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ADDITIONAL FROST HEAVE TESTING ON CAEN SILT

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

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## Abstract

Preliminary measurements of segregation potential were made on two samples of Caen silt similar to that used in experiments at the pipeline test facility in Caen. The measurements conducted under conditions of varying pressure and thermal gradient show a lower frost susceptibility than similar studies of the Calgary silt although the data shows considerably more scatter.

## Résumé

Des mesures préliminaires du potentiel de ségrégation (PS) sont présentées pour deux échantillons de limon de Caen provenant de l'essai de gel autour d'un gazoduc refroidi et enterrée à la station expérimentale à Caen. Ces mesures ont été effectuées pour différentes charges appliquées et sous différents gradients thermiques. Les résultats indiquent que, pour des conditions d'essai semblables, le limon de Caen est moins susceptible au gel que le limon de Calgary. De plus les valeurs PS pour le limon de Caen sont plus dispersées.





# HARDY ASSOCIATES (1978) LTD.

CONSULTING ENGINEERING & PROFESSIONAL SERVICES

Our Project No.

Your Reference No.

CG-14048

January 4, 1984

Dr. A. Judge  
Dept. of Energy Mines & Resources  
Earth Physics Branch  
OTTAWA, Ontario  
K1A 0E4

Dear Alan:

Re: Additional Frost Heave Testing  
on Caen Silt

On November 14, 1983, we submitted our report on a series of frost heave tests on Calgary silty clay, using the recently-developed segregation potential method of testing. Subsequently, you requested an additional series of tests on Caen silt from the joint Canada-France pipeline test facility. This letter provides the results and frost heave predictions based on this test series.

## 1. TEST PROCEDURES

These tests were carried out in the same general test environment as the Calgary silty clay tests described in our November 14 report, with the following differences.

A total of two samples were tested. The first was prepared in the cell by placing a saturated slurry, overconsolidating the sample to a pressure of 200 kPa, and rebounding to the desired initial test pressure of 30 kPa. The first freezing cycle was carried out using an initial cold side temperature of  $-5^{\circ}\text{C}$ , and a warm side temperature of  $+1^{\circ}\text{C}$ . These conditions were requested by Mr. S. Dallimore of Carleton University in a letter dated October 19, 1983, following discussions with yourself. The thermal gradients in these tests were considerably higher than those experienced at the test facility, but it is understood



that they were required for comparison with prior frost susceptibility testing. A subsequent test at the same pressure was carried out using a cold side temperature of  $-1.0^{\circ}\text{C}$ , which resulted in much lower thermal gradients on the sample. The pressure was then increased in steps to 100 kPa and 200 kPa with freezing tests being carried out at each pressure.

A second sample was mixed at a water content of 17.5% by dry weight, and then compacted in the cell using Standard Proctor Compactive effort. The sample was then placed under an initial stress of 20 kPa, and frozen at the lower cold side temperature of  $-5^{\circ}\text{C}$ . A repeat test at  $-1^{\circ}\text{C}$  was subsequently carried out. The pressure was increased in steps to 75 kPa and 200 kPa, to generate the necessary relationship between the segregation potential, SP, and pressure. In order to confirm the shape of this relationship, the sample was rebounded following thawing to the initial test pressure of 20 kPa, and the test at  $-1^{\circ}\text{C}/+0.5^{\circ}\text{C}$  was repeated. The results confirmed the results of the initial test.

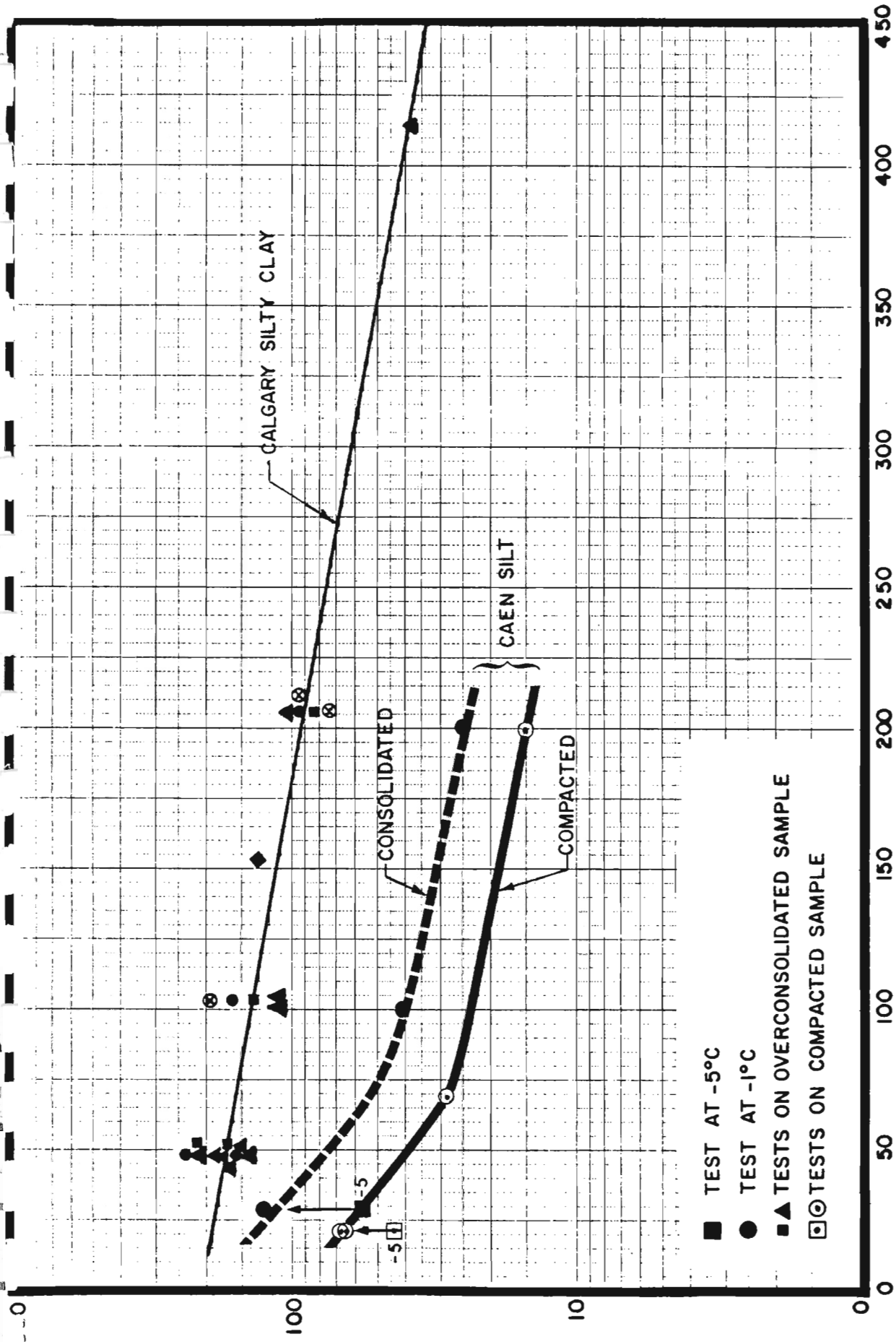
## 2. TEST RESULTS

Plots of frost heave, the heave due to water attraction, frost advance and temperature gradient are given in Appendix "A", for each of the seven freezing cycles.

Table 1 shows a summary of the relevant data for the nine tests carried out on the two samples. The dependence of the frost heave parameter, SP, on applied pressure is shown on Figure 1. The data are shown for comparison with the previous data base for Calgary silty clay. The major findings of the testing are as follows:

- a) The tests at the colder temperature ( $-5^{\circ}\text{C}$ ) provide a significantly lower SP frost heave parameter than the tests at  $-1^{\circ}\text{C}$ . Although the total frost heave was higher,

SEGREGATION POTENTIAL SP ( $\text{mm}^2/\text{sec} \cdot \text{C} \times 10^{-5}$ )



OVERBURDEN PRESSURE (kPa)



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# SEGREGATION POTENTIAL FROST HEAVE TESTS ON CAEN SILT

CG14048

FIGURE 1



TABLE 1

SUMMARY OF FROST HEAVE TEST RESULTS FOR CAEN SILT  
(Remoulded)

Test	Total Duration (hour)	Water Content (%)		Dry Density (kg/m <sup>3</sup> )	Cold Side (°C)	Warm Side (°C)	Initial Heave Rate (mm/day)		Final Frost Depth (mm)	Final Heave (mm)	Pressure (kPa)	v (mm/sec) × 10 <sup>-5</sup>	Grad T (°C/mm)	SP (mm <sup>2</sup> /Cs) × 10 <sup>-5</sup>	dT/dt (°C/hr)
		Initial (%)	Final (%)				Initial (mm/day)	Final (mm/day)							
FR-1A	43.0	15.4*	17.8	1803	-5.0	+1.5	10.92	86.0	9.0	29.6	3.47	0.0612	57.0	0.010	
FR-1B	49.5				-1.0	+0.5	3.57	69.0	5.6	29.6	1.80	0.0143	126.0	0.0028	
FR-1C	62.7				-1.0	+0.5	1.02	71.5	2.17	100.0	0.568	0.0140	41.0	0.00083	
FR-1D	47.5	17.8	17.8	1803	-1.0	+0.5	0.29	72.0	0.68	200.1	0.352	0.0141	25.0	0.0022	
FR-2A	25	17.5**	17.8	1835	-5.9	+1.0	4.56	102.0	3.5	20.7	2.10	0.0634	33.1	0.010	
FR-2B	52.5				-0.96	+0.1	2.10	74.0	3.85	20.7	0.978	0.0127	77.0	0.0023	
FR-2C	80.5				-1.05	+0.5	0.96	80.0	2.05	69.0	0.372	0.0131	28.3	0.0006	
FR-2D	72				-1.08	+0.5	0.18	84.0	0.5	200.1	0.194	0.0127	15.2	0.0007	
FR-2E	70	19.4	17.8	1728	-1.08	+0.5	2.76	87.0	5.4	20.7	0.82	0.0122	66.8	0.0012	

\* Consolidated

\*\* Compacted



the apparent SP parameter was lower, due to the much larger rate of cooling ( $dT/dt$ ) involved with these tests.

- b) The compacted sample heaved less than the sample fabricated from a saturated, over-consolidated slurry.
- c) The dependence of SP on pressure appears to be distinctly non-linear when plotted on the semi-logarithmic scale on Figure 1. This may be characteristic of silts, and is different from the relationships between SP and pressure developed previously for silty clays and clays.
- d) The frost susceptibility of the Caen silt as evidenced by the SP parameter is lower than the Calgary silty clay tested previously. This is to be expected, in view of the coarser grained soil type (see Grain Size Curve at end of this letter report).

### 3. FROST HEAVE PREDICTIONS

A report on the summary of the frost heave tests results for the Caen pipeline test facility was provided by Dr. P.J. Williams of the Geotechnical Science Laboratories. (Final Report - "Investigation of Soil Freezing in Association with a Buried Chilled Pipeline in a Large Scale Test Facility - Phase 2", to Energy Mines and Resources, Earth Physics Branch.)

The 273 mm pipe was buried with a depth of cover of 300 mm in the locally obtained silt. For much of the test, the water table was maintained 0.3 m below the pipe. The insulated base of the soil test bed was about 1.4 m below pipe base.



The pipe temperature varied as shown on Figure 2 between 0°C and -1.9°C during the test, with an average of -1.53°C. Due to difficulties in controlling the initial temperature of the soil in the test bed, the initial soil temperature was not constant, but rather varied between +2 and about +8°C as shown on Figure 3.3 of the above-referenced report (see Figure 3).

Without carrying out a detailed 2-D geothermal finite difference prediction that would model the variable initial ground temperatures, time-varying pipe temperatures and the presence of the insulated base of the test soil, it is necessary to make some simplifying assumptions, as follows:

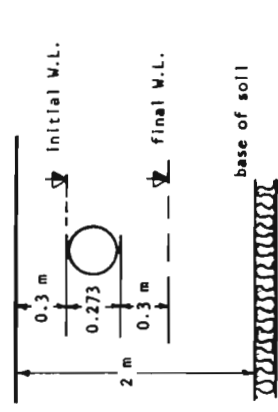
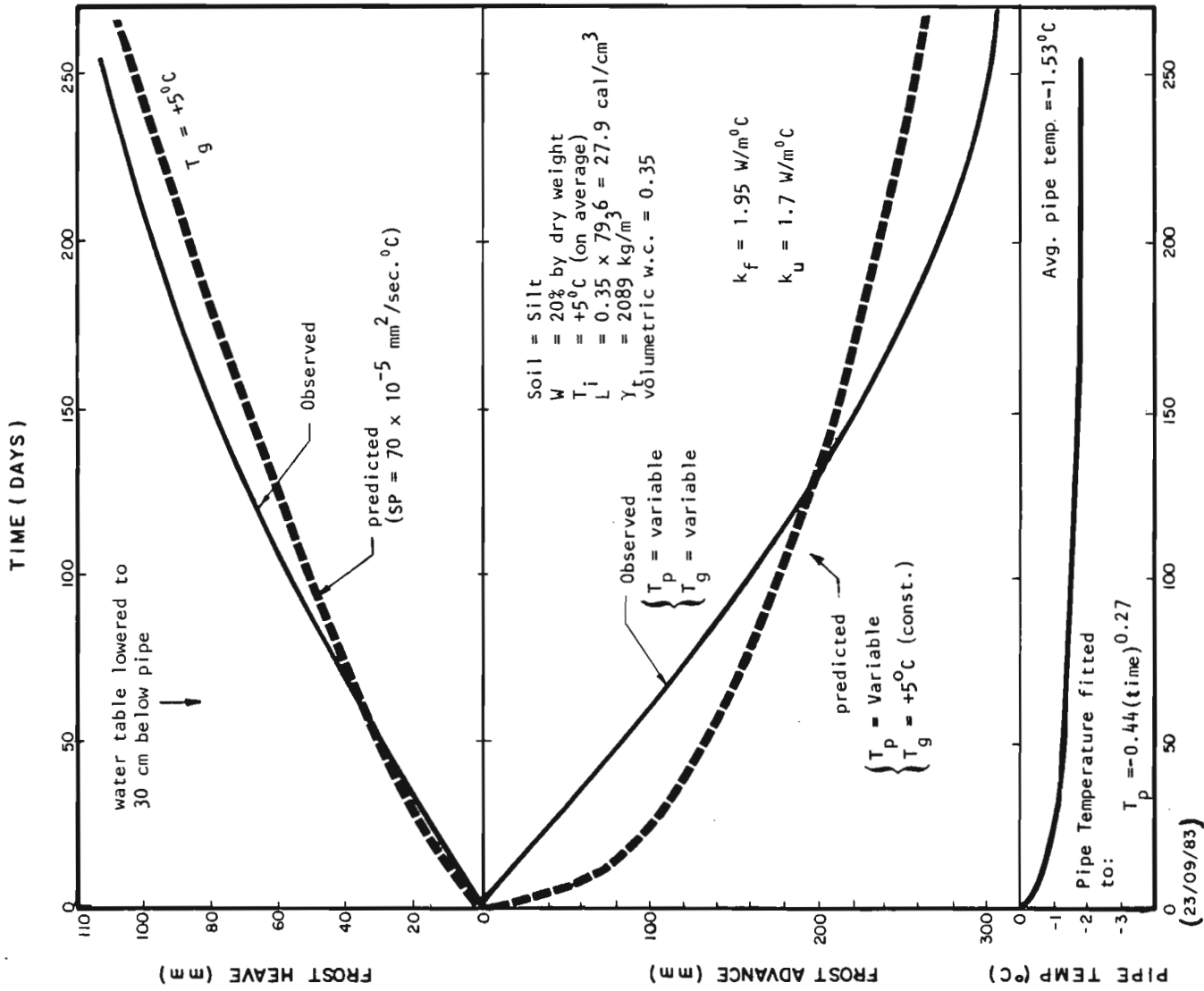
- i) The pipe temperature was fitted to the power law function,

$$T_p = 0.44 (\text{time})^{0.27}$$

- ii) The initial ground temperature was assumed constant at +5°C, even though a significant positive thermal gradient existed at start-up, and
- iii) The presence of the insulating layer was ignored.

The simplified "quasi-static" method of geothermal analysis with the segregational potential frost heave method were used to predict frost advance and frost heave beneath the pipe. The predictions for heave and frost advance are shown on Figure 2, for comparison with observation. The frost advance prediction is not in good agreement with observation, due to the non-uniform ground and pipe temperatures maintained at the facility. However, the frost heave prediction after 250 days is 102 mm vs the 106 mm observed for the pipe. The agreement is therefore very encouraging, considering the very approximate nature of the thermal boundary conditions used in the test. The frost heave





**FROST HEAVE AND PENETRATION AT CAEN TEST FACILITY**  
 FIGURE 2

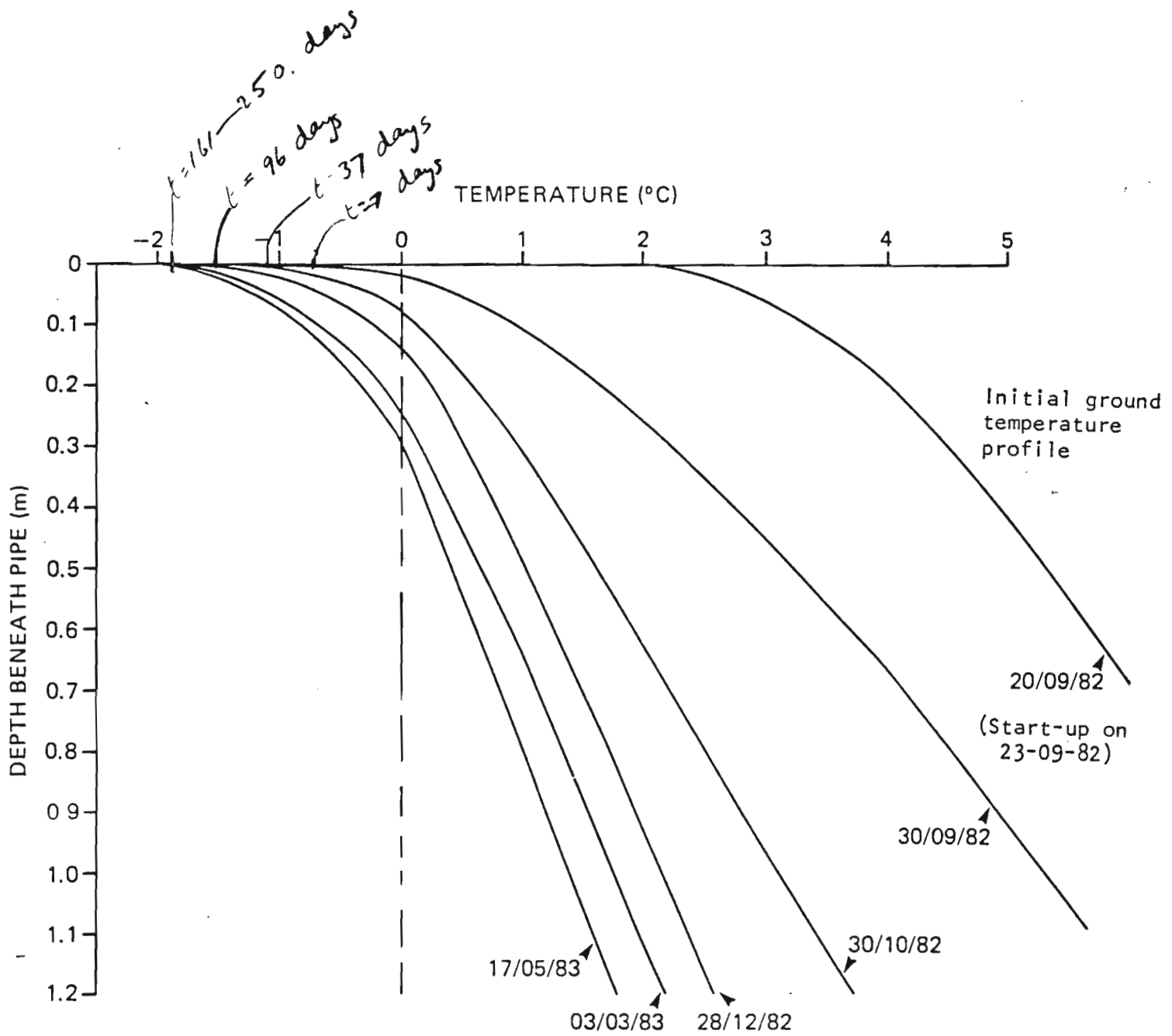


Figure 3 Generalized temperature profiles beneath centreline of pipe. Silt section BB. (Best fit profiles derived from thermistor and corrected thermocouple observations).



prediction was based on an SP parameter of  $70 \times 10^{-5} \text{ mm}^2/\text{sec}^\circ\text{C}$ , and this was considered appropriate for the compacted soil at an overburden pressure of about 20 kPa (see Figure 1). This pressure can be estimated for the soil beneath an unstressed pipe at the test facility. Information obtained from Dr. M. Smith of Carleton University indicated that the vertical soil stress may have fallen below 15 kPa at some pipe locations due to upward pipe motion later in the test. This is difficult to quantify at this time, and a constant soil pressure of 20 kPa was assumed.

The geothermal prediction used here should be refined using a more rigorous simulator such as the Hardy Associates (HAL) 2-Dimensional thermal model, in order to better predict the frost depth and heave obtained by the approximation outlined here.

Yours truly,

HARDY ASSOCIATES (1978) LTD.

Per: 

J.F. (Derick) Nixon, Ph.D., P.Eng.  
Associates

DN/mm  
11/62

cc: D. Cheung, HAL

Encl: Frost Heave Test Data

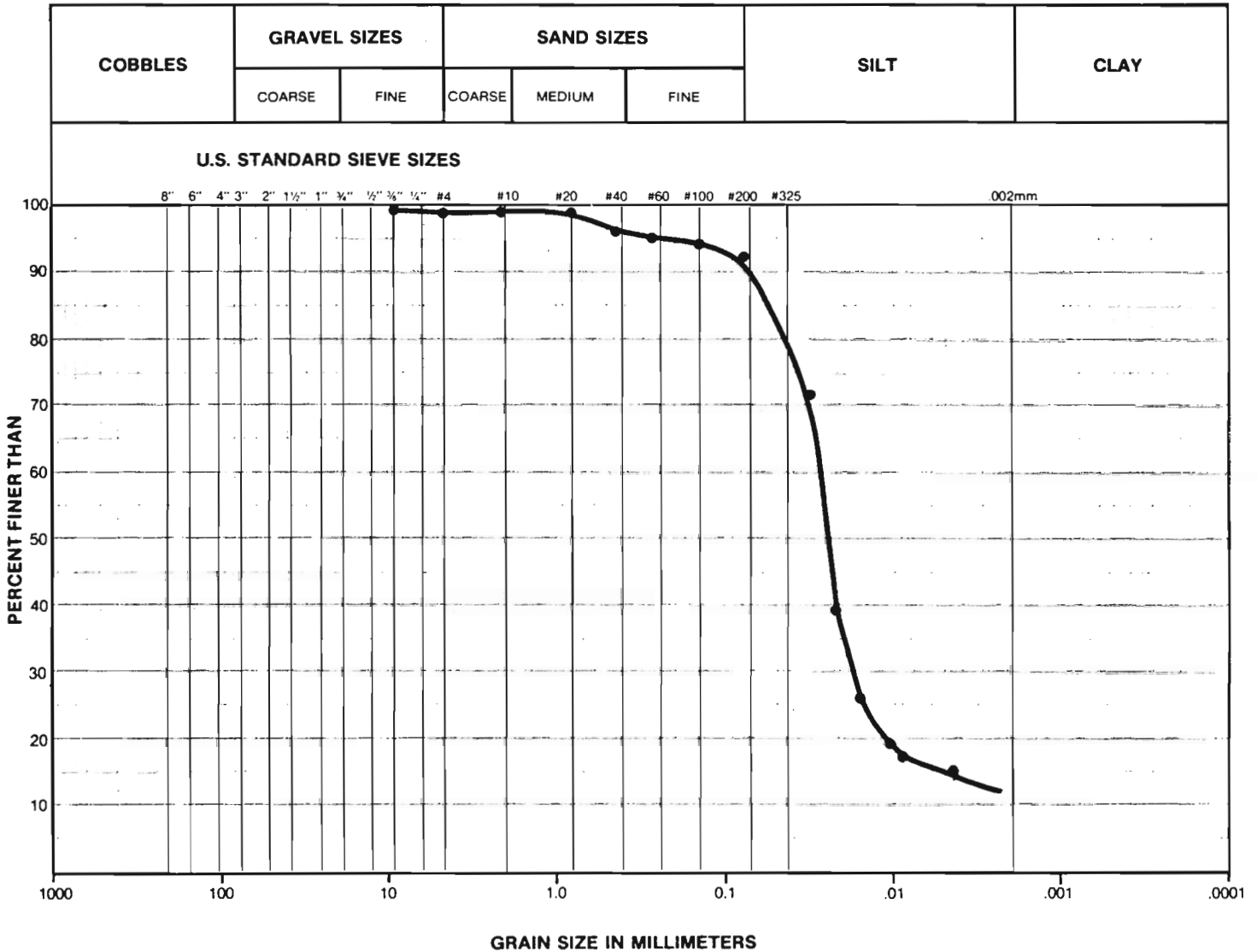




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**GRAIN SIZE CURVE**

CLIENT:	DSS/FMR
PROJECT NUMBER:	CG 14048
LAB. NUMBER:	
LOCATION:	
HOLE:	SAMPLE: Caen Silt
DEPTH:	
TECHNICIAN:	DATE:



REMARKS: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

NOTE: UNIFIED SOIL CLASSIFICATION SYSTEM

SUMMARY	
D <sub>10</sub> = _____ mm	GRAVEL _____ %
D <sub>30</sub> = _____ mm	SAND <u>10</u> %
D <sub>60</sub> = _____ mm	SILT <u>80</u> %
C <sub>U</sub> = _____ mm	CLAY <u>10</u> %
C <sub>C</sub> = _____ mm	

NOTICE: Hardy Associates (1978) Ltd. has not interpreted or analysed the test results reported above. Use of these results is therefore subject to the following terms and conditions:  
 (1) Any oral presentation made or opinion given by Hardy Associates (1978) Ltd. or any of its officers, agents, servants or employees with respect to the interpretation of these test results is or was given without responsibility for the accuracy of any such presentations or opinions, regardless of whether such representations or opinions were negligently formed or given.  
 (2) The liability of Hardy Associates (1978) Ltd. for the use of these test results shall in any and all events be limited to the fees received by it for providing the said test results.



**APPENDIX "A"**  
**Frost Heave Test Data**

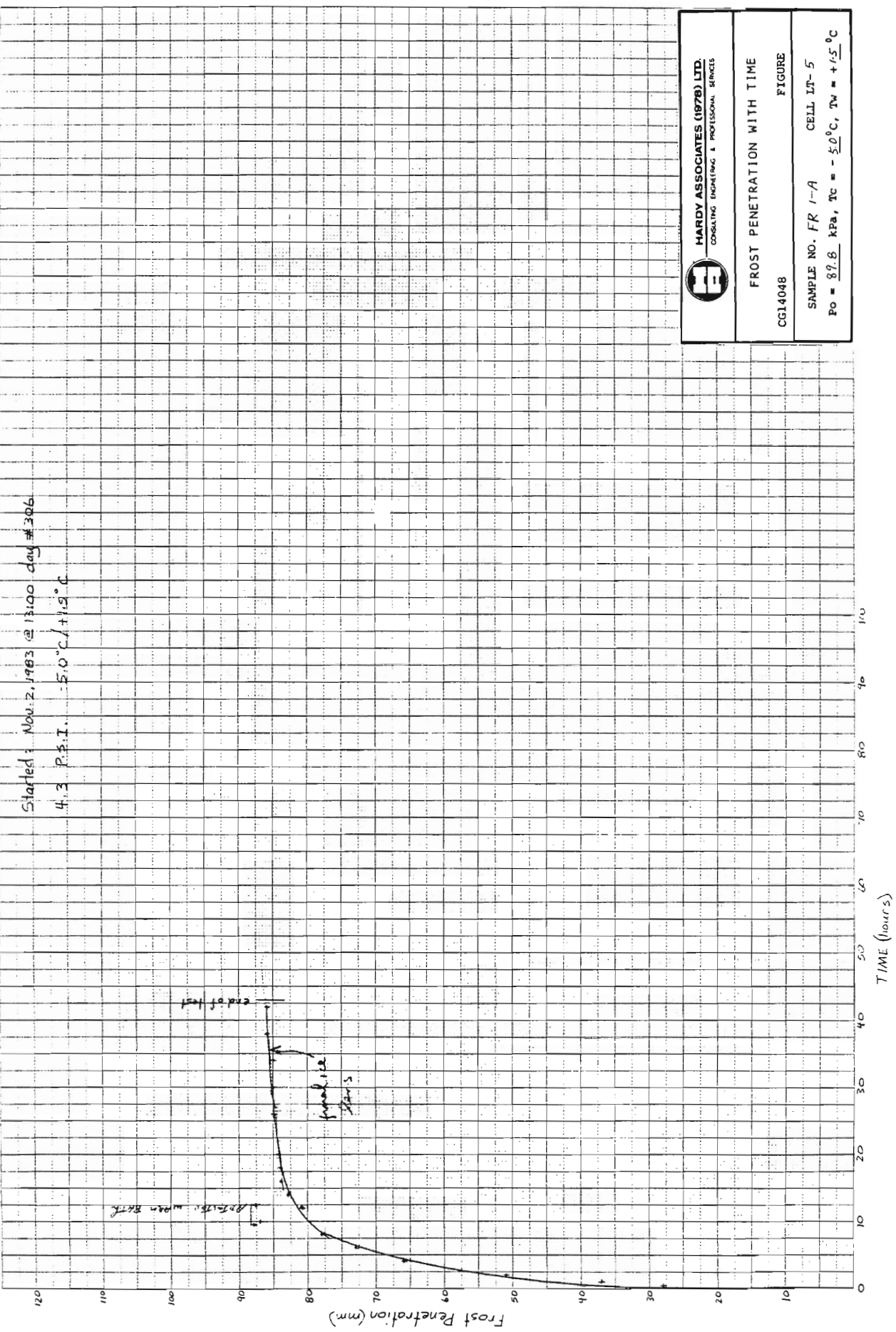
F.B. IA 47-5 Cown Sill Renovided  
 Started: Nov. 2, 1983 @ 13:00 day # 306  
 4.3 P.S.I. -5.0°C / +1.5°C

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**FROST PENETRATION WITH TIME**

CG14048

SAMPLE NO. FR 1-A CELL IT-5  
 $P_0 = 89.8 \text{ kPa}$ ,  $T_c = -5.0^\circ\text{C}$ ,  $T_w = +1.5^\circ\text{C}$



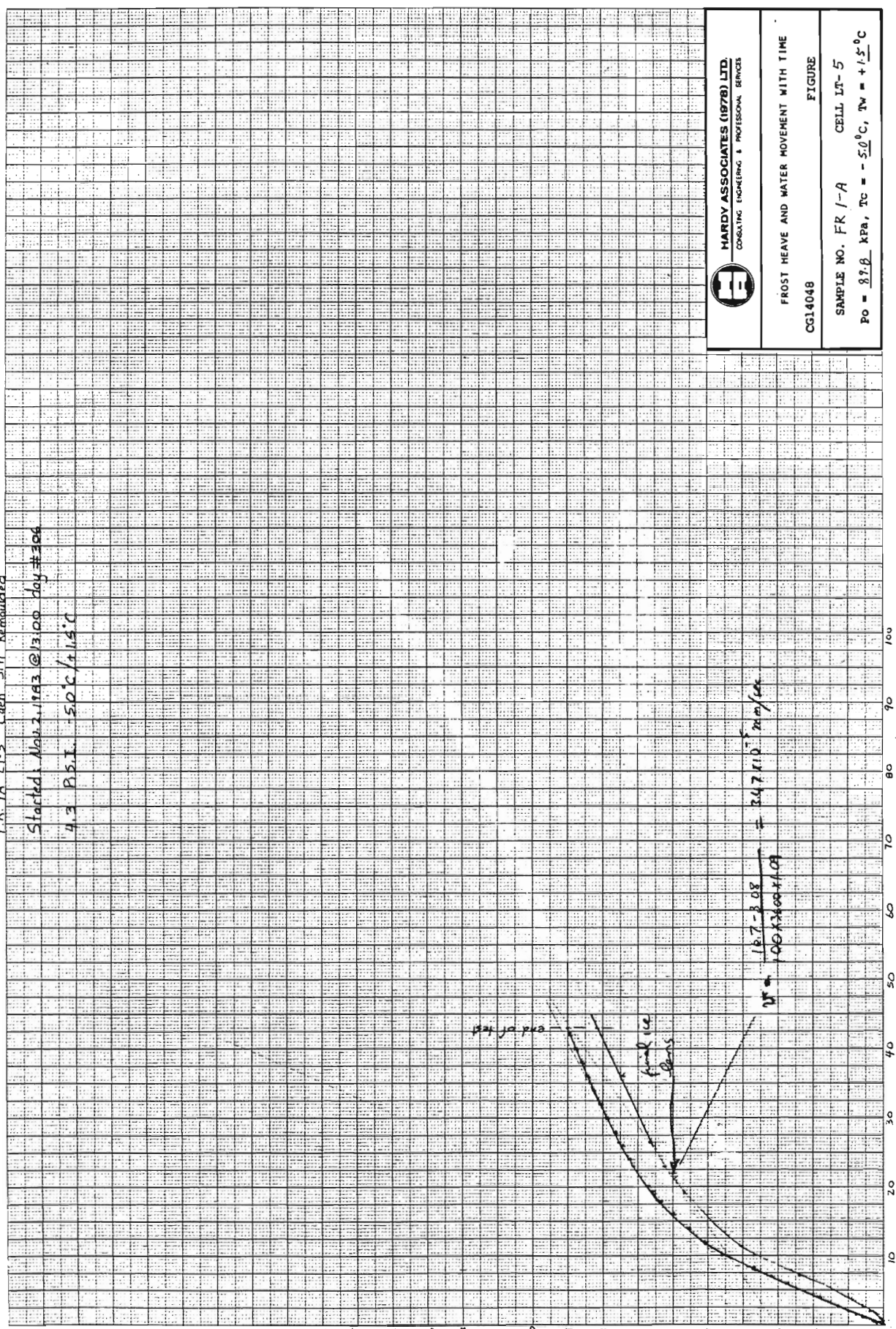
47 1510

K•M 10 X 10 TO THE CENTIMETER X X CM



FR 1A LITS Caen S.I.H Remoulded  
 Started Nov 21 1983 @ 13:00 Day #306  
 4.3 P.S.I. -5.0°C / +1.5°C

47 1510  
 Heave By Water Movement + Frost Heave (mm)  
 K-E 10 X 10 THERM CENTIMETER 2 X CM  
 KEOPPEL & ESKIN CO. MADE IN U.S.A.



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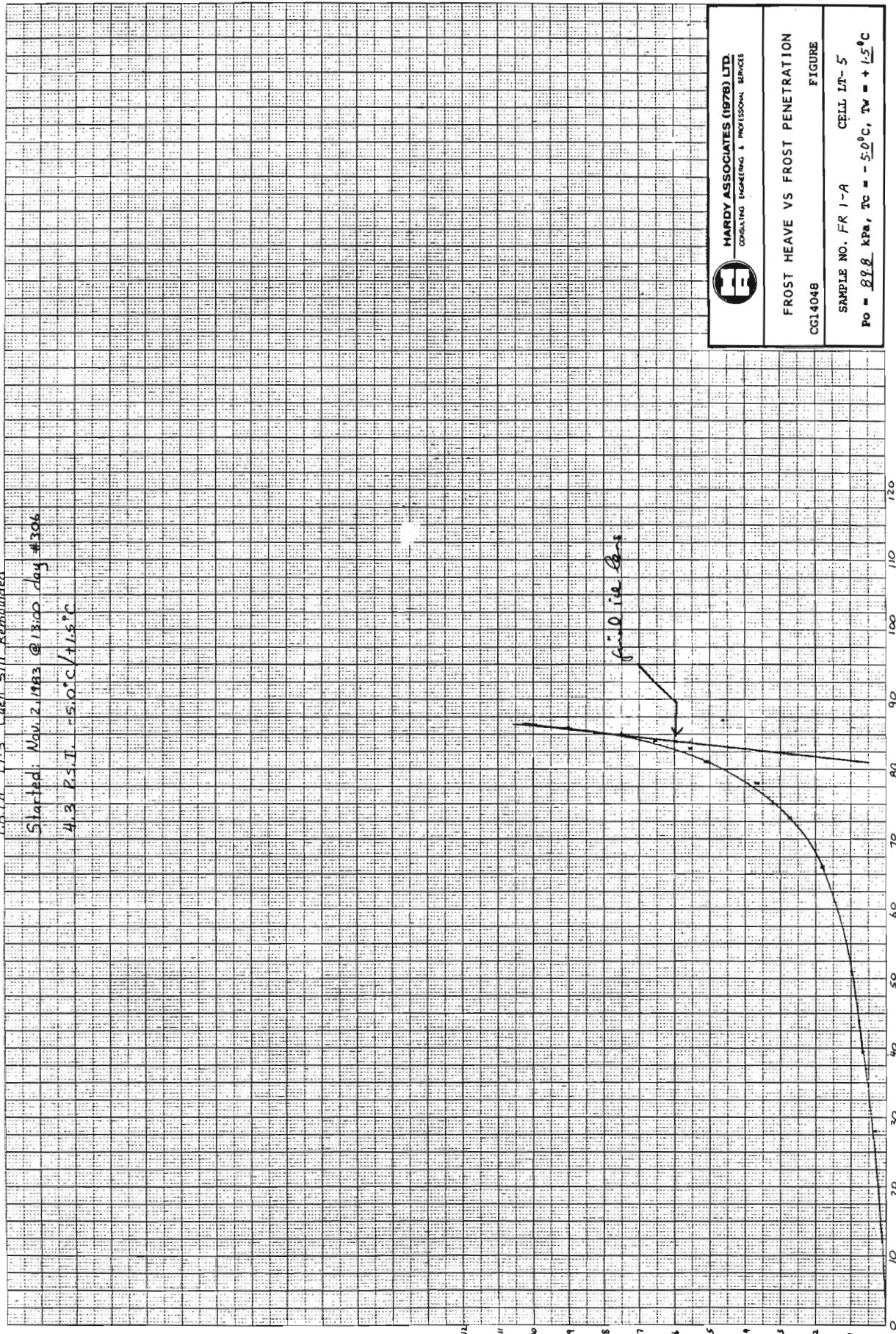
FIGURE  
 CG14048  
 FROST HEAVE AND WATER MOVEMENT WITH TIME

SAMPLE NO. FR 1-A CELL LT-5  
 Po = 87.8 kPa, Tc = -5.0°C, Tw = +1.5°C

ER 1A LT-5 Caen silt Remoulded

Started: Nov. 2, 1983 @ 13:00 day #306

4.3 PSI -5.0°C / +1.5°C



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FROST HEAVE VS FROST PENETRATION  
CG1404B

FIGURE

SAMPLE NO. FR 1-A CELL IT-5

Po = 88.8 kPa, Tc = -5.0°C, Tv = +1.5°C



F.R. 1A I.T.S. Coen s/H Remoulded

Started: Nov. 7, 1983 @ 13:00 day # 306

4.3 P.S.T. - 5.0°C / 1.5°C

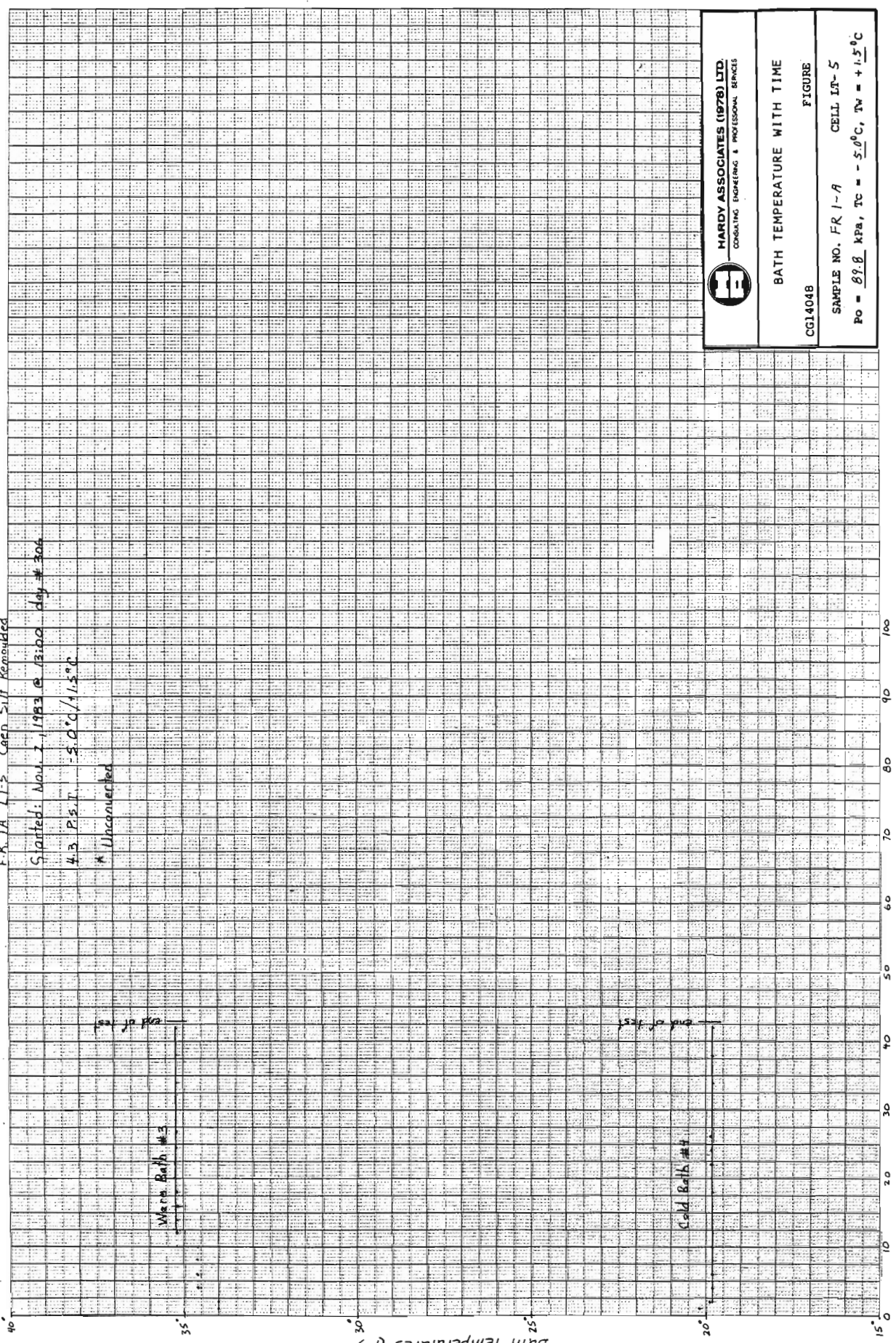
\* Unconverted

end of test

Warm Bath #3

end of test

Cold Bath #1



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BATH TEMPERATURE WITH TIME

FIGURE

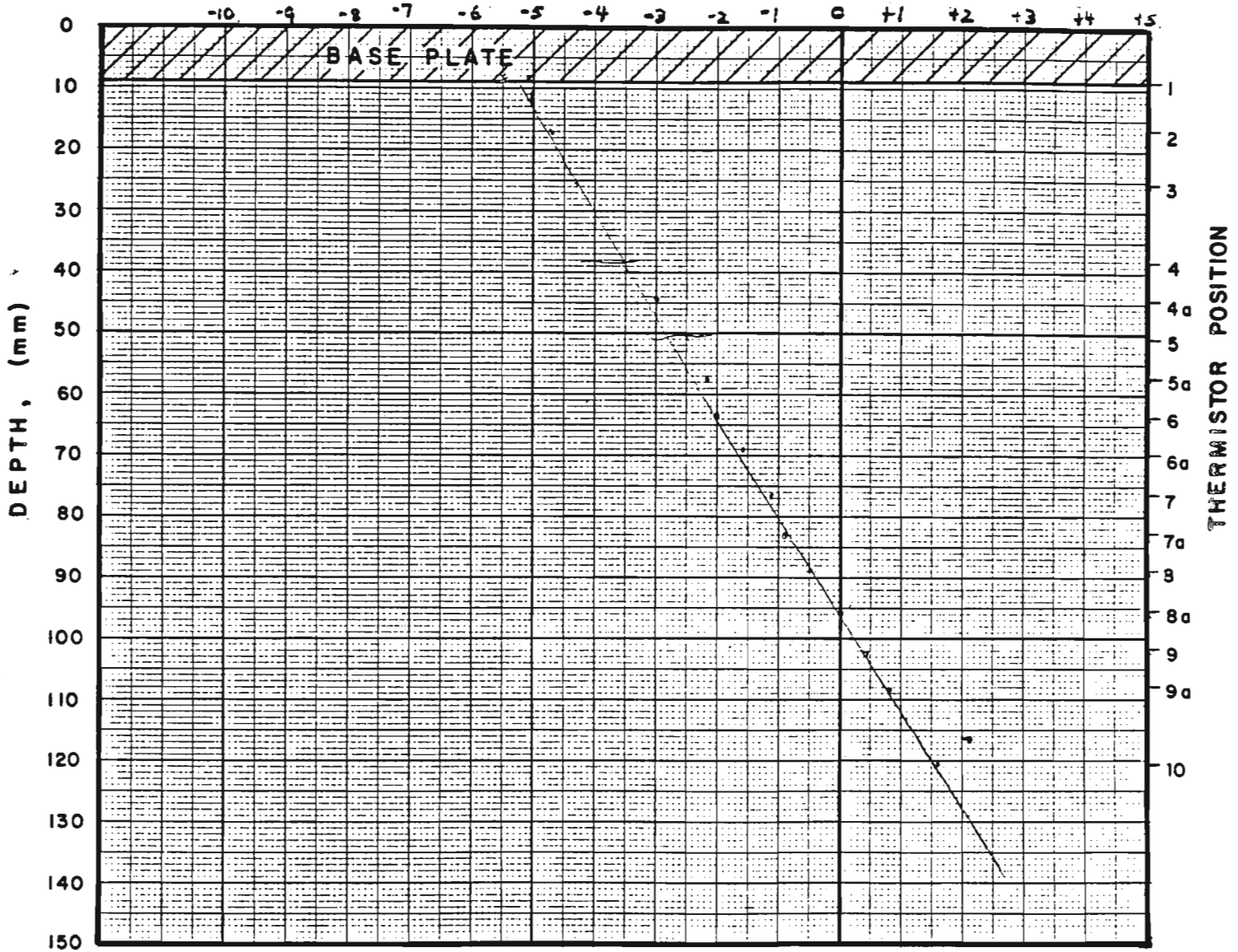
CG14048

SAMPLE NO. FR 1-A CELL ET-5

Po = 89.8 kPa, Tc = -5.0°C, Tw = +1.5°C

# TEMPERATURE PROFILE

TEMPERATURE (°C)

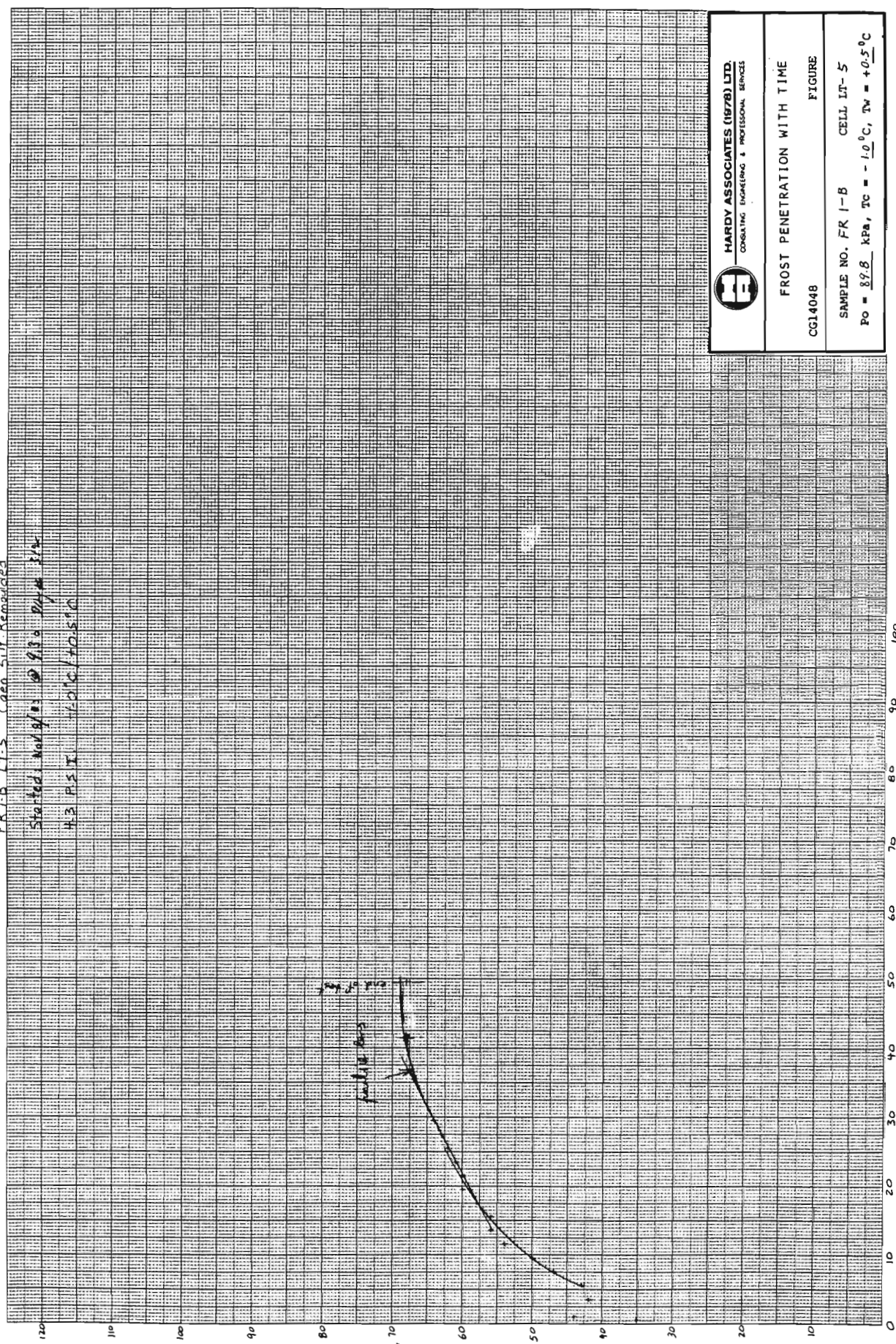


THICKNESS OF BASE PLATE = 10.0 mm

NOTE : Thermistor No 10a in bottom plate

TEST	<u>FR 1-A</u>
CELL	<u>LT-5</u>
DATE	<u>NOV. 4, 1983</u>
SOIL	<u>REMOULDED</u>
$\Delta t$	<u>42.0 HR.</u>

FR-1-B I.T.S. Coen silt Remoulded  
 Started working @ 9:30 PM 1/12  
 4.3 PSI 101C/10.5°C



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**FROST PENETRATION WITH TIME**

CGI4048      FIGURE

SAMPLE NO. FR 1-B      CELL LT-5  
 Po = 89.8 kPa, Tc = -1.0°C, Tw = +0.5°C



FR 1-B LT-5 Coen. Silt Remoulded

Started Nov 8/83 @ 9:30 AM. Day # 322

H3 P.S.T. -10°C / 10.5°C

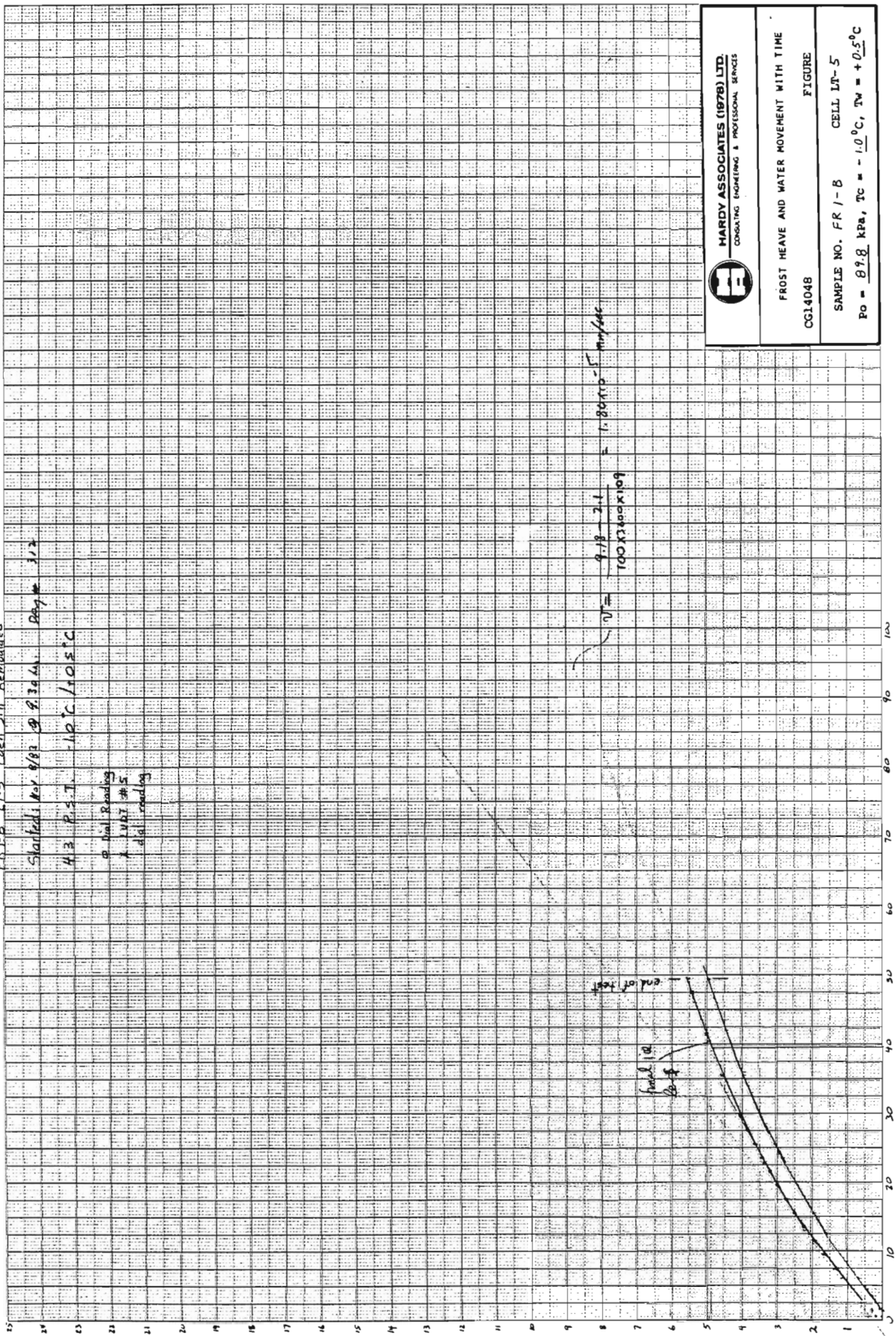
o Dial Reading  
x LVAT #5  
dial reading

47 1510

K-E 18 X 18 TO 1 CM. CENTIMETER X 30 CM

Heave By Water Movement + Frost Heave (mm)

TIME (hours)



HARDY ASSOCIATES (1978) LTD.  
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FIGURE  
CG14048  
FROST HEAVE AND WATER MOVEMENT WITH TIME

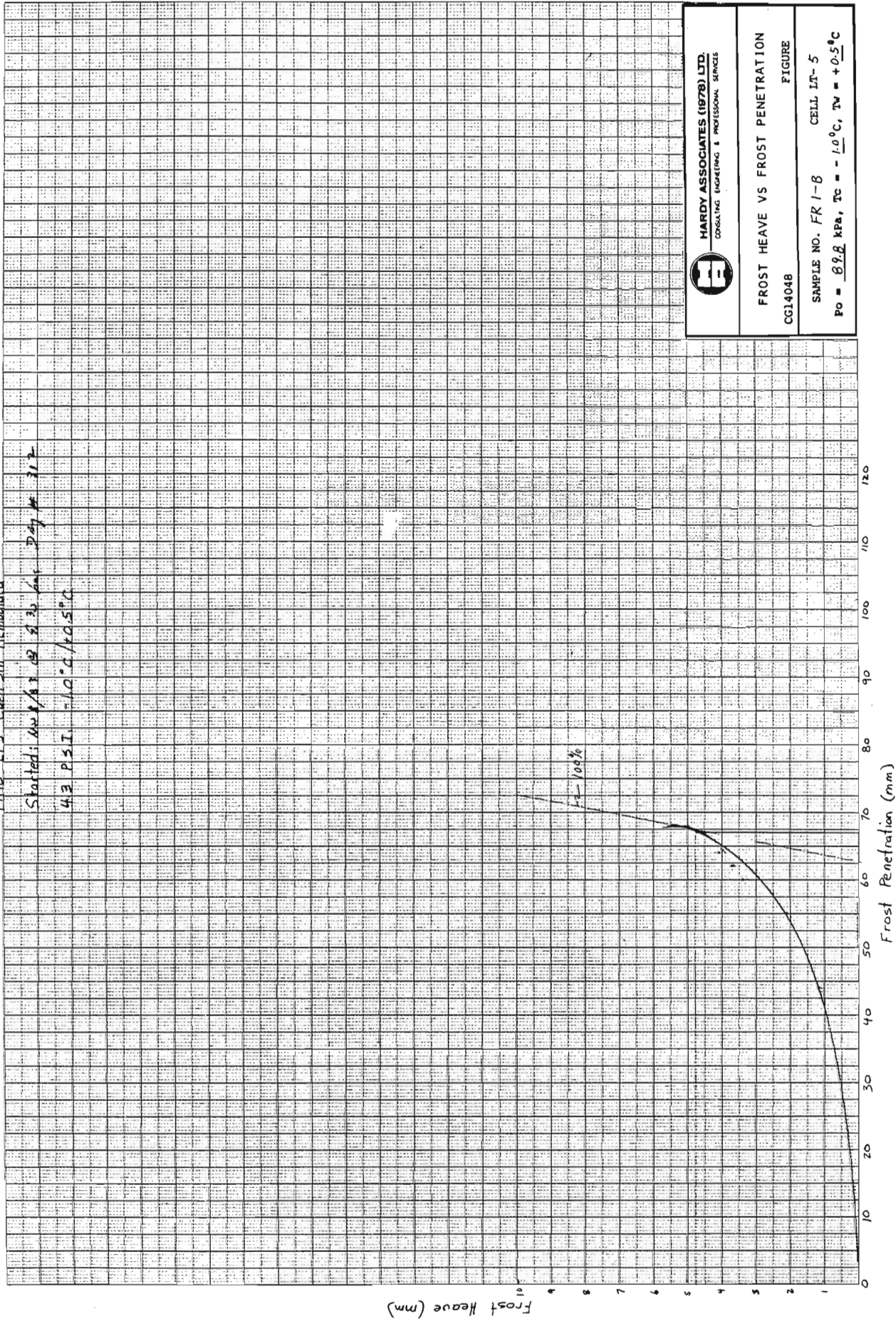
SAMPLE NO. FR 1-B CELL LT-5  
Po = 99.8 kPa, Tc = -1.0°C, Tw = +0.5°C

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**FROST HEAVE VS FROST PENETRATION**  
 FIGURE

SAMPLE NO. FR 1-β CELL LT-5  
 Po = 89.8 kPa, Tc = -1.0°C, Tv = +0.5°C

ER18 LT-5 Caen silt Remoulded  
 Started: Nov 8/83 19 51 25 hrs Day No 312  
 43 PSI, -10°C/40.5°C





FRIR LT-5 Case silt Remoulded

Started: M 4/8/62 @ 8:30 hrs Day # 312

4.3 P.S.T. - 10°C / +0.5°C

\* Unconverted

K&E RECORDING THERMOMETER • 2 X 3 CM  
47 1510

Warm Bath #3  
end of test

Cold Bath #4  
end of test

TIME (hours)



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BATH TEMPERATURE WITH TIME

CG1404B

FIGURE

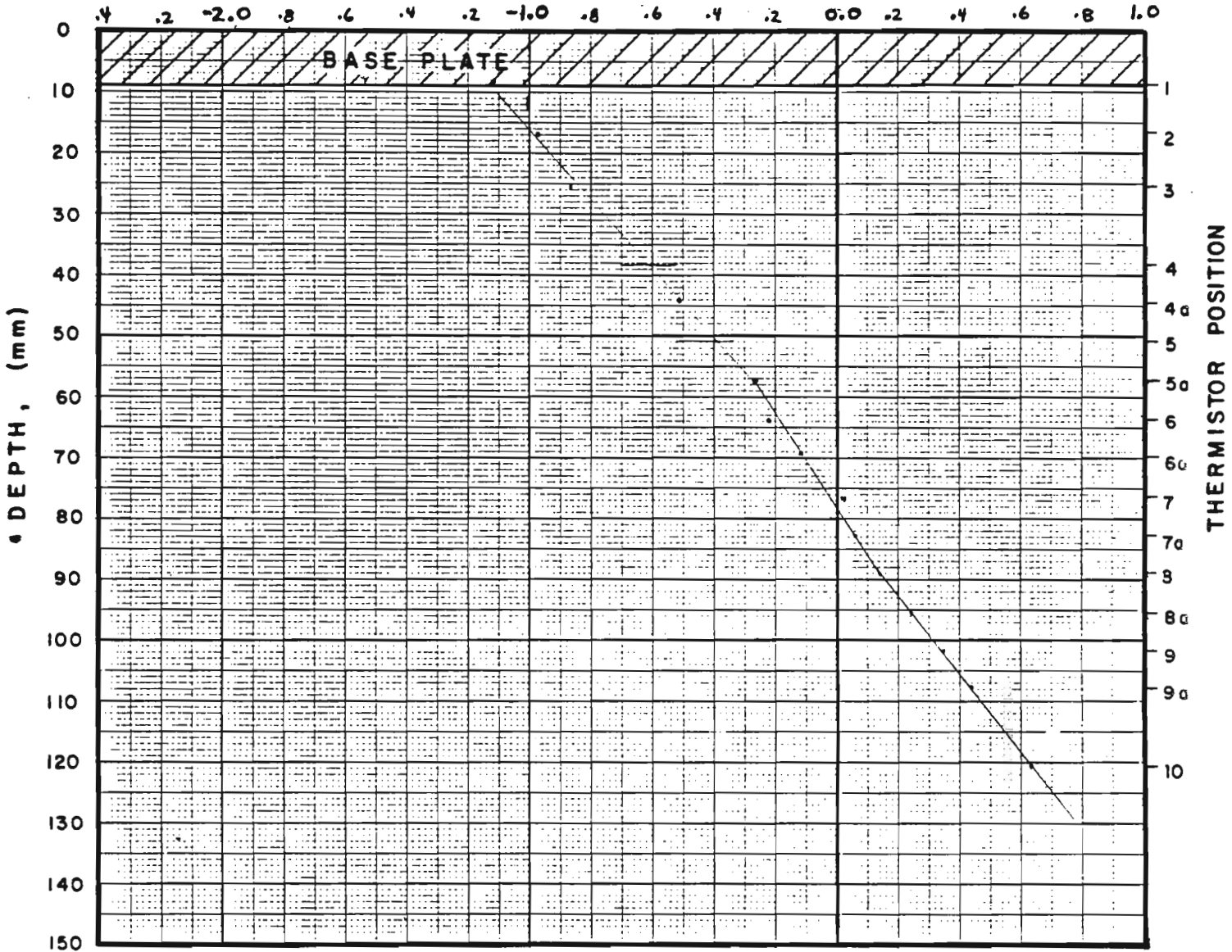
SAMPLE NO. FR 1-B CELL LT-5

Po = 89.8 kPa, Tc = -1.0°C, Tw = +0.5°C



# TEMPERATURE PROFILE

TEMPERATURE (°C)

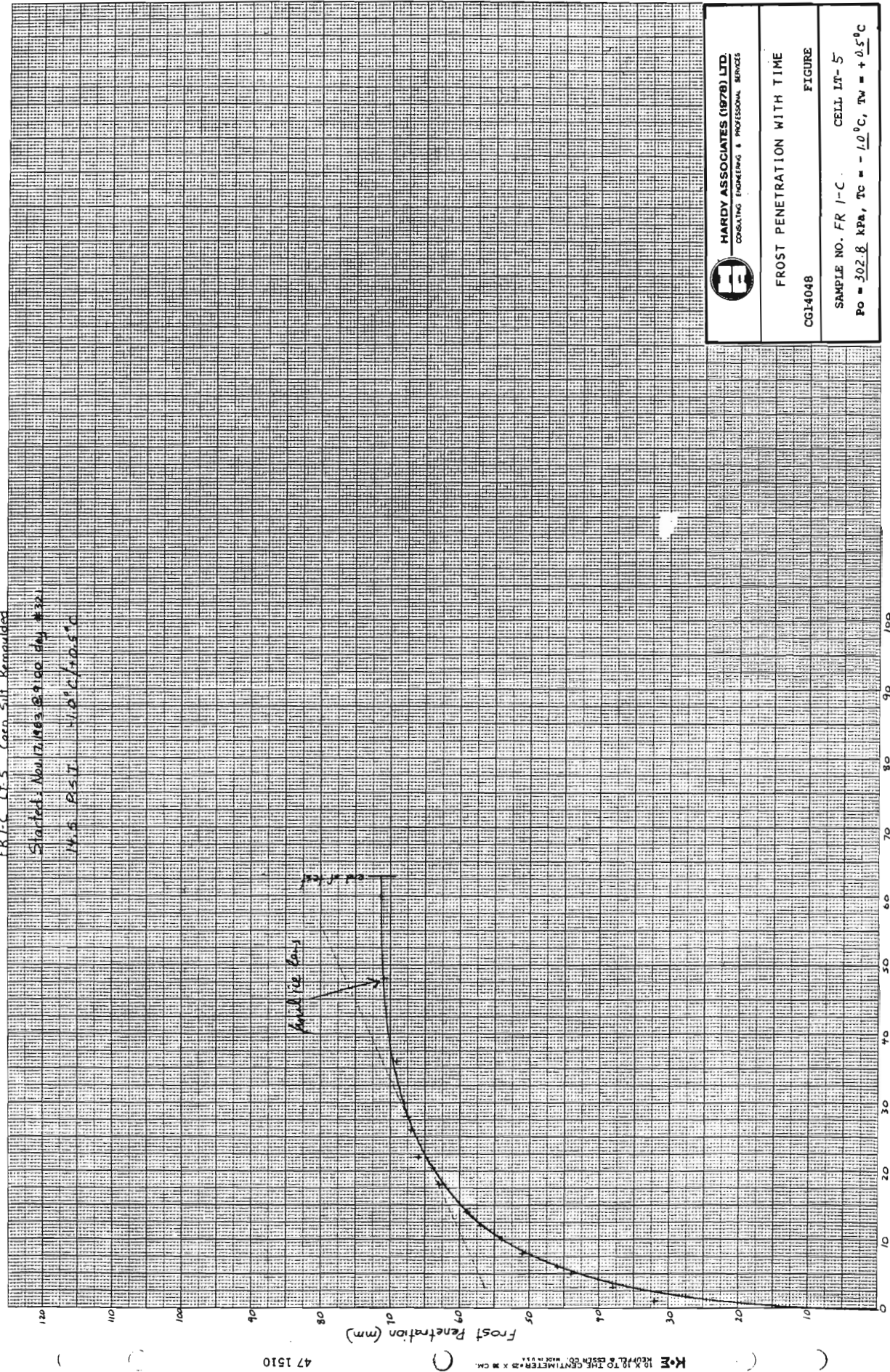


THICKNESS OF BASE PLATE = 10.0 mm

NOTE : Thermistor No 10a in bottom plate

TEST	<u>FR 1-B</u>
CELL	<u>LT-5</u>
DATE	<u>NOV. 10, 1983</u>
SOIL	<u>REMOULDED</u>
$\Delta t$	<u>47.5 HR</u>

FR-1-C LI-5 Core 5.11 Remoulded  
 Started Nov 17/1963 8.4.00 Day #32  
 14.5 PSI 4.0°C / 40.5°C



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**FROST PENETRATION WITH TIME**

CGI4048      FIGURE

SAMPLE NO. FR 1-C      CELL LT-5  
 Po = 302.8 kPa, Tc = -1.0°C, Tw = +0.5°C



ERIC LT-5 Core Silt Remoulded  
 Standard Moist. 19.83 @ 9:00 day #121  
 MS P.H.T. 17.6°C / 0.55  
 Dial Reading  
 X 1.001 MS

Heave By Water Movement + Frost Heave (mm)

47 1510

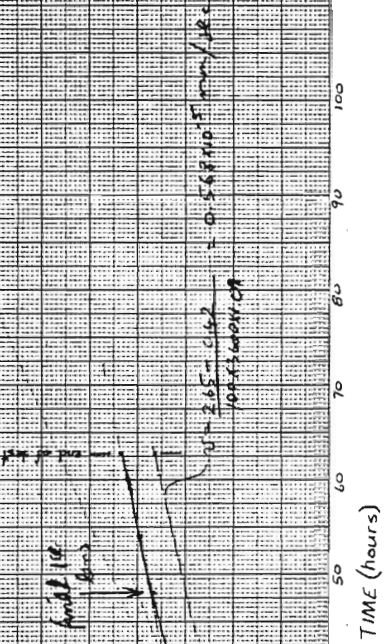
K-E 10 X 10 TO THE CENTIMETER X 3 CM  
 KOPPEL & BISHOP CO. MADE IN U.S.A.

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 CONSULTING ENGINEERING & PROFESSIONAL SERVICES

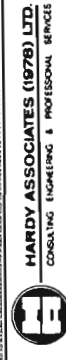
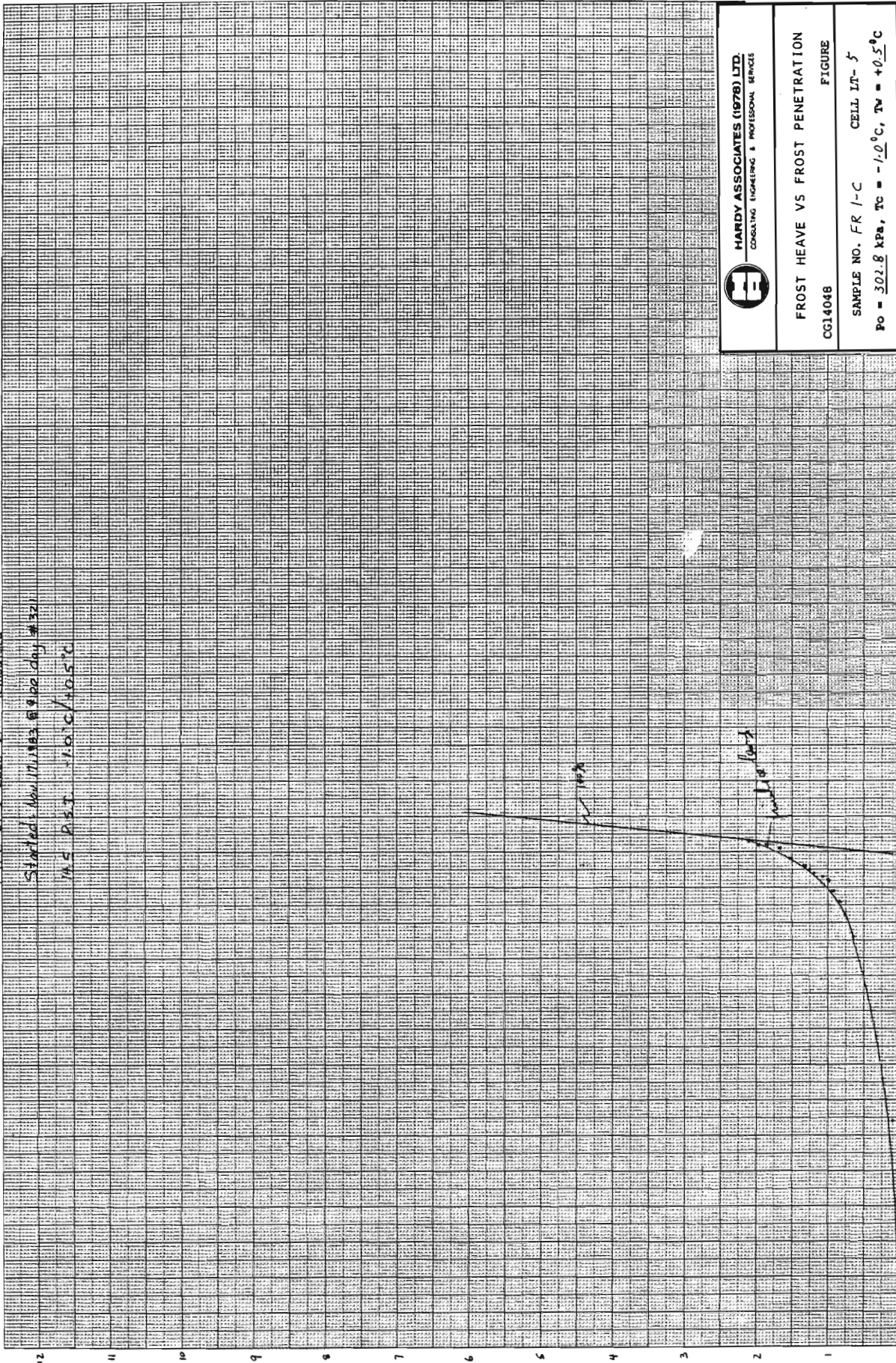
**FROST HEAVE AND WATER MOVEMENT WITH TIME**

CG14048 **FIGURE**

SAMPLE NO. FR 1-C CELL IT-5  
 $P_0 = 302.8 \text{ kPa}$ ,  $T_C = -1.0^\circ\text{C}$ ,  $T_W = +0.5^\circ\text{C}$



ERIC L.T.S. Coarse Silt Remoulded  
 Started Nov 17, 1953 @ 9:00 AM #321  
 ME P.S.T. -1.0°C / +0.5°C



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FROST HEAVE VS FROST PENETRATION  
 CG14048

FIGURE  
 SAMPLE NO. FR 1-C CELL LR-5  
 Po = 302.8 kPa, Tc = -1.0°C, Tw = +0.5°C

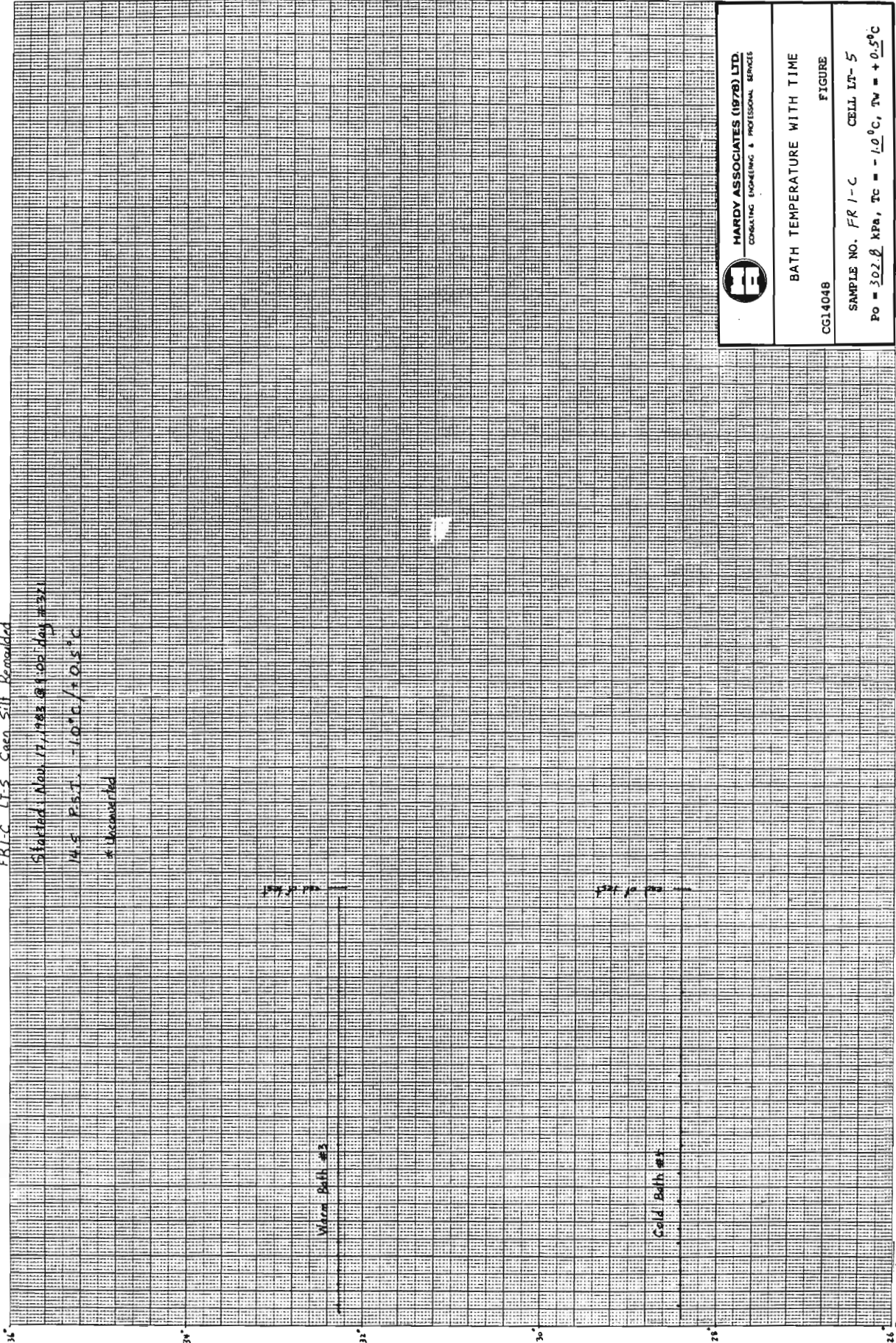


FRIC LT-5 Case Silt Remanded

Started Nov. 17, 1988 @ 1:00 PM #321

14.5 PSI,  $-1.0^{\circ}\text{C} / +0.5^{\circ}\text{C}$

\* Uncovered



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**BATH TEMPERATURE WITH TIME**

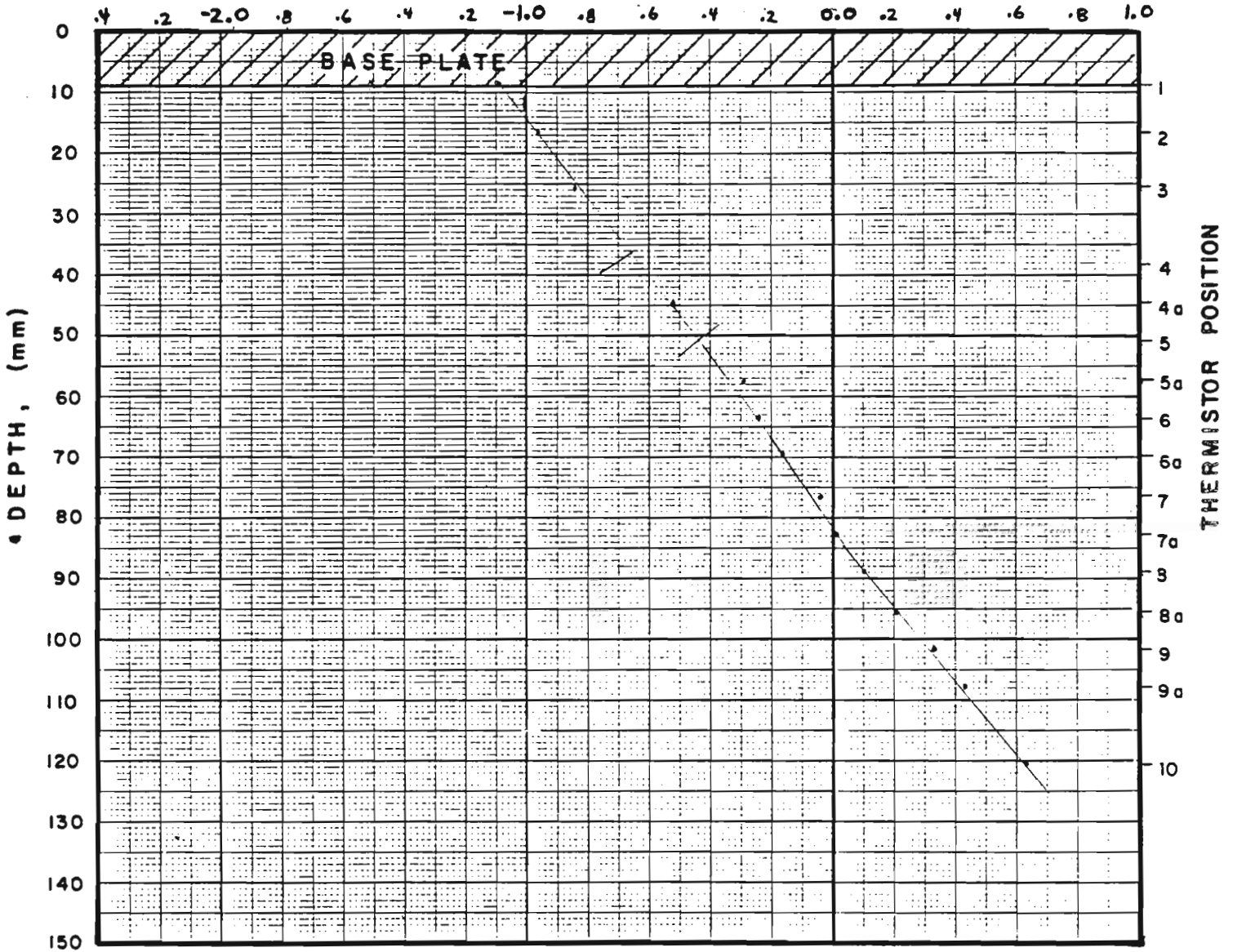
CG14048

SAMPLE NO. FR1-C CELL LT-5  
Po = 302.8 kPa, Tc = -1.0°C, Tw = +0.5°C

FIGURE

# TEMPERATURE PROFILE

TEMPERATURE (°C)



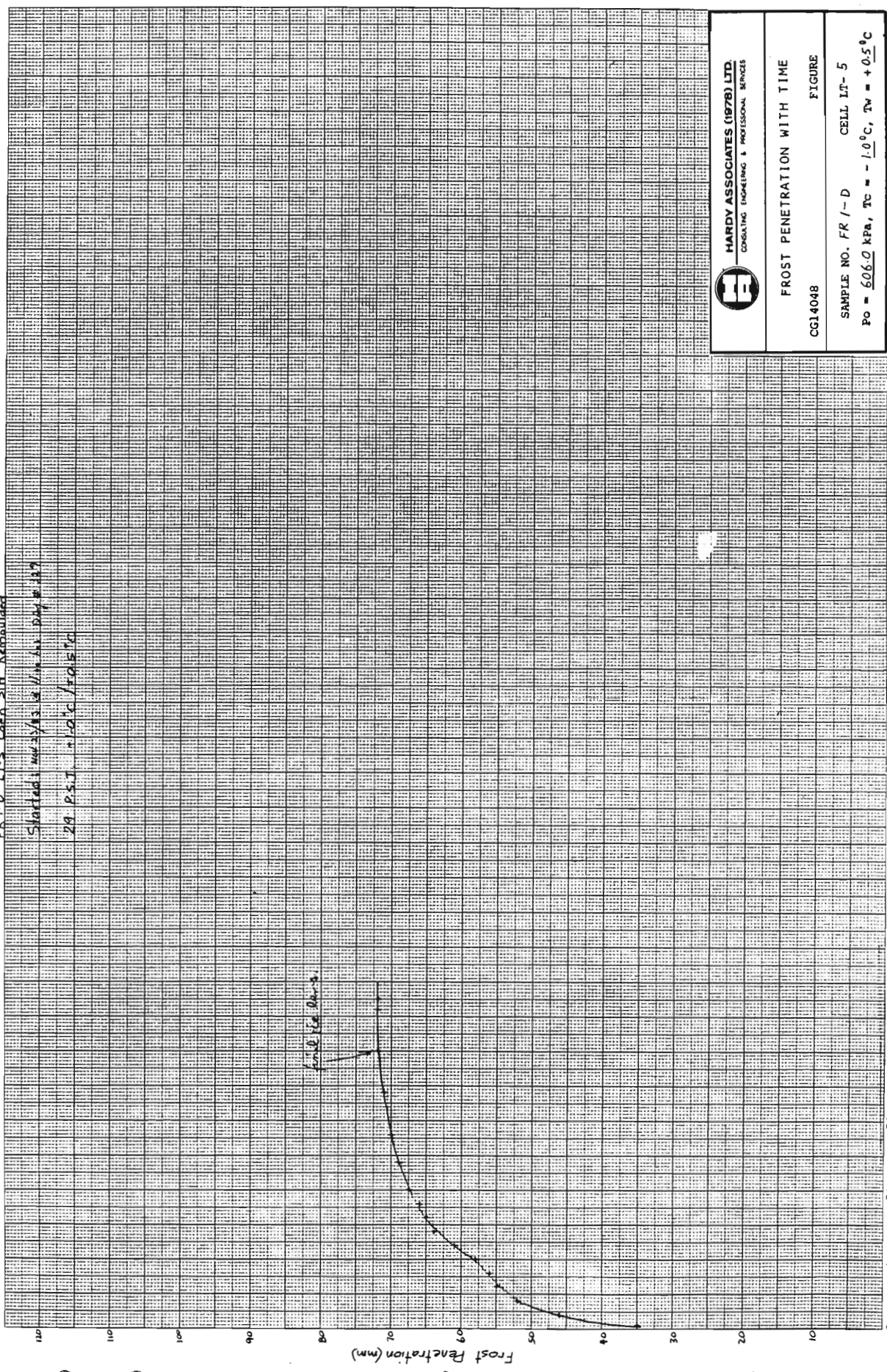
THICKNESS OF BASE PLATE = 10.0 mm

NOTE : Thermistor No 10a in bottom plate

TEST FR 1-C  
 CELL LT-5  
 DATE NOV. 19, 1983  
 SOIL REMOULDED  
 $\Delta t$  60.0 HR



FR-1-D ITS Core SH Remoulded  
 Started 11/23/53 at 11:00 AM Day 109  
 29 P.S.T.  $+10.5^{\circ}\text{C}$  /  $+0.5^{\circ}\text{C}$



Final Ice Bar

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**FROST PENETRATION WITH TIME**

CG14048

SAMPLE NO. FR 1-D CELL LT-5  
 $P_0 = 606.0 \text{ kPa}$ ,  $T_c = -1.0^{\circ}\text{C}$ ,  $T_v = +0.5^{\circ}\text{C}$

FIGURE

C C

47 1510

Q

K-E 10 KMPH TO 2500 CM PER HOUR

FR I-D IT-5 Coen silt Remoulded

Started: 11/25/51 @ 11:00 hrs. Day # 1517

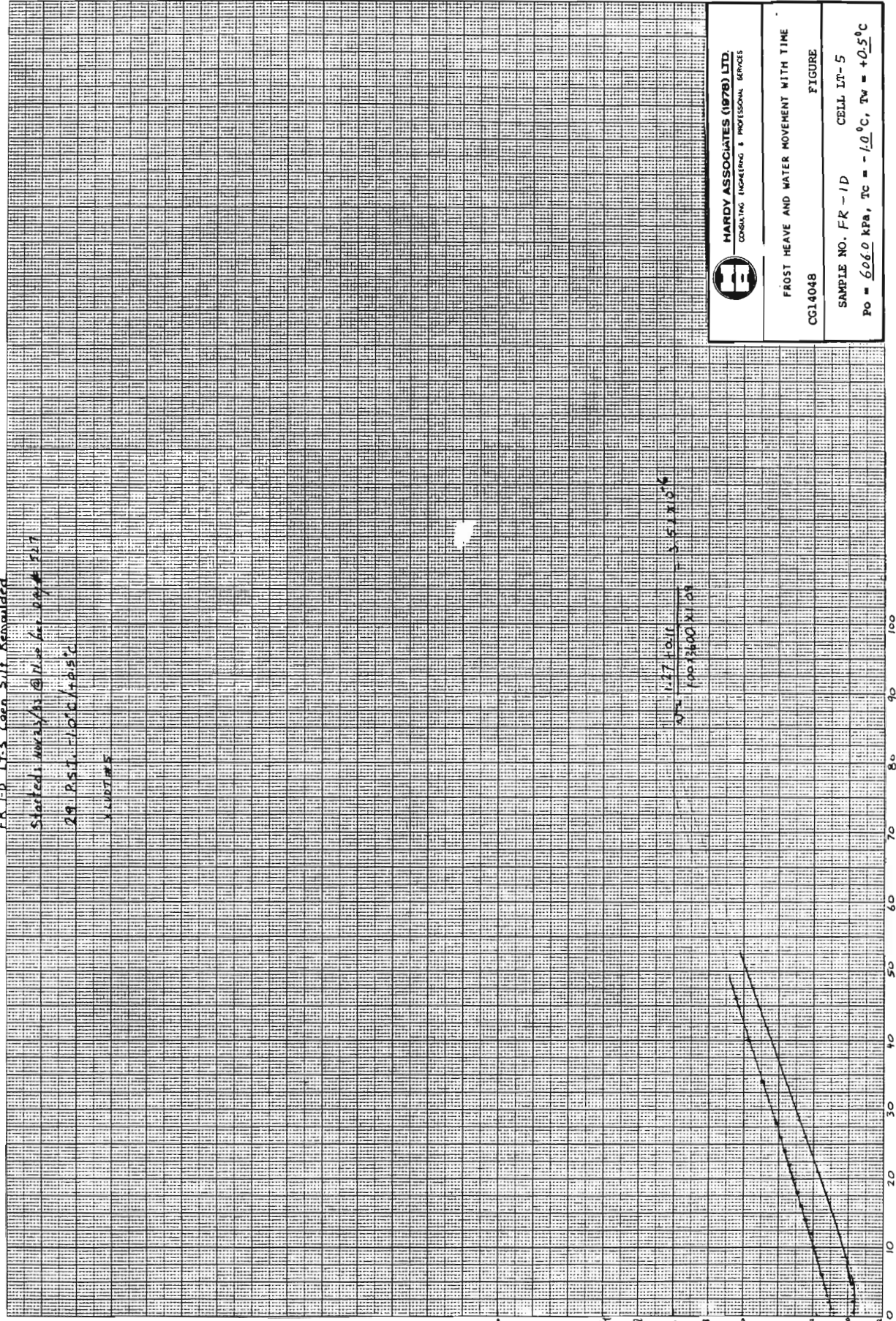
29 PSI. -10°C / +0.5°C

SLUDG#5

Heave By Water Movement + Frost Heave (mm)

47 1510

K-E 10% TO THE CENTIMETER X 1 CM



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

FROST HEAVE AND WATER MOVEMENT WITH TIME

CGI4048

FIGURE

SAMPLE NO. FR -1D CELL IT-5  
Po = 606.0 kPa, Tc = -1.0°C, Tw = +0.5°C




FR-10 L.T.S. Core Sill Remoulded

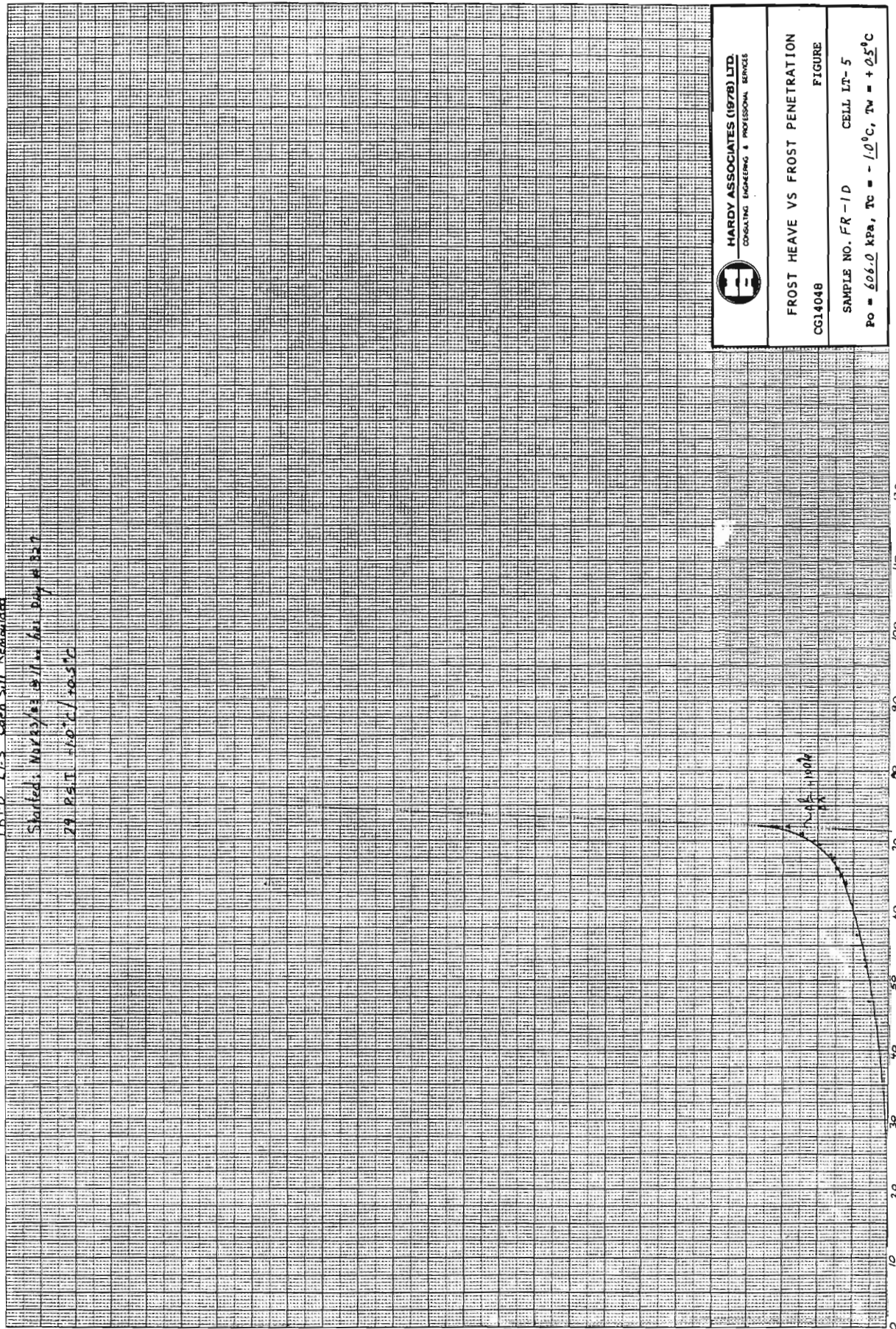
Started: No 223/83.18 / 1.1.61 Day # 327

29 PSI -10°C / 10.5°C

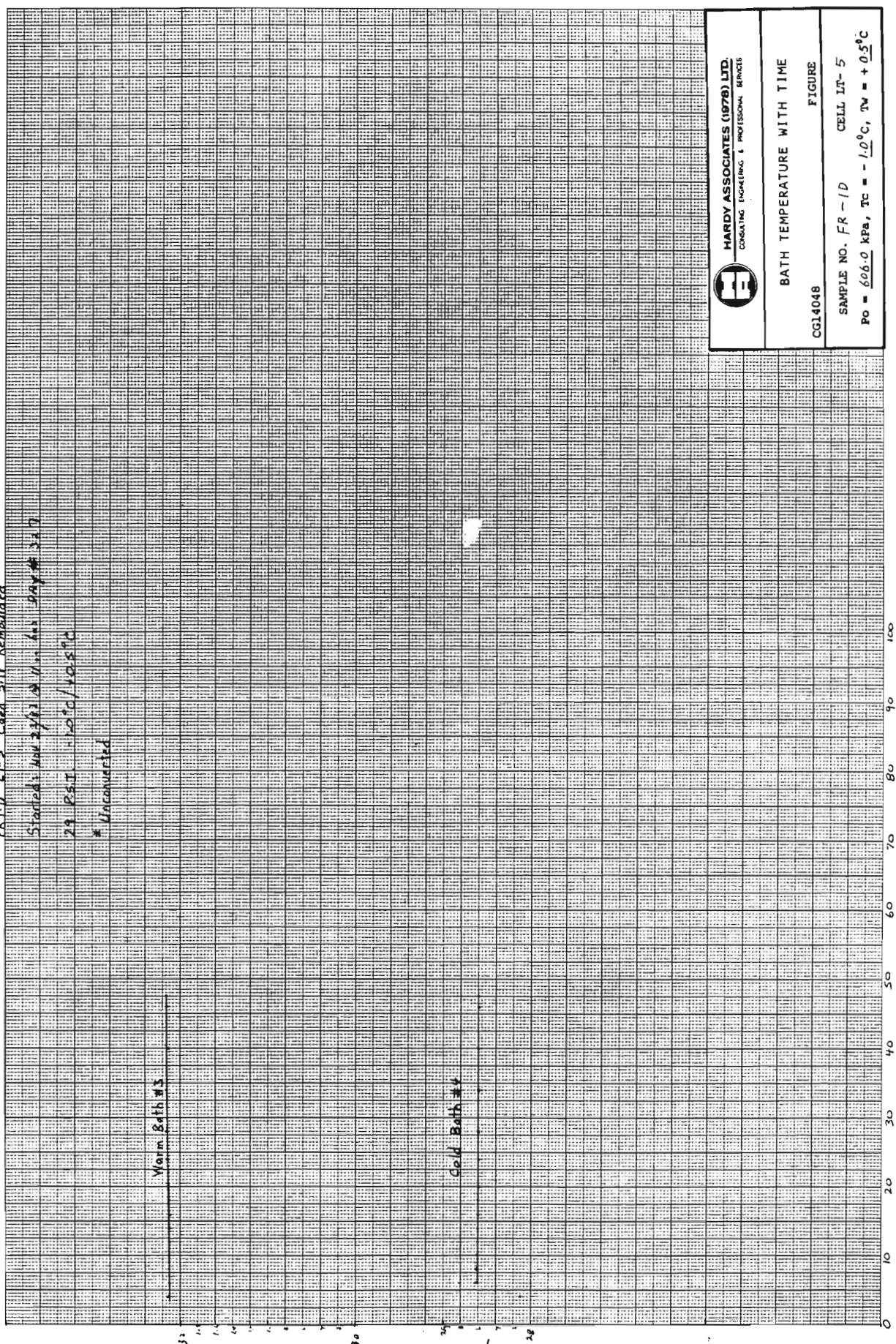
Frost Heave (mm)

Frost Penetration (mm)

	<b>HARDY ASSOCIATES (1978) LTD.</b> CONSULTING ENGINEERING & PROFESSIONAL SERVICES
<b>FROST HEAVE VS FROST PENETRATION</b>	
CG14048	FIGURE
SAMPLE NO. FR-10	CELL LT-5
Po = 606.0 kPa, Tc = -10°C, Tw = +0.5°C	



FR-1-D LT-5 Coen. S. it Remoulded  
 Started: Nov 23/83 @ 11:00 AM Day # 327  
 29 PST = 10:00 / 10:50°C  
 \* Unconverted



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

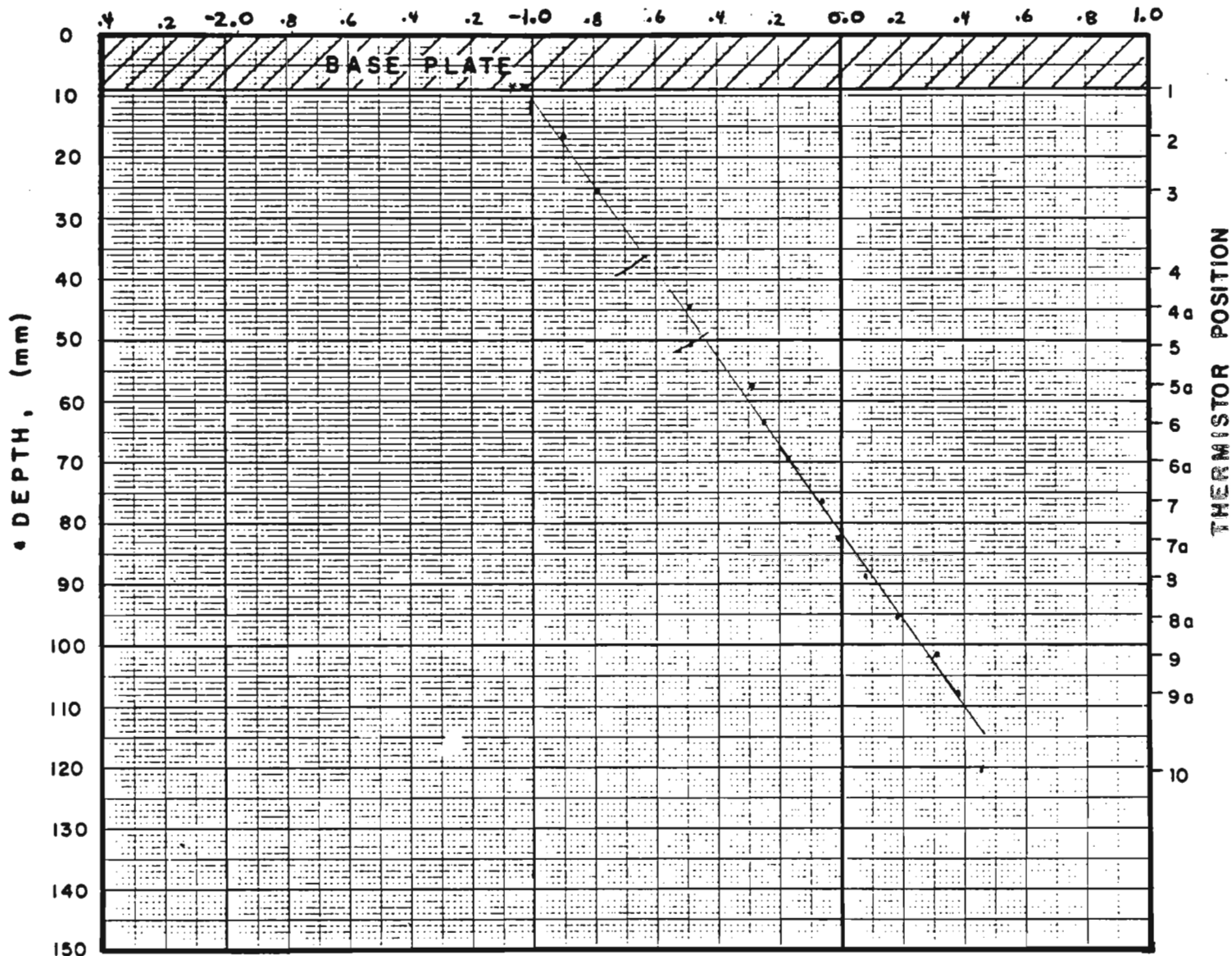
**BATH TEMPERATURE WITH TIME**

CC14048

SAMPLE NO. FR-1-D CELL IT-5  
 Po = 606.0 kPa, Tc = -1.0°C, Tw = +0.5°C

# TEMPERATURE PROFILE

TEMPERATURE (°C)



THICKNESS OF BASE PLATE = 10.0 mm

NOTE : Thermistor No 10a in bottom plate

TEST FR 1-D  
 CELL LT-5  
 DATE NOV. 24, 1983  
 SOIL REMOULDED  
 $\Delta t$  47.5 HR

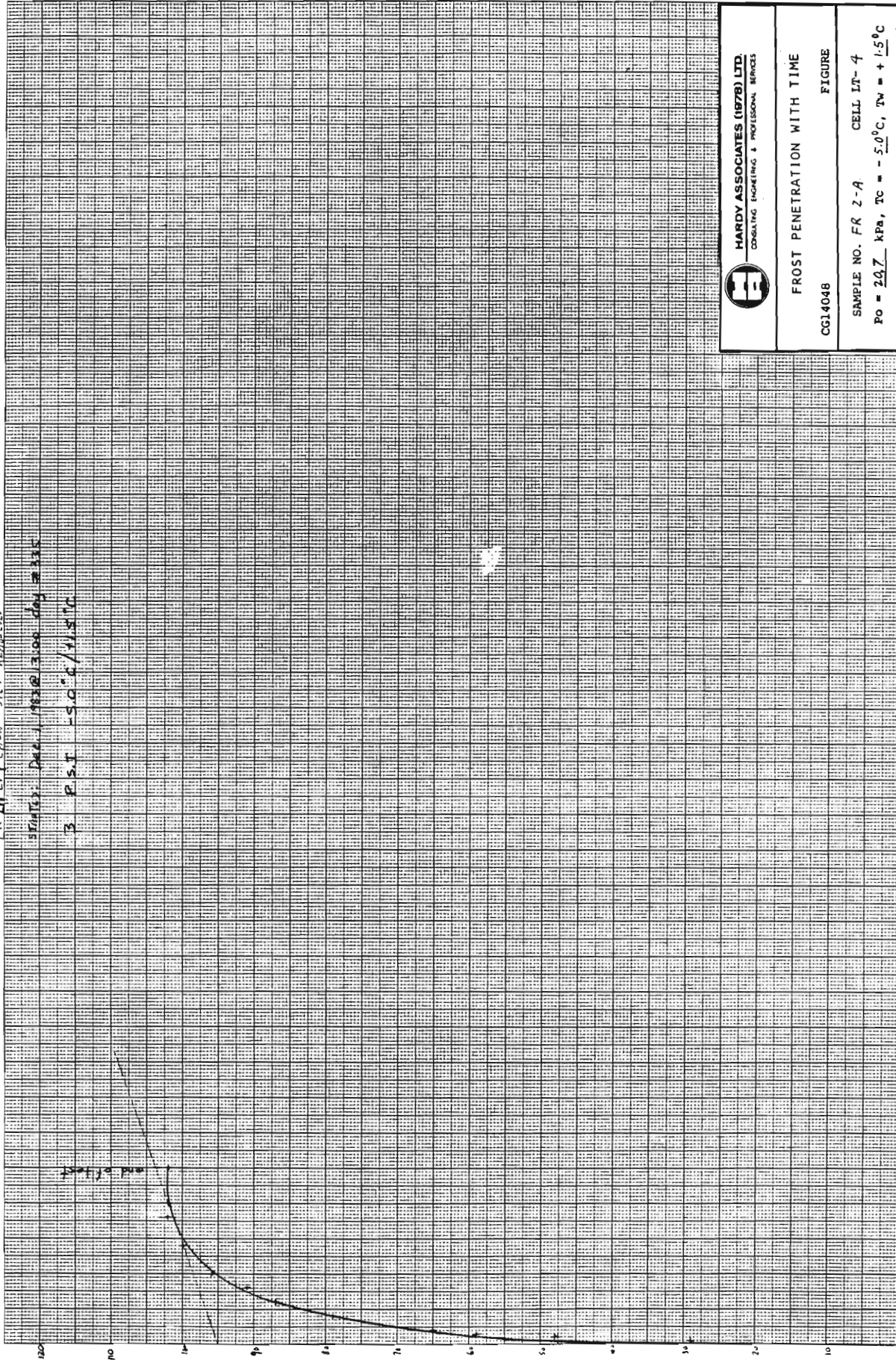


FRZ 2A LITH. CLAY SILT Penetration

STARTS: Dec 1, 1953 @ 3:00 PM

3 PSI -5.0°C/1.5°C

end of test



HARDY ASSOCIATES (1878) LTD.  
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FROST PENETRATION WITH TIME

CG14048

FIGURE

SAMPLE NO. FR 2-A CELL LT-4

Po = 20.7 kPa, Tc = -5.0°C, Tw = +1.5°C

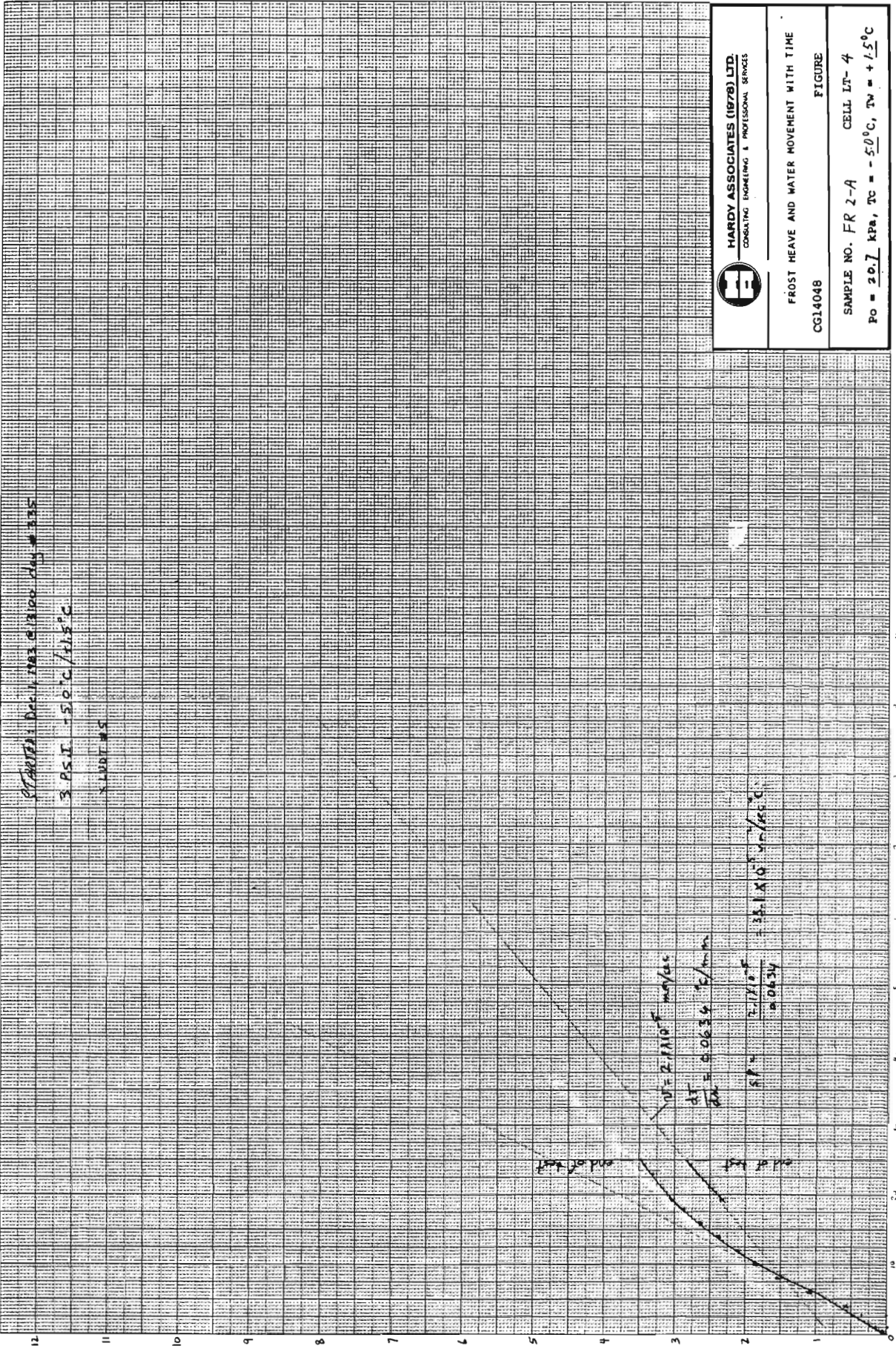
Tide (mm)

FR-24 LT-4 Caen silt Remoulded

STARTED: Dec 1, 1963 @ 1300 hrs # 335

3 Ps.T. -50°C / +15°C

X 100T 45



47 1510

K·E 10 X 10 TO THE CENTIMETER X 25 CM



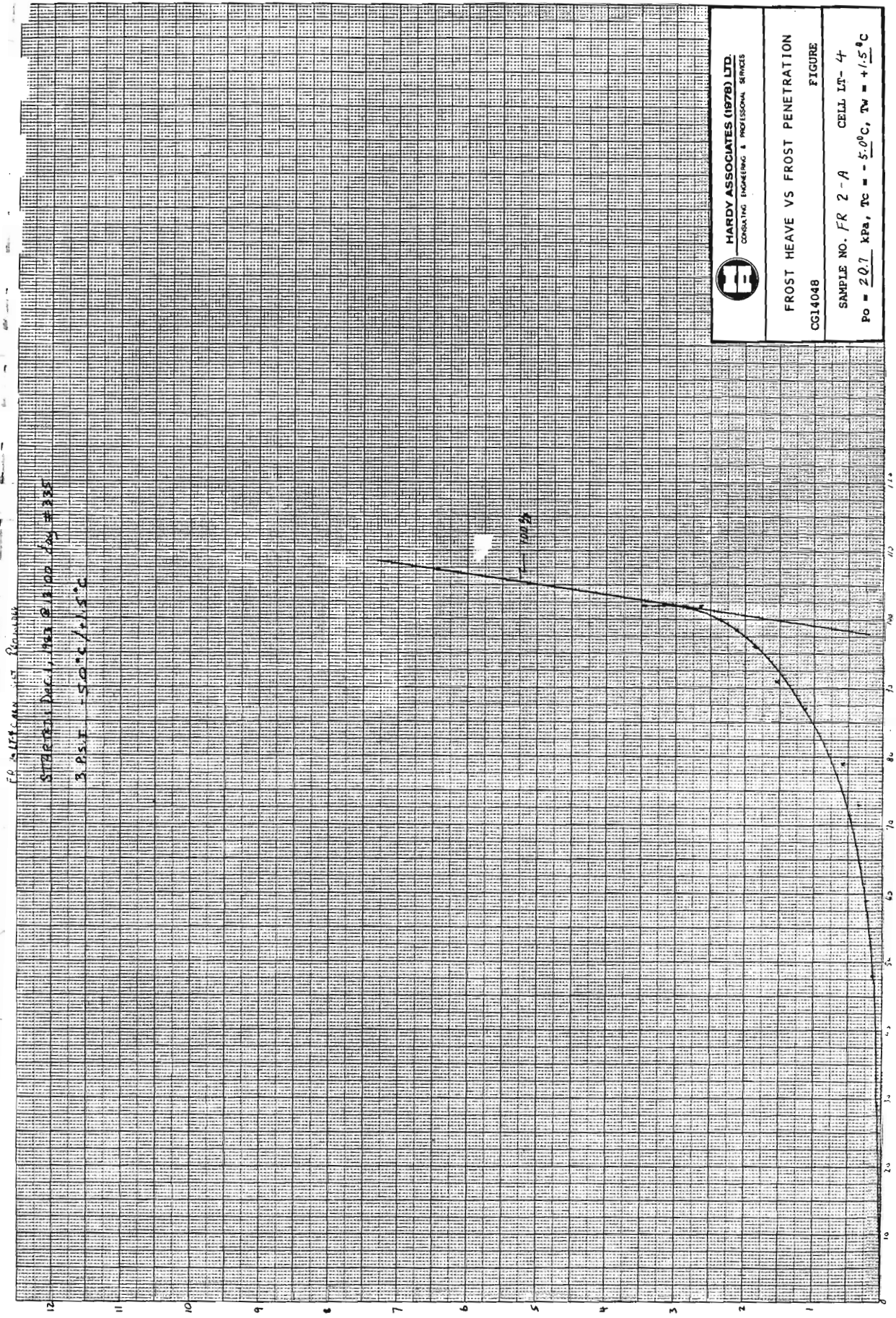
HARDY ASSOCIATES (1978) LTD.  
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

FIGURE  
CGL4048  
FROST HEAVE AND WATER MOVEMENT WITH TIME

CELL LT-4  
SAMPLE NO. FR 2-A  
 $P_0 = 20.7 \text{ kPa}$ ,  $T_c = -5.0^\circ\text{C}$ ,  $T_v = +1.5^\circ\text{C}$

Time (min)





FROST HEAVE TEST RECORD  
 STEPHEN DEC 1, 1961 @ 1.00 PM #385  
 P.S.I.E. -5.0°C / +1.5°C

K&E 10 X 10 TO THE CENTIMETER X 30 CM  
 FROST HEAVE (mm)

47 1510



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 CONSULTING ENGINEERING & PROFESSIONAL SERVICES

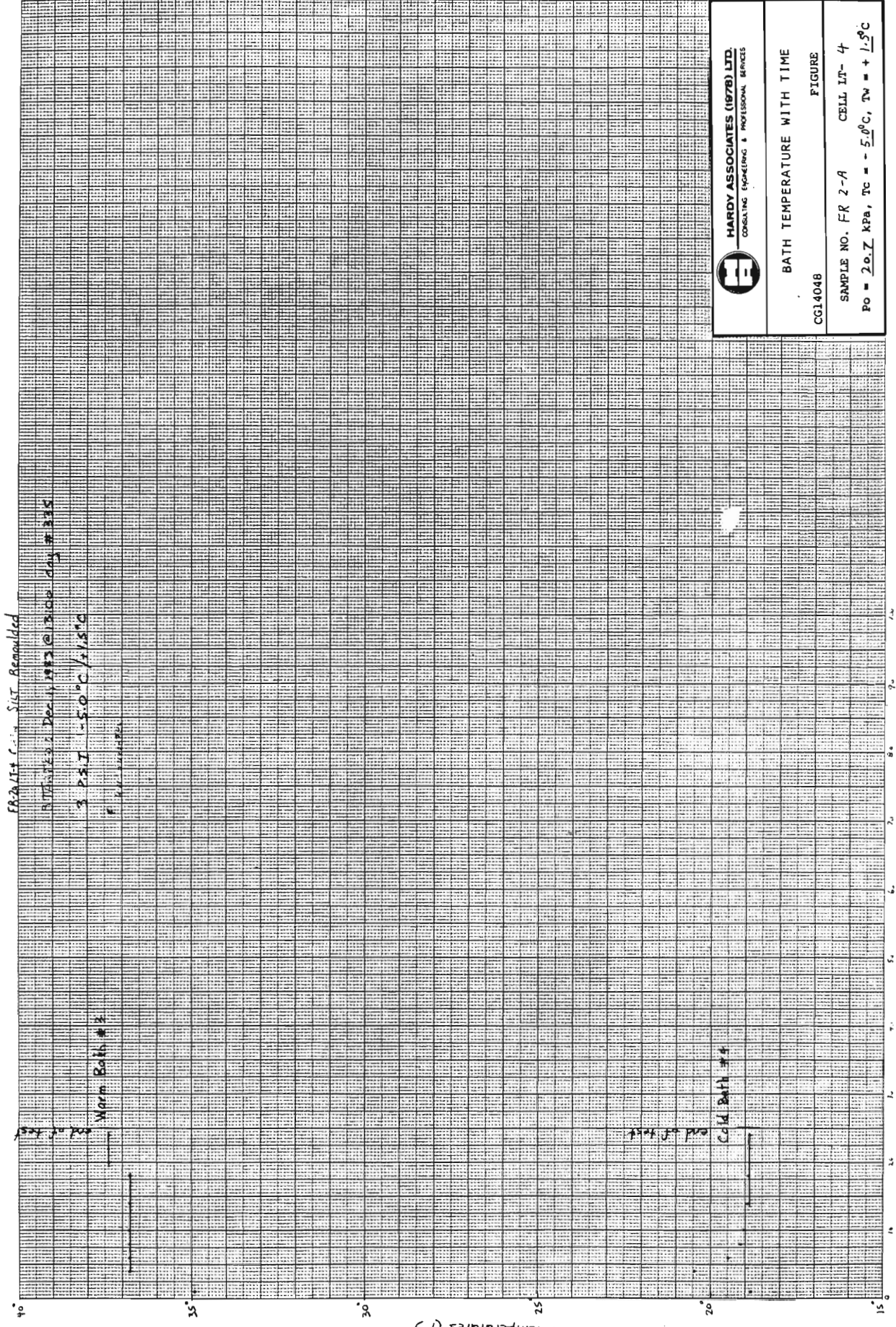
FROST HEAVE VS FROST PENETRATION


CG14048

FIGURE

SAMPLE NO. FR 2-A CELL IT-4  
 P<sub>0</sub> = 20.7 kPa, T<sub>C</sub> = -5.0°C, T<sub>m</sub> = +1.5°C

Frost Penetration (mm)





**HARDY ASSOCIATES (1978) LTD.**  
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**BATH TEMPERATURE WITH TIME**

FIGURE

SAMPLE NO. *FR 2-A*      CELL IT- 4


Po = *20.7* kPa, Tc = *-5.0*°C, Tw = *+1.5*°C



SAM SITE FR-2 B  
 STRATA: 20.7 kPa  
 1 P.S. -1°C + F.C.

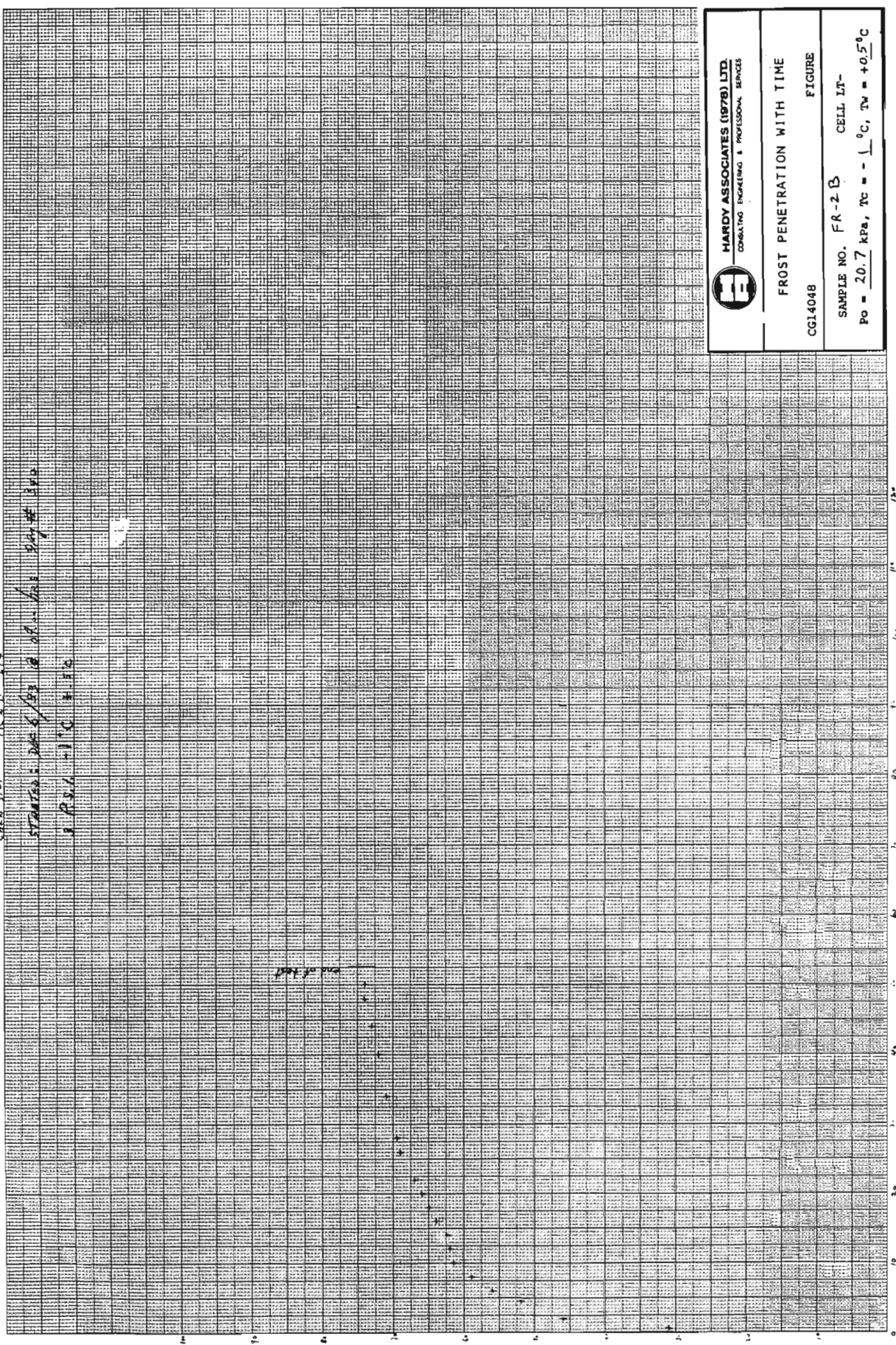
End of Test

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



**FROST PENETRATION WITH TIME**  
 FIGURE  
 CG14048

SAMPLE NO. FR-2 B CELL LT-  
 Po = 20.7 kPa, Tc = -1°C, Tw = +0.5°C



Time (min)



CELL SIT FA 2A 153  
 STARTED DELTA P on 11/24/50

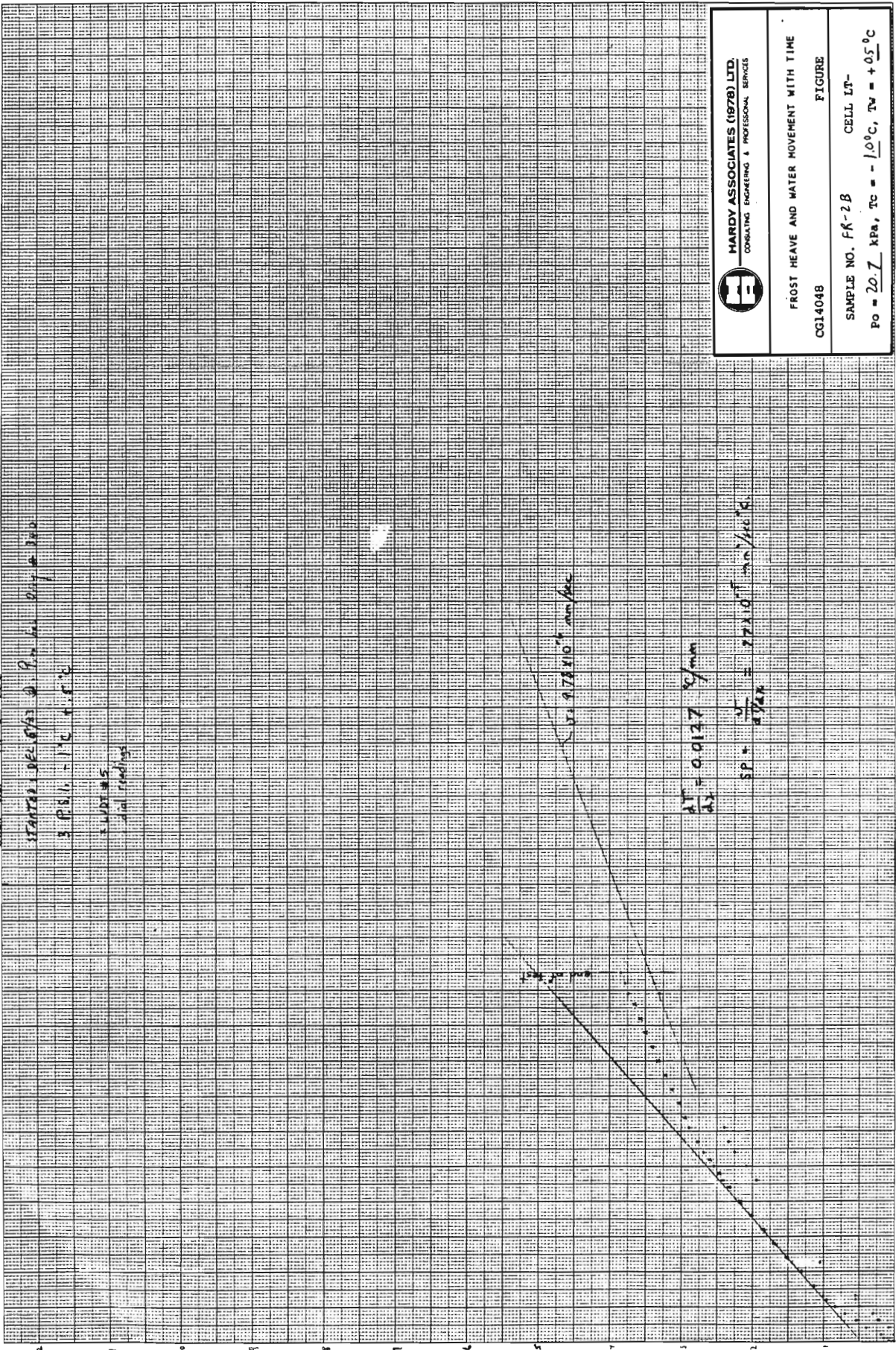
3 P.S.I. - 1°C + 0.5°C

3 readings  
 data readings

$U = 9.78 \times 10^{-6}$  mm/sec

$$\frac{AT}{dL} = 0.0127 \text{ } \mu\text{m/min}$$

$$SP = \frac{U}{dL} = 7.7 \times 10^{-7} \text{ sec/} \mu\text{m}^2$$



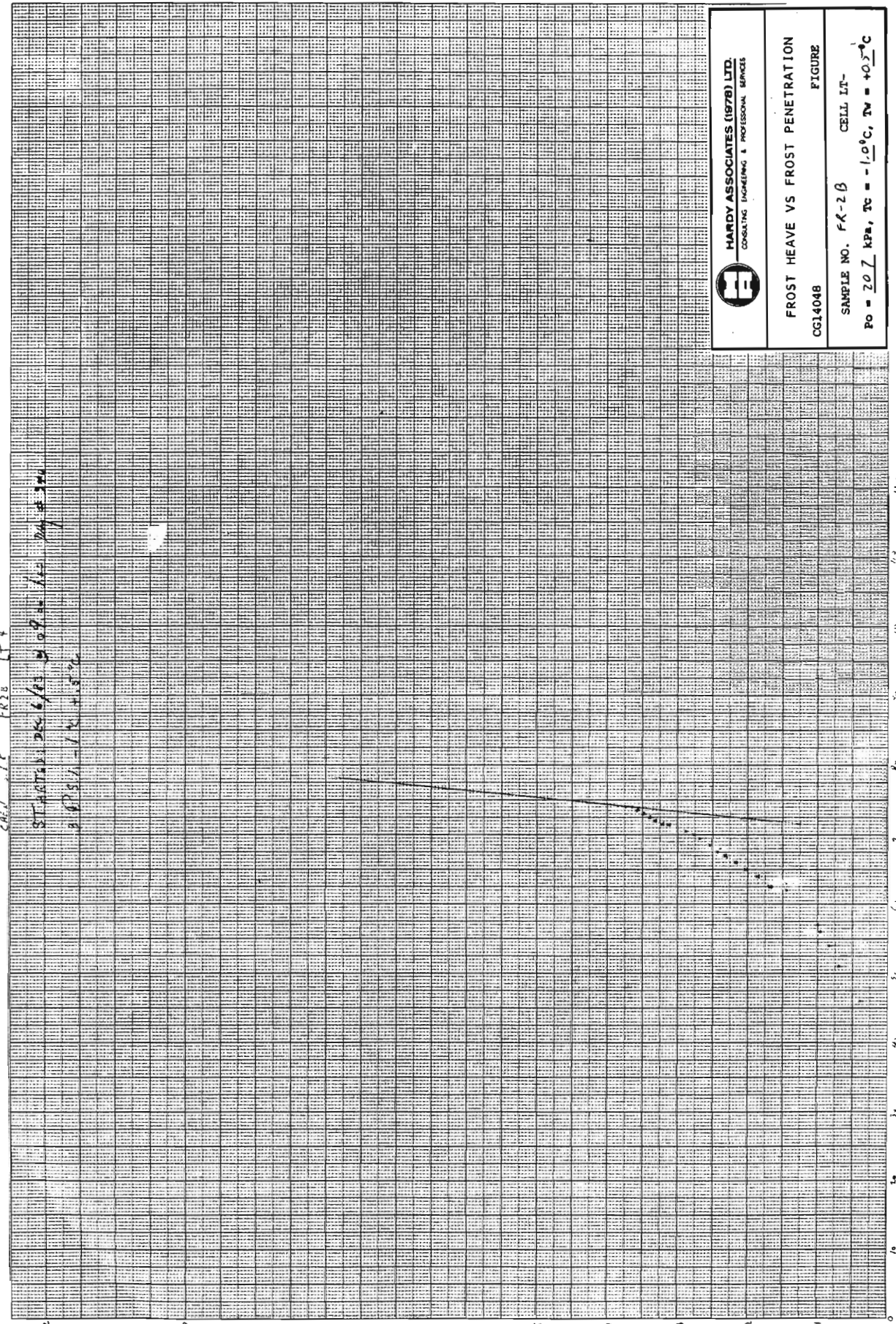
**HARDY ASSOCIATES (1978) LTD.**  
 CONSULTING ENGINEERING & PROFESSIONAL SERVICES

**FROST HEAVE AND WATER MOVEMENT WITH TIME**

CG14048 **FIGURE**


SAMPLE NO. **FA-2B** CELL LT-

$P_0 = 20.7$  kPa,  $T_C = -1.0^\circ\text{C}$ ,  $T_w = +0.5^\circ\text{C}$



CELL 21K FROST LT\*  
 STARTED ON 6/13 9 09 AM 24.5°C  
 2.057 - 1.2 4.5°C

Frost Penetration (mm)

 <b>HARDY ASSOCIATES (1978) LTD.</b> CONSULTING ENGINEERING & PROFESSIONAL SERVICES	<b>FROST HEAVE VS FROST PENETRATION</b>	
	SAMPLE NO. F-2-2β Po = 207 kPa, Tc = -1.0°C, Tw = +0.5°C	CELL LT- FIGURE





HARDY ASSOCIATES (1878) LTD.  
CONSULTING ENGINEERING & PROFESSIONAL SERVICE

BATH TEMPERATURE WITH TIME

FIGURE

SAMPLE NO. FA-23 CELL IT-  
Po = 20.7 kPa, Tc = -1.0°C, Tw = +0.5°C

CAN 4 514 F228 IT 4

STARTED: 08:05/01 of 01. 11. Day of 1960  
3 PSC 1/2 1/2  
unconnected

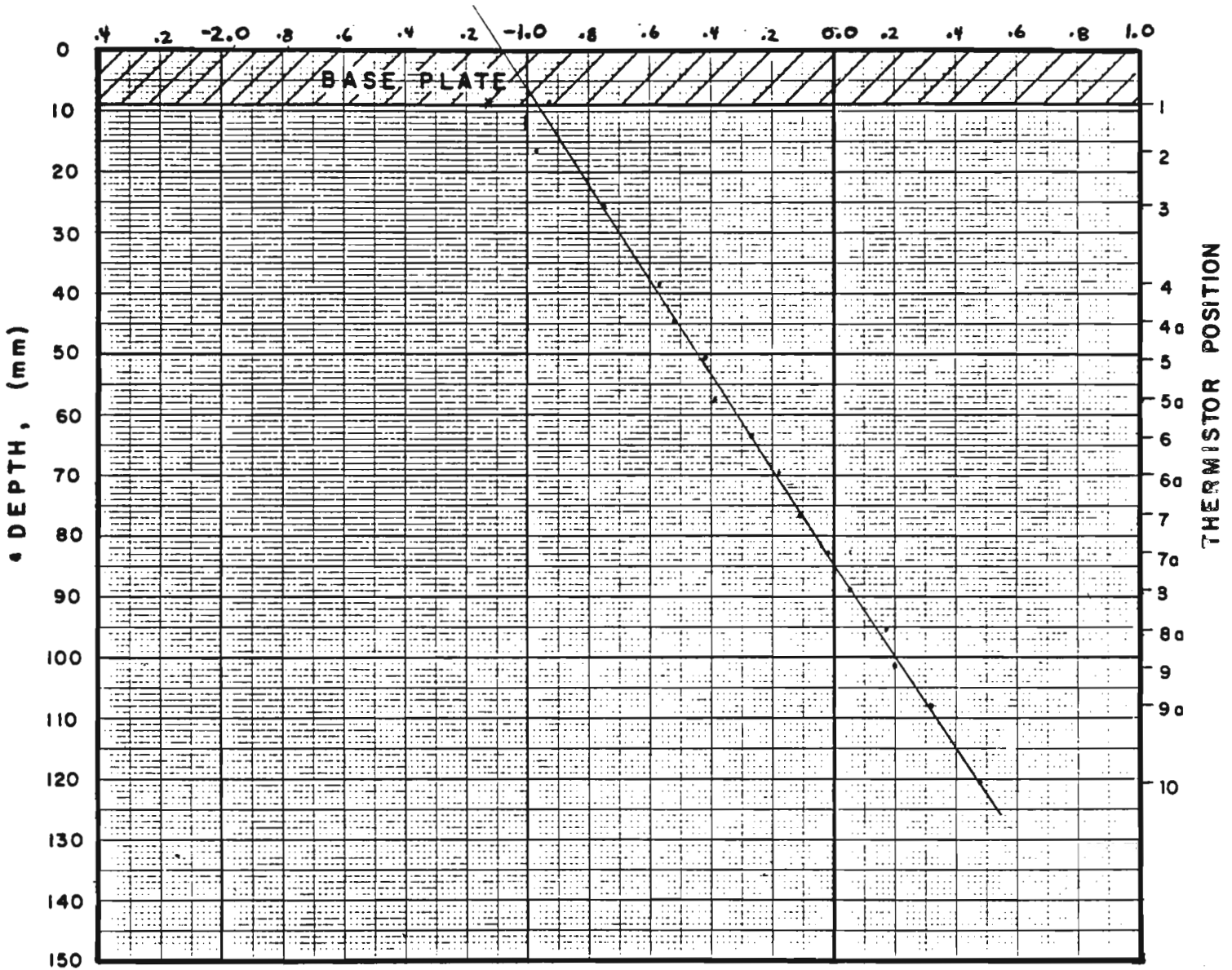
end of test  
Warm Bath #3

end of test  
Cold Bath #4

Time (min)

# TEMPERATURE PROFILE

TEMPERATURE (°C)



THICKNESS OF BASE PLATE = 11mm.

NOTE : Thermistor No 10a in bottom plate

$$\frac{dT}{dz} = 0.0127$$

TEST F.R.2-B

CELL LT-4

DATE Dec. 8/53 342

SOIL Coar. silt Remoulded

$\Delta t$  50.0 11:00

last one.

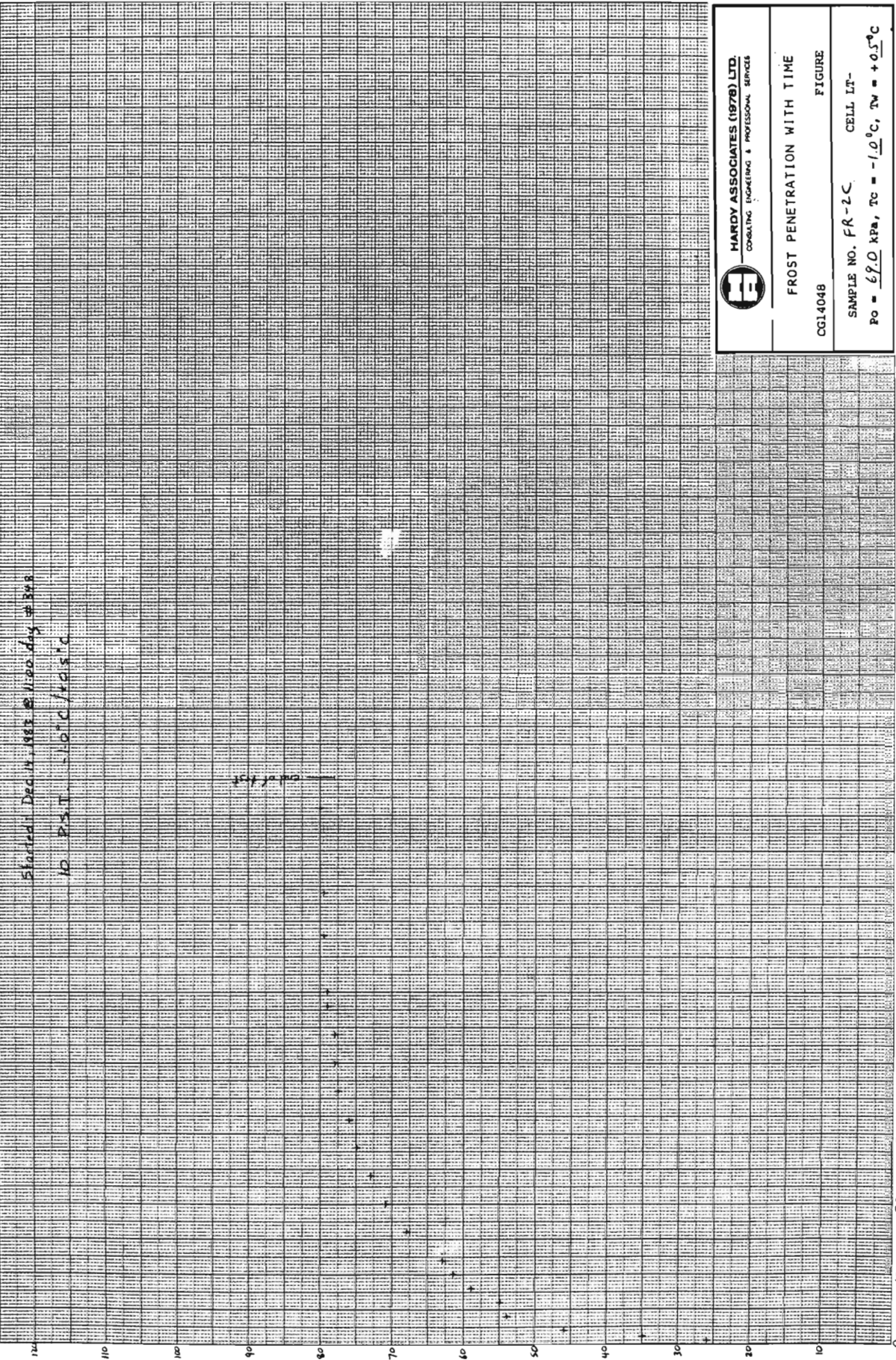


FR-2-C LT-4 Coen Silt Remoulded  
 Started: Dec 14, 1983 @ 1:00 Day #348  
 10 P.S.T. -10°C / 125°C

End of Test

Frost Penetration (mm)

TIME (Hours)



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

FROST PENETRATION WITH TIME

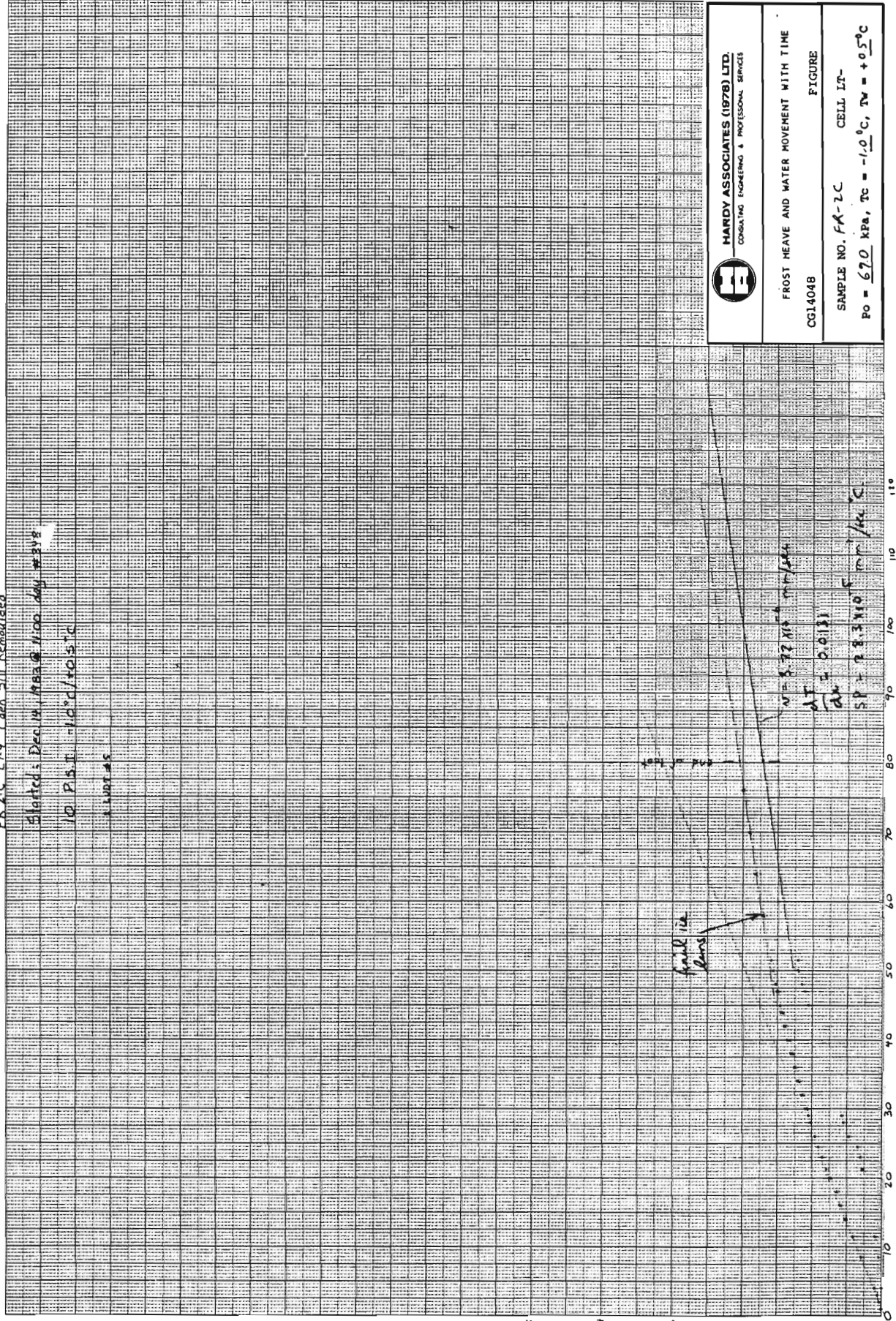
CG14048

FIGURE

SAMPLE NO. FR-2-C CELL LT-

Po = 69.0 kPa, Tc = -1.0°C, Tm = +0.5°C

Heave By Water Movement + Frost Heave (mm)



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

FROST HEAVE AND WATER MOVEMENT WITH TIME

CG1404B

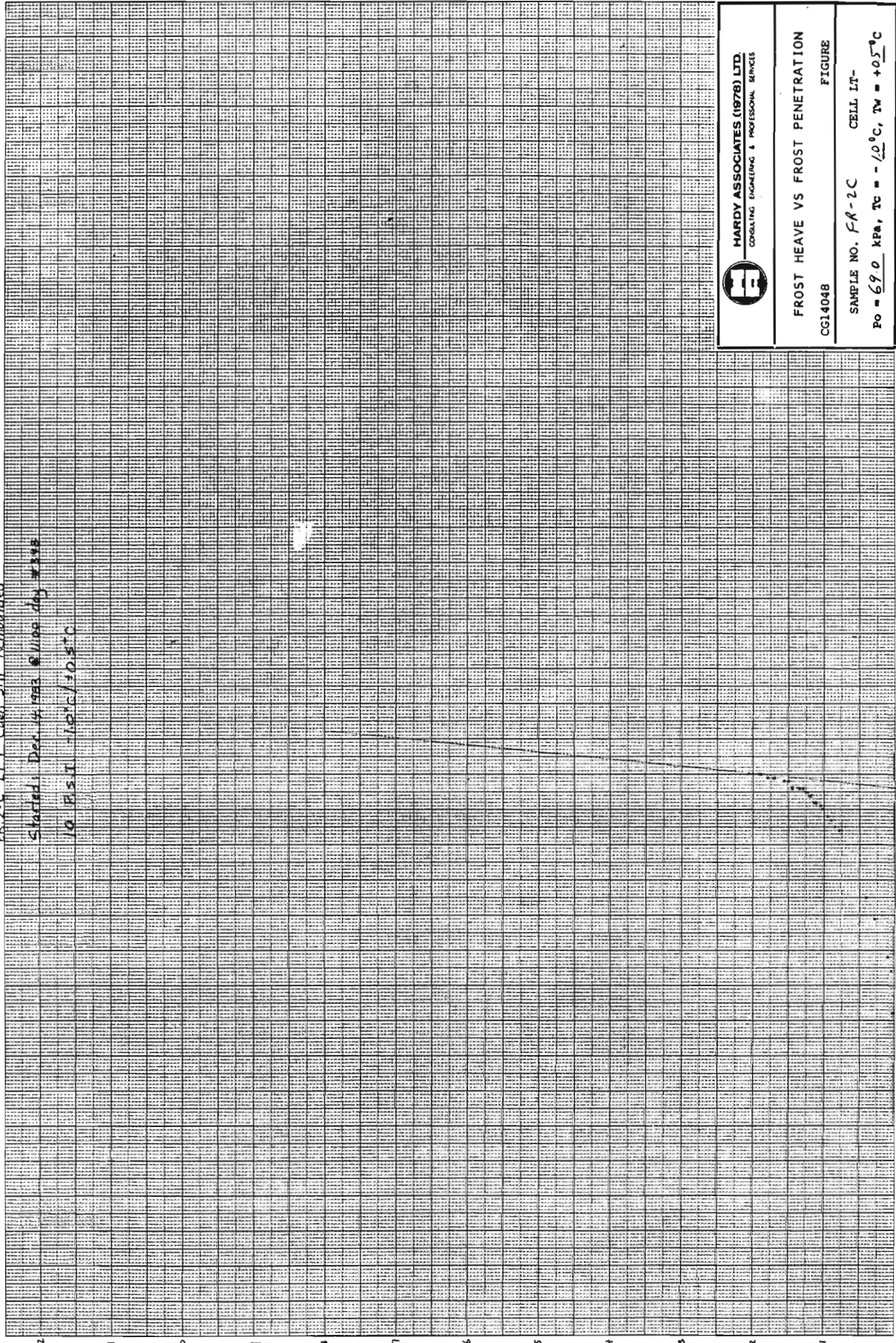
FIGURE

SAMPLE NO. FA-2-C CELL LT-

Po = 670 kPa, Tc = -1.0°C, Tw = +0.5°C



FR-7-G II-4 Cast Silt Recoupled  
Started Dec. 4, 1953 @ 1:00 day #315  
10 PSI -10°C / +0.5°C



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

**FROST HEAVE VS FROST PENETRATION**  
CG14048

FIGURE

SAMPLE NO. *FR-2C* CELL IT-

$P_0 = 69.0$  kPa,  $T_c = -10.0^\circ\text{C}$ ,  $T_w = +0.5^\circ\text{C}$

FR-2-C AT-4 Caen Silt Remoulded

Started: Dec 14, 1952 @ 11:00 day #310

10 P.S.T.  $+10^{\circ}\text{C}/+05^{\circ}\text{C}$

\* Unconverted

Marm Bath #3

Cold Bath #4

Bath Temperatures (F) \*

TIME (hours)



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

BATH TEMPERATURE WITH TIME

FIGURE

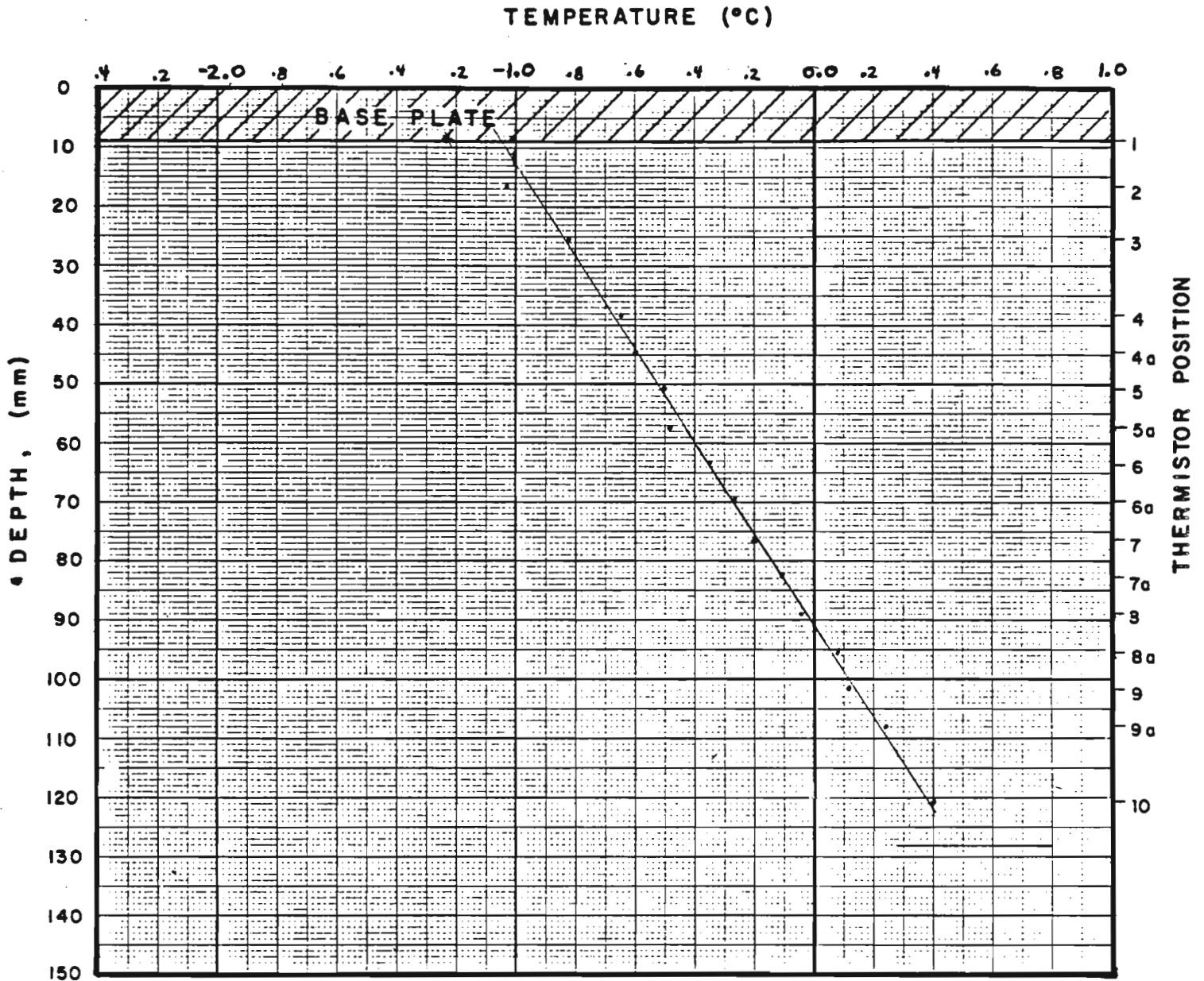
CG14048

SAMPLE NO. FR-2C CELL LT-

Po = 69.0 kPa, Tc =  $-10^{\circ}\text{C}$ , Tv =  $+45^{\circ}\text{C}$



# TEMPERATURE PROFILE



80

THICKNESS OF BASE PLATE = 11mm.  
 NOTE : Thermistor No 10a in bottom plate

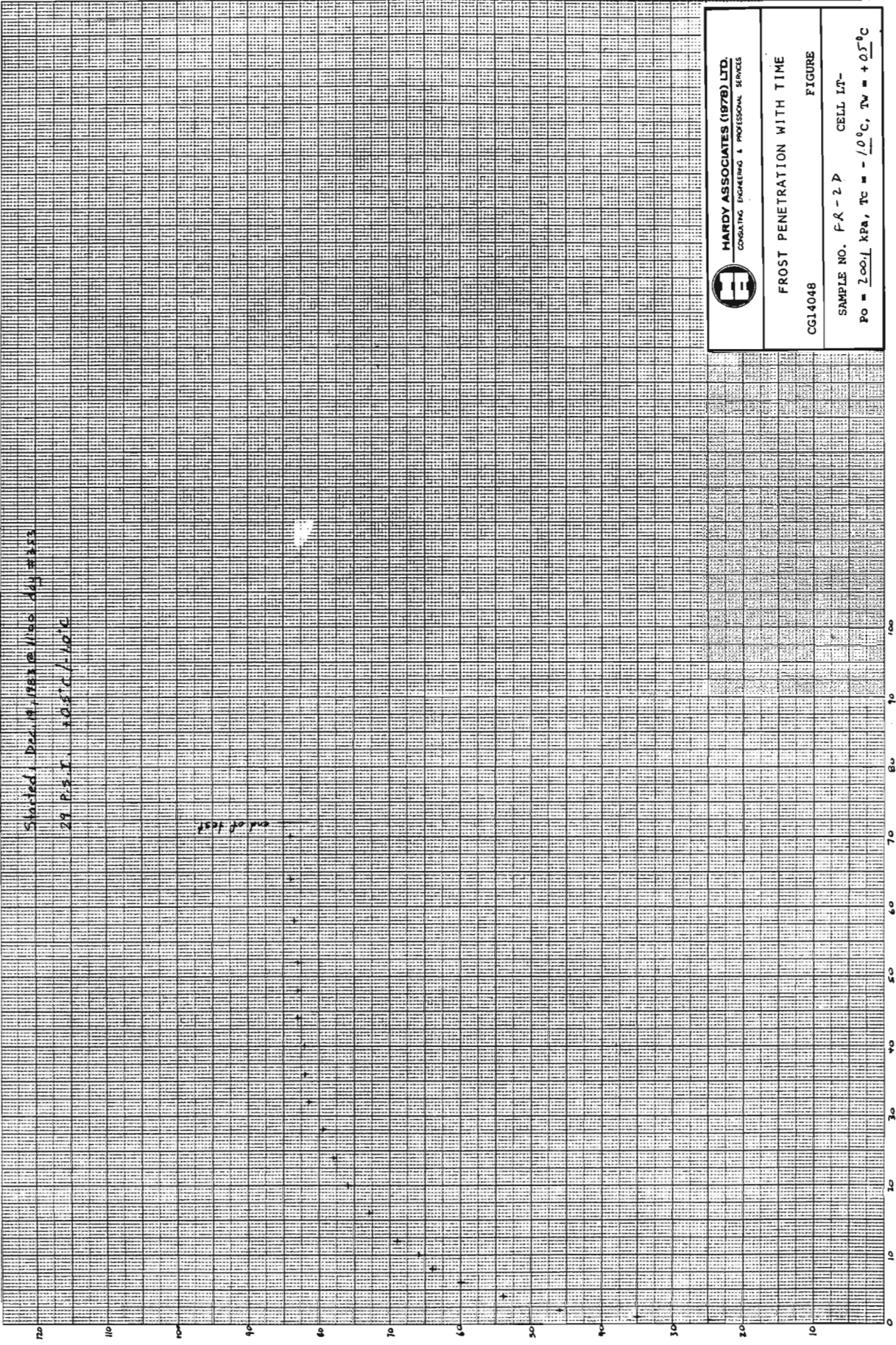
TEST FR2-C  
 CELL LT-4  
 DATE Dec. 17/83 351  
 SOIL Remoulded  
 $\Delta t$  76.0 15:00  
 last one.

ER2-D LT-4 Coen silt Remoulded


Started Dec 11 1953 @ 11:00 AM

29 P.S.T. +0.5°C / 1.0°C

end of test



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



**FROST PENETRATION WITH TIME**  
FIGURE  
CG14048

SAMPLE NO. F.2-2P CELL LT-  
PO = 200.1 kPa, TC = -1.0°C, Tw = +0.5°C

TIME (hours)

Frost Penetration (mm)

FR-2-D LT-4 Coen silt Remoulded

Started, Dec 19, 1963 @ 11:00 day #353

29 P.S.T. +0.5°C / -10°C

0 Hour mark

Heave By Water Movement + Frost Heave (mm)

TIME (hours)



HARDY ASSOCIATES (1878) LTD.  
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

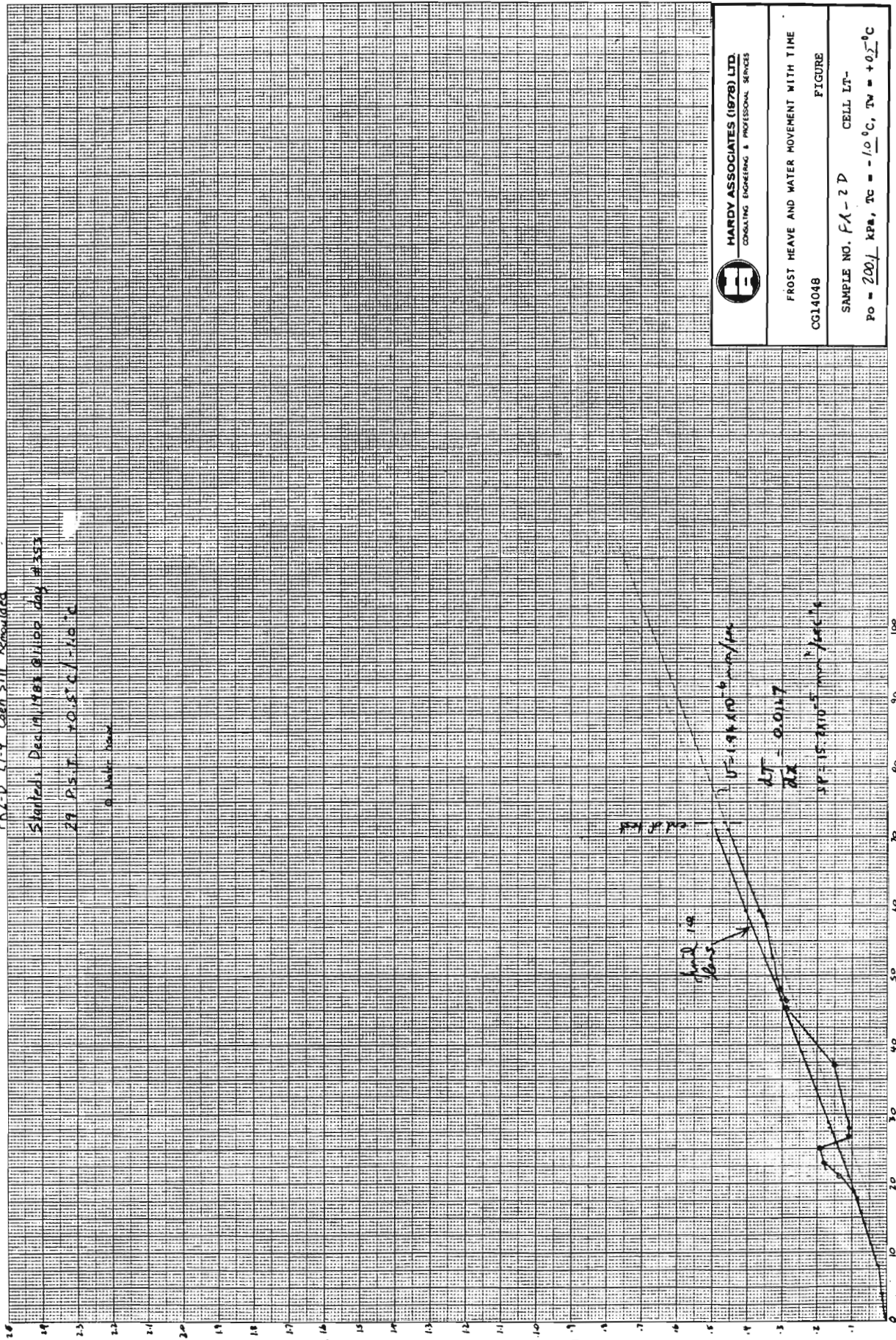
FROST HEAVE AND WATER MOVEMENT WITH TIME

FIGURE

CG14048

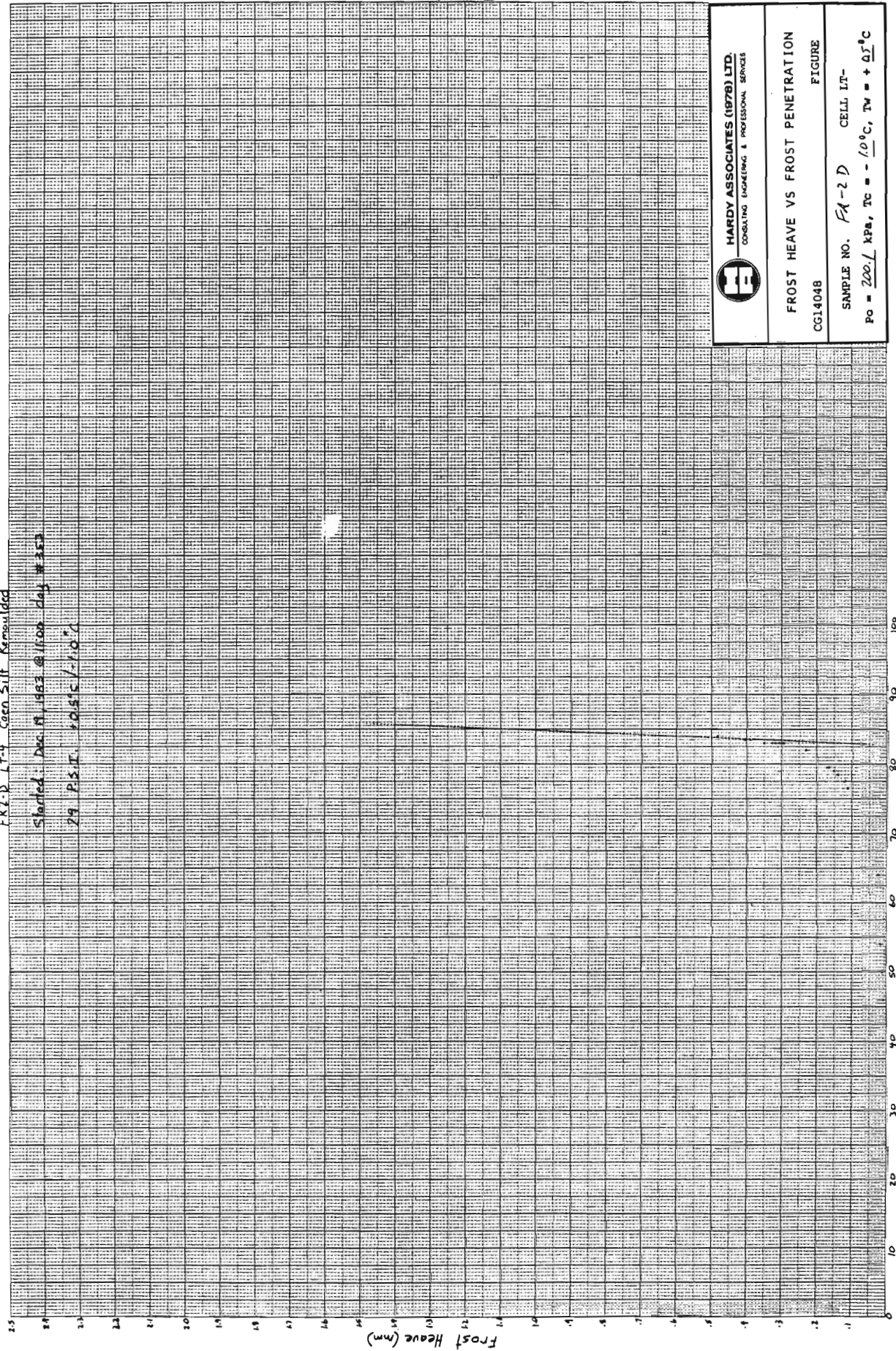
SAMPLE NO. FA-2 D CELL LT-


PO = 200.1 kPa, TC = -1.0°C, TW = +0.5°C





FR2-D LT-4 Coen Silt Remoulded  
 Started Dec 11, 1983 @ 11:00 Day #353  
 29 PSI, 10.5°C / -10°C



 <b>HARDY ASSOCIATES (1978) LTD.</b> CONSULTING ENGINEERING & PROFESSIONAL SERVICES	
<b>FROST HEAVE VS FROST PENETRATION</b>	
CCL1404B	FIGURE
SAMPLE NO. FA-2 D	CELL LT-
$P_0 = 200.1 \text{ kPa}$ , $T_0 = -10.0^\circ\text{C}$ , $T_w = +0.7^\circ\text{C}$	

FB2-D LI-4 Case Silt Remoulded

Started Dec 19, 1953 @ 1:00 day #353

29 P.M. 10.5°C / 16°C

\* Uncontrolled

end of test

end of test

Warm Bath #3

Cold Bath #3

Bath Temperatures (F°)

TIME (hours)



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

BATH TEMPERATURE WITH TIME

CG14048

FIGURE

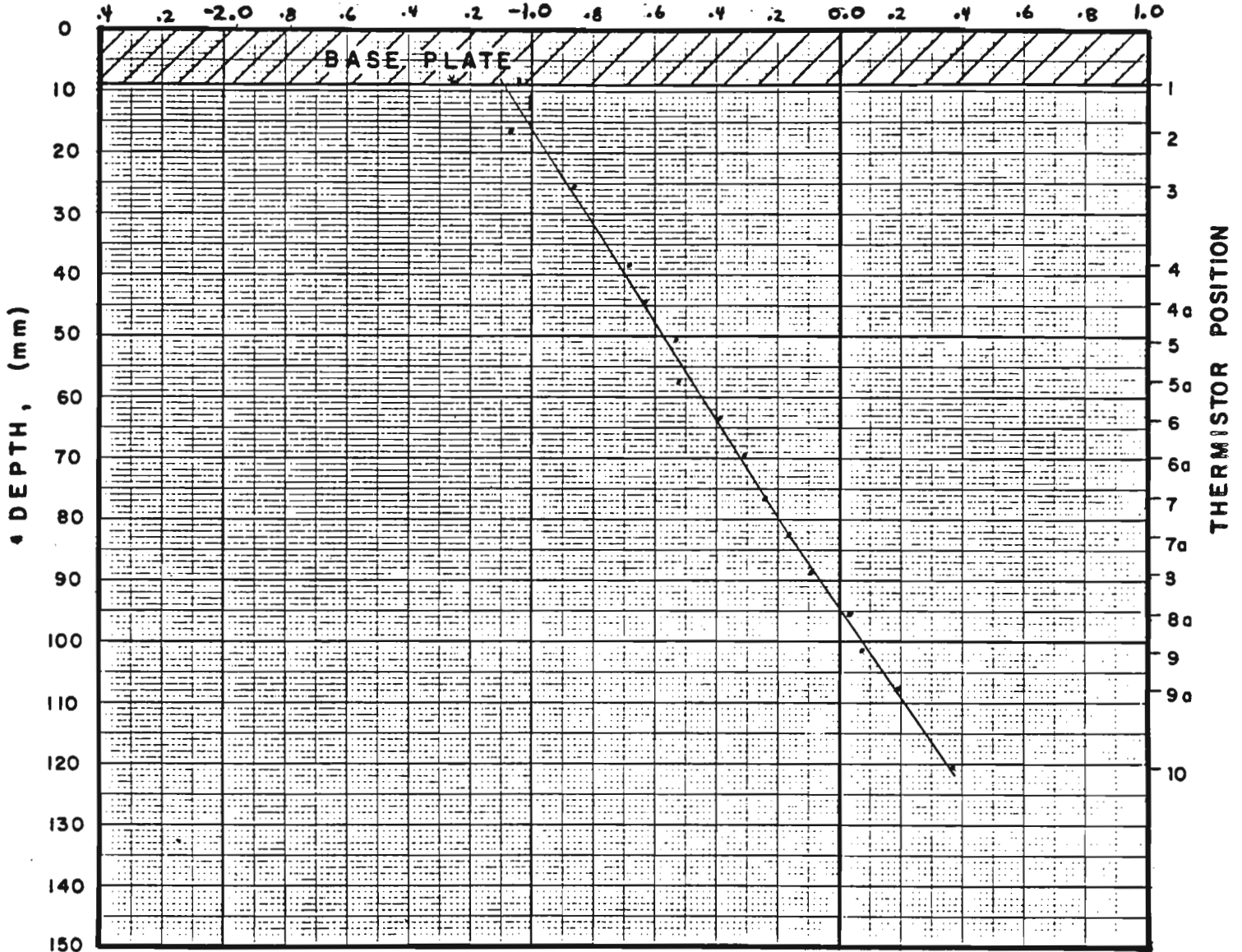
SAMPLE NO. FR-2D CELL LT-

Po = 220 / kPa, Tc = - / 0°C, Tw = + 0.5°C



# TEMPERATURE PROFILE

TEMPERATURE (°C)



THICKNESS OF BASE PLATE = 11mm.

NOTE : Thermistor No 10a in bottom plate

84

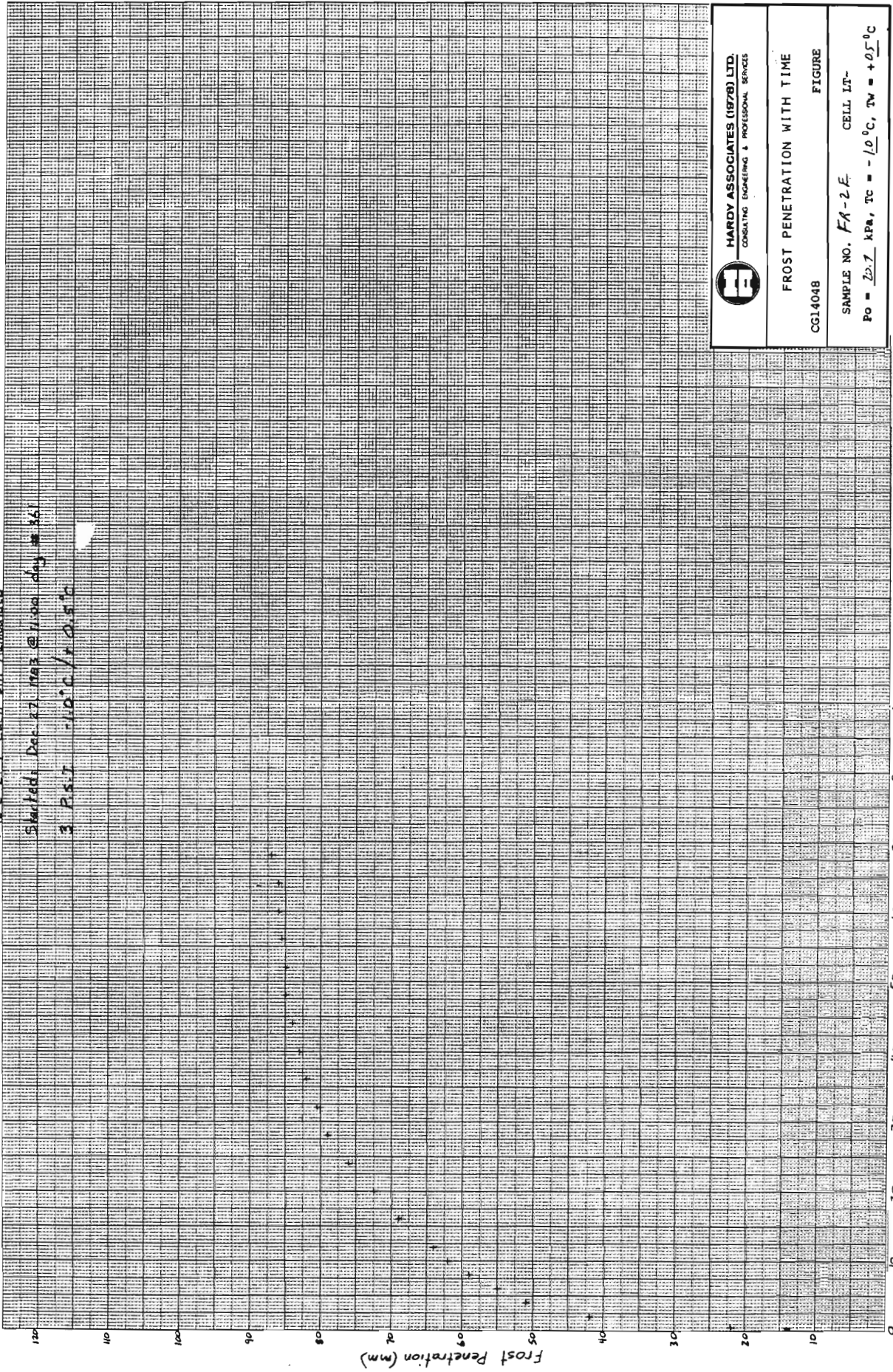
TEST FRZ-D  
 CELL -LT-4  
 DATE Dec. 22/83 355  
 SOIL Remoulded  
 Δt 70.0 9:00



FR2-E LI-4 Coen Silt Remoulded

Sealed: Dec 27, 1963 @ 11:00 AM # 361

3 PSI -10°C / +0.5°C



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

FROST PENETRATION WITH TIME

CGI4048

FIGURE

SAMPLE NO. FR-2E CELL IT-

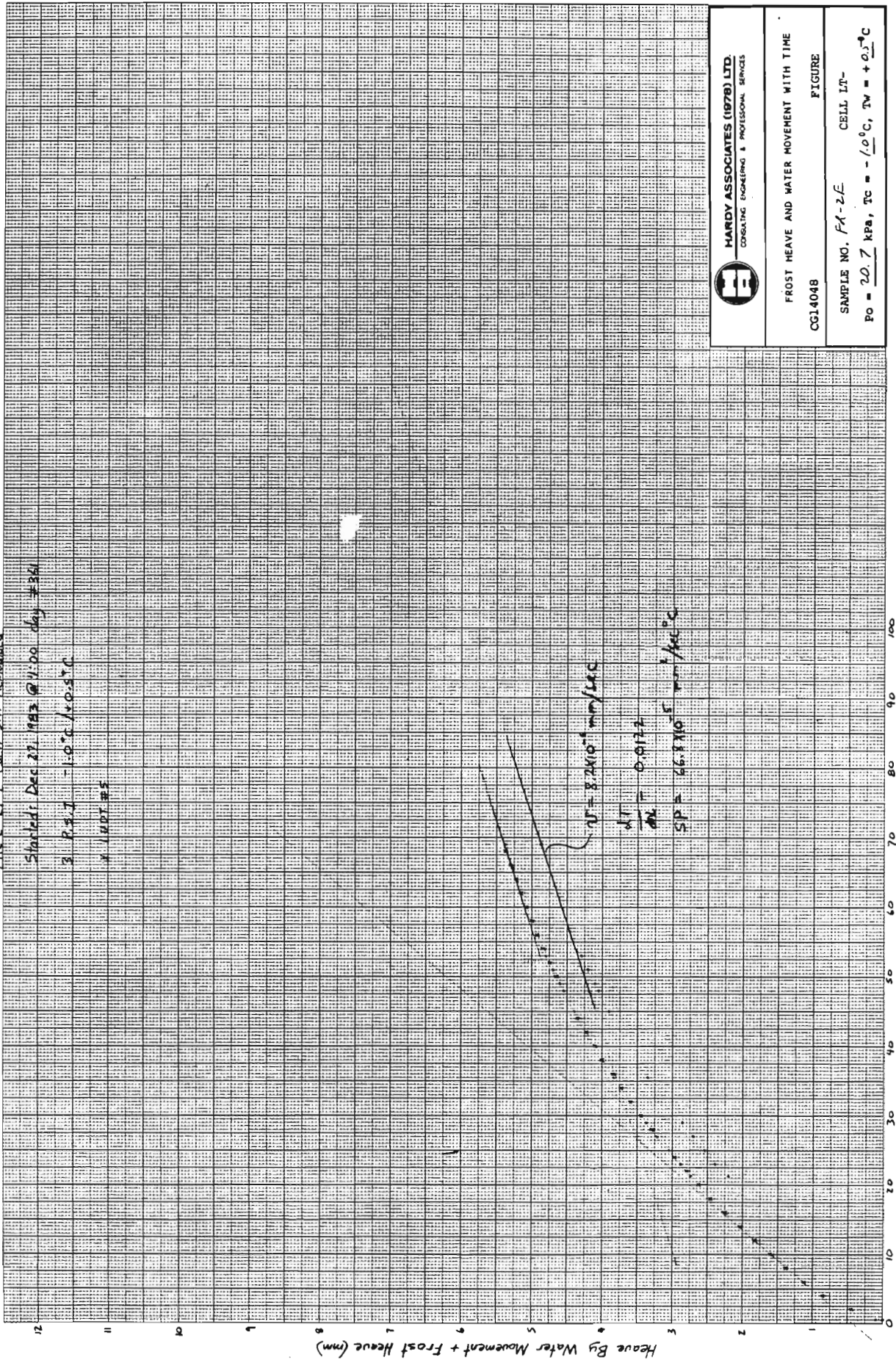
Po = 2.7 kPa, Tc = -10°C, Tw = +0.5°C

FR2-E IT-4 Coen Silt Reconstituted

Started Dec 22 1983 @ 11:00 day #384

3 P.S.T. -1.0°C / +0.5°C

X LUPT #5



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

FROST HEAVE AND WATER MOVEMENT WITH TIME

CG14048

FIGURE

SAMPLE NO. FA-2E CELL IT-

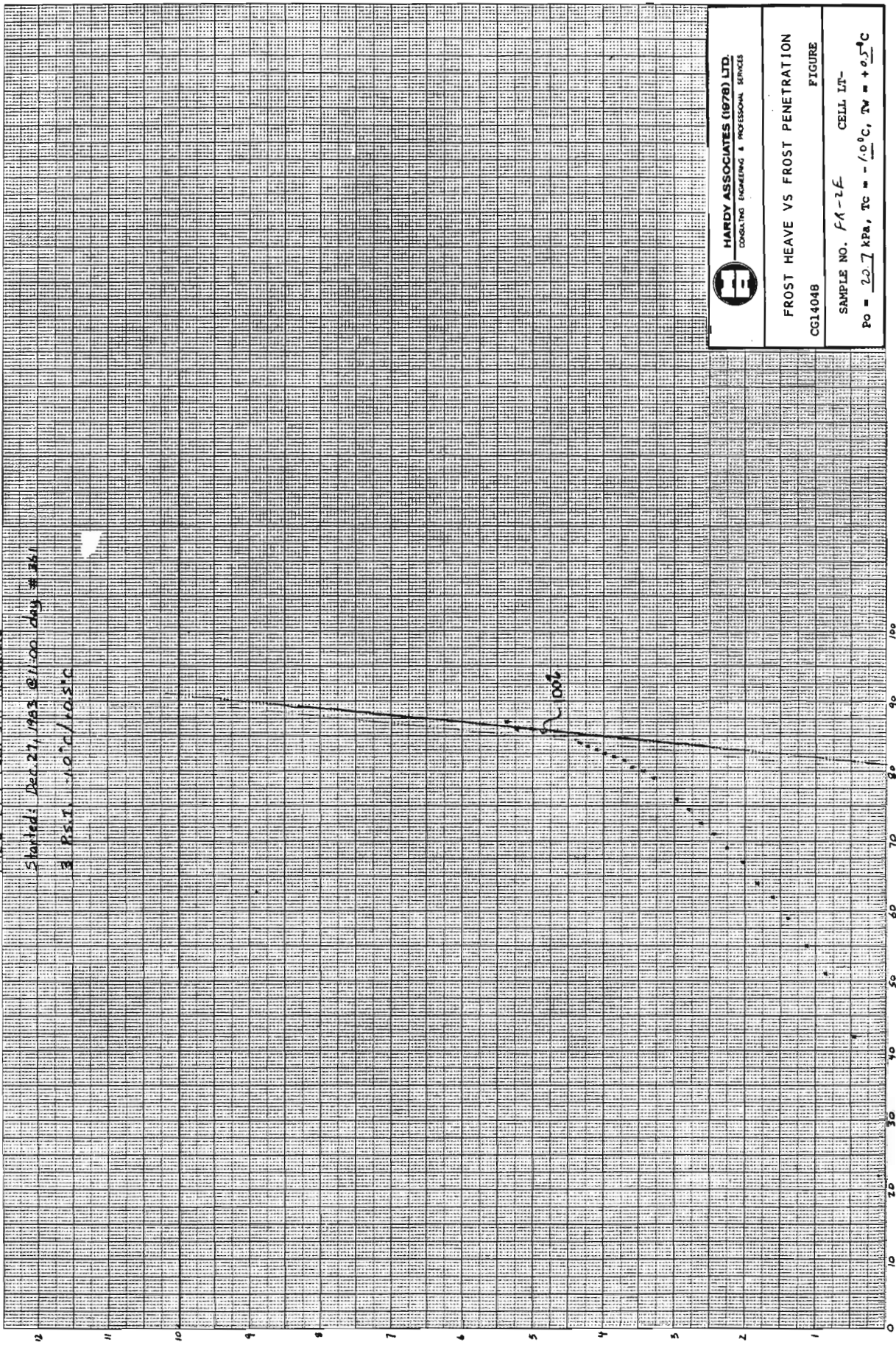
PO = 20.7 kPa, TC = -1.0°C, TW = +0.5°C



FRZ-E LT-4 Coen Silt Remolded

Started: Dec 27, 1963 @ 11:00 day # 361

3 P.S.I. -10°C / +0.5°C



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

FROST HEAVE VS FROST PENETRATION

CC1404B

FIGURE

SAMPLE NO. FA-1E CELL IT-

Po = 20.7 kPa, Tc = -10.0°C, Tm = +0.5°C

Frost Penetration (mm)

Frost Heave (mm)



FR2-E LT-4 Coen Silt Remoulded

Started Dec. 27, 1983 @ 11:00 day #361

3 P.S.T. -1.0°C / +0.5°C

\* unremoulded

Warm Bath #1

Cold Bath #1

Bath Temperatures (°C)

TIME (hours)

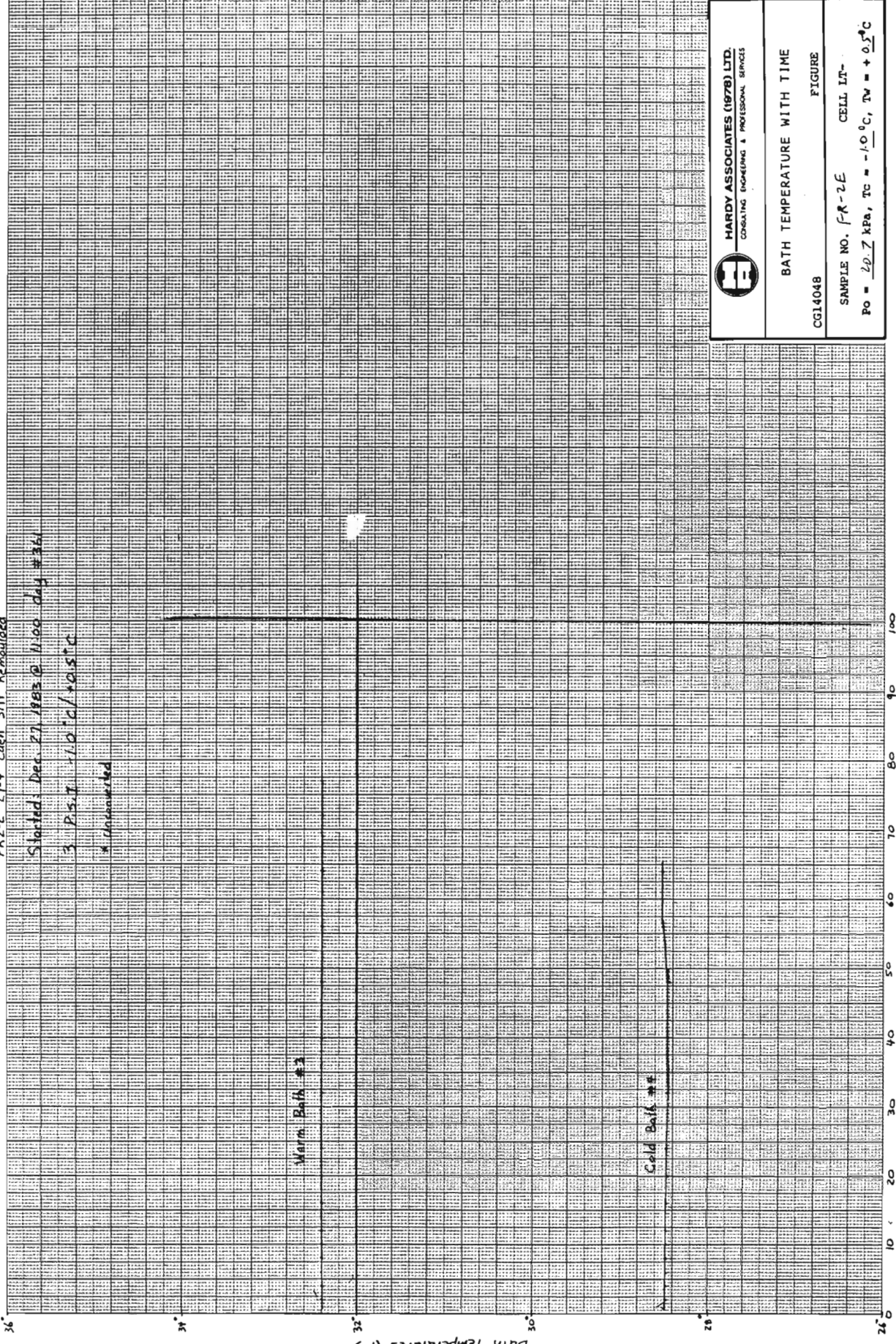
**HARDY ASSOCIATES (1978) LTD.**  
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

**BATH TEMPERATURE WITH TIME**

CG14048 FIGURE

SAMPLE NO. FA-2E CELL LT-

Po = 20.7 kPa, TC = -1.0°C, TW = +0.5°C

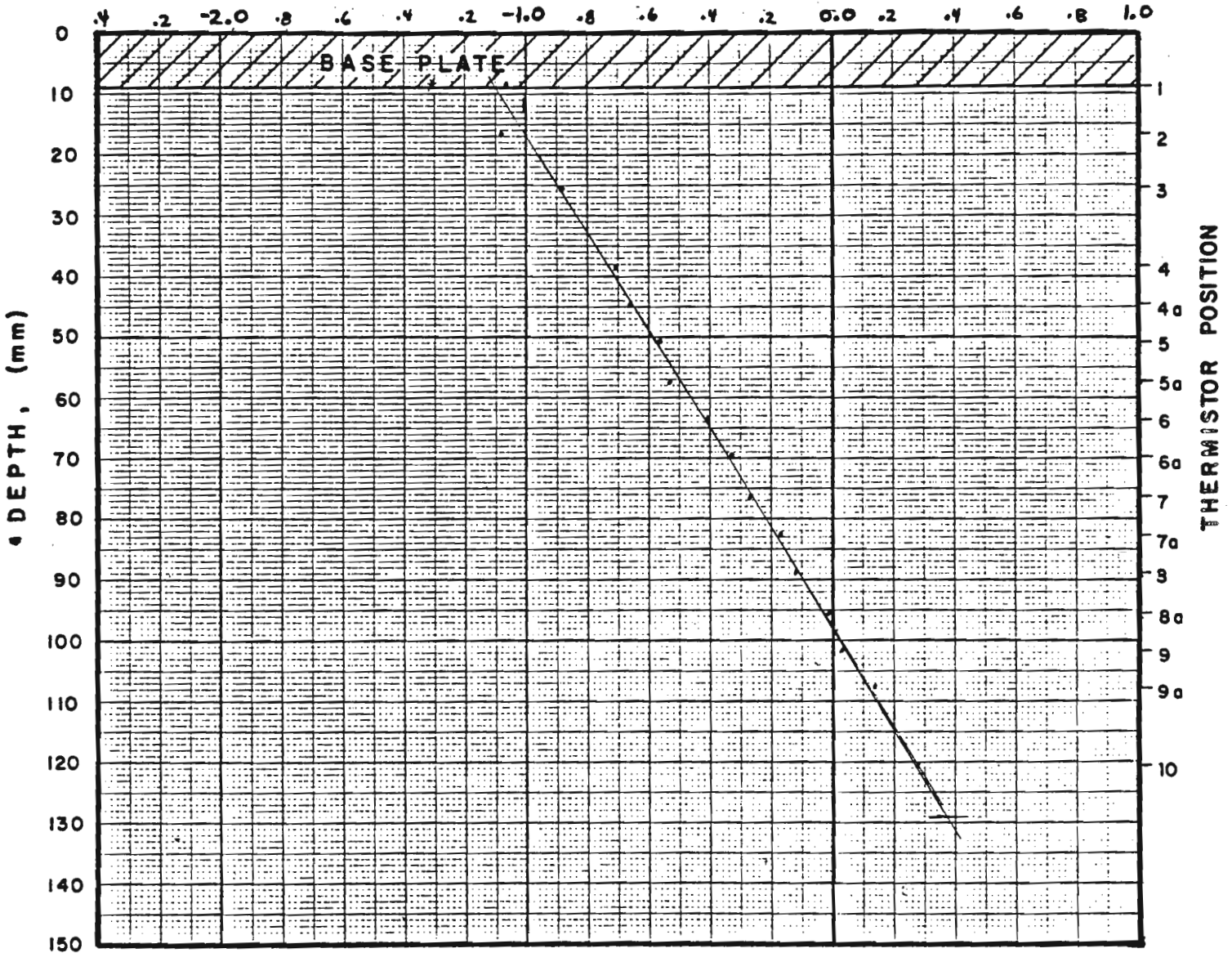


47 1510

K-E 10 X 10 TO THE CENTIMETER 2 X 2 CM

# TEMPERATURE PROFILE

TEMPERATURE (°C)



DEPTH, (mm)

THERMISTOR POSITION

THICKNESS OF BASE PLATE = 11mm.

NOTE : Thermistor No 10a in bottom plate

87

TEST FRZ-E  
 CELL LT-4  
 DATE Dec. 30/83 364  
 SOIL Remoulded  
 $\Delta t$  68.0 7:00



