Energy, Mines and Resources Canada
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Earth Physics Branch
Direction de la physique du globe

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**Geothermal Service of Canada**

**Service géothermique du Canada**

# REPORT ON FROST HEAVE TESTING OF CALGARY SILTY CLAY

Hardy Associates (1978) Ltd.
Consulting Engineering & Professional Services
Calgary, Alberta

Earth Physics Branch Open File Number 83-26
Dossier public de la Direction de la Physique du Globe No. 83-26



Department of Energy, Mines & Resources Canada
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Ministere de l'Energie, des Mines et des Ressources du Canada
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Abstract

The report summarises measurements of the frost segregation potential of soils from the Calgary test loop made under several conditions of temperature gradient and imposed stress. The SP values, ranging from $40 \times 10^{-5}$ to $240 \times 10^{-5}$ mm$^2$/sec°C, are used to predict long term heave of the deep buried test section.



Résumé

La mesure du potentiel de ségrégation (PS) de sols provenant de la station expérimentale à Calgary a été faite pour des essais de gel sous différents gradients de température et différentes charges appliquées. Les valeurs de PS, comprises entre $40 \times 10^{-5}$ et $240 \times 10^{-5}$ mm$^2$/sec°C, servent à prédire le soulèvement à long terme de la section de conduite enterrée le plus profondément.

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CONSULTING ENGINEERING & PROFESSIONAL SERVICES

# REPORT ON

# FROST HEAVE TESTING OF CALGARY SILTY CLAY

Prepared For
DEPARTMENT OF ENERGY, MINES & RESOURCES
and
DEPARTMENT OF SUPPLY AND SERVICES
Ottawa, Ontario

By
HARDY ASSOCIATES (1978) LTD.
Calgary, Alberta

CG-14048
November 1983
11/48

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# 1.0 INTRODUCTION

## 1.1 AUTHORIZATION

On May 3, 1983, Hardy Associates (1978) Ltd. submitted a letter to Dr. J. Pilon of the Earth Physics Branch, Division of Gravity, Geothermics and Geodynamics with EMR in Ottawa. This letter described a proposed program of Laboratory frost heave testing to provide a much-needed data base for predicting frost heave at this facility. The contractual details were discussed later with Mr. P. Monnelly of Supply and Services Canada. The program of testing as described in the above letter was approved by Drs. A. Judge and J. Pilon of EMR, and the contractual details are contained in Supply and Services Canada contract #03SQ-23235-3-1005 dated September 20, 1983.

## 1.2 HISTORICAL BACKGROUND

Since 1974, several test pipe sections have operated continuously at the Calgary test site, which is now operated jointly by EMR and Foothills Pipe Lines. The results to date are published by Slusarchuk et al (1978) and subsequently by Carlson et al (1981). In addition, two frost heave test plates were installed and operated (see Nixon et al (1981)). These tests have provided extremely valuable observations of frost heave in a highly frost susceptible soil beneath full scale chilled structures.

Recently, the Konrad-Morgenstern theory of frost heave has provided a method of predicting frost heave in fine-grained soils. Some preliminary predictions of heave were made that relied on some older Arctic Gas frost heave tests. These tests were short-term, and had relatively poor temperature control. No laboratory tests have been carried out to directly measure the "SP" segregational potential parameter, which is necessary for a frost heave prediction using this theory. Therefore, precise comparisons between laboratory tests to measure SP, and the frost heave observed over many years in the full size pipe tests have not been carried out to date. It is important to evaluate whether a relatively simple and inexpensive frost heave test and a currently available frost heave theory are capable of predicting long term frost heave beneath a chilled pipeline.

## 1.3 PROPOSED PROGRAM

In order to provide a comparison between observed pipe behaviour and a prediction using the segregation potential theory in its simplest form, a series of laboratory frost heave tests were carried out for different test pressures, and three different freezing conditions. Existing thermal models can then be used to predict the rate of growth of the frost bulb and the temperature gradient at the frost front. These are necessary inputs to the frost heave prediction based on the SP parameter. As the frost line progresses deeper, the SP value will reduce somewhat, due to increasing pressure on the frost bulb. For an example of frost heave calculations using the segregation potential theory, see Nixon (1982).

A series of frost heave tests were carried out on remoulded samples in the 10 cm diameter cells and peripheral equipment present in our laboratory. Soil from the 4 m depth at the

Calgary facility was previously obtained and stored in the Hardy Associates laboratory. No field work was required to collect samples for this program.

Some small disturbed blocks of soil were available and one of these was large enough to permit trimming and testing. However most samples were remoulded, slurried soils, over-consolidated in the test cells and rebounded to the test pressure. Test pressures were 50, 100 and 200 kPa for the most part. Each sample was frozen once at the initial pressure of 50 kPa, and then thawed and re-consolidated. The cold and warm side temperatures were normally -1°C and +0.5°C respectively. A repeat test was then carried out at the same pressure of 50 kPa to determine any differences in the SP parameter from the first to the second freeze-thaw cycle. The pressure was then increased to 100 and 200 kPa, for each cycle of freezing, thawing and subsequent consolidation. Results included total heave, depth of frost measured by thermistors, water influx measured with a burrette, and final observations of ice lensing, frost depth, water content and soil density. The SP parameter itself was determined from the ratio of the velocity of pore water to the freezing front as the final ice lens forms, to the thermal gradient in the frozen soil at the same time.

A simplified quasi-static thermal program is implemented on the Hardy Associates computer. This program predicts the depth of frost around a pipe, and the associated frost heave based on the estimated thermal gradient at the frost front. This program requires a few seconds of CPU time to run several predictions of frost advance and heave, and was employed to provide basic predictions of frost heave based on the laboratory SP data.

## 2.0 TEST PROCEDURES

### 2.1 SOIL PROPERTIES

The soil tested was the Calgary silty clay, collected from a depth of 3-4 m below present ground surface at the University of Calgary frost heave test facility.

A grain size distribution curve and Atterberg Limits were carried out on a representative sample of the soil tested (see Figure 2.1). The material has 26 percent clay sizes, with most of the remaining particle sizes comprised of silt. The soil is classified as a medium plastic silty clay, or CI in the Unified Classification System. The air dried soil was subsequently mixed as a slurry with a water content in excess of its liquid limit, to ensure a uniform soil with a high degree of saturation could be obtained subsequent to consolidation in the frost heave cell. After consolidation and prior to first-time freezing, the water content was typically about 23 percent by dry weight.

### 2.2 FROST HEAVE TESTING

For disturbed samples (all samples except CS-1), the specimens were prepared by mixing soil and distilled water such that water content of the soil mass was in the range of 30 to 35%. The soil mass was then filled and tamped into a test cell which had a greased membrane inside it and had a length of 11 cm and a diameter of 10.1 cm (see Figure 2.2). For undisturbed sample (sample CS-1), the specimen was trimmed to a length of about 11 cm, encapsulated in a greased membrane,

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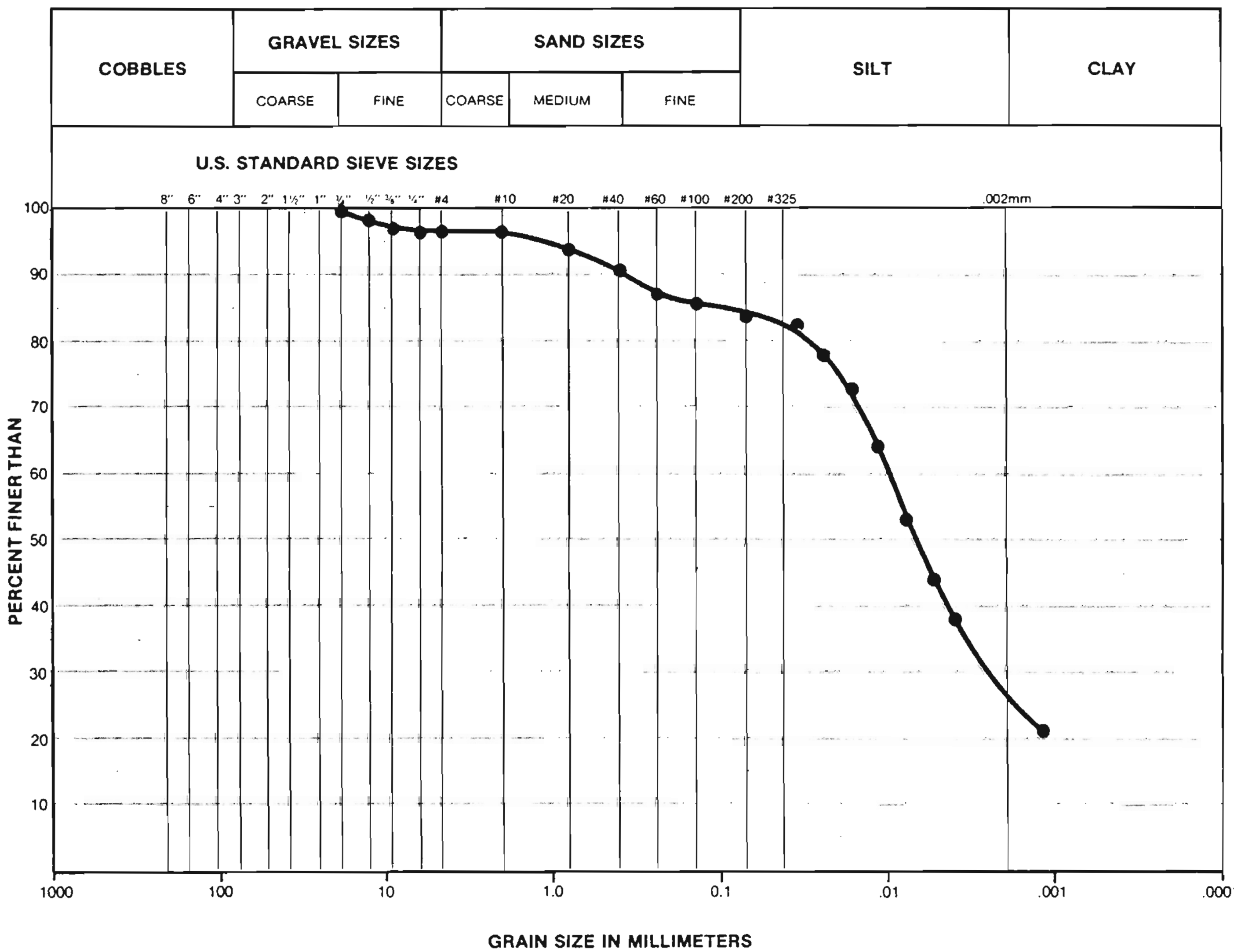
# GRAIN SIZE CURVE

| | |
|---|---|
| CLIENT: EMR | |
| PROJECT NUMBER: CG 14048 | |
| LAB. NUMBER: | |
| LOCATION: | |
| HOLE: | SAMPLE: CS-1 |
| DEPTH: 4.0 mm | |
| TECHNICIAN: | DATE: Nov 7, 1983 |




REMARKS: CALGARY SILTY CLAY

Liquid Limit = 31.5

Platic Limit = 17.8

Soil Type - CI, medium plastic, silty clay

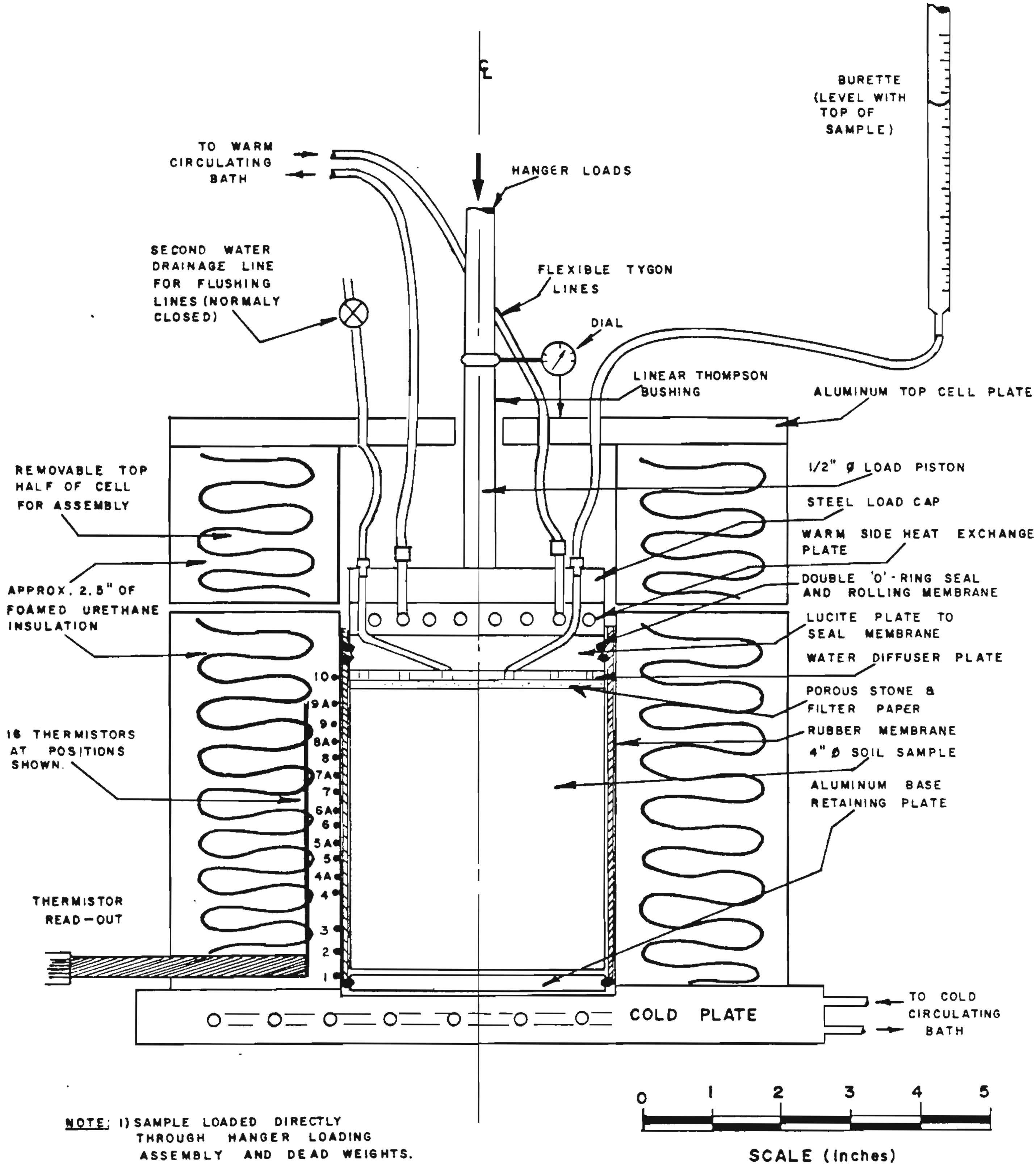
RECONSTITUTED SILT

NOTE: UNIFIED SOIL CLASSIFICATION SYSTEM

**SUMMARY**

| | | | |
|---|---|---|---|
| $D_{10}$ = | mm | GRAVEL | 4.0 % |
| $D_{30}$ = | mm | SAND | 12.0 % |
| $D_{60}$ = | mm | SILT | 58.0 % |
| $C_U$ = | mm | CLAY | 26.0 % |
| $C_C$ = | mm | | |

Figure 2.1. Grain Size Curve

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SCALE DRAWING OF HARDY ASSOC. FROST HEAVE TEST CELLS

CG14048

FIGURE 2.2

and forced into the 10.1 cm diameter test cell. A static load of about 138 kPa was placed on the samples and the progress of settlement was monitored until secondary consolidation was completed. The sample was then rebounded to a specified test pressure. During this period, the sample was thermally conditioned by the cold room set at a temperature of +2$^{o}$C. Prior to freezing, both end plates were controlled at a temperature of about +0.5$^{o}$C or +1$^{o}$C to obtain a uniform initial temperature profile. At the onset of freezing, a temperature of about -15$^{o}$C was applied to the base of the specimen for about one minute, to obtain nucleation of ice crystals at the cold end of the sample. The cold side temperature was controlled thereafter at a specified test value for the duration of the test. Meanwhile, the warm side temperature was maintained unchanged at about +0.5$^{o}$C or +1.0$^{o}$C.

The progress of the frost line was monitored by measuring temperatures using 16 thermistors embedded in the wall of the cell. These thermistors were installed at a spacing of about 6 mm, and allowed delineation of the frost line to an accuracy of a few millimeters. Frost heave was measured using a 0.0025 mm dial gauge mounted on the load piston of the cell. Water influx to the sample was monitored using a burrette connected to the load piston of the cell, accurate to 0.1 ml. The bath temperatures were monitored using thermistors, accurate to about 0.02$^{o}$C. At regular intervals, a plot of temperature versus depth was plotted, and the position of freezing isotherm extracted to obtain the depth of frost.

The test was stopped when the frost line approached thermal equilibrium, i.e. when the rate of frost advance became extremely low. At this point no significant heave occurred except heave due to the growth of an ice layer at the base of the frost line. The sample was then thawed out. Once a uniform temperature profile of above $0^oC$ was established in the specimen and primary consolidation was completed, the whole test process was repeated for the next freezing cycle with a new applied pressure.

Samples CS-1, CS-2R and CS-3 were tested for four times with pressures of 48.3, 48.3, 103.4 and 206.9 kPa, and sample CS-2 was tested five times with an additional test pressure of 413.7 kPa. Sample CS-4 was tested twice with pressures of 103.4 and 206.9 kPa.

At the completion of the last test, the sample was removed and photographed and measured. The final height of frozen soil was determined by measurement with a Vernier caliper. The sample was then split in half and both halves photographed. Water contents of the frozen and unfrozen soil segments were then obtained. Water contents of previous cycles were obtained by back calculation from the water content of the last freezing cycle.

The results were plotted concurrently as the test proceeded. These involved plots of total frost heave, water movement (on heave resulting from water movement), and frost advance. In addition, the cold and warm baths and the cell temperature were monitored and plotted. The temperature of the cold room adjacent to the frost heave cells was measured at regular intervals and was generally found to vary between +1 and +4$^{\circ}$C.

# 3.0 RESULTS OF TEST PROGRAM AND SEGREGATION POTENTIALS

## 3.1 RESULTS OF TEST PROGRAM

Tests CS-2, CS-2R, CS-3 and CS-4 were carried out on disturbed samples, and CS-1 was carried out on an undisturbed sample. The warm side and cold side temperatures of tests CS-1, CS-2, CS-3 and first two tests of CS-2R had values of +0.5°C and -1.0°C, respectively. The corresponding temperatures for tests CS-4 and the last freezing cycle of CS-2R were +1.0°C and -4.0°C, respectively.

The data plots for all the tests are presented in Appendix "A". Generally, each test required a total of five plots. The first summarizes the total heave and heave resulting from water influx. The second plot shows the depth of frost penetration, and the third tracked the cold and warm side temperatures. The fourth plot shows the heave plotted with frost advance, and this graph assists in determining the location of the final ice lens. The final graph shows the temperature profile at the end of the test. Tables 3.1 to Table 3.5 shows summaries of all the relevant results for these tests. The initial and final water contents of the samples were typically 19% and 23%, respectively. The initial density generally was in the range of 2.03 to 2.15 kg/m$^3$. The average heave rate for the samples at different stresses varied from 0.76 to 3.74 mm/day at the higher stress and 1.50 to 3.20 mm/day at the lower stress levels. The total frost heave measured in the samples varied between 0.92 and 19.53 mm depending upon the amount of soil frozen, the stress levels. The total depth of soil frozen was between 55 and 99 mm. The

TABLE 3.1

**SUMMARY OF FROST HEAVE TEST RESULTS**
**CS-1 UNDISTURBED**

| Test | Total Duration | Water Content | | Initial Density | Cold Side | Warm Side | Average Heave Rate | Avg Frost Penetr. Rate* | Final Ice Lens | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Final | | | | | | Pressure | $\nu$ | Grad T | SP | dT/dt |
| | (hour) | % | % | (kg/m$^3$) | ($^o$C) | ($^o$C) | (mm/day) | (mm/day) | (kPa) | (mm/sec) | ($^o$C/mm) | (mm$^2$/$^o$C sec) | ($^o$C/hr) |
| CS-1 | 192.1 | (17.7) | (25.3) | (2.06) | -1.0 | +0.5 | 1.88 | 4.00 | 48.3 | $3.18 \times 10^{-5}$ | 0.0133 | $239.0 \times 10^{-5}$ | 0.0025 |
| CS-1A | 173.4 | (19.3) | (24.6) | (2.06) | -1.0 | +0.5 | 1.50 | 5.33 | 48.3 | $2.06 \times 10^{-5}$ | 0.013 | $159.0 \times 10^{-5}$ | 0.0005 |
| CS-1B | 147.5 | (19.3) | (23.4) | (2.09) | -1.0 | +0.5 | 1.38 | 2.82 | 103.4 | $2.31 \times 10^{-5}$ | 0.0142 | $163.0 \times 10^{-5}$ | 0.0033 |
| CS-1C | 101.8 | (19.6) | 21.9 | 2.10 | -1.0 | +0.5 | 1.60 | 2.40 | 206.9 | $1.41 \times 10^{-5}$ | 0.0148 | $95.3 \times 10^{-5}$ | 0.0025 |

( ) Back calculated values.
* Average penetration rates after first 24-48 hours of test.

TABLE 3.2

**SUMMARY OF FROST HEAVE TEST RESULTS**
**CS-2 REMOULDED**

| Test | Total Duration | Water Content | | Initial Density | Cold Side | Warm Side | Average Heave Rate | Avg Frost Penetr. Rate* | Final Ice Lens | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Final | | | | | | Pressure | $\nu$ | Grad T | SP | dT/dt |
| | (hour) | % | % | (kg/m$^3$) | ($^o$C) | ($^o$C) | (mm/day) | (mm/day) | (kPa) | (mm/sec) | ($^o$C/mm) | (mm$^2$/$^o$C sec) | ($^o$C/hr) |
| CS-2 | 167.5 | (23.5) | (33.2) | (2.03) | -1.0 | +0.5 | 2.17 | 10.29 | 48.3 | $3.76 \times 10^{-5}$ | 0.0175 | $215.0 \times 10^{-5}$ | 0.0017 |
| CS-2A | 145.4 | (23.4) | (31.0) | (2.03) | -1.0 | +0.5 | 1.97 | 3.20 | 48.3 | $3.14 \times 10^{-5}$ | 0.0180 | $174.0 \times 10^{-5}$ | 0.0067 |
| CS-2B | 71.0 | (22.2) | (25.8) | (2.06) | -1.0 | +0.5 | 1.95 | 3.83 | 103.4 | $2.12 \times 10^{-5}$ | 0.0190 | $111.6 \times 10^{-5}$ | 0.0025 |
| CS-2C | 33.0 | (20.7) | (20.0) | (2.08) | -1.0 | +0.5 | 1.66 | 0.90 | 206.9 | $1.7 \times 10^{-5}$ | 0.0168 | $101.0 \times 10^{-5}$ | 0.005 |
| CS-2D | 29.0 | (19.0) | 19.4 | 2.13 | -1.0 | +0.5 | 0.76 | 1.60 | 413.7 | $0.8 \times 10^{-5}$ | 0.02 | $40.0 \times 10^{-5}$ | 0.0025 |

( ) Back calculated values.
* Average penetration rates after first 24-48 hours of test.

TABLE 3.3

**SUMMARY OF FROST HEAVE TEST RESULTS**
**CS-2 (REPEAT) REMOULDED MATERIAL FROM CS-3**

| Test | Total Duration | Water Content | | Initial Density | Cold Side | Warm Side | Average Heave Rate | Avg Frost Penetr. Rate* | Final Ice Lens | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Final | | | | | | Pressure | $\nu$ | Grad T | SP | dT/dt |
| | (hour) | % | % | (kg/m$^3$) | ($^o$C) | ($^o$C) | (mm/day) | (mm/day) | (kPa) | (mm/sec) | ($^o$C/mm) | (mm$^2$/$^o$C sec) | ($^o$C/hr) |
| CS-2R | 29.0 | (22.12) | (23.4) | (2.04) | -1.0 | +0.5 | 2.52 | 5.75 | 48.3 | $2.67 \times 10^{-5}$ | 0.01421 | $188 \times 10^{-5}$ | 0.01 |
| CS-2R-A | 72.7 | (21.6) | (24.6) | (2.04) | -1.0 | +0.5 | 2.13 | 2.73 | 48.3 | $2.32 \times 10^{-5}$ | 0.01333 | $174 \times 10^{-5}$ | 0.0025 |
| CS-2R-B | 29.0 | (20.8) | (21.6) | (2.06) | -1.0 | +0.5 | 1.65 | 1.76 | 103.4 | $1.70 \times 10^{-5}$ | 0.01530 | $111 \times 10^{-5}$ | 0.0010 |
| CS-2R-C | 48.3 | (19.6) | 22.9 | 2.10 | -4.0 | +1.0 | 3.74 | 5.67 | 206.9 | $3.64 \times 10^{-5}$ | 0.0394 | $92 \times 10^{-5}$ | 0.0156 |

( ) Back calculated values.
* Average penetration rates after first 24-48 hours of test.

TABLE 3.4

**SUMMARY OF FROST HEAVE TEST RESULTS**
**CS-3 REMOULDED**

| Test | Total Duration | Water Content | | Initial Density | Cold Side | Warm Side | Average Heave Rate | Avg Frost Penetr. Rate* | Final Ice Lens | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Final | | | | | | Pressure | $\nu$ | Grad T | SP | dT/dt |
| | (hour) | % | % | (kg/m$^3$) | ($^o$C) | ($^o$C) | (mm/day) | (mm/day) | (kPa) | (mm/sec) | ($^o$C/mm) | (mm$^2$/$^o$C sec) | ($^o$C/hr) |
| CS-3 | 146.4 | (17.5) | (30.4) | (2.07) | -2.0 | +0.5 | 3.20 | 3.20 | 48.3 | $5.25 \times 10^{-5}$ | 0.0238 | $221.0 \times 10^{-5}$ | 0.0139 |
| CS-3A | 145.5 | (19.3) | (31.0) | (2.03) | -2.0 | +0.5 | 2.95 | 2.95 | 48.3 | $4.56 \times 10^{-5}$ | 0.0245 | $186.0 \times 10^{-5}$ | 0.0050 |
| CS-3B | 102.0 | (24.7) | (20.3) | (2.08) | -2.0 | +0.5 | 2.59 | 2.59 | 103.4 | $4.00 \times 10^{-5}$ | 0.0286 | $140.0 \times 10^{-5}$ | 0.0050 |
| CS-3C | 189.0 | (19.5) | 24.4 | 2.13 | -2.0 | +0.5 | 1.81 | 1.81 | 206.9 | $2.45 \times 10^{-5}$ | 0.0286 | $87.1 \times 10^{-5}$ | 0.0025 |

( ) Back calculated values.
* Average penetration rates after first 24-48 hours of test.

TABLE 3.5

**SUMMARY OF FROST HEAVE TEST RESULTS**
**CS-4 REMOULDED**

| Test | Total Duration | Water Content | | Initial Density | Cold Side | Warm Side | Average Heave Rate | Avg Frost Penetr. Rate* | Final Ice Lens | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Final | | | | | | Pressure | $\nu$ | Grad T | SP | dT/dt |
| | (hour) | % | % | ($kg/m^3$) | ($^oC$) | ($^oC$) | (mm/day) | (mm/day) | (kPa) | (mm/sec) | ($^oC/mm$) | ($mm^2/^oC$ sec) | ($^oC/hr$) |
| CS-4 | 46 | (19.9) | (22.5) | (2.11) | -4.0 | +1.0 | 3.20 | 3.00 | 103.4 | $8.50x10^{-5}$ | 0.0434 | $196x10^{-5}$ | 0.0050 |
| CS-4A | 23.5 | (18.3) | 19.4 | 2.15 | -4.0 | +1.0 | 2.86 | 4.80 | 206.9 | $3.54x10^{-5}$ | 0.0472 | $75x10^{-5}$ | 0.0238 |

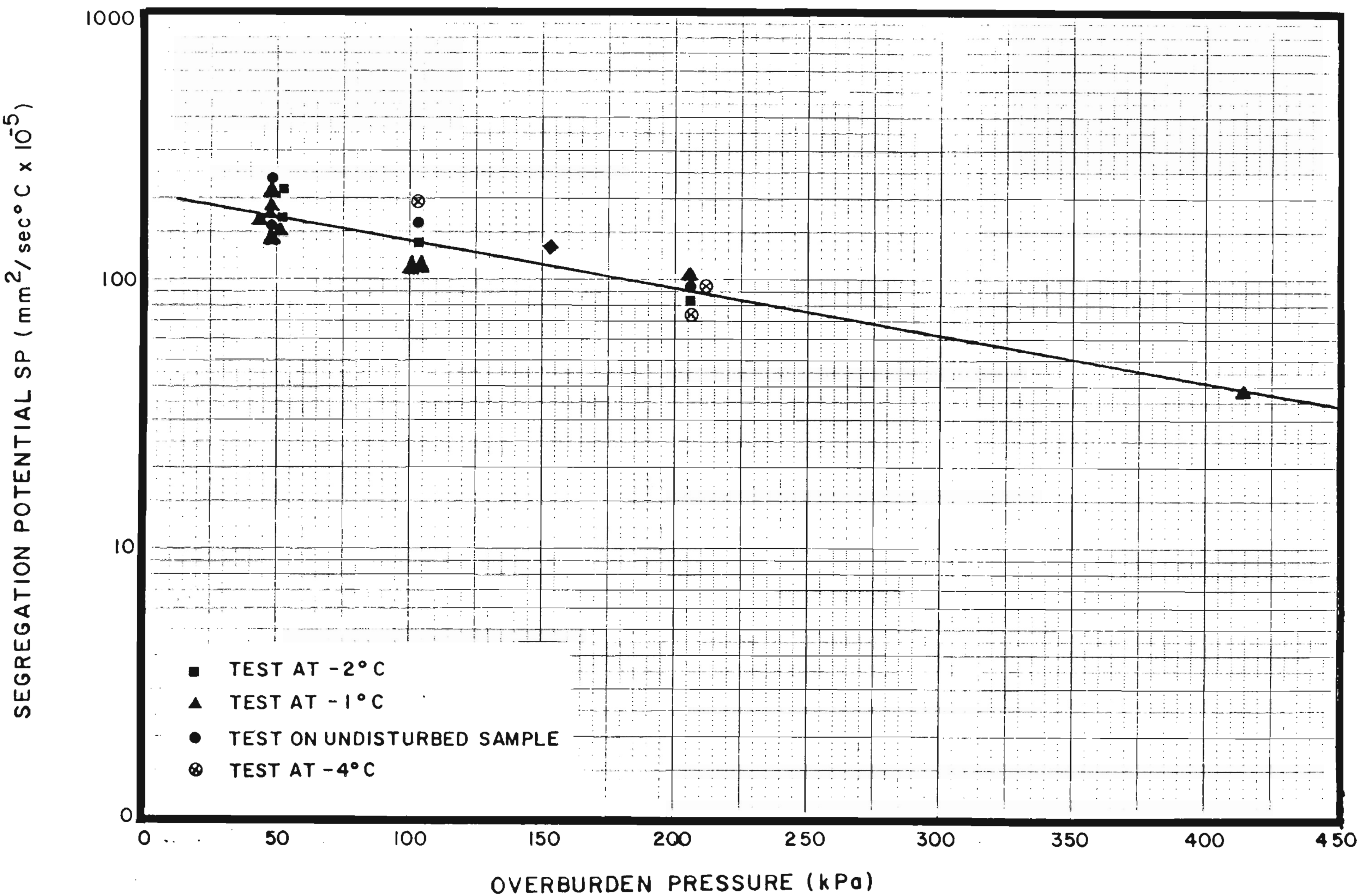
( ) Back calculated values.
* Average penetration rates after first 24-48 hours of test.

pore water velocity was measured by the burrette varied between 0.8 x $10^{-5}$ and 8.5 x $10^{-5}$ mm/sec. The temperature gradient for the tests were in the range of 0.0133 to 0.0472 $^{o}$C/mm. The calculated SP values varied between 40 x $10^{-5}$ and 239 x $10^{-5}$ mm$^2$/$^{o}$C sec. The cooling rate dT/dt varied from a high of 0.0238 to a low of 0.0005 $^{o}$C/hr.

## 3.2 SEGREGATION POTENTIAL

The purpose of the test series was to determine the Segregation Potential parameter for a variety of freezing conditions. It is defined in the next section as the ratio of the pore water velocity to the freezing point, to the temperature gradient in the frozen zone. It is determined from the lab tests by calculating this ratio at the formation of the final ice lens. This occurs when the frost heave rate equals the frost advance rate, or when the frost heave rate by water attraction equals the total heave rate as measured by the dial gauge. When these conditions are realized, the frost line is not advancing into new unfrozen soil, and all heave is resulting from the final ice lens. At this point, the SP parameter is calculated, and the freezing cycle can be terminated soon afterward.

The Segregation Potential (SP) values as determined from the tests are plotted on Figure 3.1 which shows the SP plotted with pressure on a semi-logarithmic scale. This plot was later used to predict frost heave for Calgary silt. The SP values for these tests was in the range of 40 x $10^{-5}$ to 240 x $10^{-5}$ mm$^2$/sec.$^{o}$C.

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SUMMARY OF SP FROST HEAVE TEST ON CALGARY SILT

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FIGURE 3.1

## 4.0 PREDICTION OF HEAVE AT CALGARY TEST SITE

The prediction of frost heave for the full size test sections is carried out by first estimating the average effective stress on the frost bulb, and then selecting the appropriate SP value from the test data. This value, together with the pipe geometry and the soil in situ expansion value are input to a simple computer program that integrates frost heave with time.

In a series of four papers, Konrad and Morgenstern have developed their theory of frost heaving using the concept of segregation potential in fine-grained soils (see Konrad and Morgenstern 1980, 1981, 1982). In its simplest form the theory predicts the frost heave resulting from two components, namely the water arriving at the freezing front and the freezing of in situ pore water. The water arrival causing segregational heave is predicted from the relationship

$$v = SP.\text{grad } T \qquad (1)$$

where SP = the segregation potential ($mm^2/s.^{\circ}C$)

grad T = the temperature gradient adjacent to the growing ice lens ($^{\circ}C/mm$), and

v = the velocity of arriving pore water (mm/s).

The frost heave increment, $\Delta h_s$, that occurs in a time interval, $\Delta t$, is obtained from

$$\Delta h_s = 1.09 v.\Delta t \qquad (2)$$

To this quantity is added another amount of heave to account for the freezing of in situ pore water. This is given by

$$\Delta h_i = 0.09 n \Delta X$$

where $n$ = the soil porosity,

$\Delta h_i$ = the amount of heave resulting from freezing of in situ pore water, and

0.09 = the volumetric expansion that occurs when water is frozen.

The last quantity may be reduced somewhat to account for the percentage of soil pore water remaining unfrozen at sub-zero temperatures. These quantities are added to produce the total heave occurring in the fine-grained soil.

The effective pressure calculation is complicated by two factors, namely side-shear on the prism of soil after some heave takes place, and (b) the 1.5 m berm which was added after about one year of operation.

The SP value at the start of freezing at the pipe base, $SP_o$, is obtained by summing the stress contributions of the berm, the soil above the water table, and the soil below the water table. The water table varies between 1.5 and 2.4 m below the surrounding ground surface with a mean of about 2.0 m (6.5 feet) below ground. Assuming densities of 1923 and 923 kg/m$^3$ above and below the water table respectively, the effective stress after berm placement over the deep burial section was 73 kPa. The berm was present for 8 of the 9 years of operation, so it has been assumed present for the entire operating period. As the frost bulb grows and heaves the soil over the pipe, some additional stress is imposed on the pipe due to the uplift resistance of the soil over or adjacent to the pipe. Observations of surface soil movement at the site indicate upward flexure of the unfrozen soil, and the formation of distinct shear planes at some distance offset from the pipe centre-line. An estimate of the contribution by side shear must be made, as earth pressures in the soil above or below the pipe were not measured directly. In the early data presentation by Slusarchuk et al (1978), the depth to the widest point of the frost bulb was about 3 m, or roughly equal to the depth to the pipe base. The total contribution to vertical stress on both sides of the frost bulb, 2T, can be written as

$$2T = 2\,(0.5\,K_o \tan \phi\ \gamma H^2)/W$$

where $K_o$ = 0.5

$\tan \phi$ = 0.58

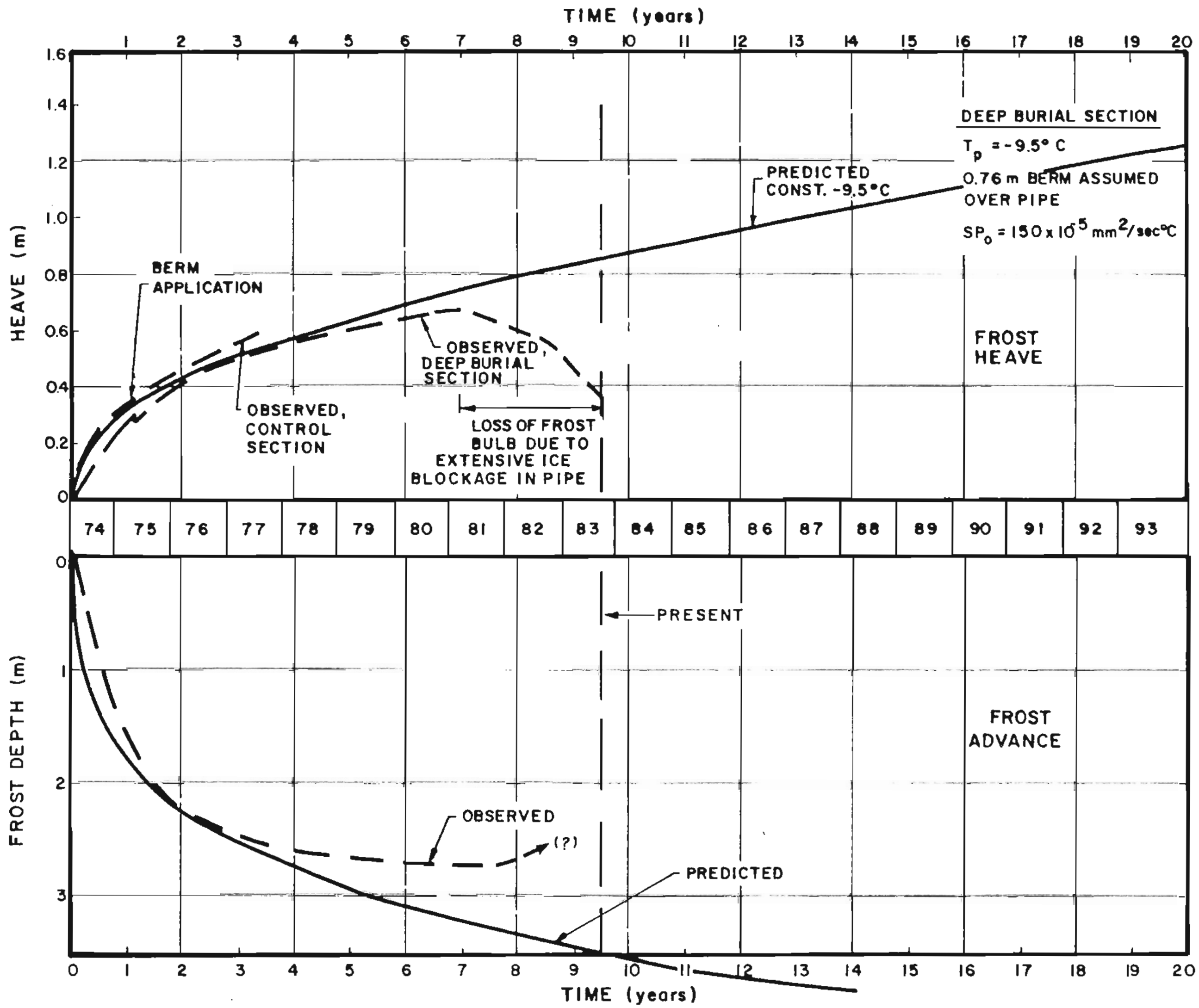
$\gamma$ = average density
= 1523 $kg/m^3$ for this case

H = depth of shear plane
= 3 m

W = width of frost bulb
= typically 6 m

This is calculated to be about 6.6 kPa (138 psf) thereby increasing the vertical stress to 80 kPa. The SP value at this stress is $150 \times 10^{-5}$ $mm^2/sec^oC$, based on the best fit line to the laboratory data reviewed earlier. A small decrease on SP with depth was also incorporated for the frost heave prediction, to account for the increasing effective stresses with depth. Consequently, the value of SP decreases from 150 x $10^{-5}$ at the pipe base to 130 x $10^{-5}$ $mm^2/sec^oC$ at a depth of 6 m below ground surface.

These values were input to a computer program that calculates the frost depth and thermal gradient at the frost line beneath a chilled buried pipe. The program uses the so-called "quasi-static" method for calculating these quantities (see Thornton 1976, for example). The program completes a 20 year prediction in a matter of seconds, and the predictions for frost depth and heave are shown on Figure 4.1. Also shown for comparison are the frost depth and frost heave observed for the deep burial section at the Calgary facility. The agreement between observation and prediction is certainly excellent, considering the many parameters such as pipe temperature and soil properties that are subject to variation in the field. No attempt has been made to refine this prediction, or adjust the frost heave input parameters to obtain a better agreement. Further predictions to study the possible variations in frost heave could be carried out in the future, in order to assess the sensitivity of the pipe heave

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OBSERVED AND PREDICTED FROST HEAVE WITH TIME

CG14048

FIGURE 4.1

to variations in the laboratory data. Pipe heave could be affected by as much as plus or minus 20%, depending on whether an upper, lower or average bound on the lab SP data was used to predict frost heave.

Respectfully submitted,

HARDY ASSOCIATES (1978) LTD.

Per:

Dave Cheung, M.Eng., P.Eng.

Per:

J.F. (Derick) Nixon, Ph.D., P.Eng.
Associate
Head Permafrost Group

DN/mm
11/48

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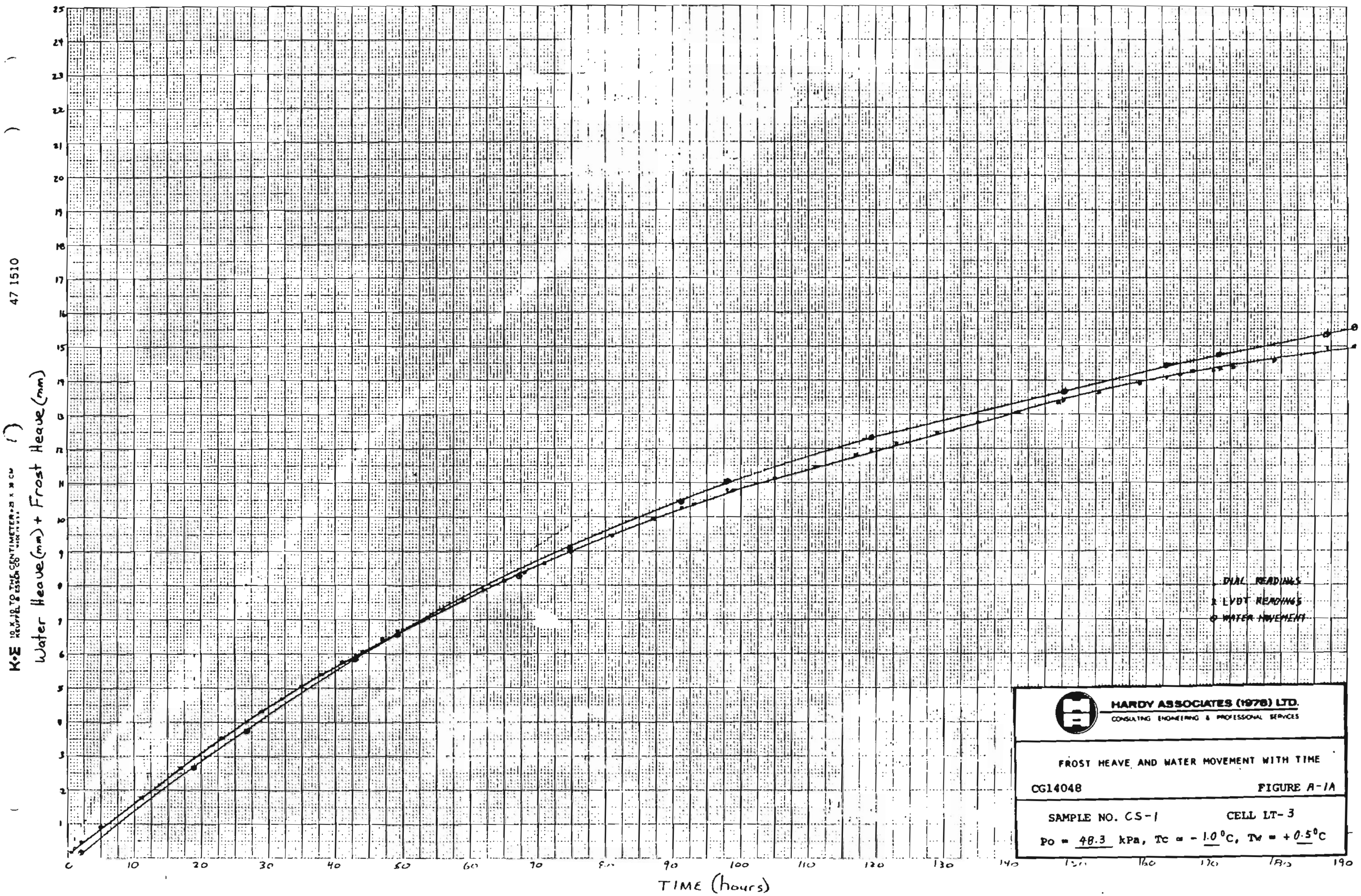
Slusarchuk, W., J. Clark, J. Nixon, N. Morgenstern, and P. Gaskin, 1978. Field test results of a chilled pipeline buried in unfrozen ground. Proc. 3rd Intl. Permafrost Conf., pp 877-883, Edmonton.

Thorton, D.E., 1976. Steady-state and quasi-static thermal results for bare and insulated pipes in permafrost. Can. Geotech. 13, pp 161-120.

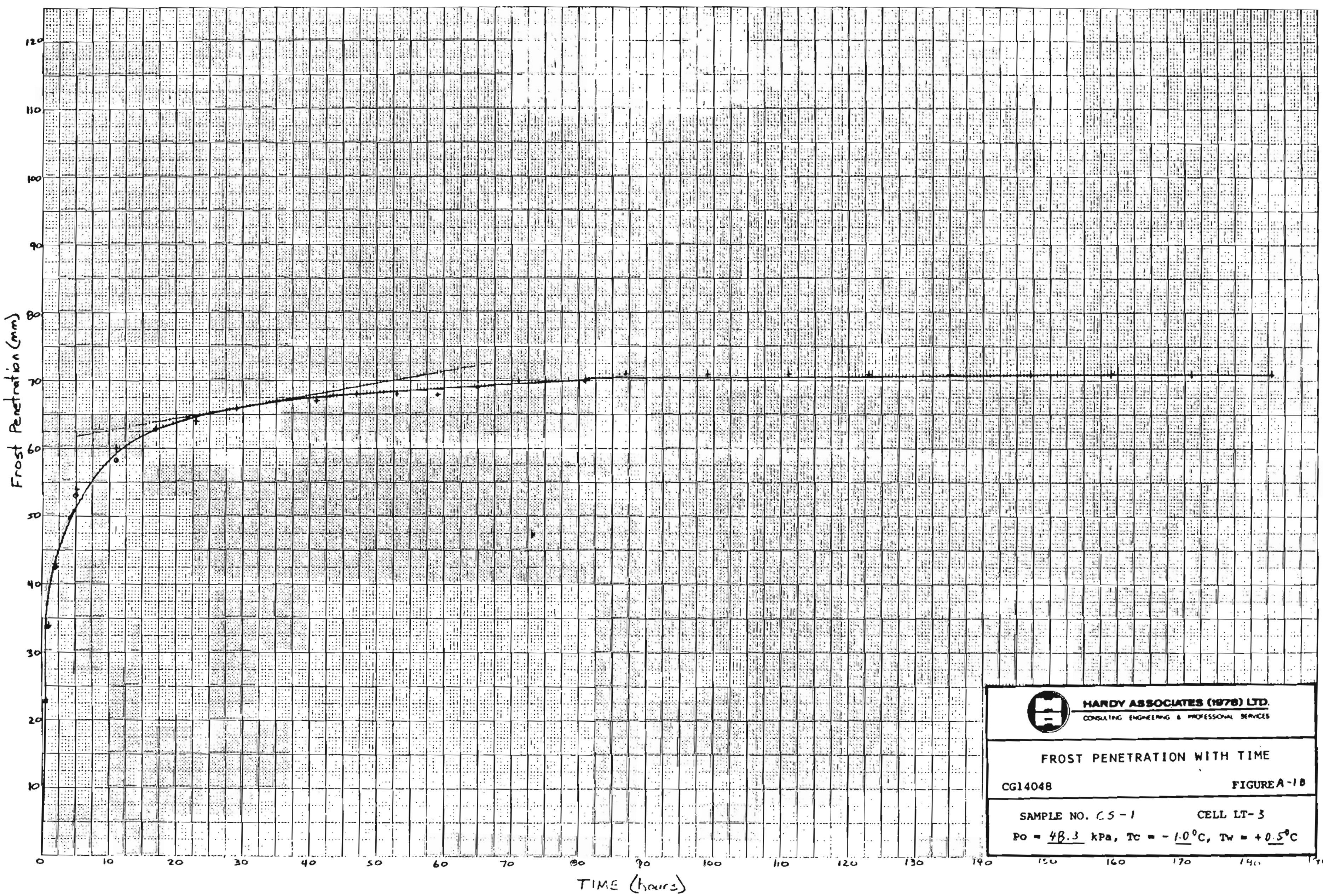
# APPENDIX "A"

## Plots of Frost Heave Test



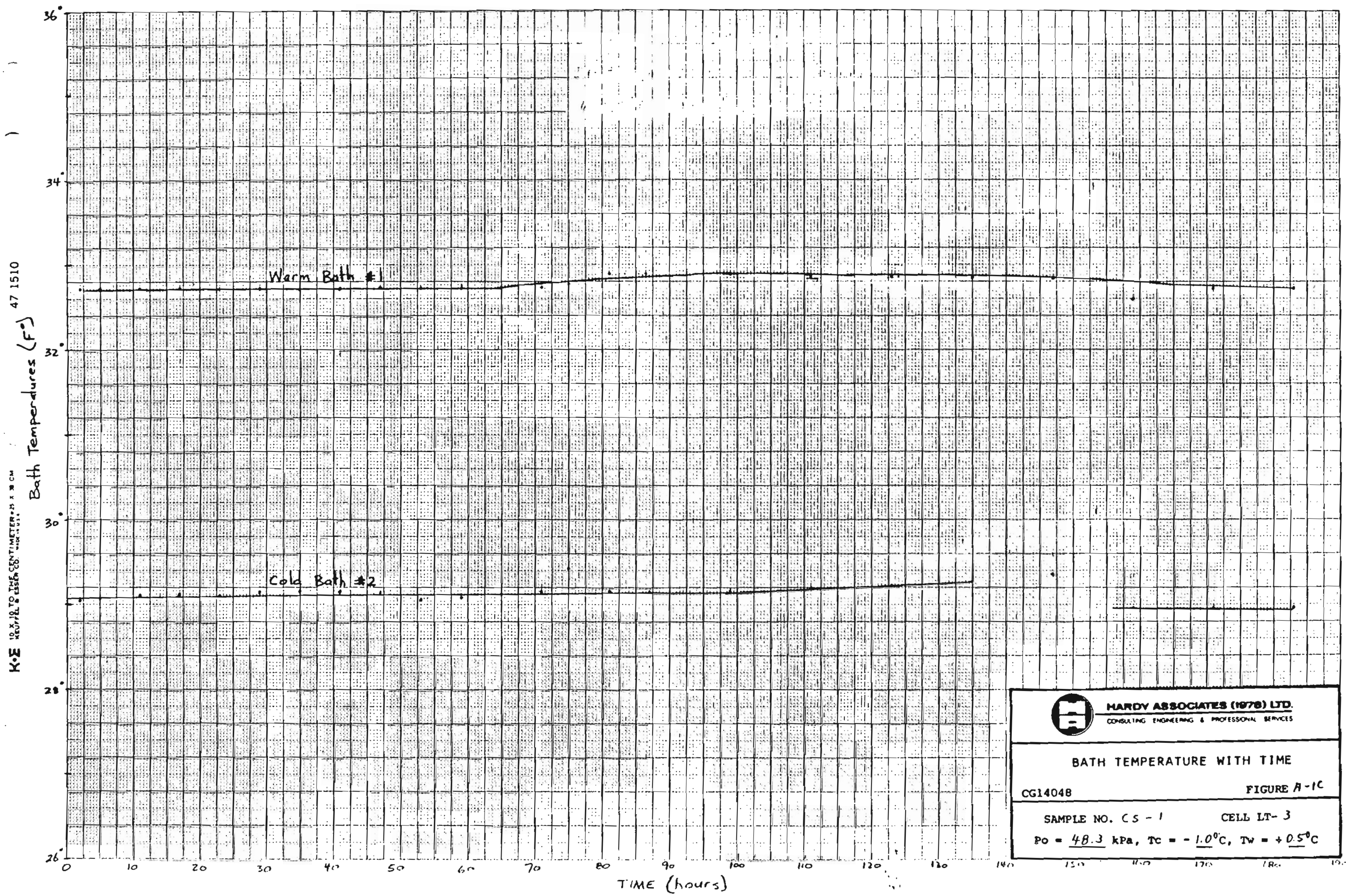

K·E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO.

47 1510




K•E 10 X 10 TO THE CENTIMETER • 23 X 38 CM KEUFFEL & ESSER CO. MADE IN U.S.A.

47 1510

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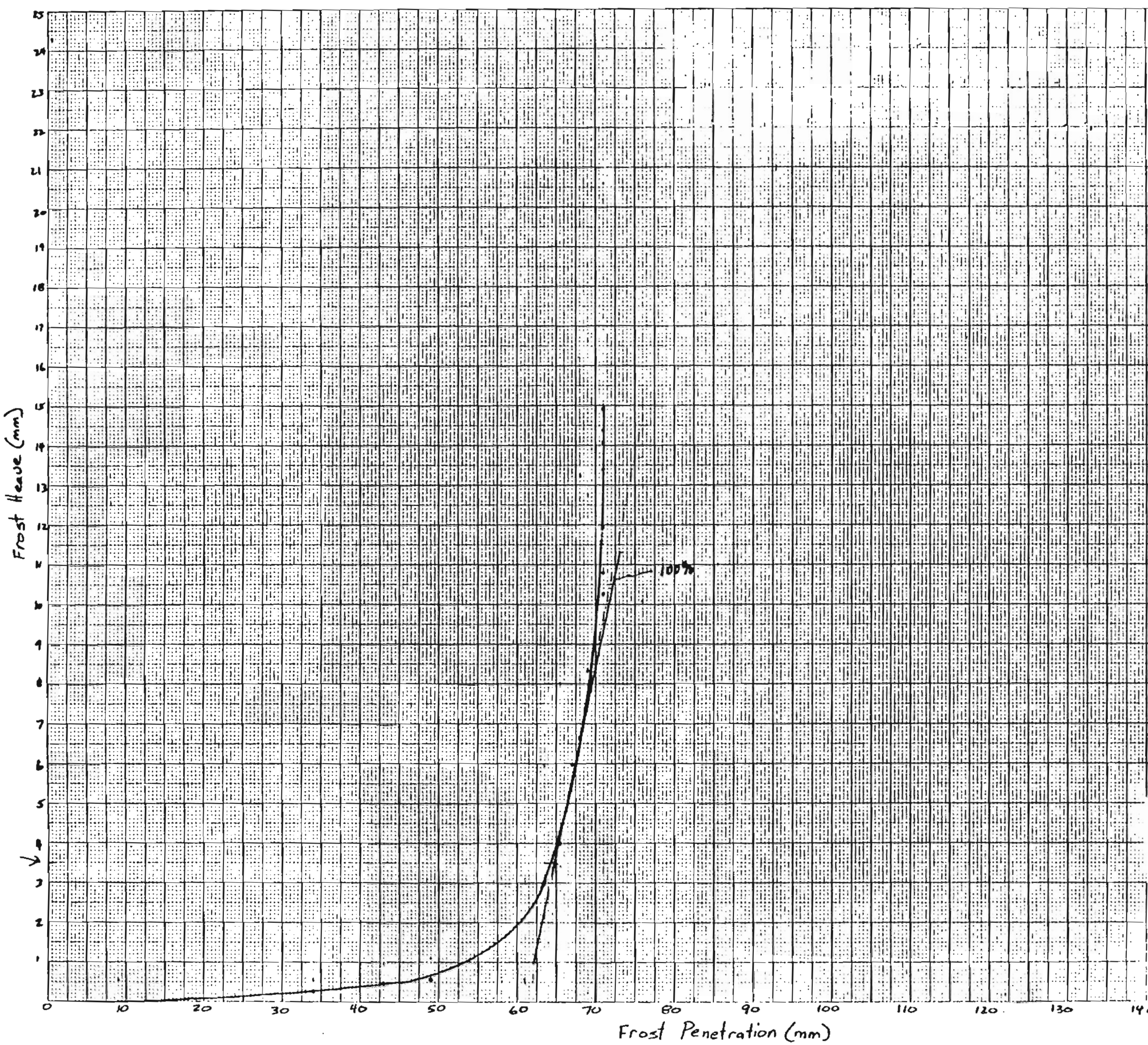
BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-1C

SAMPLE NO. CS - 1 CELL LT- 3

Po = 48.3 kPa, Tc = - 1.0°C, Tw = + 0.5°C

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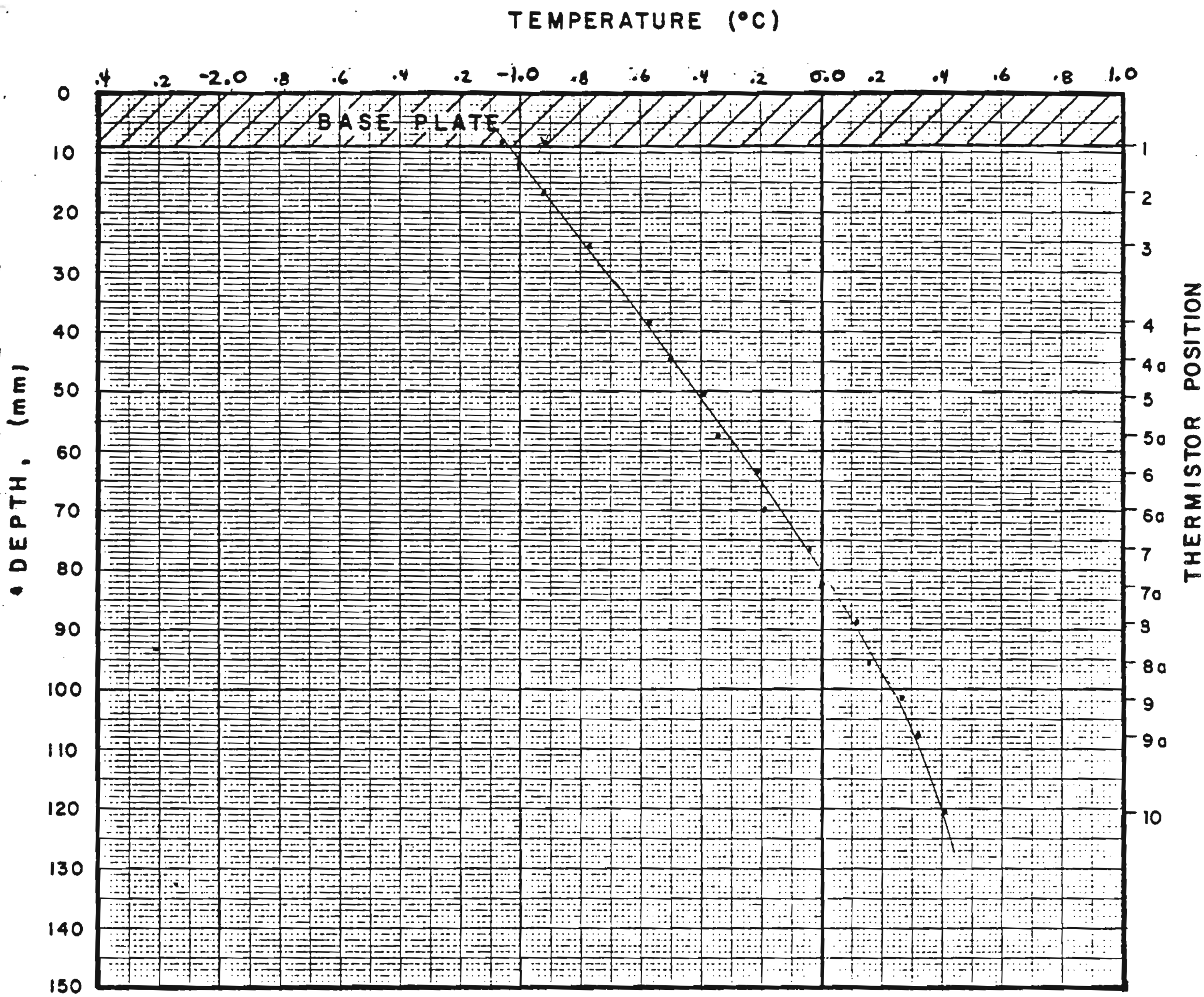
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-1D

SAMPLE NO. CS-1 CELL LT-3

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 9 mm

NOTE : Thermistor No. 10a in bottom plate

TEST C.S. - 1

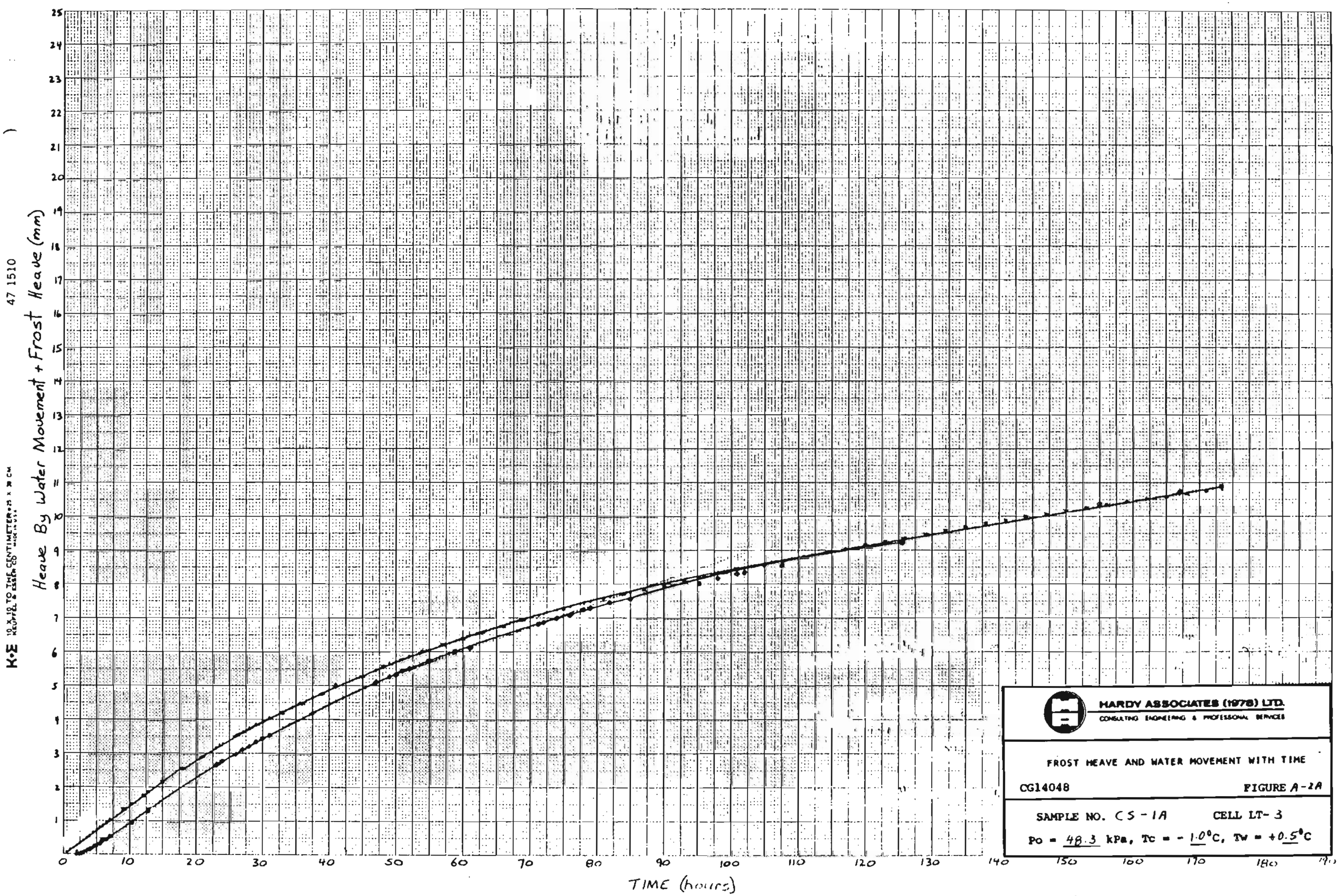
CELL LT-3

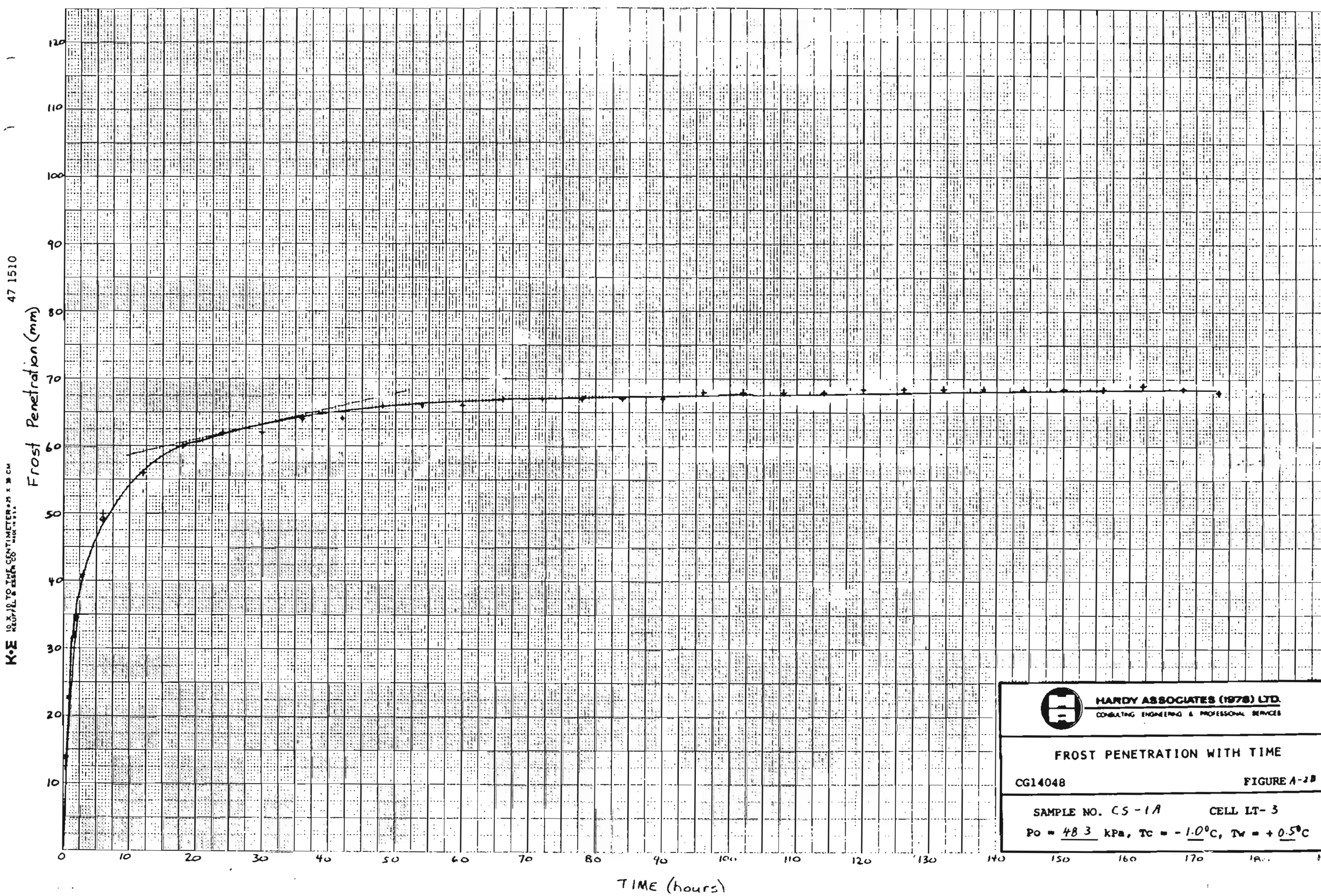
DATE MAY 3, 198[illegible]

SOIL UNDISTURBED

Δt 183.0 HRS.

FIGURE A-1E


Heave By Water Movement + Frost Heave (mm)
TIME (hours)
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST HEAVE AND WATER MOVEMENT WITH TIME
CG14048
FIGURE A-2A
SAMPLE NO. CS-1A
CELL LT-3
Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C
K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO.
47 1510

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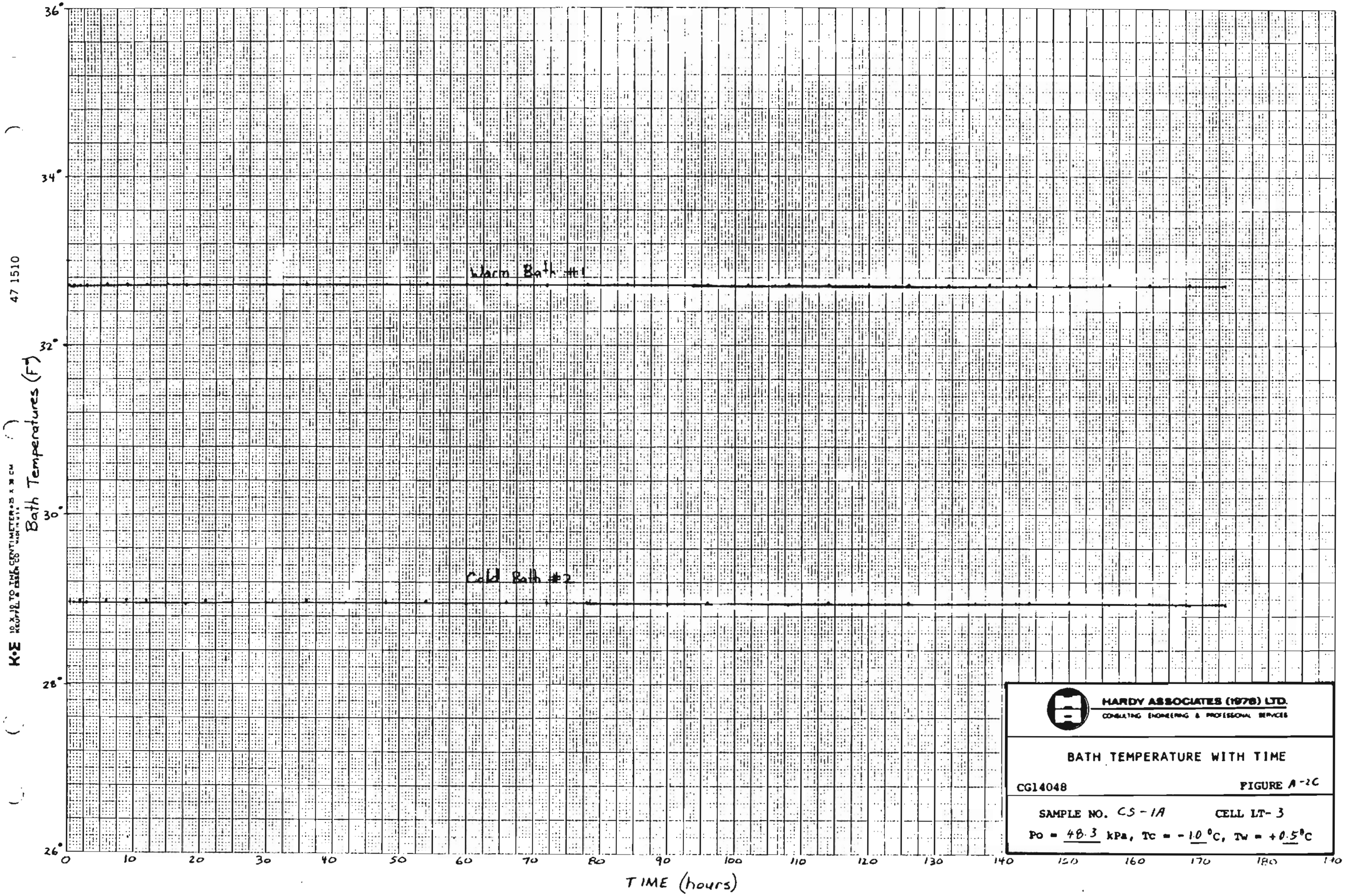
FROST PENETRATION WITH TIME

CG14048 FIGURE A-2B

SAMPLE NO. CS-1A CELL LT-3

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C

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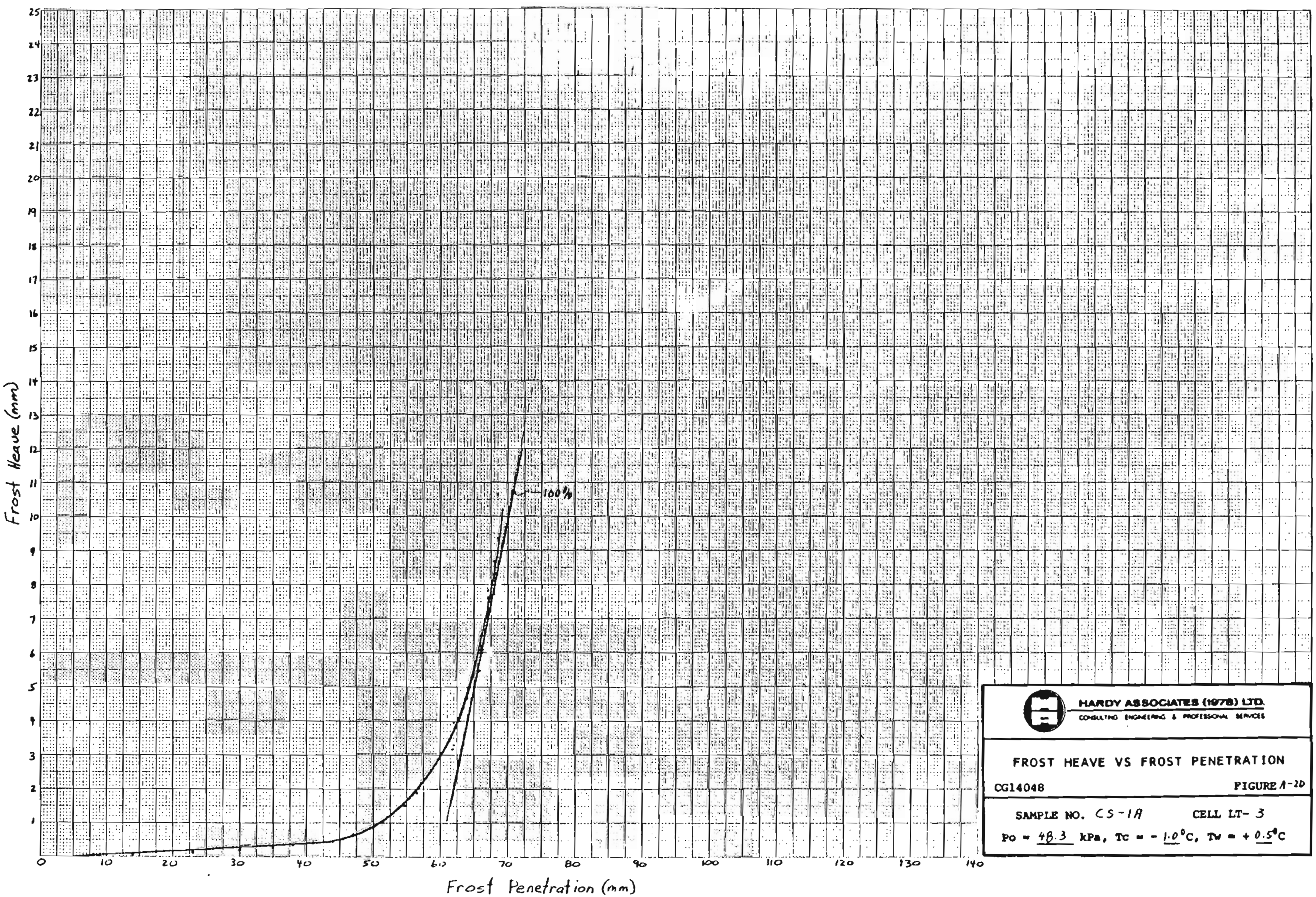
BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-2C

SAMPLE NO. CS-1A CELL LT-3

Po = 48.3 kPa, Tc = -1.0 °C, Tw = +0.5 °C

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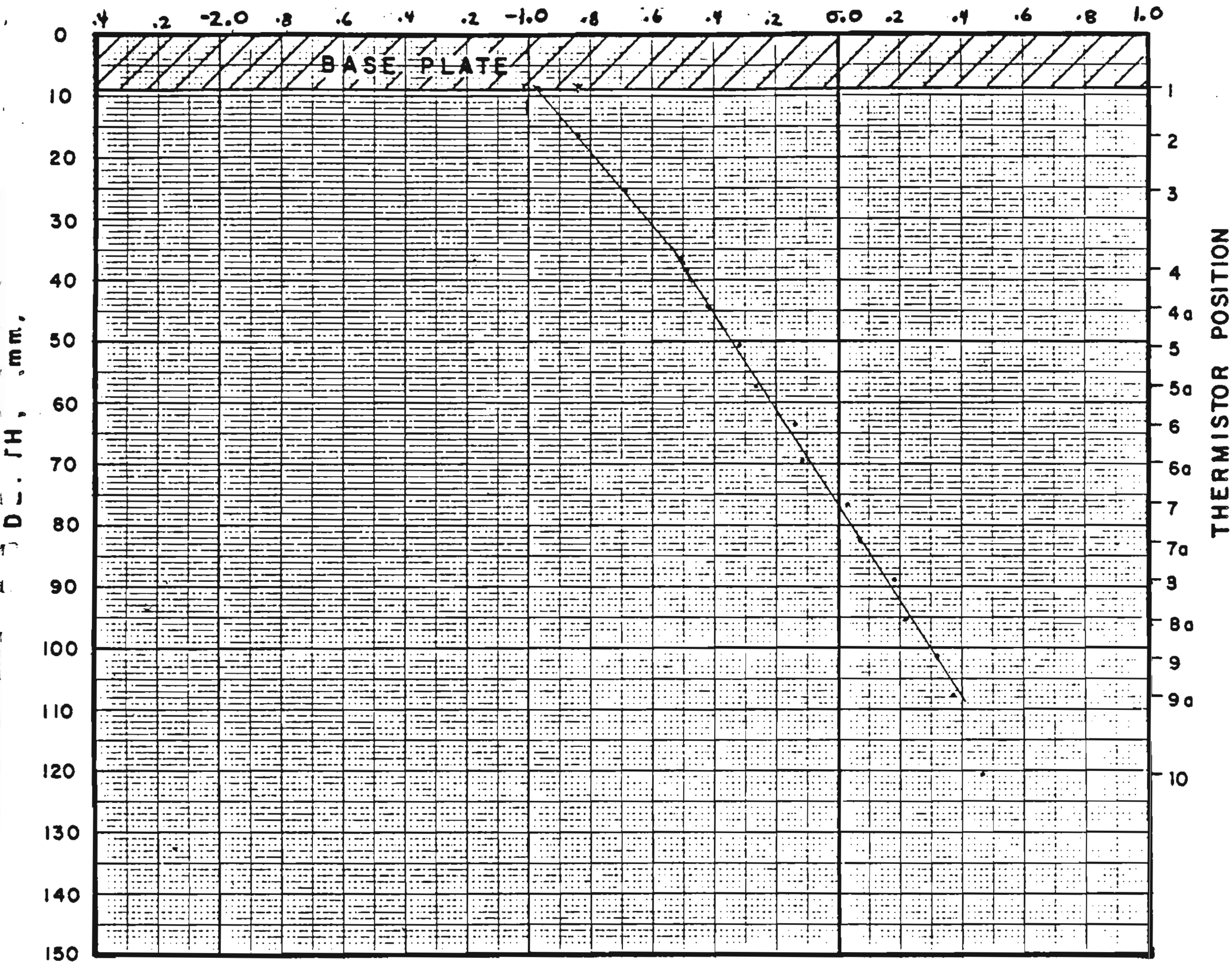
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-2D

SAMPLE NO. CS-1A CELL LT-3

Po = 48.3 kPa, Tc = - 1.0°C, Tw = + 0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 9 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS – 1A

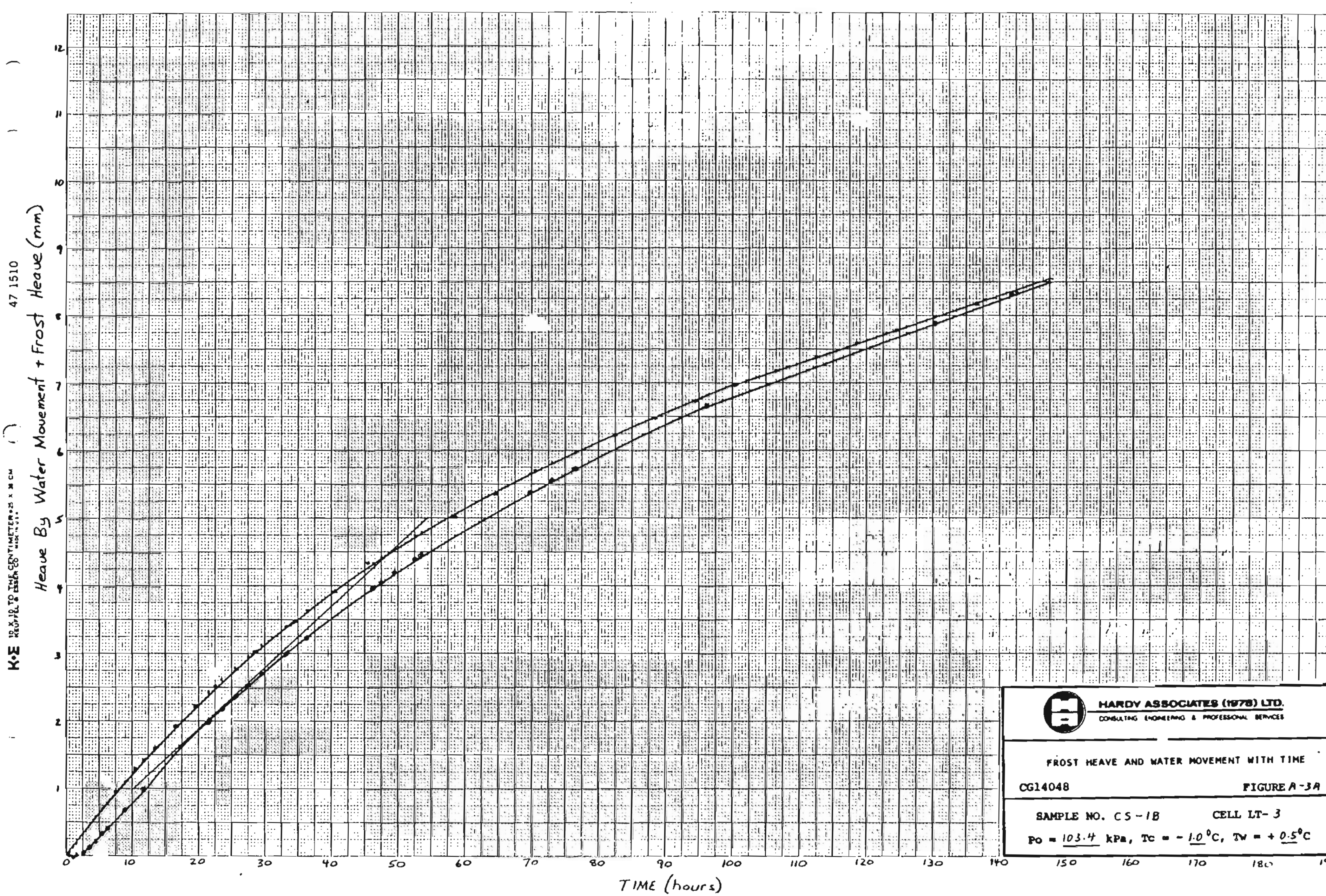
CELL LT – 3

DATE MAY 16, 1983

SOIL UNDISTURBED

Δt 173.45 HRS

FIGURE A-2E

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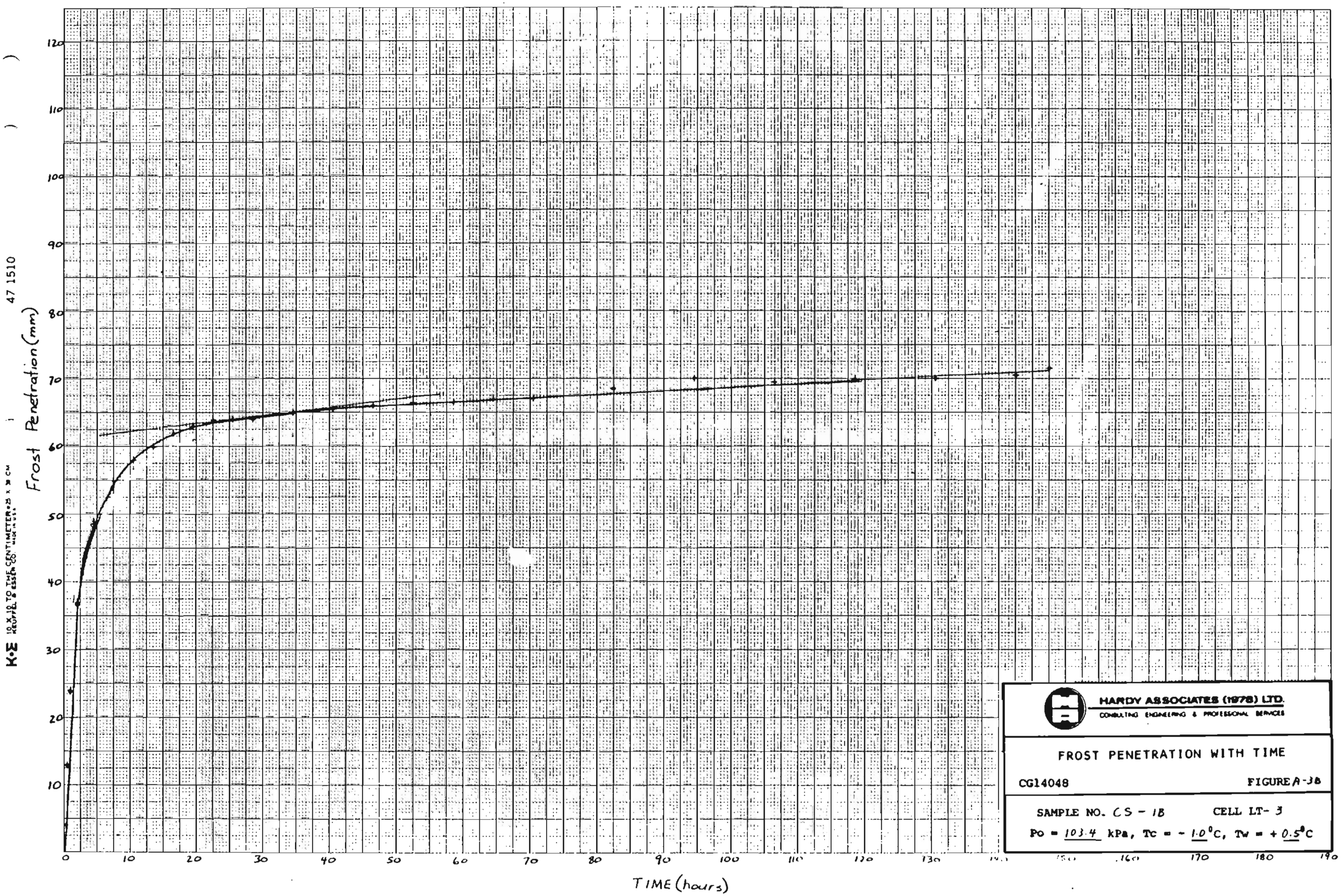
FROST HEAVE AND WATER MOVEMENT WITH TIME

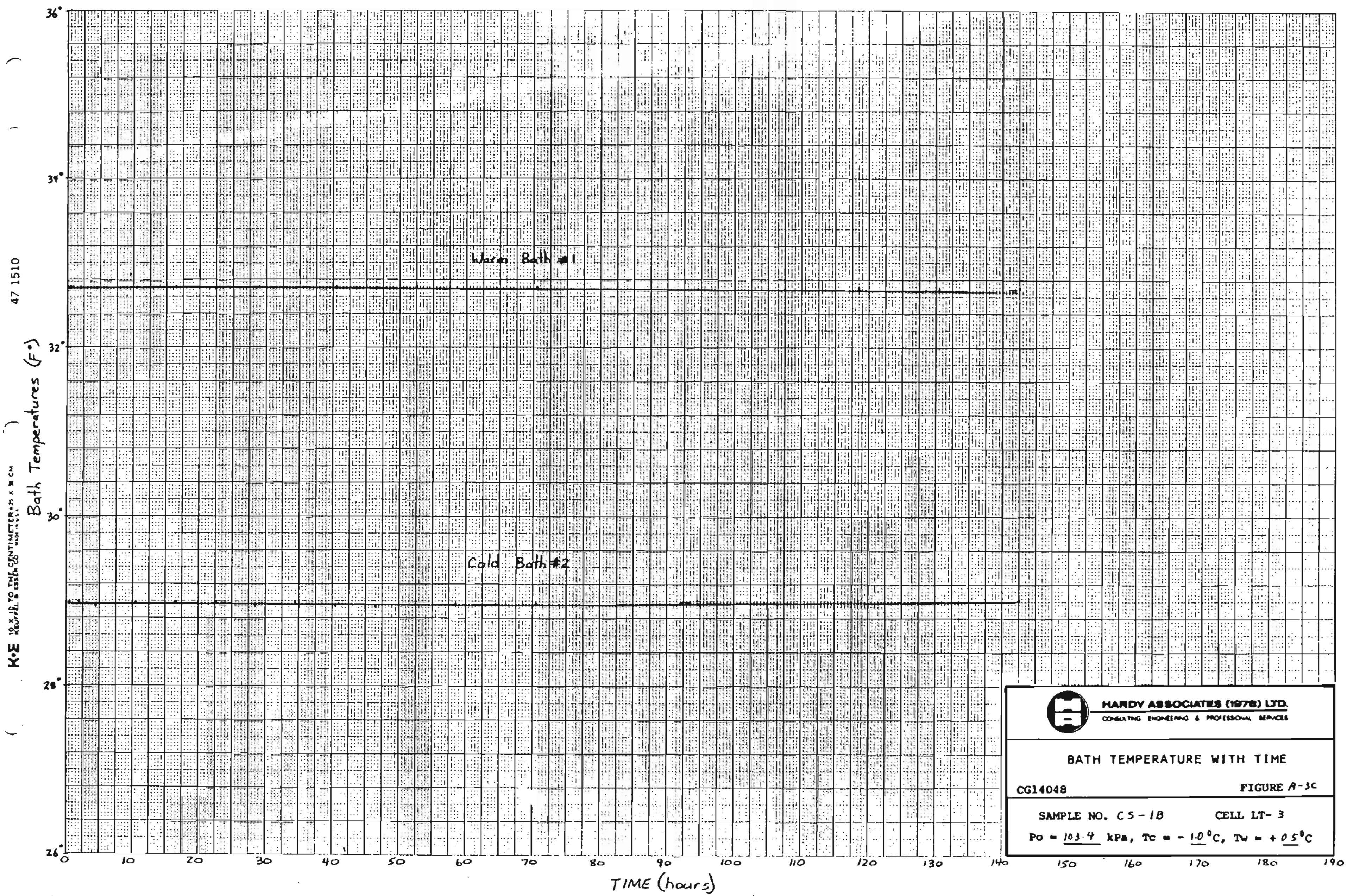
CG14048 FIGURE A-3A

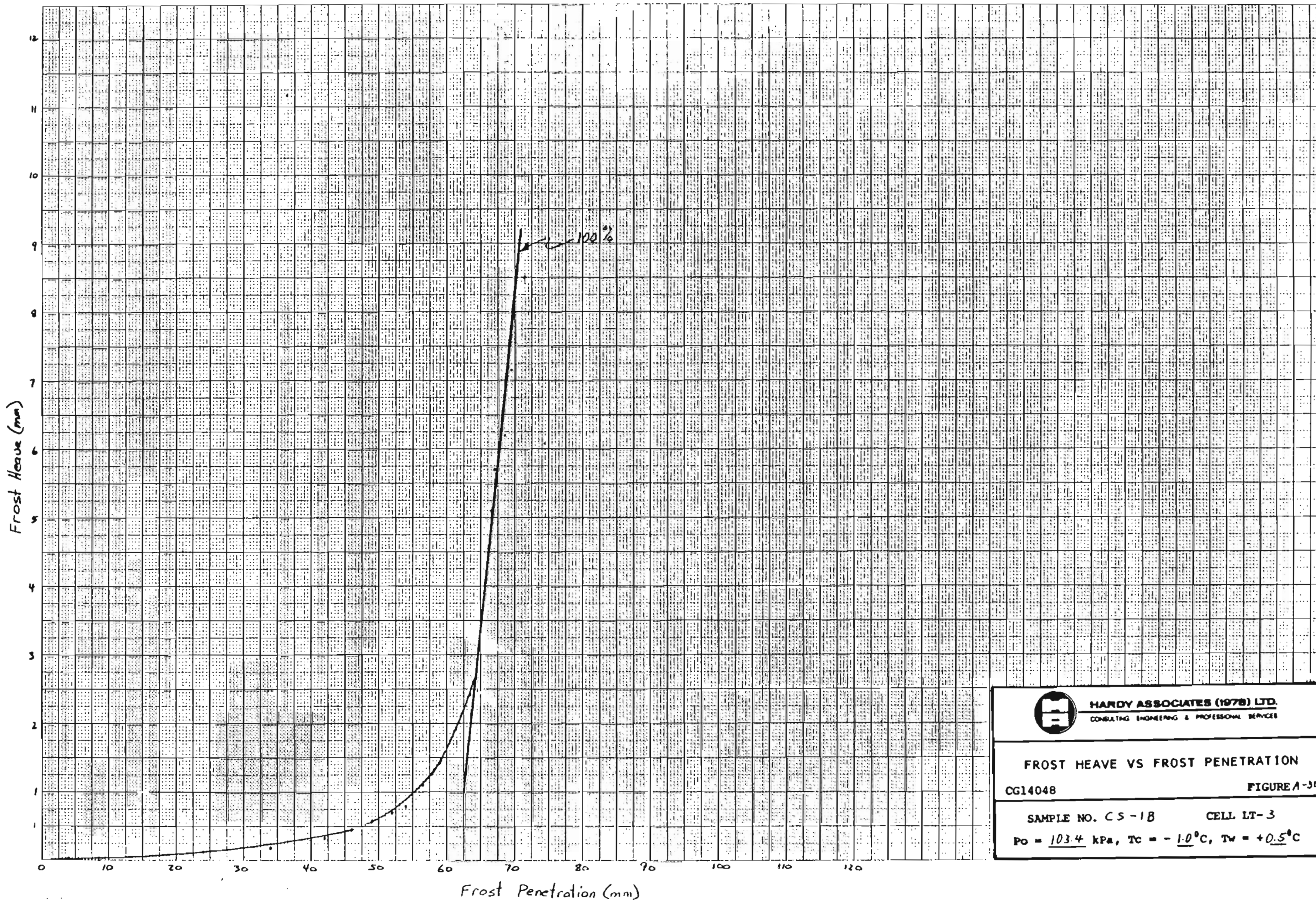
SAMPLE NO. CS-1B CELL LT-3

Po = 103.4 kPa, Tc = -1.0°C, Tw = +0.5°C



HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST PENETRATION WITH TIME
CG14048
FIGURE A-3B
SAMPLE NO. CS - 1B
CELL LT- 3
Po = 103.4 kPa, Tc = - 1.0°C, Tw = + 0.5°C
Frost Penetration (mm)
TIME (hours)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
170
180
190
K+E 10 X 10 TO THE CENTIMETER 25 X 38 CM KEUFFEL & ESSER CO.
47 1510


36°
34°
32°
30°
28°
26°
Bath Temperatures (F°)
Warm Bath #1
Cold Bath #2
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
TIME (hours)
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
BATH TEMPERATURE WITH TIME
CG14048
FIGURE A-3C
SAMPLE NO. CS-1B
CELL LT-3
Po = 103.4 kPa, Tc = -1.0°C, Tw = +0.5°C
K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A.
47 1510

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CONSULTING ENGINEERING & PROFESSIONAL SERVICES

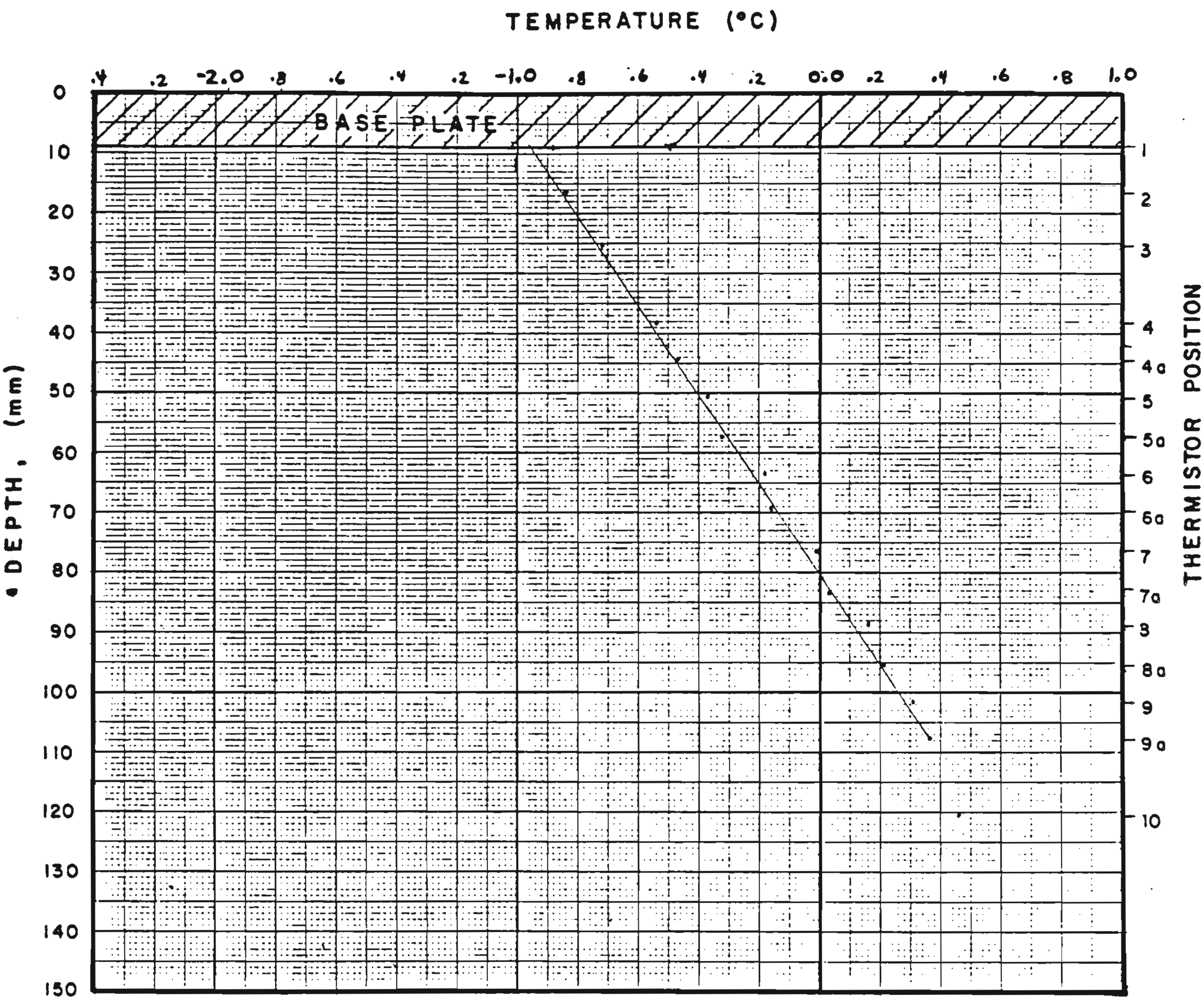
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-3D

SAMPLE NO. CS-1B CELL LT-3

Po = 103.4 kPa, Tc = - 1.0°C, Tw = +0.5°C

## TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 9 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS - 1B

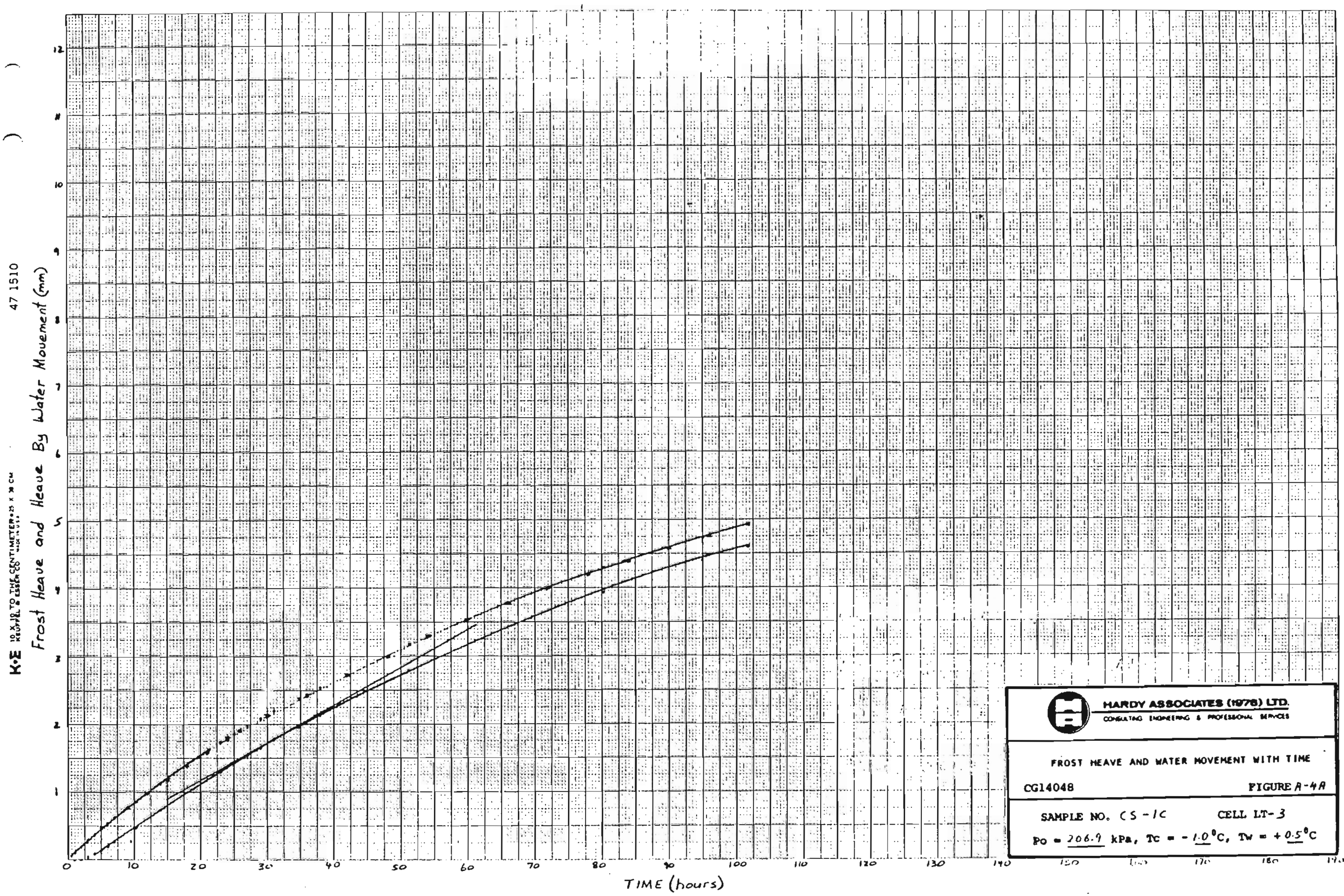
CELL LT - 3

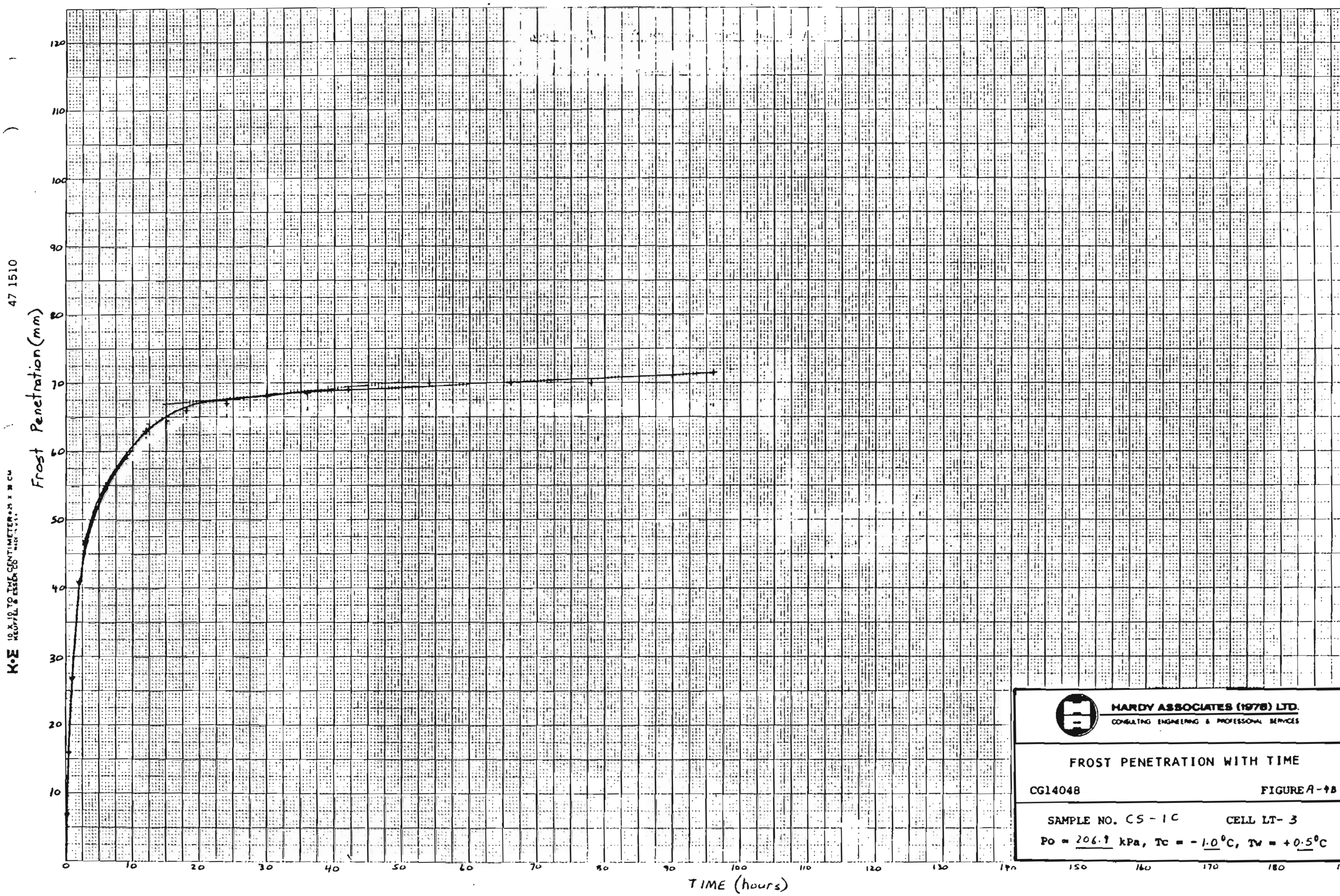
DATE MAY 30, 1983

SOIL UNDISTURBED

Δt 147.75 HRS

FIGURE A-3E


HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST HEAVE AND WATER MOVEMENT WITH TIME
CG14048
FIGURE A-4A
SAMPLE NO. CS-1C
CELL LT-3
Po = 206.9 kPa, Tc = -1.0°C, Tw = +0.5°C
Frost Heave and Heave By Water Movement (mm)
TIME (hours)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
1
2
3
4
5
6
7
8
9
10
11
12

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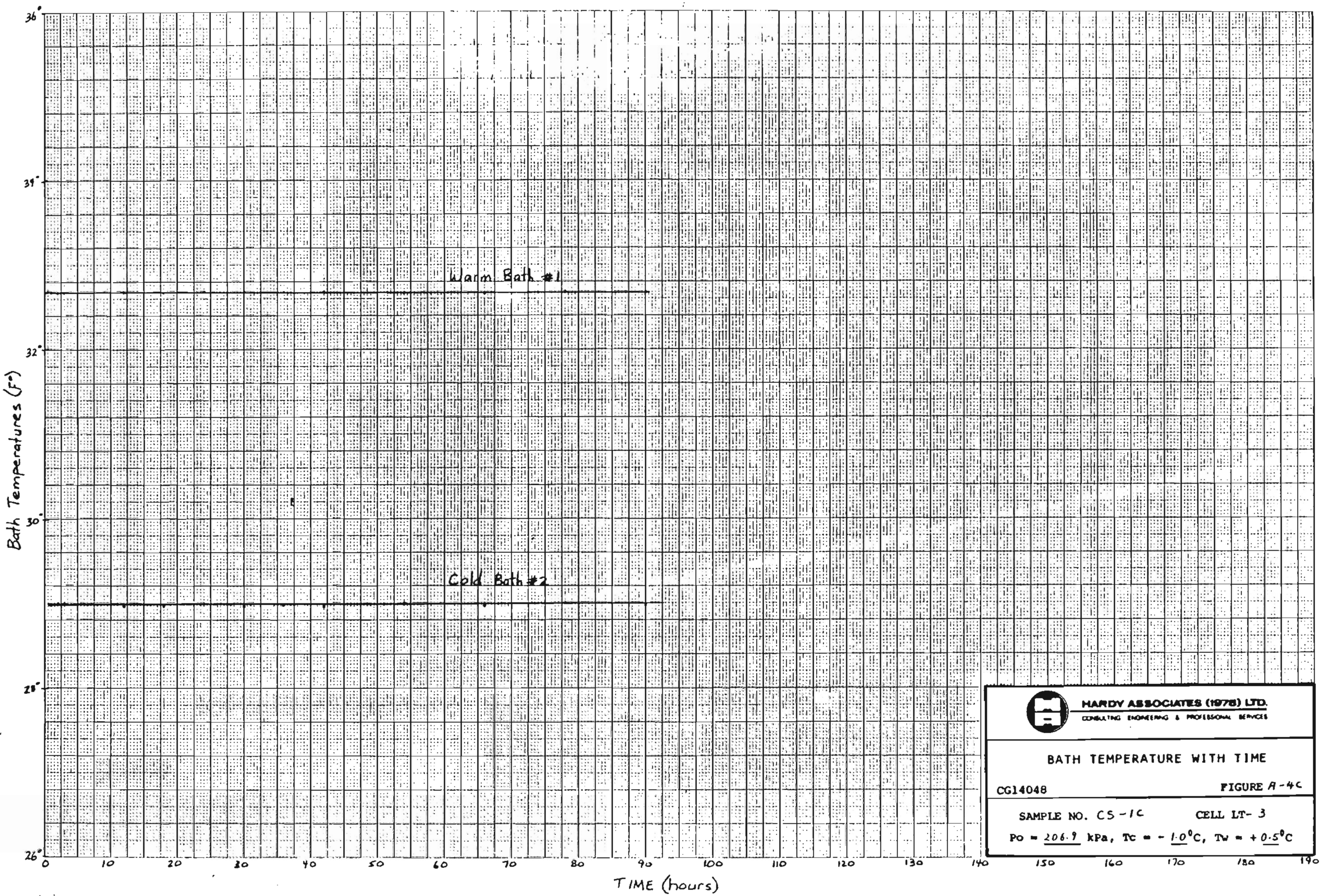
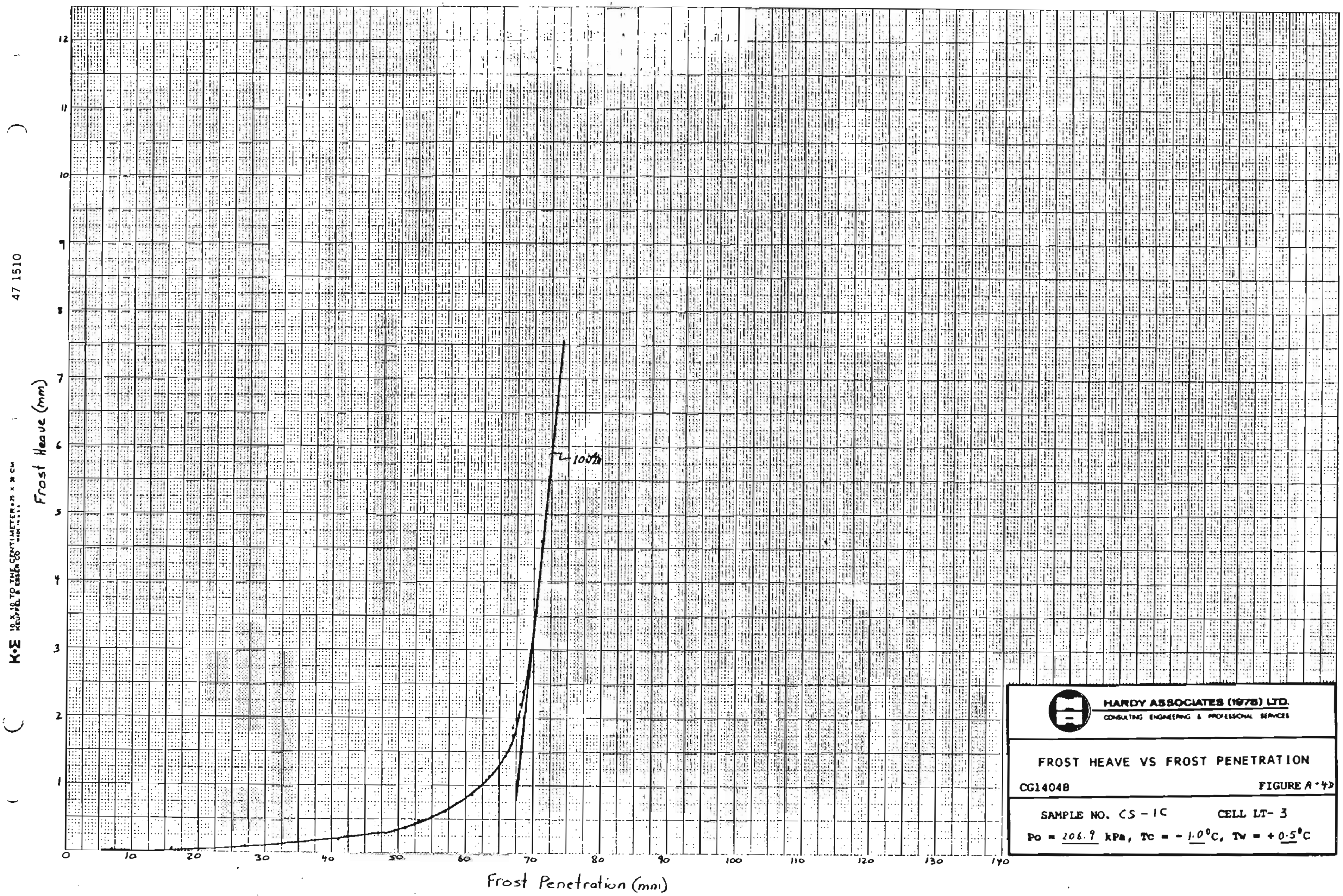
FROST PENETRATION WITH TIME

CG14048 FIGURE A-4B

SAMPLE NO. CS - 1C CELL LT- 3

Po = 206.9 kPa, Tc = - 1.0°C, Tw = + 0.5°C


Warm Bath #1
Cold Bath #2
36°
34°
32°
30°
28°
26°
Bath Temperatures (F°)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
TIME (hours)
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
BATH TEMPERATURE WITH TIME
CG14048
FIGURE A-4C
SAMPLE NO. CS-1C
CELL LT-3
Po = 206.9 kPa, Tc = - 1.0°C, Tw = + 0.5°C

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CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-4D

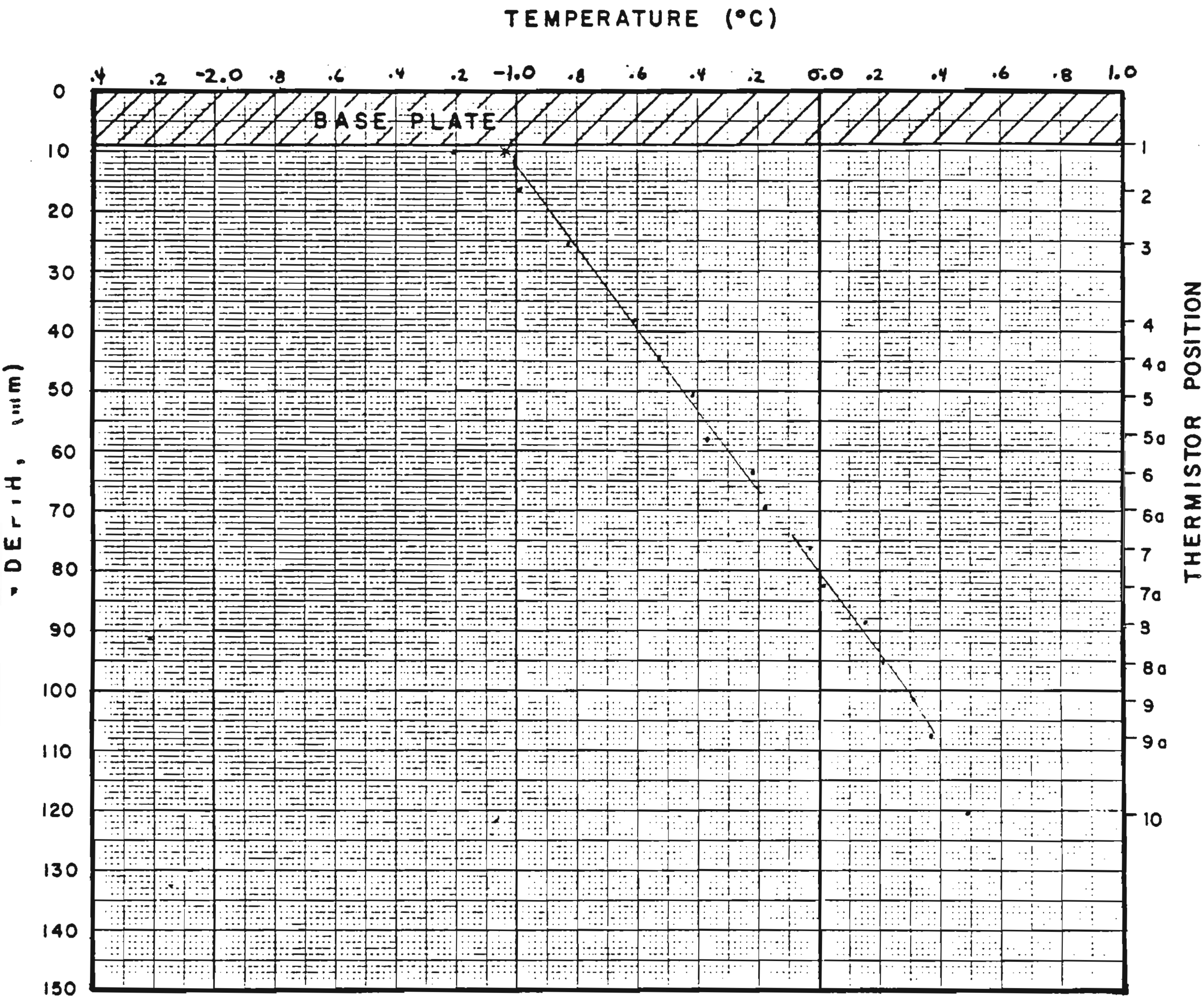
SAMPLE NO. CS-1C CELL LT-3

Po = 206.9 kPa, Tc = -1.0°C, Tv = +0.5°C

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A.

47 1510

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 9mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS - 1C

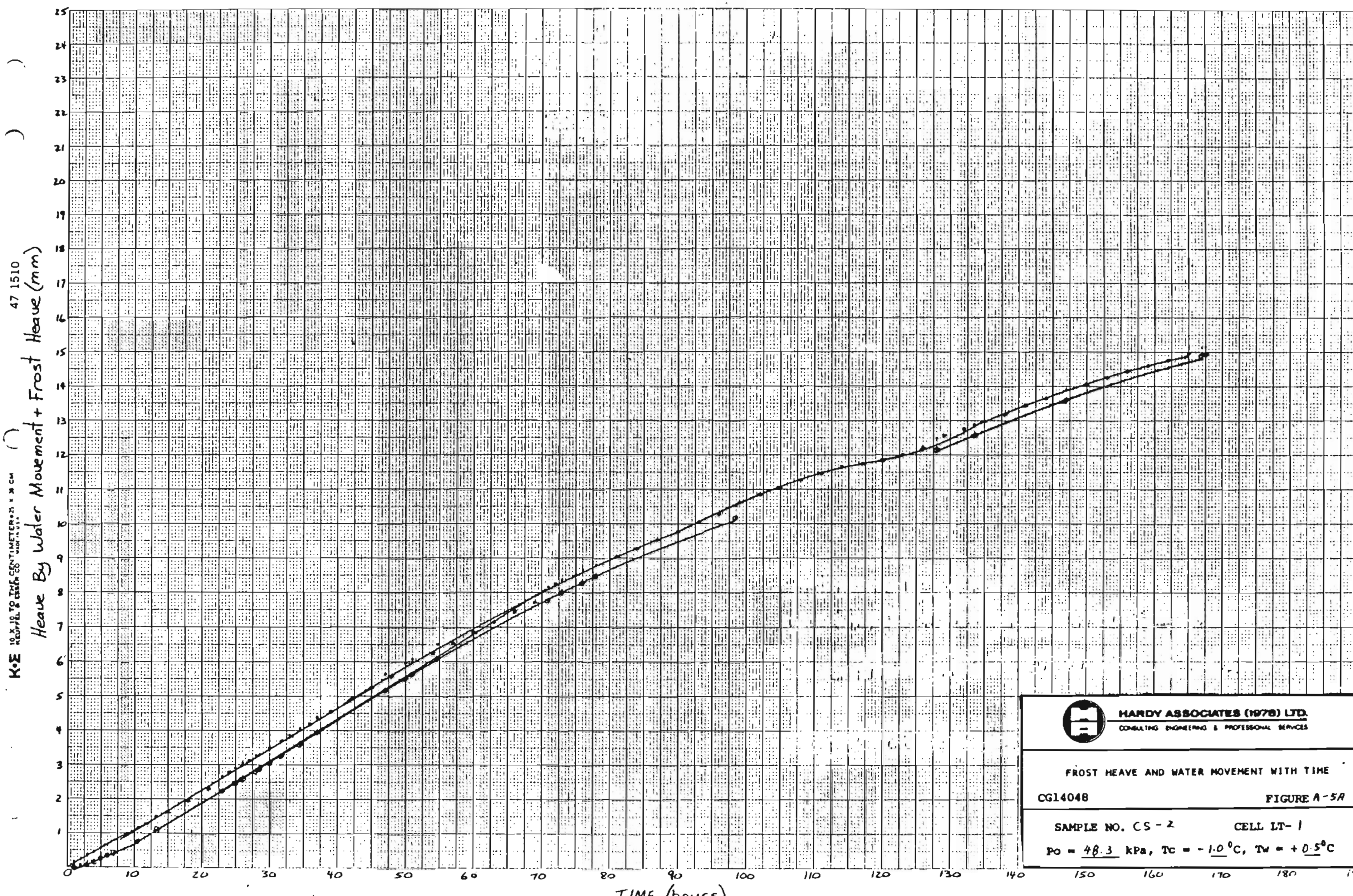
CELL LT - 2

DATE JUN. 13, 1953

SOIL UNDISTURBED

Δt 96.0 HRS

FIGURE A - 4E

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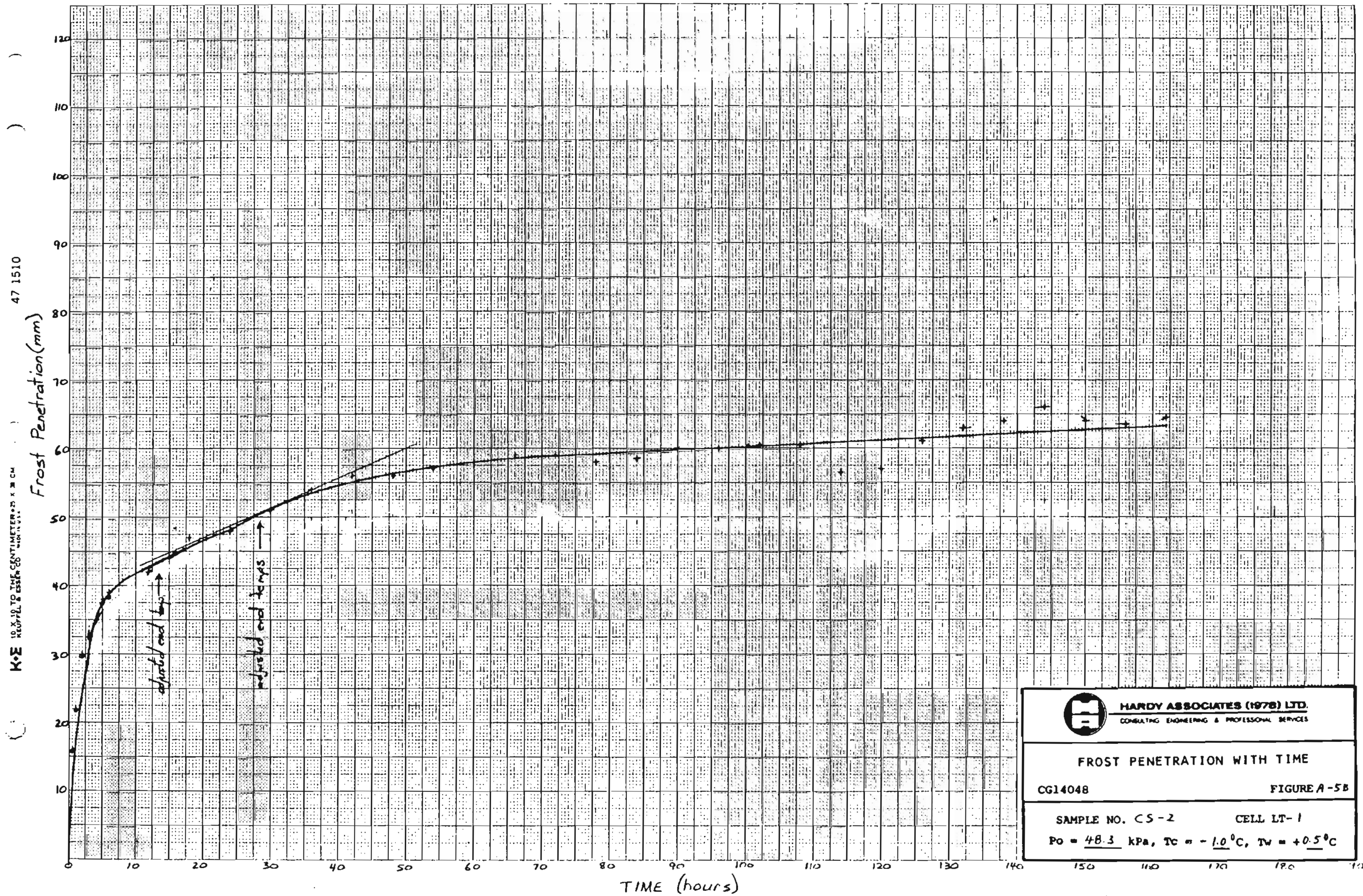
FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048 FIGURE A-5A

SAMPLE NO. CS-2 CELL LT-1

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C

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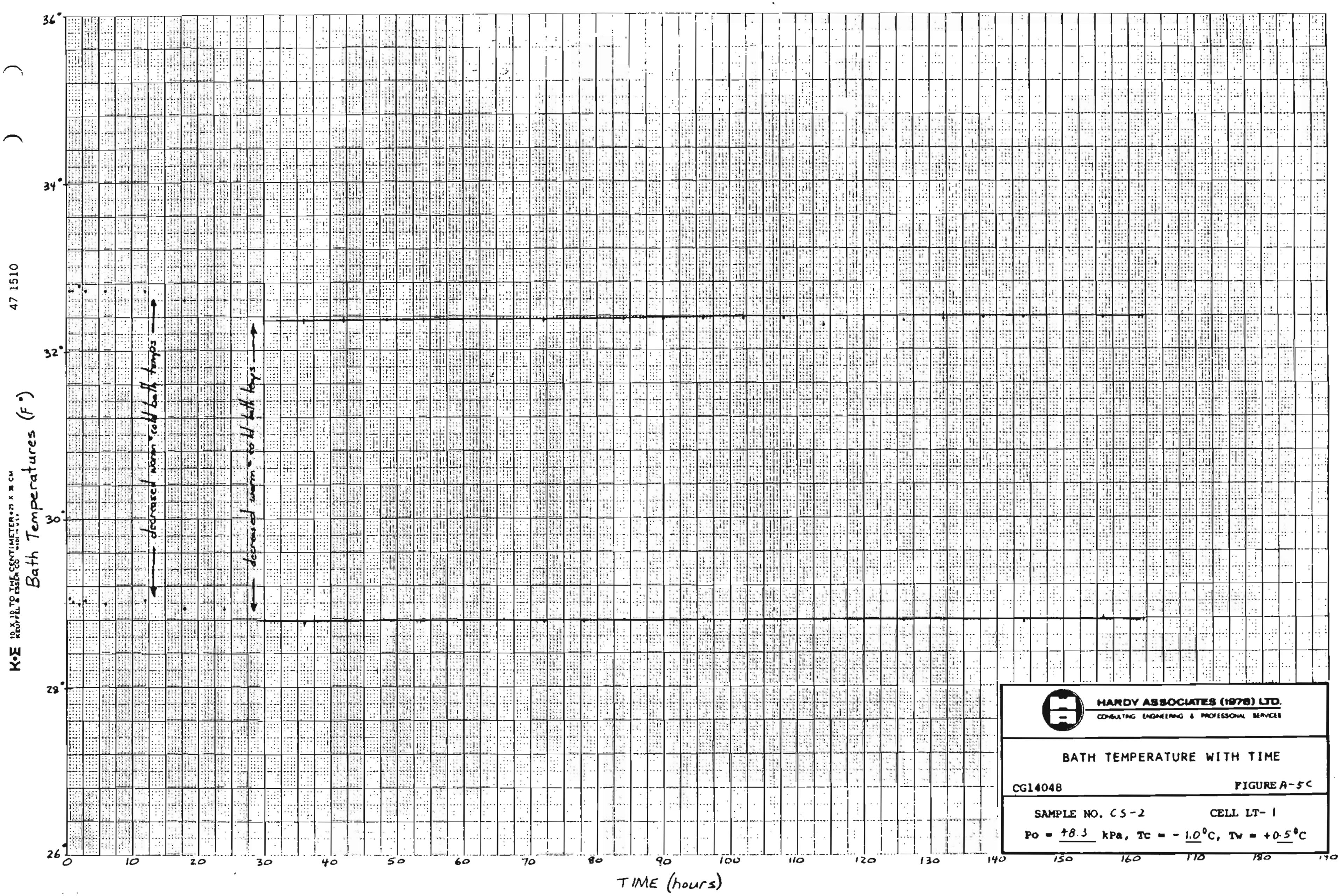
FROST PENETRATION WITH TIME

CG14048 FIGURE A-5B

SAMPLE NO. CS-2 CELL LT-1

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A. 47 1510

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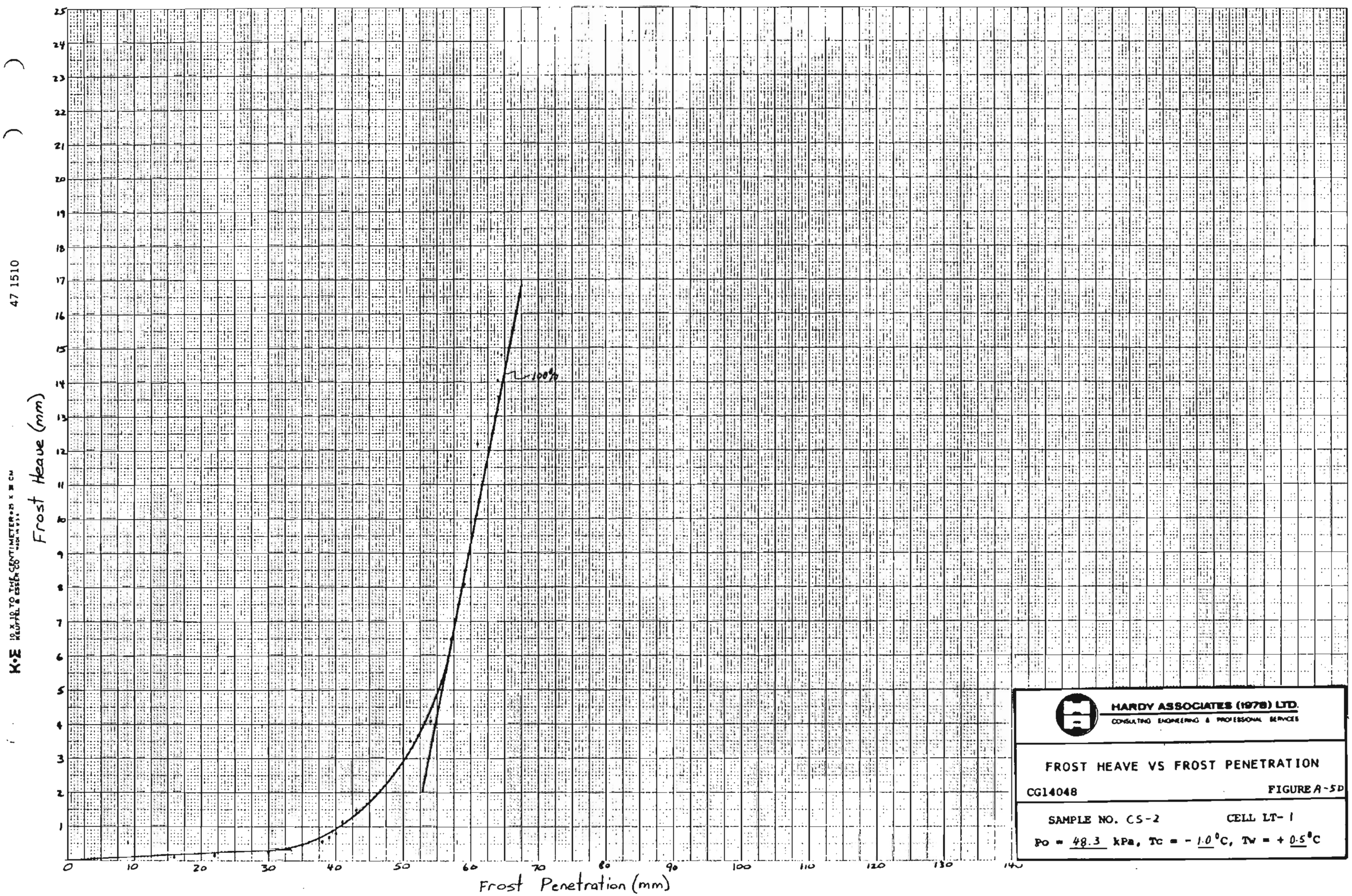
BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-5C

SAMPLE NO. CS-2 CELL LT-1

Po = 48.3 kPa, Tc = - 1.0°C, Tw = +0.5°C

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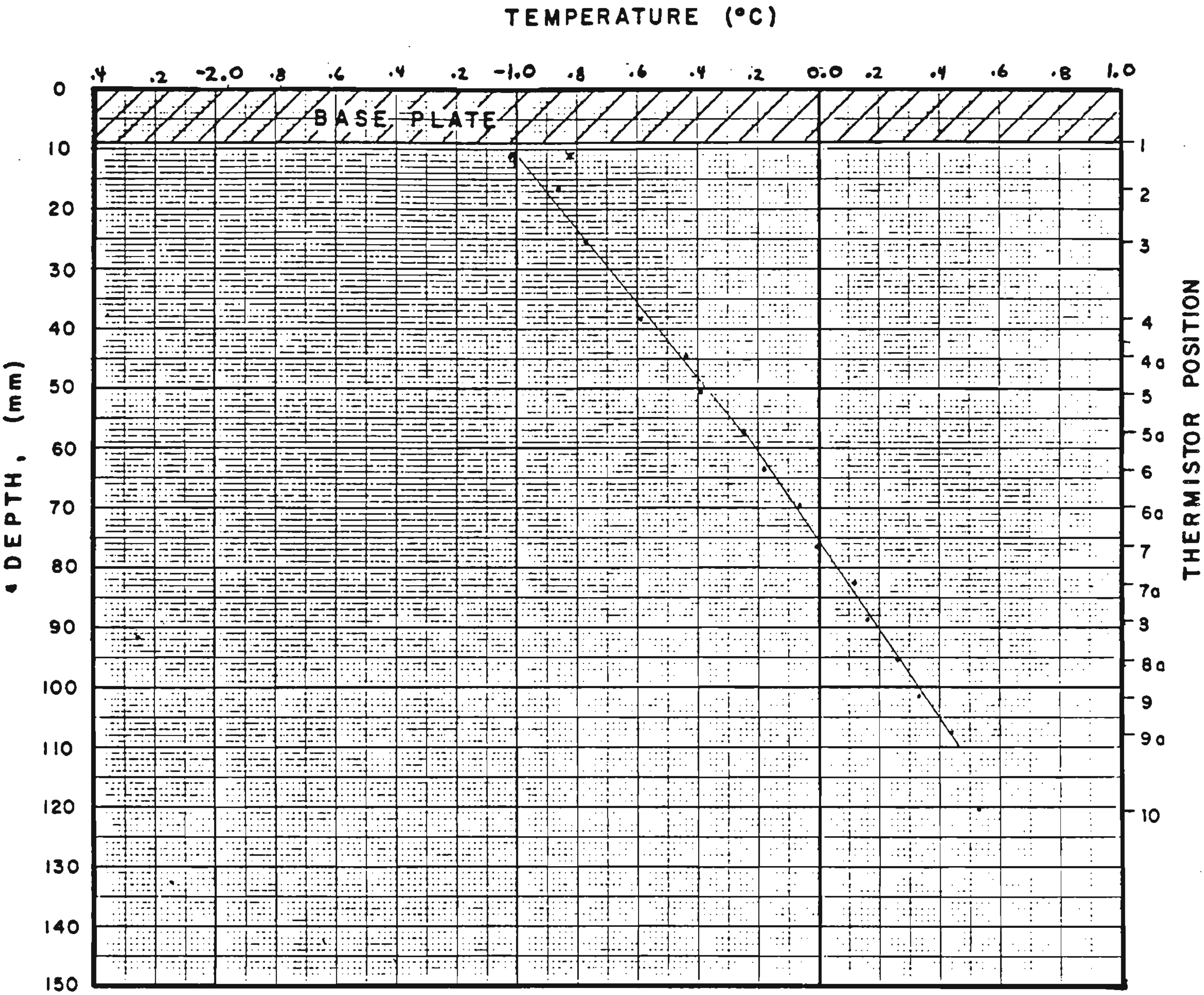
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-5D

SAMPLE NO. CS-2 CELL LT-1

Po = 48.3 kPa, Tc = - 1.0°C, Tw = + 0.5°C

# TEMPERATURE PROFILE




TEST CS - 2

CELL LT - I

THICKNESS OF BASE PLATE = 11 mm

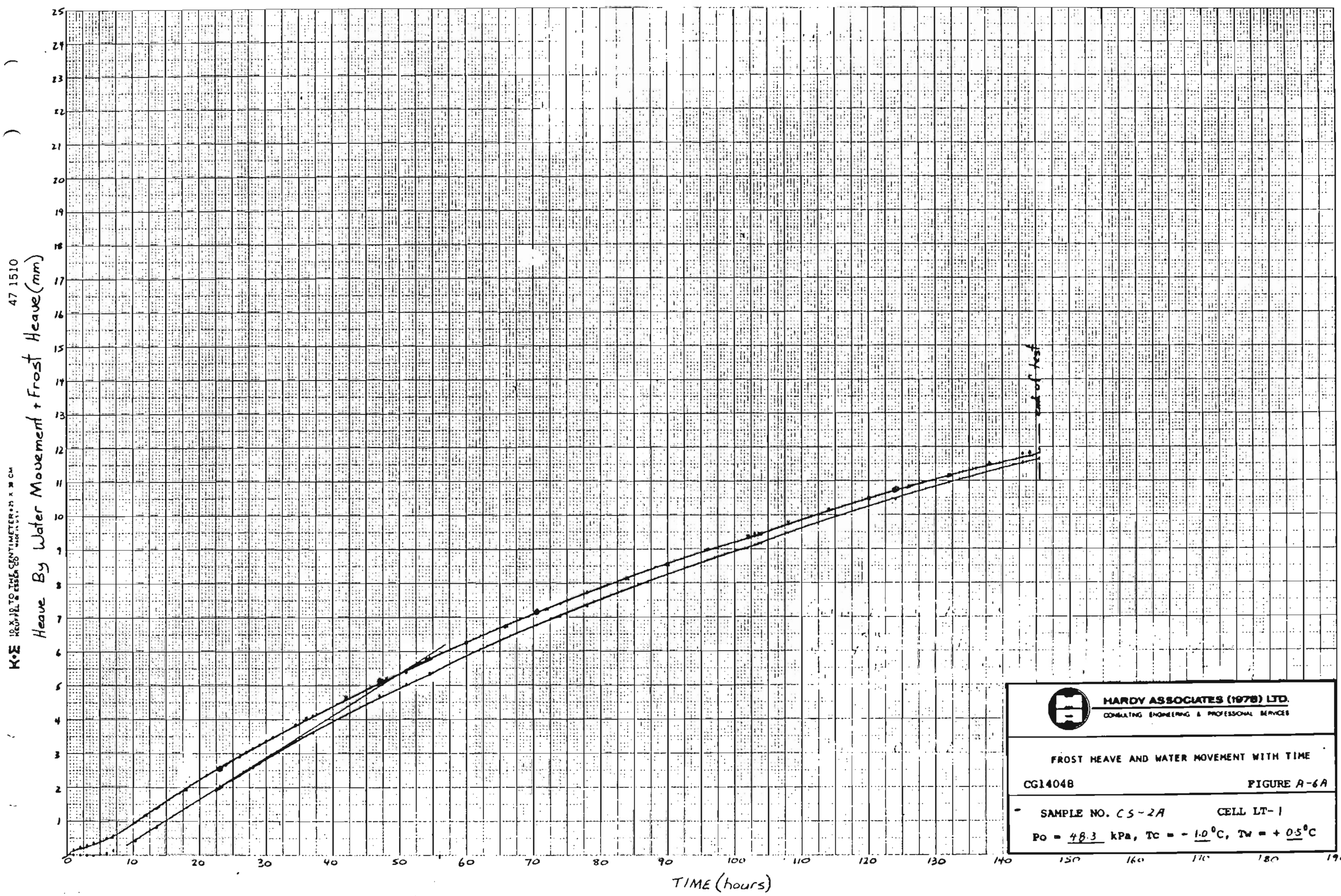
DATE MAY 24, 1983

NOTE : Thermistor No. 10a in bottom plate

SOIL REMOULDED

Δt 162.0 HRS

FIGURE A - 5E

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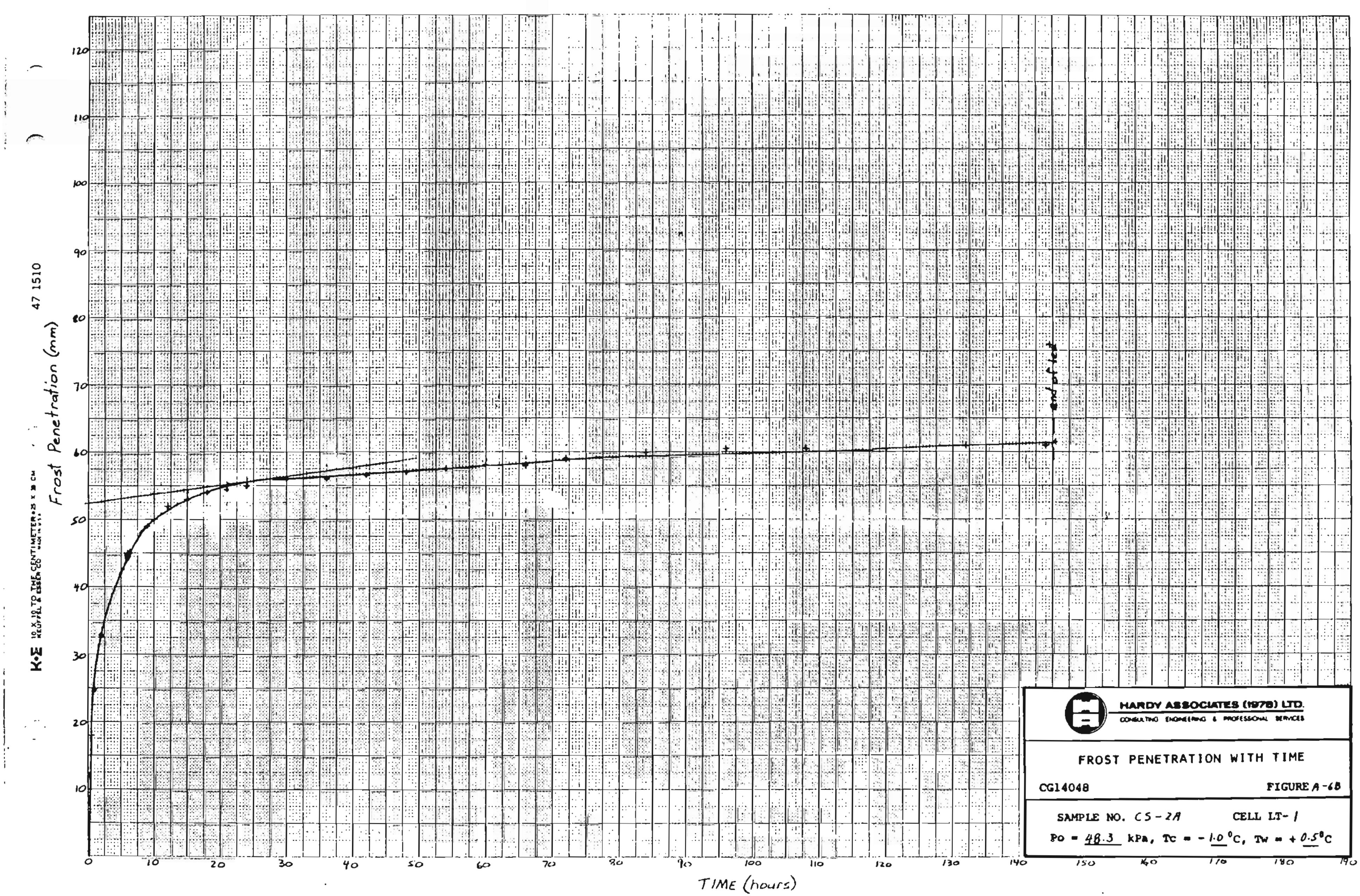
FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048 FIGURE A-6A

SAMPLE NO. CS-2A CELL LT-1

Po = 48.3 kPa, Tc = - 1.0°C, Tw = + 0.5°C

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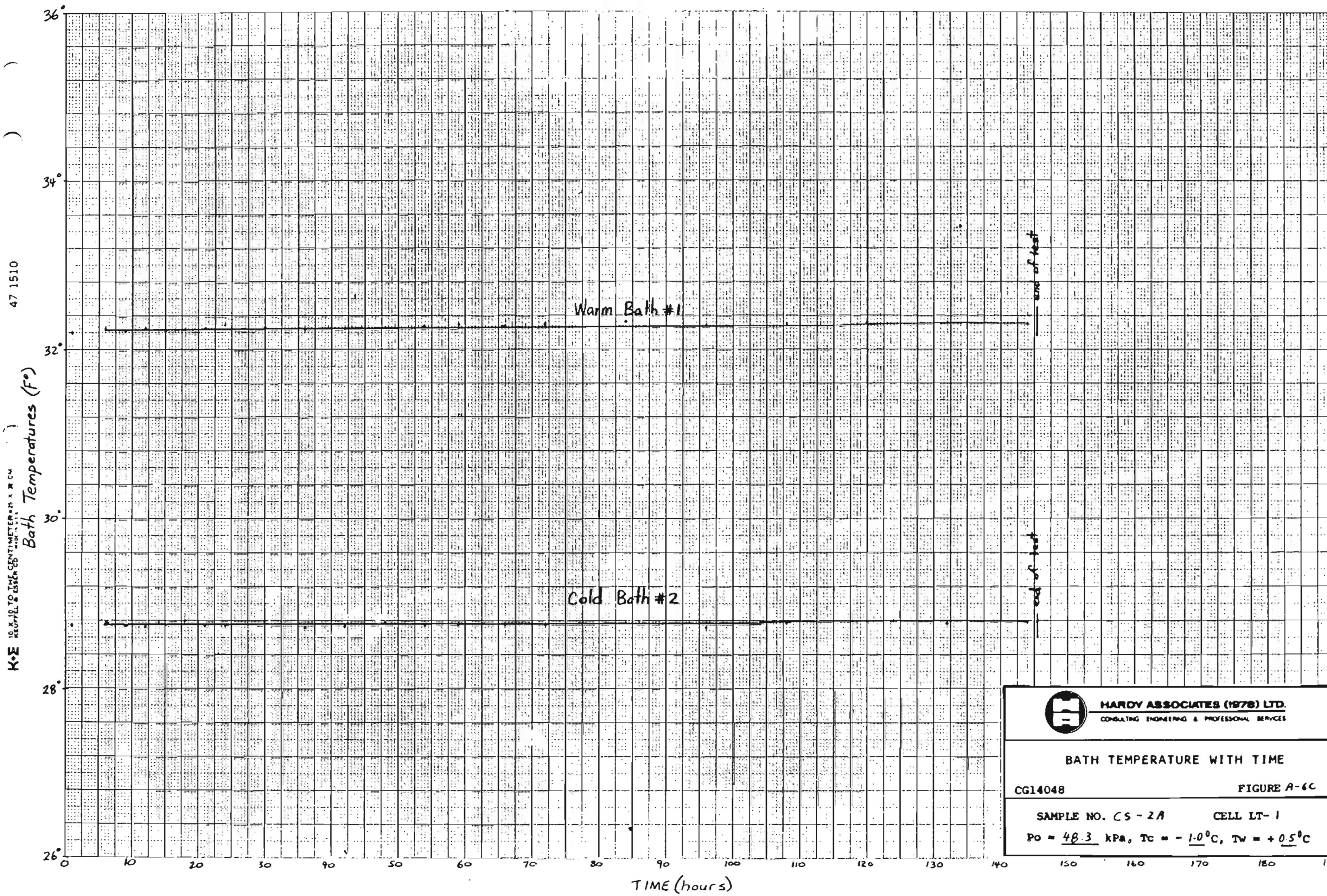
FROST PENETRATION WITH TIME

CG14048 FIGURE A-6B

SAMPLE NO. CS-2A CELL LT-1

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C

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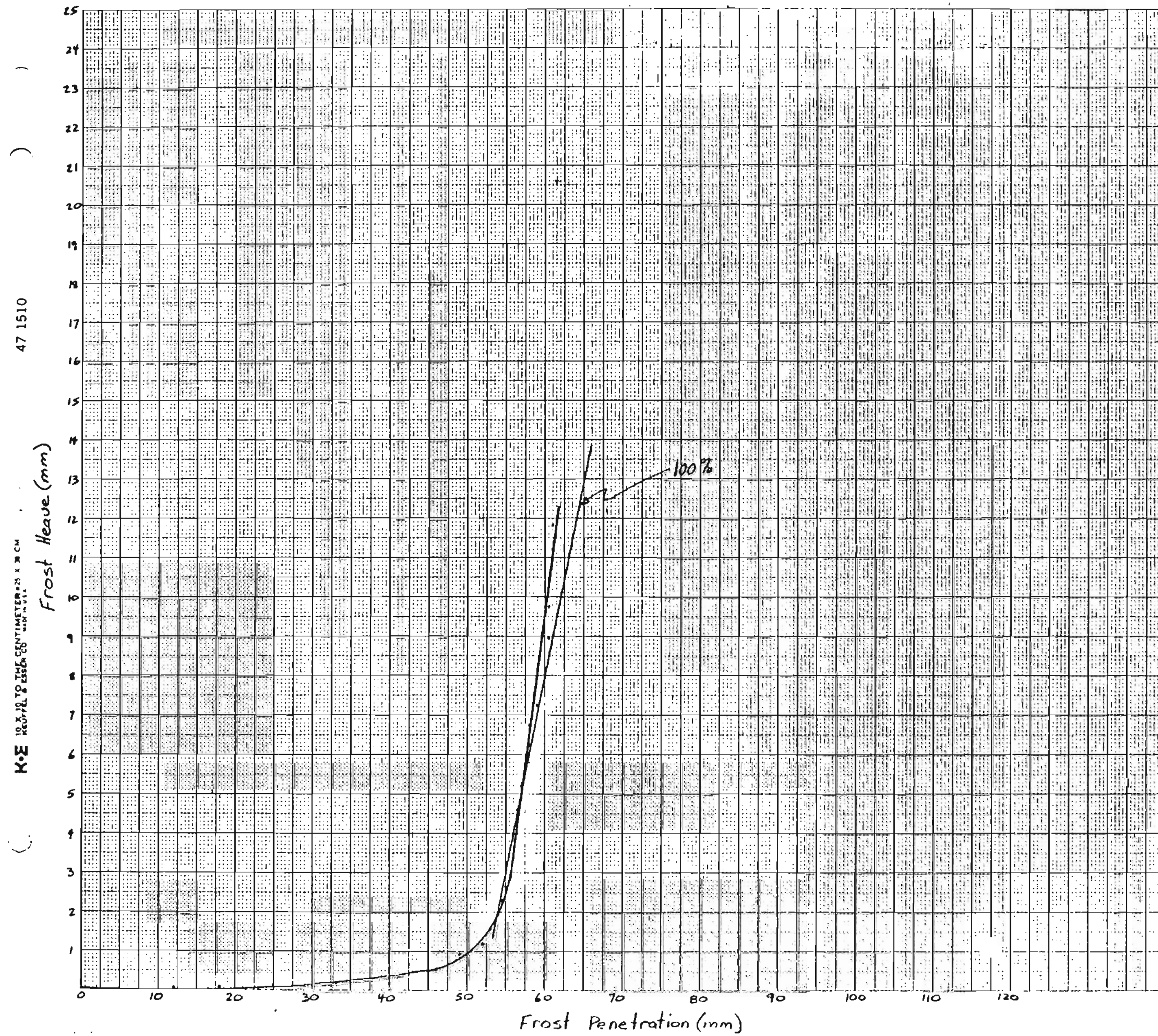
BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-6C

SAMPLE NO. CS - 2A CELL LT- 1

Po = 48.3 kPa, Tc = - 1.0°C, Tw = + 0.5°C

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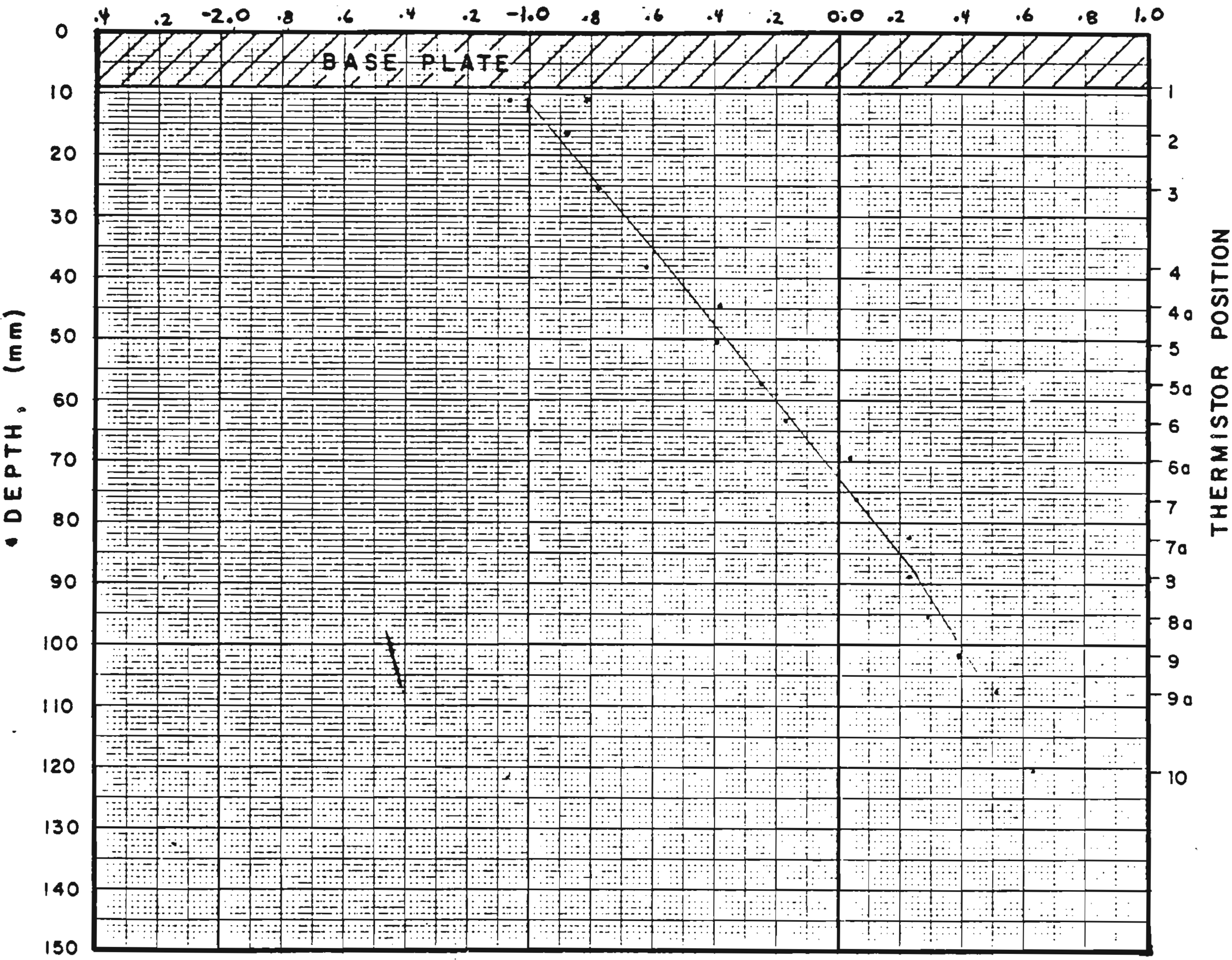
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-6D

SAMPLE NO. CS-2A CELL LT-1

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS - 2A

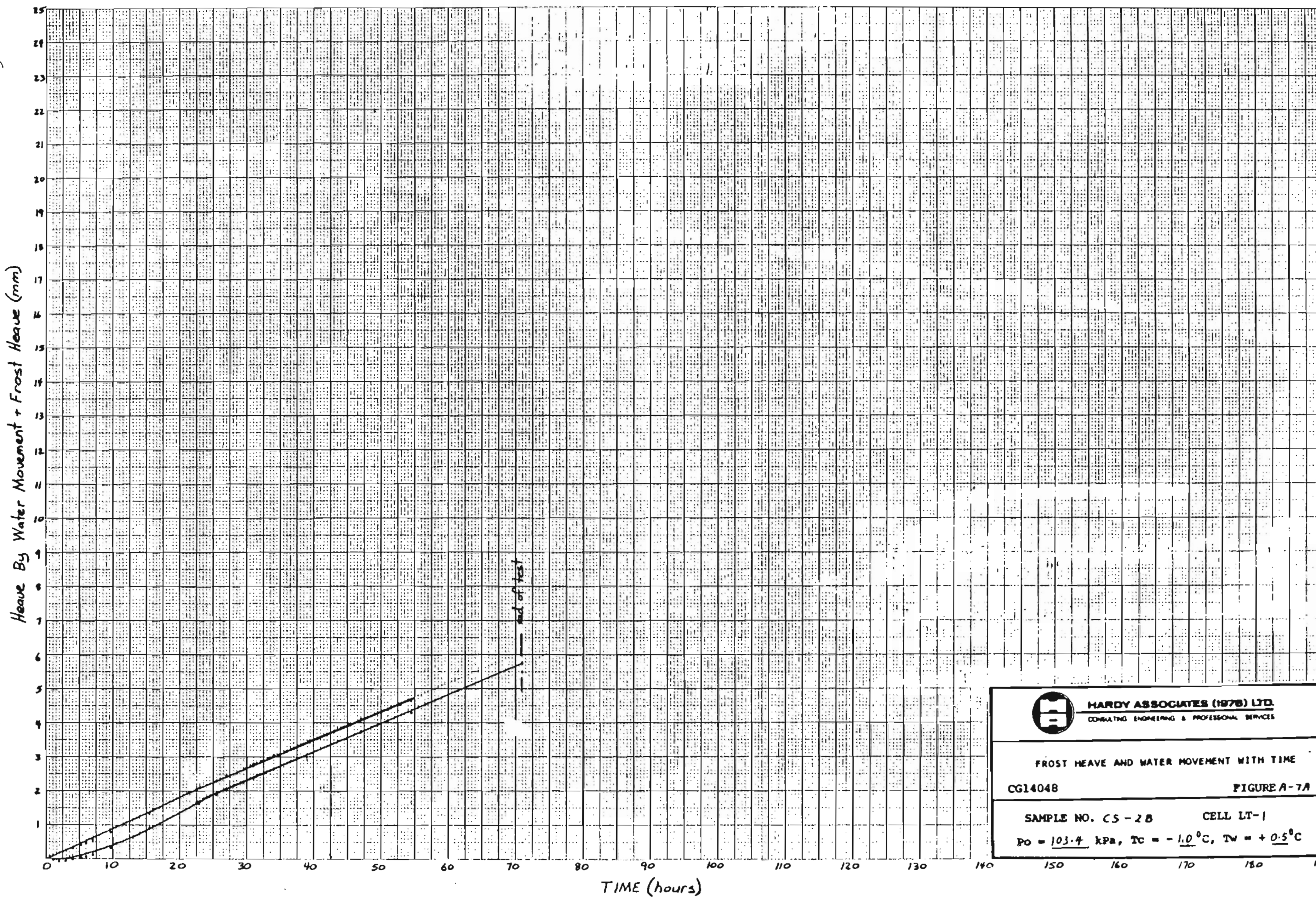
CELL I.T - I

DATE JUN. 20, 1983

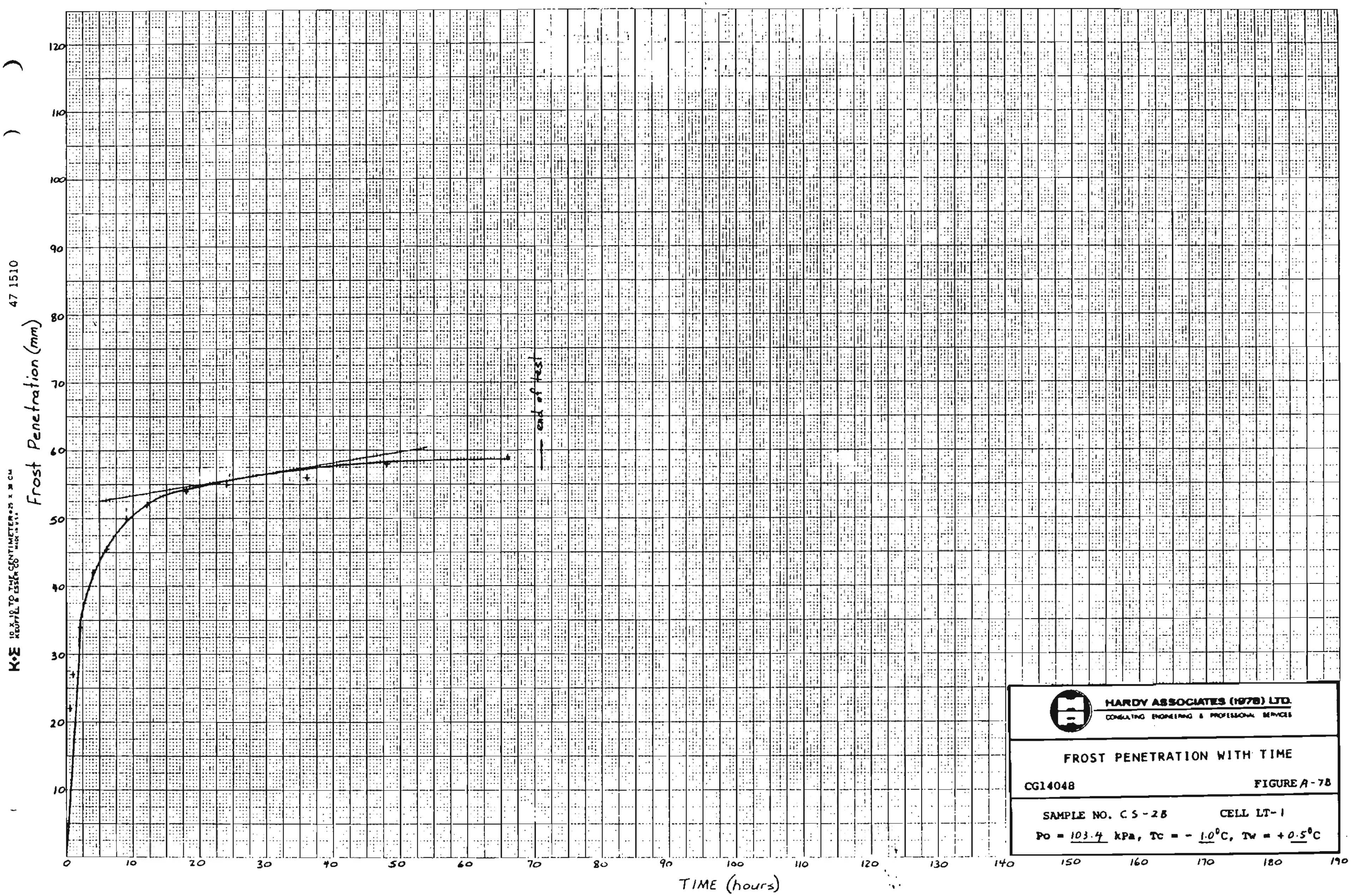
SOIL REMOULDED

Δt 145.4 HRS

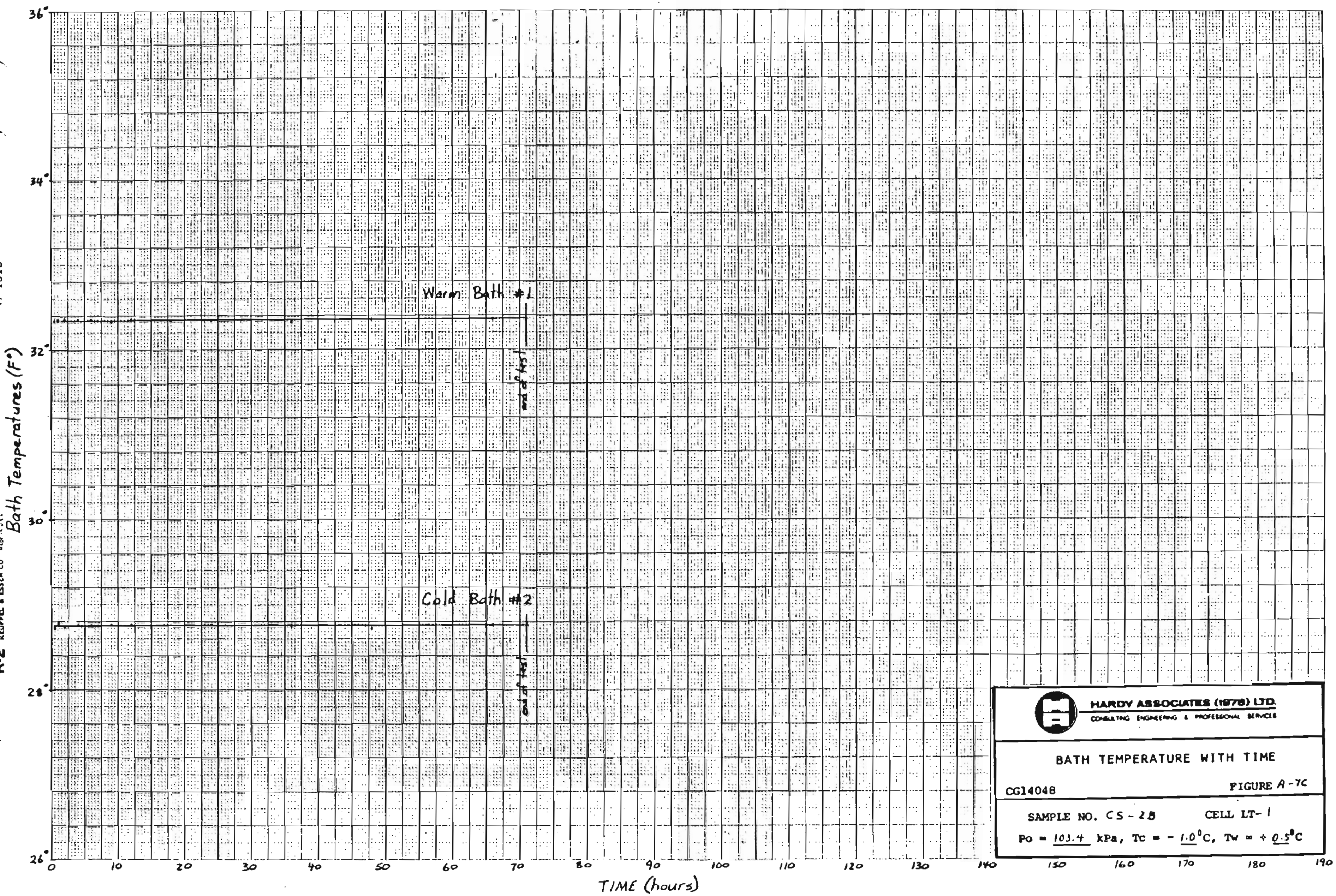
FIGURE A-6E



Heave By Water Movement + Frost Heave (mm)
TIME (hours)
end of test
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST HEAVE AND WATER MOVEMENT WITH TIME
CG14048
FIGURE A-7A
SAMPLE NO. CS-2B
CELL LT-1
Po = 103.4 kPa, Tc = -1.0°C, Tw = +0.5°C



Frost Penetration (mm)
TIME (hours)
end of test
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST PENETRATION WITH TIME
CG14048
FIGURE A-78
SAMPLE NO. CS-28
CELL LT-1
Po = 103.4 kPa, Tc = - 1.0°C, Tw = + 0.5°C
K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A.
47 1510

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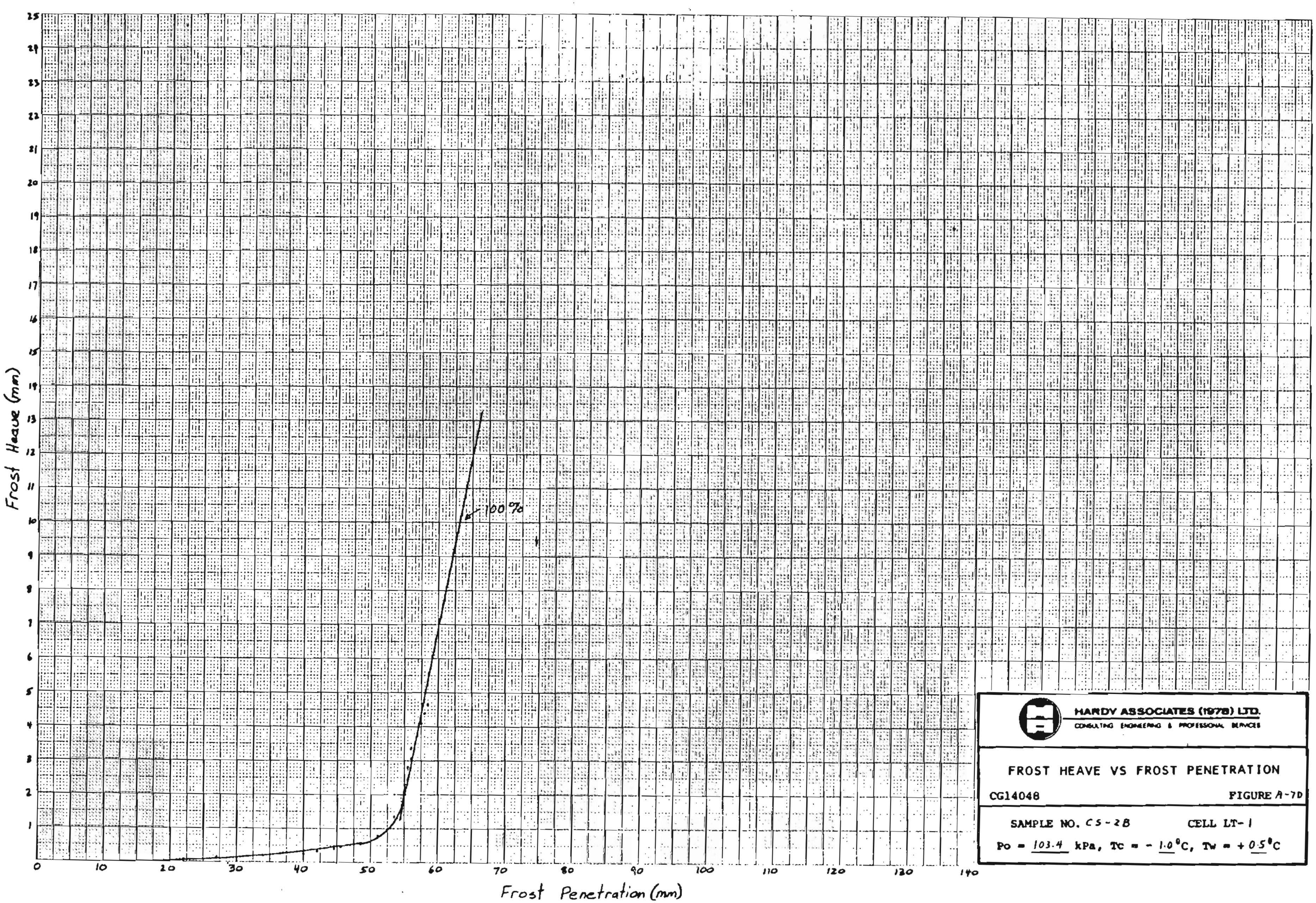
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-7C

SAMPLE NO. CS-28 CELL LT-1

Po = 103.4 kPa, Tc = - 1.0°C, Tw = + 0.5°C




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

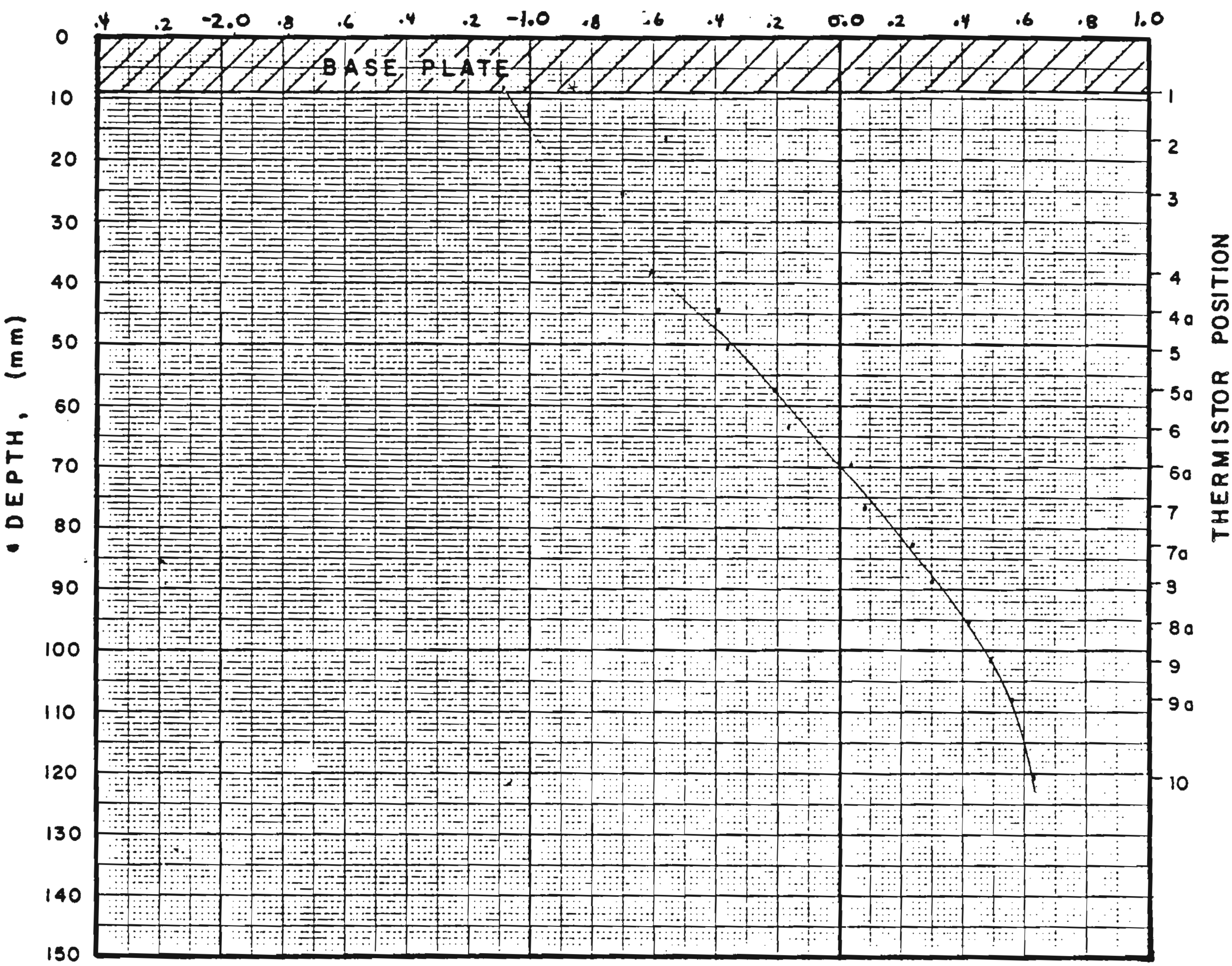
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-7D

SAMPLE NO. CS-2B CELL LT-1

Po = 103.4 kPa, Tc = - 1.0°C, Tw = + 0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS - 2B

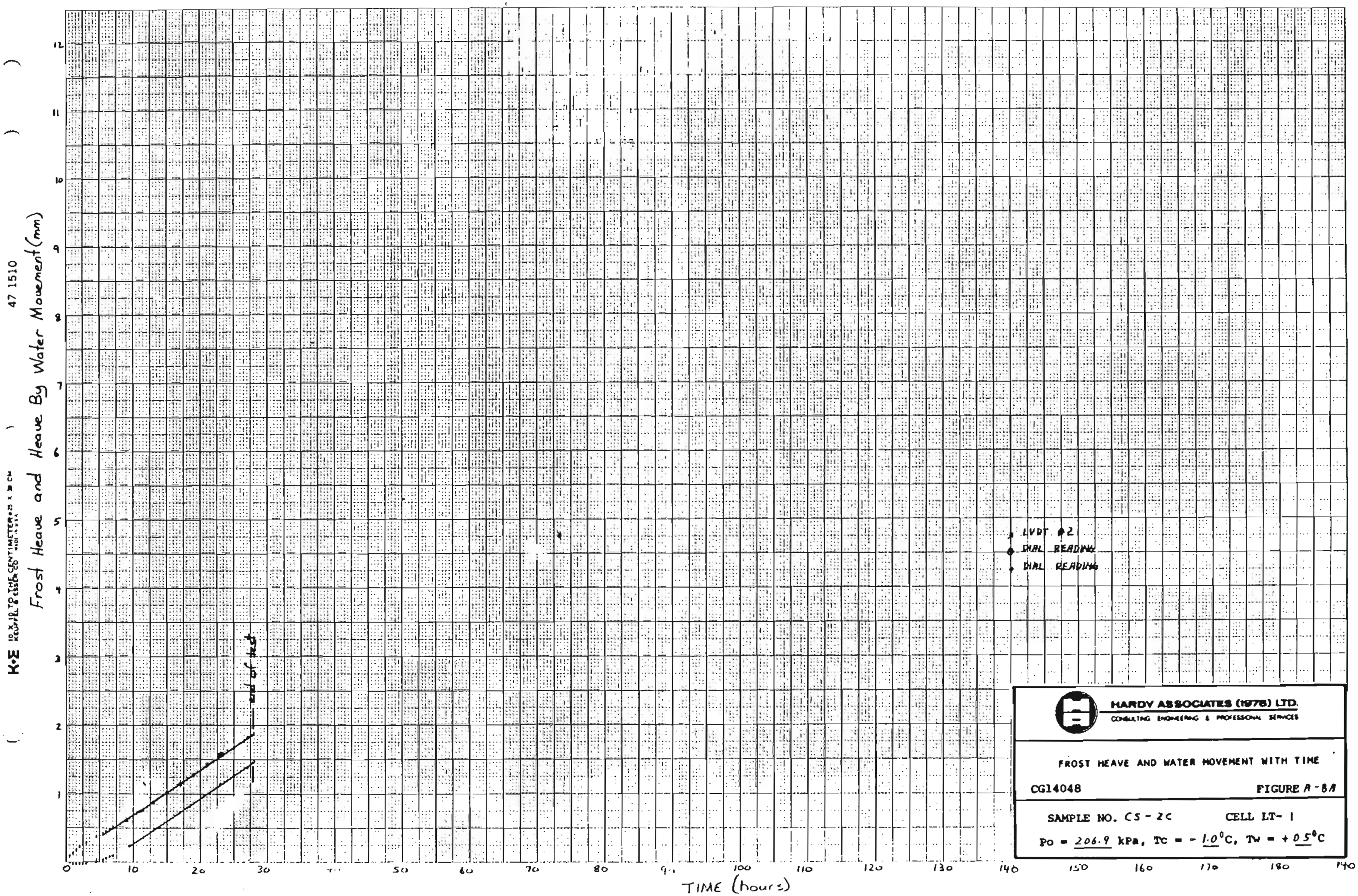
CELL LT - 1

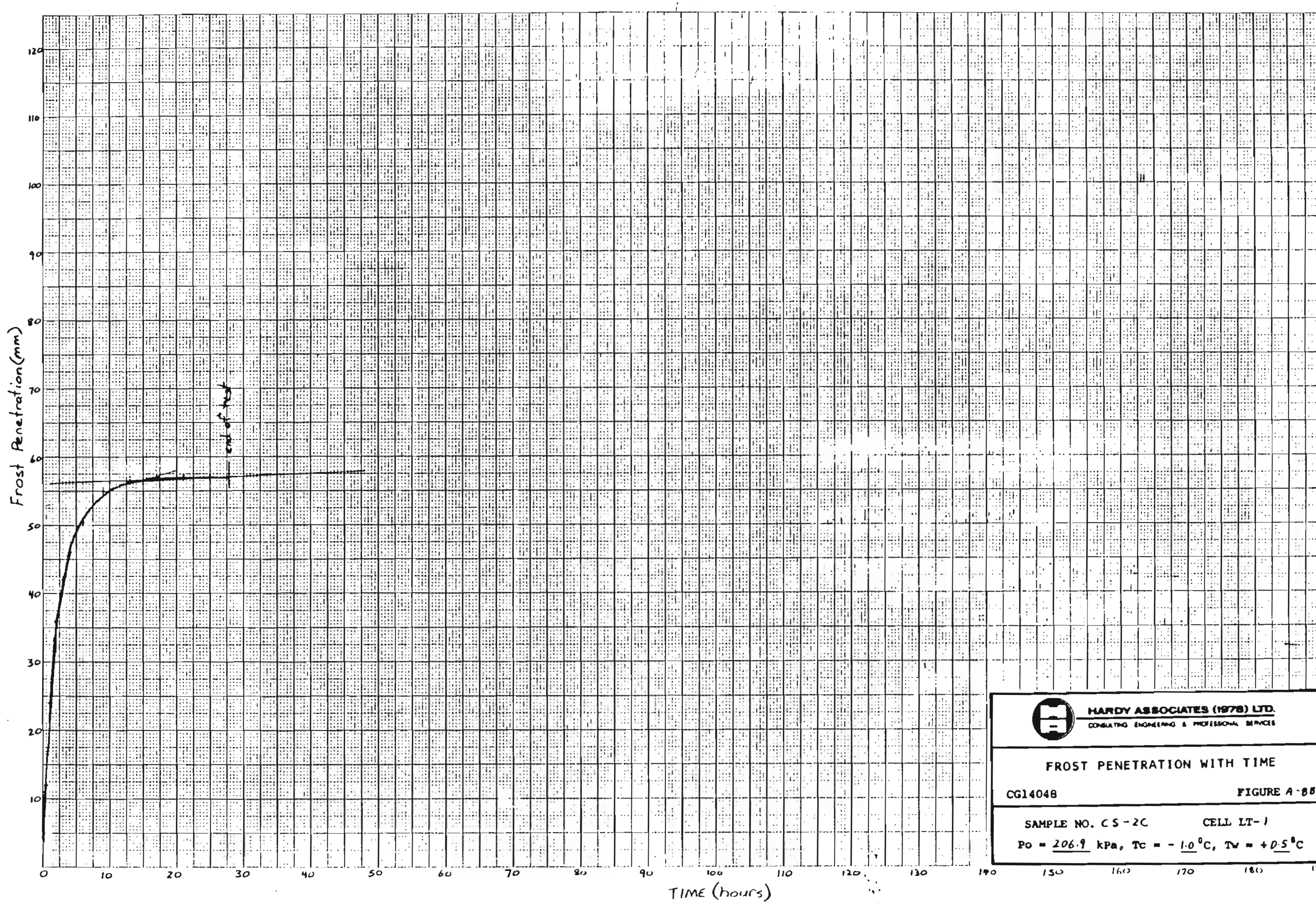
DATE JUL. 15, 1983

SOIL REMOULDED

Δt 66.0 HRS

FIGURE A-7E


K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO.
47 1510
Frost Heave and Heave By Water Movement (mm)
1
2
3
4
5
6
7
8
9
10
11
12
end of test
LVDT #2
DIAL READING
DIAL READING
0
10
20
30
4:
50
60
70
80
9:
100
110
120
130
140
150
160
170
180
190
TIME (hours)
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST HEAVE AND WATER MOVEMENT WITH TIME
CG14048
FIGURE A-8A
SAMPLE NO. CS - 2C
CELL LT- 1
Po = 206.9 kPa, Tc = - 1.0°C, Tw = + 0.5°C




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

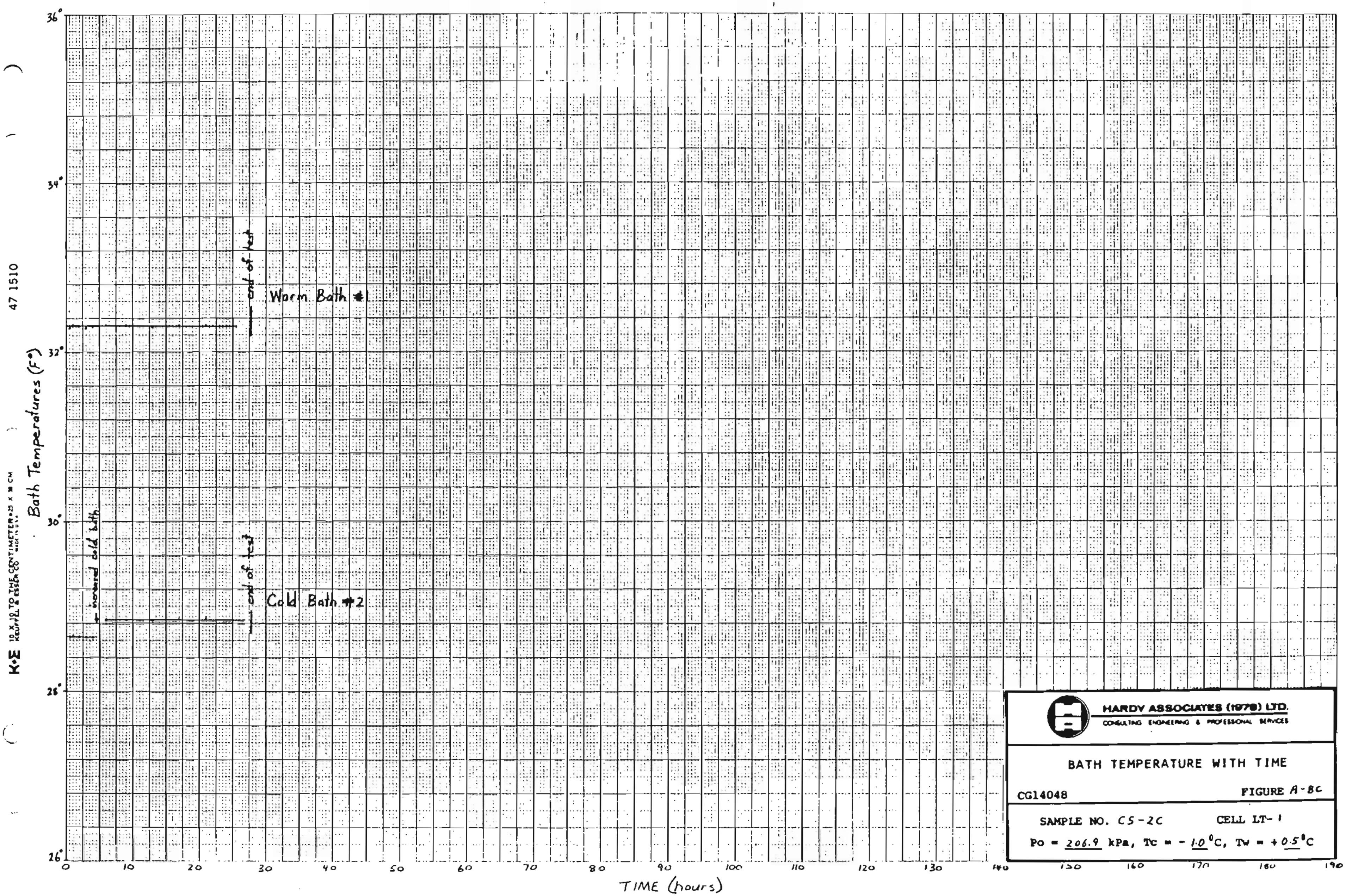
CG14048 FIGURE A-88

SAMPLE NO. CS-2C CELL LT-1

Po = 206.9 kPa, Tc = -1.0°C, Tw = +0.5°C

K•E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A.

47 1510



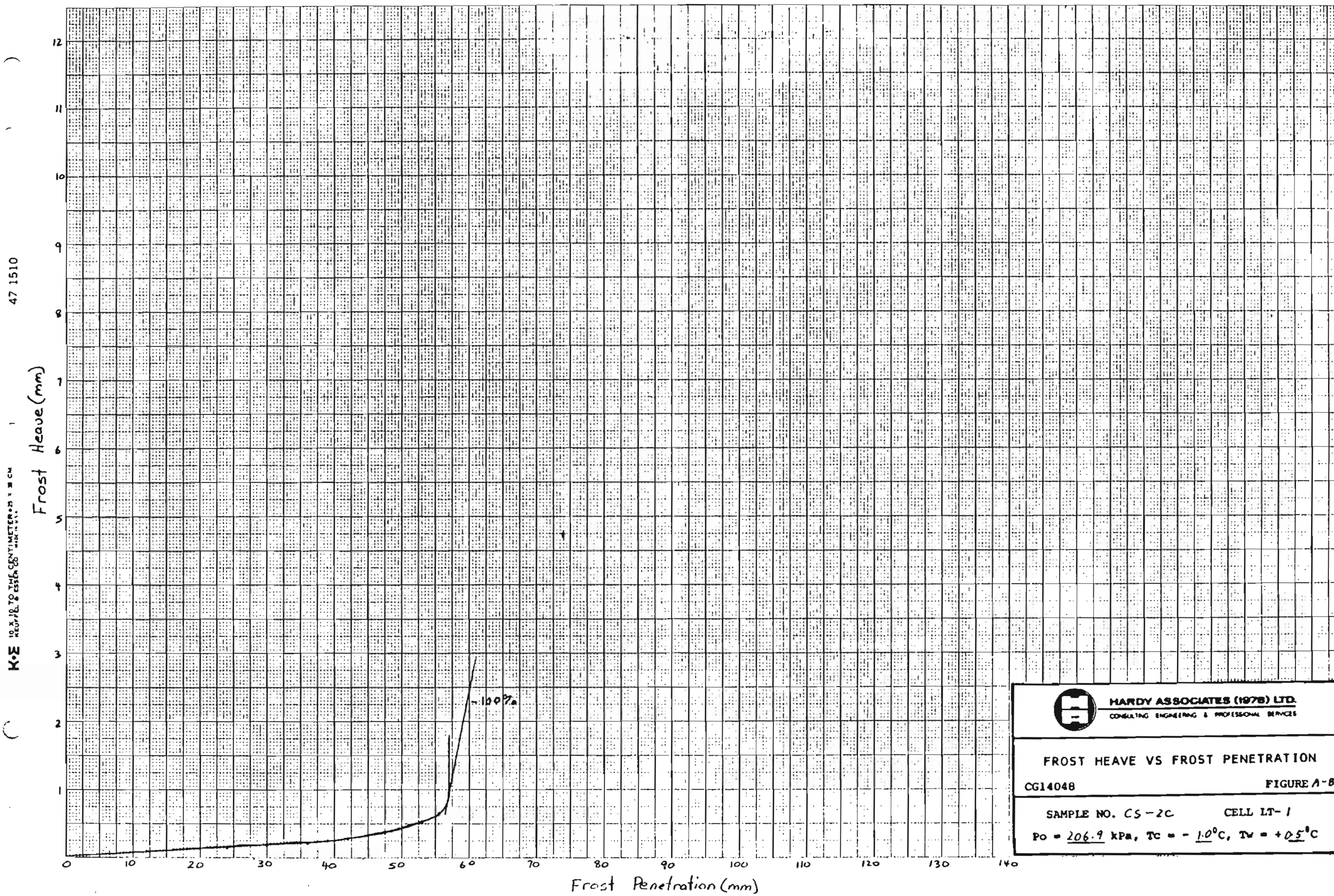

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-8C

SAMPLE NO. CS-2C CELL LT-1

Po = 206.9 kPa, Tc = -1.0°C, Tw = +0.5°C




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

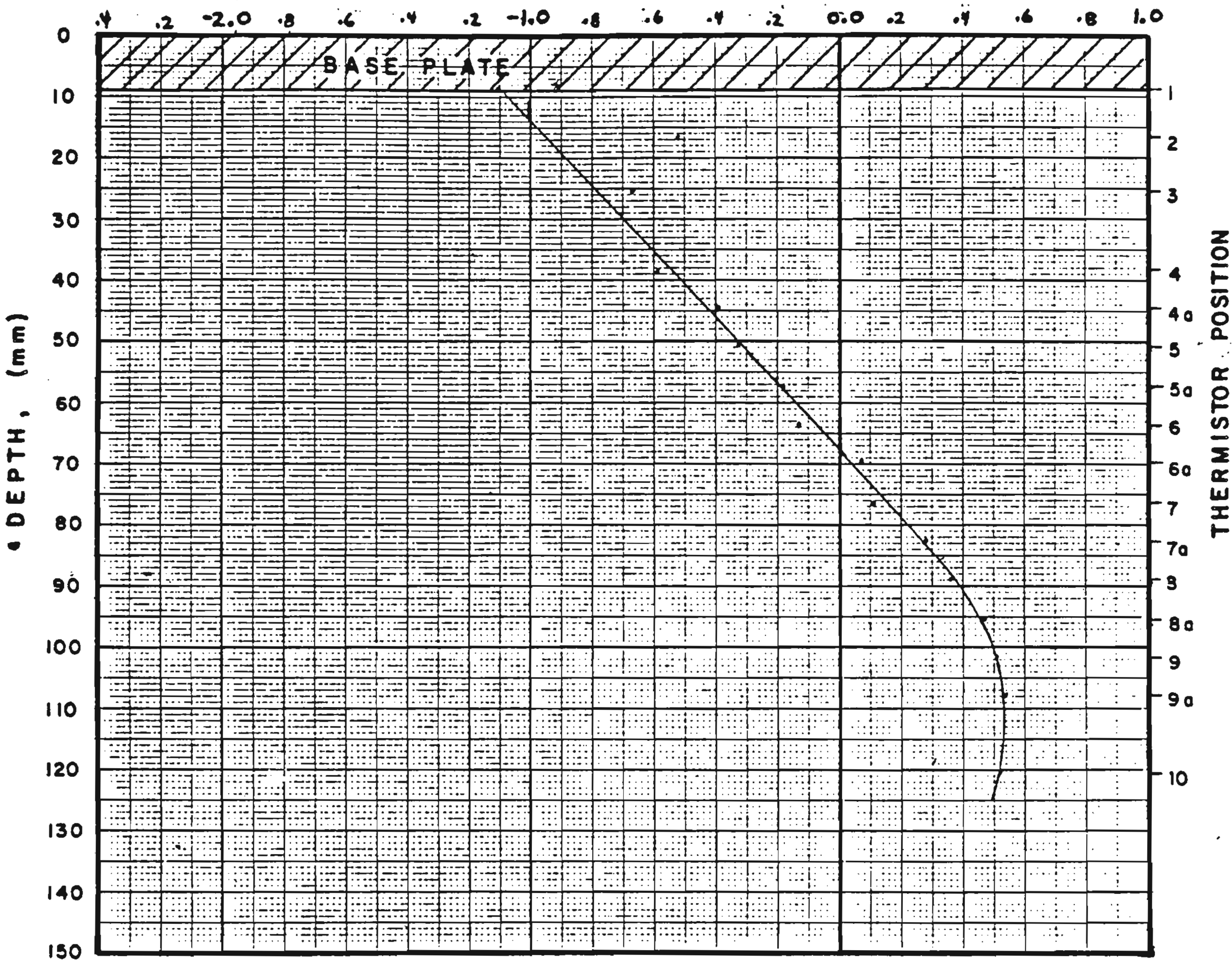
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-8D

SAMPLE NO. CS-2C CELL LT-1

Po = 206.9 kPa, Tc = -1.0°C, Tw = +0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-2C

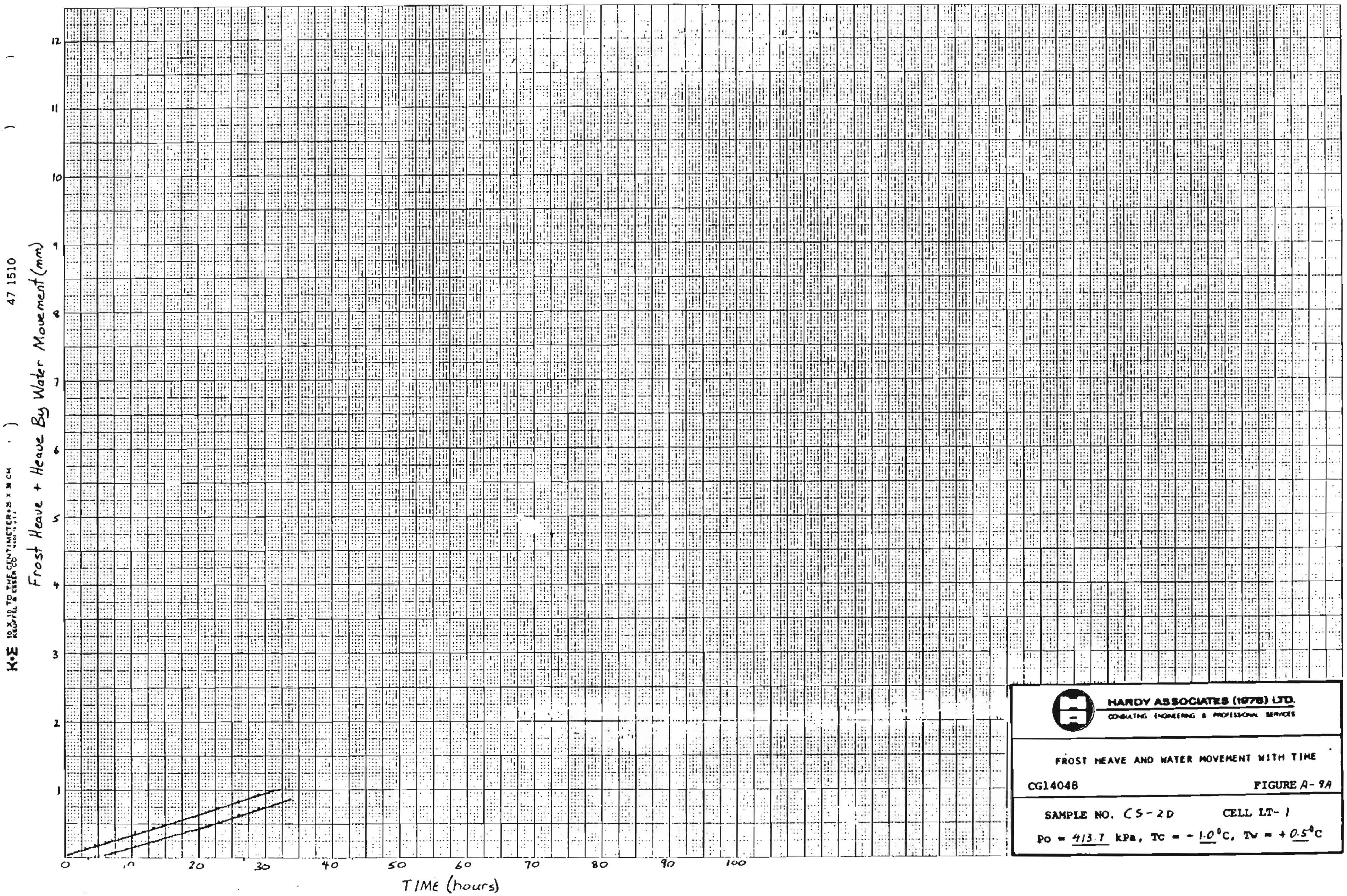
CELL LT-1

DATE JUL. 27, 1983

SOIL REMOULDED

Δt 25.0 HRS

FIGURE A-8E




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE AND WATER MOVEMENT WITH TIME

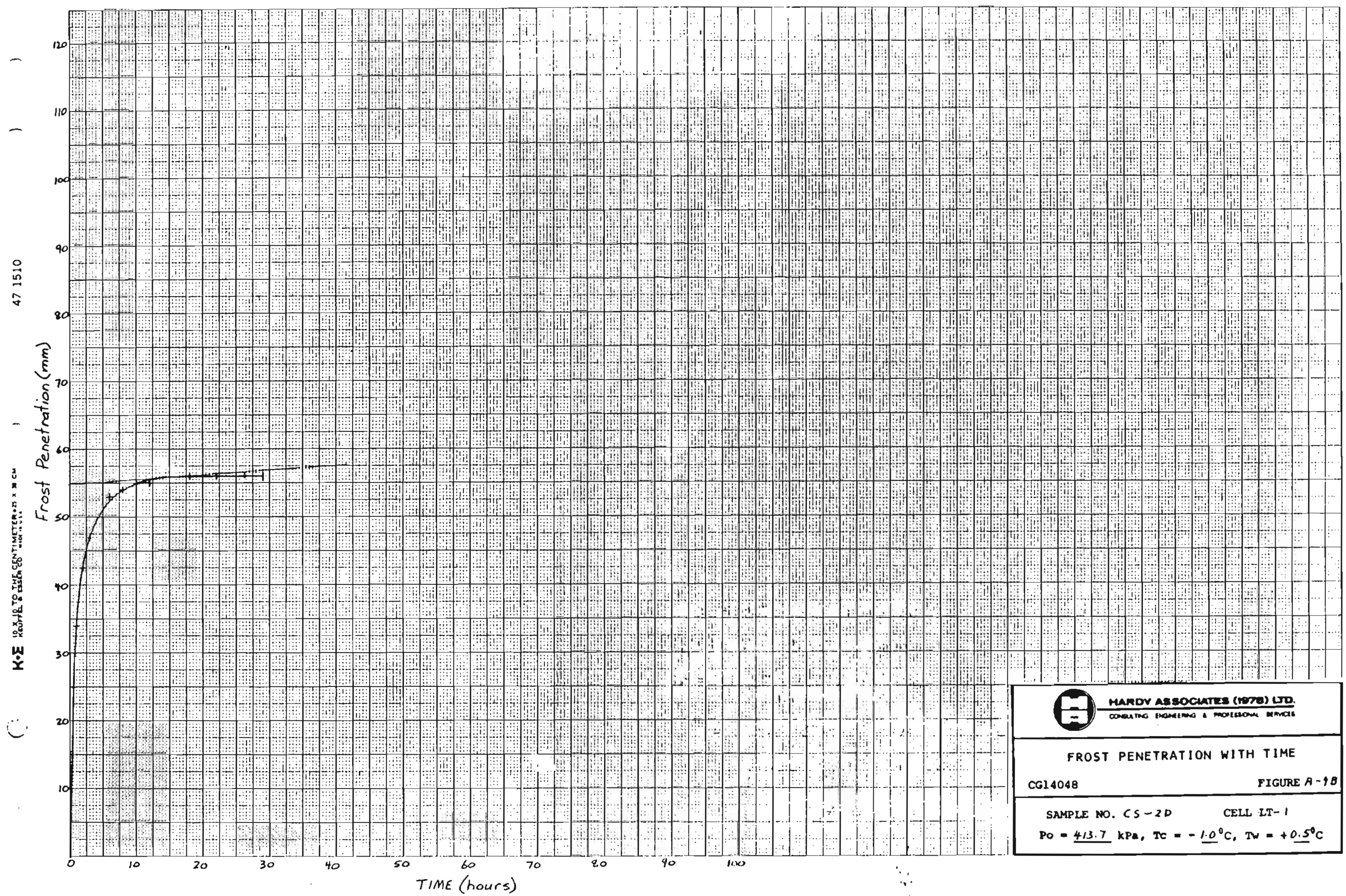
CG14048 FIGURE A-9A

SAMPLE NO. CS-2D CELL LT-1

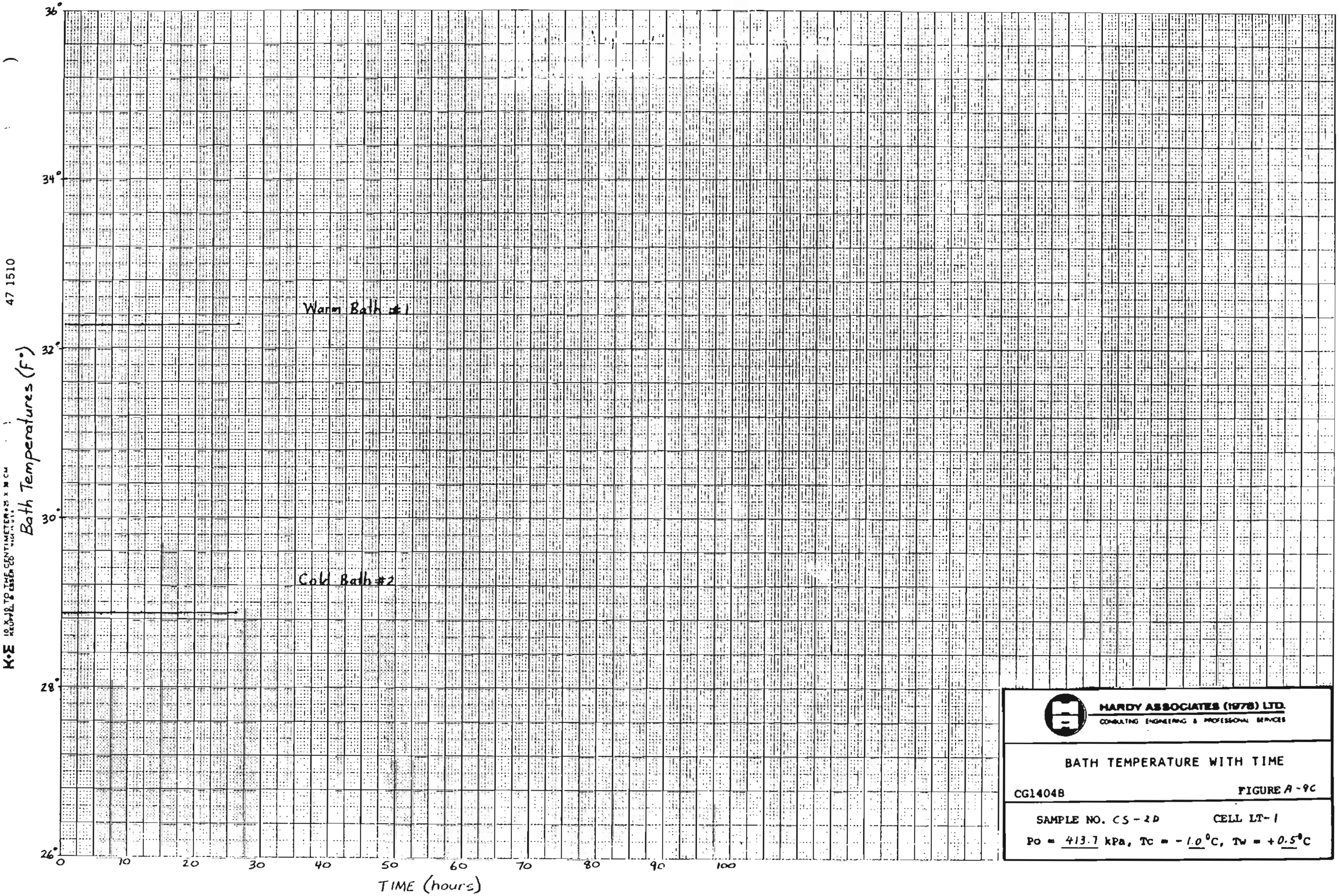
Po = 413.7 kPa, Tc = -1.0°C, Tw = +0.5°C

K•E 10 X 10 TO THE CENTIMETER 25 X 38 CM KEUFFEL & ESSER CO.

47 1510



Frost Penetration (mm)
TIME (hours)
0
10
20
30
40
50
60
70
80
90
100
110
120
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST PENETRATION WITH TIME
CG14048
FIGURE A-9B
SAMPLE NO. CS-2D
CELL LT-1
Po = 413.7 kPa, Tc = -1.0°C, Tw = +0.5°C
K+E 10 X 10 TO THE CENTIMETER 25 X 38 CM KEUFFEL & ESSER CO.
47 1510



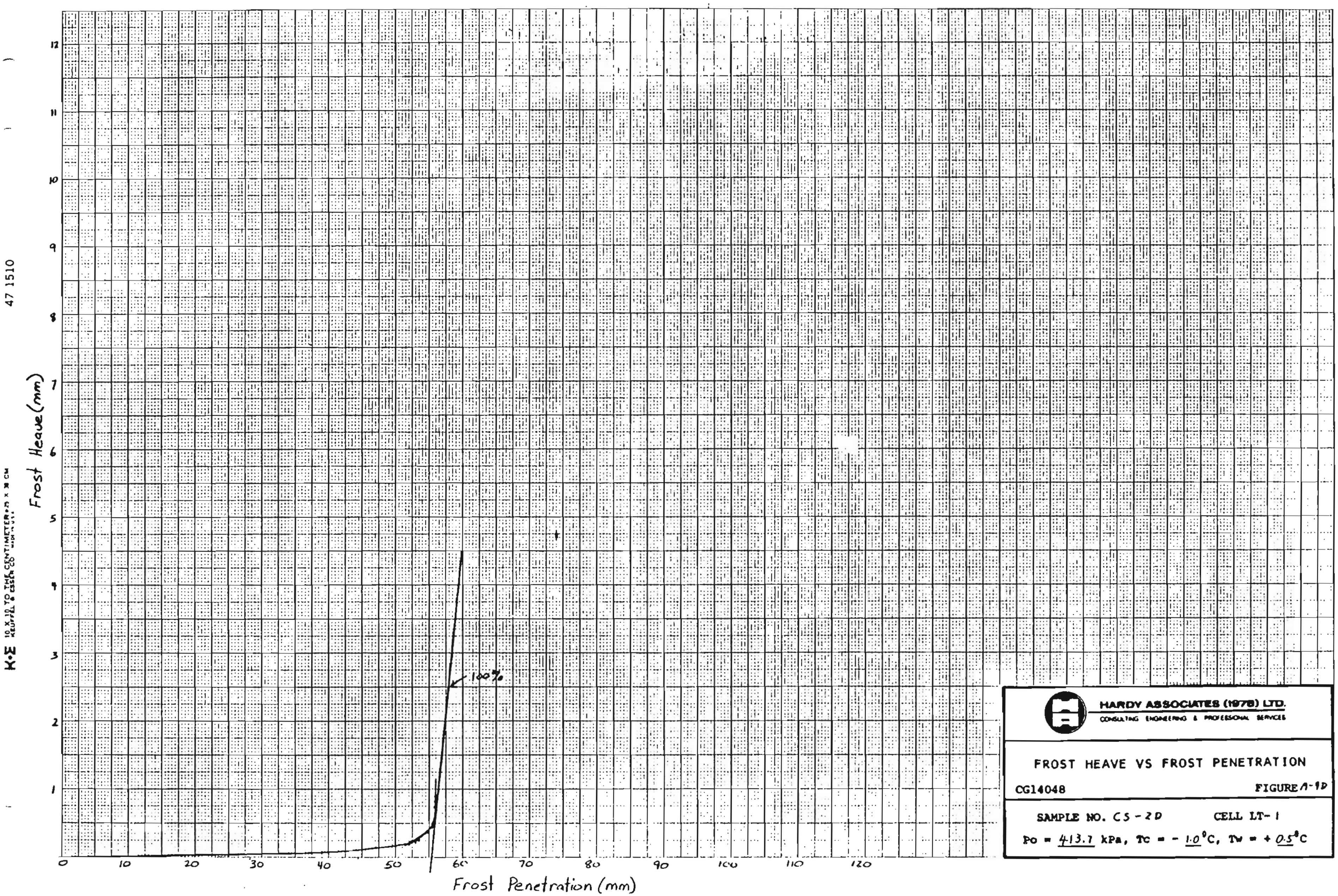

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-9C

SAMPLE NO. CS-2D CELL LT-1

Po = 413.7 kPa, Tc = -1.0°C, Tw = +0.5°C




**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE VS FROST PENETRATION

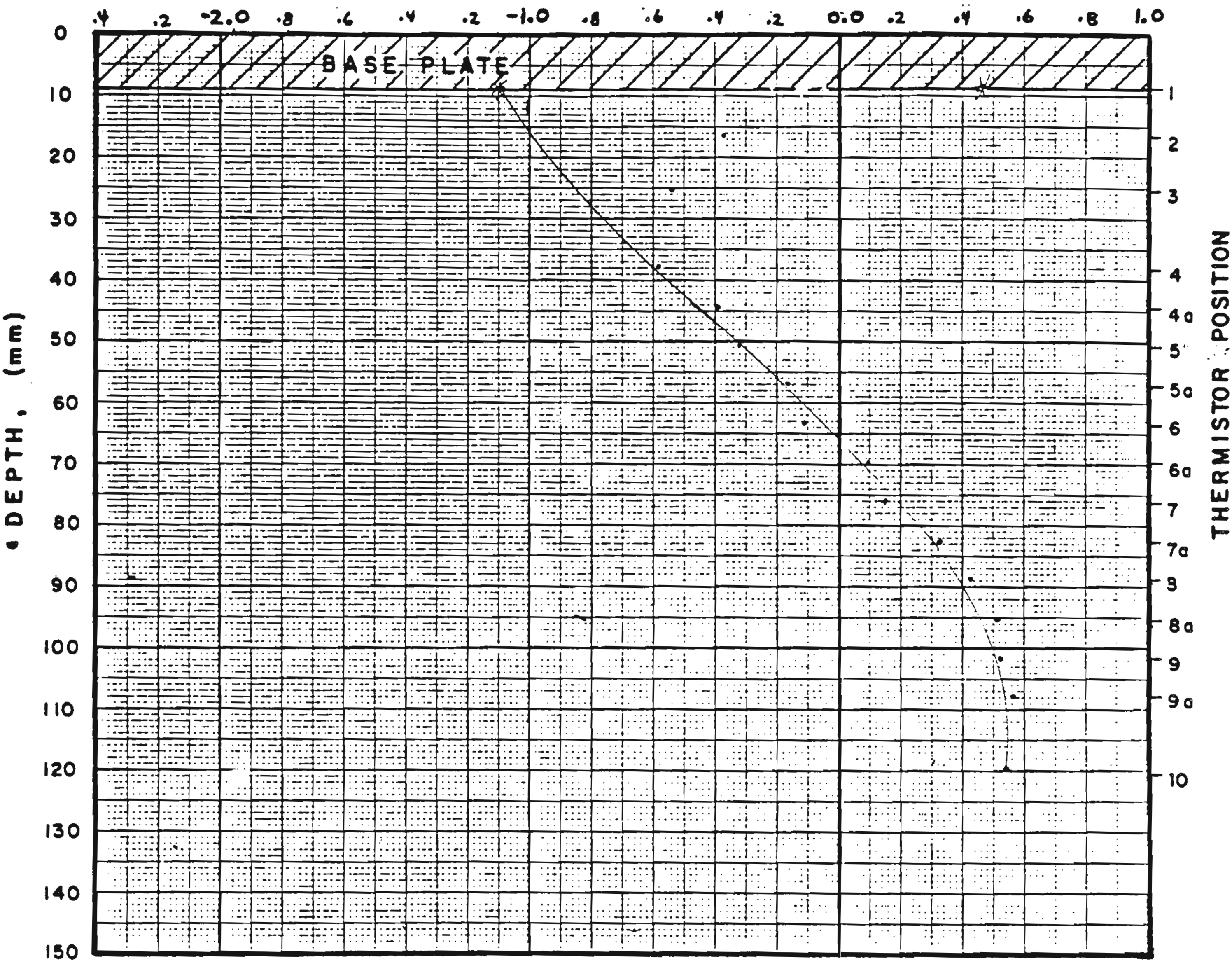
CG14048 FIGURE A-9D

SAMPLE NO. CS-2D CELL LT-1

Po = 413.7 kPa, Tc = - 1.0°C, Tw = + 0.5°C

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A. 47 1510

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-2D

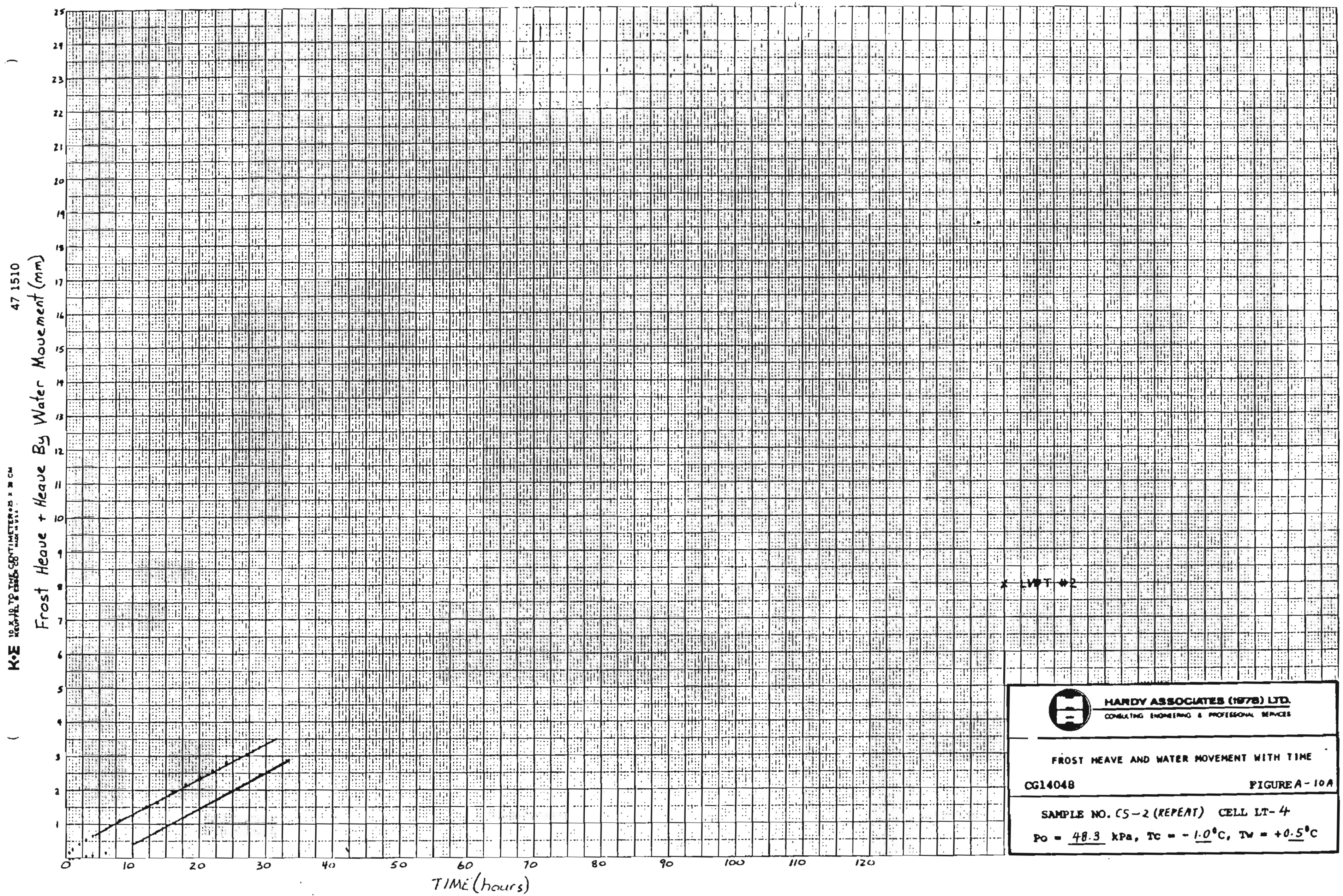
CELL LT-1

DATE AUG. 9, 1983

SOIL REMOULDED

Δt 29.0 HRS

FIGURE A-9E



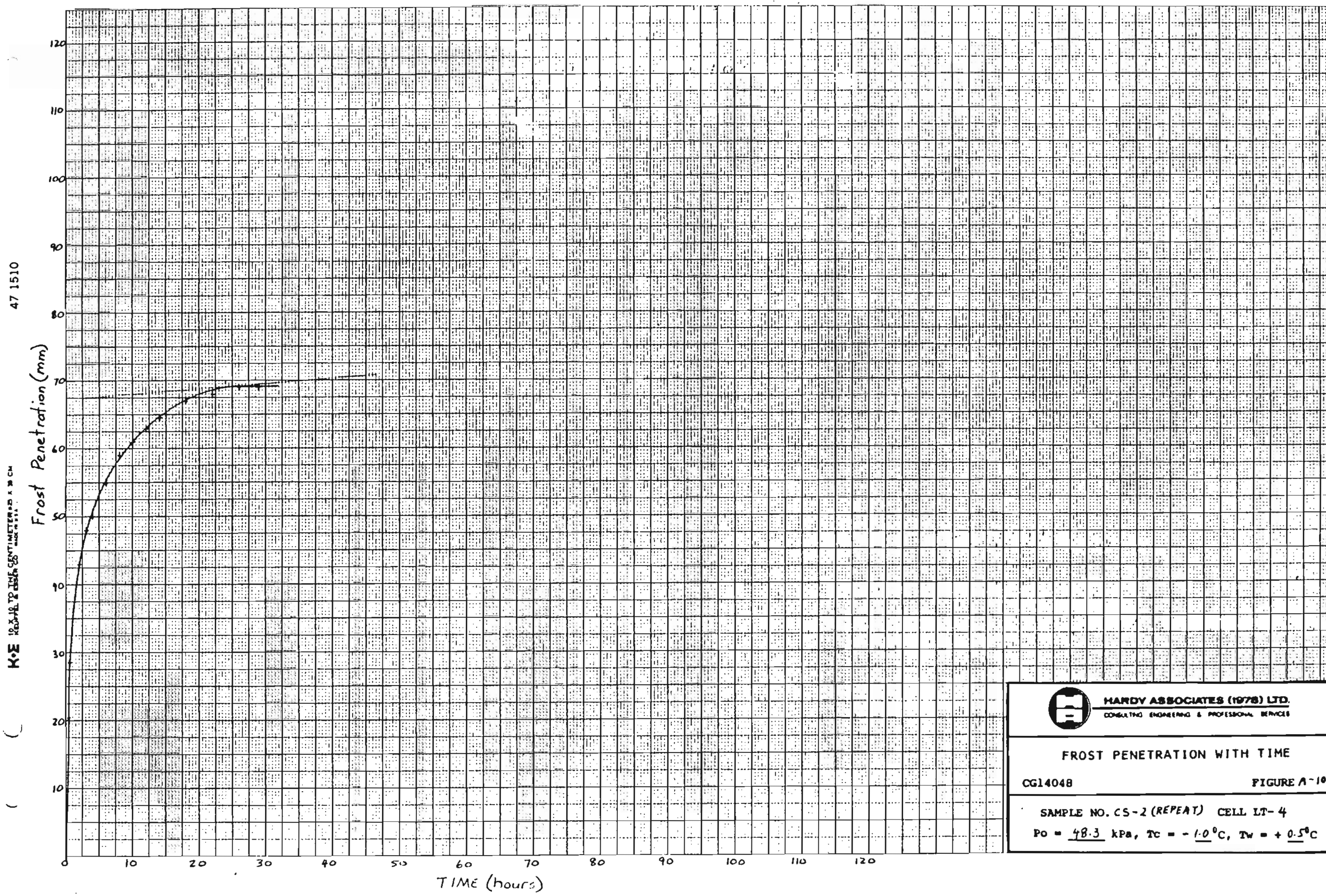

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048 FIGURE A-10A

SAMPLE NO. CS-2 (REPEAT) CELL LT-4

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C



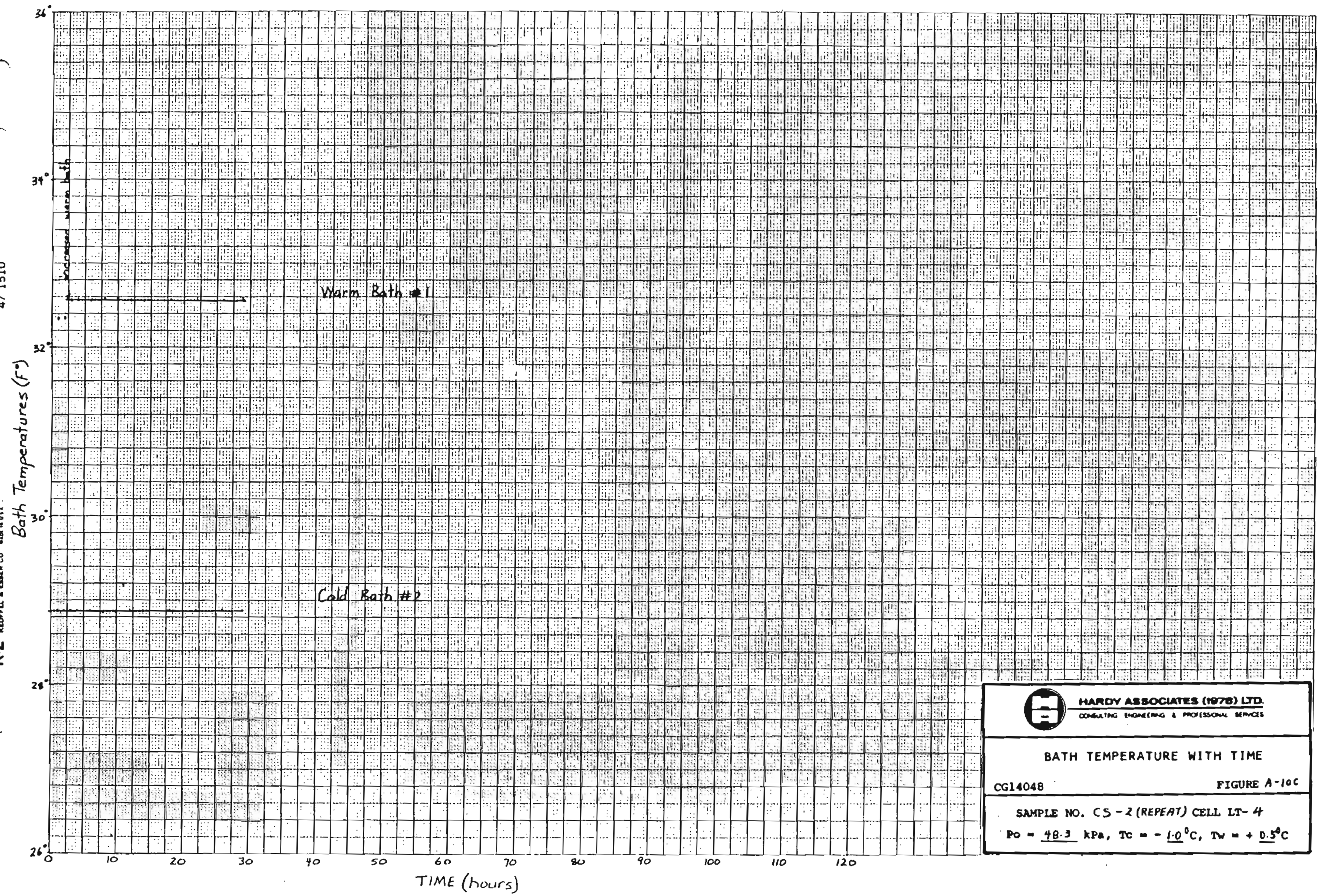

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-108

SAMPLE NO. CS-2 (REPEAT) CELL LT-4

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C



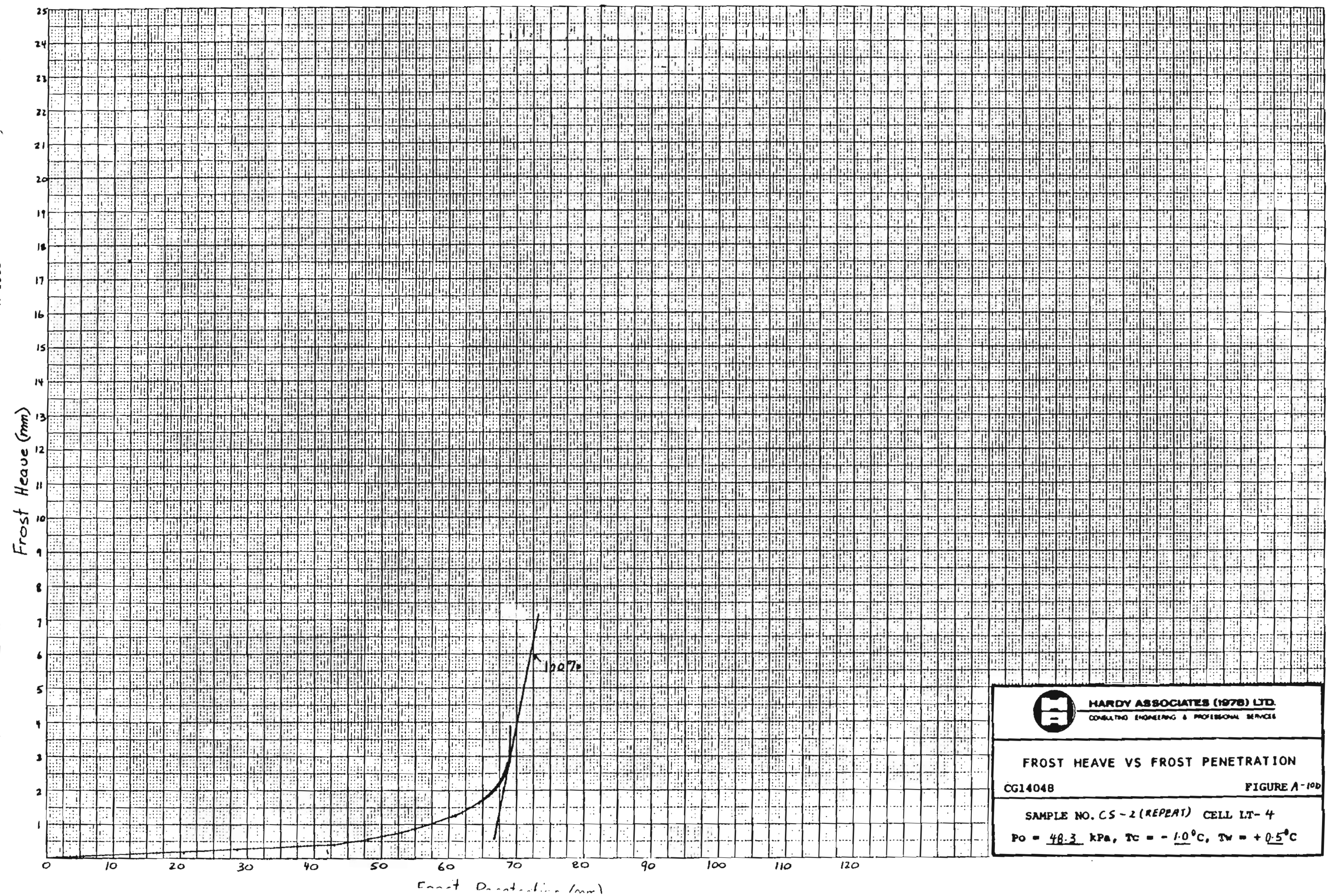

**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-10C

SAMPLE NO. CS - 2 (REPEAT) CELL LT- 4

Po = 48.3 kPa, Tc = - 1.0°C, Tw = + 0.5°C




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE VS FROST PENETRATION

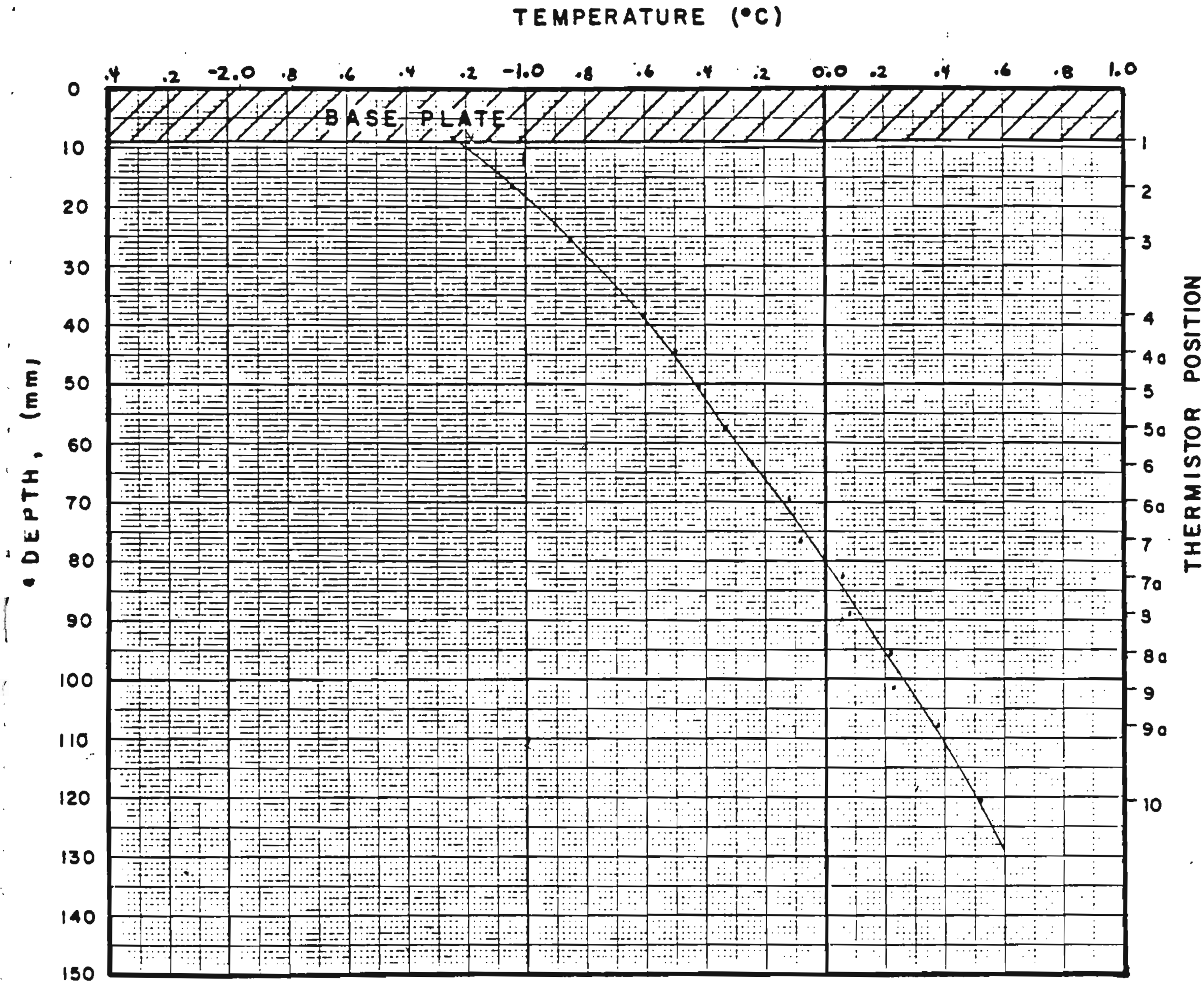
CG14048

FIGURE A-10D

SAMPLE NO. CS-2 (REPEAT) CELL LT-4

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-2 (REPEAT)

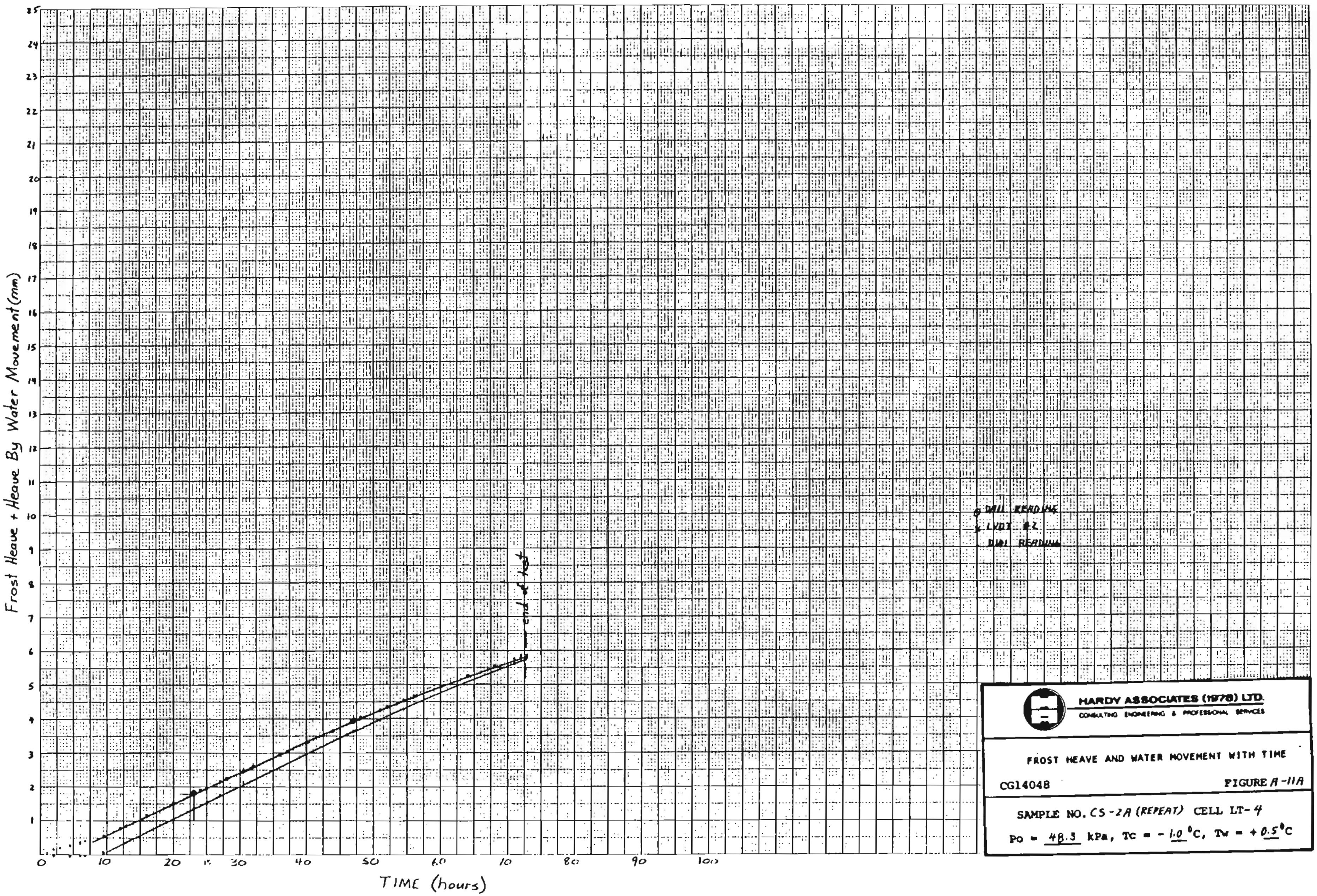
CELL LT-14

DATE SEP. 1, 1983

SOIL REMOULDED

Δt 29.0 HRS

FIGURE A-10E




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

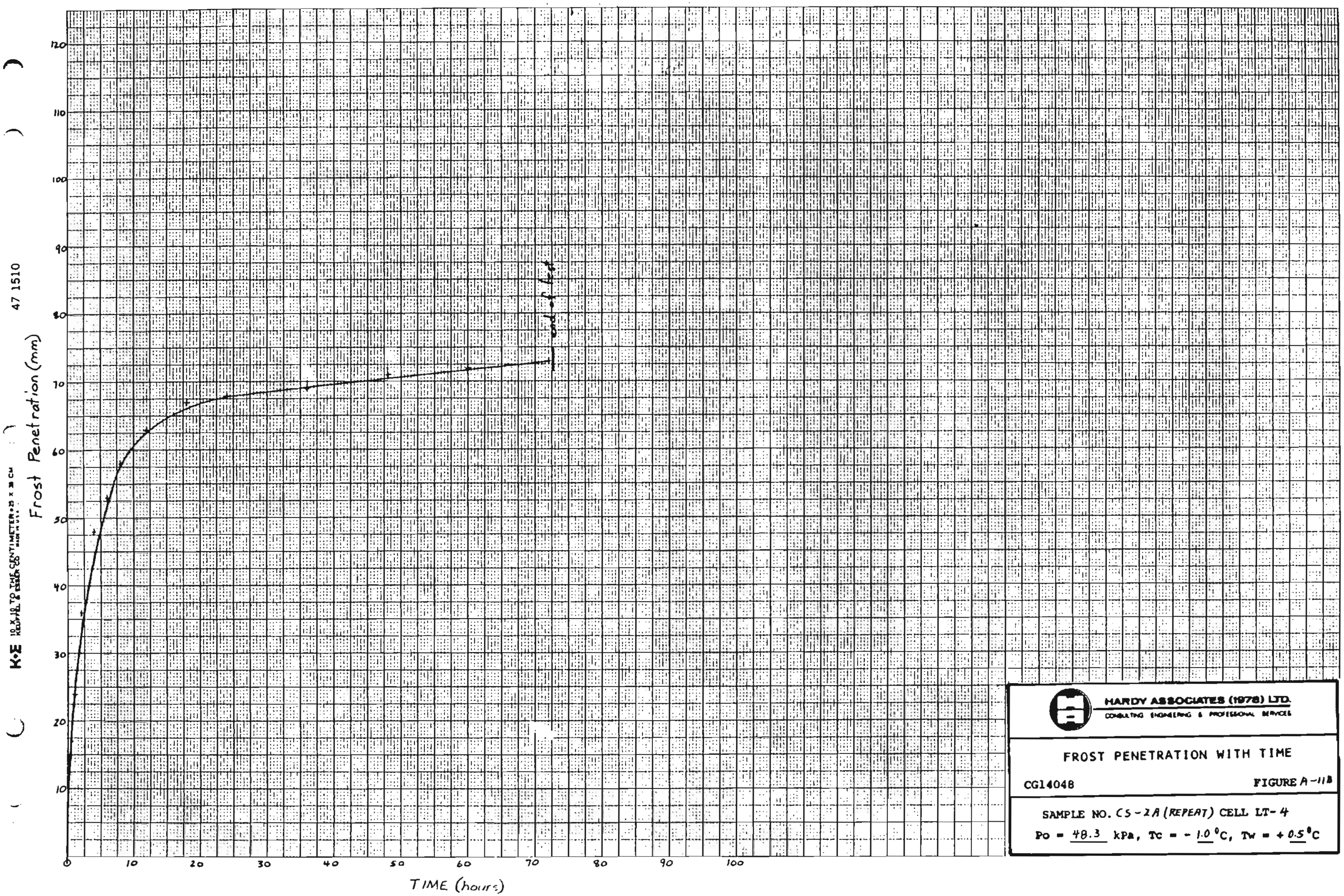
FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048

FIGURE A-11A

SAMPLE NO. CS-2A (REPEAT) CELL LT-4

Po = 48.3 kPa, Tc = -1.0 °C, Tw = +0.5 °C

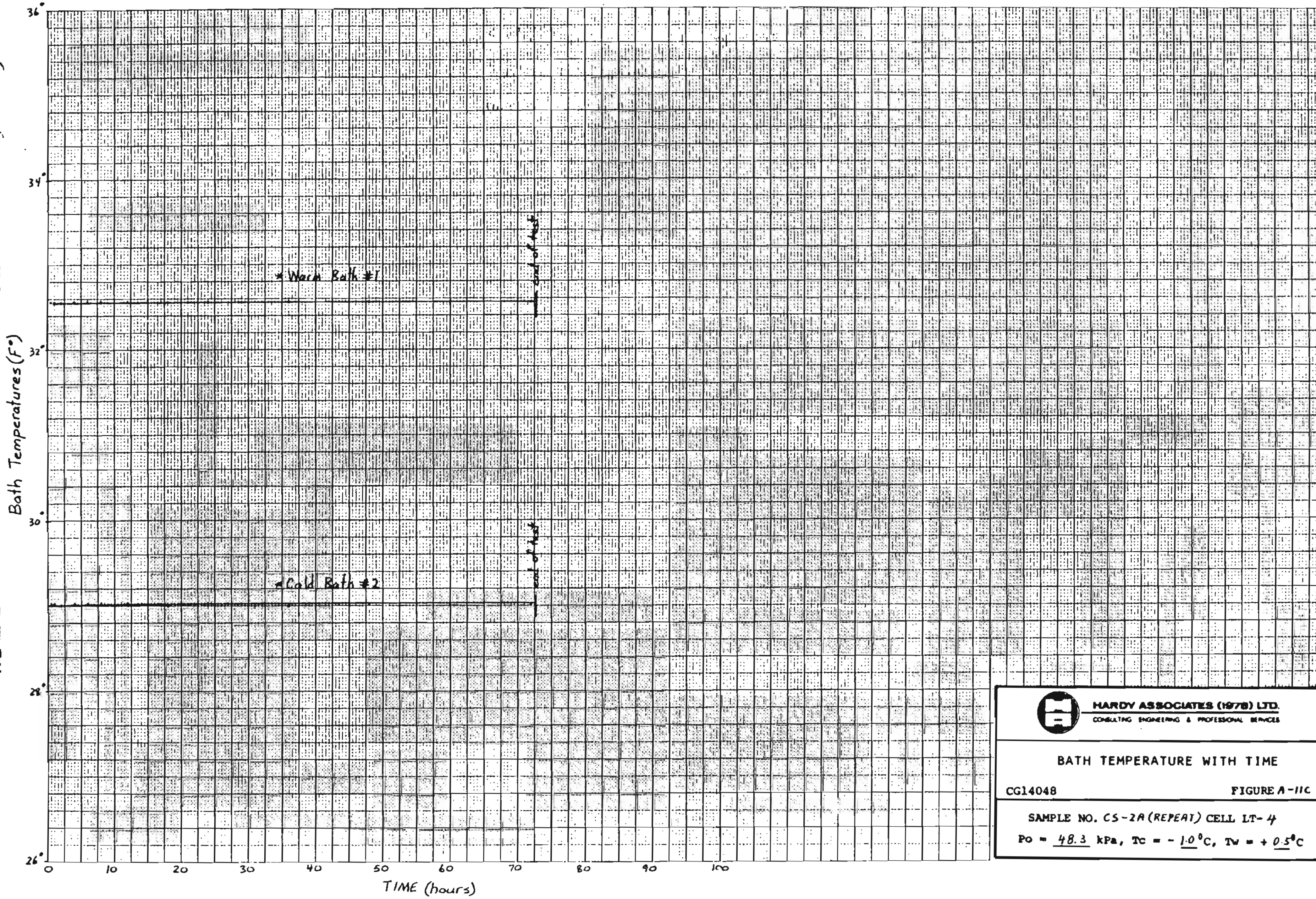



**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-11B

SAMPLE NO. CS-2A (REPEAT) CELL LT-4
Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C



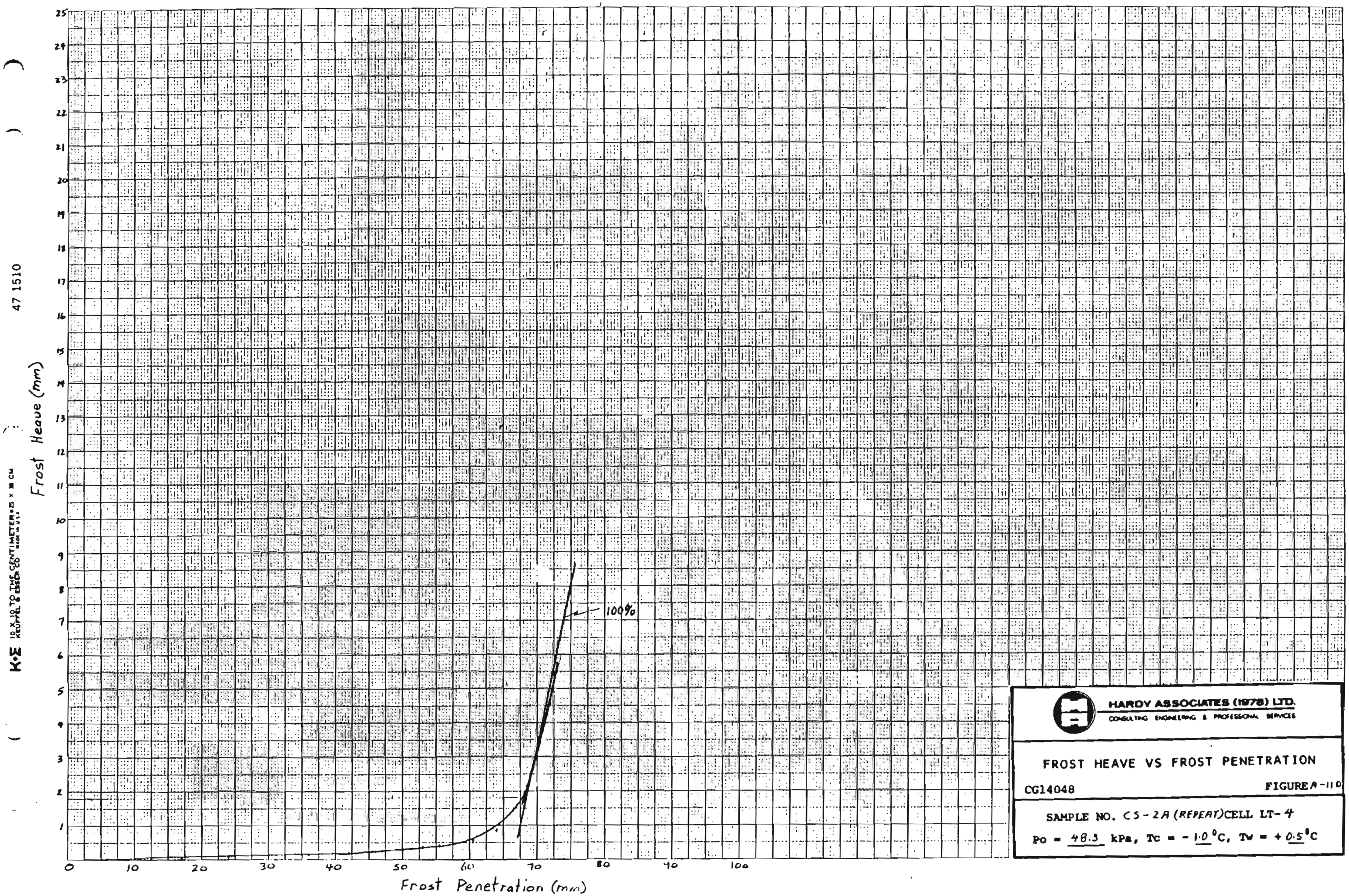

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-11C

SAMPLE NO. CS-2A (REPEAT) CELL LT-4

Po = 48.3 kPa, Tc = - 1.0°C, Tw = + 0.5°C




**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

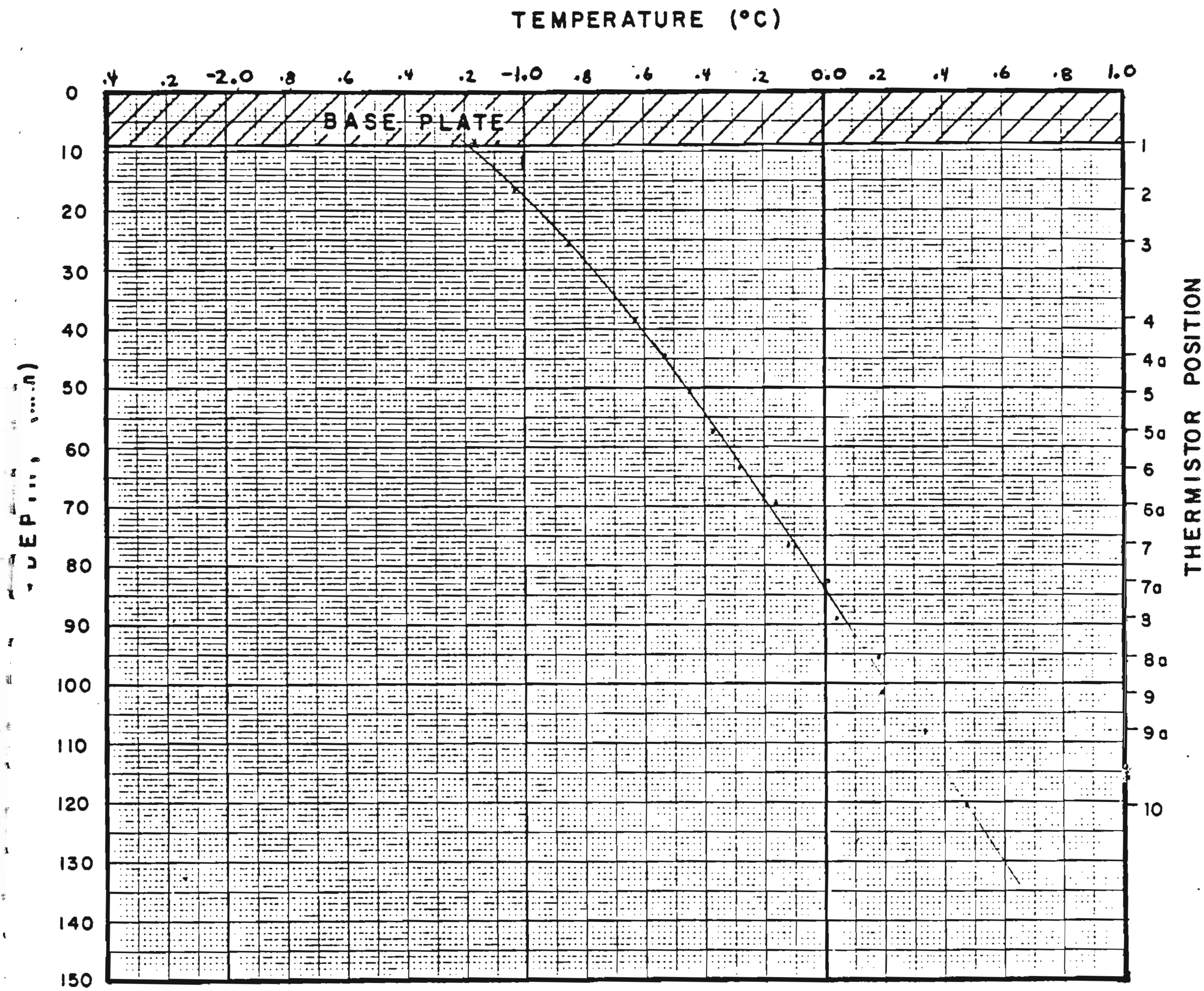
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-11D

SAMPLE NO. CS-2A (REPEAT) CELL LT-4

Po = 48.3 kPa, Tc = -1.0°C, Tw = +0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-2A (REPEAT)

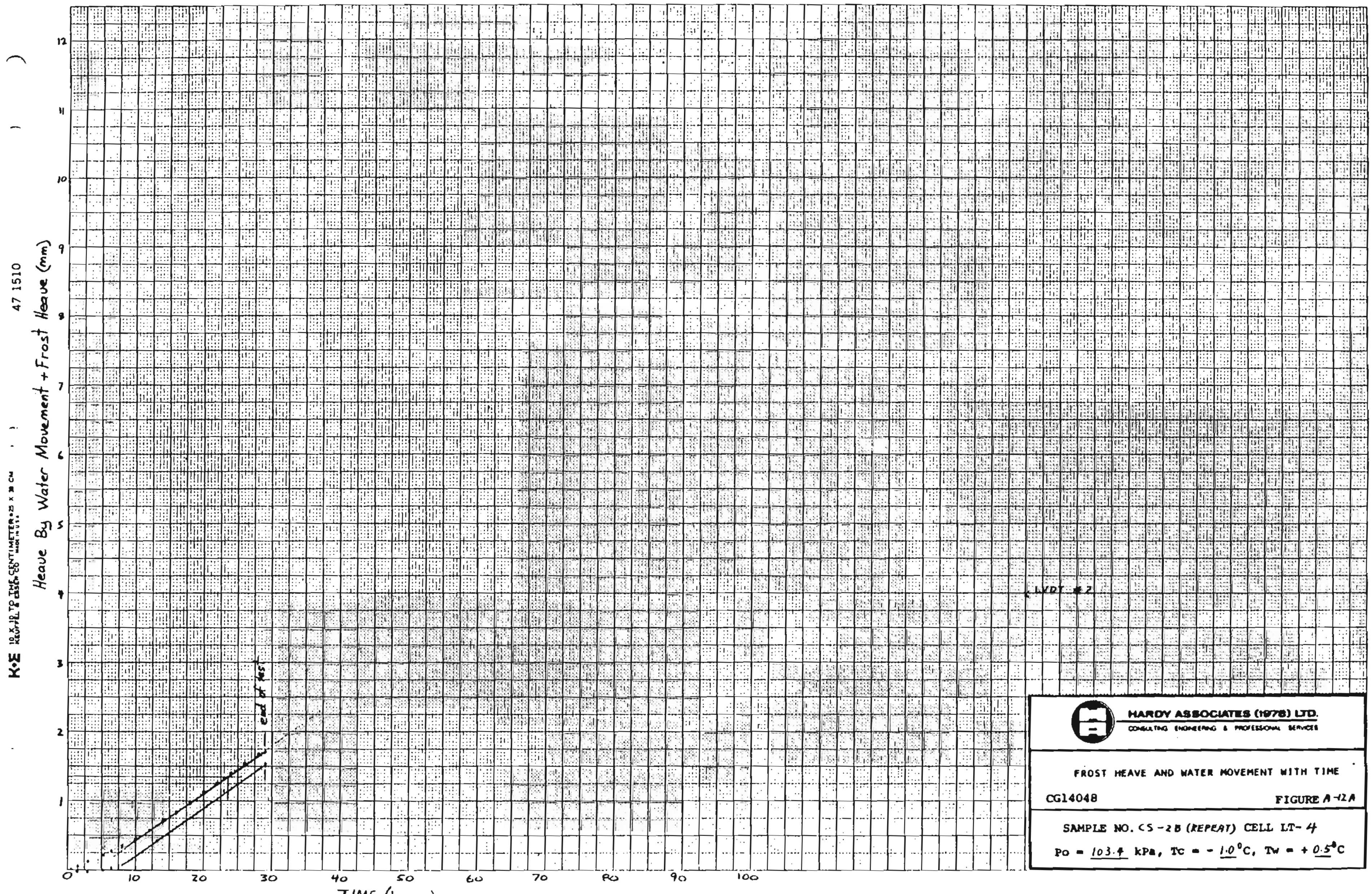
CELL LT-4

DATE SEP. 15, 1983

SOIL REMOULDED

Δt 72.0 HRS

FIGURE A-11E



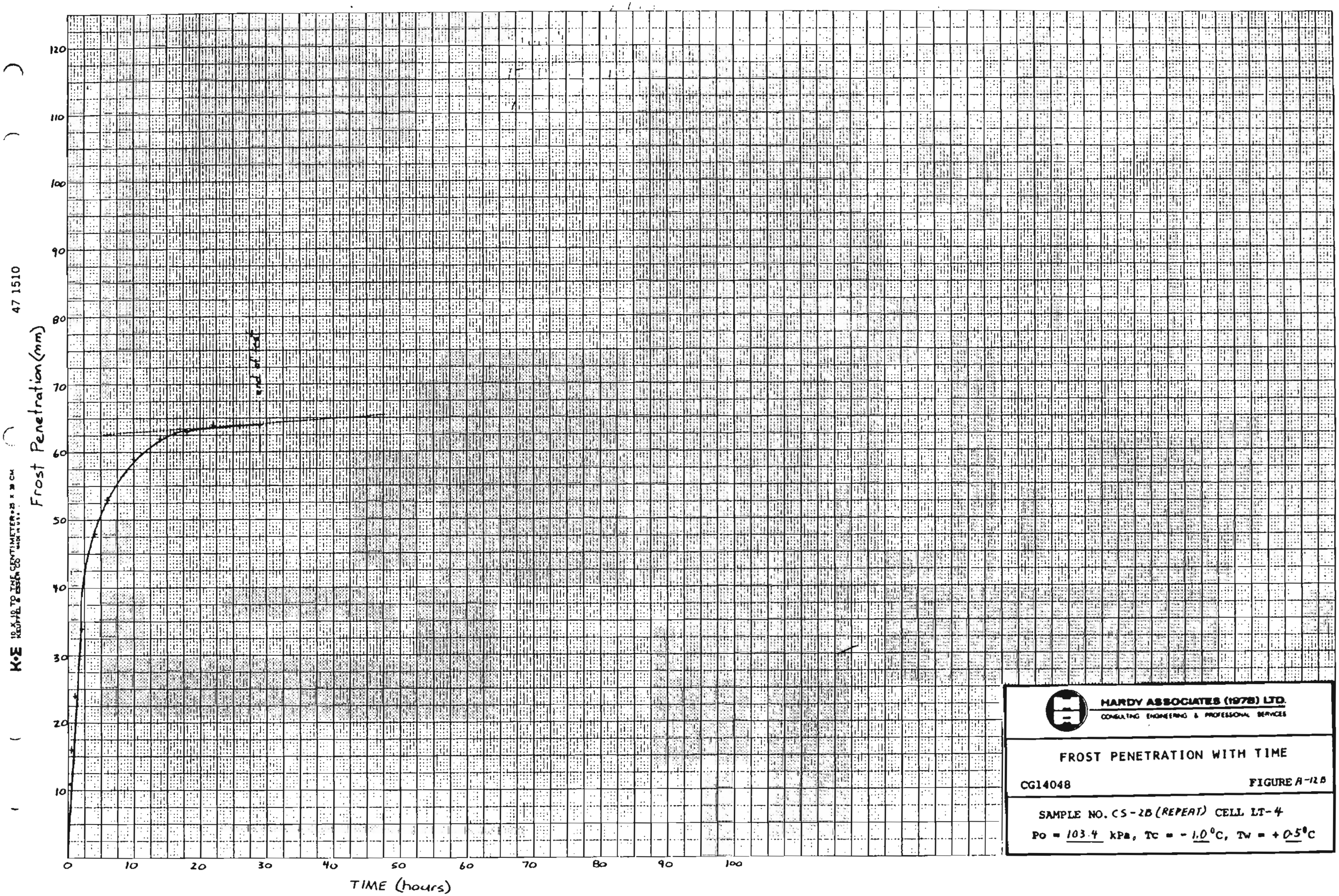

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048 FIGURE A-12A

SAMPLE NO. CS-2B (REPEAT) CELL LT-4

Po = 103.4 kPa, Tc = - 1.0°C, Tw = + 0.5°C



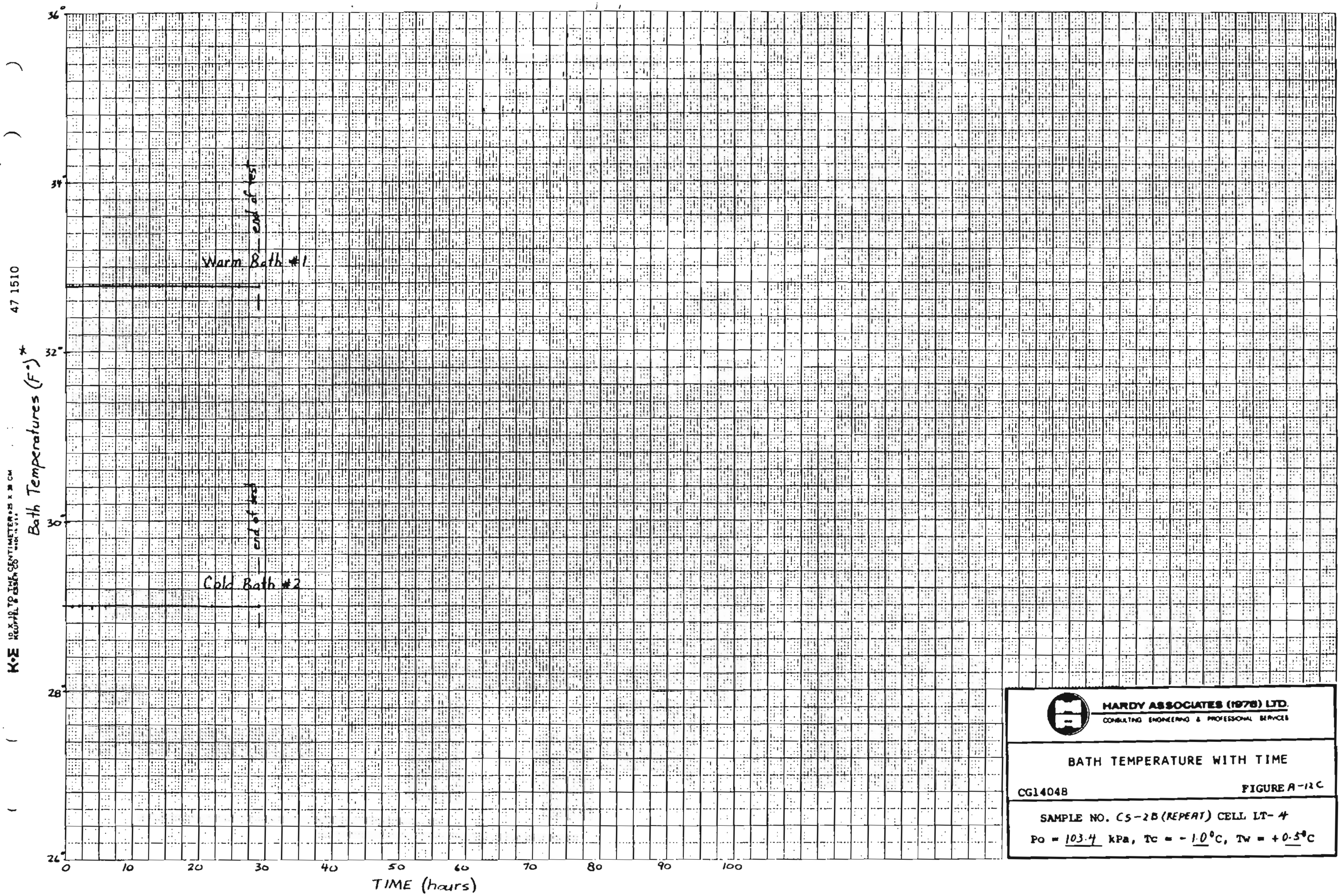

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-12B

SAMPLE NO. CS-2B (REPEAT) CELL LT-4

Po = 103.4 kPa, Tc = -1.0°C, Tw = +0.5°C



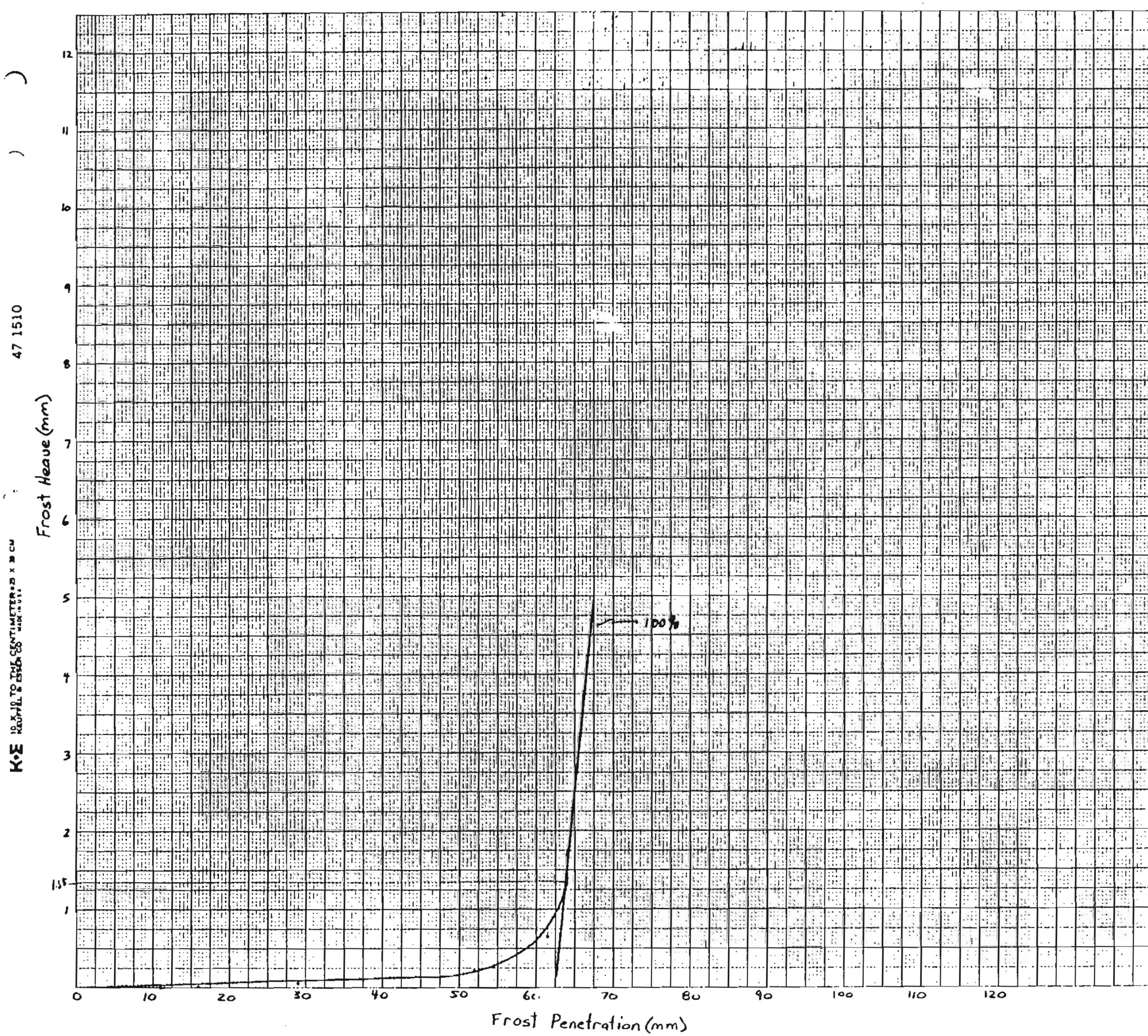

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-12C

SAMPLE NO. CS-2B (REPEAT) CELL LT-4

Po = 103.4 kPa, Tc = - 1.0°C, Tw = + 0.5°C




**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

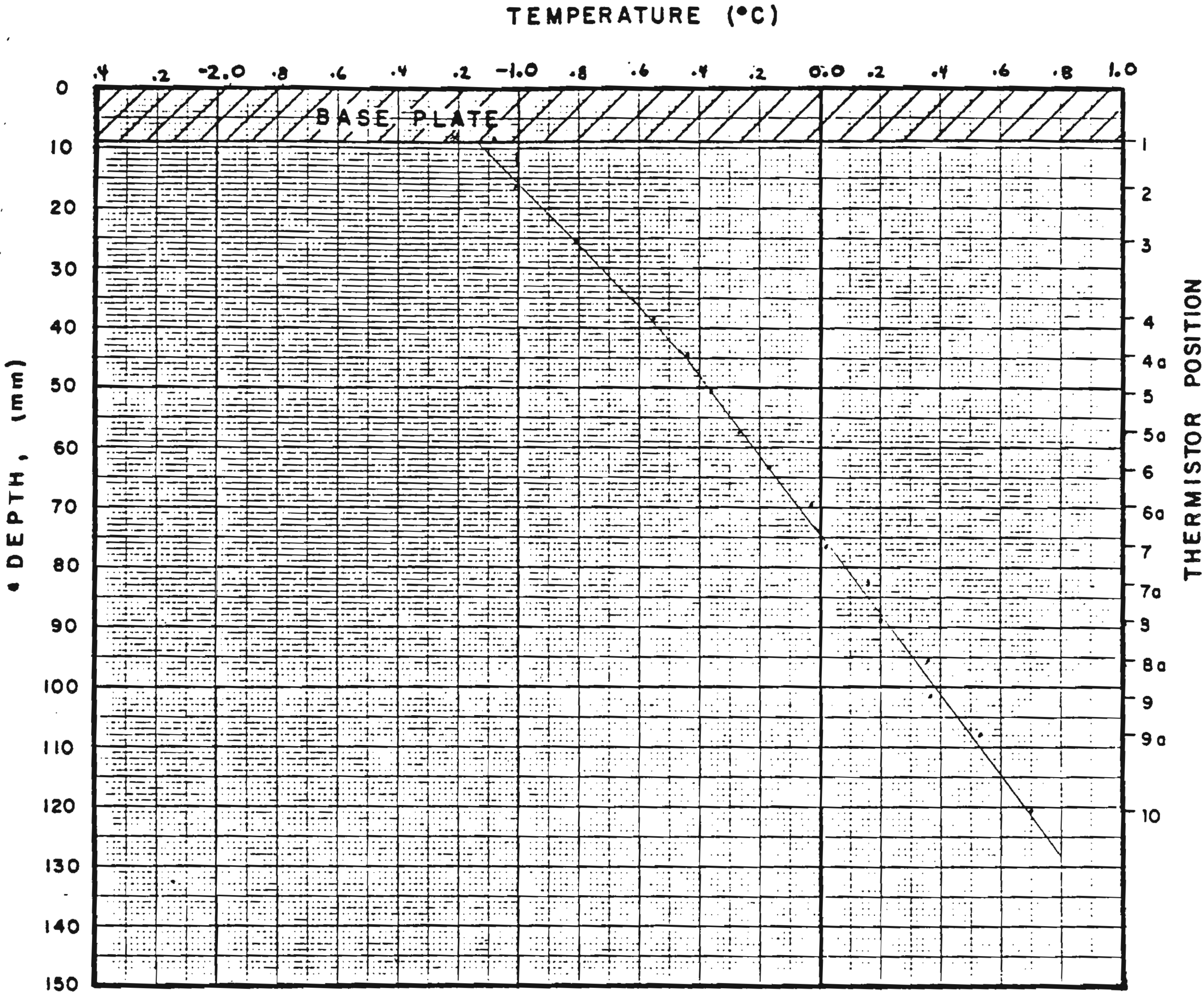
## FROST HEAVE VS FROST PENETRATION

CG14048 — FIGURE A-12b

SAMPLE NO. CS-2B (REPEAT) CELL LT-4

Po = 103.4 kPa, Tc = - 1.0°C, Tw = + 0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-2B (REPEAT)

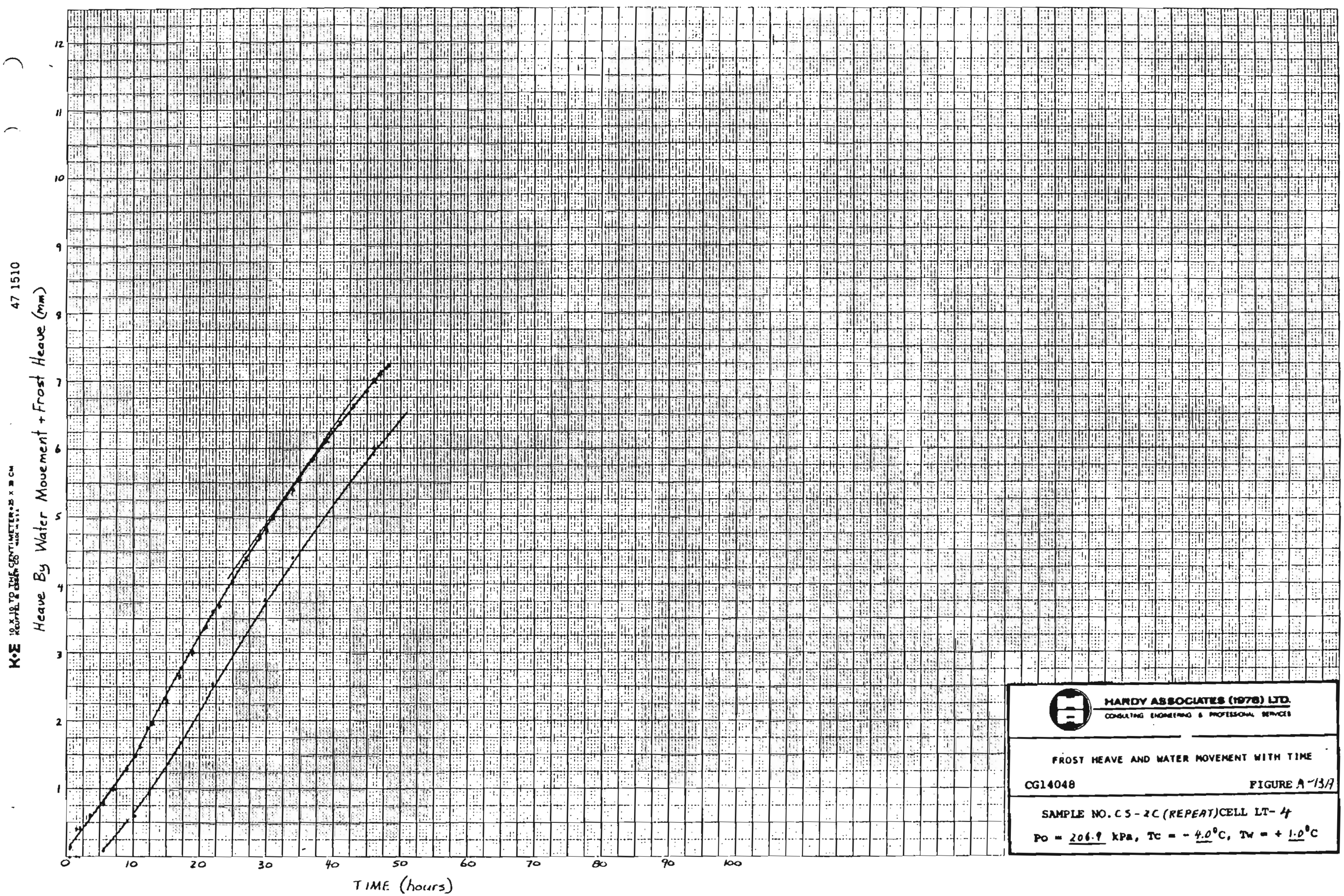
CELL LT-4

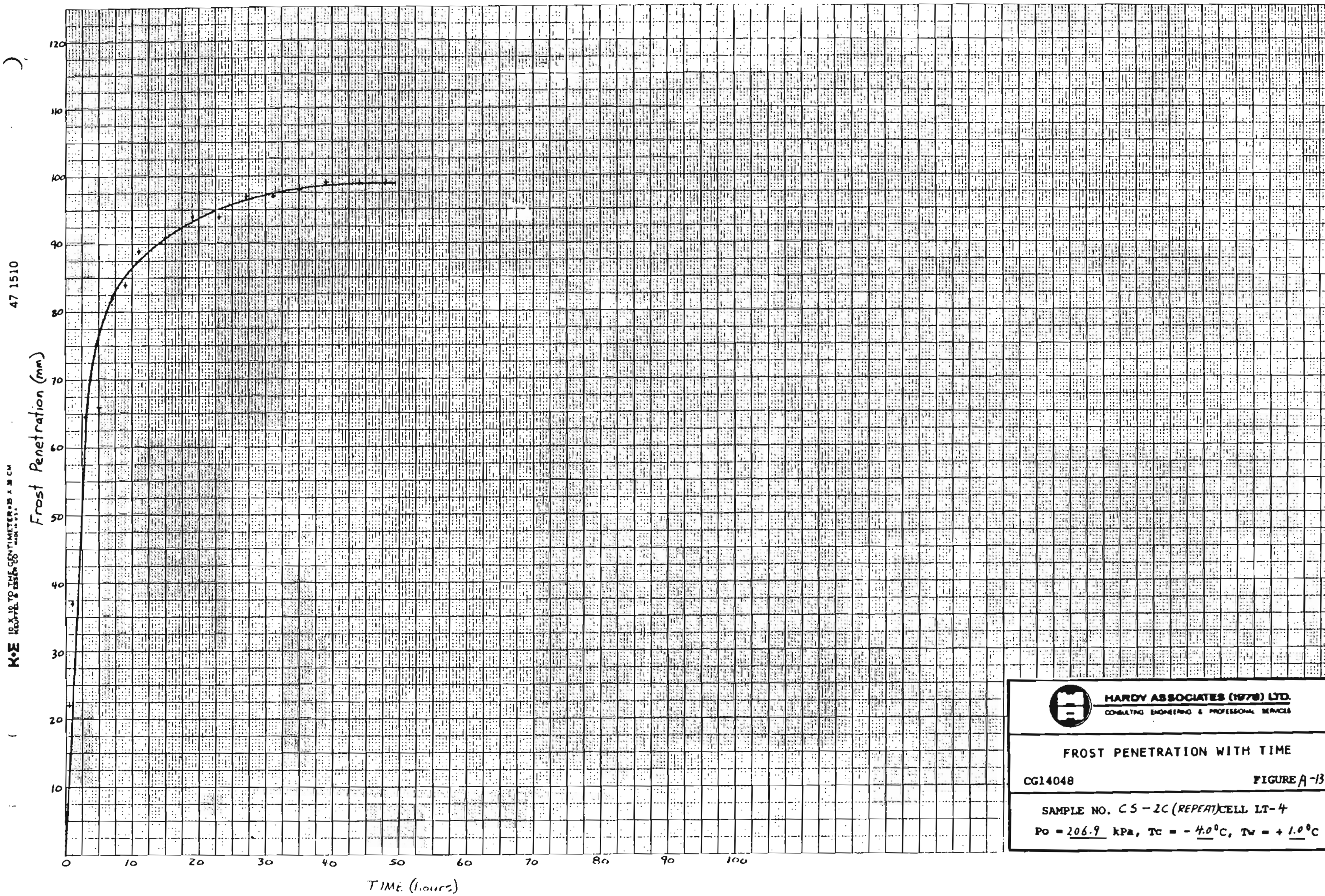
DATE OCT. 21, 1983

SOIL REMOULDED

Δt 29.0 HRS

FIGURE A-12E


Heave By Water Movement + Frost Heave (mm)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
10
20
30
40
50
60
70
80
90
100
TIME (hours)
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST HEAVE AND WATER MOVEMENT WITH TIME
CG14048
FIGURE A-13/7
SAMPLE NO. CS-2C (REPEAT) CELL LT-4
Po = 206.9 kPa, Tc = -4.0°C, Tw = +1.0°C
K•E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A.
47 1510



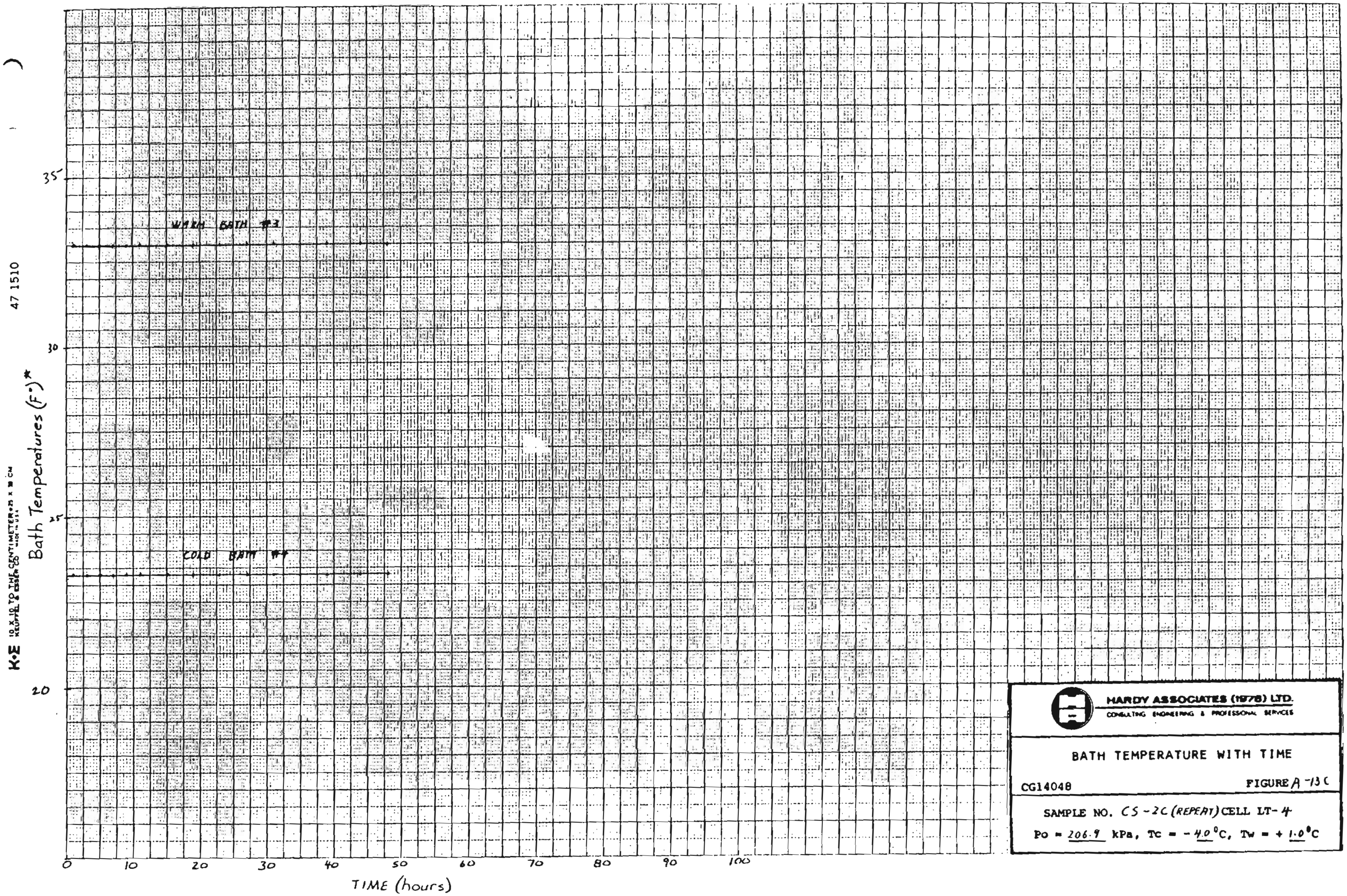

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-13B

SAMPLE NO. CS-2C (REPEAT) CELL LT-4

Po = 206.9 kPa, Tc = - 4.0°C, Tw = + 1.0°C



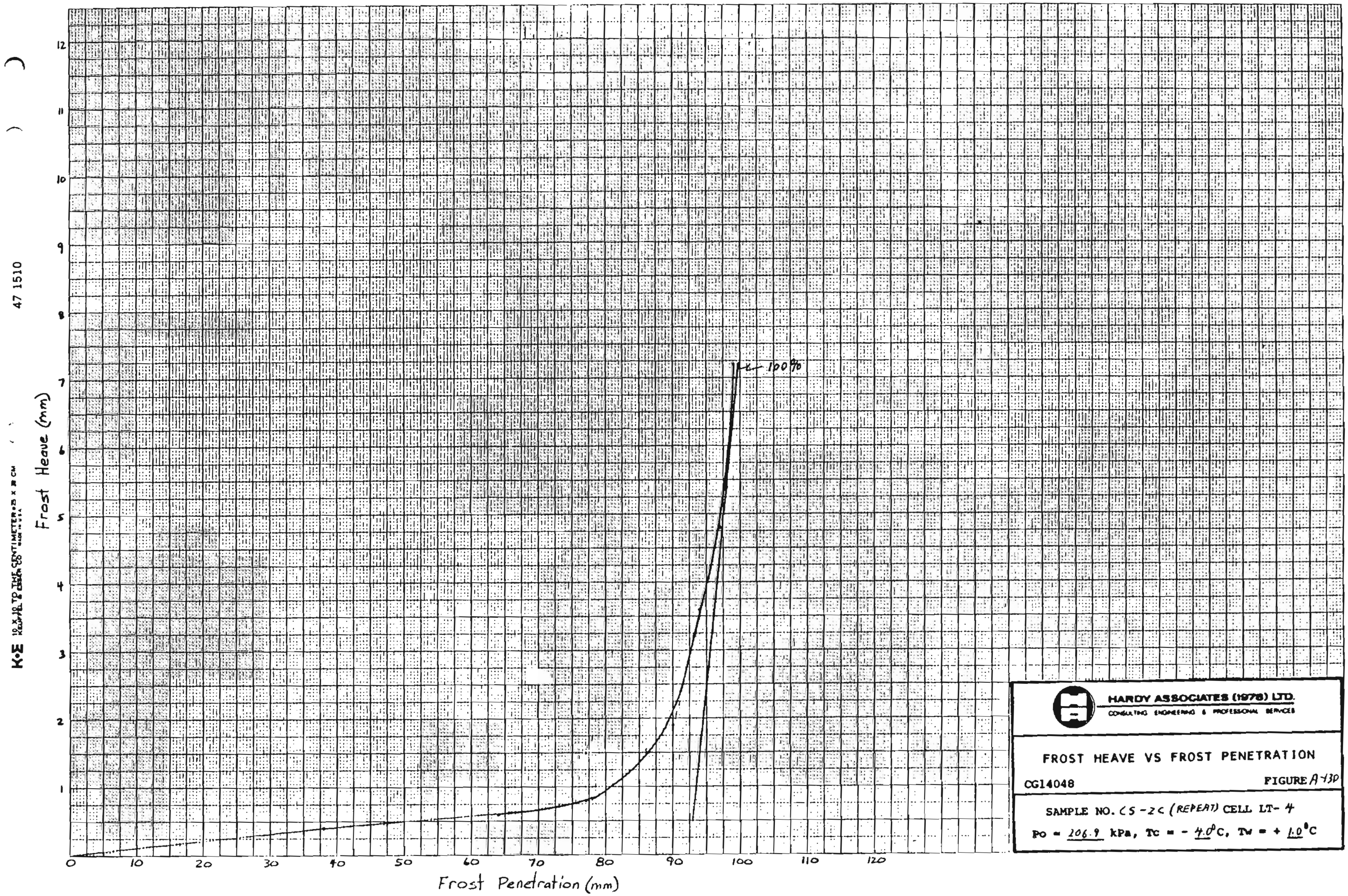

**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-13C

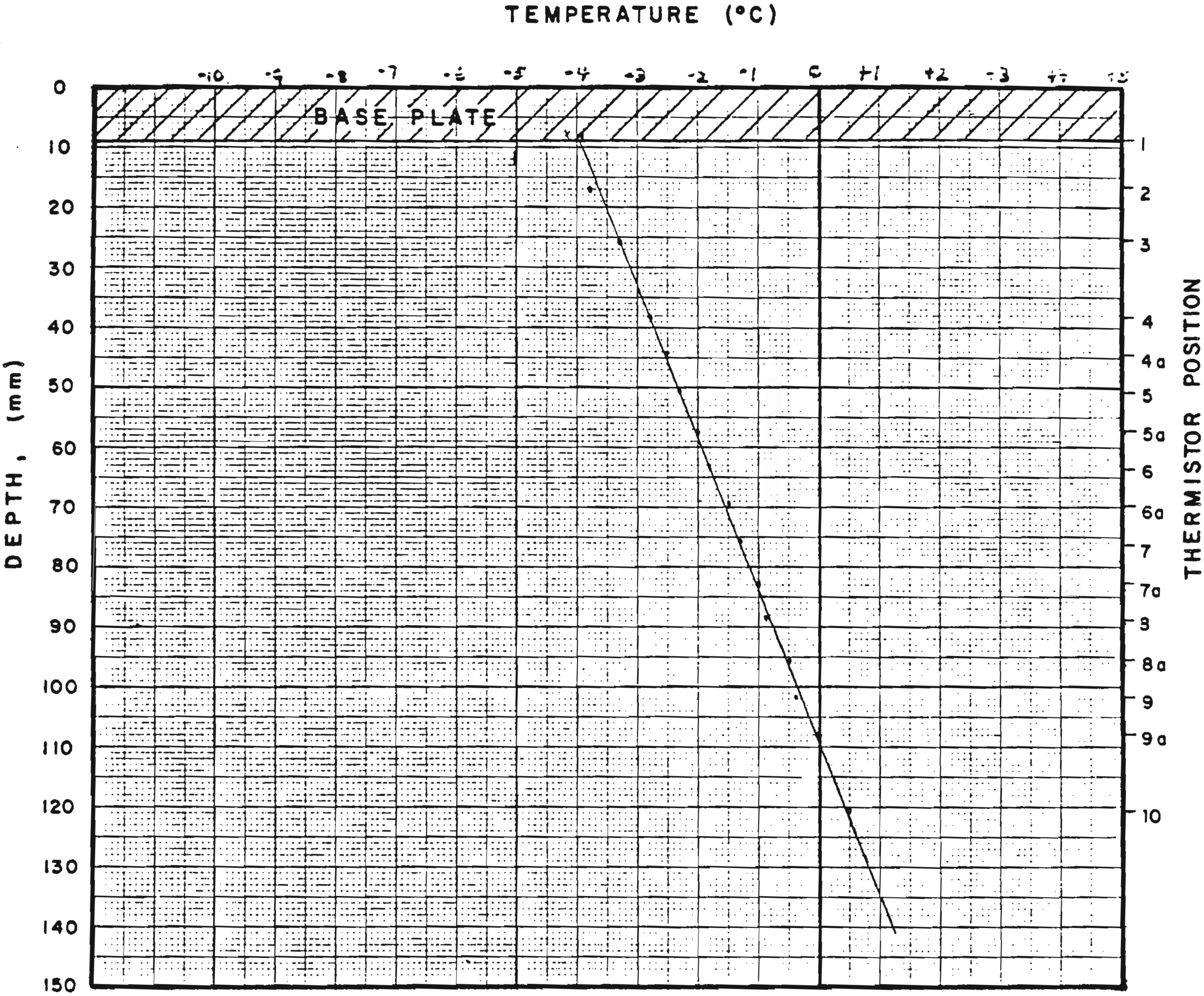
SAMPLE NO. CS-2C (REPEAT) CELL LT-4

Po = 206.9 kPa, Tc = -4.0°C, Tw = +1.0°C



12
11
10
9
8
7
6
5
4
3
2
1
Frost Heave (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
Frost Penetration (mm)
100%
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST HEAVE VS FROST PENETRATION
CG14048
FIGURE A-13D
SAMPLE NO. CS-2C (REPEAT) CELL LT-4
Po = 206.9 kPa, Tc = - 4.0°C, Tw = + 1.0°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-2C (REPEAT)

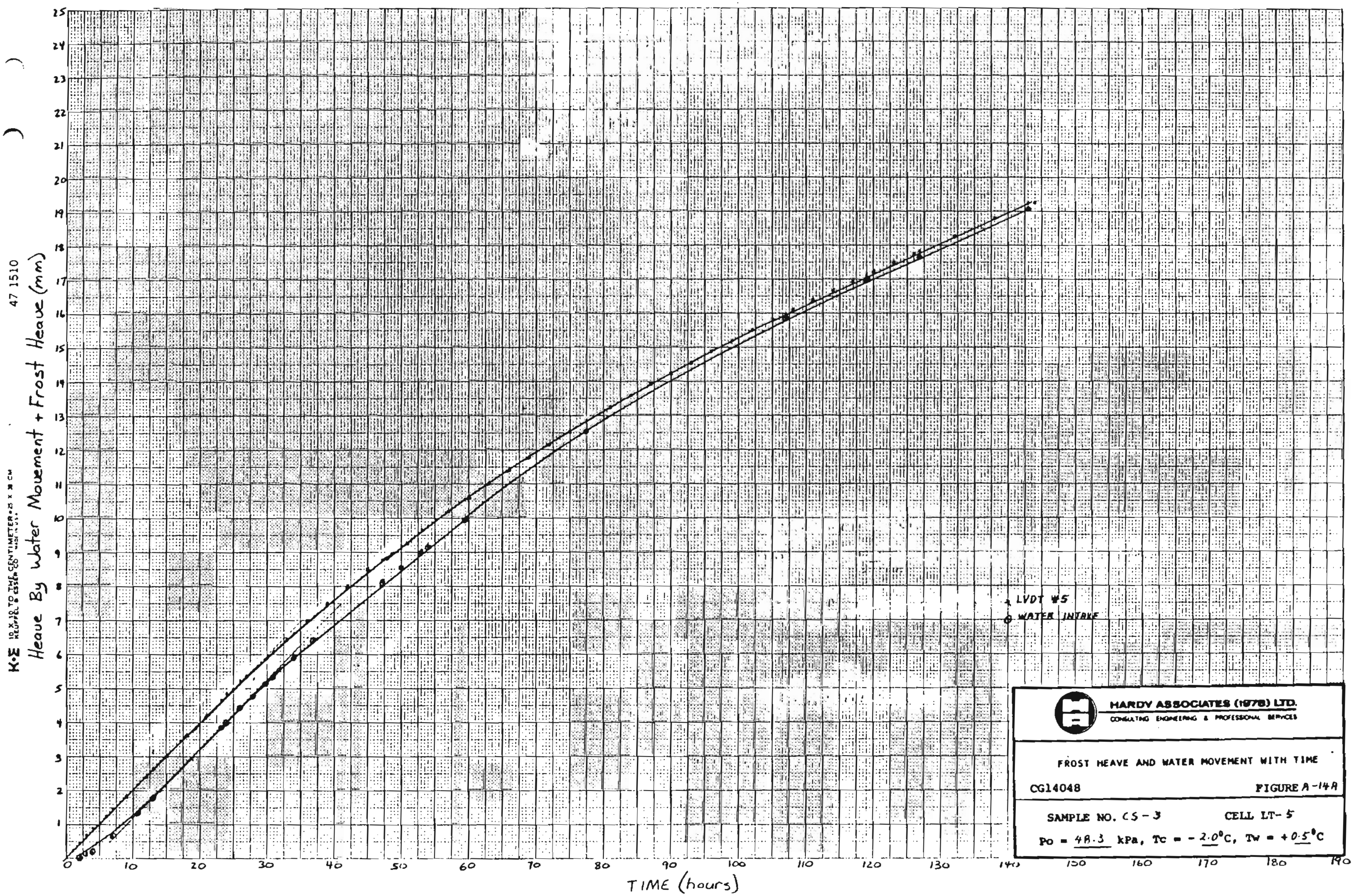
CELL LT-4

DATE NOV. 3, 1983

SOIL UNDISTURBED

Δt 48.0 HRS

FIGURE A-13E



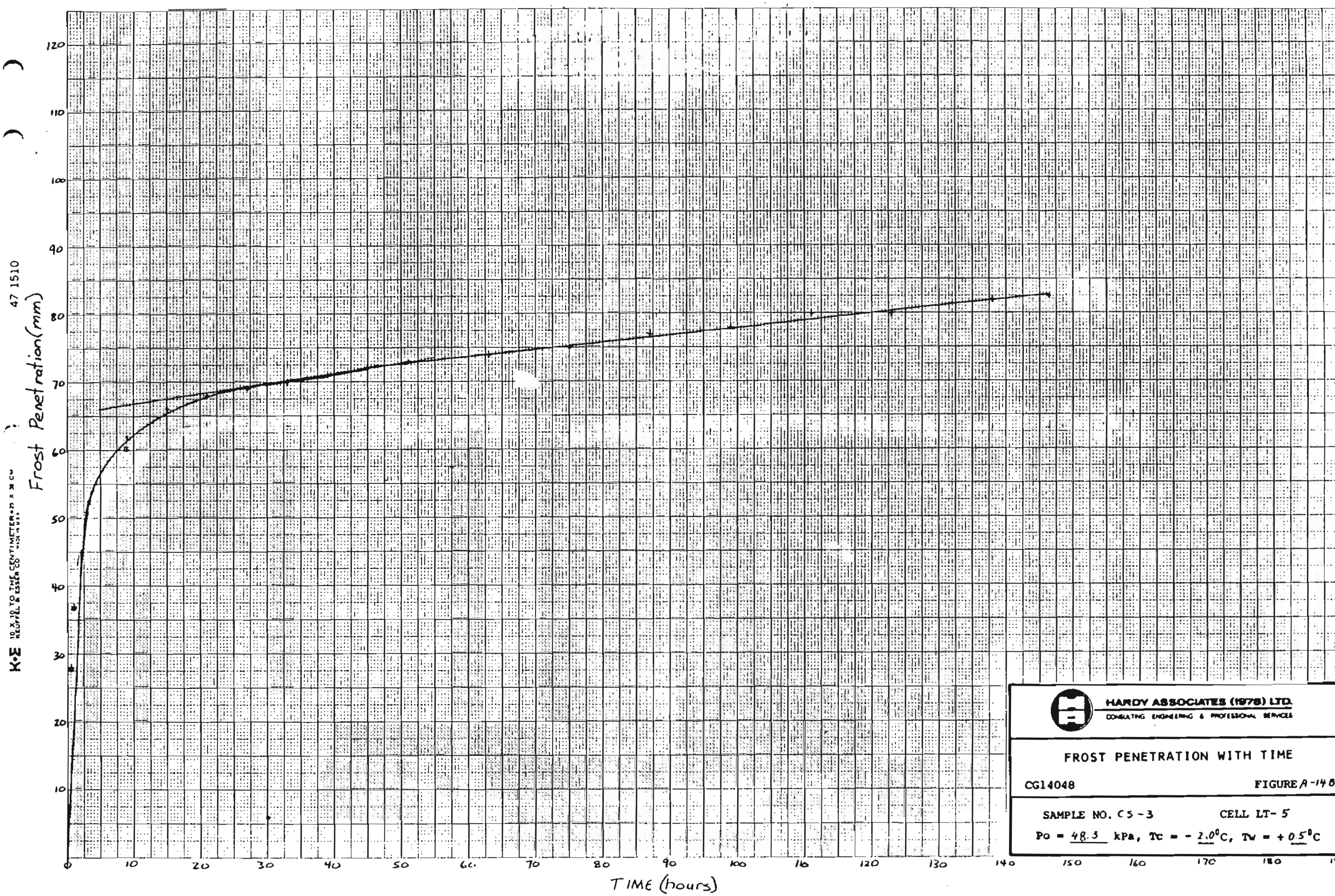

**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048 FIGURE A-14A

SAMPLE NO. CS-3 CELL LT-5

Po = 48.3 kPa, Tc = -2.0°C, Tw = +0.5°C



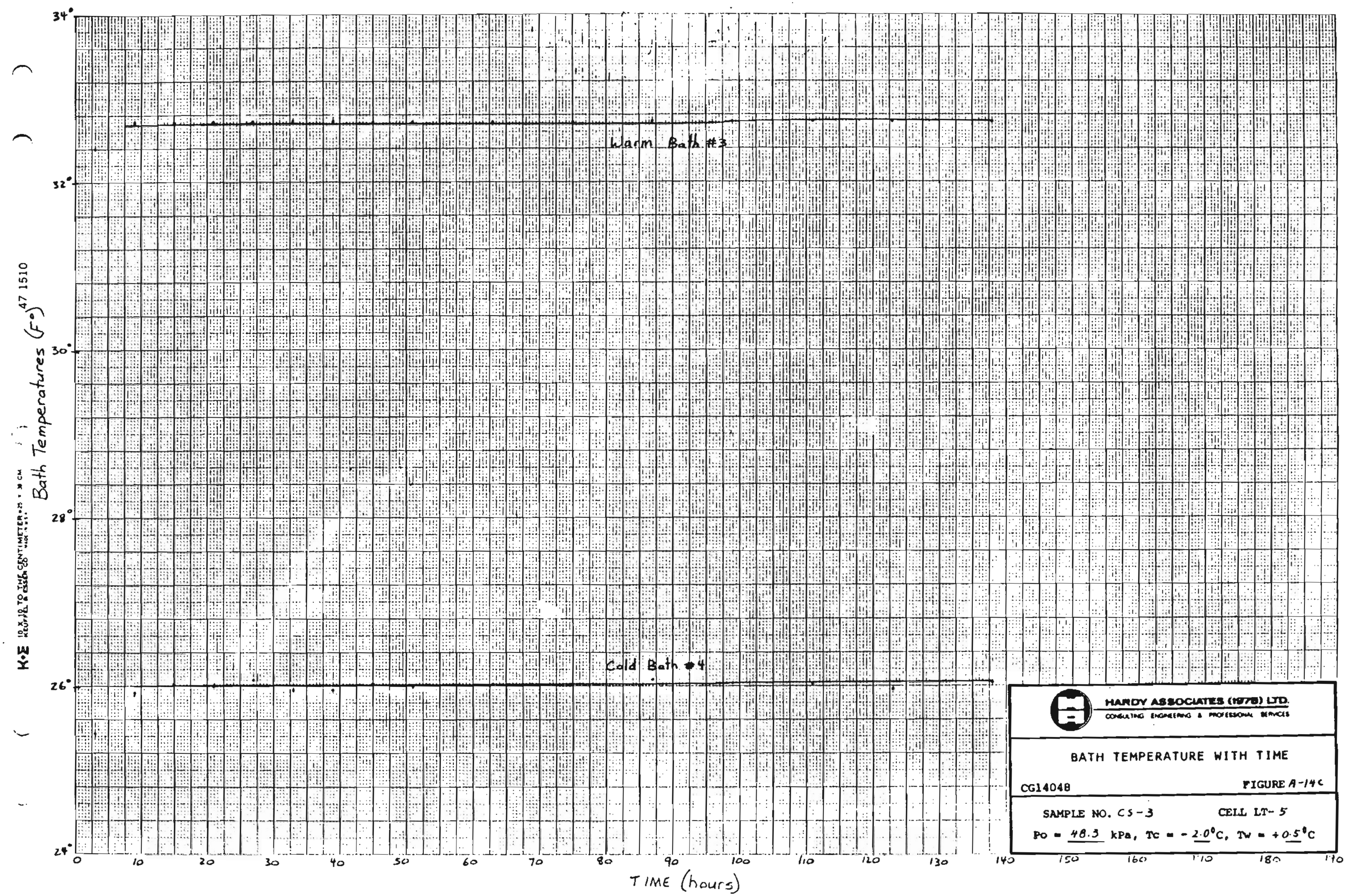

**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-148

SAMPLE NO. CS-3 CELL LT-5

Po = 48.3 kPa, Tc = - 2.0°C, Tw = + 0.5°C



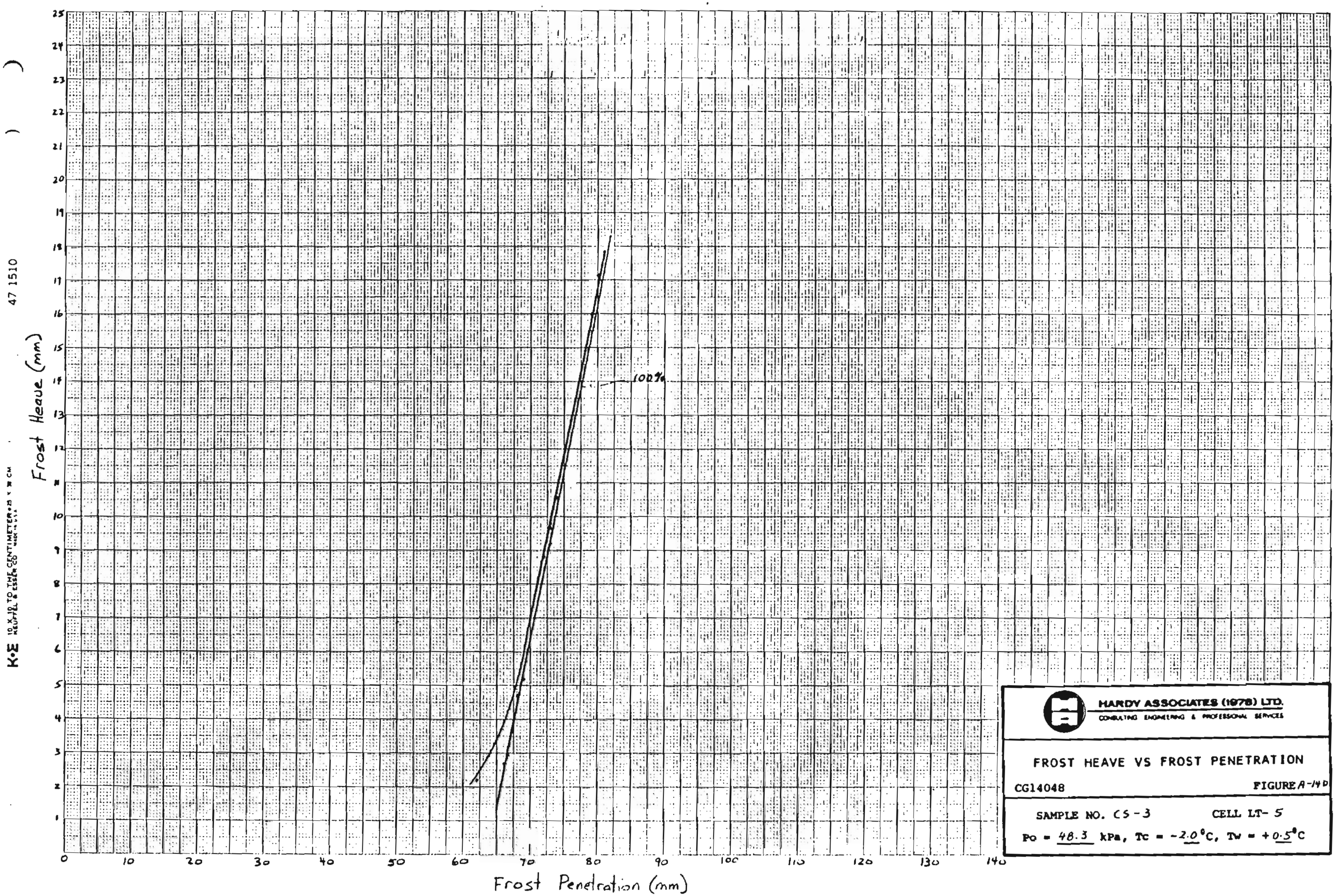

**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-14c

SAMPLE NO. CS-3 CELL LT-5

Po = 48.3 kPa, Tc = -2.0°C, Tw = +0.5°C




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

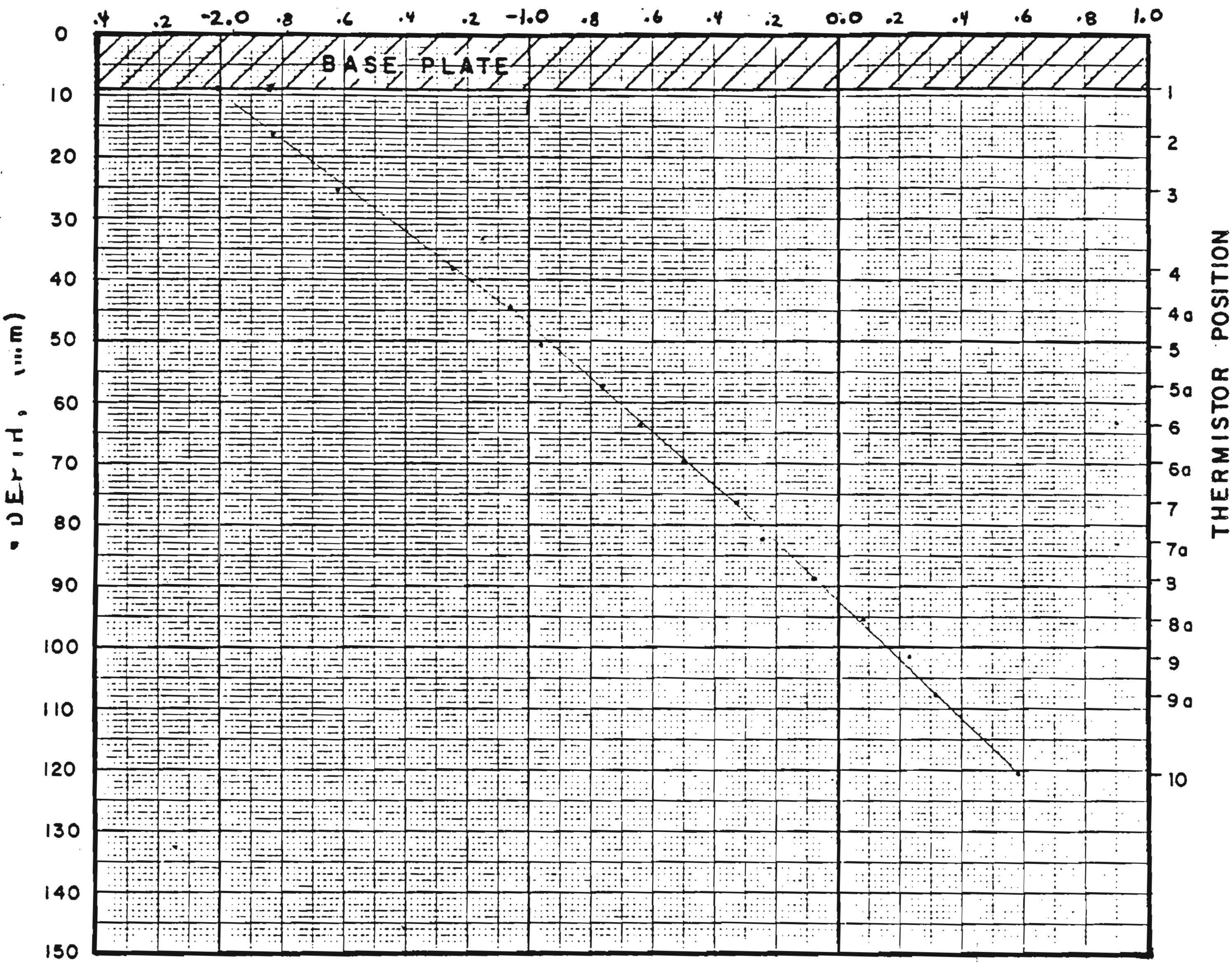
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-14D

SAMPLE NO. CS-3 CELL LT-5

Po = 48.3 kPa, Tc = -2.0°C, Tw = +0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 10 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-3

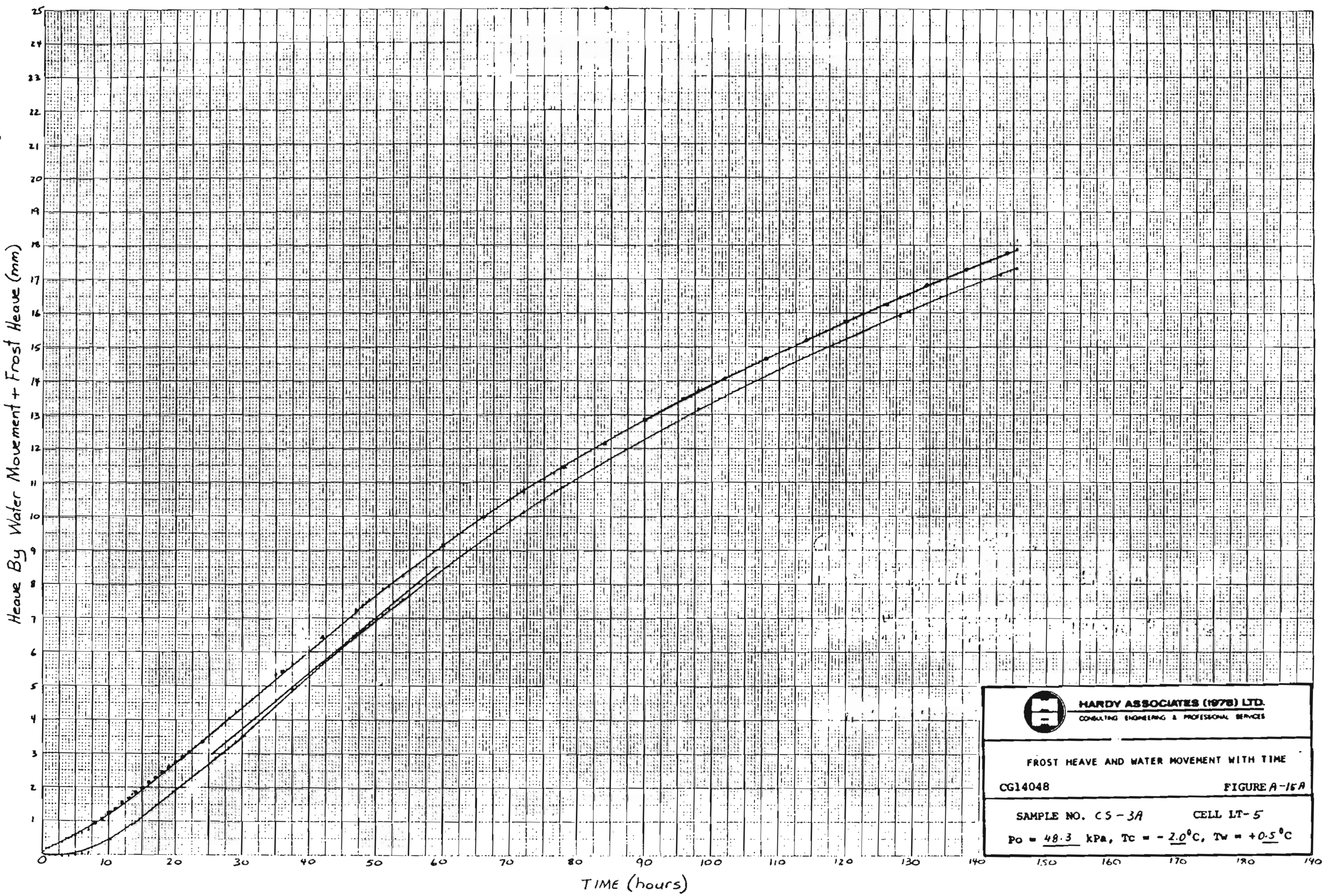
CELL LT-5

DATE MAY 17, 1983

SOIL REMOULDED

Δt 146.38 HRS

FIGURE A-14E



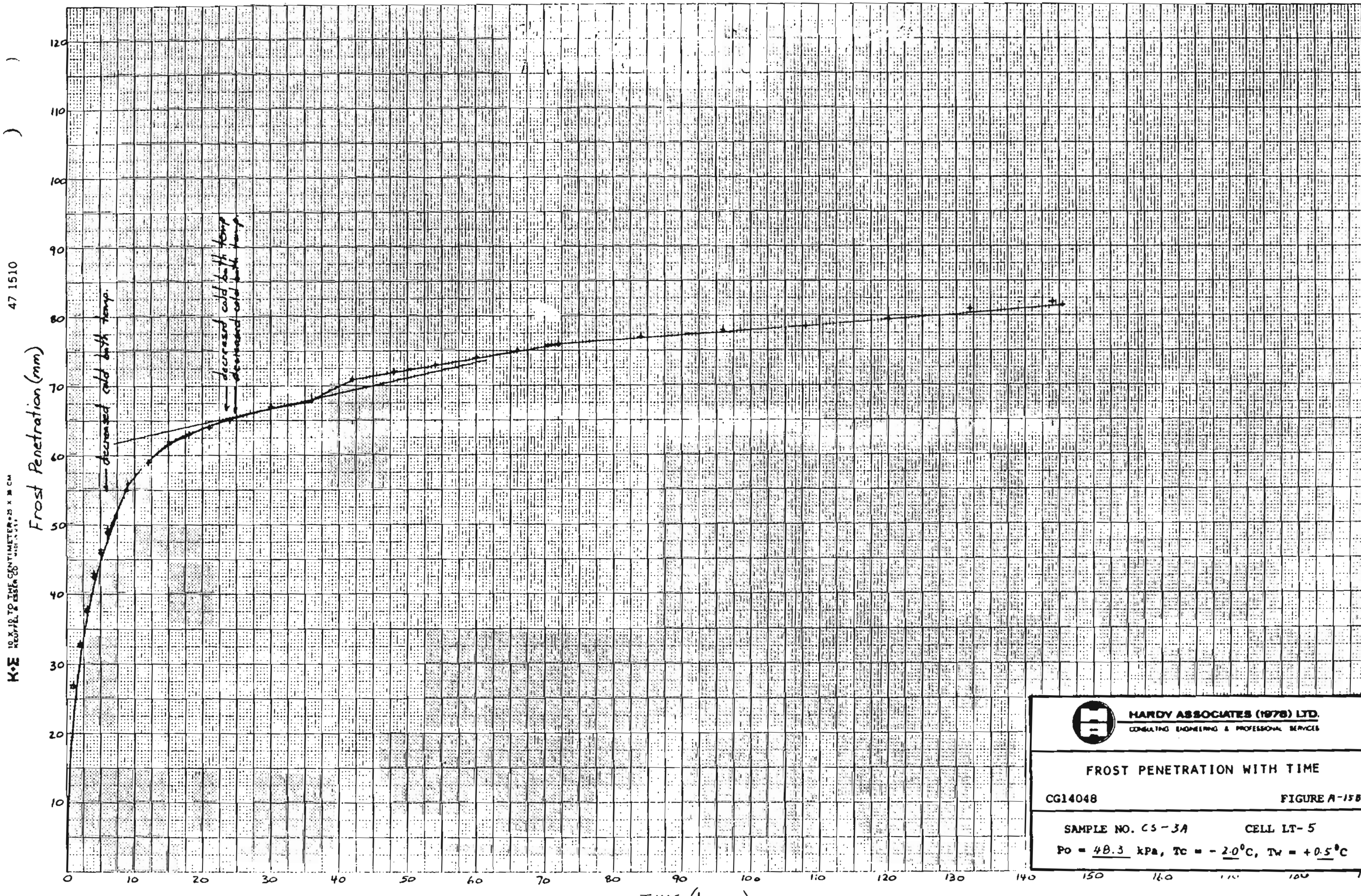

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048 FIGURE A-15A

SAMPLE NO. CS-3A CELL LT-5

Po = 48.3 kPa, Tc = -2.0°C, Tw = +0.5°C



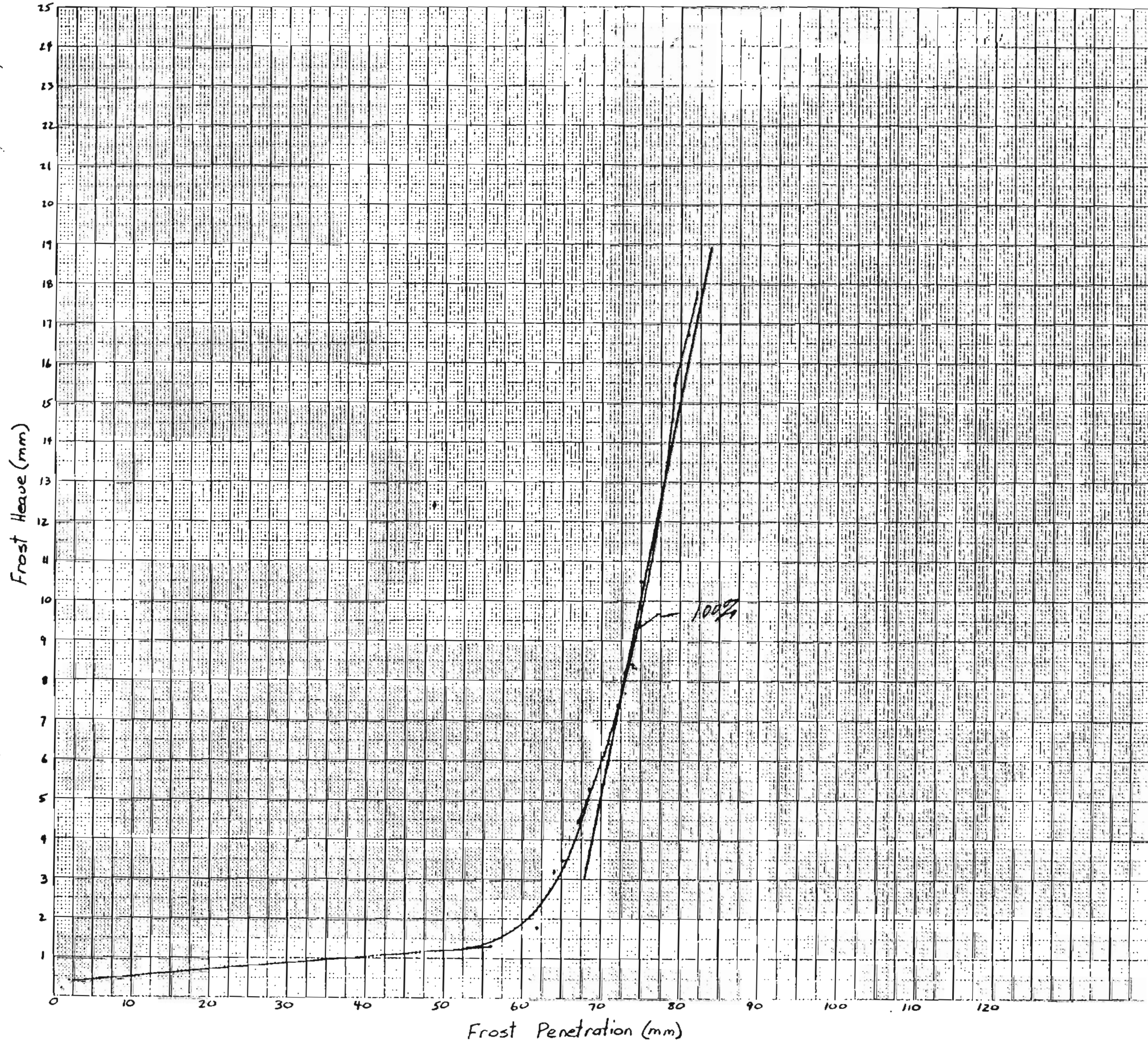

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-15B

SAMPLE NO. CS-3A CELL LT-5

Po = 48.3 kPa, Tc = -2.0°C, Tw = +0.5°C




HARDY ASSOCIATES (1978) LTD.
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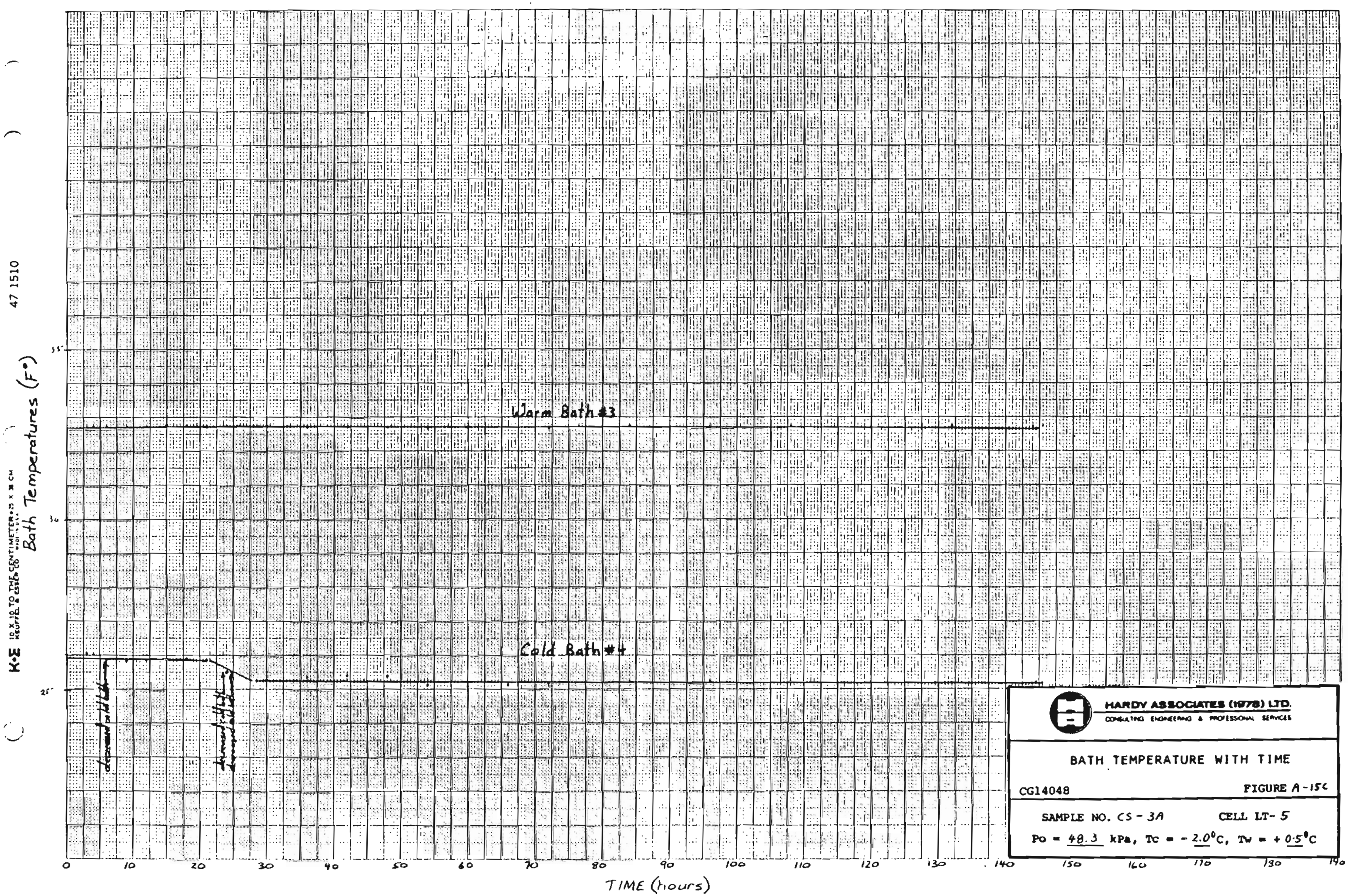
FROST HEAVE VS FROST PENETRATION

CG14048 FIGUREA-15D

SAMPLE NO. CELL LT-

Po = ____ kPa, Tc = - __°C, Tw = + __°C

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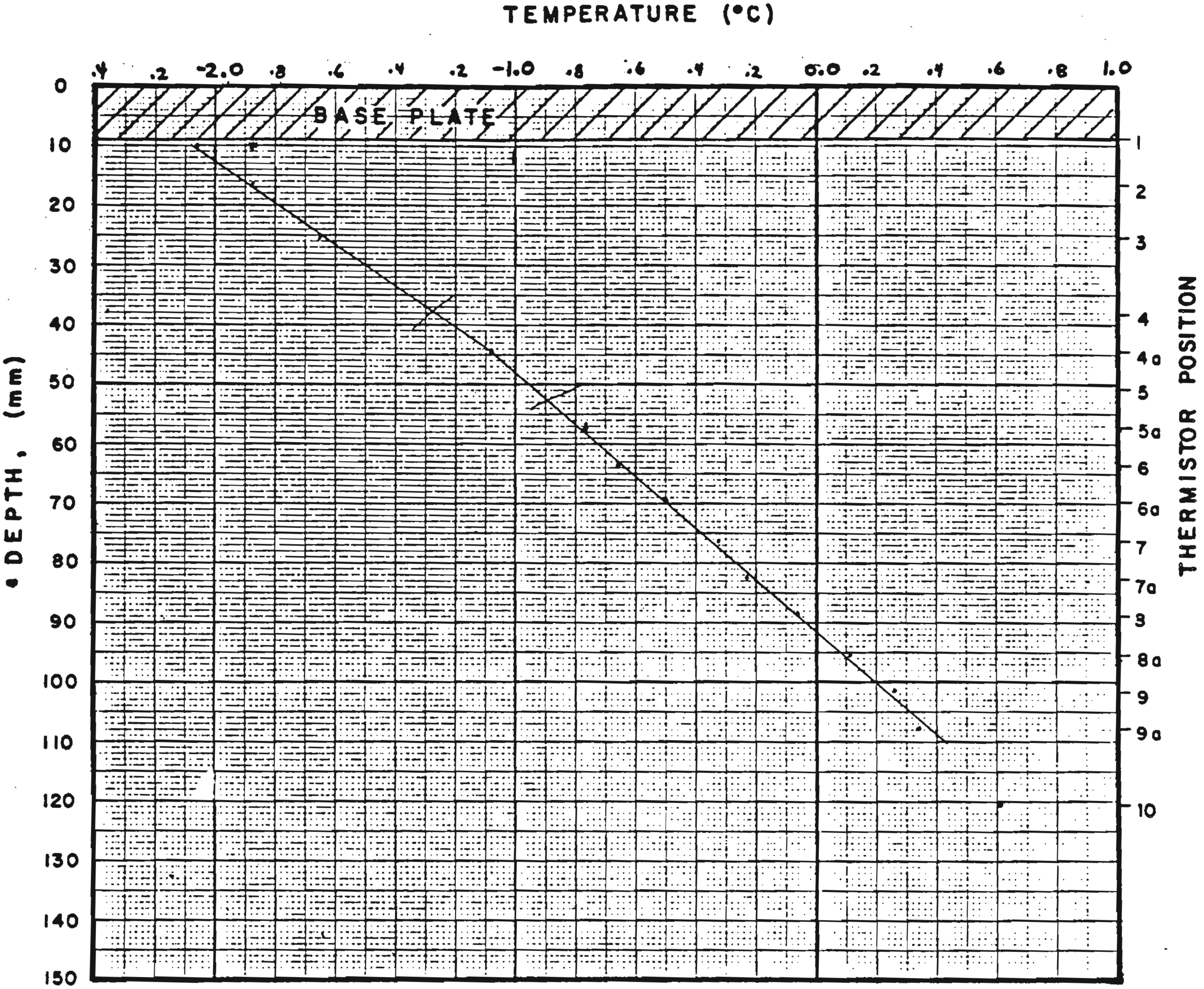
BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-15C

SAMPLE NO. CS - 3A CELL LT- 5

Po = 48.3 kPa, Tc = - 2.0°C, Tw = + 0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 10 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-3A

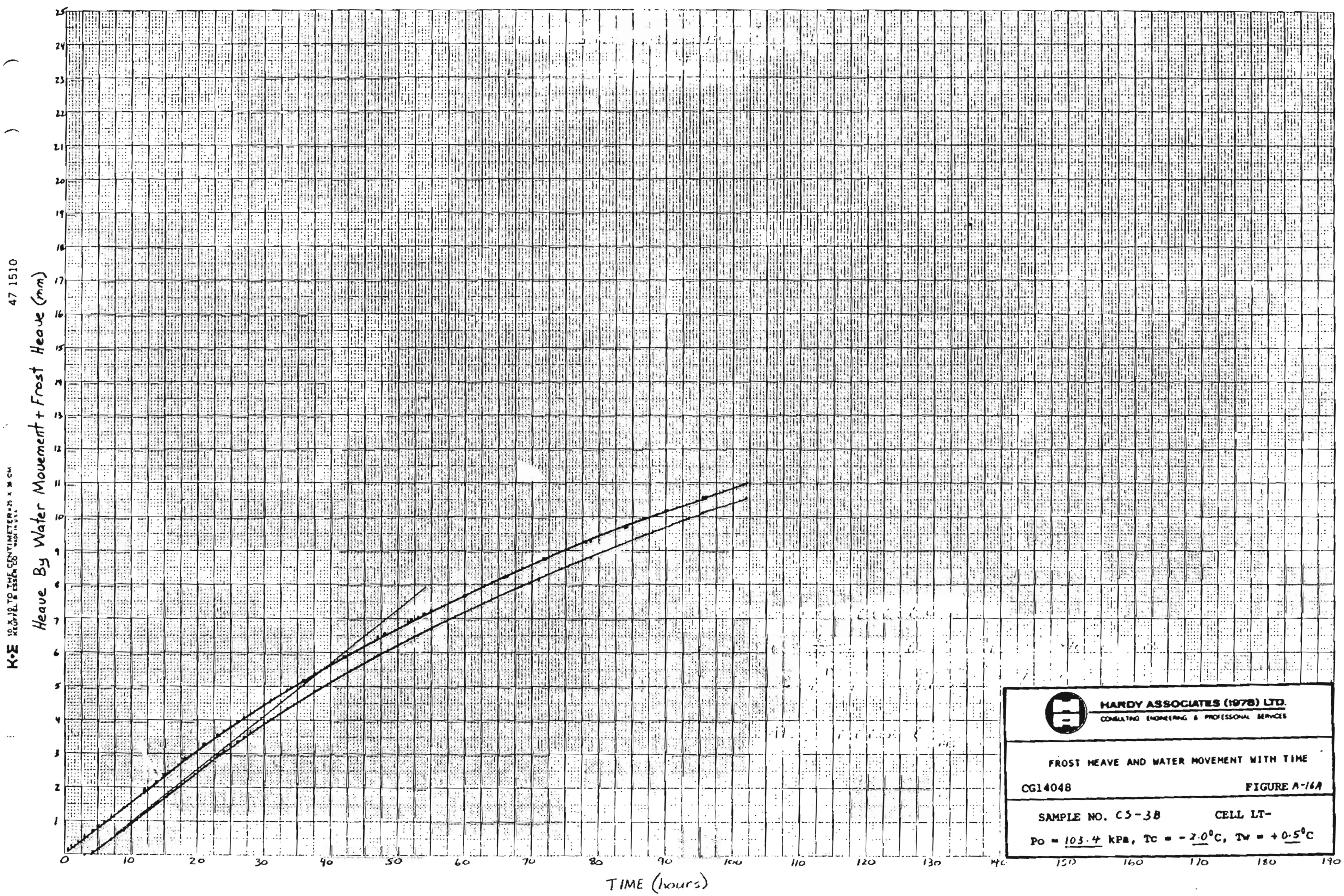
CELL LT-5

DATE JUN. 6, 1983

SOIL REMOULDED

Δt 145.5 HRS

FIGURE A-15E




HARDY ASSOCIATES (1978) LTD.
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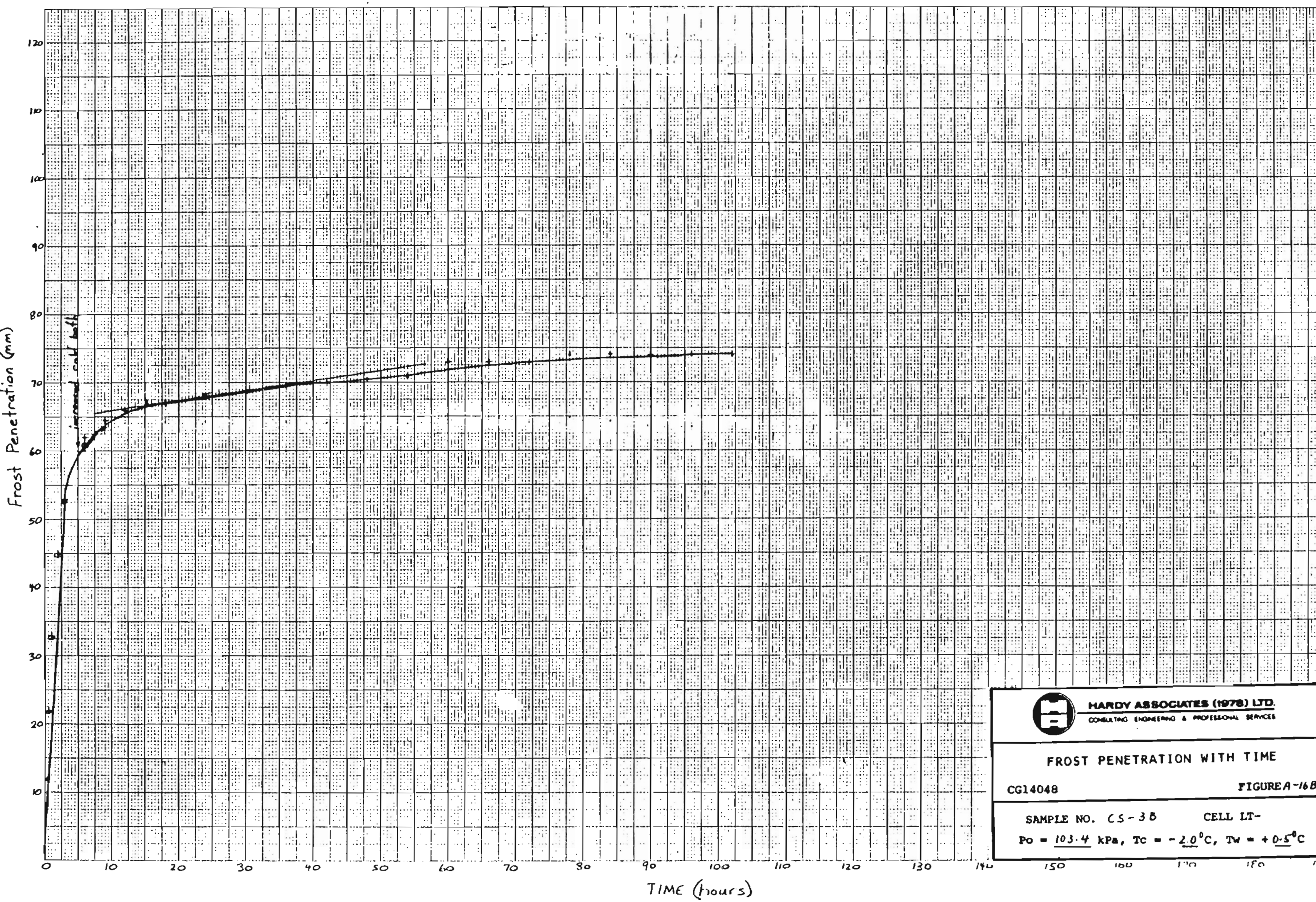
FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048 FIGURE A-16A

SAMPLE NO. CS-3B CELL LT-

Po = 103.4 kPa, Tc = -2.0°C, Tw = +0.5°C



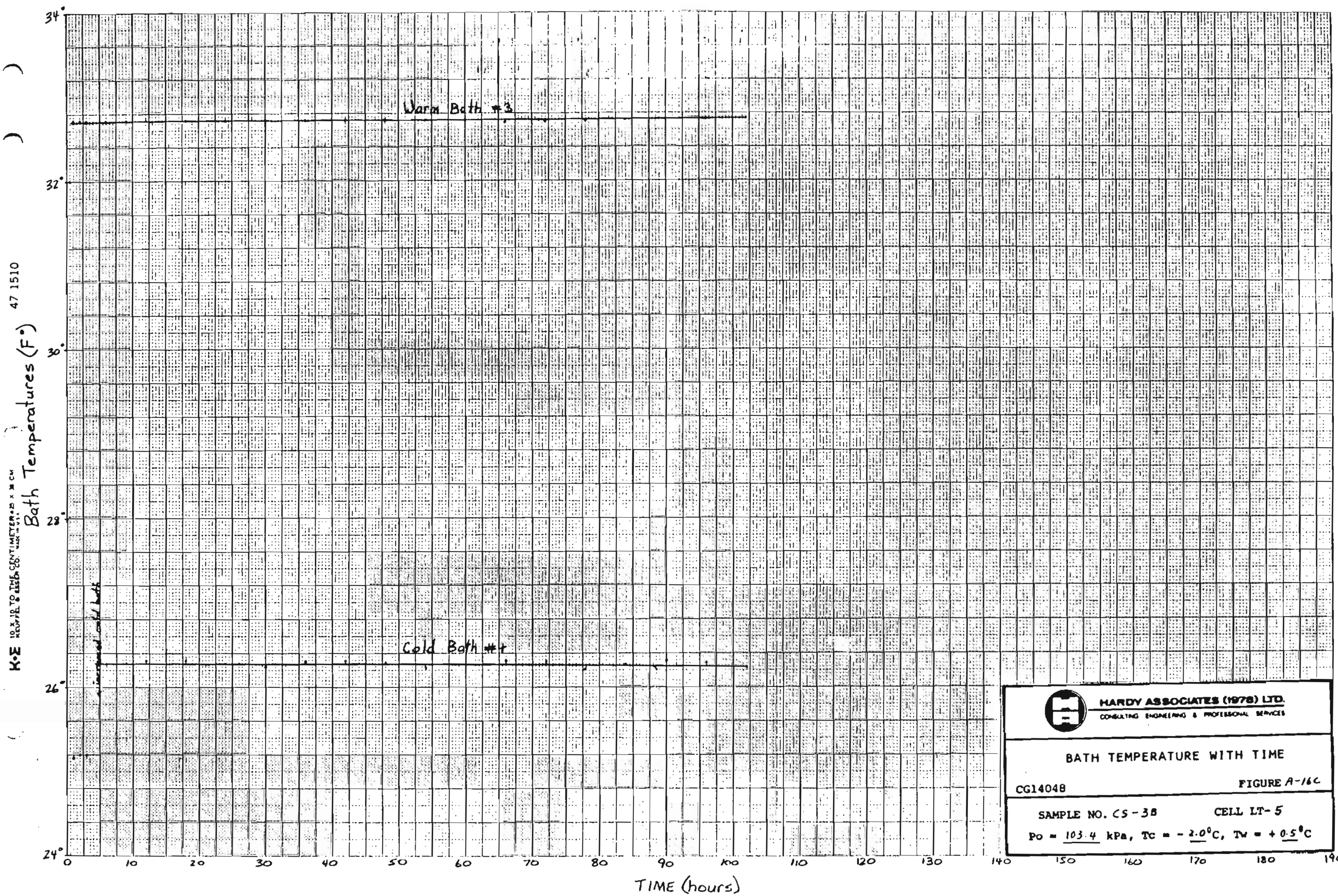

**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-16B

SAMPLE NO. CS-3B CELL LT-

Po = 103.4 kPa, Tc = -2.0°C, Tw = +0.5°C





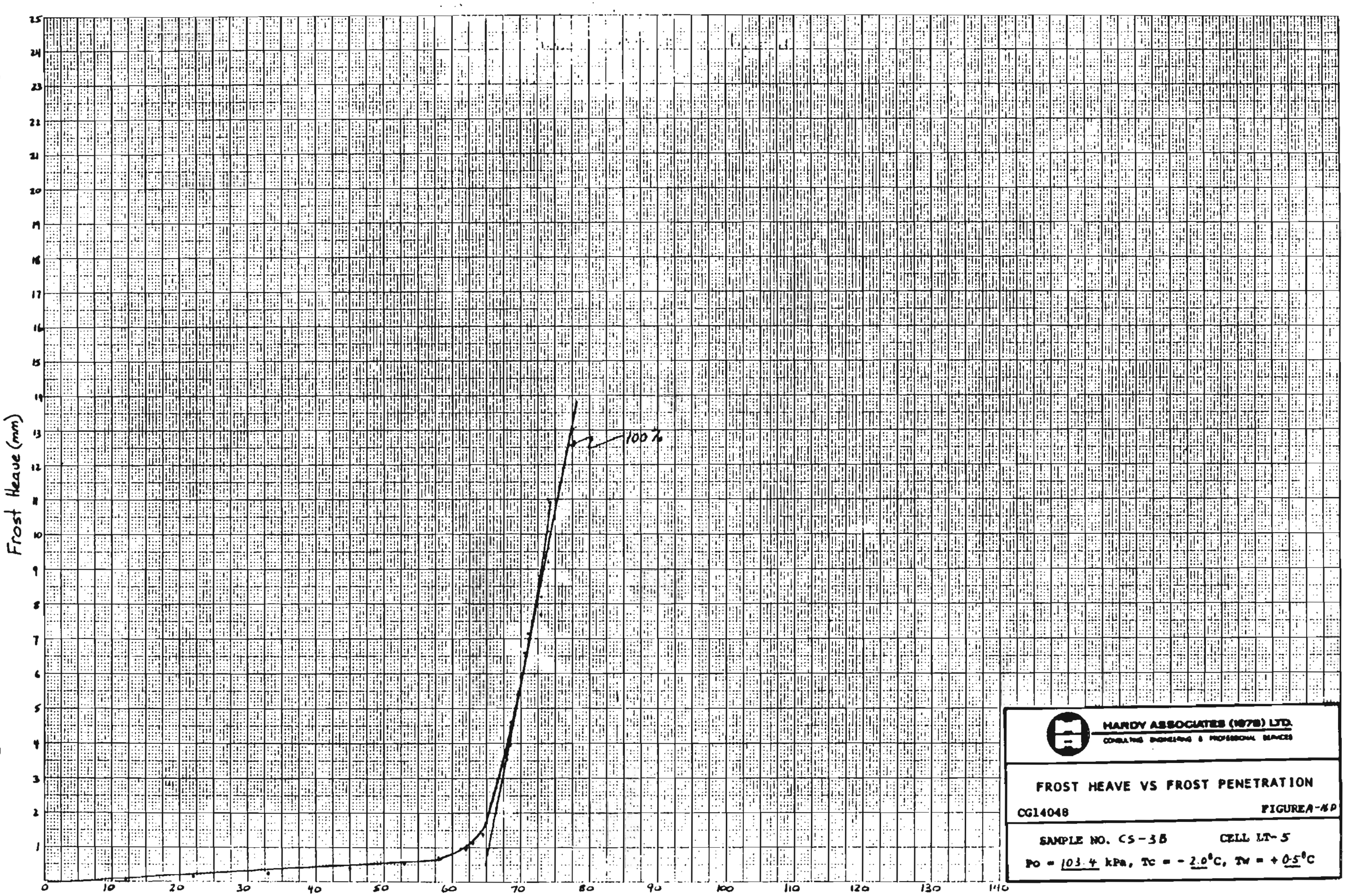

**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-16C

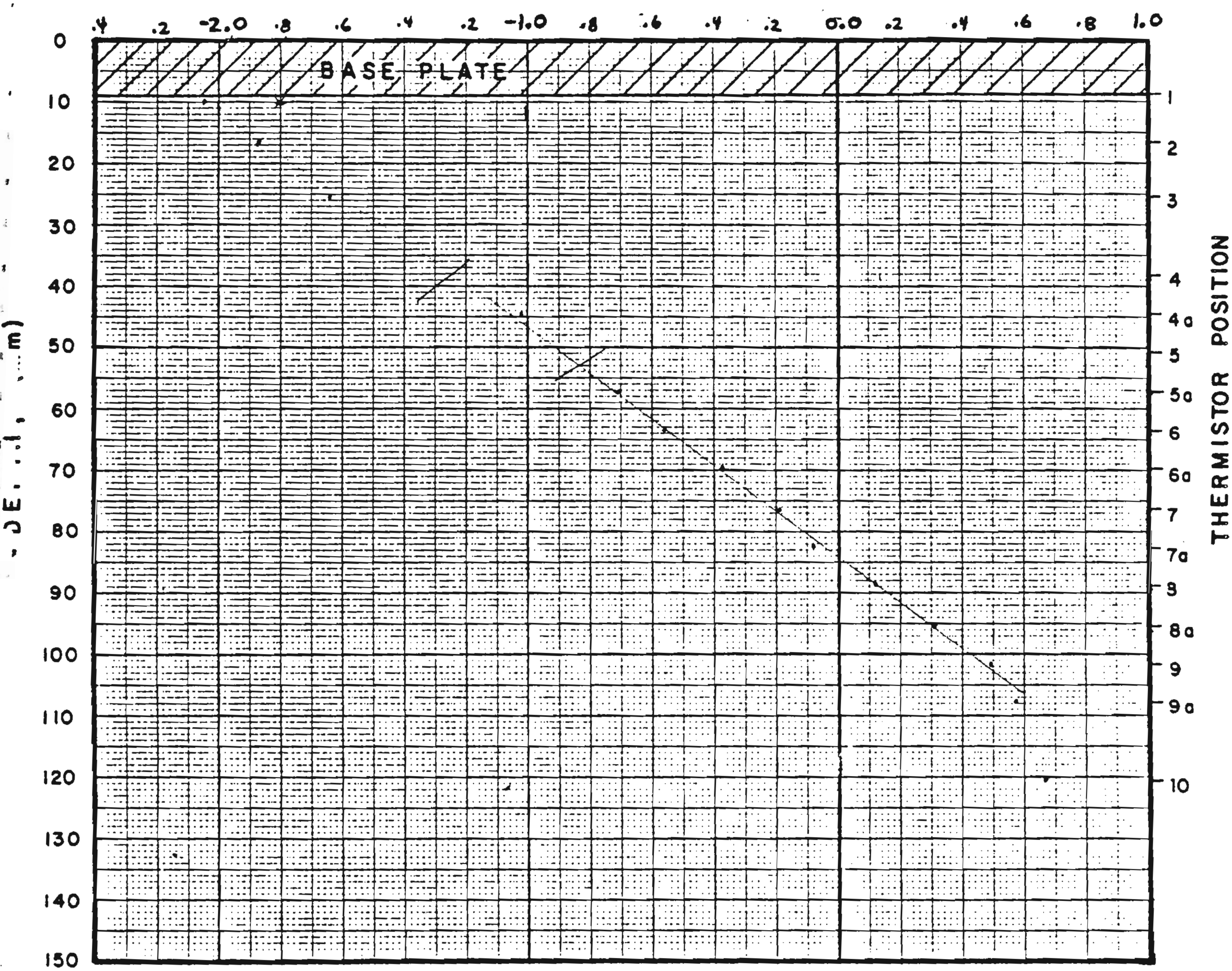
SAMPLE NO. CS-38 CELL LT-5

Po = 103.4 kPa, Tc = -2.0°C, Tw = +0.5°C



Frost Heave (mm)
100%
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST HEAVE VS FROST PENETRATION
CG14048
FIGUREA-16D
SAMPLE NO. CS-3B
CELL LT-5
Po = 103.4 kPa, Tc = - 2.0°C, Tw = + 0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 10 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS - 3B

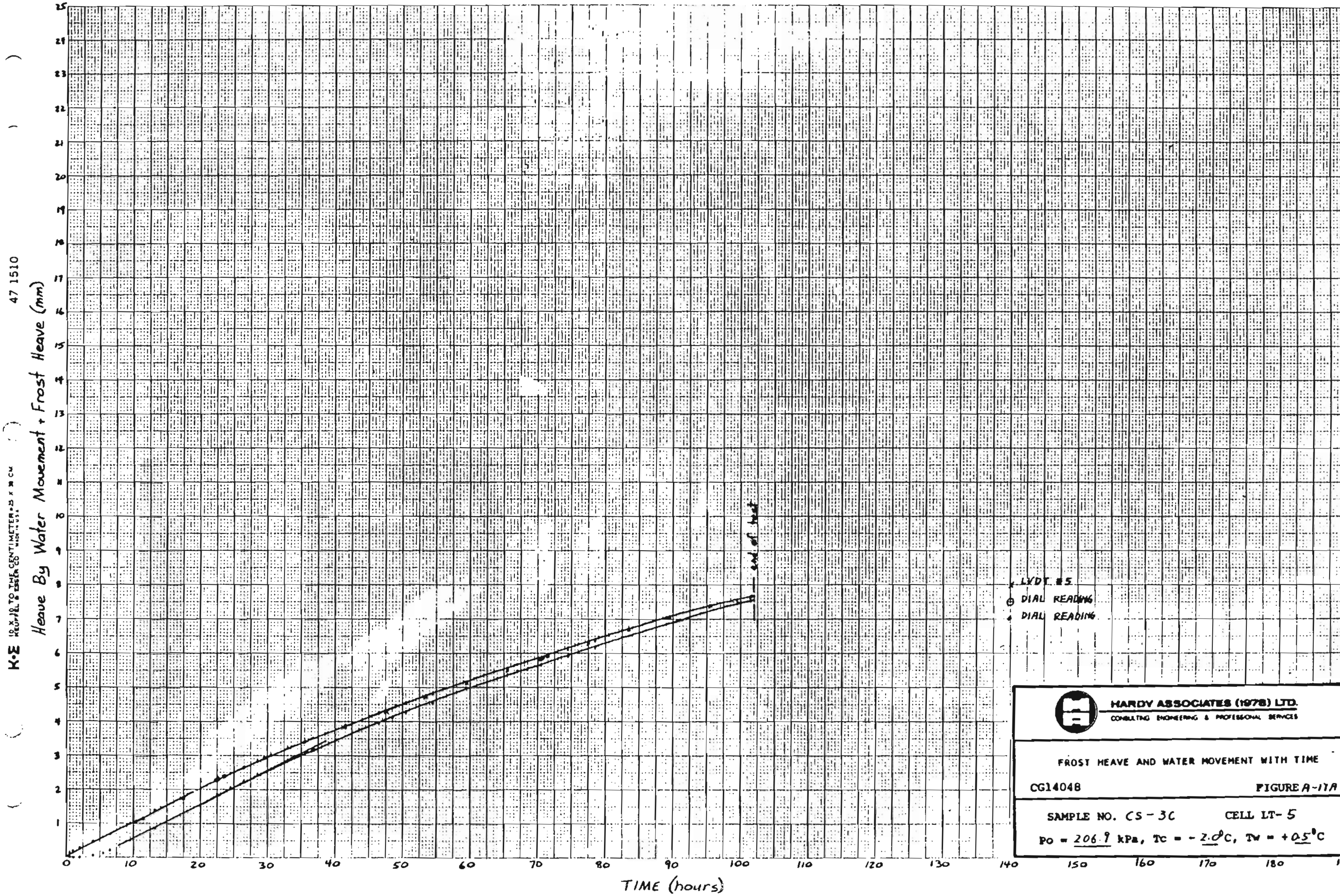
CELL LT - 5

DATE JUN. 24, 1987

SOIL REMOULDED

Δt 102.0 HRS

FIGURE A-16E




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

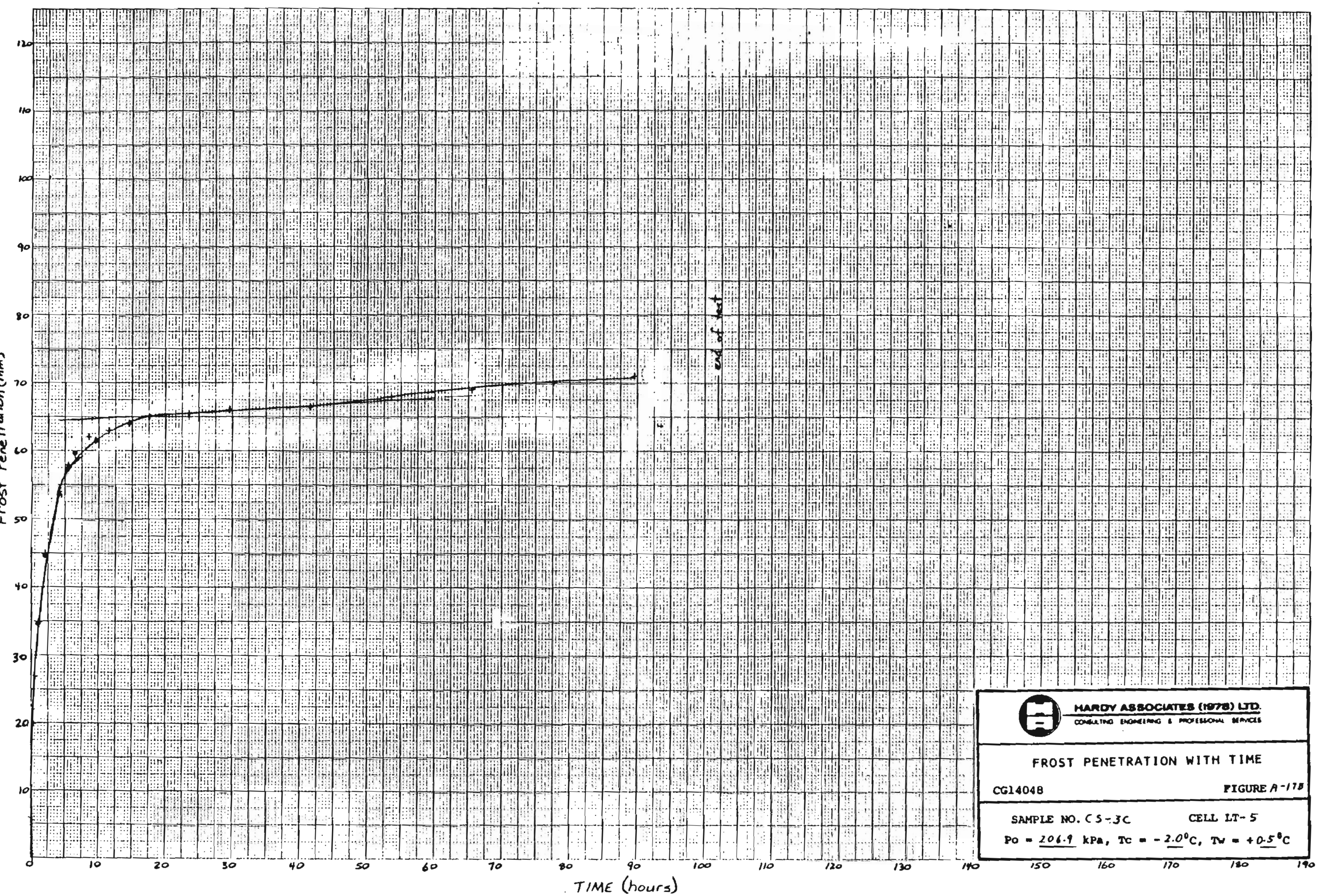
FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048

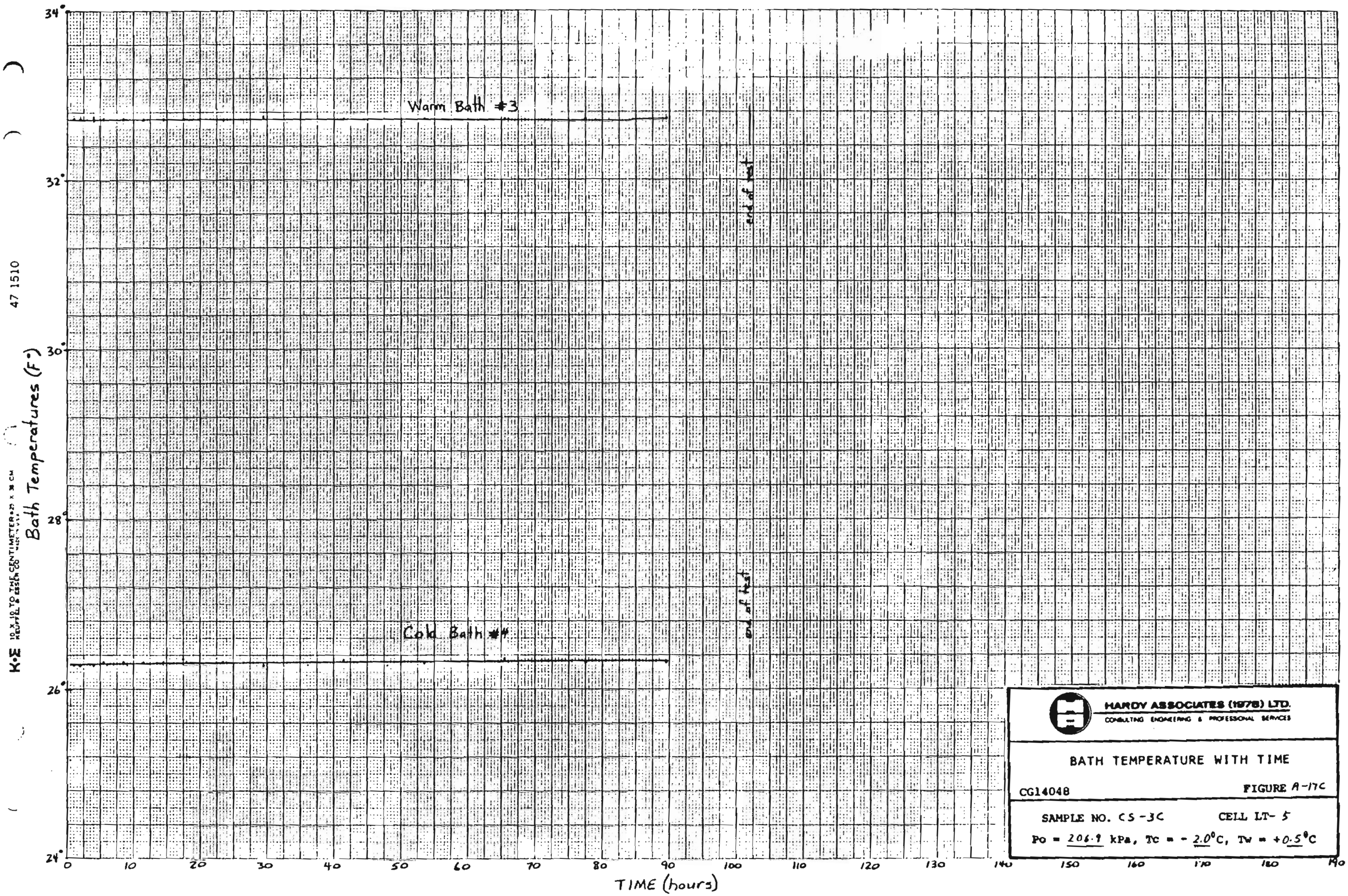
FIGURE A-17A

SAMPLE NO. CS-3C    CELL LT-5

Po = 206.9 kPa, Tc = -2.0°C, Tw = +0.5°C



Frost Penetration (mm)
TIME (hours)
end of test
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES
FROST PENETRATION WITH TIME
CG14048
FIGURE A-17B
SAMPLE NO. CS-3C
CELL LT-5
Po = 206.9 kPa, Tc = -2.0°C, Tw = +0.5°C

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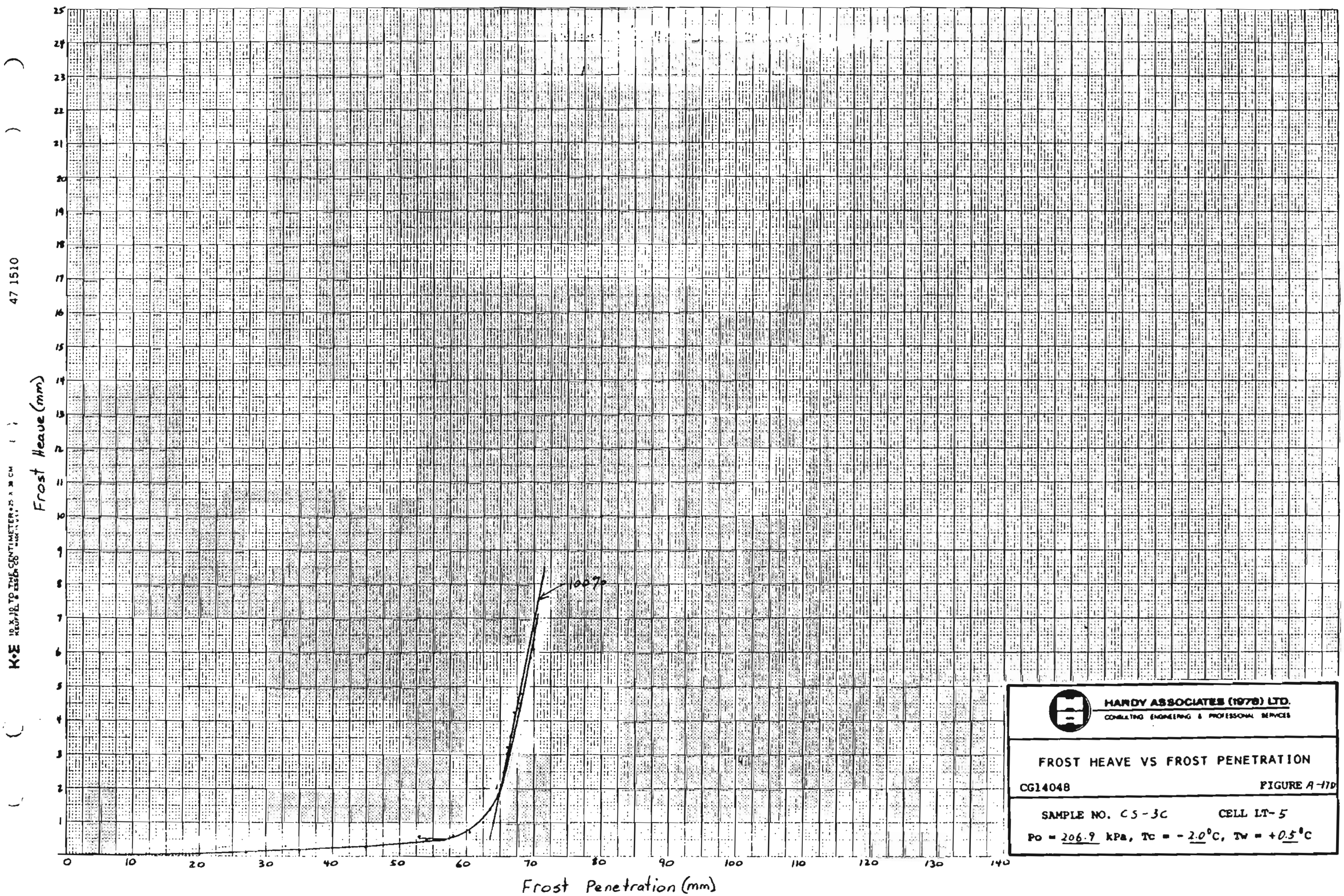
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-17C

SAMPLE NO. CS-3C CELL LT-5

Po = 206.9 kPa, Tc = - 2.0°C, Tw = +0.5°C




HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

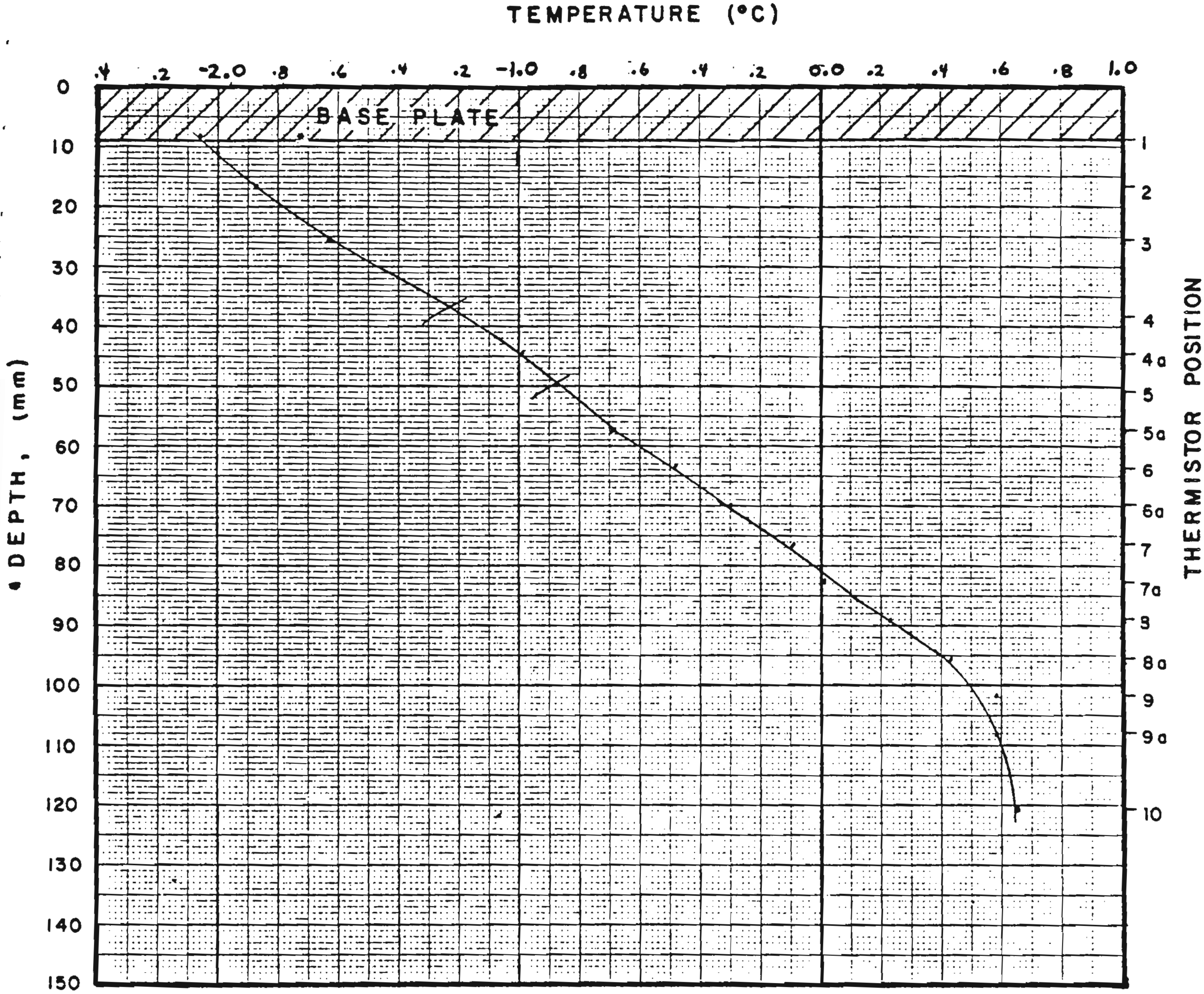
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-17D

SAMPLE NO. CS-3C CELL LT-5

Po = 206.9 kPa, Tc = -2.0°C, Tw = +0.5°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 10 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-3C

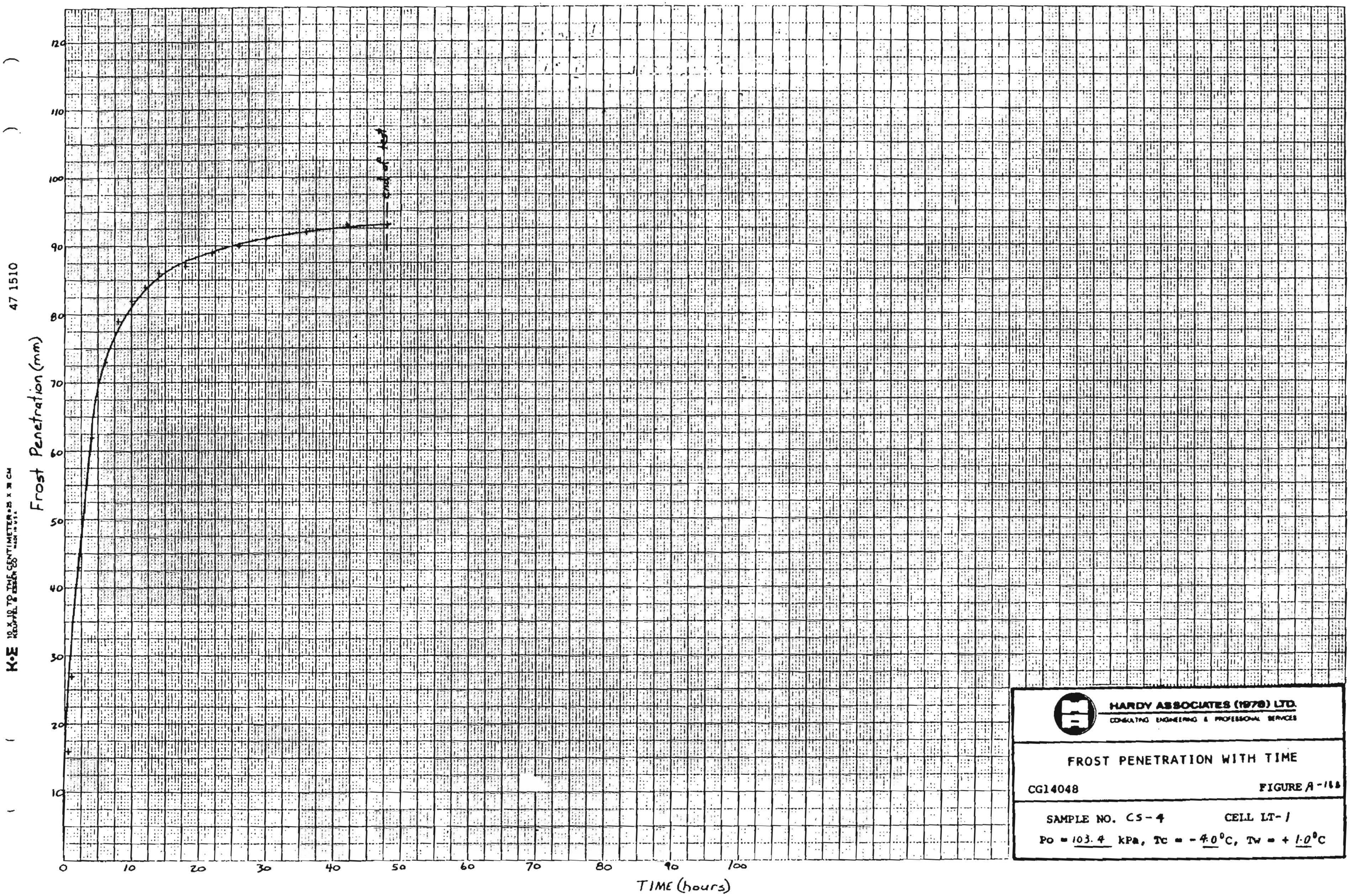
CELL LT-5

DATE JUL. 8, 1983

SOIL REMOULDED

Δt 89.5 HFS

FIGURE A-17E



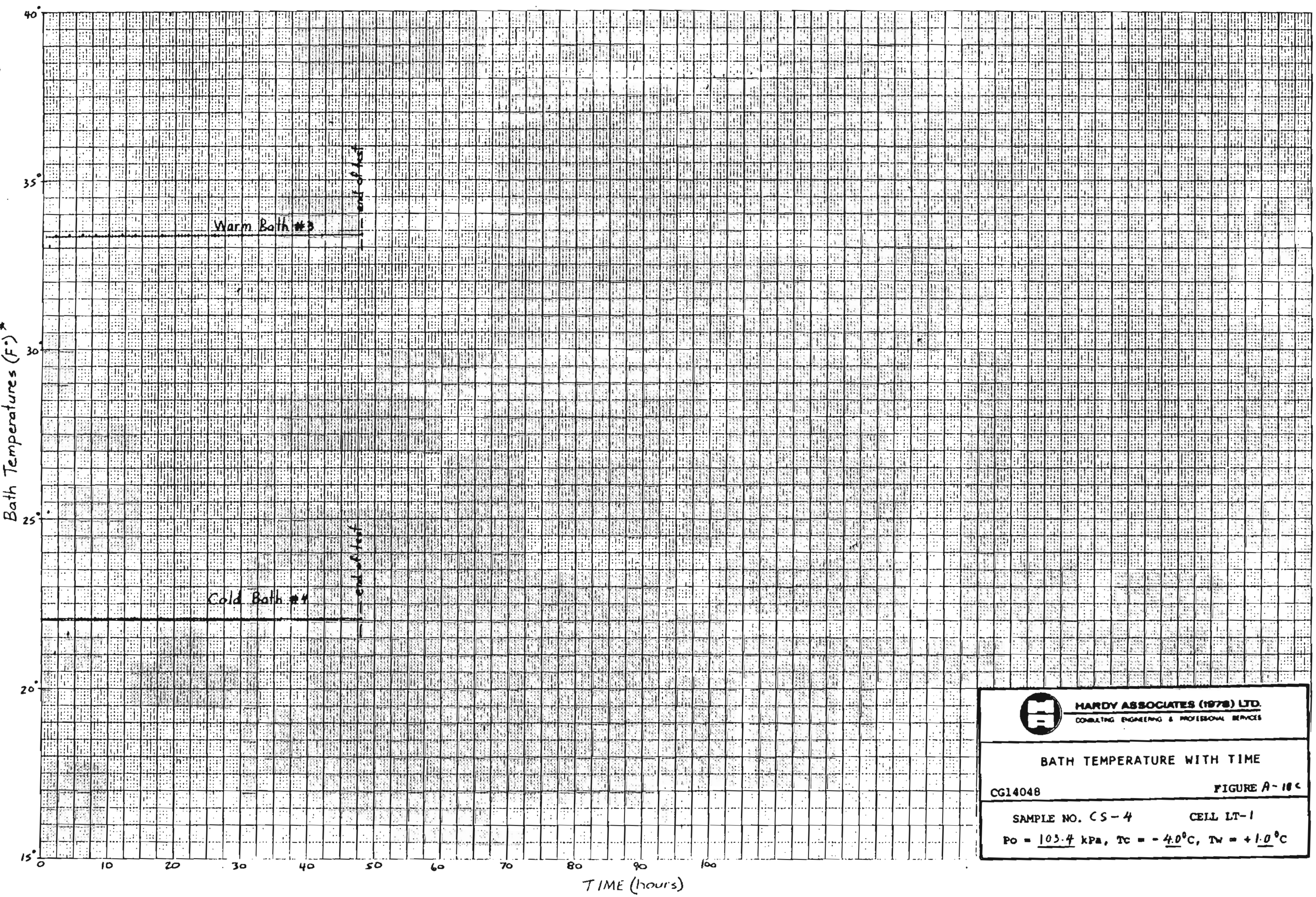

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-16b

SAMPLE NO. CS-4 CELL LT-1

Po = 103.4 kPa, Tc = -4.0°C, Tw = +1.0°C

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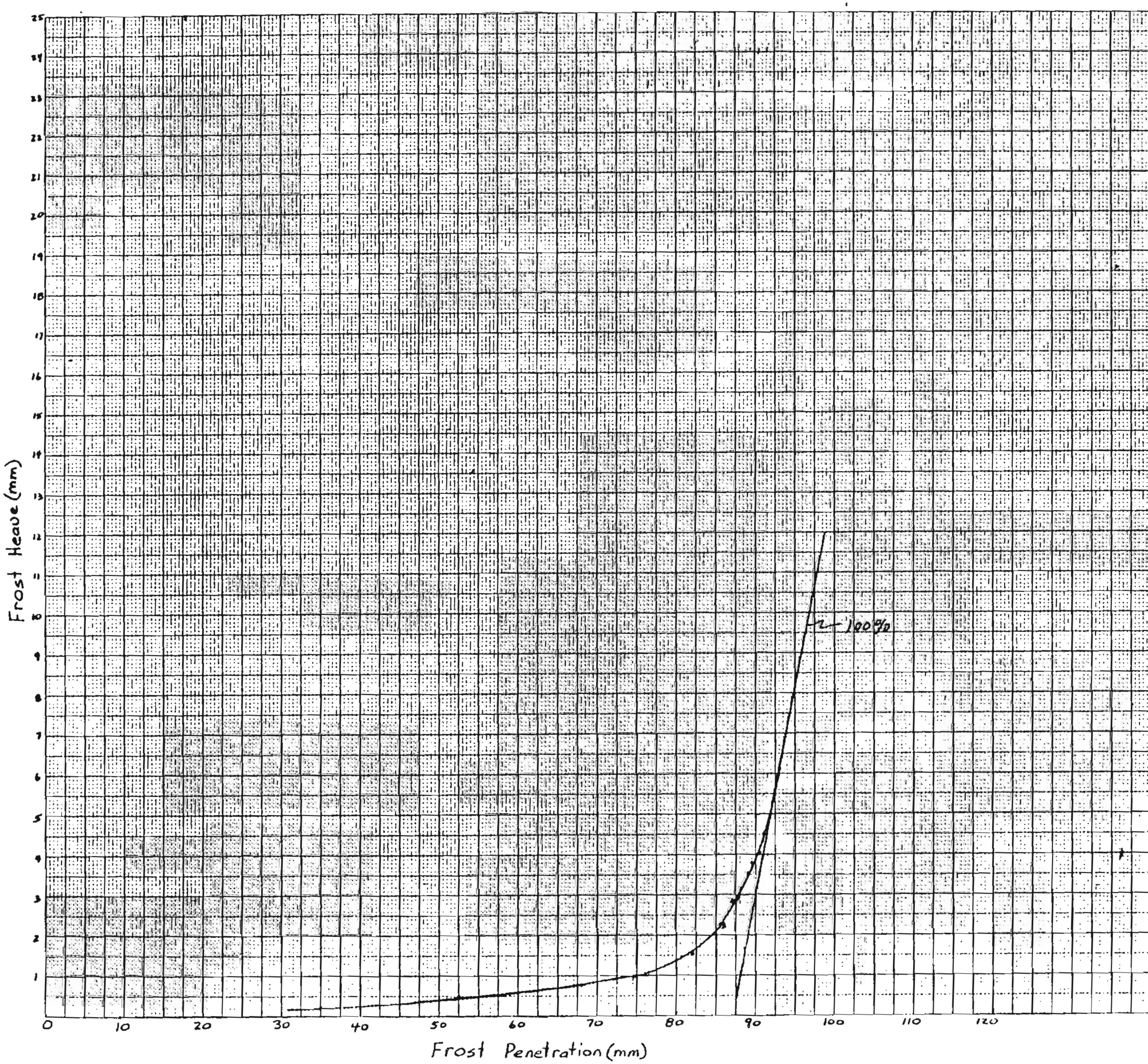
BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-10c

SAMPLE NO. CS-4 CELL LT-1

Po = 103.4 kPa, Tc = -4.0°C, Tw = +1.0°C

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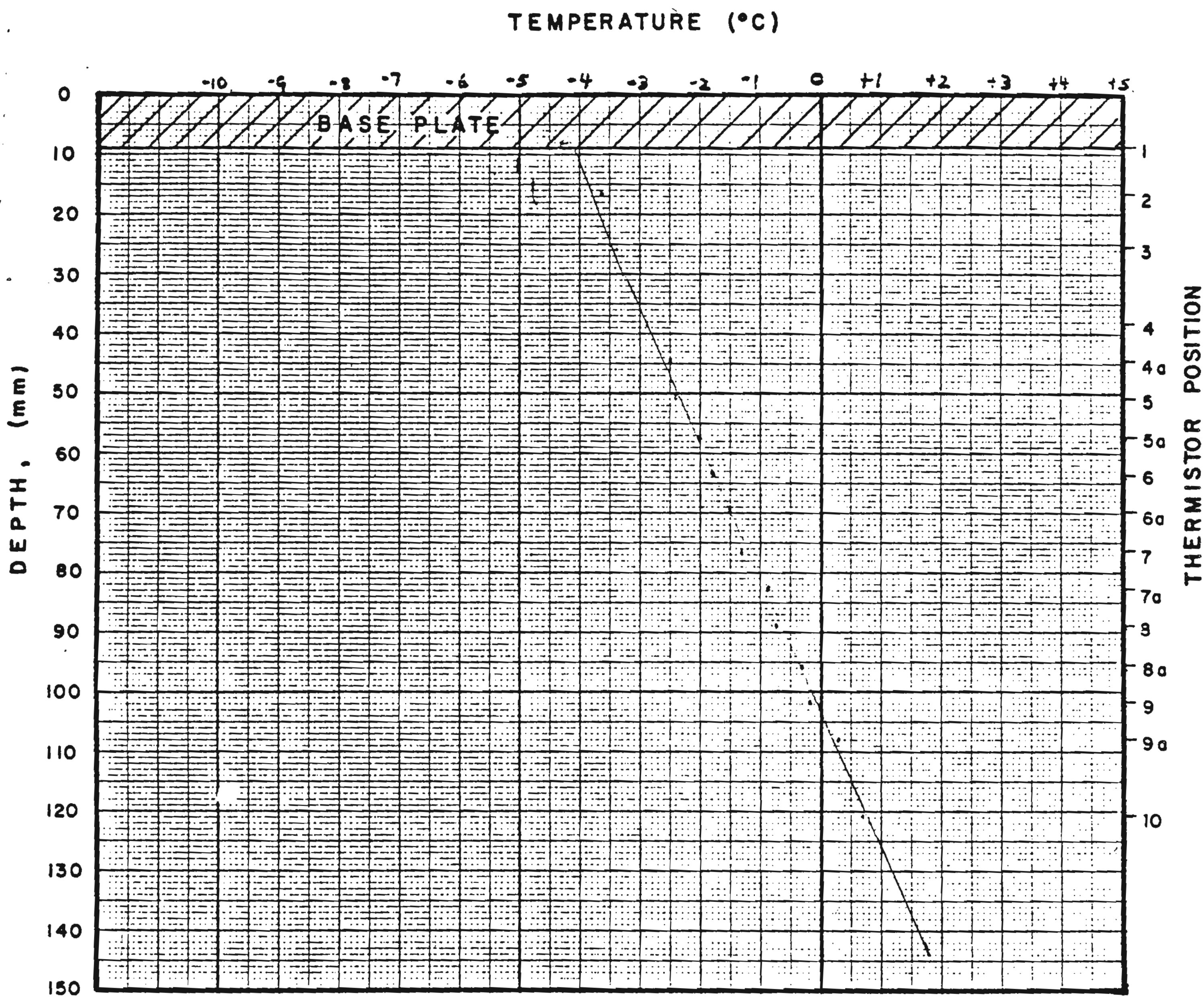
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-120

SAMPLE NO. CS-4 CELL LT-1

Po = 103.4 kPa, Tc = -4.0°C, Tw = +1.0°C

# TEMPERATURE PROFILE




TEST CS-4

CELL LT-1

THICKNESS OF BASE PLATE = 11 mm

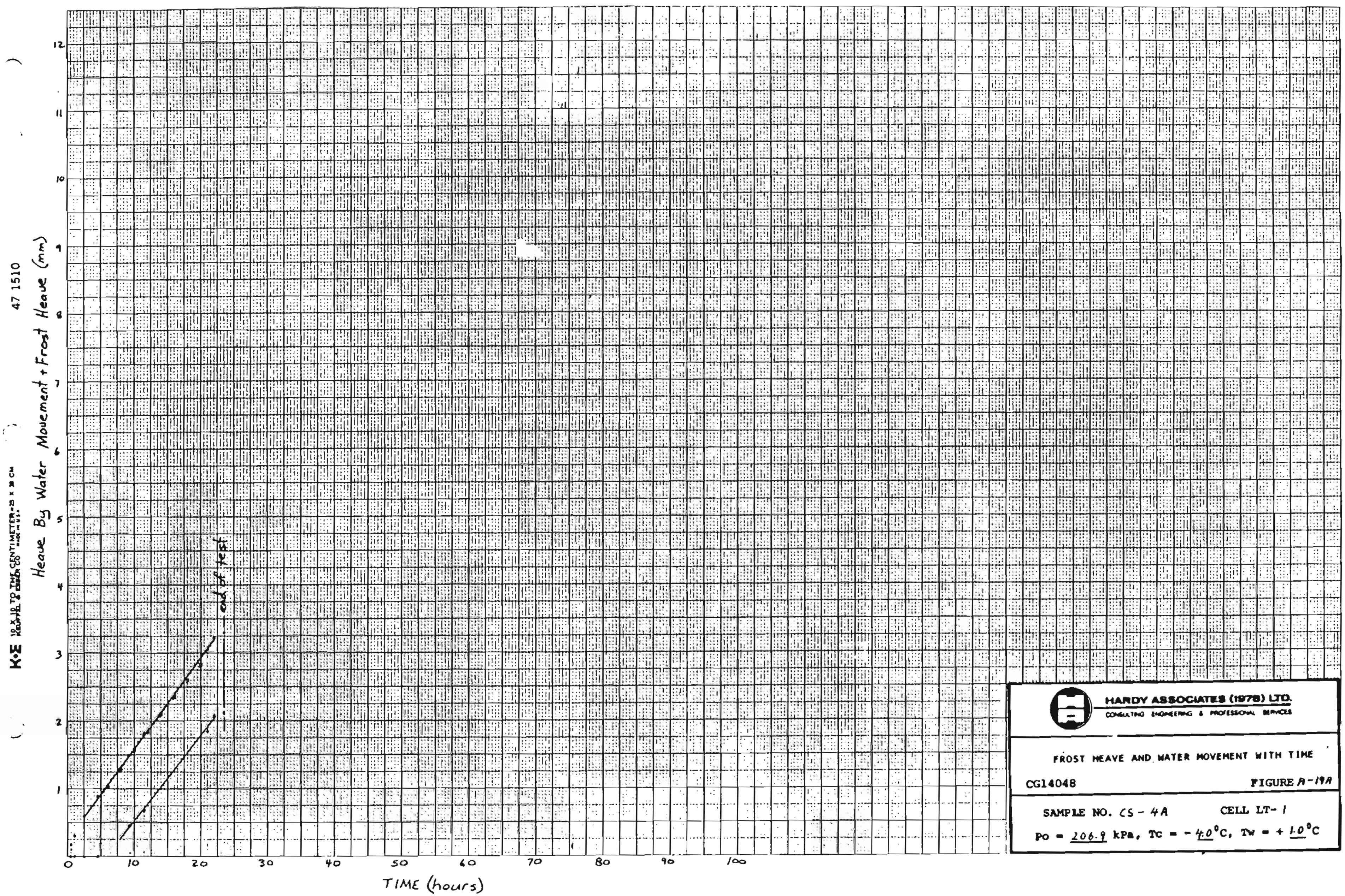
NOTE : Thermistor No. 10a in bottom plate

DATE OCT. 27, 1983

SOIL REMOULDED

Δt 48.0 HRS

FIGURE A-18E



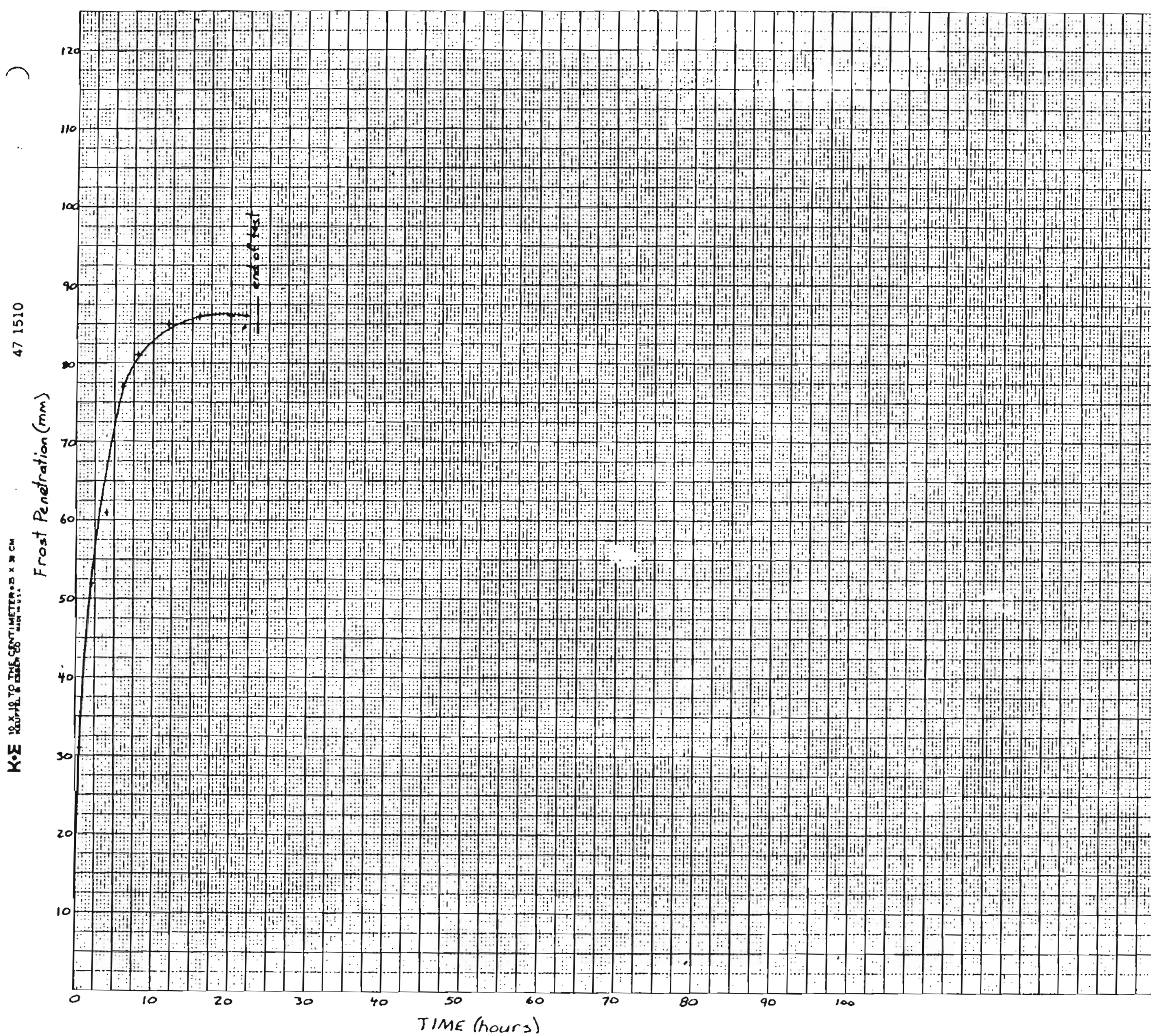

**HARDY ASSOCIATES (1978) LTD.**
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048 FIGURE A-19A

SAMPLE NO. CS - 4A CELL LT-1

Po = 206.9 kPa, Tc = -4.0°C, Tw = +1.0°C



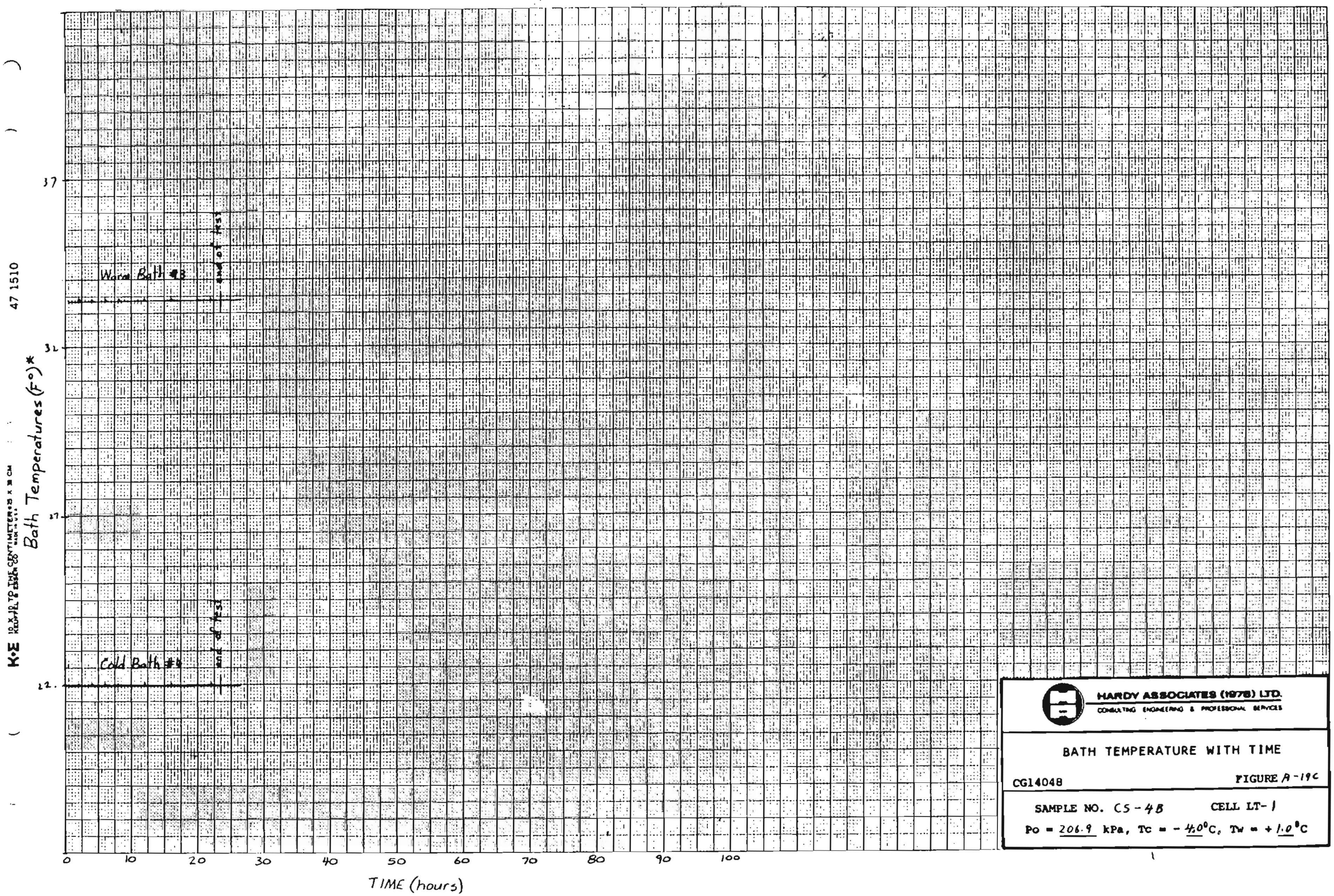

HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048 FIGURE A-198

SAMPLE NO. CS-48 CELL LT-1

Po = 206.9 kPa, Tc = -4.0°C, Tw = +1.0°C

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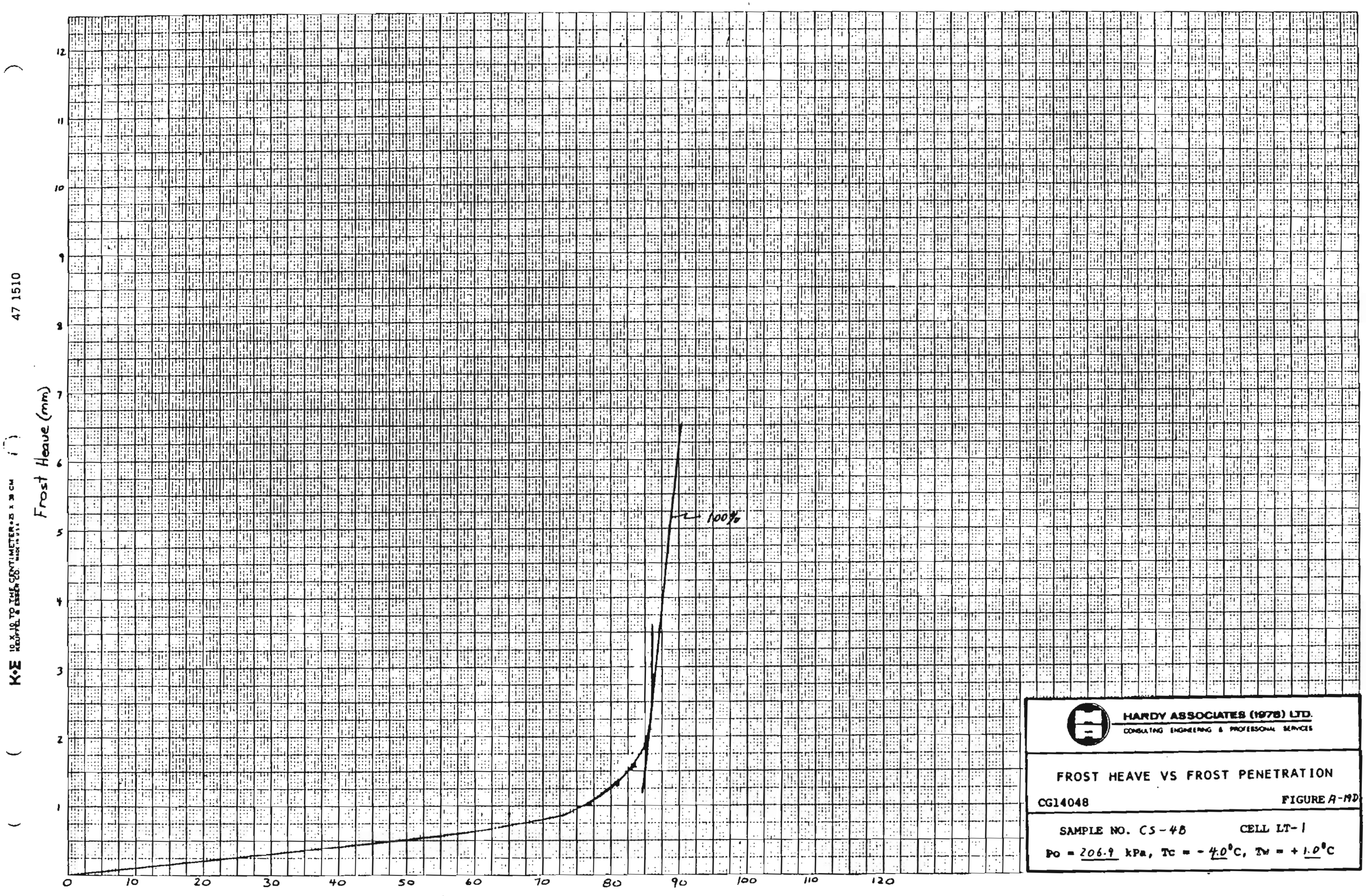
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

BATH TEMPERATURE WITH TIME

CG14048 FIGURE A-19C

SAMPLE NO. CS-4B CELL LT-1

Po = 206.9 kPa, Tc = -4.0°C, Tw = +1.0°C

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CONSULTING ENGINEERING & PROFESSIONAL SERVICES

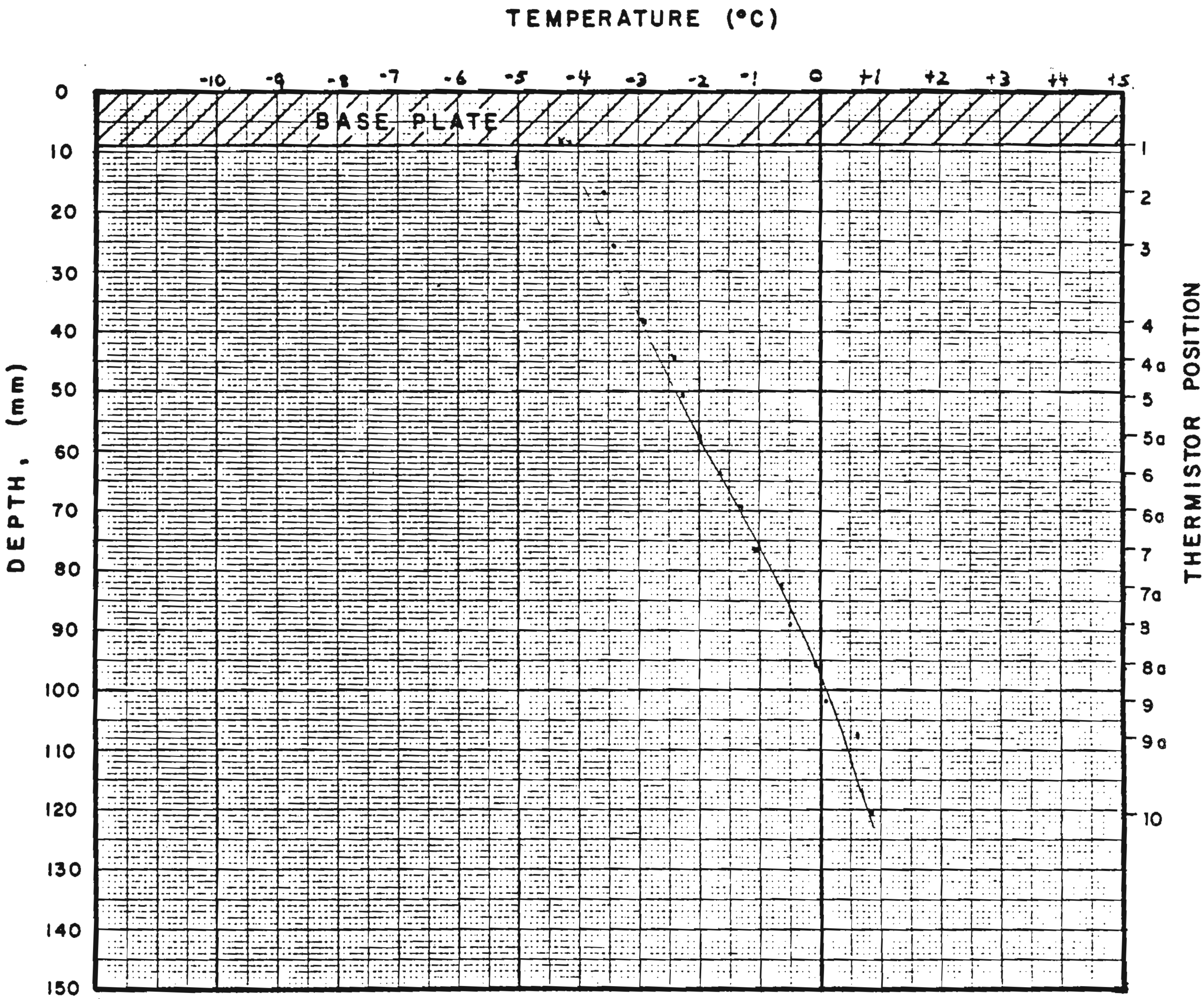
FROST HEAVE VS FROST PENETRATION

CG14048 FIGURE A-19D

SAMPLE NO. CS-4B CELL LT-1

Po = 206.9 kPa, Tc = -4.0°C, Tw = +1.0°C

# TEMPERATURE PROFILE




THICKNESS OF BASE PLATE = 11 mm

NOTE : Thermistor No. 10a in bottom plate

TEST CS-4B

CELL LT-1

DATE NOV. 2, 1983

SOIL REMOULDED

Δt 22.0 HRS

FIGURE A-19E