr	COEFFICIENT OF CONSOLIDATION c_v cm²/s	SAMPLE DESCR. USC / ICE	PHOTO
R-1A	5.65-	59.7	61.0	1.60F	2.72A	43.3	1.37									CL VS	YES
	5.85						1.44M		17.0								
							.69	35	17.0C								
									.7								
							.66	70	17.7C	29.1							
									1.4			6.6E-09	4.9E-04	4.2E 00	1.3E-03		
				1.98		22.2	.60	140	19.1C								
				1.62D													
D-2	3.30-	58.4	61.0	1.93F	2.72A	26.1	.78									CL VR VS	YES
	3.60						.78M		.8								
							.76	32	.8C								
									.3								
							.75	64	1.1C	1.8							
									.6			1.5E-06	1.7E-04	2.7E 03	8.7E-01		
				2.00		26.9	.73	128	1.7C								
				1.57D													
D-1A	5.45-	58.6	60.2	1.71F	2.72A	42.2	1.32									CL VS	YES
	5.85						1.26M		11.6								
							.88	38	11.6C								
									.5								
							.86	71	12.1C	20.1							
									.8			6.0E-08	2.0E-04	9.4E 01	3.0E-02		
				2.01		30.7	.83	153	12.9C								
				1.53D													

JOB No: 16-2195

A - Assumed Spec. Grav
C - Cumulative Deflection

D - Dry Density
F - Frozen Bulk Density

M - Void Ratio from initial measurements

EBA Engineering Consultants Ltd. eba

SUMMARY OF THAW STRAIN TESTING RESULTS

BOREHOLE NUMBER	DEPTH INTERVAL m	DIAM. d mm	LENGTH ℓ mm	DENSITY γ Mg/m³	SPECIFIC GRAVITY G_s	MOIST CONT w %	VOID RATIO e	STRESS σ kPa	DEFLECTION δ mm	THAW STRAIN %	PERMEABILITY DIRECT k m/s	PERMEABILITY INDIRECT k m/s	COEFF OF COMPRESS m_v kPa⁻¹	COEFFICIENT OF CONSOLIDATION c_v m²/yr	COEFFICIENT OF CONSOLIDATION c_v cm²/s	SAMPLE DESCR. USC / ICE	PHOTO
G-2A	4.57-	58.7	68.0	1.89F	2.72A	27.1	.87									CL	YES
	4.88						.83M		4.8								
							.74	29	4.8C							VS	
									.8			1.1E-06	4.3E-04	7.8E 02	2.5E-01		
							.72	58	5.6C	8.2							
									1.0			6.5E-07	2.6E-04	7.6E 02	2.4E-01		
				2.07		25.5	.69	116	6.6C								
				1.65D													
G-1	4.30-	58.6	62.2	1.80F	2.72A	34.0	1.16									CL	YES
	4.72						1.03M		13.1								
							.73	30	13.1C							VS	
									.4			1.4E-07	2.6E-04	1.7E 02	5.4E-02		
							.72	59	13.5C	21.7							
									.6			1.1E-07	2.0E-04	1.8E 02	5.7E-02		
				2.18		25.6	.70	118	14.1C								
				1.74D													
D-2	4.85-	58.7	63.7	1.94F	2.72A	28.2	.91									CL	YES
	5.20						.80M		7.5								
							.70	37	7.5C							VS	
									.3			1.2E-08	1.3E-04	2.9E 01	9.1E-03		
							.69	73	7.8C	12.3							
									.5			2.5E-07	1.1E-04	7.0E 02	2.2E-01		
				2.17		25.0	.68	147	8.3C								
				1.74D													

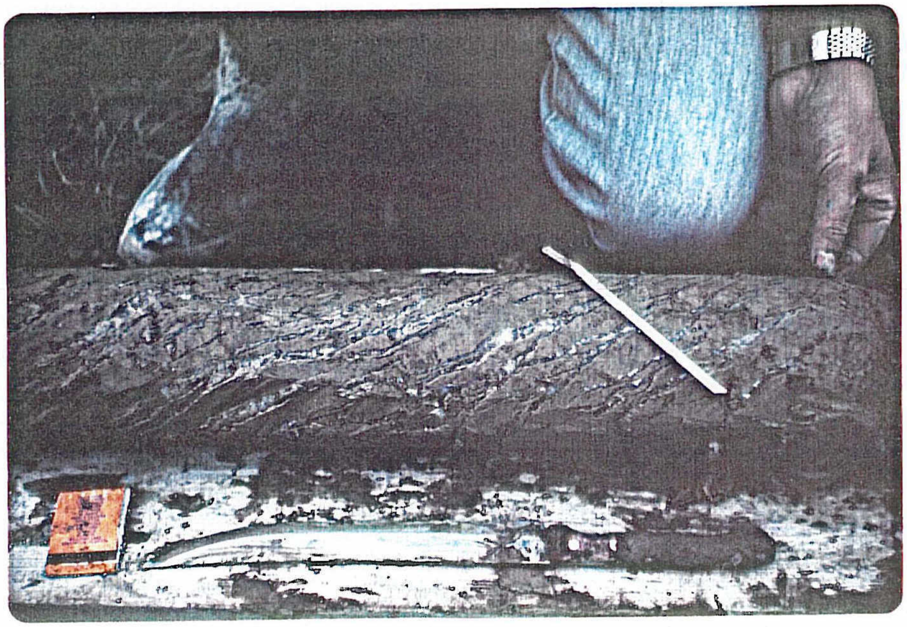
JOB No: 16-2195

A - Assumed Spec. Grav.
C - Cumulative Deflection
D - Dry Density
F - Frozen Bulk Density
M - Void Ratio from initial measurements

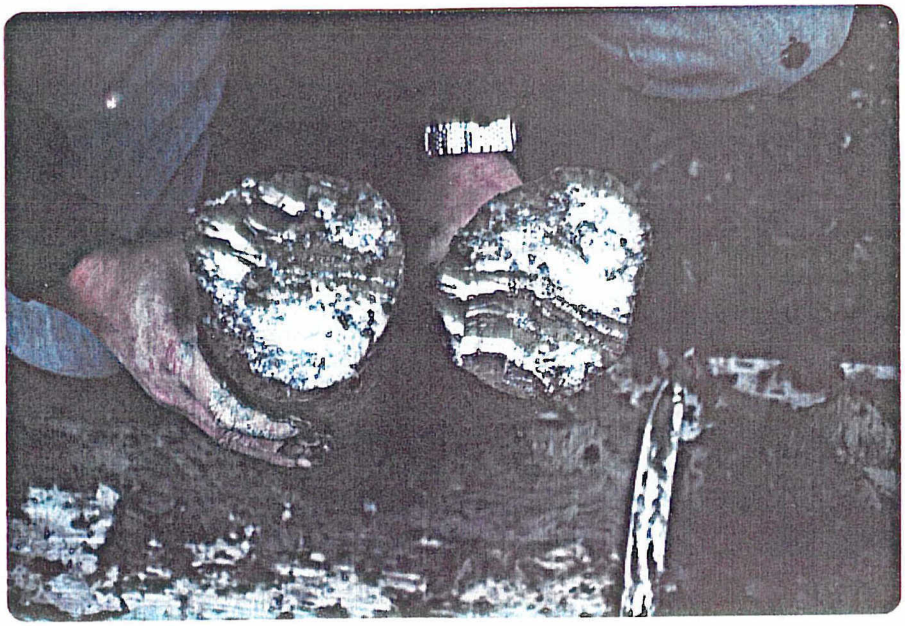
EBA Engineering Consultants Ltd.

2018

PLATES ON CORE SAMPLES



LONG CORE SAMPLE - INCLINED BOREHOLE



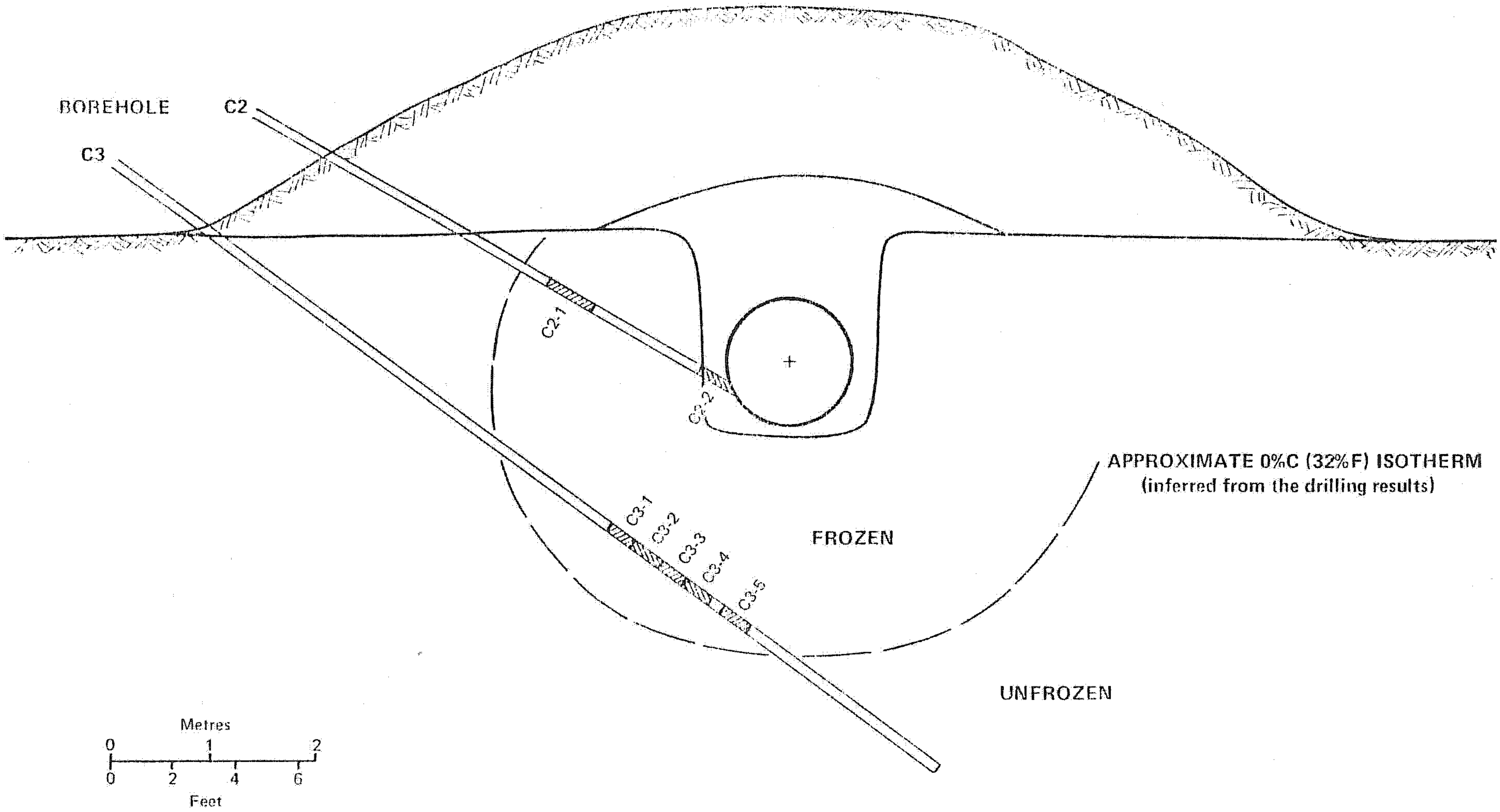
SECTION CUT ALONG ICE LENSES

SECTION CUT ACROSS ICE LENSES

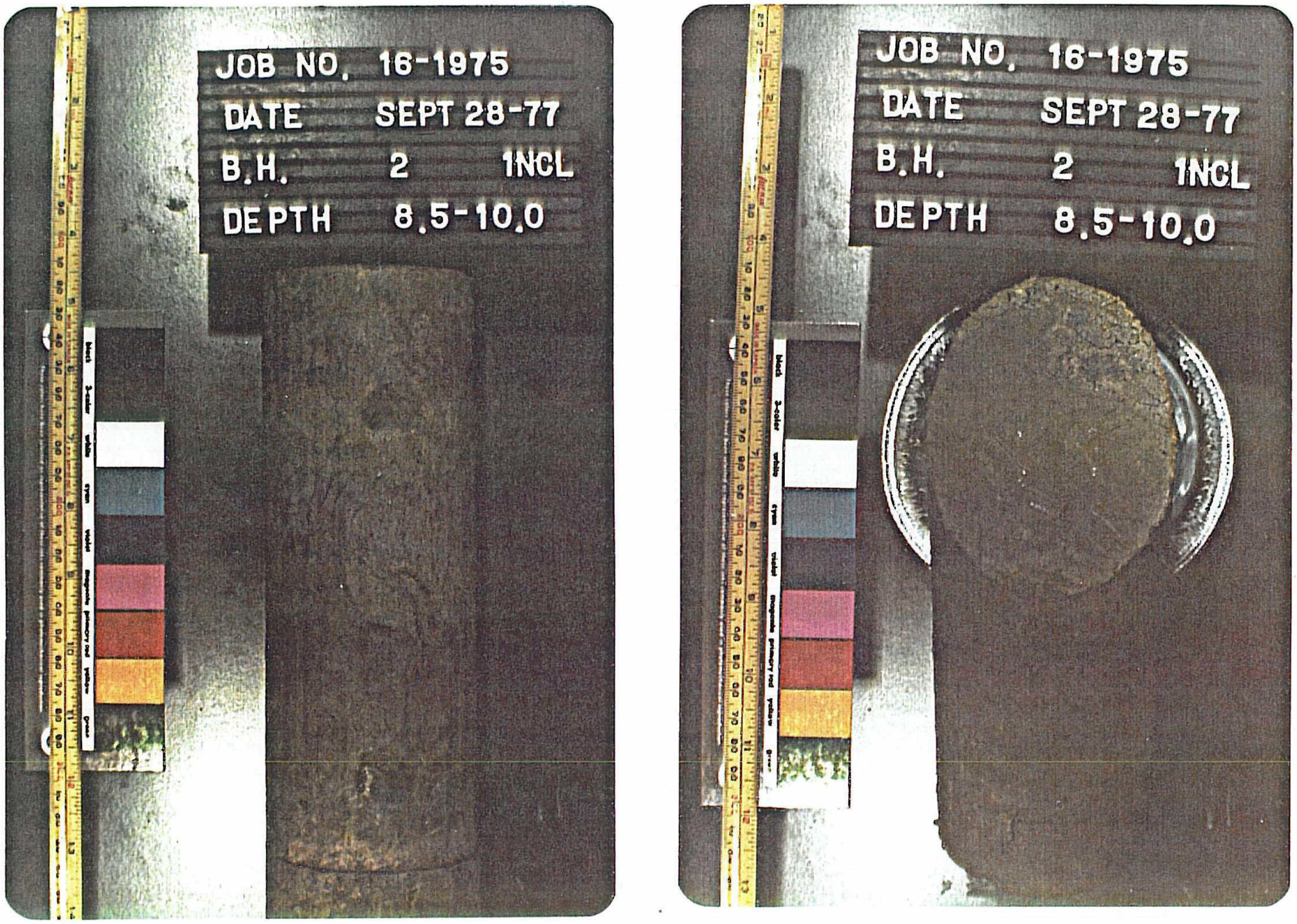
ICE SEGREGATION IN INCLINED BOREHOLES

CONTROL SECTION

FIELD DRILLING - CONTROL SECTION



APPROXIMATE BOREHOLE LOCATIONS
CONTROL SECTION
CALGARY FROST HEAVE TEST FACILITY

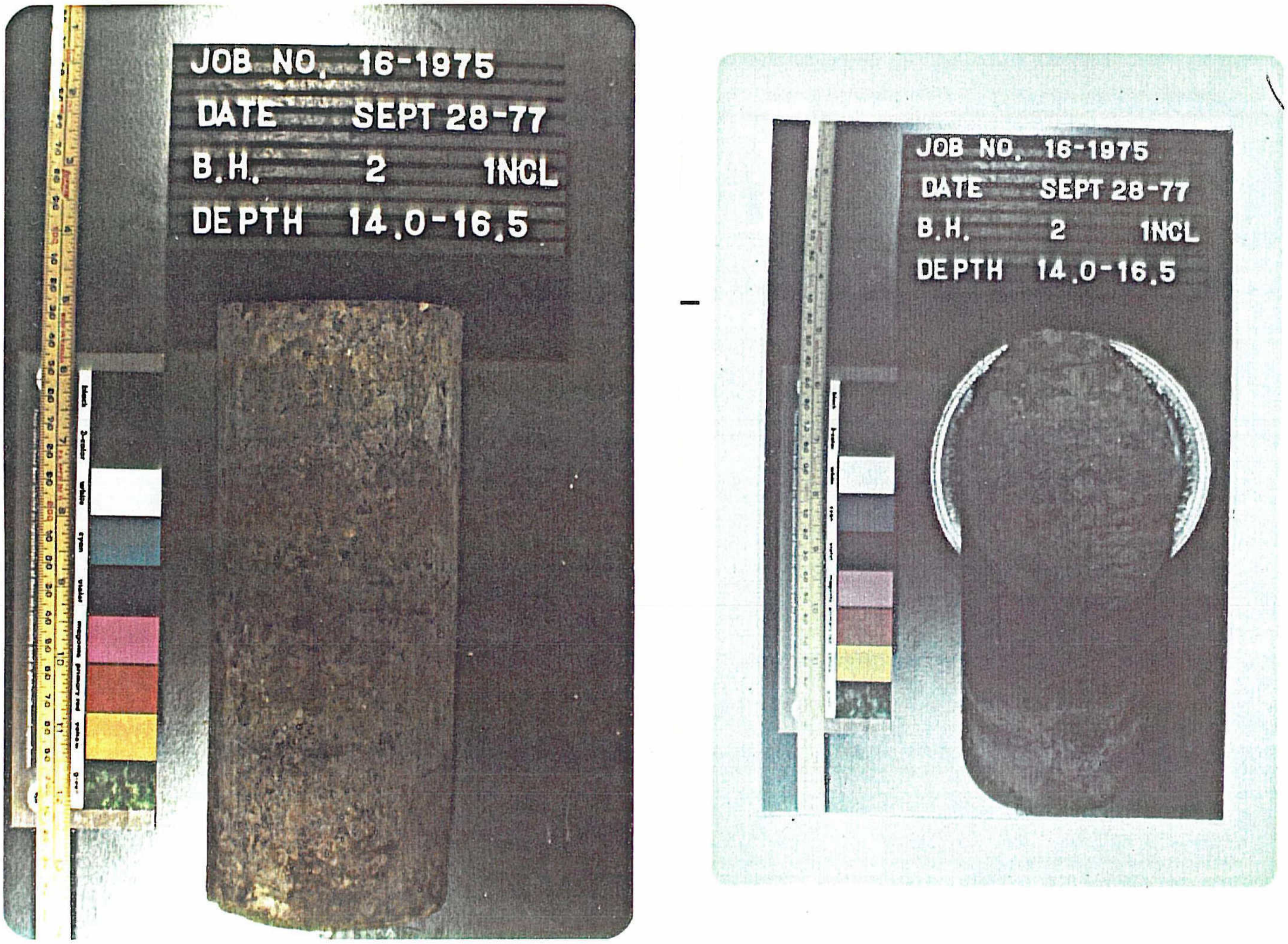


SIDE VIEW

CROSS-SECTIONAL VIEW

PLATE NO. C2-1

(Depth shown in feet, 8.5 - 10 ft = 2.6 - 3.1 m)



SIDE VIEW

CROSS-SECTIONAL VIEW

PLATE NO. C2-2

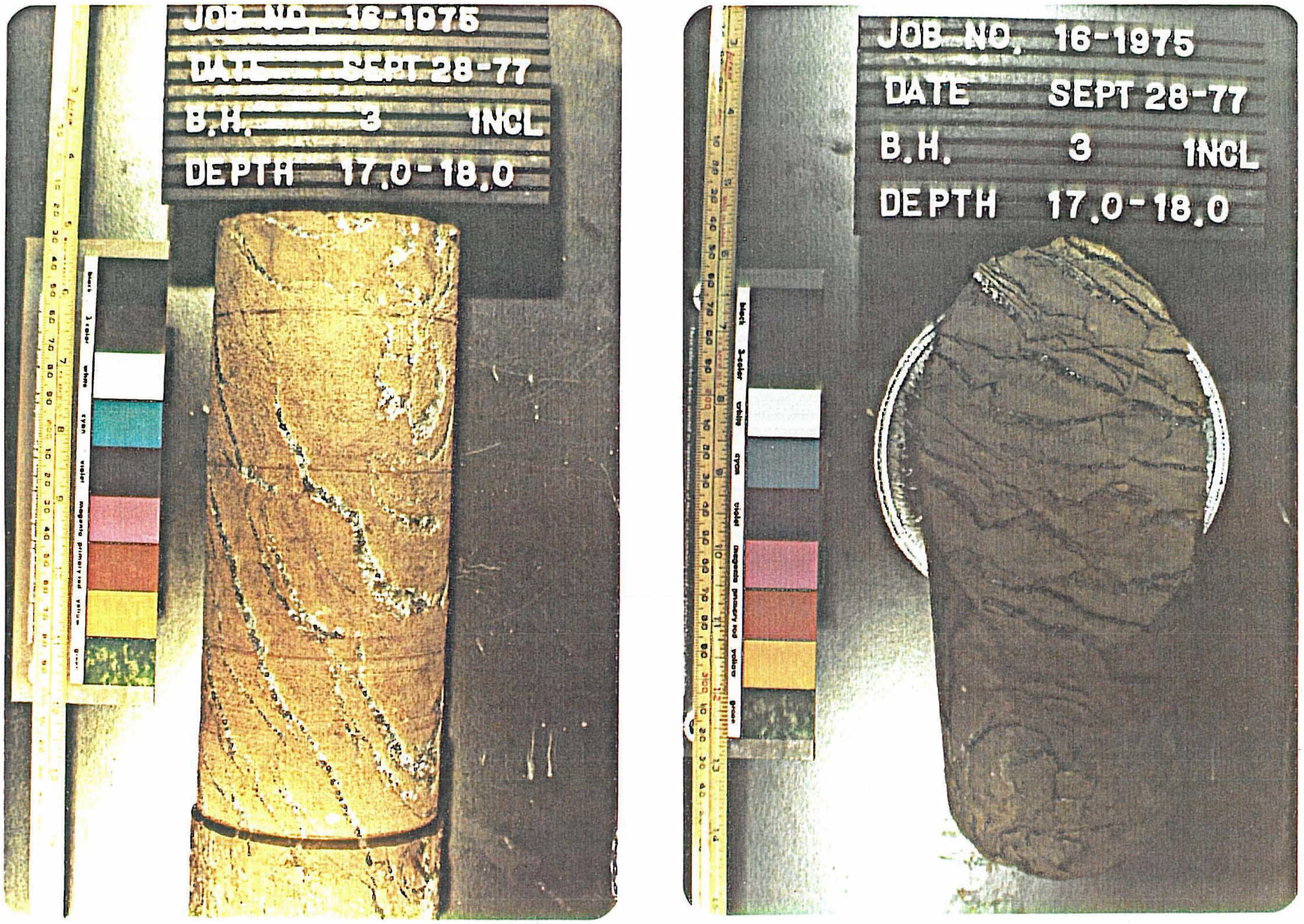
(Depth shown in feet, 14 - 16.5 ft = 4.3 - 5.0 m)

SIDE VIEW

CROSS-SECTIONAL VIEW

PLATE NO. C3-1

(Depth shown in feet, 16. - 17. ft = 4.9 - 5.2 m)

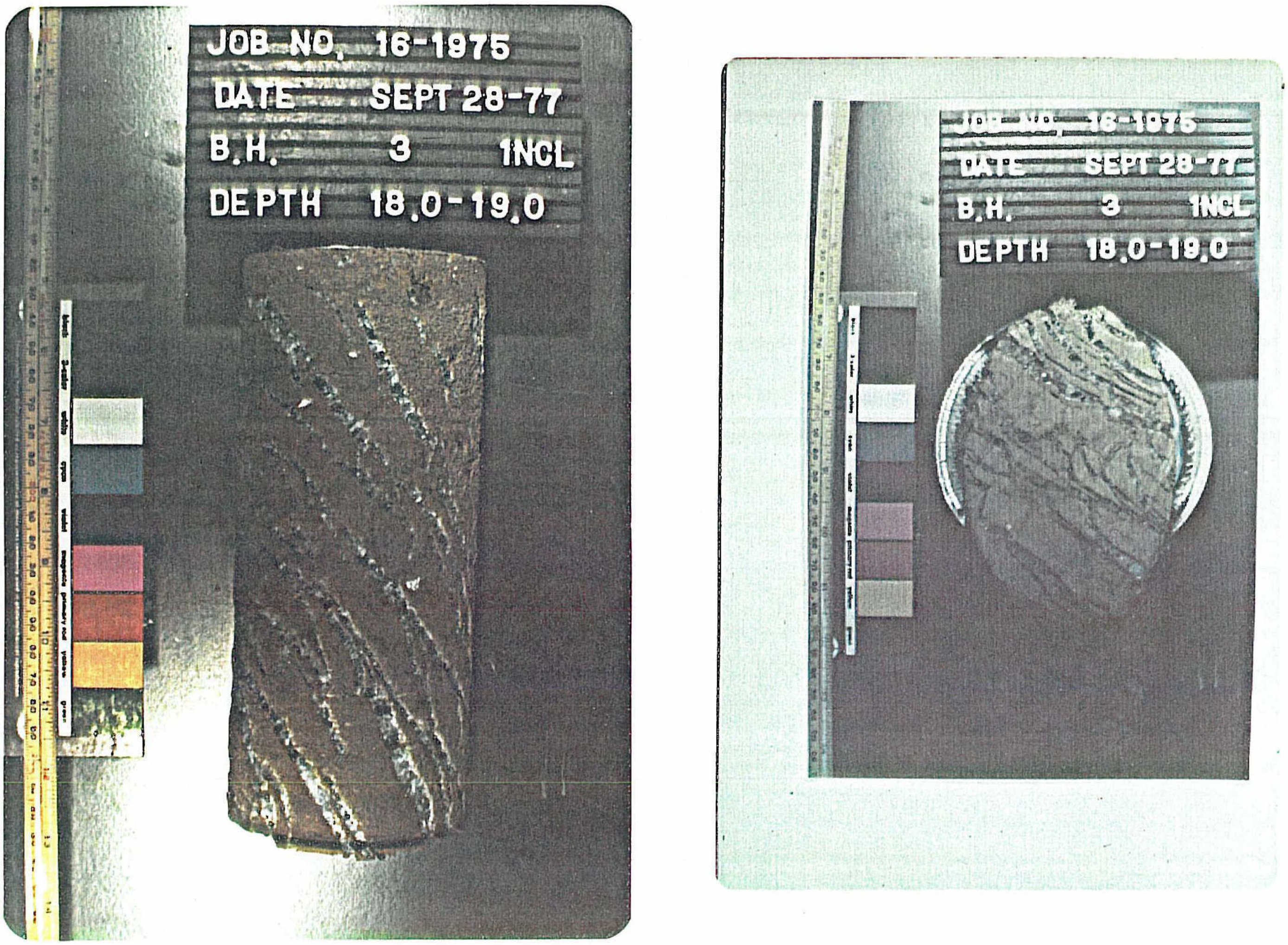


SIDE VIEW

CROSS-SECTIONAL VIEW

PLATE NO. C3-2

(Depth shown in feet, 17. - 18. ft = 5.2 - 5.5 m)



SIDE VIEW

CROSS-SECTIONAL VIEW

PLATE NO. C3-3

(Depth shown in feet, 18. - 19. ft = 5.5 - 5.8 m)

SIDE VIEW

CROSS-SECTIONAL VIEW

PLATE NO. C3-4

(Depth shown in feet, 19. - 20. ft = 5.8 - 6.1 m)

SIDE VIEW

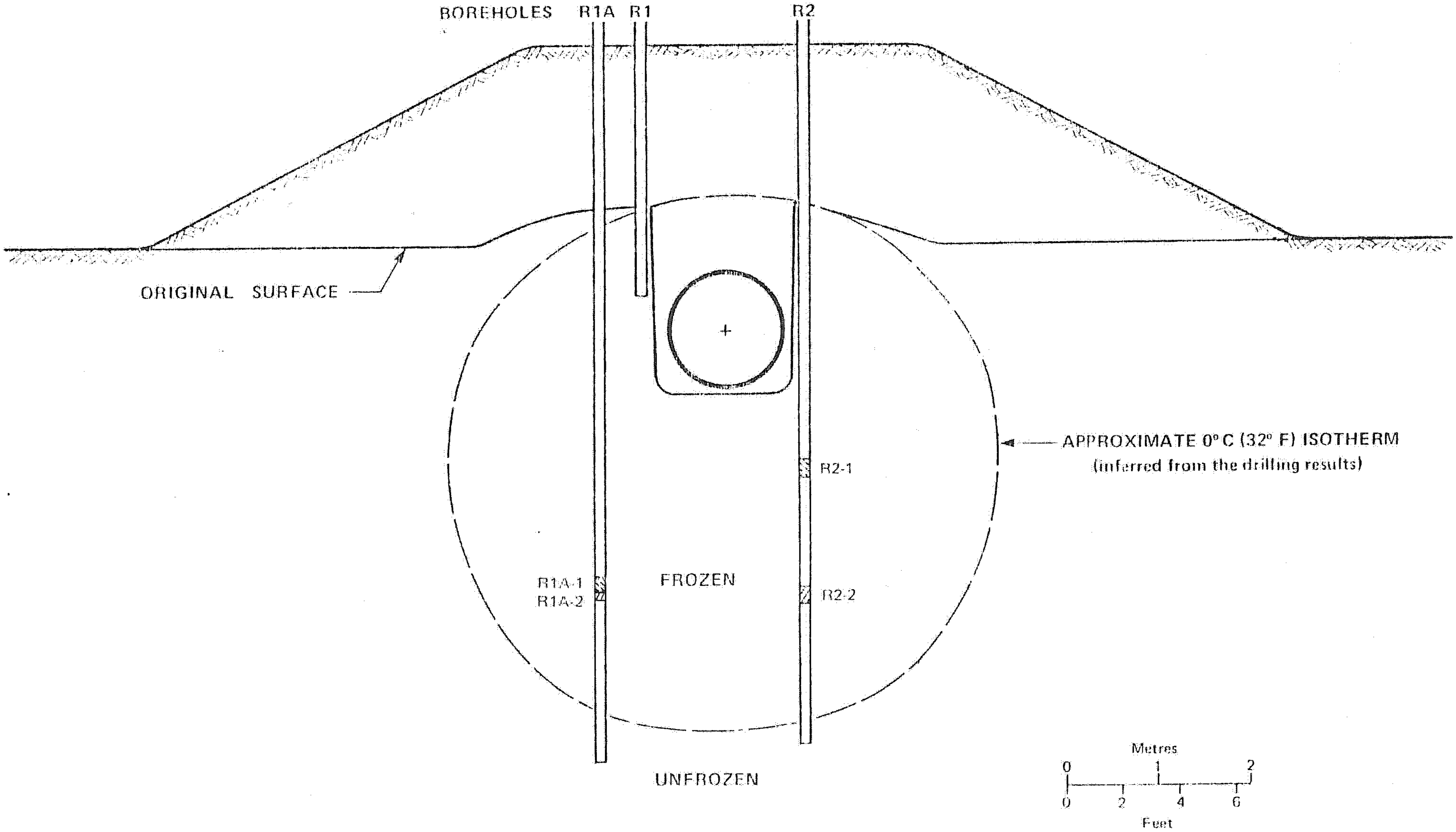
CROSS-SECTIONAL VIEW

PLATE NO. C3-5

(Depth shown in feet, 20.5 - 21.5 ft = 6.3 - 6.6 m)

RESTRAINED SECTION

RESTRAINED SECTION



BOREHOLE LOCATIONS, RESTRAINED SECTION,
CALGARY FROST HEAVE TEST FACILITY
(Section viewed facing north)

PLATE NO. RIA-1

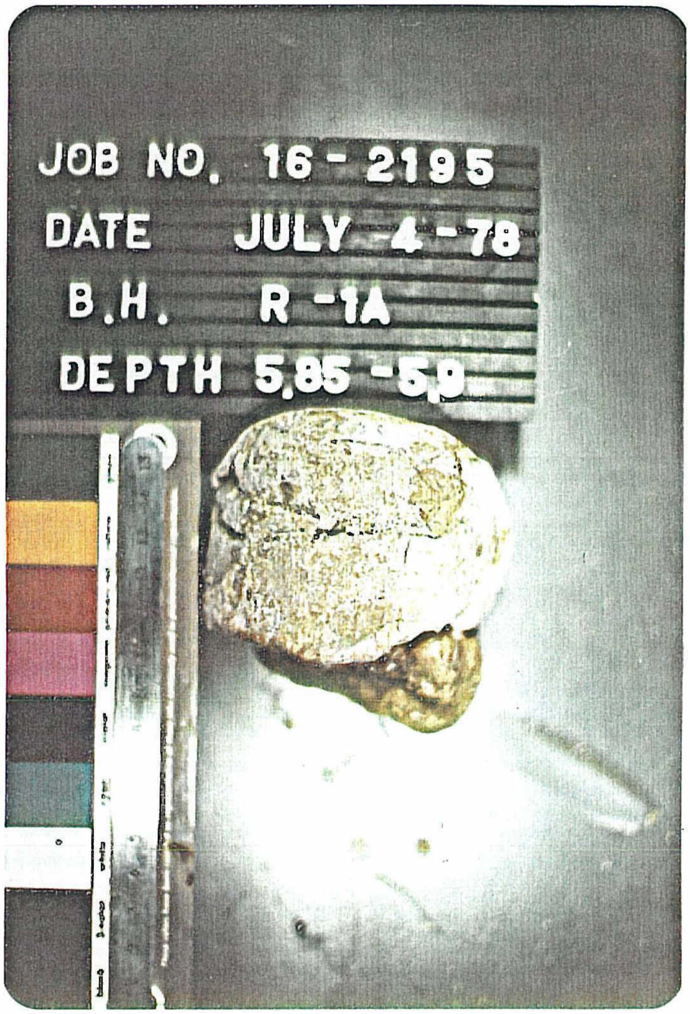


PLATE NO. RIA-2

ICE LENSES: Side View
(Depth shown in metres)

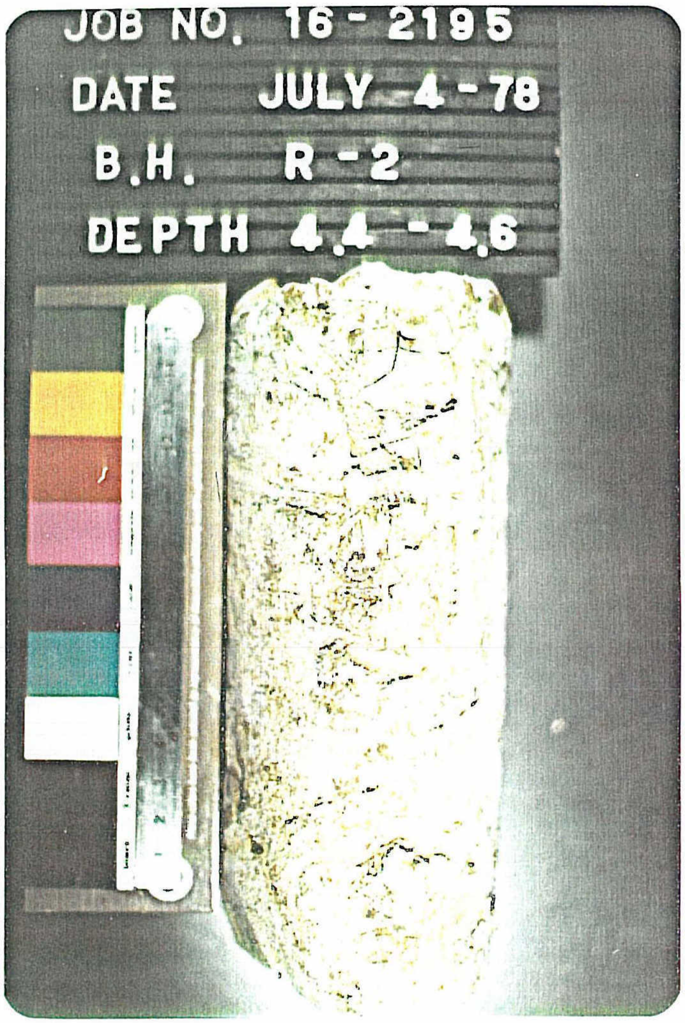


PLATE NO. R2-1

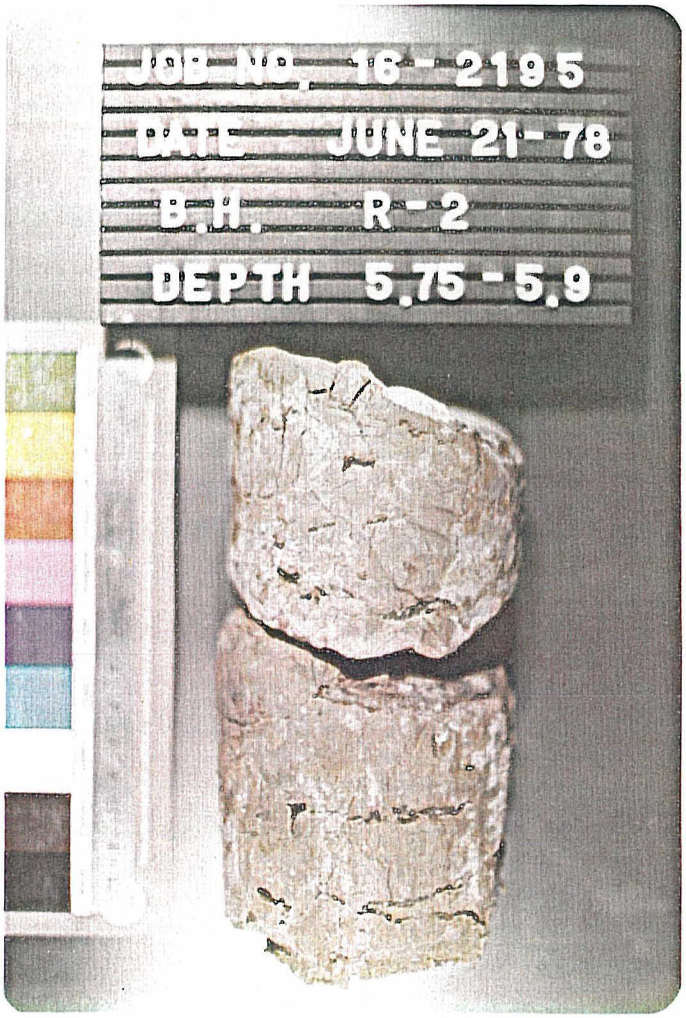
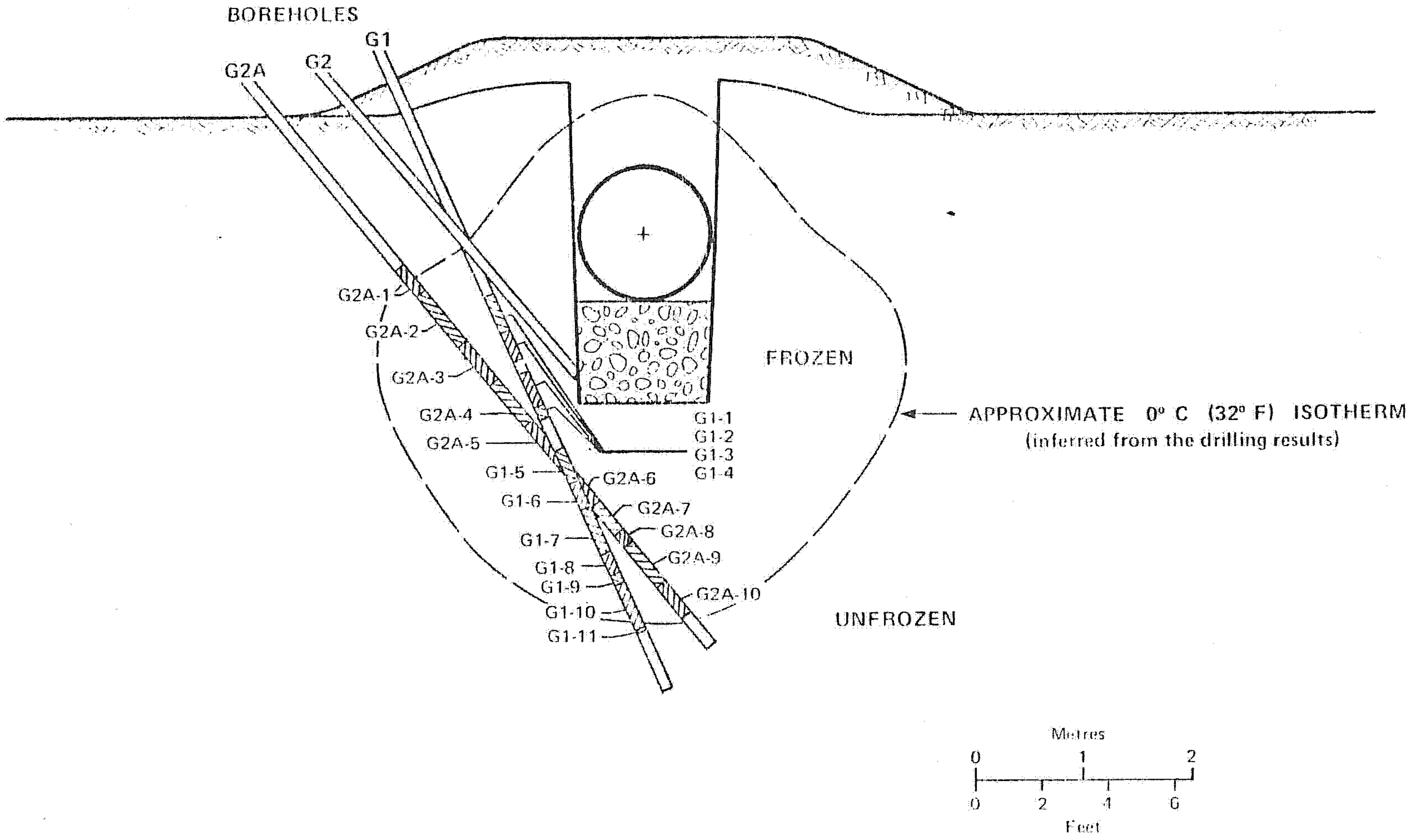


PLATE NO. R2-2

ICE LENSES: Side View
(Depth shown in metres)

FIELD DRILLING - GRAVEL SECTION



BOREHOLE LOCATIONS, GRAVEL BEDDING SECTION,
CALGARY FROST HEAVE TEST FACILITY
(Section viewed facing east)

PLATE NO. G1 - 1

PLATE NO. G1-2

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 7. - 9.1 ft. = 2.13 - 2.77 m)

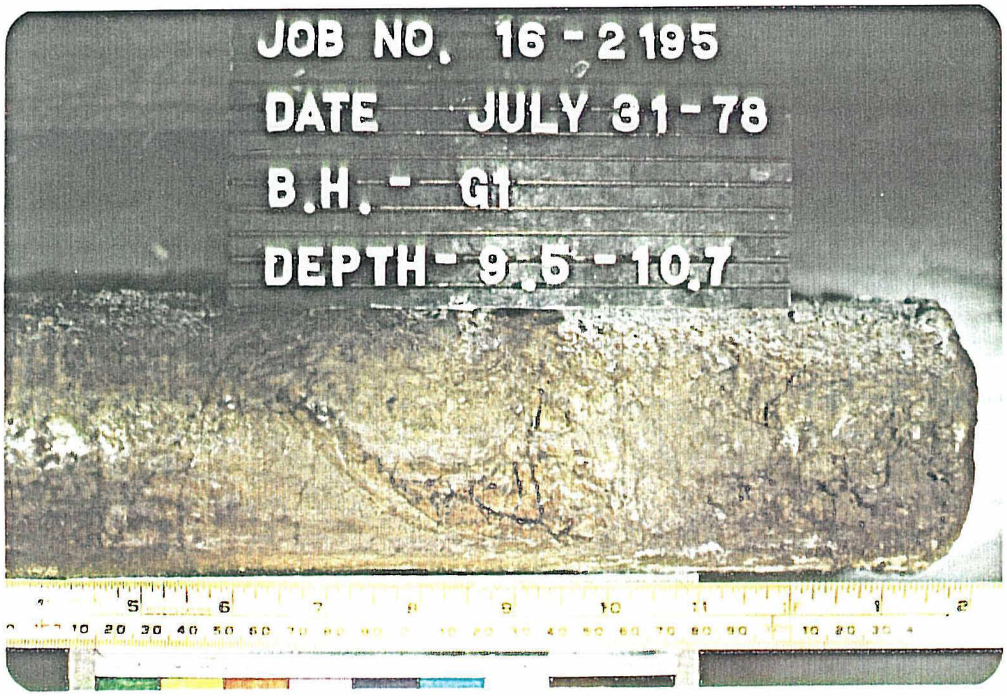


PLATE NO. G1-3

ICE LENSES: Side View of Long Core Sample
(Depth shown in feet. 9.5 - 10.7 ft. = 2.90 - 3.26 m)

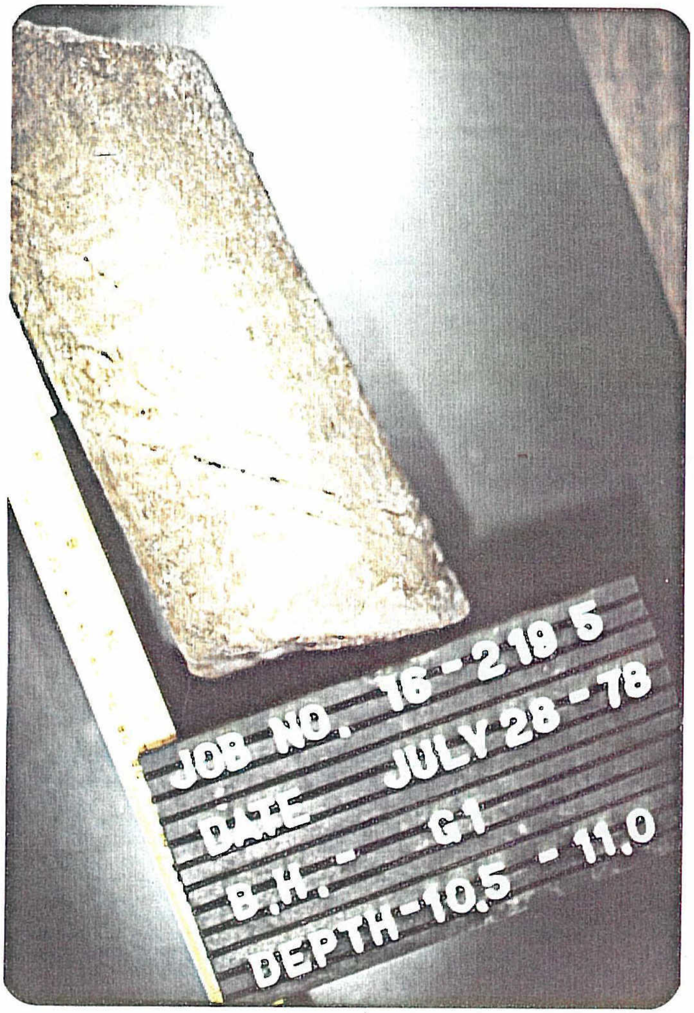


PLATE NO. G1-4

ICE LENSES: Side View
(Depth shown in feet, 10.5 - 11.0 Ft. = 3.20 - 3.35 m)

PLATE NO. G1-5

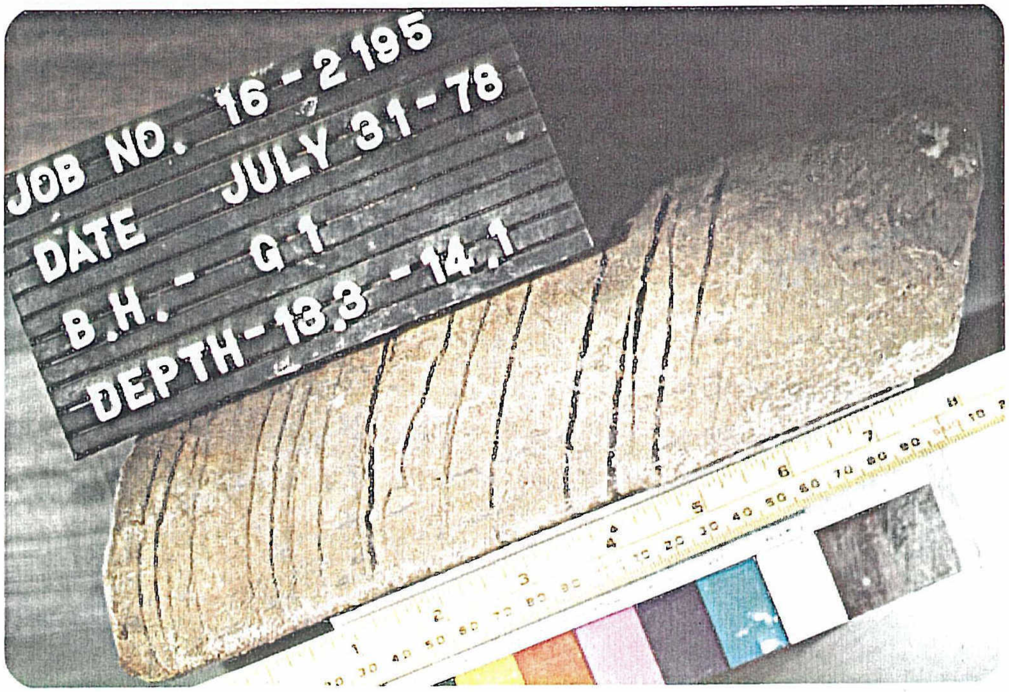


PLATE NO. G1-6

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 12.2 - 14.1 ft. = 3.72 - 4.30 m)

PLATE NO. G1-7

PLATE NO. G1-8

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 14.1 - 16.1 ft. = 4.30 - 4.91 m)

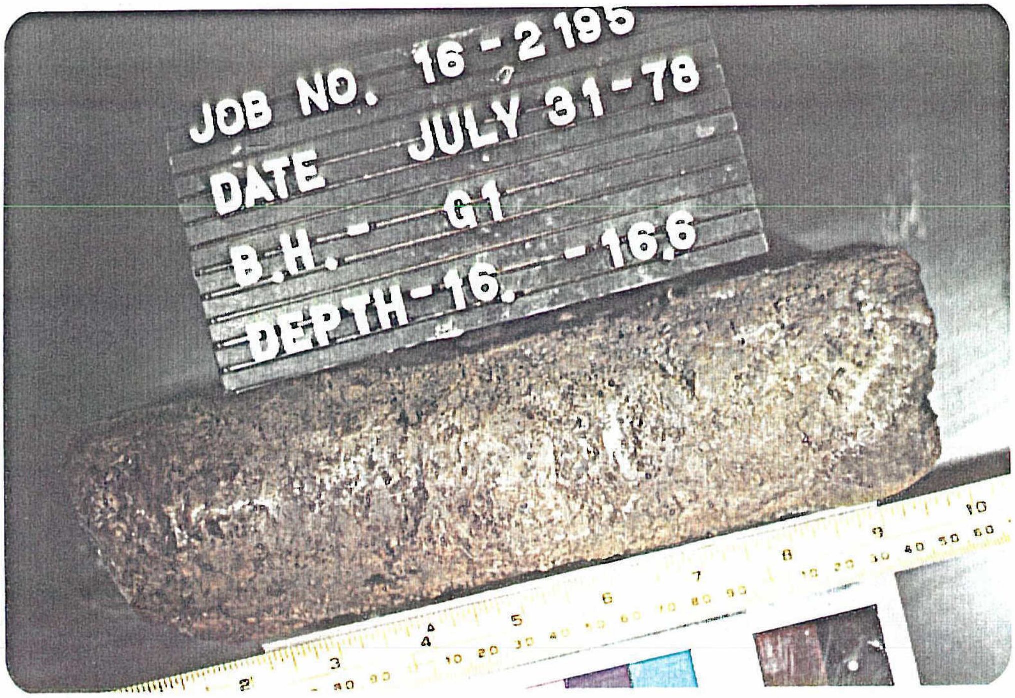


PLATE NO. G1-9

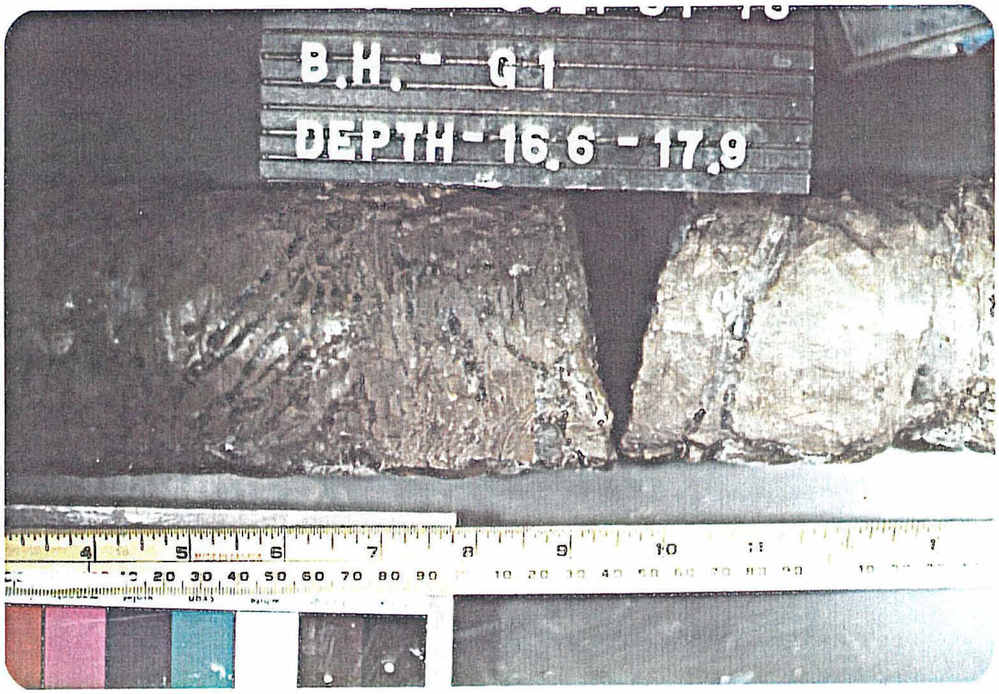


PLATE NO. G1-10

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 16. - 17.9 ft. = 4.88 - 5.46 m)

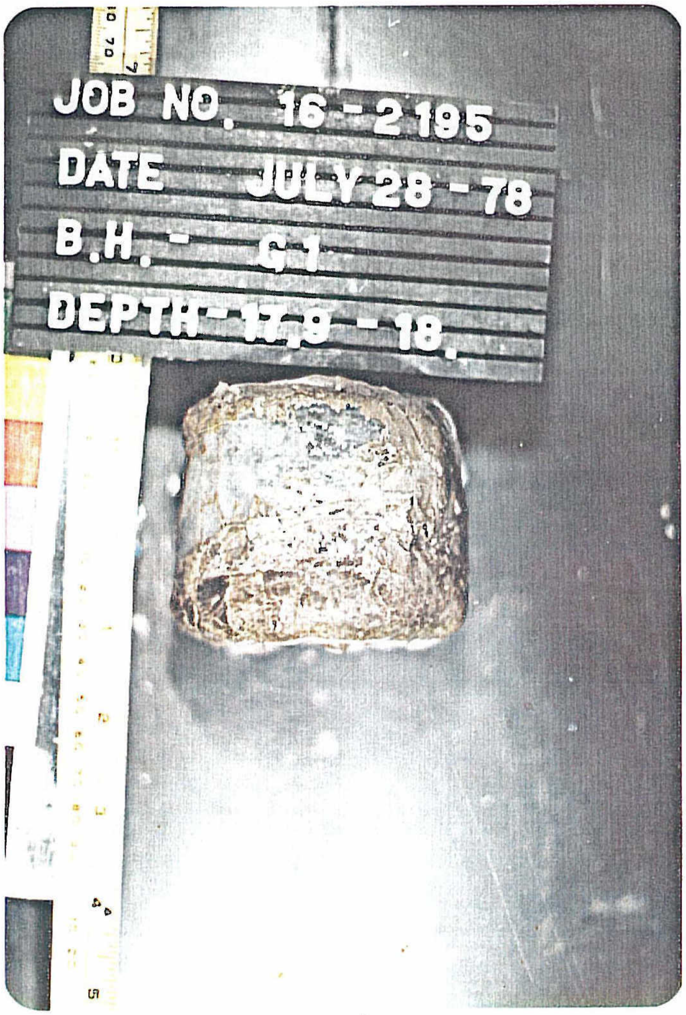


PLATE NO. G1-11

ICE LENSES: Side View

(Depth shown in feet, 17.9 - 18. ft. = 5.46 - 5.49 m)

PLATE NO. G2A - 1

Plate No. G2A-2

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 6. - 9. ft = 1.83 - 2.74 m)

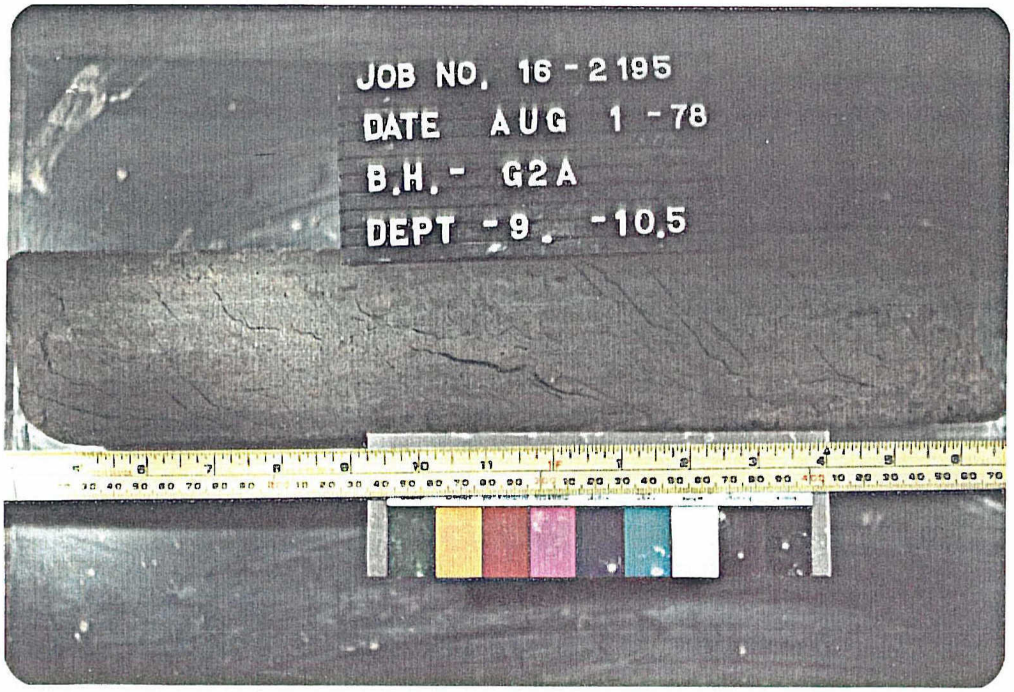


PLATE NO. G2A-3

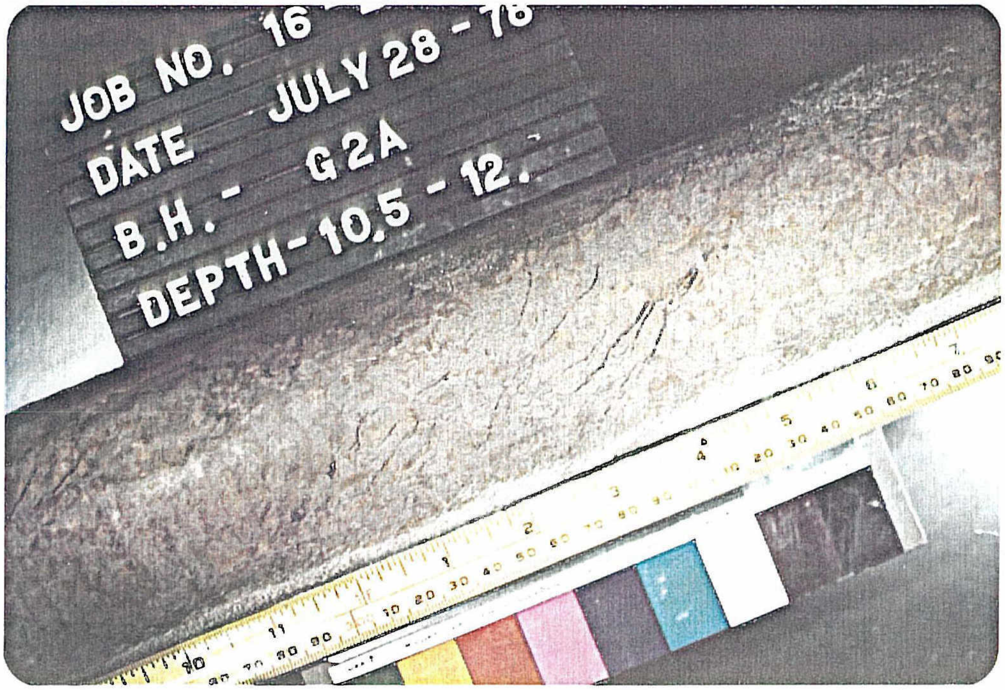


PLATE NO. G2A-4

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 9. - 12. ft = 2.74 - 3.66 m)

PLATE NO. G2A-5

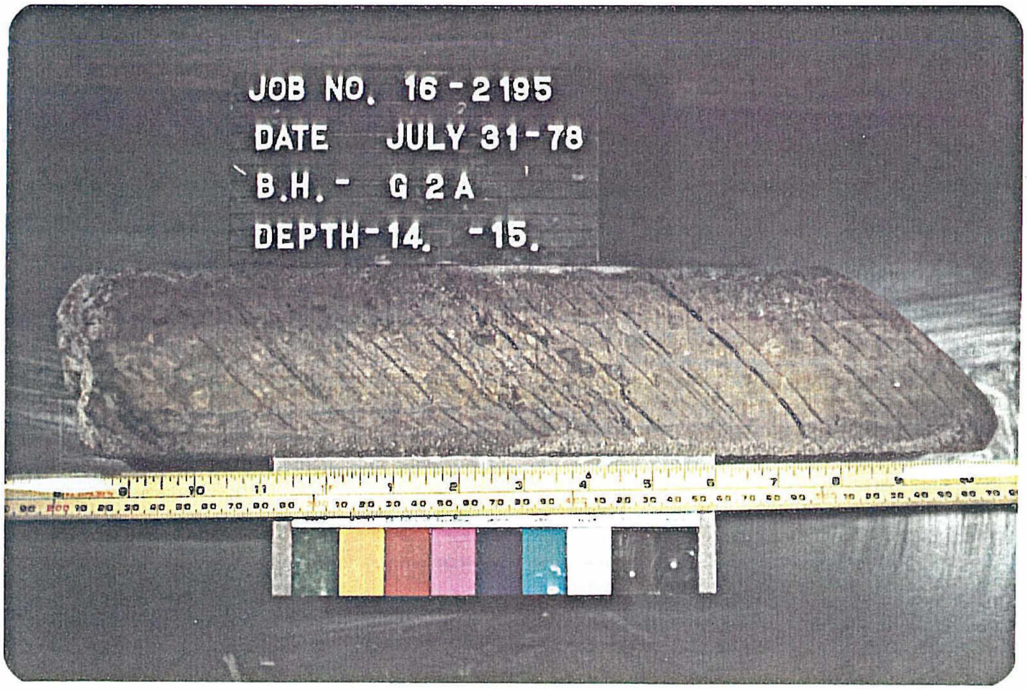


PLATE NO. G2A-6

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 12. - 15. ft = 3.66 - 4.57 m)

PLATE NO. G2A-7

ICE LENSES: Side View of Long Core Sample

(Depth shown in feet, 15. - 16. ft = 4.57 - 4.88 m)

503.3.4

NORTHWEST ALASKAN PIPELINE COMPANY

1801 K Street, N.W.
Washington, D.C. 20006
(202) 466-5850

GOA-80-1024

RECEIVED
FEB 26 1980
State of Alaska
Office of
Pipeline Coordinator

FC C
DPC
AO
SA
LMO
F&G
DEC
ANCH
AG
OTHER

FILE COPY

February 22, 1980

The Honorable John T. Rhett, Jr.
Federal Inspector
Alaska Natural Gas Transportation System
P.O. Box 19400
Washington, DC 20036

Attn: Earl Ausman

Re: <u>Frost Heave Document Transmittal (#1)</u>

Dear Mr. Rhett:

During the frost heave meeting in Reston on February 5,6, and 7, 1980, Northwest agreed to provide sufficient updated information so that an in-depth review of our frost heave program could be made at least two weeks prior to the March 12-13 meeting in Irvine, California.

The information to be provided concerned:

a. Frost Heave Field Test Sites for 1980
b. Laboratory Tests and Model Development
c. Calgary Frost Heave Test Facility Performance Analysis, and
d. Fairbanks Test Facility Frost Heave Predicitons

Items "a" and "b" have been combined into one report which will be distributed under separate cover by express delivery.

We don't have yet, CEB. 5-9-80

Item "c," entitled "Performance Analysis of Calgary Frost Heave Test Facility," dated September 1, 1979, was recently approved for release by Foothills and is enclosed for your immediate review. It provides considerable heretofore unpublished data on the longest existing full-scale frost heave testing program.

Item "d" is still incomplete, but is undergoing final revisions by our consultant. It will be forwarded to you as soon as it is received. Item "d" is the least important of these documents for purposes of understanding our design approach. As we have discussed with Mr. Earl Ausman of your staff, who agrees, this delayed item will not inhibit a thorough review of the NWA frost heave programs.

A SUBSIDIARY OF NORTHWEST ENERGY COMPANY

We are distributing the enclosure directly to the persons on the attached distribution list, which was provided by Mr. Paul Fisher. The remaining documents described above will be handled in the same manner.

Yours truly,

NORTHWEST ALASKAN PIPELINE COMPANY

Edwin A. Kuhn

Edwin (Al) Kuhn
Director
Government and Environmental Affairs

EAK/rlc

Enclosures

cc: (w/enc; see attached
distribution list)

2/22/80

Distribution for Frost Heave Documents

Quantity	Names	Location
1	Paul Fisher	U.S. Army Corps of Engineers 20 Massachusetts Ave, NW Room 6135 Washington, DC 20314
2	Earl Ausman	Office of Federal Inspector 2000 M Street, NW Room 3104 Washington, DC 20036
1	Phil Essley	FERC 941 N. Capitol St., NE Room 3004 Washington, DC 20426
1	Lloyd Ulrich	U.S. DOT NASSIF Bldg. Room 8105 400 7th St., SW Washington, DC 20590
3	Reuben Katchadoorian John Williams Tom Overshine	USGS, Branch of Alaska Geology, Bldg. No. 2 354 Middlefield Road Menlo Park, CA 94025
3	Harlan Moore (COE) Don Keyes (DOI) Charles Sloan (USGS)	COE, Alaskan Dist., Eng. Div. Bldg 21700, Elmendorf AFB Anchorage, AK 99502
1	Charles Behlke	Alaska State Pipeline Coord. 1001 Noble Street, Suite 450 Fairbanks, AK 99701
4	William Quinn	CRREL P.O. Box 345 Lyme Rd. Hanover, NH 03755
1	Prof. R.O. Miller	Dept. of Agronomy Cornell University Ithaca, NY 14853
1	Edward Penner	Div. of Building Research National Reserach Council of Canada Montreal Road Laboratories Bldg. M20 Ottawa, CANADA K1AOR6

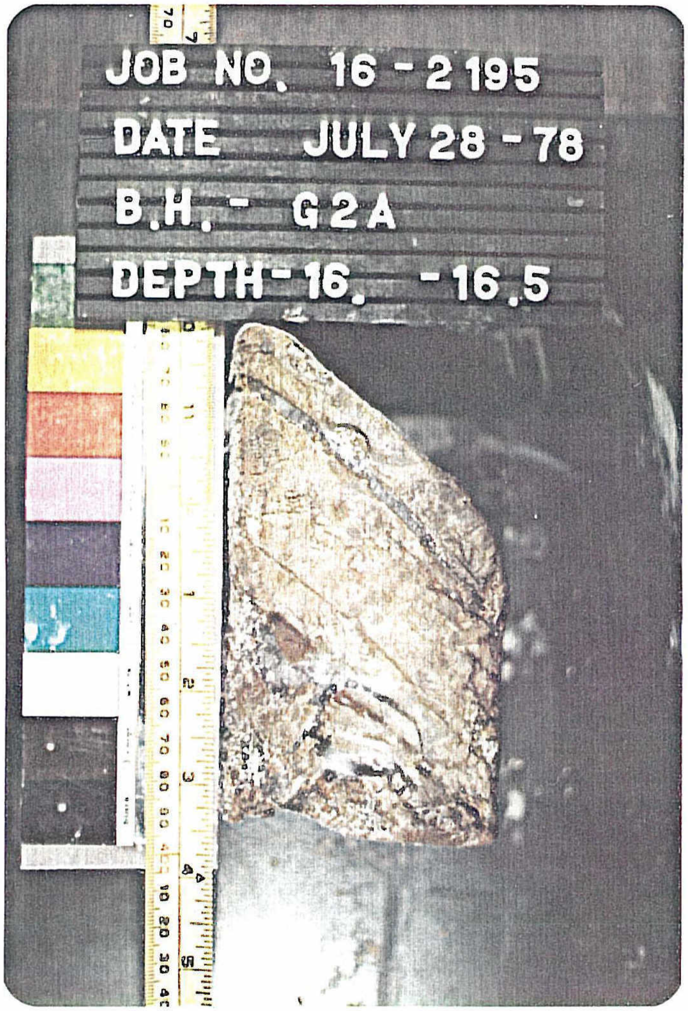


PLATE NO. G2A-8

ICE LENSES: Side View

(Depth shown in feet, 16. - 16.5 ft = 4.88 - 5.03 m)

PLATE NO. G2A-9

ICE LENSES: Side View of Long Core Sample
(Depth shown in feet, 16.5 - 18.2 ft = 5.03 - 5.55 m)

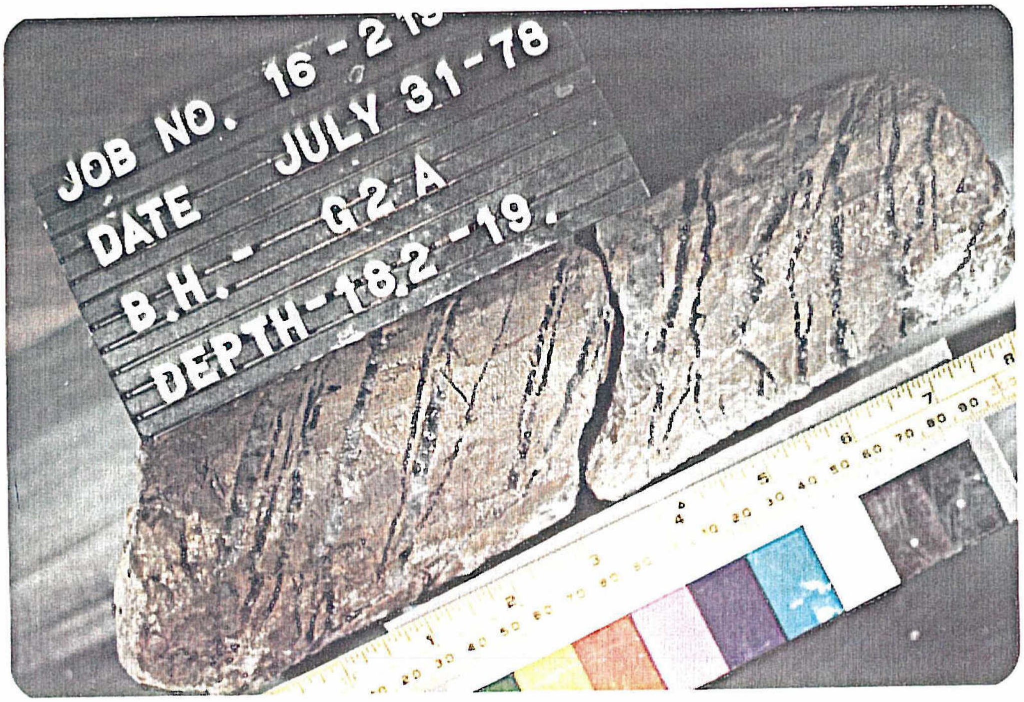
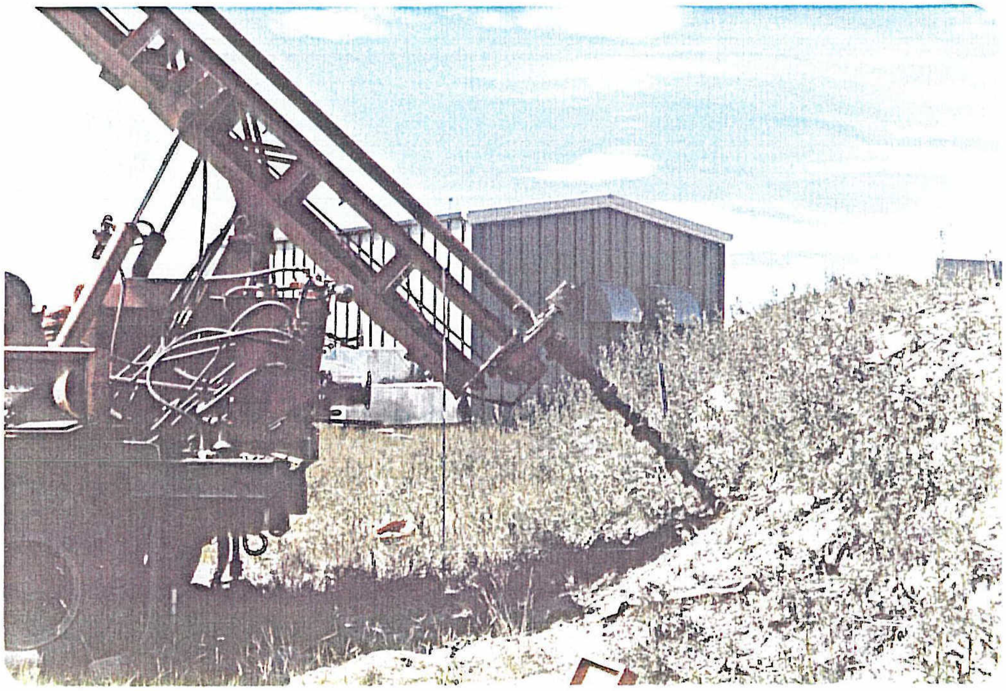


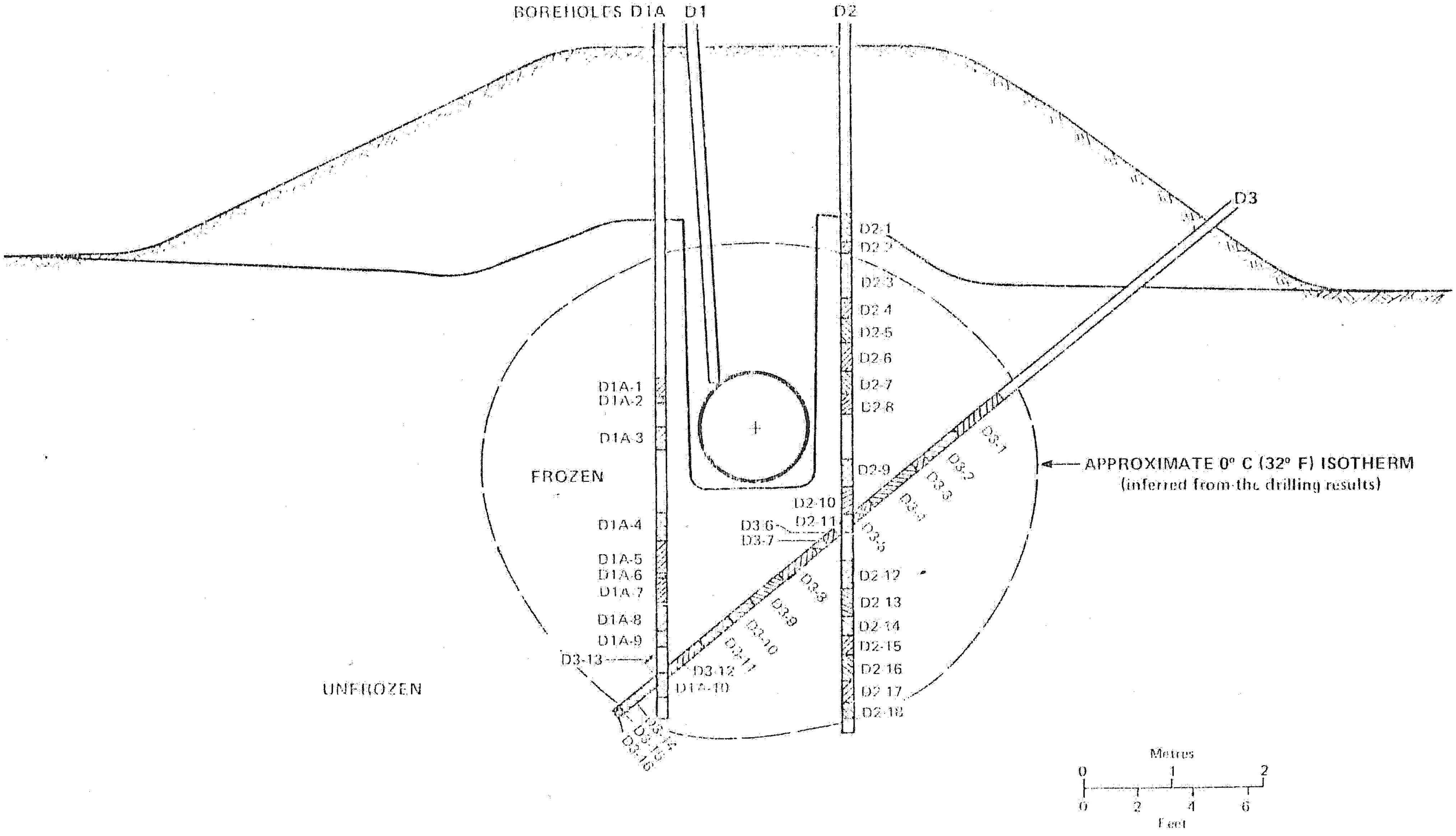
PLATE NO. G2A-10

ICE LENSES: Side View
(Depth shown in feet, 18.2 - 19. ft = 5.55 - 5.79 m)

DEEP BURIAL SECTION



FIELD DRILLING - DEEP BURIAL SECTION



BOREHOLE LOCATIONS, DEEP BURIAL SECTION,
CALGARY FROST HEAVE TEST FACILITY
(Section viewed facing north)

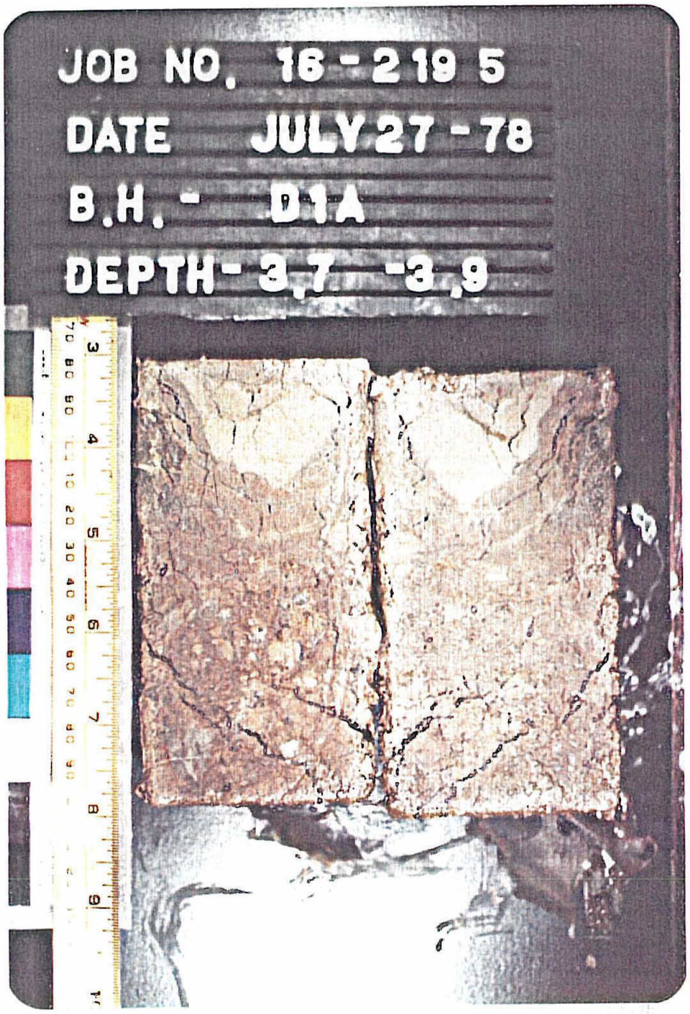


PLATE NO. D1A - 1

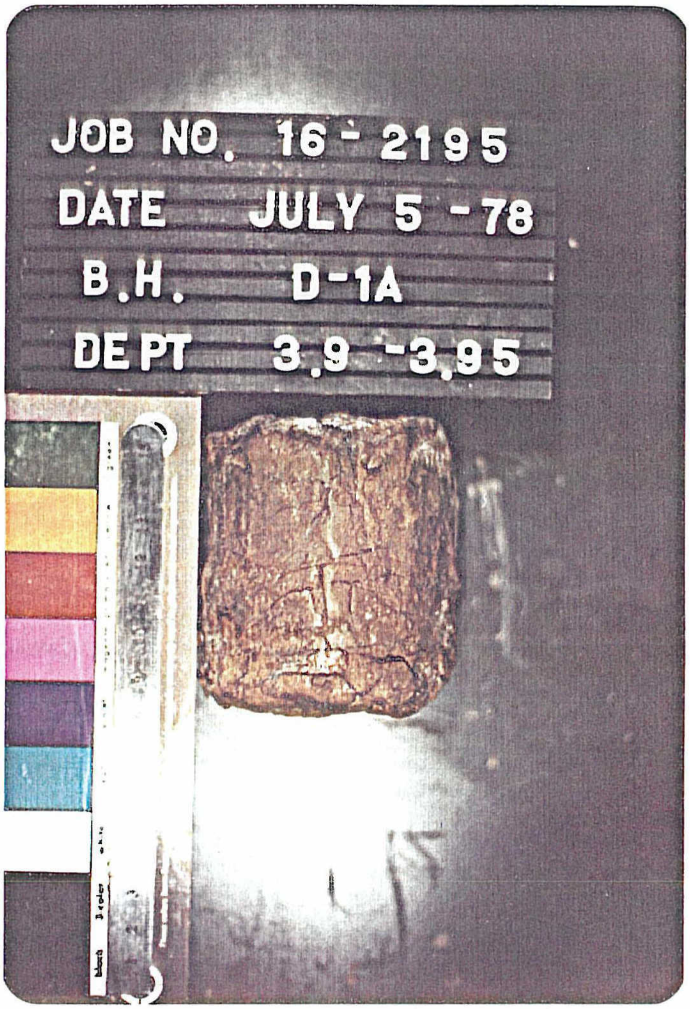


PLATE NO. D1A -2

ICE LENSES: Cross-Sectional View (D1A - 1)
Side View (D1A - 2)
(Depth shown in metres)

PLATE NO. D1A - 3

ICE LENSES: Cross-Sectional View
(Depth shown in metres)

SIDE VIEW

CROSS-SECTIONAL VIEW

PLATE NO. D1A - 4

(Depth shown in metres)

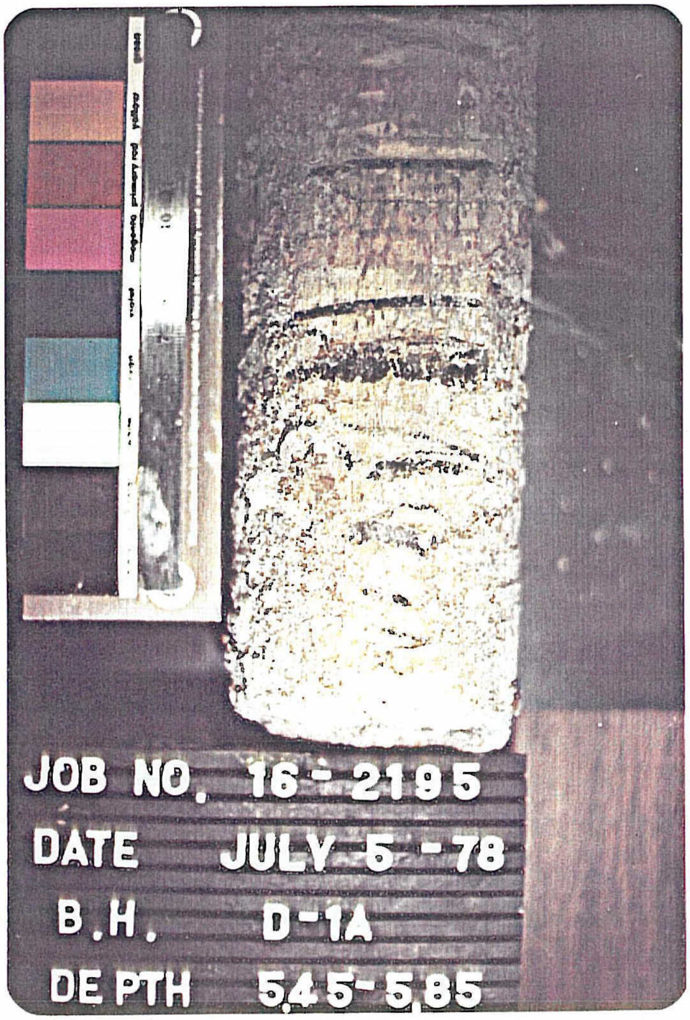


PLATE NO. D1A - 5

ICE LENSES: Side View
(Depth shown in metres)

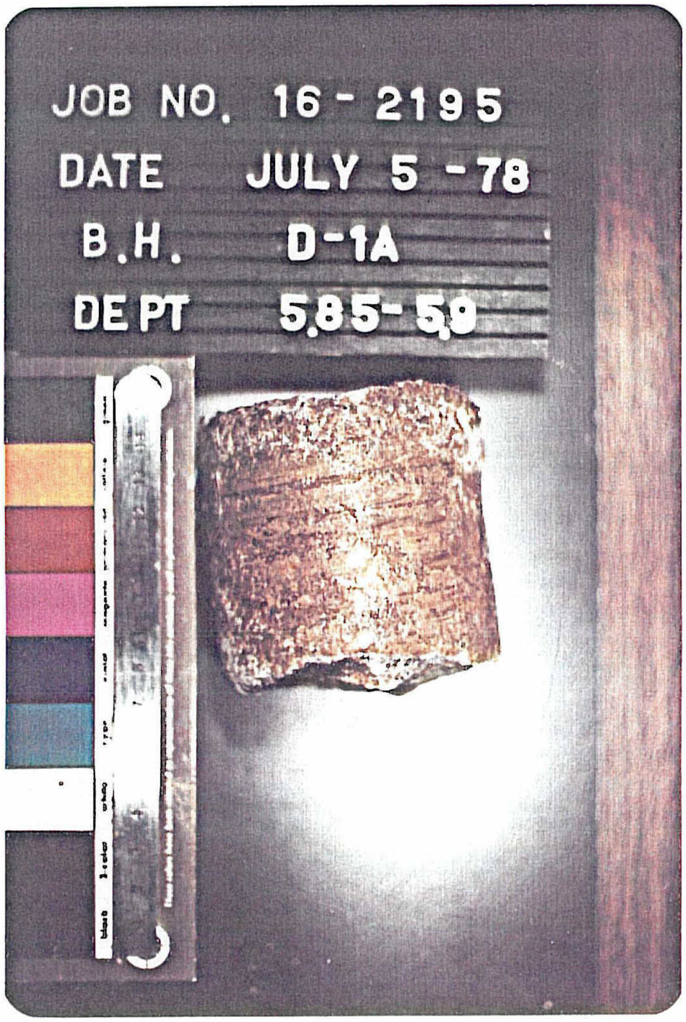


PLATE NO. D1A - 6

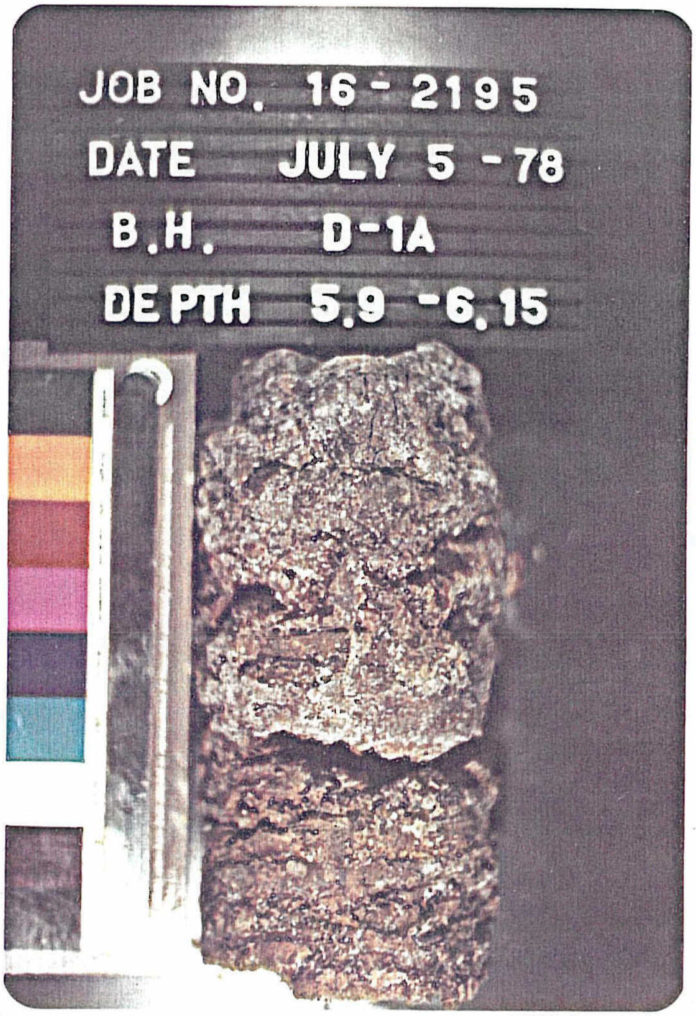


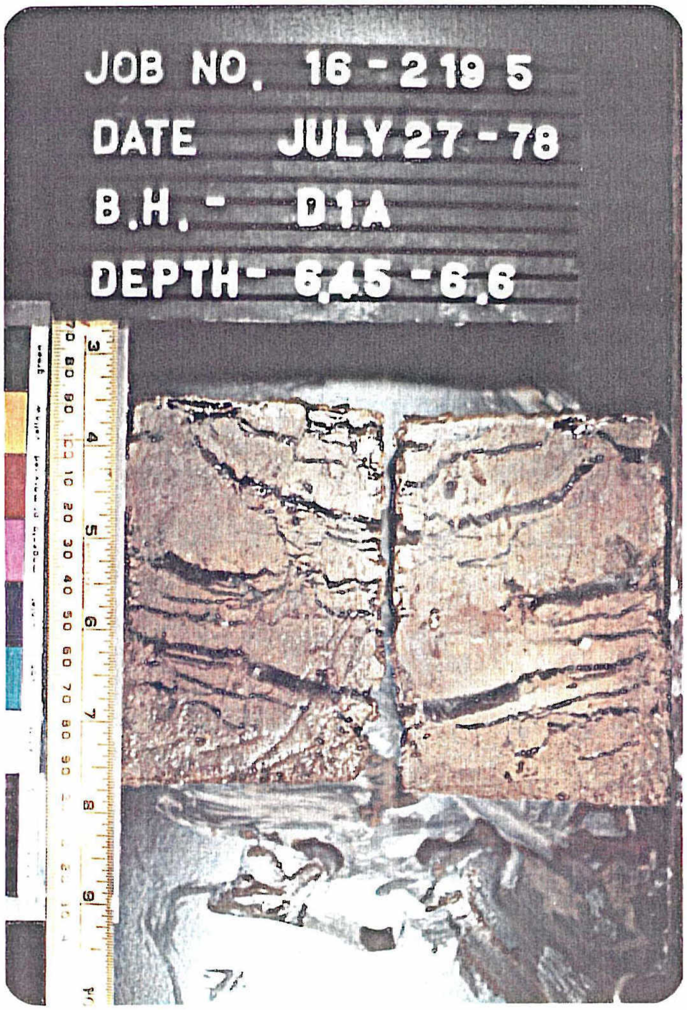
PLATE NO. D1A - 7

ICE LENSES: Side View
(Depth shown in metres)

PLATE NO. D1A - 8

ICE LENSES : Side View
(Depth shown in metres)

SIDE VIEW



CROSS-SECTIONAL VIEW

PLATE NO. D1A - 9

(Depth shown in metres)

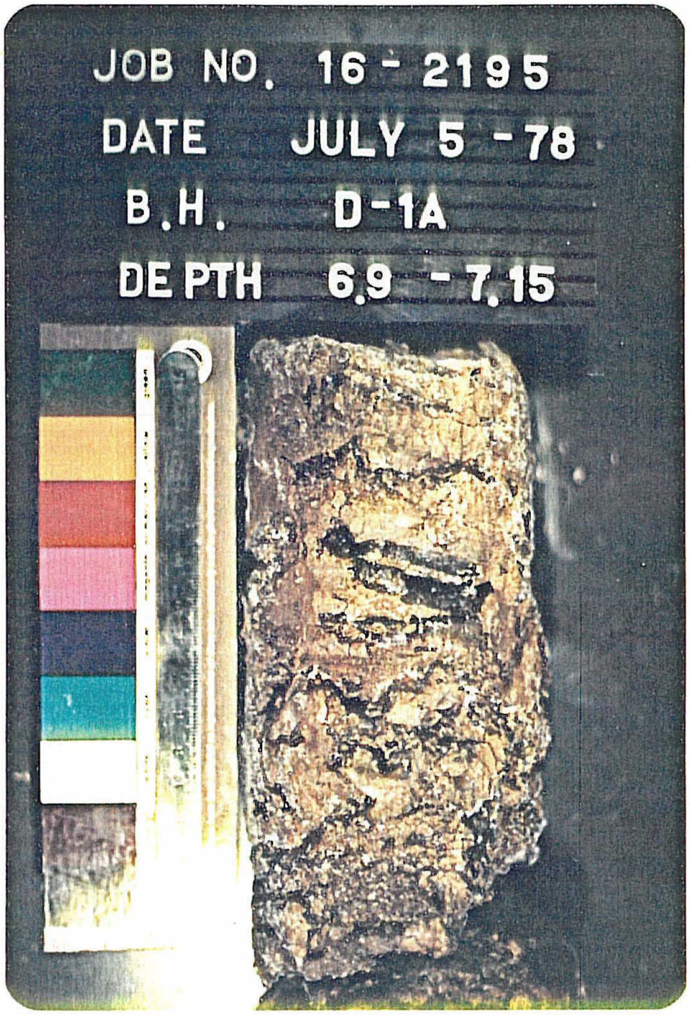


PLATE NO. D1A - 10

ICE LENSES: Side View
(Depth shown in metres)

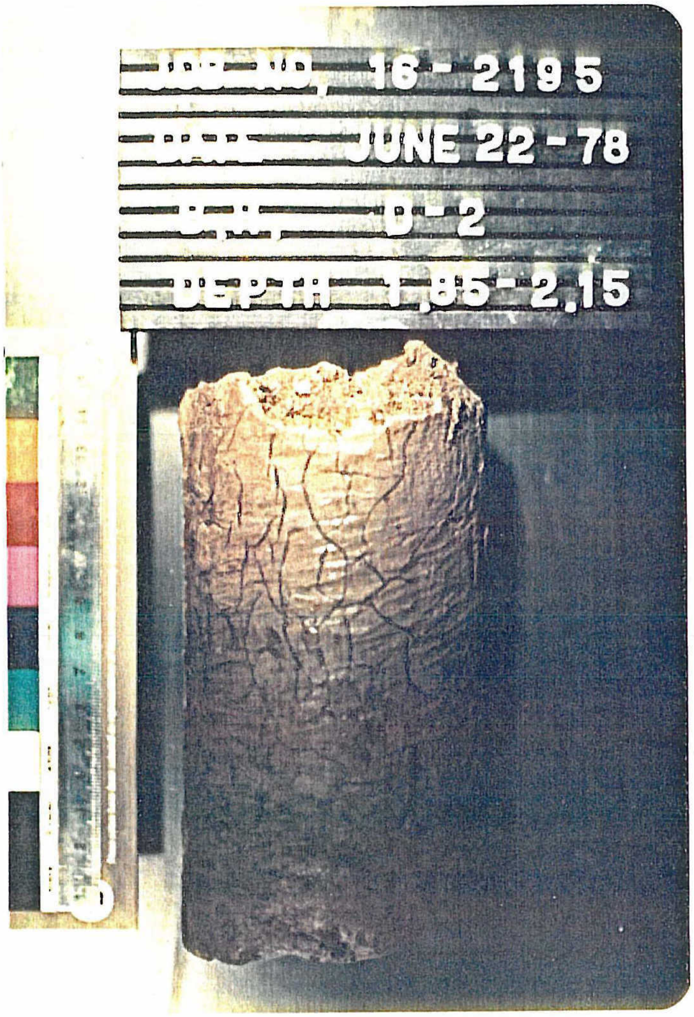


PLATE NO. D2 - 1

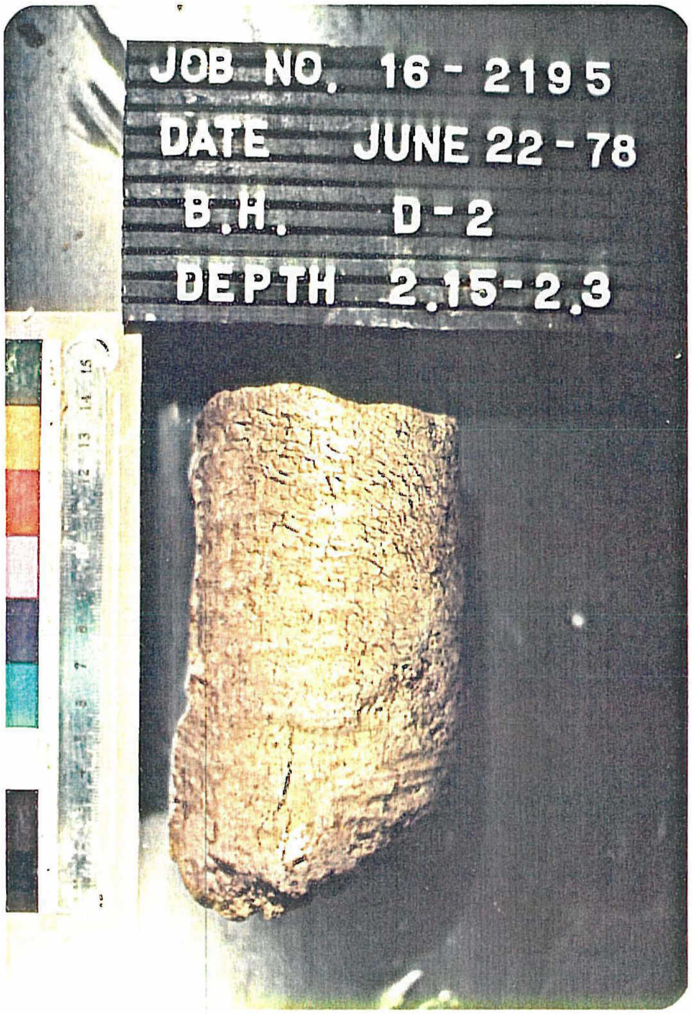


PLATE NO. D2 - 2

ICE LENSES: Side View

(Depth shown in metres)

PLATE NO. D2 - 3

PLATE NO. D2 - 4

ICE LENSES: Cross-Sectional View (D2-3)

Side View (D2-4)

(Depth shown in metres)

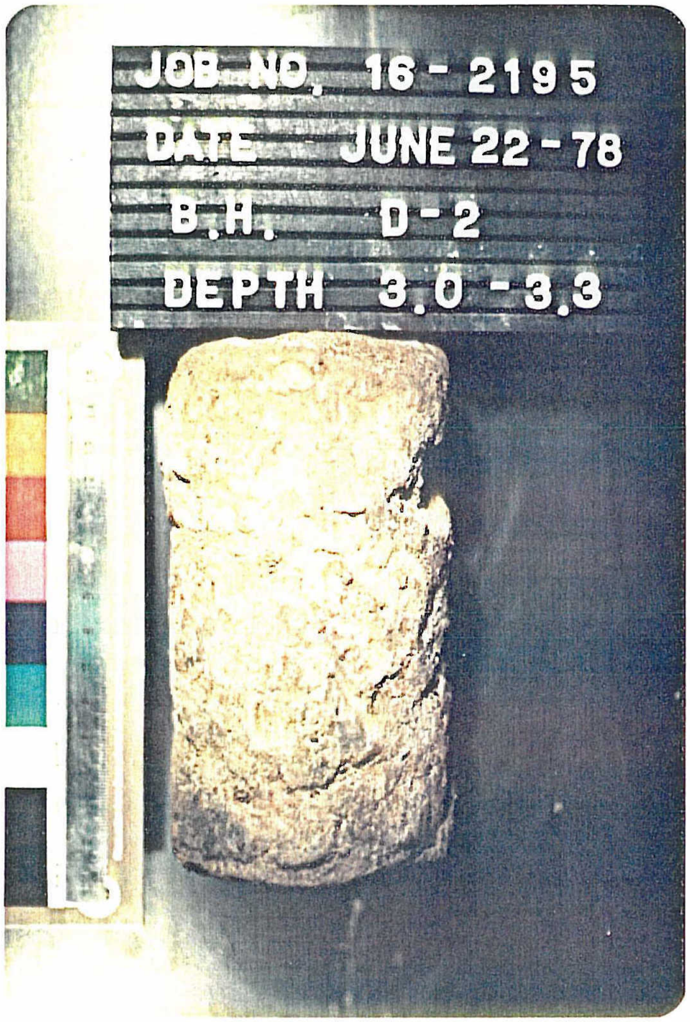


PLATE NO. D2-5

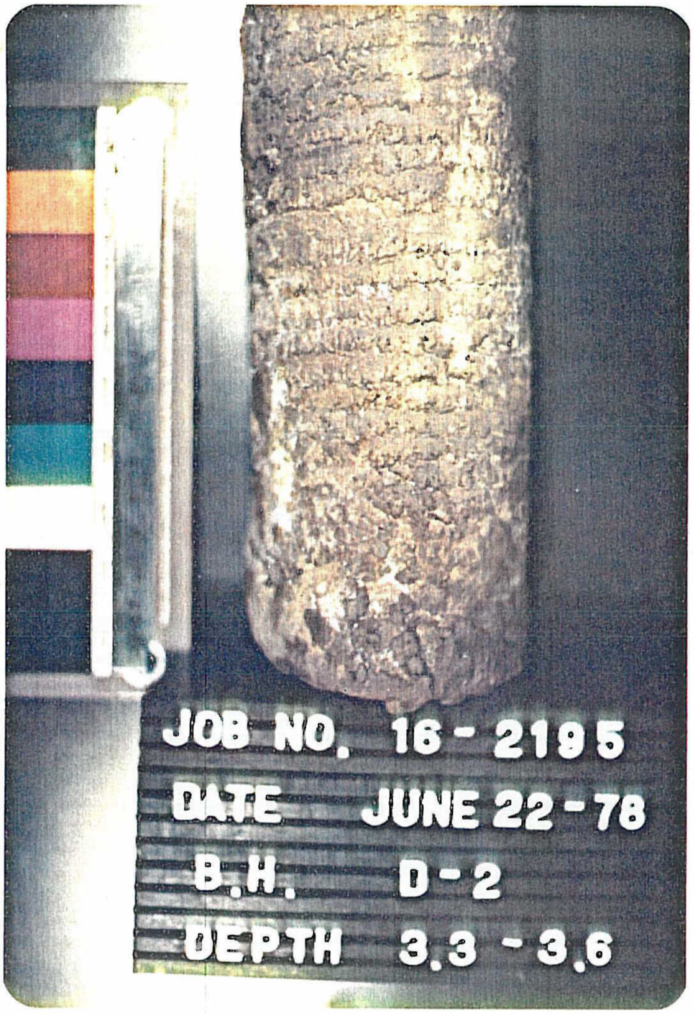


PLATE NO. D2-6

ICE LENSES: Side View
(Depth shown in metres)

PLATE NO. D2-7

PLATE NO. D2-8

ICE LENSES: Side View

(Depth shown in metres; D2-8: 3.9 - 4.1 m)

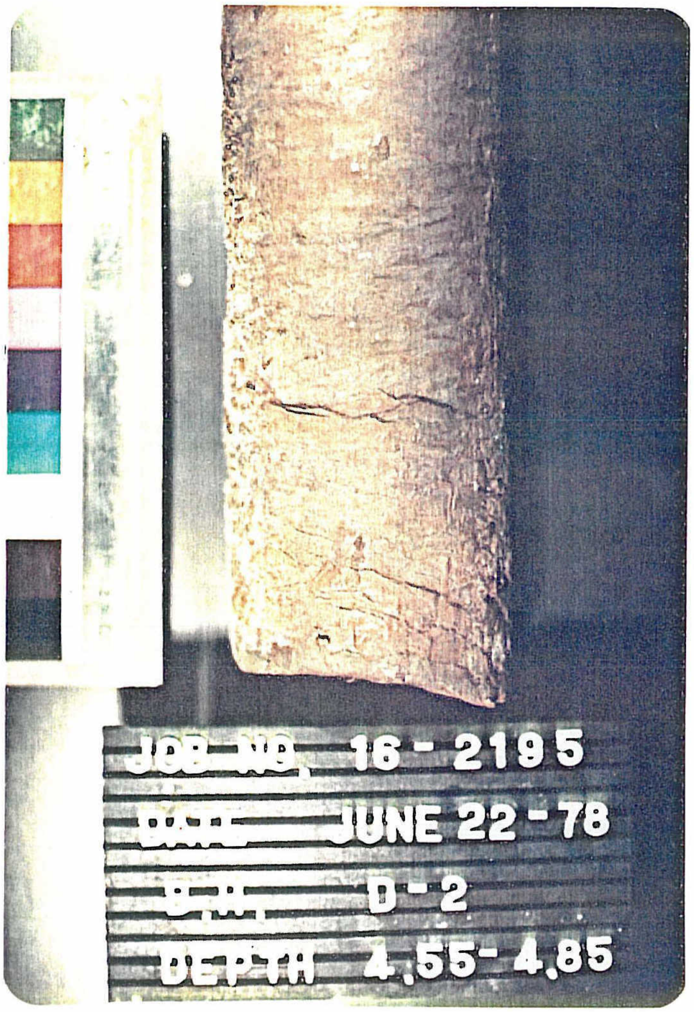


PLATE NO. D2-9

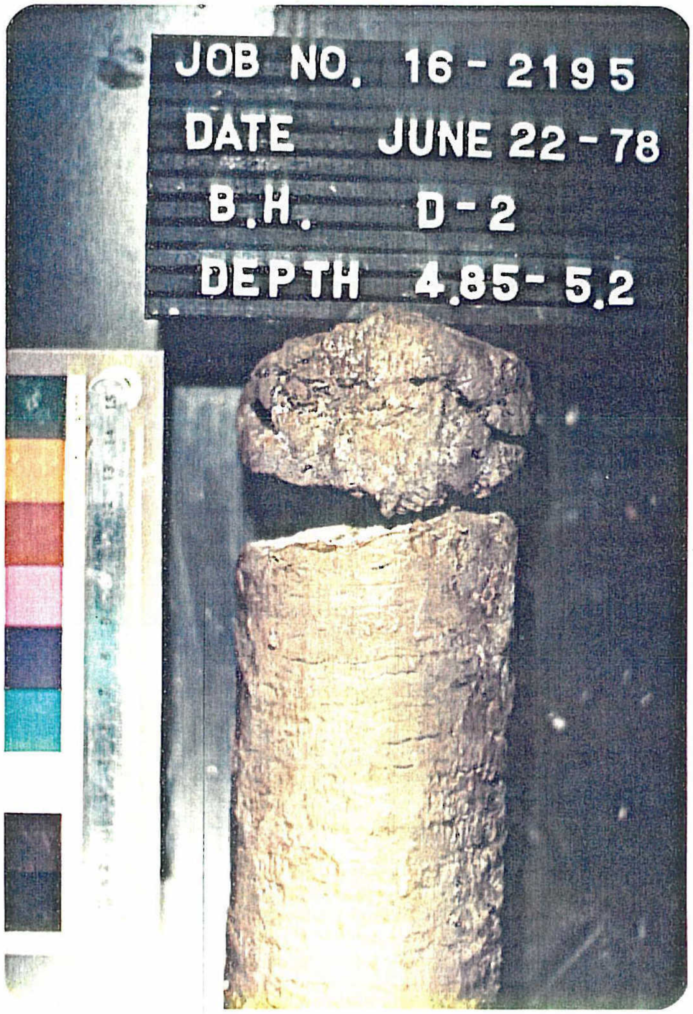


PLATE NO. D2-10

ICE LENSES: Side View
(Depth shown in metres)

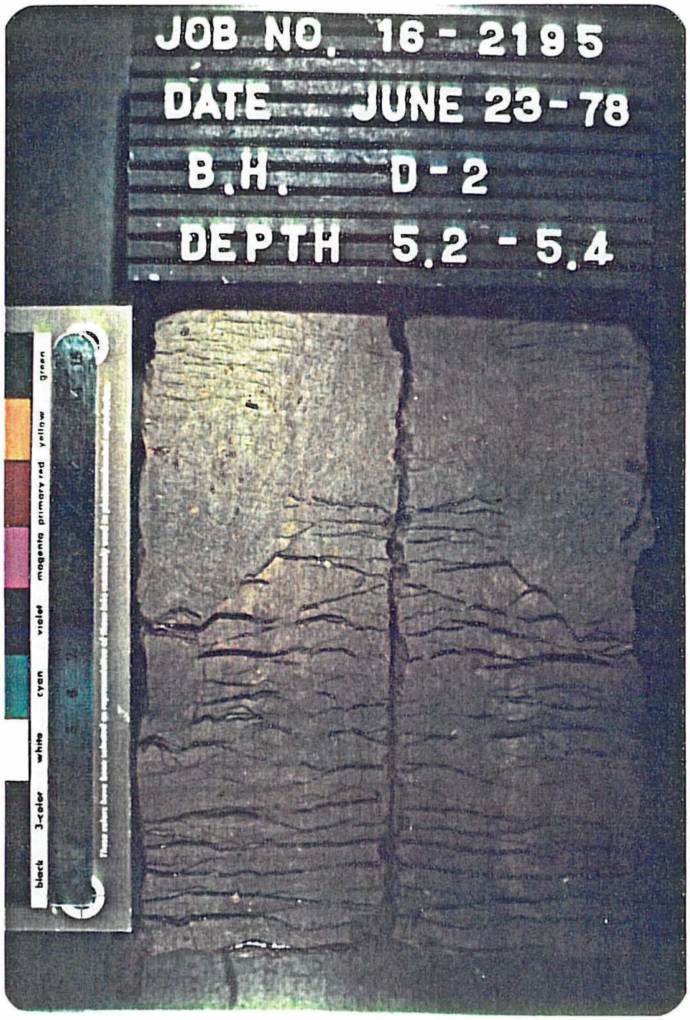


PLATE NO. D2-11

PLATE NO. D2-12

ICE LENSES: Cross-Sectional View (D2-11)
Side View (D2-12)
(Depth shown in metres)

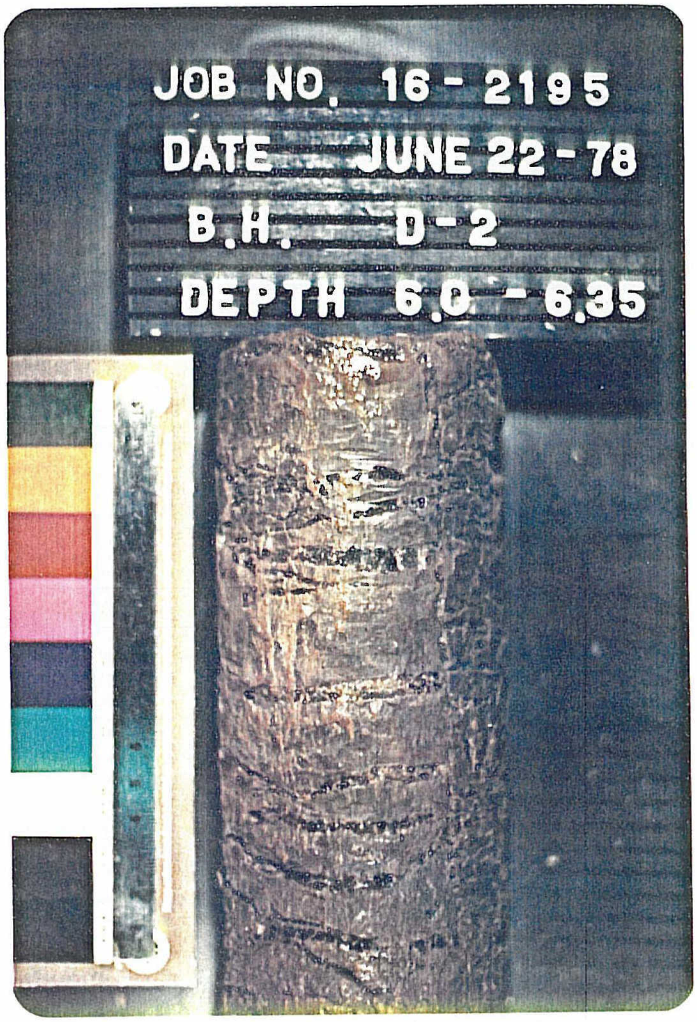


PLATE NO. D2-13

ICE LENSES: Side View
(Depth shown in metres)

PLATE NO. D2-14

PLATE NO. D2-15

ICE LENSES: Cross-Sectional View
(Depth shown in metres)

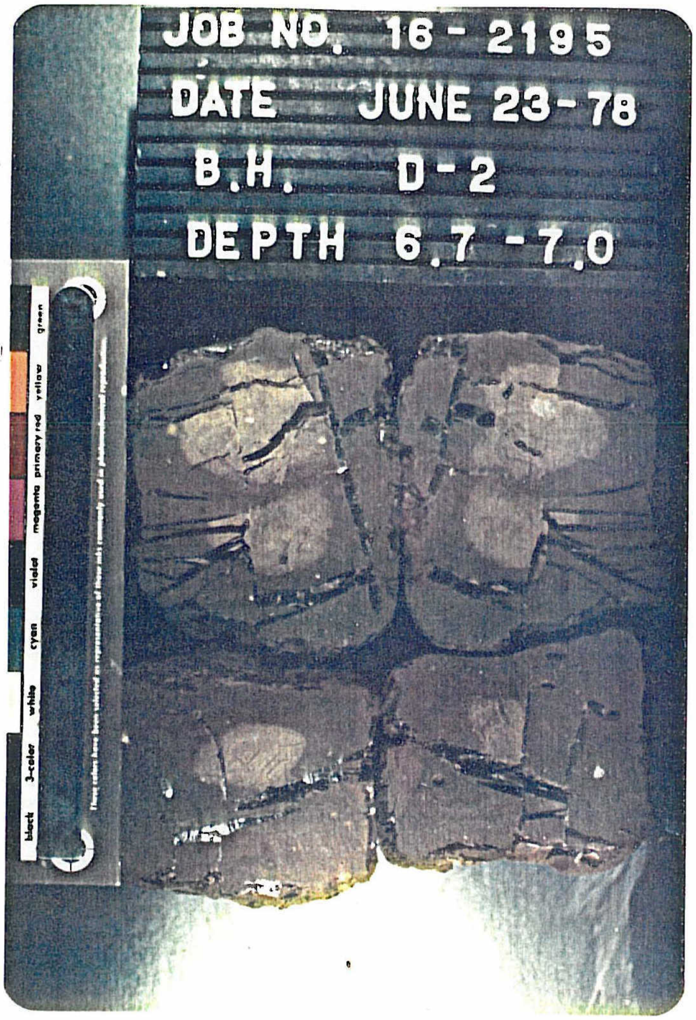


PLATE NO. D2-16

PLATE NO. D2-17

ICE LENSES: Cross-Sectional View

(Depth shown in metres)

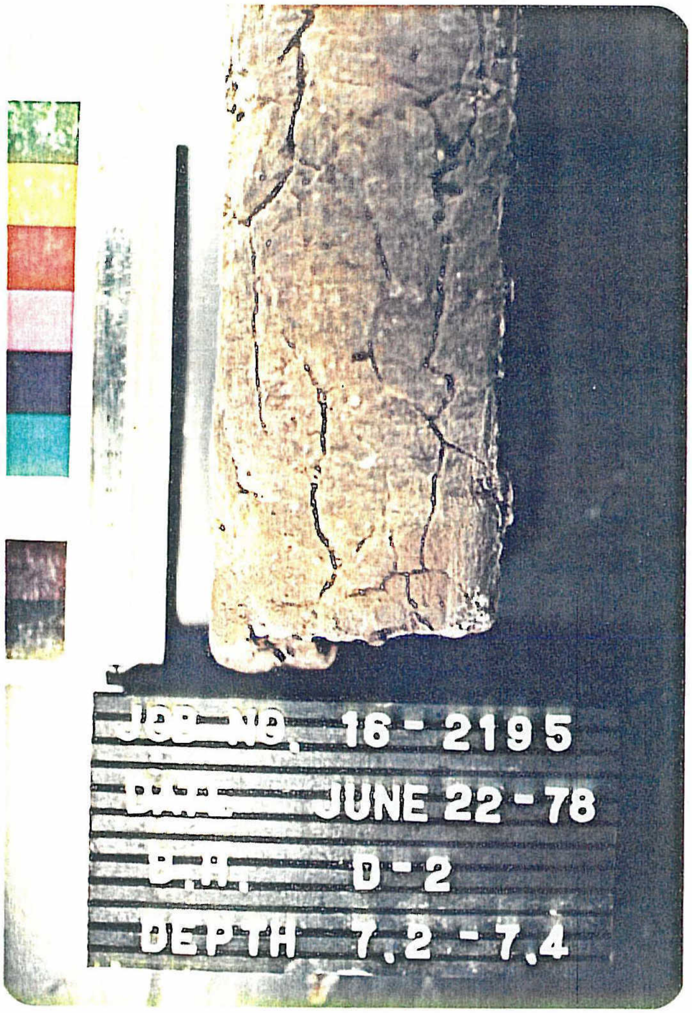


PLATE NO. D2-18

ICE LENSES: Side View
(Depth shown in metres)

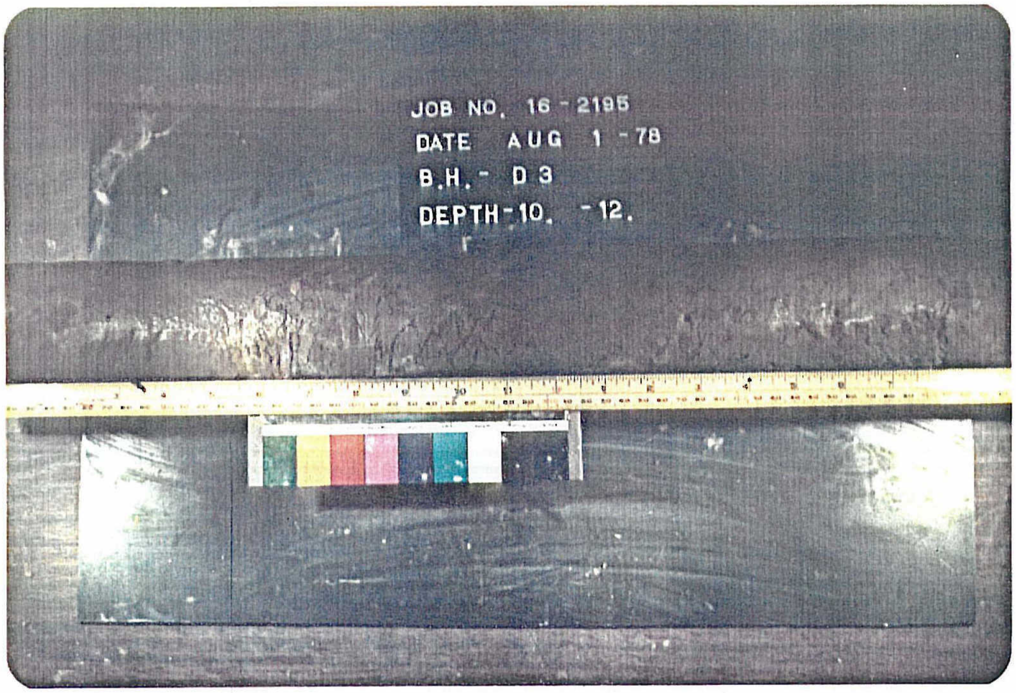


PLATE NO. D3-1

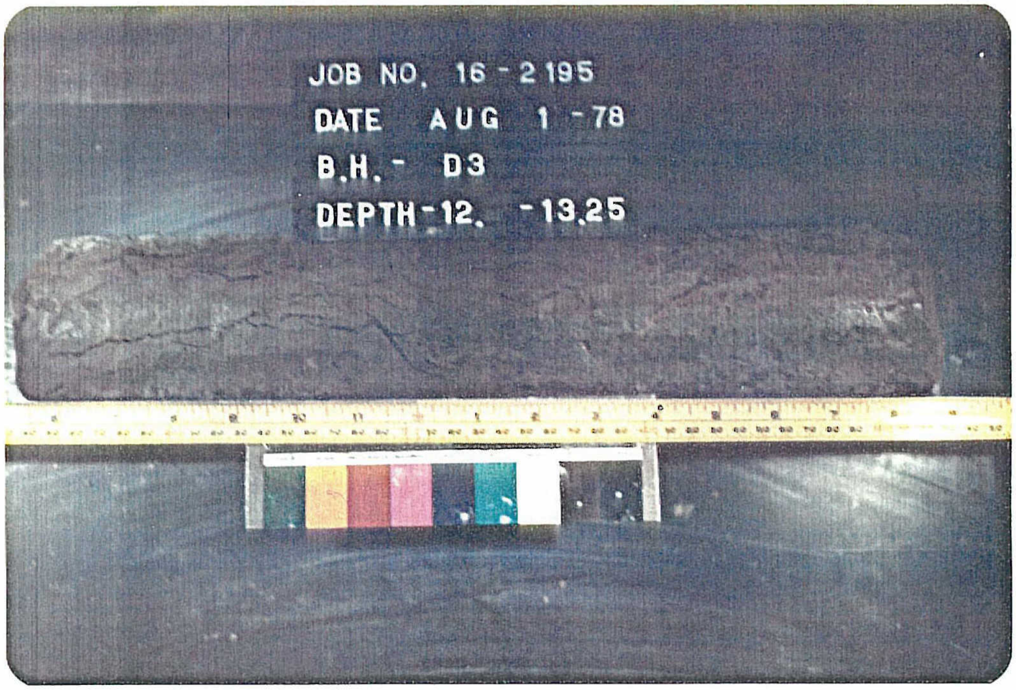


PLATE NO. D3-2

ICE LENSES: Side View of Long Core Samples
(Depth shown in feet, 10. -13.25 ft. = 3.05 - 4.04 m)

PLATE NO. D3-3

ICE LENSES: Side View
(Depth shown in feet, 13.25 - 14.0 ft. = 4.04 -4.27 m

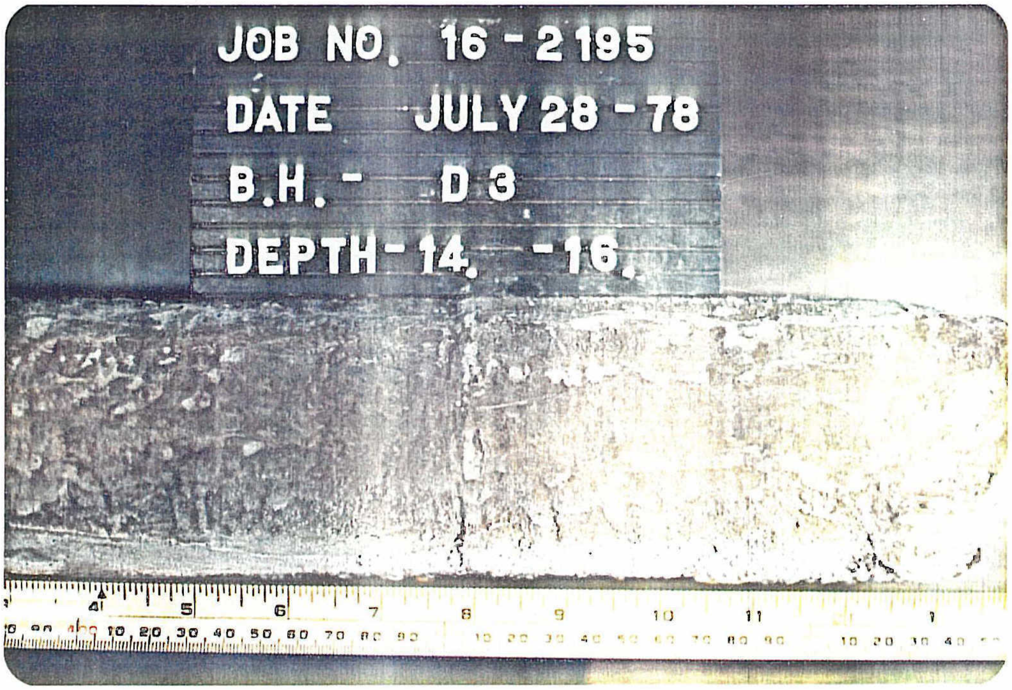


PLATE NO. D3-4

ICE LENSES: Side View of Long Core Sample
(Depth shown in feet, 14. - 16. ft. = 4.28 - 4.88 m)

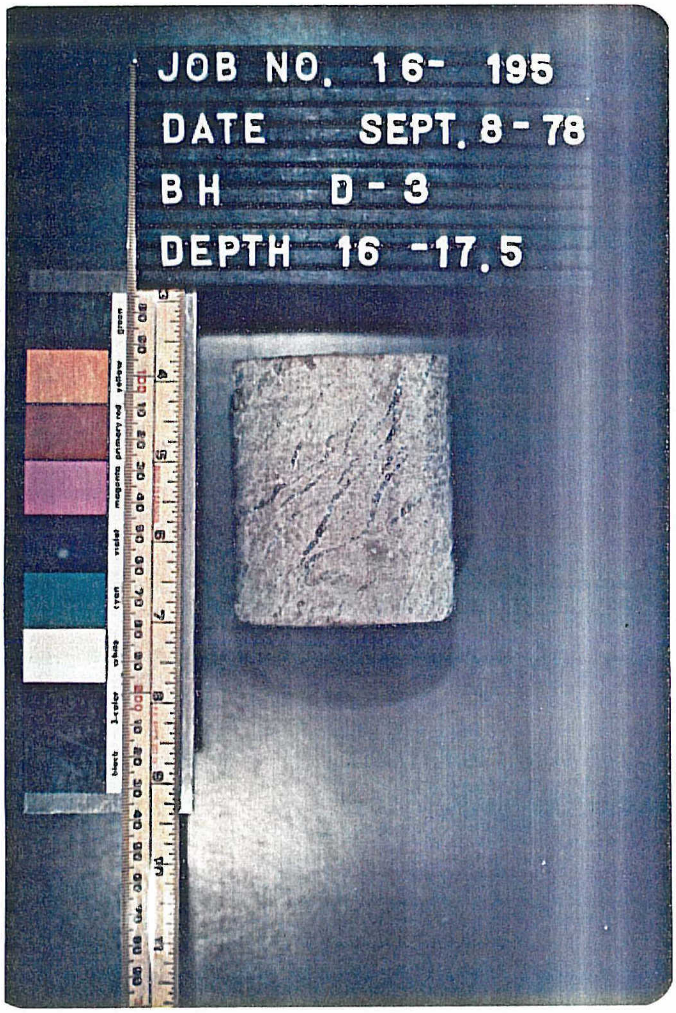


PLATE NO. D3-5

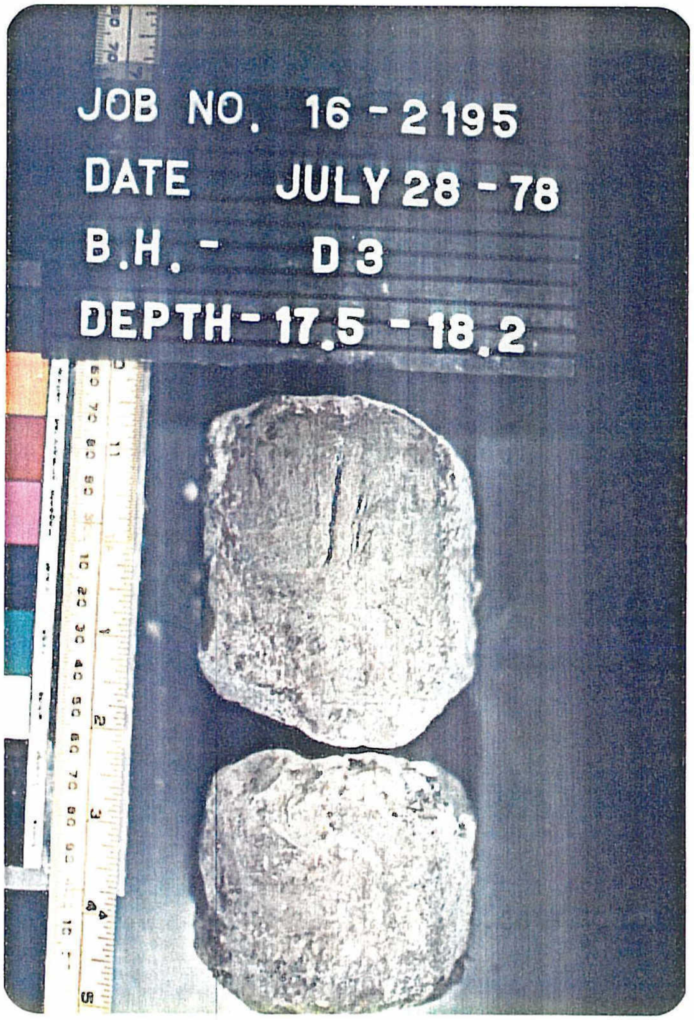


PLATE NO. D3-6

ICE LENSES: Side View
(Depth shown in feet, 16.-18.2ft = 4.88 - 5.55 m)

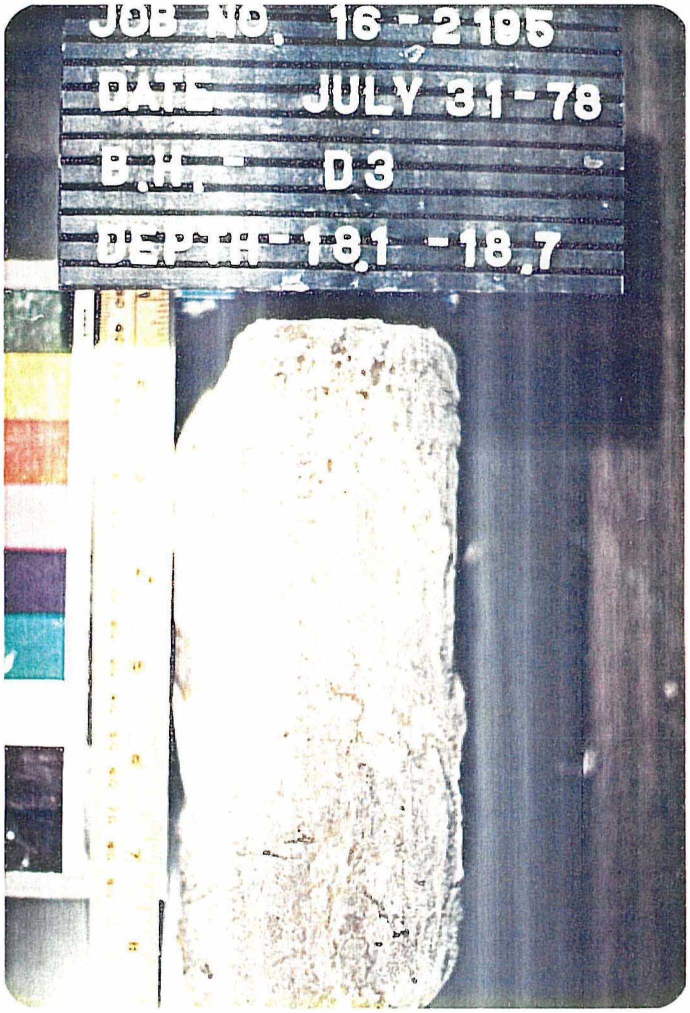


PLATE NO. D3-7

ICE LENSES: Side View
(Depth shown in feet,
18.1 - 18.7 ft. = 5.52 - 5.70 m)

PLATE NO. D3-8

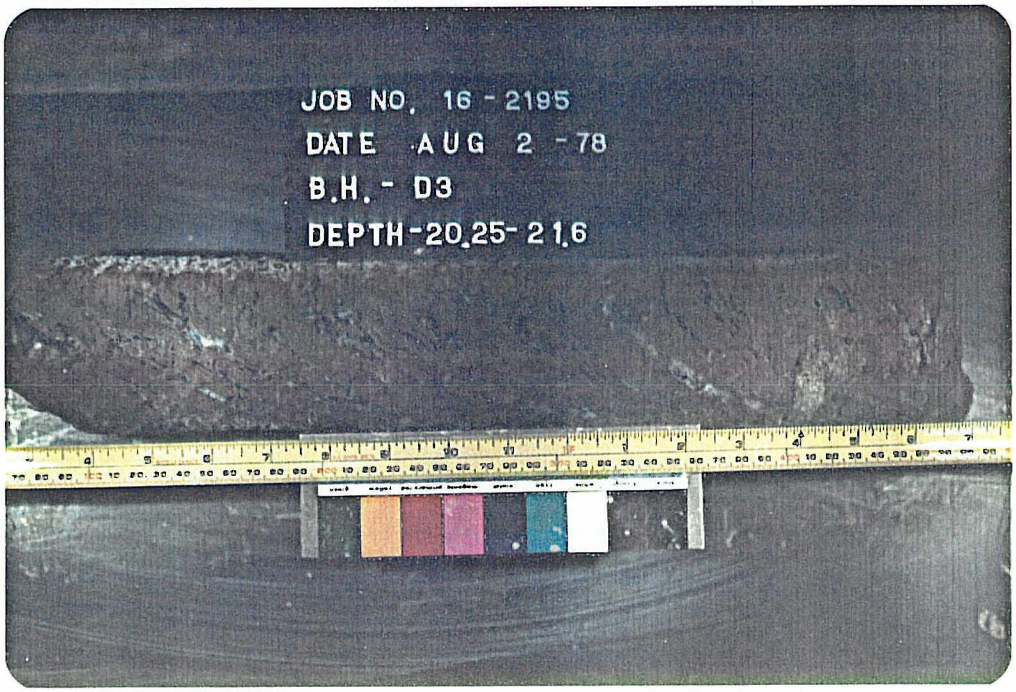


PLATE NO. D3-9

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 18.7-21.6 ft. = 5.70 - 6.58 m)

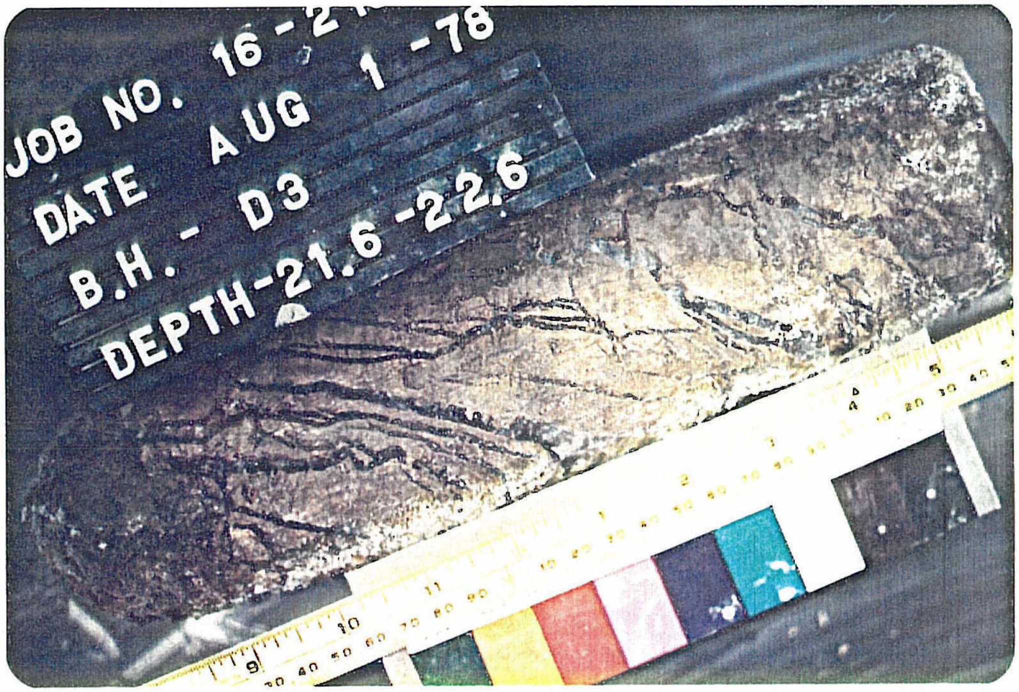


PLATE NO. D3-10

ICE LENSES: Side View

(Depth shown in feet, 21.6 - 22.6 ft. = 6.58 - 6.89 m)

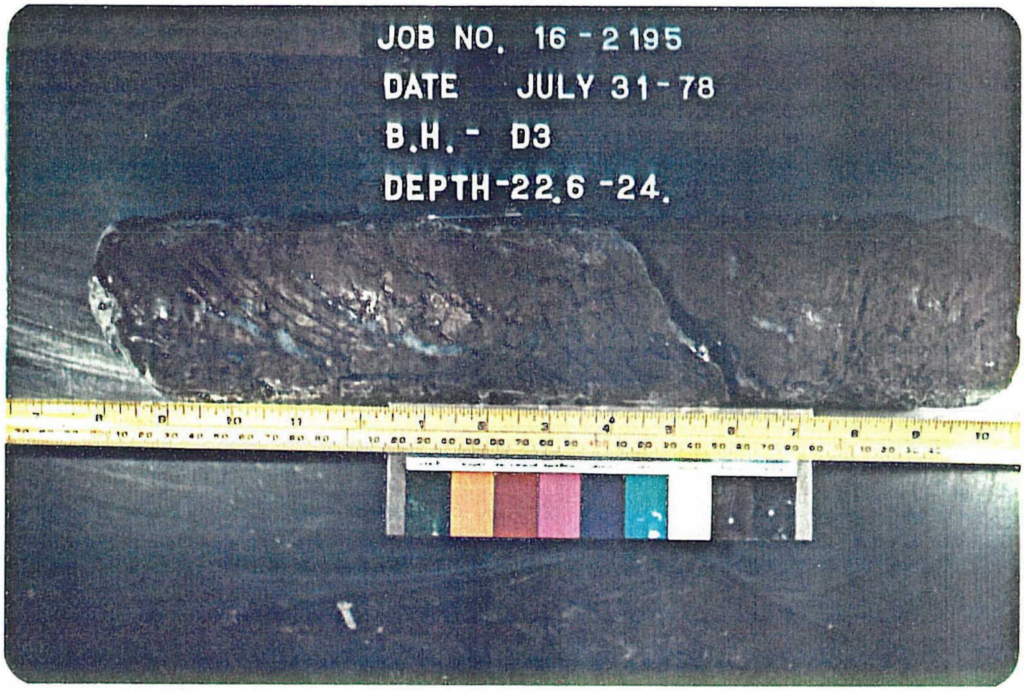


PLATE NO. D3-11

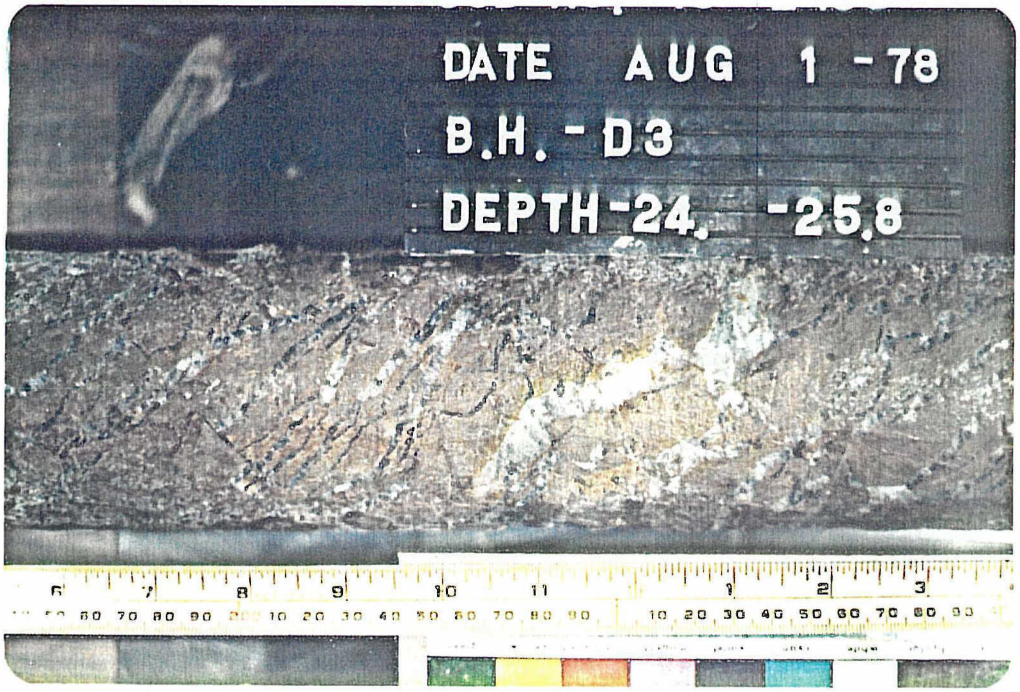


PLATE NO. D3-12

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 22.6 - 25.8 ft. = 6.89 - 7.86 m)

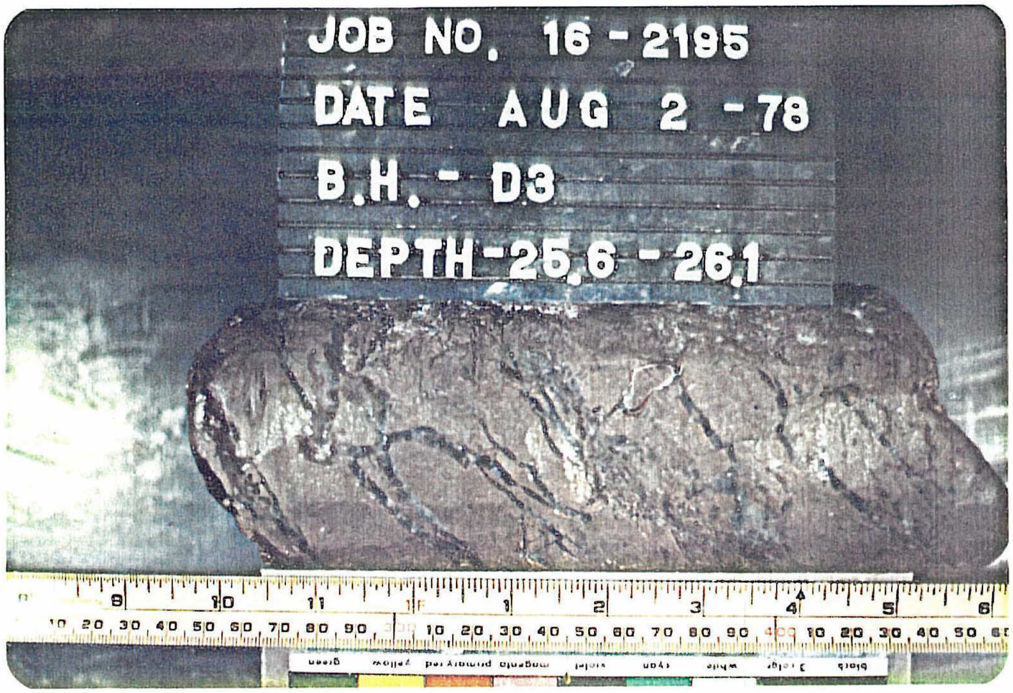


PLATE NO. D3-13

PLATE NO. D3-14

ICE LENSES: Side View of Long Core Samples

(Depth shown in feet, 25.6 - 28.0 ft. = 7.80 - 8.53 m)

PLATE NO. D3-15

ICE LENSES: Side View
(Depth shown in feet, 28. - 28.3 ft. = 8.53 - 8.63 m)

PLATE NO. D3-16

ICE LENSES: Side View

(Depth shown in feet, 28.3 - 28.8 ft. = 8.63 - 8.78 m)