DATABASE

FOR THE

CAEN FROST FEAVE

TEST FACILITY

BY

L.E.C. ENGINEERING LTD

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FOREWORD

The Geotechnical Science Laboratories (GSL) of Carleton University, funded by Energy, Mines and Resources Canada, has been operating and collecting data at the joint Canada-France chilled buried pipeline test facility since 1982. This ground freezing experiment is being carried out at the "station de gel" at the Centre de Geomorphologie, Caen, France.

The purpose of this report is to make the data collected during this project, over the past four freeze/thaw cycles, available to interested parties. The data is provided in the form of Lotus 1-2-3 spreadsheets for use on personal computers.

Substantial analyses of the thermodynamics of the freezing soils and of their creep properties have been carried out and reported by the Geotechnical Science Laboratories. Large volumes of data have been presented in the form of GSL internal reports and conference papers (see Bibliography).

Test data can be categorized into two groups:

1) Data on the elevation changes (heave or settlement) of the pipe and its corresponding bending strains.

2) Data on the soil temperature, heave and pressure buildup around the pipe.

A previous report (L.E.C. 1989) presented and described databases for the group 1 data for the first three freeze thaw cycles, plus the initial stage of the fourth freeze period.

The database HEAVE.WK1 presents the relative pipe elevation changes for the four freeze-thaw periods up to the shutdown of August 1989. The corresponding pipe bending strain data is presented in the database STRAIN.WK1. The databases which have been updated to include the complete fourth freeze and thaw periods are described in chapter 2.

Sample plots of

- Pipe heave time history of selected measuring stations
- Pipe bending strain time history of selected measuring stations
- Pipe profile at selected times during the 3rd freeze period
- Pipe bending strain along the pipe at selected times during the 3rd freeze period

are presented to give an overview of the data.

Soil temperature initially was measured using thermocouples and later for the third and fourth cycles using thermistor strings. Thermocouple data was collected every six hours. This data was analyzed to provide daily temperatures, as discussed in Appendix 1. Thermistor data is presented in a series of files named TEMP?F#.WK1, where ? is the string number (1 to 10) and # is 3 or 4, the freeze/thaw cycle number. This terminology is followed for all files mentioned below.

Soil pressure has been recorded using Glotzl and Petur cells. This data is presented for all cycles in files named GLOTZ#.WK1 and for cycles 3 and 4 in files named PETUR#.WK1.

Soil heave was recorded initially using telescopic rod assemblies and later using magnetic heave sensors. The telescopic rod data is in files HVEROD#.WK1. More refined measurements of soil heave, taken in the 3rd and 4th cycles using magnetic heave sensors, are presented in the files MAG?F#.WK1. Sample calculations of soil heave are given in the document files HVRODDOC.WK1 and MAGNTDOC.WK1.

Finally, data on the ground surface heave and settlement for the four cycles is given in files SURF#.WK1.

The data bases reported here have been prepared with the assistance of Geotechnical Science Laboratories staff. It is assumed that anyone using this database has read the corresponding GSL internal reports and conference papers, listed in the references.

1.0 INTRODUCTION

The Geotechnical Science Laboratory of Carleton University has been funded by Energy, Mines and Resources Canada to participate in a joint Canada-France investigation of the effects of frost heave around a cold pipeline. This ground freezing experiment is being carried out at the "station de gel" at the Centre de Geomorphologie, Caen, France. A detailed description of the test facility and initial set-up of the experiment is given in the Carleton Geotechnical Science Laboratory internal report number IR-29 (Burgess et al 1982).

The project is a multi-disciplinary study involving many aspects of soil freezing/thawing as well as the particular effects unique to soil freezing associated with a buried pipe. The investigation of stresses developed in a pipeline, and of the complex soil-structure interactions which occur when a chilled pipeline traverses two soils of different frost susceptibility, is an integral part of the study.

The main focus of the Caen project was to undertake a full scale experiment with precise control of the physical, thermal and hydrological conditions. The experiment does not attempt to model any particular field situation or pipeline foundation design.

The Caen project started in early 1982, with the first freeze period commencing on 21 September 1982. Resulting data from this and the subsequent freeze/thaw periods has been presented in several Carleton Geotechnical Science Laboratory internal reports (IR-29, IR-33, IR 36, IR-43, IR-50, IR-51, IR-54), in Dallimore et. al. (1984) and Smith and Patterson (1989).

Databases of both the pipe elevation data and the pipe strain data are presented in the form of Lotus 1-2-3 spreadsheets for use on personal computers. Details of these databases are presented in section 2. Section 3 disscusses temperature data, section 4 soil pressures and section 5 soil heave data. Finally, soil surface profile data is presented in section 6.

1.1 TEST FACILITY

The facility consists of a refrigerated hall 18 m long, 8 m wide and 5 m high with adjacent rooms to accommodate instrumentation and mechanical equipment. The base or trough of the hall, shown in Figures 1.1-1 and 1.1-2, is 1.75 m deep and was specifically prepared for the experiment in order to isolate the thermal and hydraulic regime from natural conditions. This isolation allows control of experimental air and ground temperatures and water table level conditions. Different soil types have been placed in each half of the trough. An 18 m long, 273 mm diameter buried

steel pipeline with an independent refrigeration system was used to freeze the ground.

1.2 CHARACTERISTICS OF SOIL MATERIALS

The pipeline is buried with 33 cm of cover in a frost susceptible silt and a non-frost susceptible sand. The Caen silt is eolian in origin and is composed of about 3 to 10 percent sand (2-0.076 mm), 75 to 85 percent silt (0.076-0.002 mm), and 10 to 20 percent clay (<0.002 mm). It has a low plasticity and can be designated as ML by the Unified Soil Classification System.

The SNEC sand is fluvial in origin and is composed of about 10 to 20 percent gravel (10-2 mm), 70 to 85 percent sand (2- 0.076 mm) and trace amounts of silt. It is poorly graded and can be classified as SP by the Unified Soil Classification system.

The two soils were placed in the trough in 300 mm lifts compacted to an approximate dry density of 1,700 kg/cu.m, for the Caen silt, and 1,850 kg/cu.m for the SNEC sand. A large number of laboratory tests have been carried out on the soils to determine heaving character, thermal properties, salt content, frozen soil strength, creep behaviour and mineralogy (see Burgess et al 1982 and Geotechnical Science Laboratories 1983, IR-36)

The unfrozen water content characteristics of the two soils has been determined by time-domain reflectometry and by the suction-moisture content relationship. A summary of the results showing unfrozen water content vs. temperature is presented in Dallimore & Williams (in Pipelines and Frost Heave, 1984).

1.3 INSTRUMENTATION

The experimental hall is heavily instrumented and a large number of readings are taken on a regular schedule. Burgess et al (1982) outline the main types of instruments and present a summary of the frequency of readings. Included are thermocouples and heat flux meters which are monitored automatically with a data acquisition unit. Regular measurements are also taken manually of thermistors, water levels, surface levelling, tensiometers, pressure cells, telescopic heave tubes, magnetic heave detectors, frost depth tubes, TDR moisture content probes, pipe deflection, pipe curvature and pipe strain. Periodic measurements include soil density profiling and gravimetric water content determinations. Where possible, all data is entered into a micro-computer on site. It is then transferred onto a magnetic tape which is sent to Canada and Paris for analysis.

1.4 OPERATING CONDITIONS

A timetable summarizing the operating conditions of the freeze and thawback cycles is seen in Table 1.4-1.

The first freeze period began in September 1982 after preparation of the facility, installation of the instrumentation, stabilization of ground water levels and cooling of the two soils. The operating conditions during the freeze period called for an ambient air temperature in the hall of -0.75 and an average pipe temperature of -2 C. The water table was regulated at an approximate depth of 90 cm below the original ground surface (initially the water table had been maintained at a 30 cm depth but due to excessive heave of the pipe and only limited frost penetration, after 3 months it was lowered to a 90 cm depth). The first freeze period continued for 8 months until June 1983. A period of thawing of the ground surface, which continued for 4 months until October 1983, followed the first freeze period. During this phase, the ambient air temperature in the hall was raised to +4 C, while the pipe temperature was held at -2 C. At the end of the thaw period a thin frozen soil zone remained below the pipe.

Following several modifications to instrumentation, a second freeze period was initiated in October 1983. The operating conditions were similar to the first freeze period, except that the average temperature of the pipe was reduced to -5 C, in order to increase the depth of frost penetration. The air temperature of the hall was set at -0.75 C and the ground water table was maintained at 90 cm below the ground surface. The second freeze period continued for 23 months until September 1985. It was followed by a second thaw cycle which lasted 5 months. During this thawback phase the pipe was not chilled, and therefore the ambient air temperature in the hall of +4 C completely thawed out the soil around the pipe.

Significant changes in instrumentation were made for the third freeze cycle in order to provide additional information on the soil freezing and frost heave process. These changes are outlined in IR-54 (1986). This third freeze period lasted 12 months from March 1986 to February 1987, during which pipe temperature was maintained at -5.25 C with an ambient air temperature of -0.75 C. A third thaw period, having identical thermal conditions to the second one, lasted three months. It was followed by a seven month shutdown of the facility.

The fourth freeze period commenced in January 88 and ran for 504 days until May 89. Thermal conditions were identical to those for the previous freeze period. Some newly-constructed measuring equipment (see IR-55 (1988)) was installed for examination of ground stress conditions. A fourth thaw period, similar to the third, lasted 83 days to Aug 89.

Table 1.4-1

Timetable of Events

EVENT	DAYS	DATE		OPERATING TEMP	
		FROM	TO	AIR/GROUND [C]	PIPE [C]
First Freeze	262	21 SEP 82	8 JUN 83	-0.75	-2
Surface Thaw	96	8 JUN 83	12 SEP 83	4	-2
Second Freeze	702	17 OCT 83	18 SEP 85	-0.75	-5
Second Thaw	136	18 SEP 85	1 FEB 86	4	ambient
Re-instru-mentation		1 FEB 86	3 MAR 86		
Third Freeze	359	3 MAR 86	25 FEB 87	-0.75	-5.25
Third Thaw	85	25 FEB 87	21 MAY 87	4	ambient
Shutdown		21 MAY 87	6 JAN 88		
Fourth Freeze	504	6 JAN 88	24 May 89	-0.75	-5.25
Fourth Thaw	83	24 May 89	15 Aug 89	4	ambient

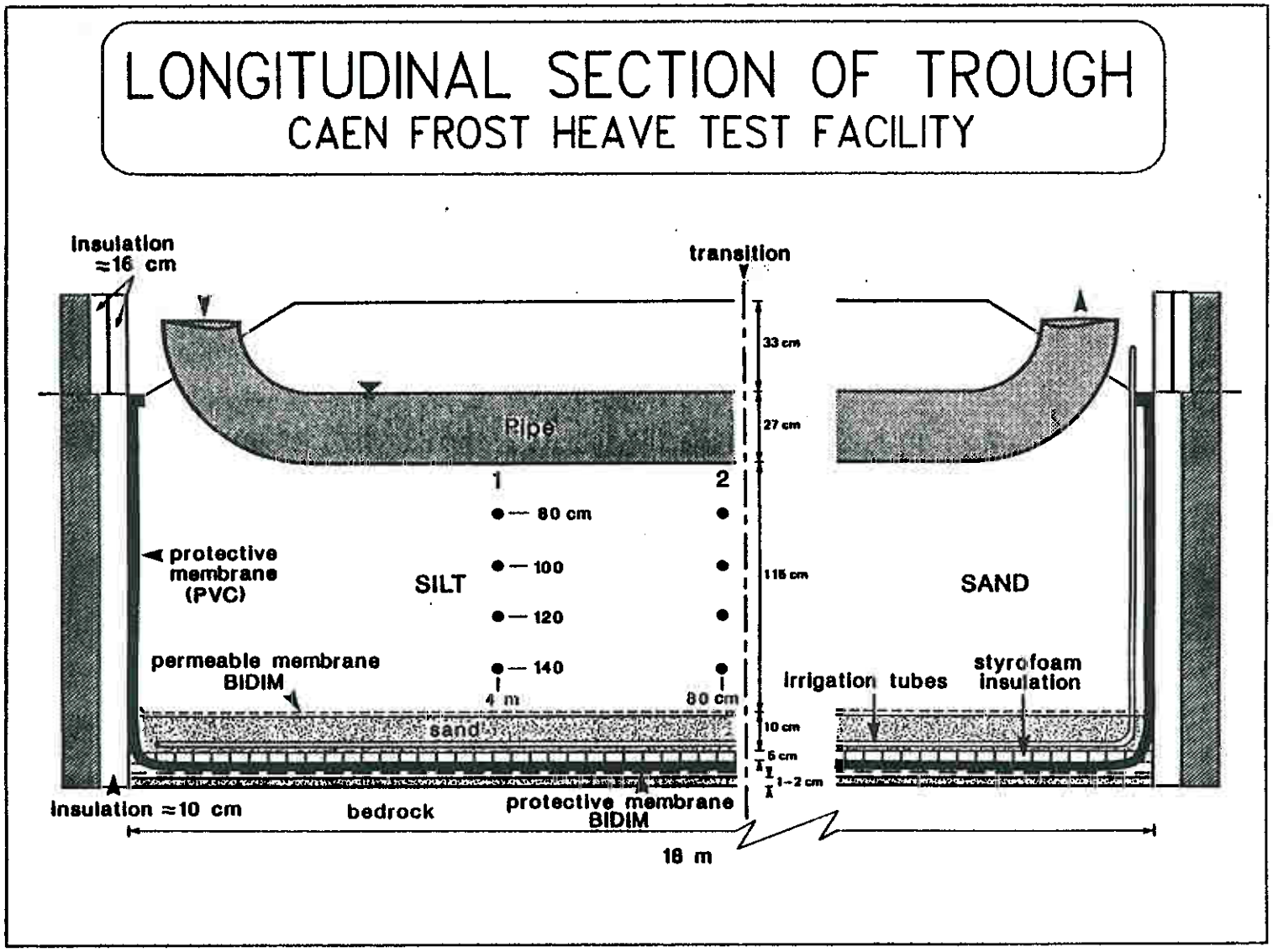
LONGITUDINAL SECTION OF TROUGH
CAEN FROST HEAVE TEST FACILITY
insulation ≈16 cm
transition
33 cm
27 cm
Pipe
1
2
80 cm
100
120
140
protective membrane (PVC)
SILT
115 cm
SAND
permeable membrane BIDIM
4 m
80 cm
irrigation tubes
styrofoam insulation
sand
10 cm
5 cm
1-2 cm
insulation ≈10 cm
bedrock
protective membrane BIDIM
18 m

FIGURE 1.1-1

CROSS SECTION OF TROUGH
CAEN FROST HEAVE TEST FACILITY

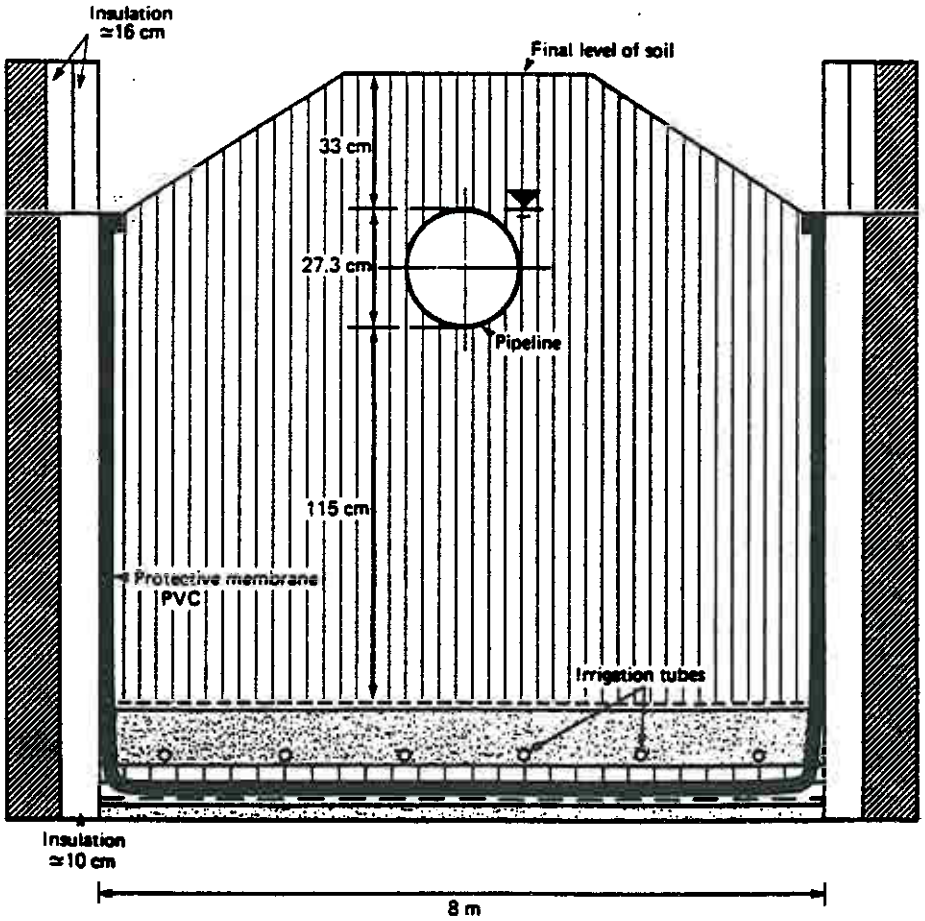

FIGURE 1.1-2

2.0 PIPE ELEVATION AND BENDING STRAIN DATA

2.1 PIPE ELEVATION DATABASE (HEAVE AND SETTLEMENT)

Pipe heave/settlement over the four cycles is seen in Figure 2.1-1, for selected stations along the pipe. A list of the heave rod locations is seen in Table 2.1. Typical pipe profile data are shown in Figure 2.1-2. These plots are for selected dates of the 3rd freeze period.

The database HEAVE.WK1, a Lotus 1-2-3 worksheet, presents the relative pipe elevation changes for the four freeze-thaw periods. A schematic layout of the spreadsheet is given in Figure 2.1-3.

DATA FILE NAME = HEAVE.WK1 (on DISK 1)

2.2 PIPE BENDING STRAIN DATABASE.

Strain gauges were mounted on the pipe at various locations prior to the first freeze. Several of these gauges have since ceased to function and will need to be replaced when a complete refurbishment of the facility is undertaken. The initial placement of the gauges is given in Table 2.2-1.

Bending strain readings for gauge pairs JA06 and JA17 are seen in Figure 2.2-1 for the four cycles. These locations showed the maximum bending strains. Typical pipe bending strain values along the pipe are seen in Figure 2.2-2. This plot is also for selected dates of the 3rd freeze period. The database STRAIN.WK1 presents the pipe bending strain data for the four freeze-thaw periods. This database is also a Lotus 1-2-3 worksheet, whose schematic layout is given in Figure 2.2-3.

The numerical values presented in the database are identical to those given in the many Geotechnical Science Laboratories reports. These values represent the strain difference measured by each strain gauge pair. They are actually <u>twice</u> the bending strain at that location along the pipe.

Stress values are calculated as

$$\text{stress(MPA)} = (E) \cdot (\text{EPSILON} / 2)$$

where EPSILON is the strain gauge pair reading in the database, and E is the Young's modulus for steel.

DATA FILE NAME = STRAIN.WK1 (on DISK 1)

TABLE 2.1-1

PIPE HEAVE ROD LOCATIONS

RODS	LOCATION ALONG PIPE [METRES]	RODS	LOCATION ALONG PIPE [METRES]
SILT END			
NP01	-7.37	NP15	0.00
NP02	-6.20	NP16	0.30
NP03	-5.70	NP17	0.80
NP04	-5.20	NP18	1.30
NP05	-4.70	NP19	1.80
NP06	-4.20	NP20	2.30
NP07	-3.70	NP21	2.80
NP08	-3.20	NP22	3.30
NP09	-2.70	NP23	3.80
NP10	-2.20	NP24	4.30
NP11	-1.70	NP25	4.80
NP12	-1.20	NP26	5.30
NP13	-0.70	NP27	5.80
NP14	-0.20	NP28	6.30
NP15	0.00	NP29	7.36
		SAND END	

TABLE 2.2-1

PIPE STRAIN GAUGE PAIR LOCATIONS

STRAIN GAUGE PAIR	OCATION ALONG PIPE [METRES]	STRAIN GAUGE PAIR	OCATION ALONG PIPE [METRES]
SILT END			
JA01	-7.05	JA12	0.14
JA02	-5.62	JA13	0.54
JA03	-4.33	JA14	0.90
JA04	-3.59	JA15	1.24
JA05	-3.00	JA16	1.60
JA06	-2.33	JA17	2.35
JA07	-1.49	JA18	3.05
JA08	-1.09	JA19	3.64
JA09	-0.79	JA20	4.40
JA10	-0.48	JA21	5.68
JA11	-0.09	JA22	7.13
		SAND END	

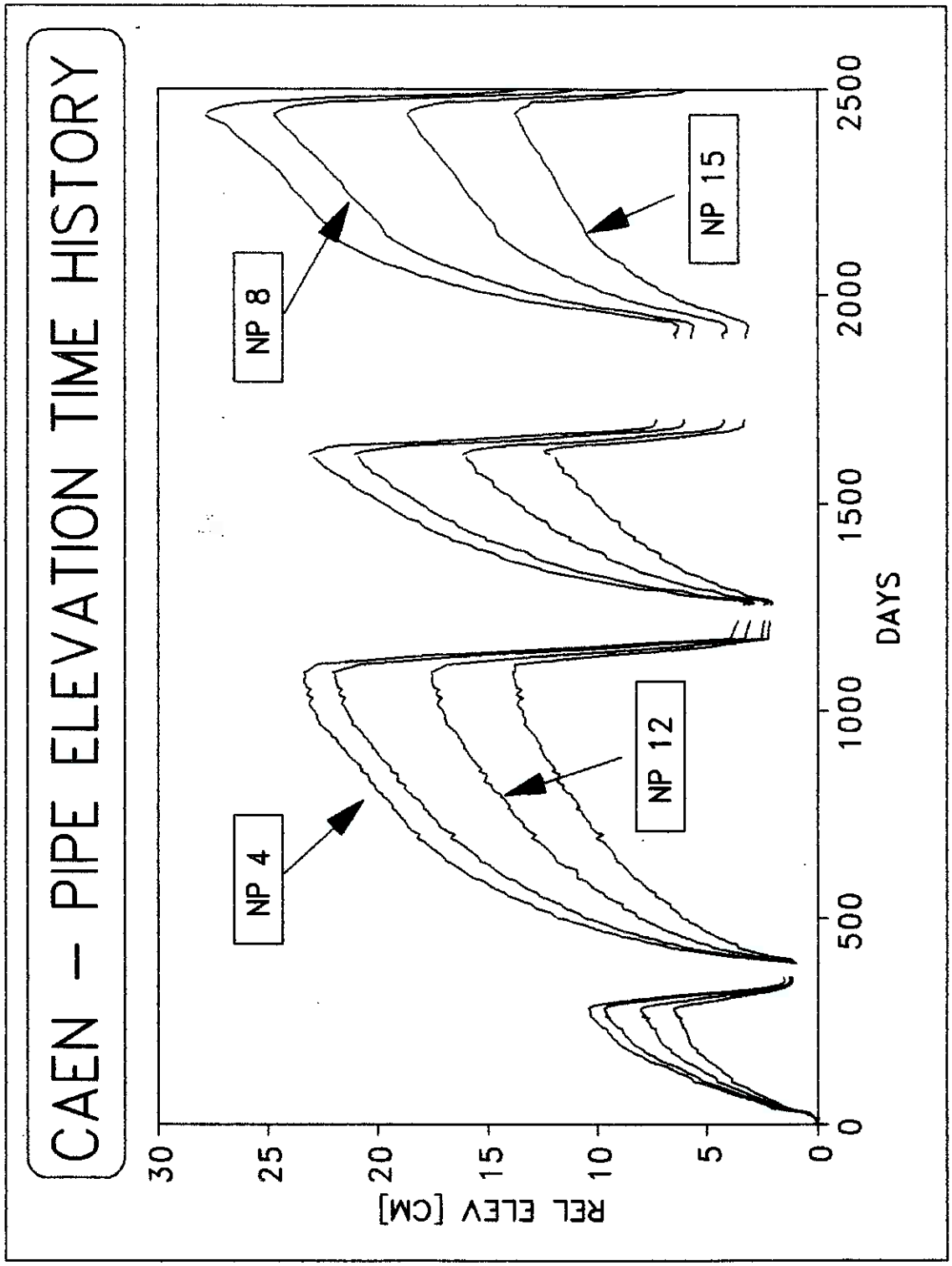
CAEN – PIPE ELEVATION TIME HISTORY
NP 4
NP 8
NP 12
NP 15
REL ELEV [CM]
30
25
20
15
10
5
0
0
500
1000
1500
2000
2500
DAYS

FIGURE 2.1-1

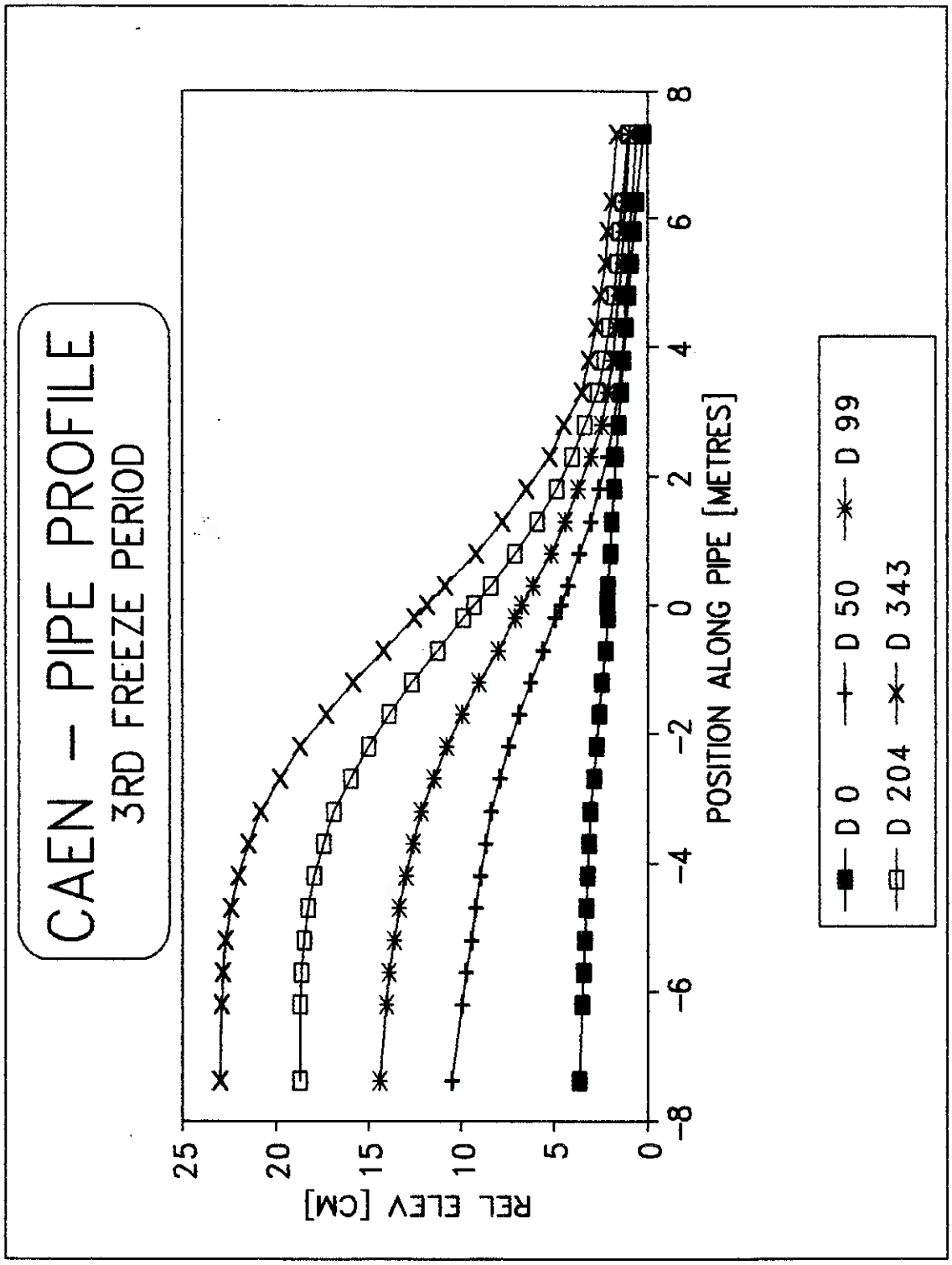
CAEN – PIPE PROFILE
3RD FREEZE PERIOD
REL ELEV [CM]
25
20
15
10
5
0
-8
-6
-4
-2
0
2
4
6
8
POSITION ALONG PIPE [METRES]
D 0
D 50
D 99
D 204
D 343

FIGURE 2.1-2

HEAVE.WK1
LOTUS 1-2-3 SPREADSHEET LAYOUT

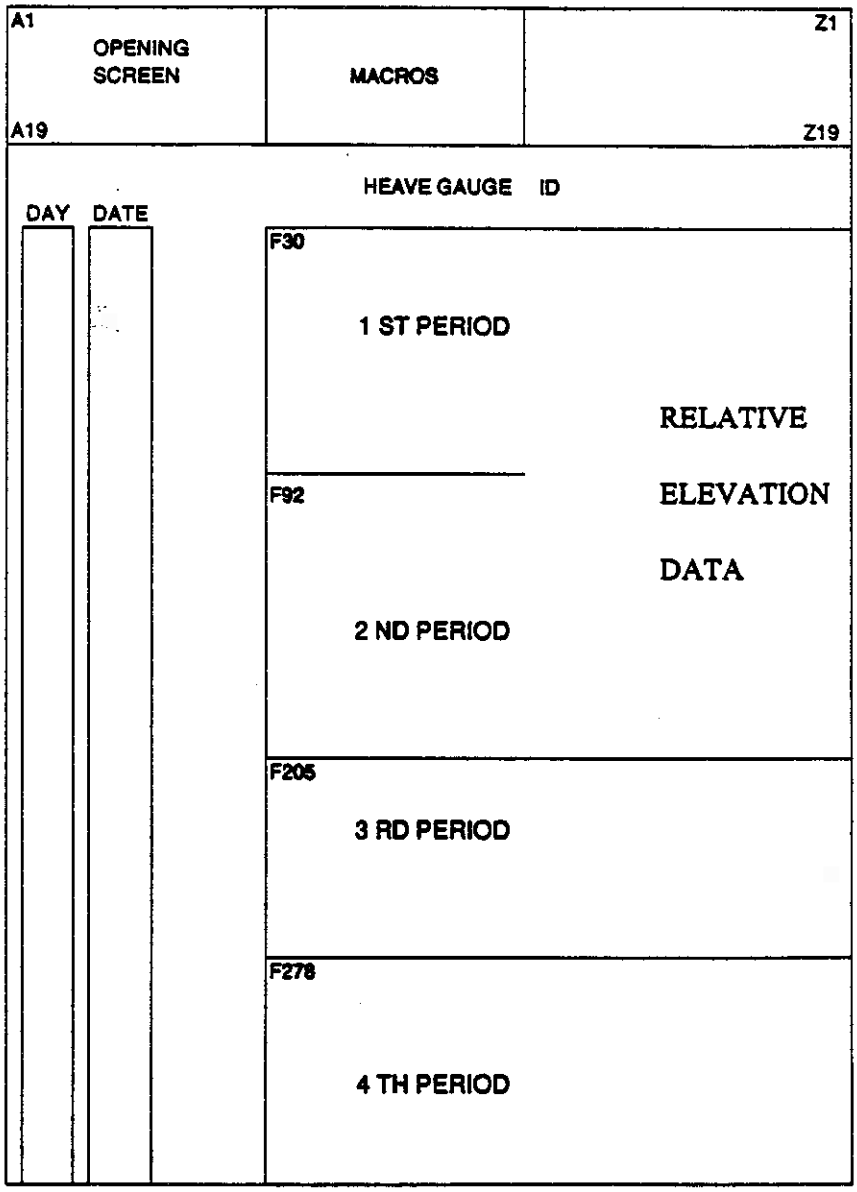

FIGURE 2.1-3

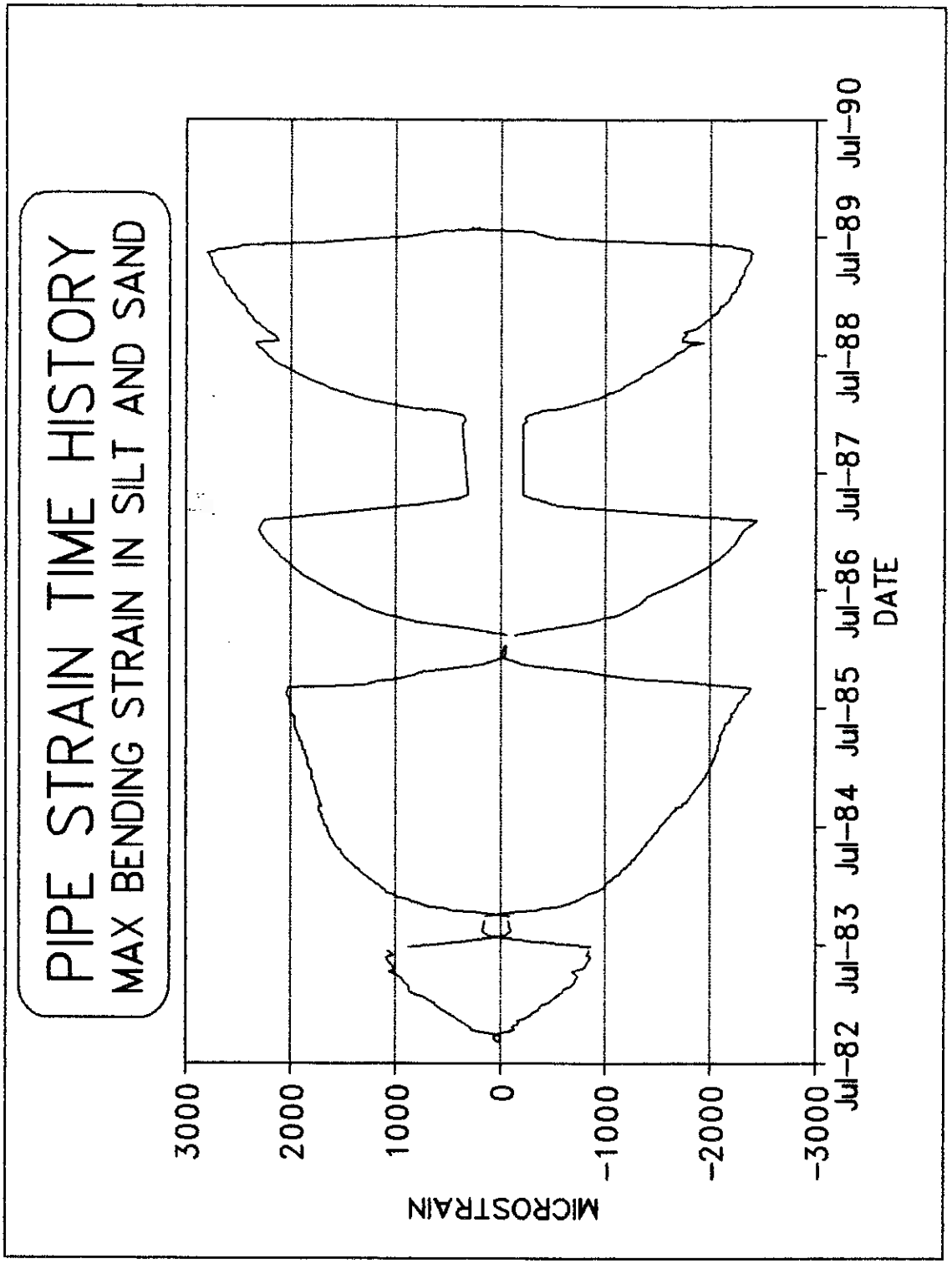
PIPE STRAIN TIME HISTORY
MAX BENDING STRAIN IN SILT AND SAND
MICROSTRAIN
3000
2000
1000
0
-1000
-2000
-3000
Jul-82
Jul-83
Jul-84
Jul-85
Jul-86
Jul-87
Jul-88
Jul-89
Jul-90
DATE

FIGURE 2.2-1

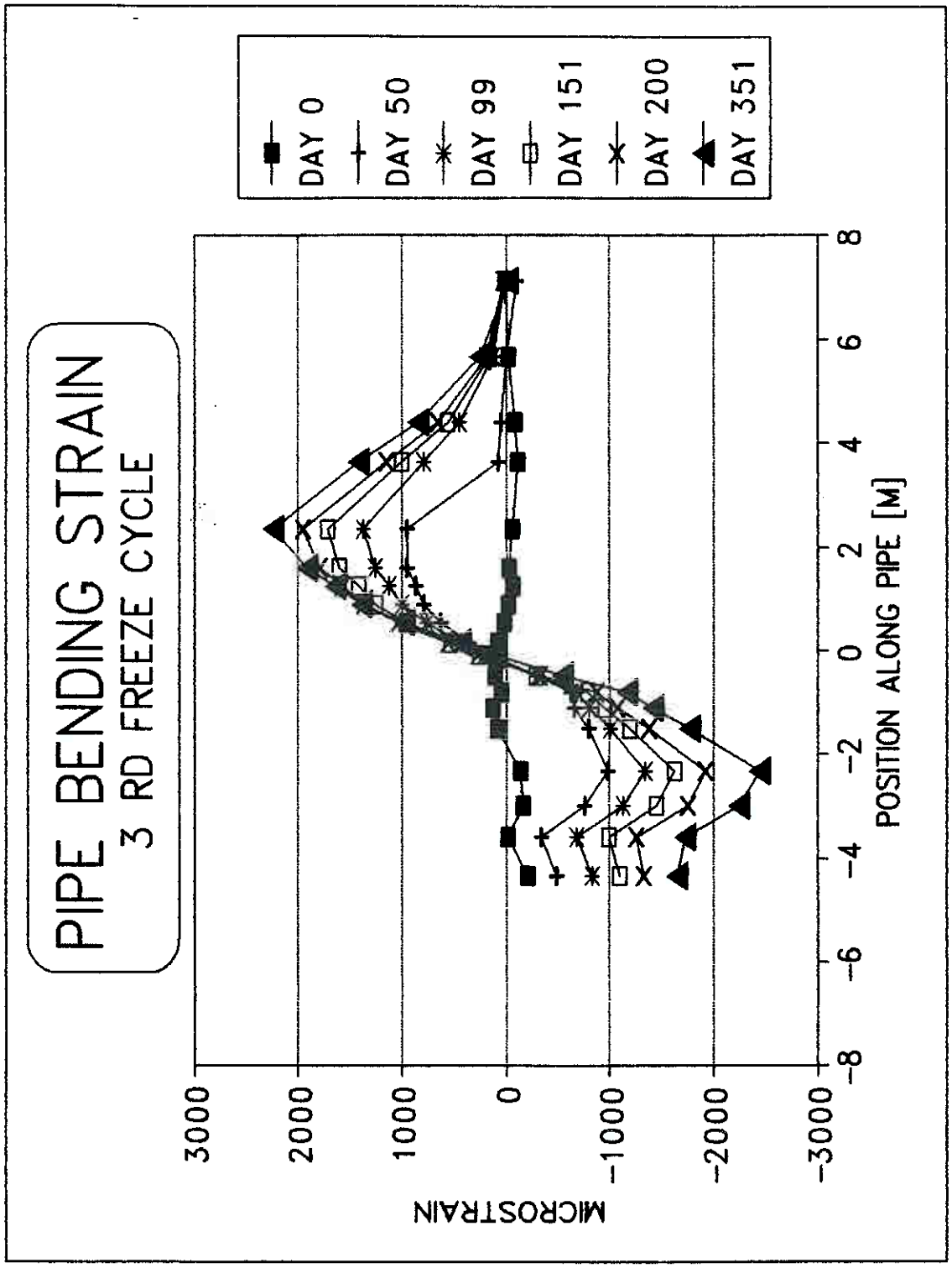
PIPE BENDING STRAIN
3 RD FREEZE CYCLE
DAY 0
DAY 50
DAY 99
DAY 151
DAY 200
DAY 351
MICROSTRAIN
3000
2000
1000
0
-1000
-2000
-3000
-8
-6
-4
-2
0
2
4
6
8
POSITION ALONG PIPE [M]

FIGURE 2.2-2

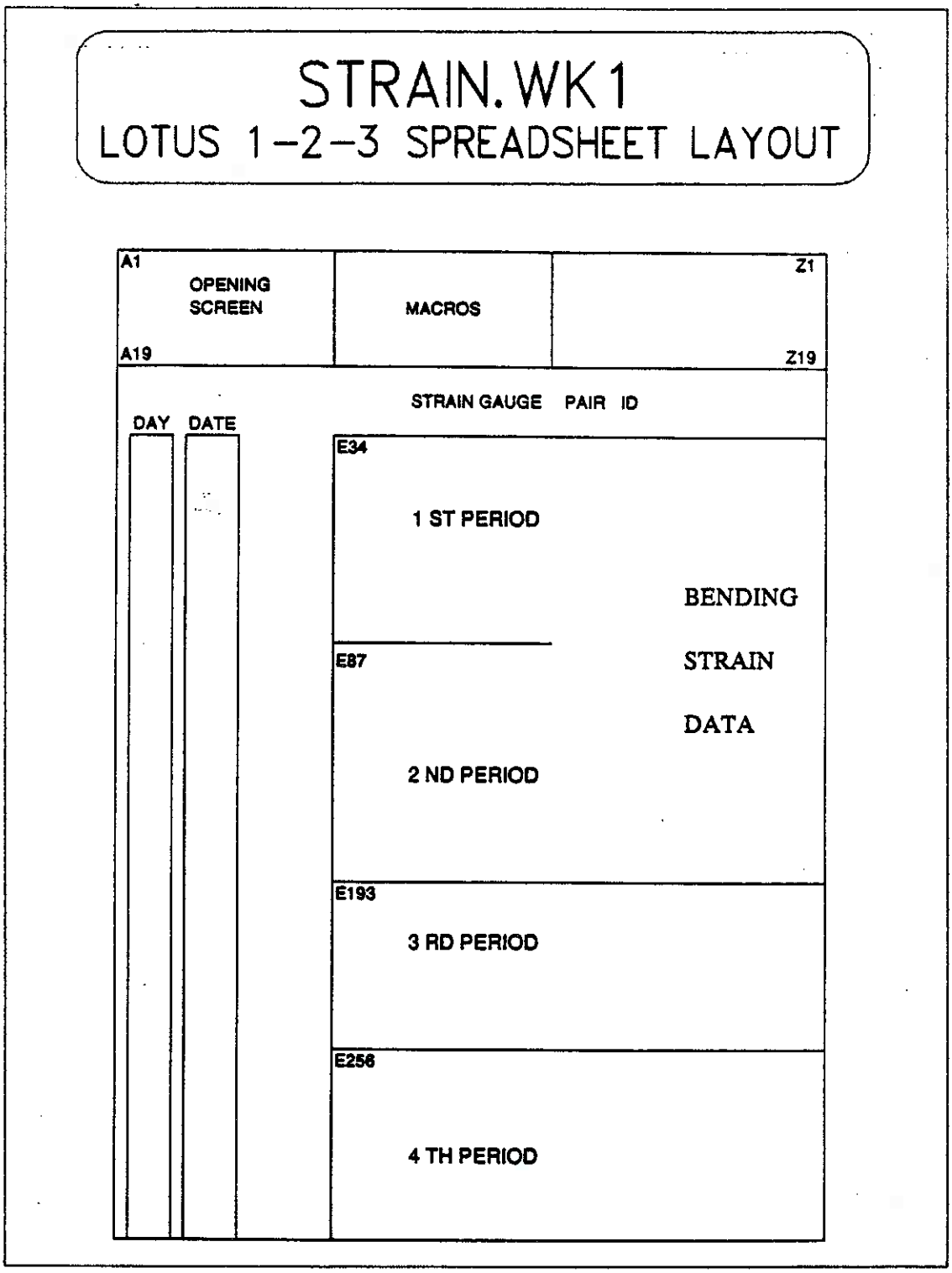
STRAIN.WK1
LOTUS 1-2-3 SPREADSHEET LAYOUT
A1
OPENING SCREEN
A19
MACROS
Z1
Z19
STRAIN GAUGE PAIR ID
DAY
DATE
E34
1 ST PERIOD
E87
2 ND PERIOD
E193
3 RD PERIOD
E256
4 TH PERIOD
BENDING
STRAIN
DATA

FIGURE 2.2-3

3.0 Soil temperature

Chilling of the buried pipe freezes the surrounding soil. Growth of this frost bulb is accompanied by soil and pipe frost heave. In order to correlate this heave with the frost bulb growth, it is necessary to measure the soil temperature.

This was done during the 1st and 2nd freeze periods using thermocouples individually placed in the soil around the pipe. Due to the cyclic heave and thaw settlement of the soil, the exact location of each thermocouple, relative to the pipe, became uncertain. Therefore, additional instruments in the form of vertical strings of thermistors were installed before the 3rd freeze period. These strings have a fixed spacing between thermistors and the overall movement of the strings is surveyed periodically. The thermistor strings were adjusted so that the #1 thermistor was at local ground surface for the beginning of both the third and fourth freeze cycles.

3.1 Thermocouples

The thermocouples (copper-constantan) were placed around the pipelines along the different sections (Figure 3.1-1). In sections AA and BB a high density of observations is important in order to follow the development of the frost front precisely. These sections each contain 47 thermocouples as seen in Fig. 3.1-2, whereas sections CC,DD,EE, and FF each contain only 14 thermocouples (Fig. 3.1-3). File XSECTION.wk1 contains the original coordinates of the thermocouples.

The thermocouples, with four readings per day, produced volumes of data. For purpose of this database, the datalogger data has been filtered and analyzed (by Goetechnical Science Laboratories personnel) to produce daily temperatures for each thermocouple location. An outline of the procedure is given in Appendix 1.

Data files for the A-A and B-B cross-sections, as well as along the pipe axis, are presented in spreadsheet files.

DATA FILE NAMES =	?-A.WK1,	?-B.WK1,	?-PIPE.WK1	(DISKs 3-8)
	XSECTION.WK1			(on DISK 1)

where ? stands for periods 1, 2, 3 & 4.

3.2 Thermistors

Sets of thermistor cables were installed, for the 3rd freeze period, in the soil at ten locations as shown in Fig. 3.2-1. The new temperature sensors were installed to augment the existing thermocouple sensors and to provide better resolution of soil temperature with depth. The thermistors used are YSI 44004 which have been individually calibrated. Table 3.2-1 gives the string locations. The thermistors were installed in multiconductor cables, which in turn were placed in oil-filled tubes extending from the soil surface to about 165 cm. depth. Thermistors are located at 0, 15, 30, 45, 60, 75, 90, 105, 120, 135, and 160 cm. The top thermistor was placed at the soil surface for the start of both the 3rd and 4th freeze periods.

Optical surveys of the thermistor tubes on a regular basis ensured that the position of each thermistor was known exactly (see file THERHVE4.WK1).

Each thermistor string is located adjacent to a set of magnetic heave sensors so that an improved correlation between heave and temperature could be obtained. The thermistors are read three times a week.

```
DATA FILE NAME = TEMP1F3.WK1  to TEMP10F3.WK1    and
                 TEMP1F4.WK1  to TEMP10F4.WK1
                 THRMHVE3.WK1  & THRMHVE4.WK1     (all on DISK 2)
```

Table 3.2-1

Temperature Sensor Locations

Site No.	Distance along axis [m]	Distance off axis [m]
1	5.56	0.24
2	4.38	0.25
3	4.39	0.64
4	4.44	1.01
5	4.33	2.00
6	3.28	0.25
7	2.17	0.28
8	1.25	0.27
9	0.63	0.24
10	-0.62	0.25

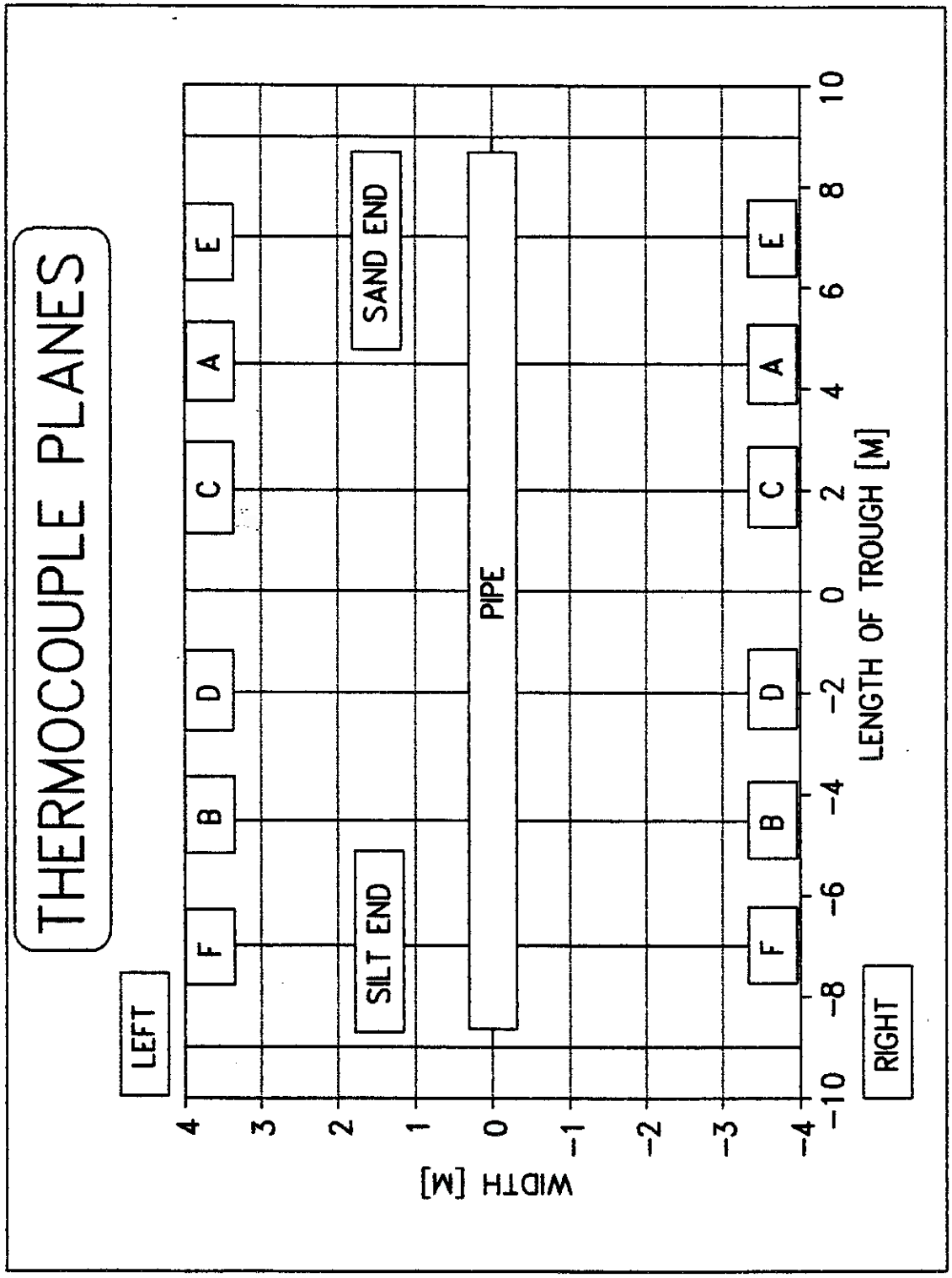
THERMOCOUPLE PLANES
LEFT
RIGHT
SILT END
SAND END
PIPE
F
B
D
C
A
E
WIDTH [M]
LENGTH OF TROUGH [M]
4
3
2
1
0
-1
-2
-3
-4
-10
-8
-6
-4
-2
0
2
4
6
8
10

FIGURE 3.1-1

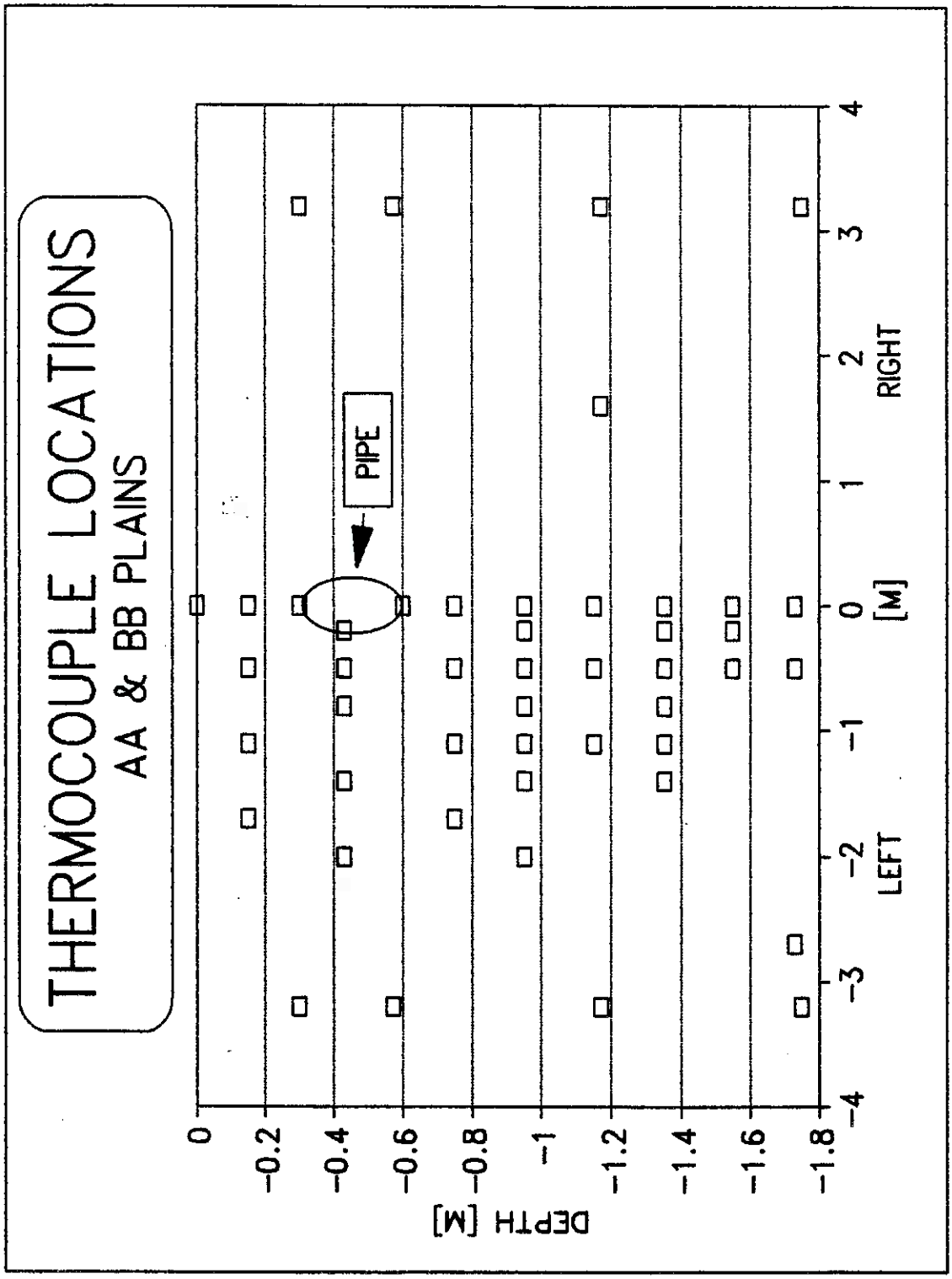
THERMOCOUPLE LOCATIONS
AA & BB PLAINS
PIPE
DEPTH [M]
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
LEFT
RIGHT
[M]
-4
-3
-2
-1
0
1
2
3
4

FIGURE 3.1-2

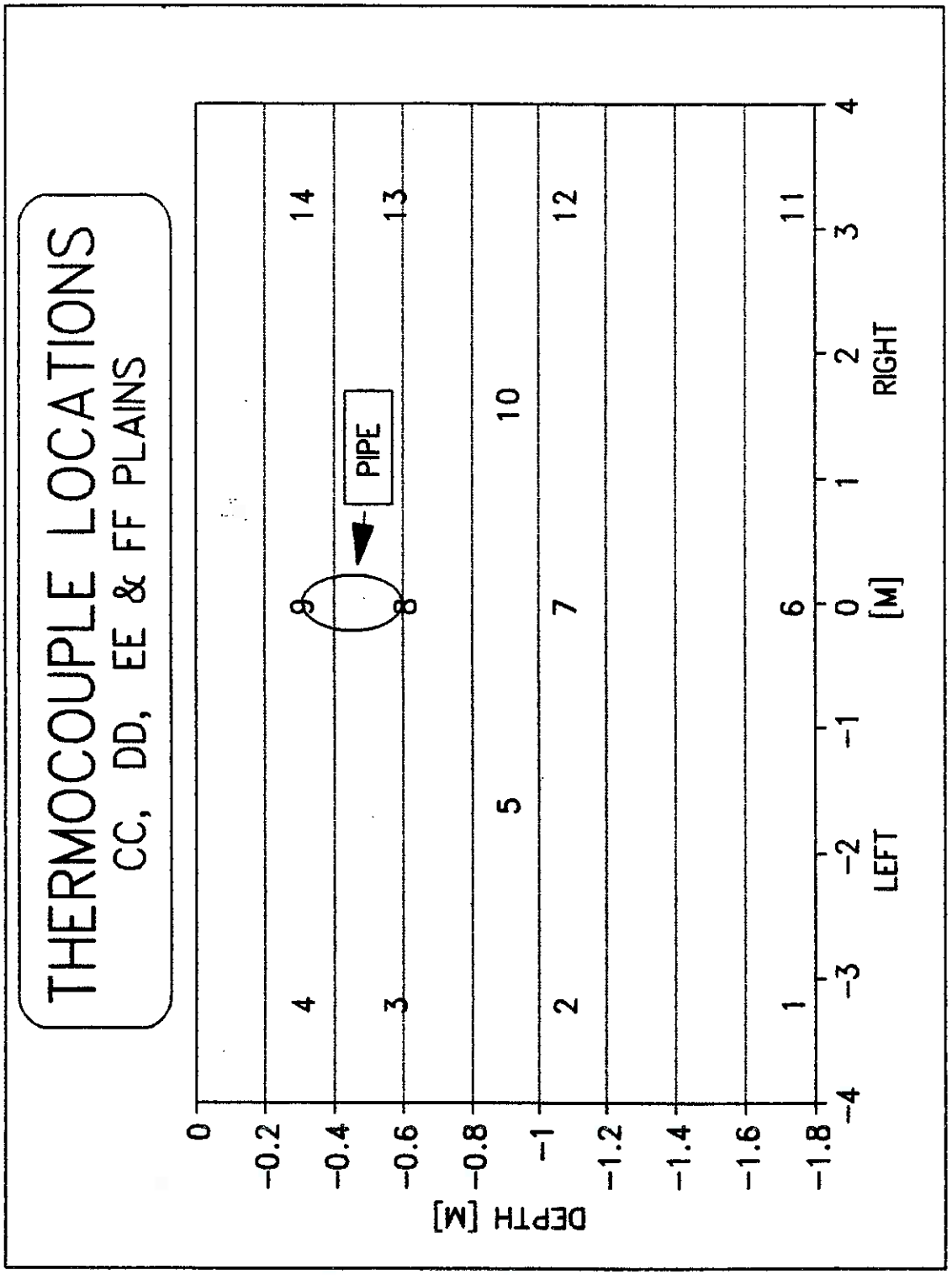
THERMOCOUPLE LOCATIONS
CC, DD, EE & FF PLAINS
PIPE
DEPTH [M]
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-4
-3
-2
-1
0
1
2
3
4
[M]
LEFT
RIGHT
1
2
3
4
5
6
7
8
9
10
11
12
13
14

FIGURE 3.1-3

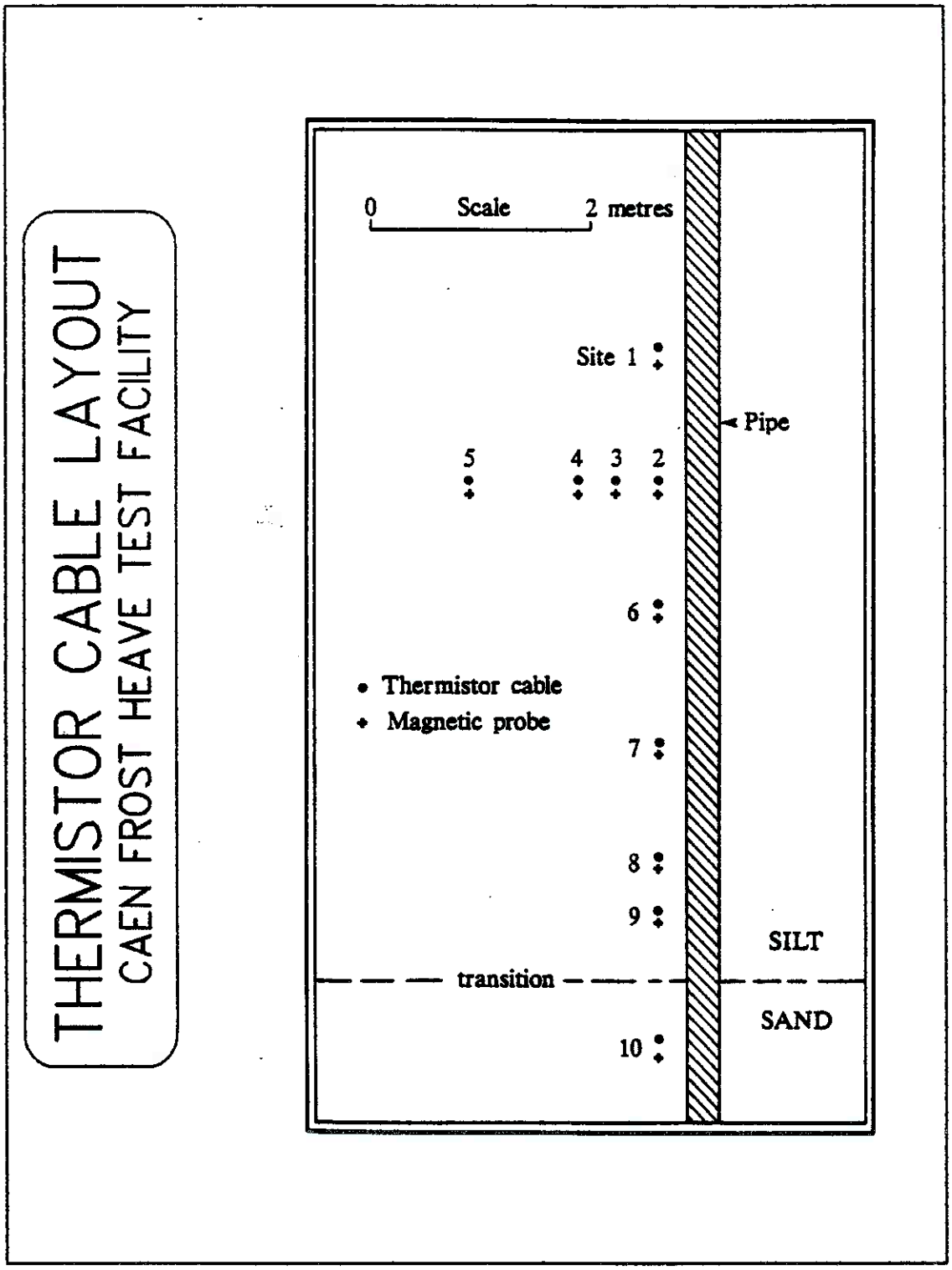
THERMISTOR CABLE LAYOUT
CAEN FROST HEAVE TEST FACILITY
0
Scale
2 metres
Site 1
Pipe
5
4
3
2
6
Thermistor cable
Magnetic probe
7
8
9
SILT
transition
SAND
10

FIGURE 3.2-1

4.0 Soil pressure data.

Soil pressure was measured using Glotzl cells for all four freeze/thaw cycles. In addition, Petur cells were added for the 3rd and 4th cycles.

4.1 Glotzl cell - placement

The total soil pressure is measured in several locations with the aid of Glotzl cells , as indicated in Figure 4.1-1 and Table 4.1-1. Each cell comprises a double membrane, which is filled with oil and is deformable on application of external pressure. One measures the pressure of the oil within the cell by bringing a nitrogen source to an equal pressure. The pressure of nitrogen is measured in the data acquisition room. Data from a typical Glotzl cell is shown in Figure 4.1-2, for the fourth freeze period.

DATA FILE NAME = GLOTZL1.WK1 to GLOTZL4.WK1 (DISK 1)

4.2 Petur cells

Petur pressure cells were installed for the 3rd freeze period in four vertical profiles directly beneath the pipe in the silt section to obtain additional information on soil stress during freezing. The installation required the excavation of pits approximately 2m deep and 70 by 70 cm cross-section. It was decided that digging these pits was easier than attempting to bore a number of inclined holes beneath the pipe. This excavation also offered the opportunity to examine the soil structure and the pipe following two freeze cycles. Cell locations are given in Table 4.2-1.

The Petur cells were excavated and refurbished prior to the fourth freeze cycle, since many of the cells failed during the third freeze cycle due to leaks in the oil-filled rubber bulbs which cover the diaphragm. The initial failure seems to have occurred because the rubber weakened when in contact with soil water for extended periods of time. A new type of rubber bulb was used which was more robust and did not weaken when wet (see IR-51 & IR-54). Soil pressure beneath the pipe near the B-B transition in the silt section are shown in Figure 4.2-1. Pressure values are given in millibars (10 mb = 1 KPa) and are shown as the change since Day 0 of the 4th freeze in order to remove the effects of overburden pressures and residual pressures which arise during sensor assembly. The sensor depths refer to their initial placement beneath the soil surface prior to the fourth freeze.

DATA FILE NAME = PETUR3.WK1 and PETUR4.WK1 (DISK 1)

Table 4.1-1

Location of Glotzl Cells

Cell #	Distance from transition	Distance from Pipe	Depth Beneath Pipe
1	7	0	0.46
2	4.5	0	0.86
3	4.5	0	0.46
4	4.5	0	0.10
5	4.5	0.25	0.46
6	4.5	1	0
7	2	0	0.46
8	-2	0	0.46
9	-4.5	0	0.86
10	-4.5	0	0.46
11	-4.5	0	0.10
12	-4.5	0.25	0.46
13	-4.5	1	0
14	-7	0	0.46

Cells 1 to 7 are in the Silt section
Cells 8 to 14 are in the Sand section

All distances are in metres from the sand-silt transition
All depths are in metres beneath the pipe.

Cells 5, 6, 12 and 13 are installed in a vertical orientation to measure lateral pressures.

Table 4.2-1

Location of Petur Cells

SITE #	Cell #	Distance from transition	Distance from Pipe	Depth Beneath Pipe	TYPE
1	1	4	0	0.80	t
	2	4.15	0	1.01	v
	3	4	0	1.01	t
	4	3.85	0	1.01	l
	5	4	0	1.18	t
	6	4	0	1.40	t
2	7	3.66	1.03	0.45	t
	8	3.66	1.03	0.75	t
	9	3.66	1.03	1.05	t
	10	3.66	1.03	1.35	t
3	11	2.35	0	0.10 *	t
	12	2.35	0	0.30 *	t
4	13	0.85	0	0.80	t
	14	1	0	1.01	v
	15	0.85	0	1.01	t
	16	0.7	0	1.01	l
	17	0.85	0	1.18	t
	18	0.85	0	1.40	t
5	19	-2.35	0	0.10 *	t
	20	-2.35	0	0.30 *	t

t total pressure
v directional (vertical component)
l directional (lateral component)

Sites 1 to 4 are in the silt section and site 5 is in the sand.

All distances are in metres from the sand-silt transition and all depths are in metres beneath the soil surface except those noted below.

Depths marked with a * denote sensors located beneath the cavity which has formed between the pipe and the soil. The depths noted are beneath this cavity.

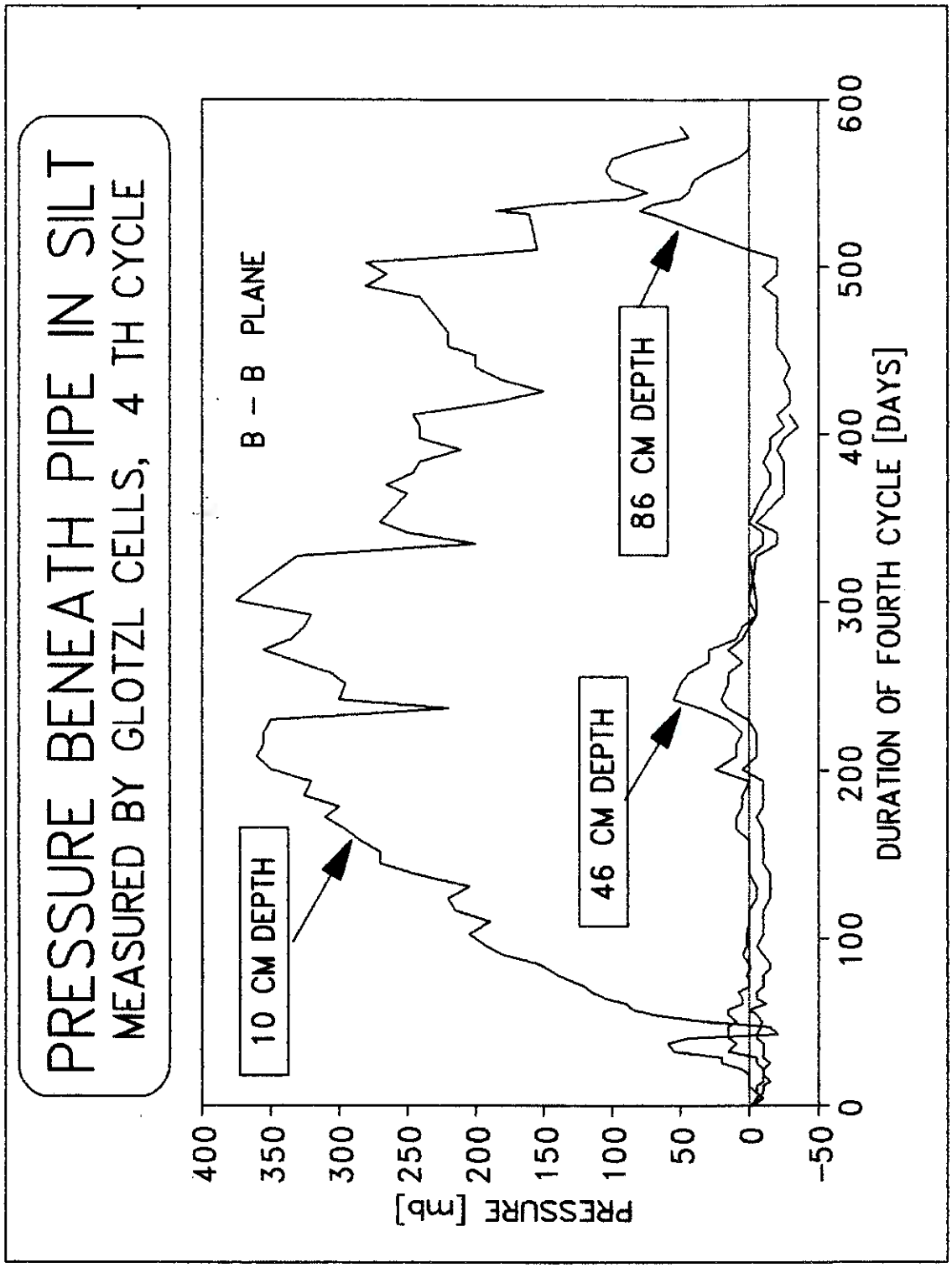
PRESSURE BENEATH PIPE IN SILT
MEASURED BY GLOTZL CELLS, 4 TH CYCLE
B – B PLANE
10 CM DEPTH
46 CM DEPTH
86 CM DEPTH
PRESSURE [mb]
400
350
300
250
200
150
100
50
0
-50
0
100
200
300
400
500
600
DURATION OF FOURTH CYCLE [DAYS]

FIGURE 4.1-1

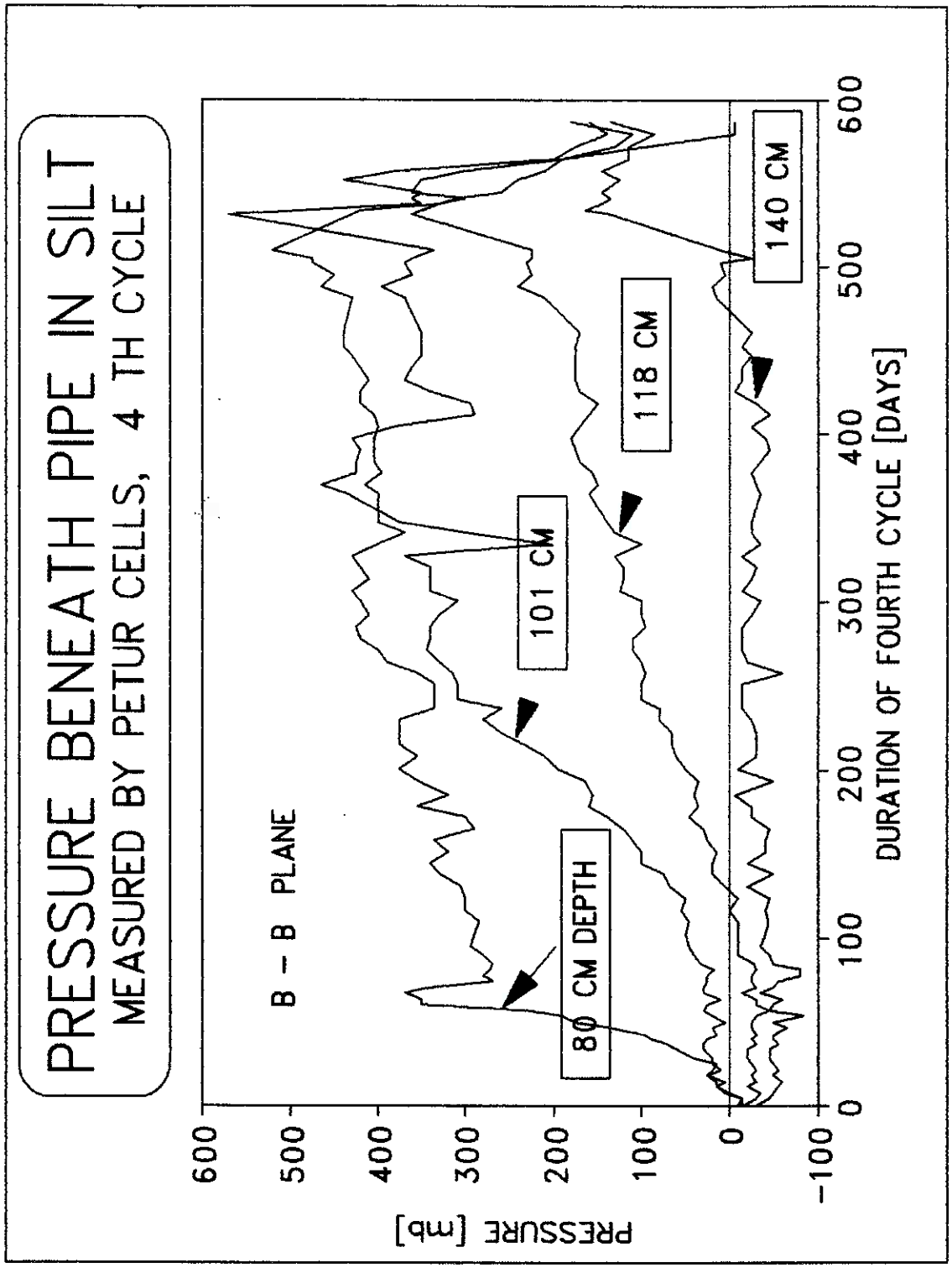
PRESSURE BENEATH PIPE IN SILT
MEASURED BY PETUR CELLS, 4 TH CYCLE
B - B PLANE
80 CM DEPTH
101 CM
118 CM
140 CM
PRESSURE [mb]
600
500
400
300
200
100
0
-100
0
100
200
300
400
500
600
DURATION OF FOURTH CYCLE [DAYS]

FIGURE 4.2-1

5.0 SOIL HEAVE

Although it used to be thought that frost heave of soils occurred at the time of first freezing, it is now known that frozen soil continues to expand (heave) slowly even after it has become firmly frozen. This is because some water remains unfrozen in frozen soils at temperatures to at least several degrees below 0 C. The progressive freezing of this water at such temperatures expands the soil. In addition, the water is mobile and water accumulations continue to occur under thermodynamic gradients - that is temperature and stress gradients - to give additional ice build-up in already frozen soil, and continuing strain. The latter effects constitute long-term frost heave which is important because of the relatively long period that a pipeline operates.

5.1 Telescopic tubes

These effects are detected by telescopic tube devices and observations are shown in Figures 5.1-1. In principle, the continuation of frost heave in a higher layer after heave has commenced in the layer below is the result of long-term heaving. The total heave, or displacement, of the shallowest tube relative to the fixed, deepest tube equals the sum of the differential heave of all tubes. The total heave so determined also corresponds closely to the heave of the pipe as shown by the optical levelling of the rods attached to the pipe.

Two series of aluminum telescoping tubes (Table 5.1-1) are installed in each soil at sections AA and BB. The first series placed to the side of the pipe has feet (plates) at the base of each tube section, which are spaced 10 cm apart. The second series without feet is arranged so as to pass through the pipeline, the tubes likewise being spaced at 10 cm. The central tube, which is deepest, descends in each case to 1 m under the pipe. The relative movement of the tubes will be measured at the surface. The telescopic tubes are placed on the axis of the pipeline in order to compare the soil heave so measured to the pipe heave.

The document file HVRODDOC.WK1 provides an explanation of the geometry of the telescopic tubes and shows a calculation of the initial soil layer thickness beneath the pipe, for each freeze/thaw period. Corresponding telescopic heave data is in files HVEROD1.WK1 TO HVEROD4.WK1.

An example analysis for the data is given in file HVERODEX.WK1.

DATA FILE NAME = HVEROD1.WK1 to HVEROD4.WK1
DOCUMENT FILES = HVRODDOC.WK1 & HVERODEX.WK1 (all on DISK 1)

5.2 Magnetic sensors

The potential use of magnetic sensors to measure soil heave was suggested by J.R. MacKay (per comm. in IR-51 1986) as an alternative to telescopic heave rods. The device which was developed and constructed in the Geotechnical Science Laboratories, and is a substantial improvement on the earlier prototype, is shown in Fig. 5.2-1 . The apparatus consists of three parts: a magnetic indicator ring, a magnetic sensing device, and a plastic access tube. The magnetic indicator is comprised of three small magnets installed in a plexiglass disc through which the access tube passes. The magnet sensing device is attached to the end of an aluminum rod which is lowered into the tube on a rack and pinion device. The rack and pinion assembly can move freely up and down the access tube.

A pilot hole about 10 cm in diameter was augured to permit installation of the magnetic indicators and the access tube. Magnetic indicators are dropped over the access tube to lie at selected depths approximately 20 cm. apart. After each indicator is installed, the augured hole is backfilled to the depth where the next indicator will be installed. A final magnetic disc was installed at the surface to provide a zero point for the profile.

To obtain the position of the magnetic heave sensors, the detector is lowered in the access tube. A digital readout indicates the position of the detector and an audible signal indicates when a magnetic disc is encountered. The position of the magnetic indicators in a profile are measured with reference to the surface magnetic disc. The position of this disc is determined monthly by optical surveying. During the third thaw period, the surface magnets on several magnet strings hung up on couplings and thus were not able to follow the ground surface settlement.

The accuracy and reproducibility of data obtained with this device represents an order of magnitude improvement over the previous design (telescopic tubes). The new digital readout reads to 0.1 mm. Normally, magnetic discs can be located to within 0.2 - 0.3 mm. It is estimated that the location of the discs is to within +/- 0.5 mm.

Magnetic sensor position data is presented in files named MAG1F3.WK1 etc, while optical survey data for the surface magnets is given in SMAGHVE3.WK1 & SMAGHVE4.WK1. A document file, MAGNTDOC.WK1, discusses the data file layout and provides sample analysis procedures for calculating total soil heave, differential heave and heave strain.

```
DATA FILE NAME = MAG1F3.WK1  to  MAG10F3.WK1  and
                 MAG1F4.WK1  to  MAG10F4.WK1
DOCUMENT FILES = MAGNTDOC.WK1            (all on DISK 2)
```

TABLE 5.1-1

Dimensions of telescoping tubes

	#	LENGTH [M]	DIAMETER [in]
inner tube	1	2.8	1/2
	2	2.6	5/8
	3	2.4	3/4
	4	2.2	7/8
	5	2.0	1
	6	1.8	1 1/8
	7	1.6	1 1/4
	8	1.4	1 1/8
	9	1.2	1 1/2
Outer tube	10	1.0	1 5/8

Diameter of the foot ring: 1.5 inches
Material: aluminum .035 inches thickness

(1) set with 10 tubes, are positioned to the sides of the pipe at the AA (sand) and BB (silt) sections. They have feet at the base of each tube.

(2) sets, without feet, passing through the pipe are at the AA (sand) and BB (silt) planes

The set in the silt comprises 10 tubes of dimensions as indicated above.

The set in the sand comprises only 8 tubes, that is the 5/8 and 1/2 inch ones are lacking. The length of the other tubes are as indicated above.

Table 5.2-1

Heave Sensor Locations

Site No.	Distance along axis (cm)	Distance off axis (cm)
1	540.0	23.5
2	429.0	27.0
3	427.5	65.5
4	434.0	102.5
5	421.5	201.0
6	318.0	25.0
7	203.5	28.0
8	102.5	26.5
9	53.0	26.0
10	-49.0	25.0

Sites 1-9 in silt section

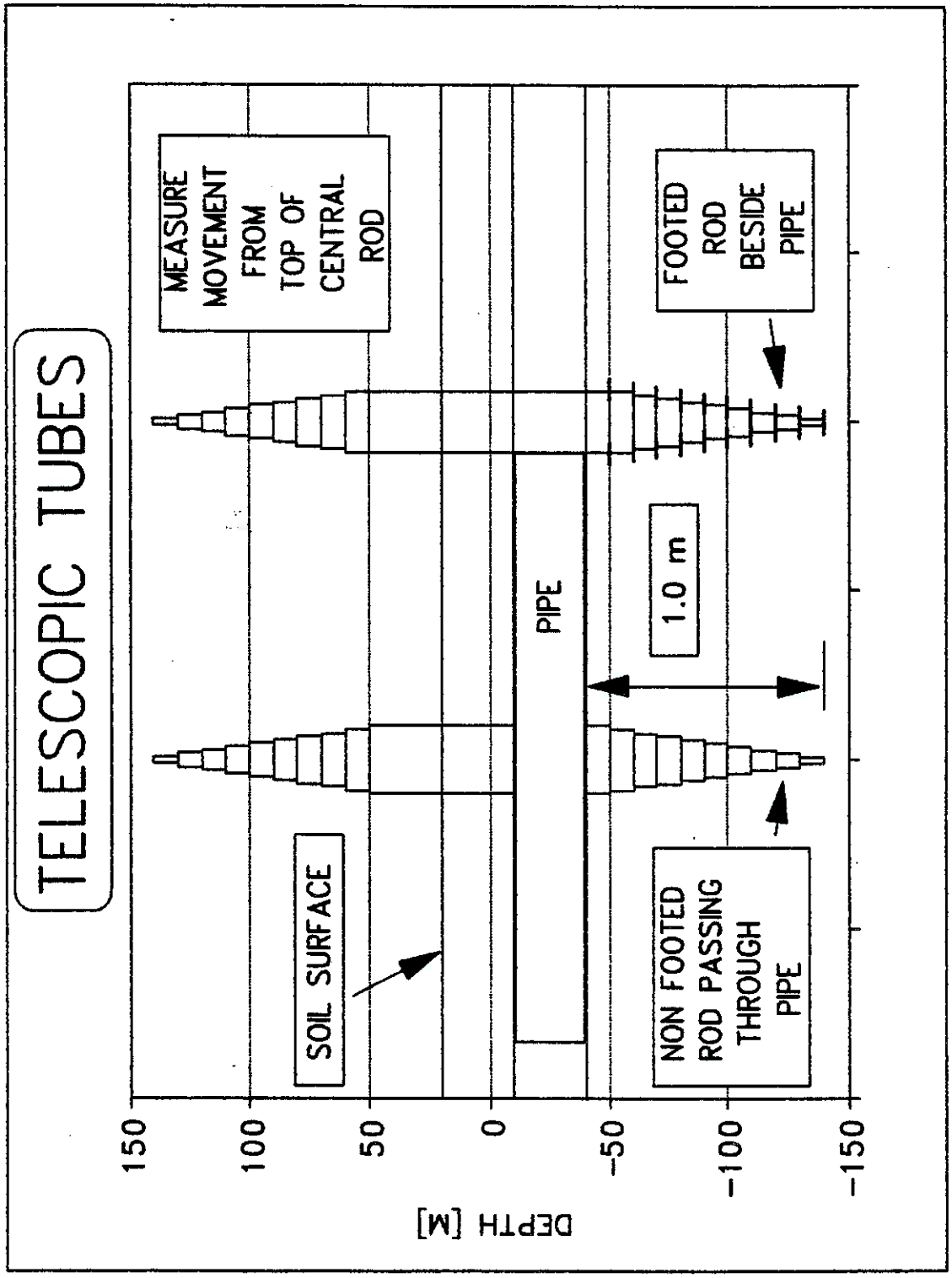
TELESCOPIC TUBES
MEASURE MOVEMENT FROM TOP OF CENTRAL ROD
FOOTED ROD BESIDE PIPE
PIPE
1.0 m
SOIL SURFACE
NON FOOTED ROD PASSING THROUGH PIPE
150
100
50
0
-50
-100
-150
DEPTH [M]

FIGURE 5.1-1

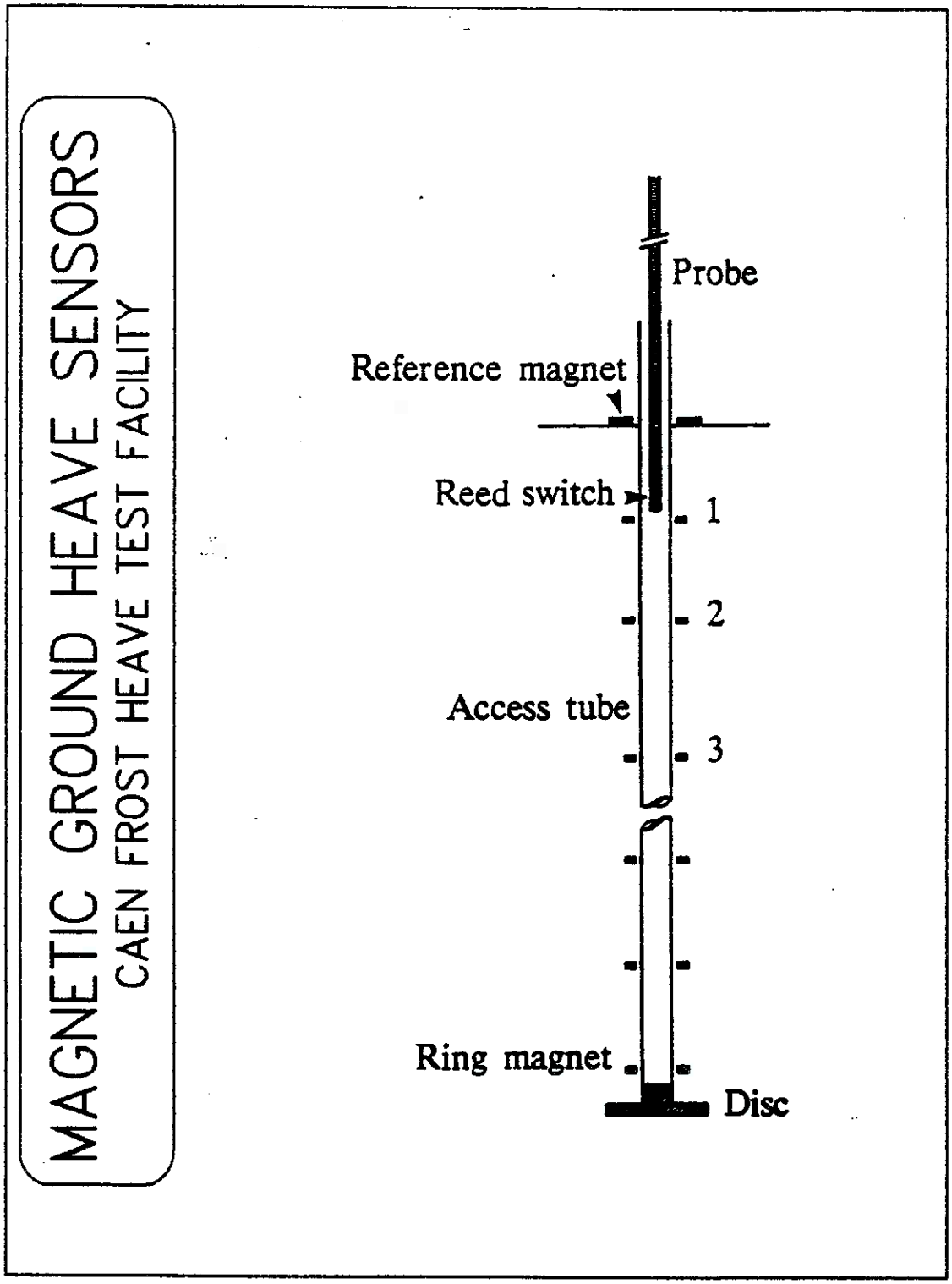
MAGNETIC GROUND HEAVE SENSORS
CAEN FROST HEAVE TEST FACILITY
Probe
Reference magnet
Reed switch
1
2
Access tube
3
Ring magnet
Disc

FIGURE 5.2-1

6.0 SOIL SURFACE PROFILE

The shape of the soil surface is recorded by optical survey of a grid of fixed points on the soil surface (0.5m and 1m apart, see Fig 6.0-1) approximately once a month (less frequently toward the end of the freeze cycle). Manipulation of this data can reveal features of the spatial and temporal variation of the soil behaviour during the experiment. In this section, results for a simple manipulation of the surface heave data are presented to show total heave, or the change in elevation from the start of the freeze cycle.

DATA FILE NAME = SURF1.WK1 to SURF4.WK1 (DISK 1)

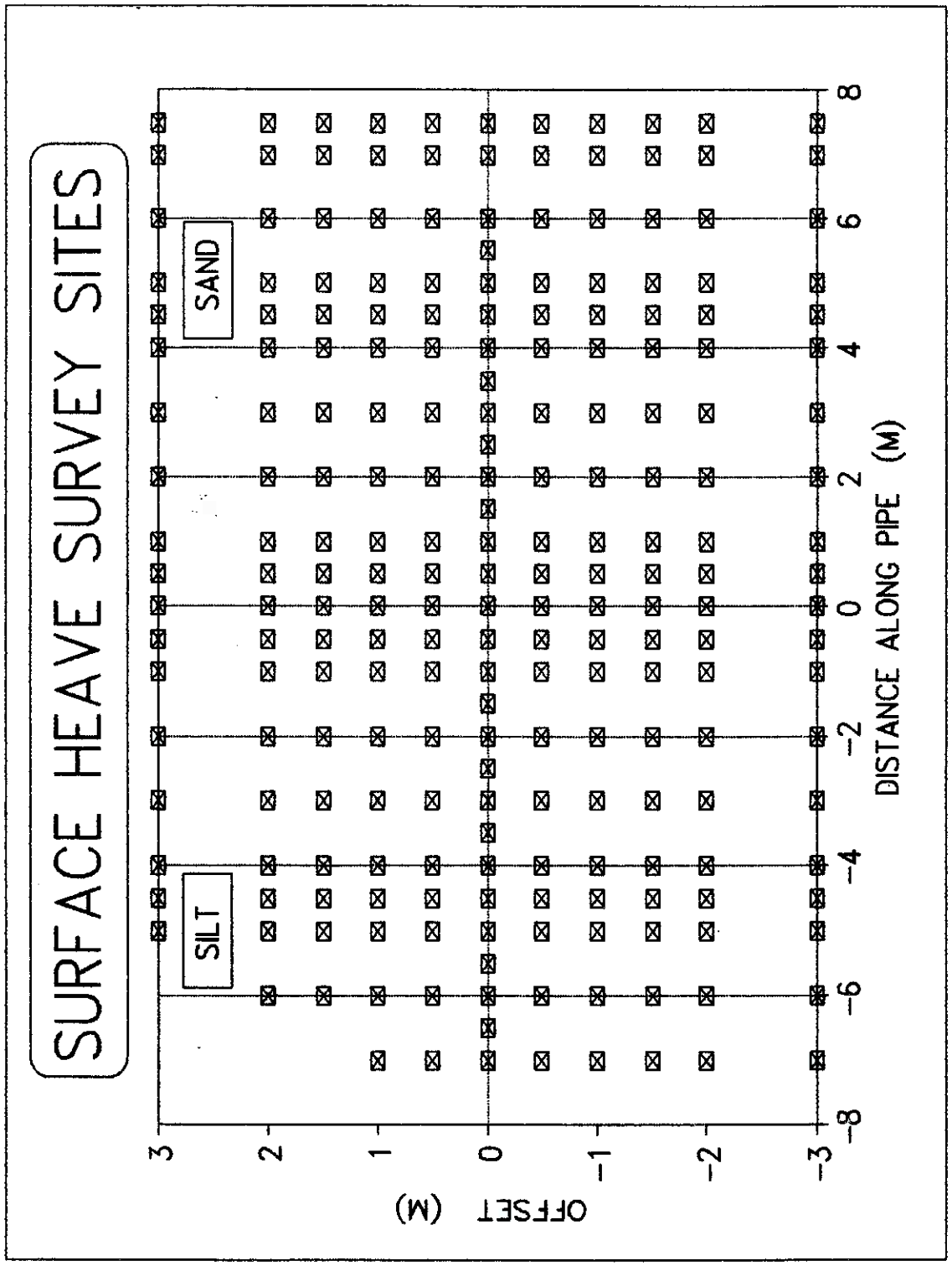
SURFACE HEAVE SURVEY SITES
SILT
SAND
OFFSET (M)
3
2
1
0
-1
-2
-3
DISTANCE ALONG PIPE (M)
-8
-6
-4
-2
0
2
4
6
8

FIGURE 6.0-1

7.0 BIBLIOGRAPHY

Dallimore,S.R., and Williams, P.J., editors, 1984. Pipelines and Frost Heave. Proceedings of a Seminar at Caen, France April 25-27, 1984.

IR-29, 1982. Burgess et. al. Investigation of Soil Freezing in association with a Buried Chilled Pipeline in a Large-Scale Test Facility - Phase I, and Feasibility Study for Stress in a Pipeline Buried in a Freezing Soil.

IR-33, 1983. Investigation of Soil Freezing in Association with a Buried Chilled Pipeline in a Large-Scale test Facility. A report by Geotechnical Science Laboratory, Carleton University, for dept. of Energy Mines and Resources, Earth Physics Branch.

IR-36, 1984. Analysis of Stresses Developed in Pipelines Buried in Freezing Ground. A report by Geotechnical Science Laboratory, Carleton University, for dept. of Energy Mines and Resources, Earth Physics Branch.

IR-43, 1985. Analysis of Stresses Developed in Pipelines Buried in Freezing Ground. A report by Geotechnical Science Laboratory, Carleton University, for dept. of Energy Mines and Resources, Earth Physics Branch.

IR-50, 1986. Investigations of Frost Heave as a Cause of Pipeline Deformation. A report by Geotechnical Science Laboratory, Carleton University, for dept. of Energy Mines and Resources, Earth Physics Branch.

IR-51, 1986. Thermodynamics and Mechanics of Freezing Soil Around a Pipeline. A report by Geotechnical Science Laboratory, Carleton University, for dept. of Energy Mines and Resources, Earth Physics Branch.

IR-54, 1988. The Third Freeze cycle of the Canada-France Ground Freezing Experiment. A report by Geotechnical Science Laboratory, Carleton University, for Permafrost Research Section, Terrain Sciences division, Geological Survey of Canada.

IR-58, 1988. The Fourth Freeze cycle of the Canada-France Ground Freezing Experiment. A report by Geotechnical Science Laboratory, Carleton University, for Permafrost Research Section, Terrain Sciences division, Geological Survey of Canada.

L.E.C. 1989. Pipe Heave and Bending Strain Data for the Caen Frost Heave Test Facility. A report by L.E.C. Engineering for Permafrost Research Section, Terrain Sciences division, Geological Survey of Canada.

Smith, M.W. and Patterson, D.E. 1989. Detailed Observtions on the Nature of Frost Heaving at a Field Scale. Canadian Geotechnical J. , vol 26, No.2, pp 306-312.

APPENDIX 1 THERMOCOUPLE DATA

The raw thermocouple data, as recorded automatically, contain measurement errors due to (presumed) electrical transients and to problems with the zero reference. Before this data can be included in the database, these errors need to be eliminated. Fortunately, with measurements every 6 hours there is sufficient redundancy in the record so that this can be accomplished with little loss of accuracy.

Raw data for one sensor for the end of the second freeze period is shown in Figure A1. Two features of the noise in the signal are apparent: Firstly, the transient errors are significant deviations from the temperature curve, on the order of 5 degrees. Secondly, the smaller order noise (zero reference errors) tend to be "one-tailed", in that the deviation is toward colder temperatures only. This is the pattern to be expected, since the reference junction will normally be at or above the melting point when the reference cell is surrounded by air at room temperature (as was the case). Figure A2 is a detail view of one part of the record: it is apparent that the one-tailed noise produces frequent spikes, but these are less frequent than the overall trend.

Both of these types of "noise" can be eliminated by filtering the data using running medians. Running medians take a short series (of say n values) from the complete data set, find the median value in the set, and replace the raw measurement from the middle of the original series (at position n/2) with the median value. Outliers in the original series are eliminated without pulling the median off of the smoothed trend, as would occur with running means. Similarly, the "one tailed noise", though more prevalent in the series, can be filtered out provided that the outlying values are sufficiently infrequent so that they do not pull the median down significantly. This can be accomplished by choosing a sufficiently long series for the running median.

Filtering of the data for a portion of the second freeze was tried using running medians of 3,5,7, and 9 values (Figures A3-A6). (Running medians normally employ an odd number of values, so that the middle value can be assigned to the central position). While the transient spikes are eliminated with the shortest series, the reference error spikes were only eliminated when the median series was extended to 9 values. As may be seen from the "detail" drawing of the raw data and smoothed curve for the running median of 9, the smoothed curve passes close to the principal trend in the original data, with relatively little influence of the outlying points. With measurements at 6 hour intervals, this represents a 2 day interval for the determination of the median value. This should be sufficiently short for the current purpose, since ground temperatures change slowly in the controlled environment facility.

Based on this analysis, the method proposed for smoothing and reducing the thermocouple data is as follows:

1. The data will be smoothed using running medians of 9 values.

2. The smoothed data will be used to produce mean daily temperatures.

The data region of Figure A1-2, along with the running median of 9 curve, are shown in Figure A1-7. Finally, the total data region for Figure A1-1 is presented along with the running median of 9 curve, in Figure A1-8.

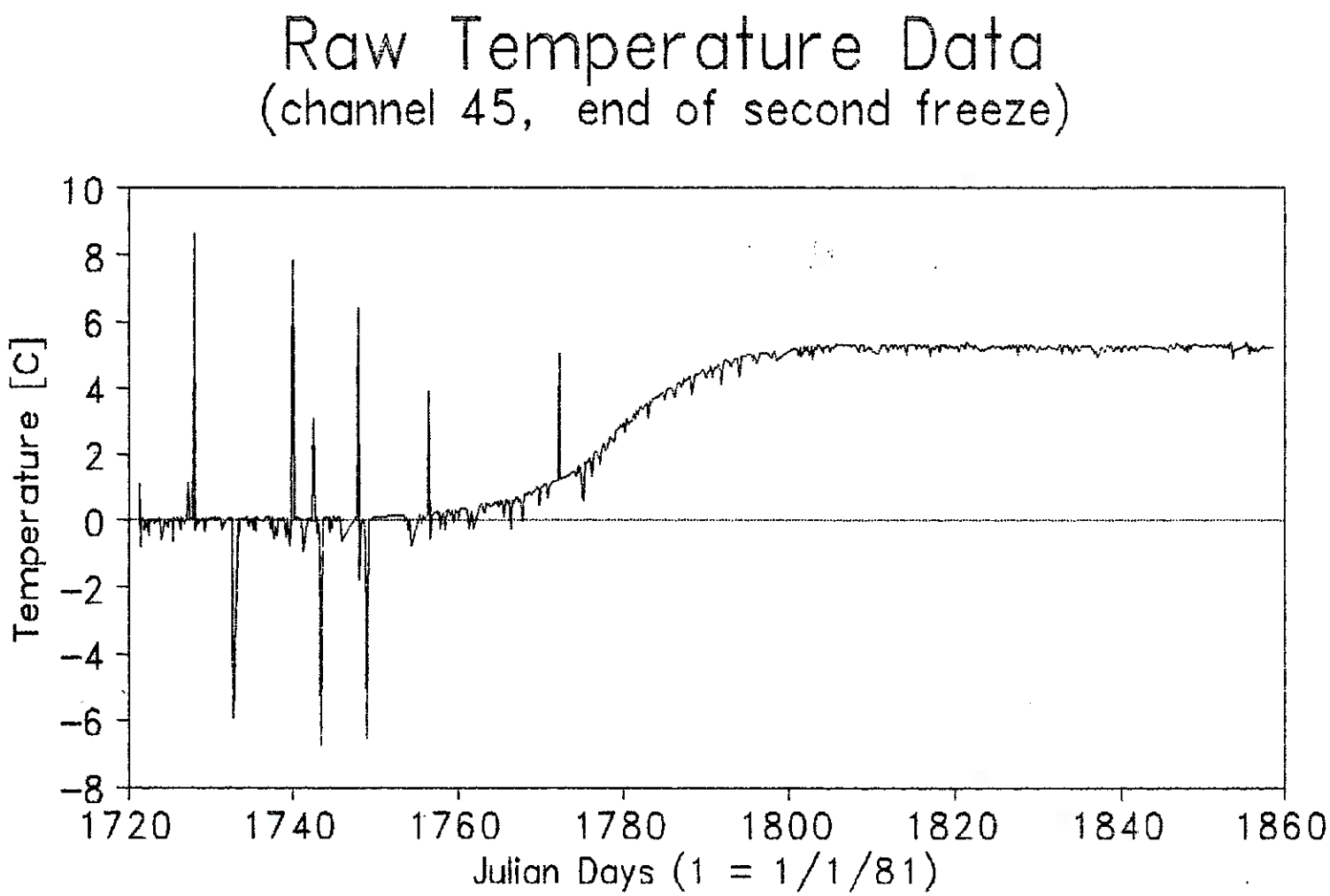
Raw Temperature Data
(channel 45, end of second freeze)
Temperature [C]
10
8
6
4
2
0
−2
−4
−6
−8
1720
1740
1760
1780
1800
1820
1840
1860
Julian Days (1 = 1/1/81)

FIGURE A1−1

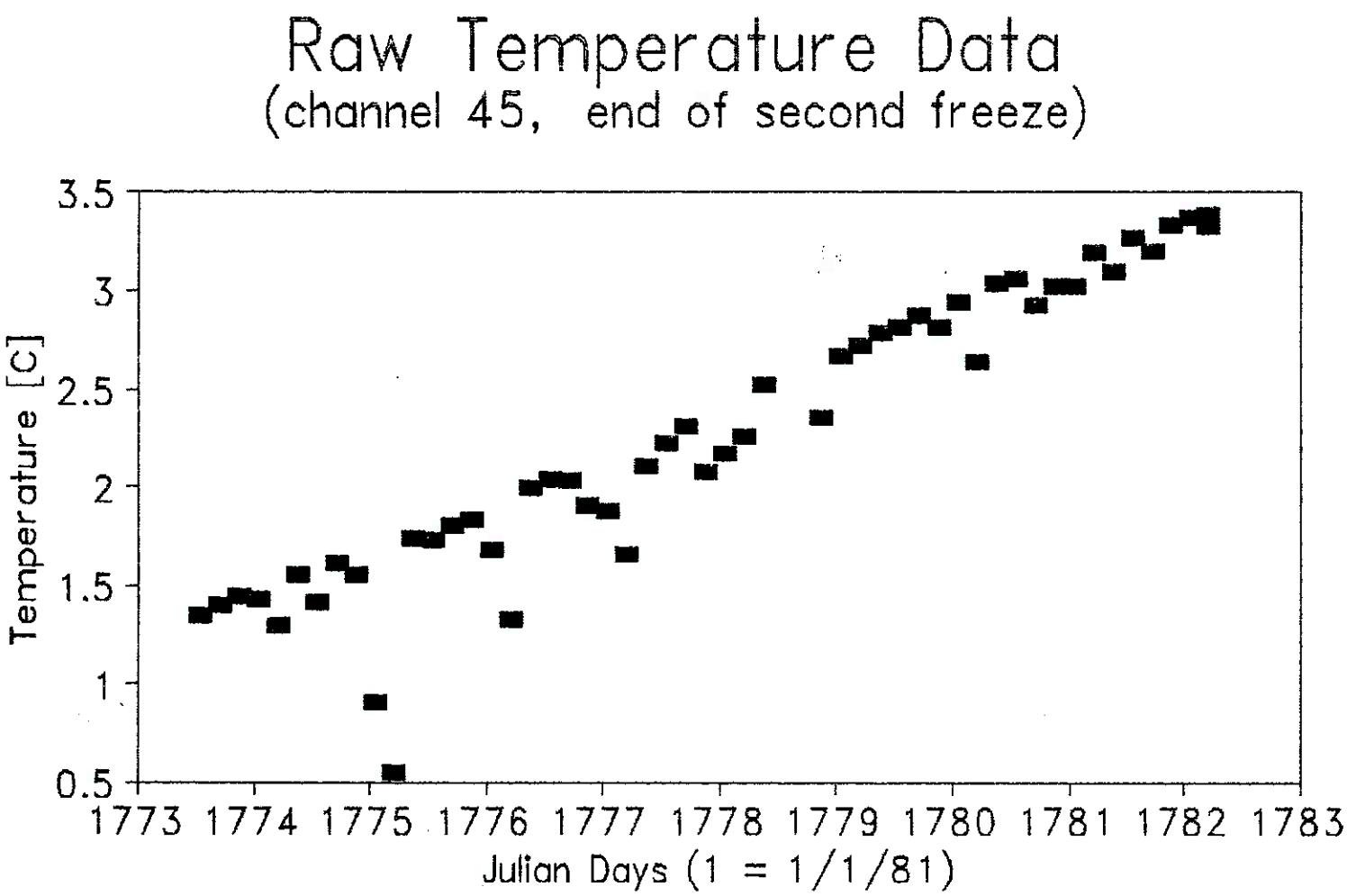
Raw Temperature Data
(channel 45, end of second freeze)
Temperature [C]
3.5
3
2.5
2
1.5
1
0.5
1773 1774 1775 1776 1777 1778 1779 1780 1781 1782 1783
Julian Days (1 = 1/1/81)

FIGURE A1-2

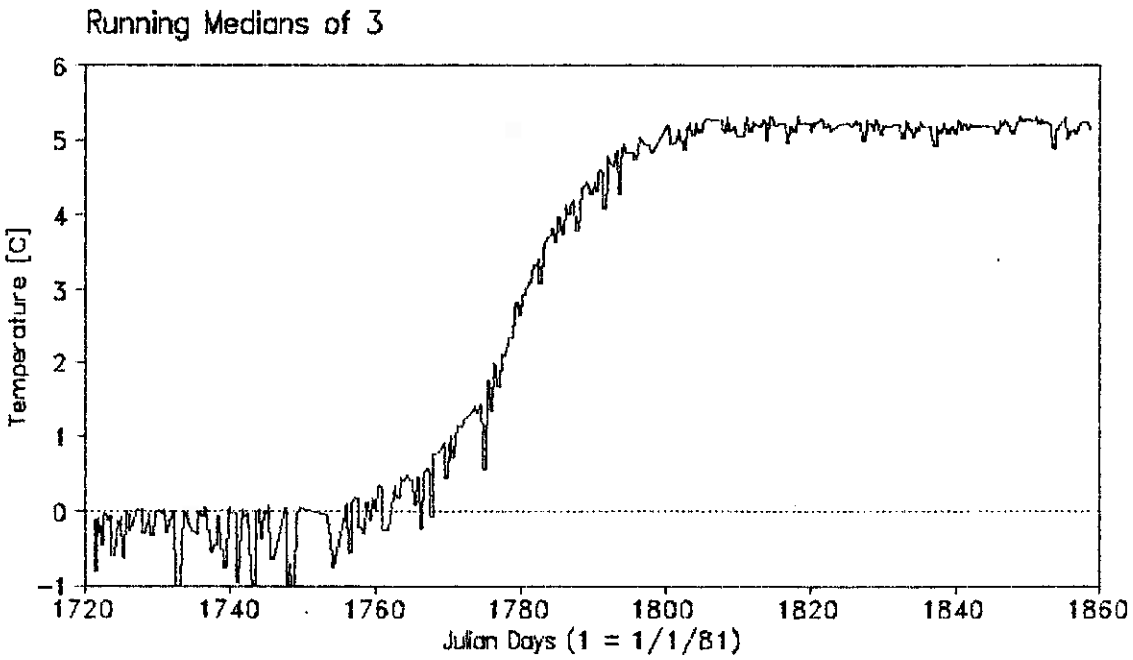

FIGURE A1-3

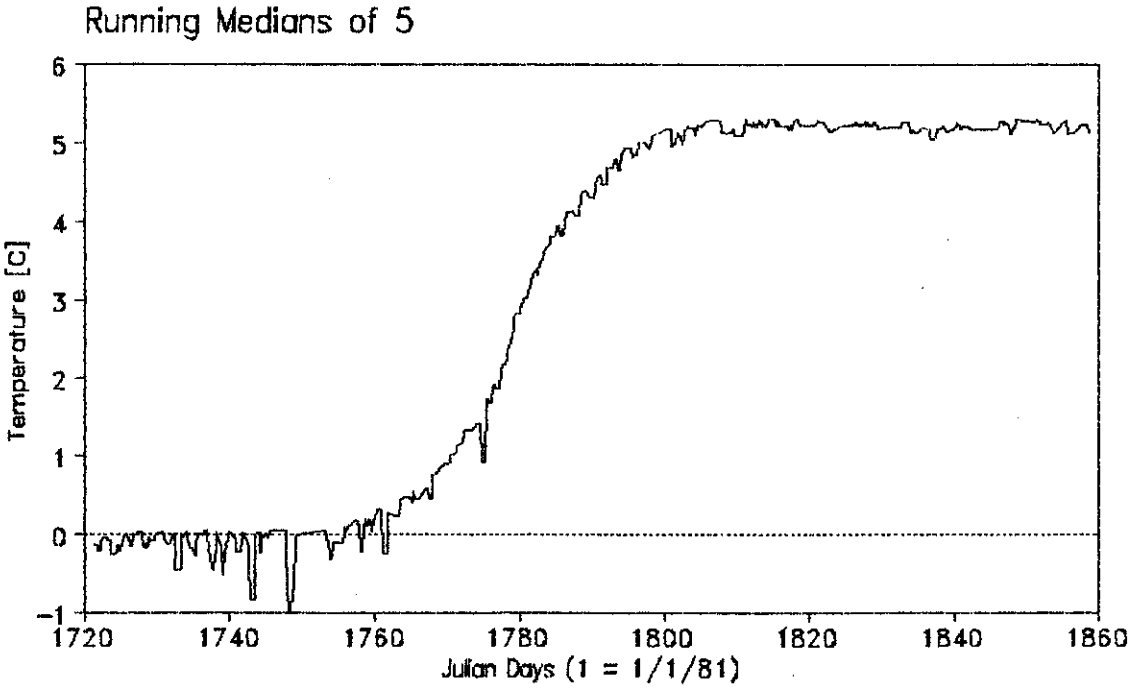

FIGURE A1-4

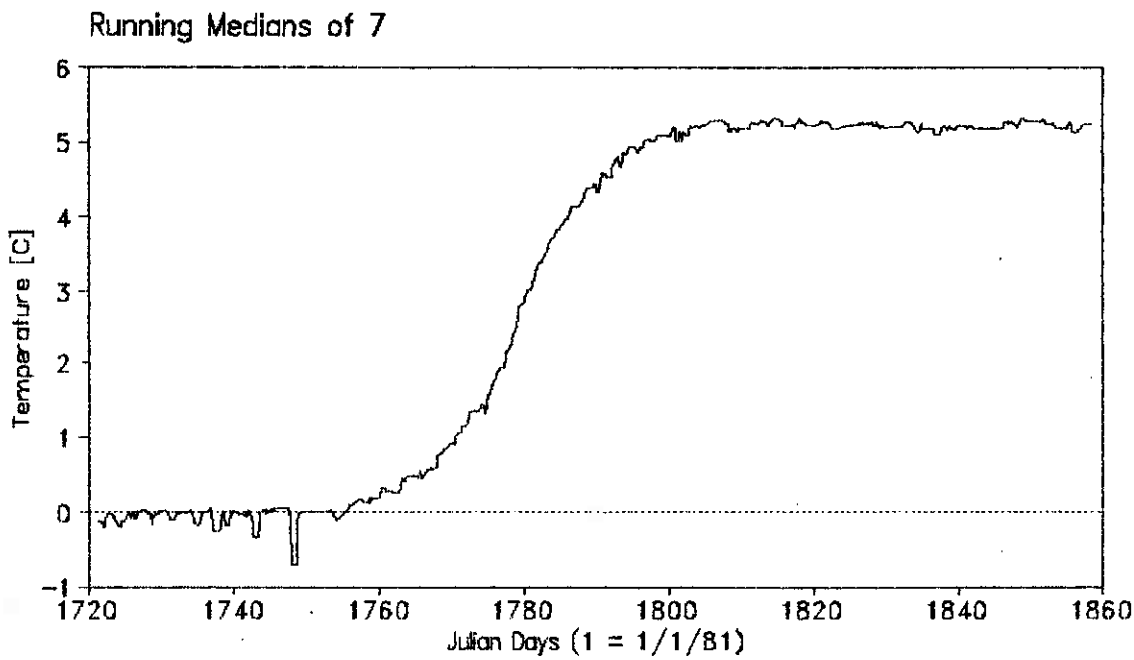

FIGURE A1-5

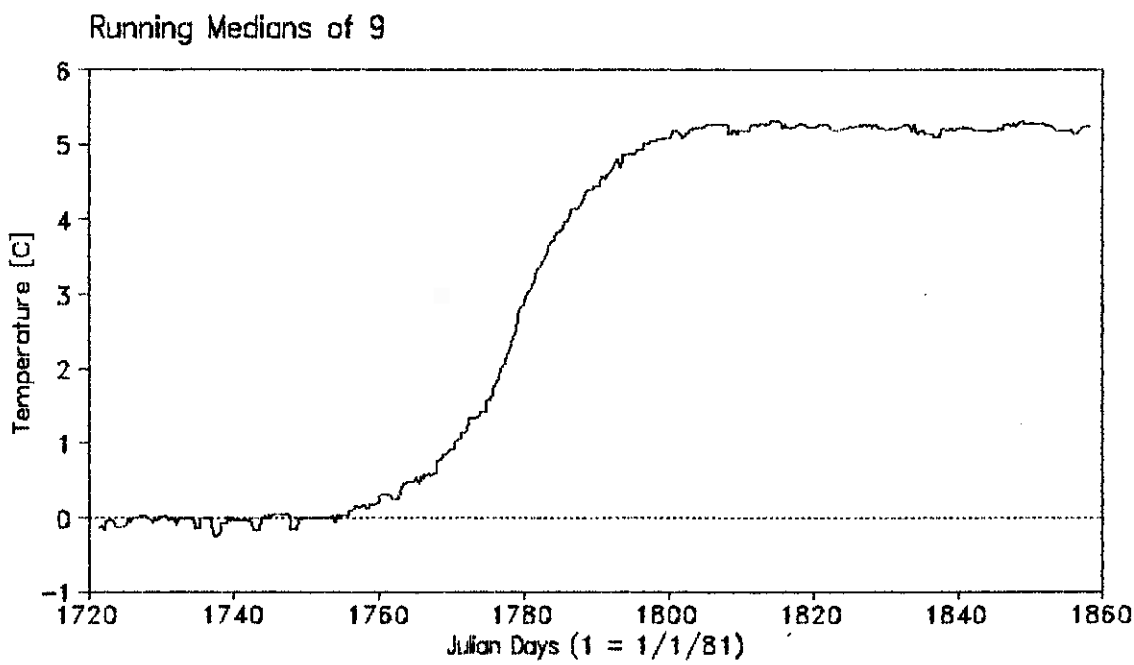

FIGURE A1-6

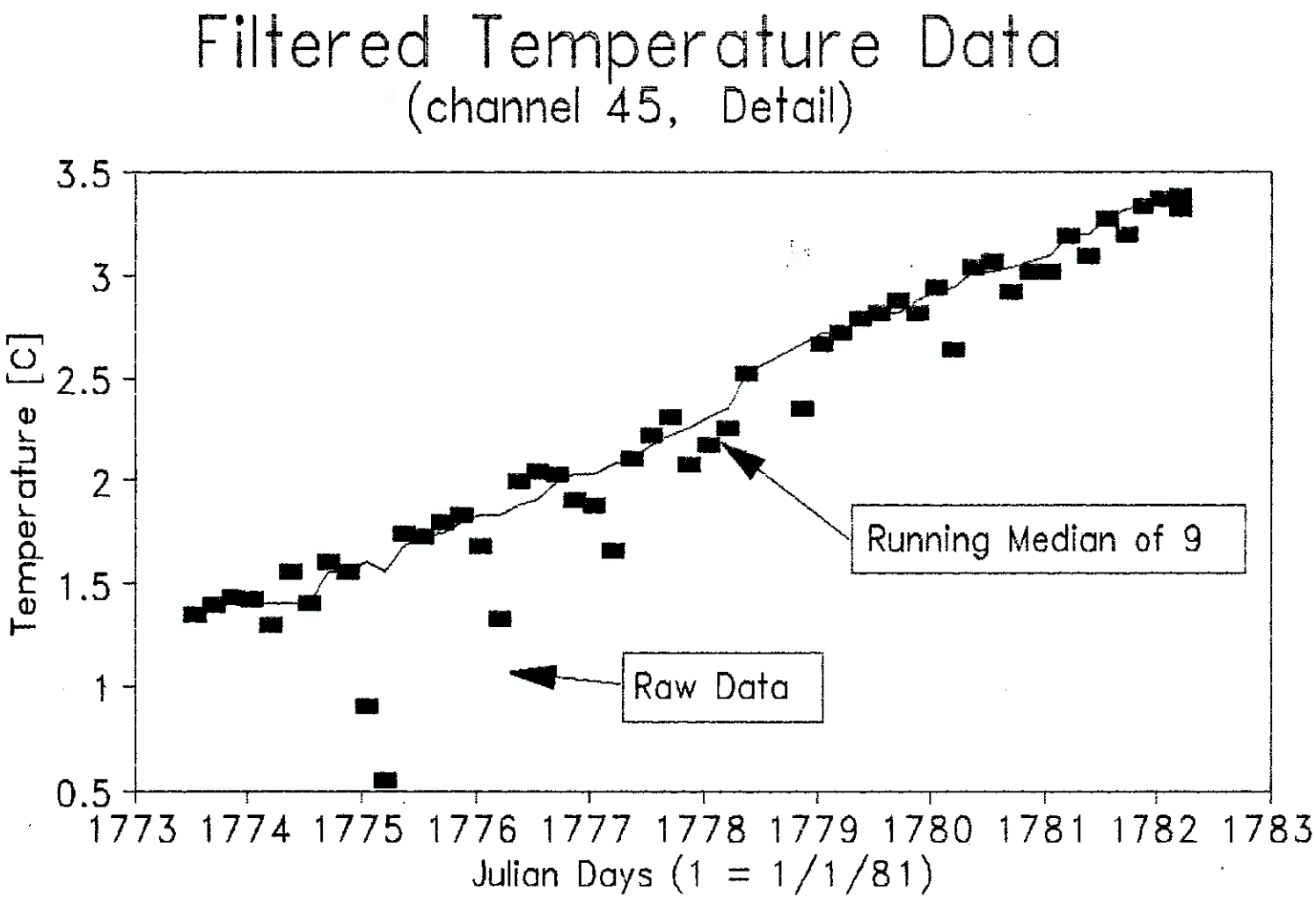
Filtered Temperature Data
(channel 45, Detail)
Temperature [C]
3.5
3
2.5
2
1.5
1
0.5
1773 1774 1775 1776 1777 1778 1779 1780 1781 1782 1783
Julian Days (1 = 1/1/81)
Running Median of 9
Raw Data

FIGURE A1-7

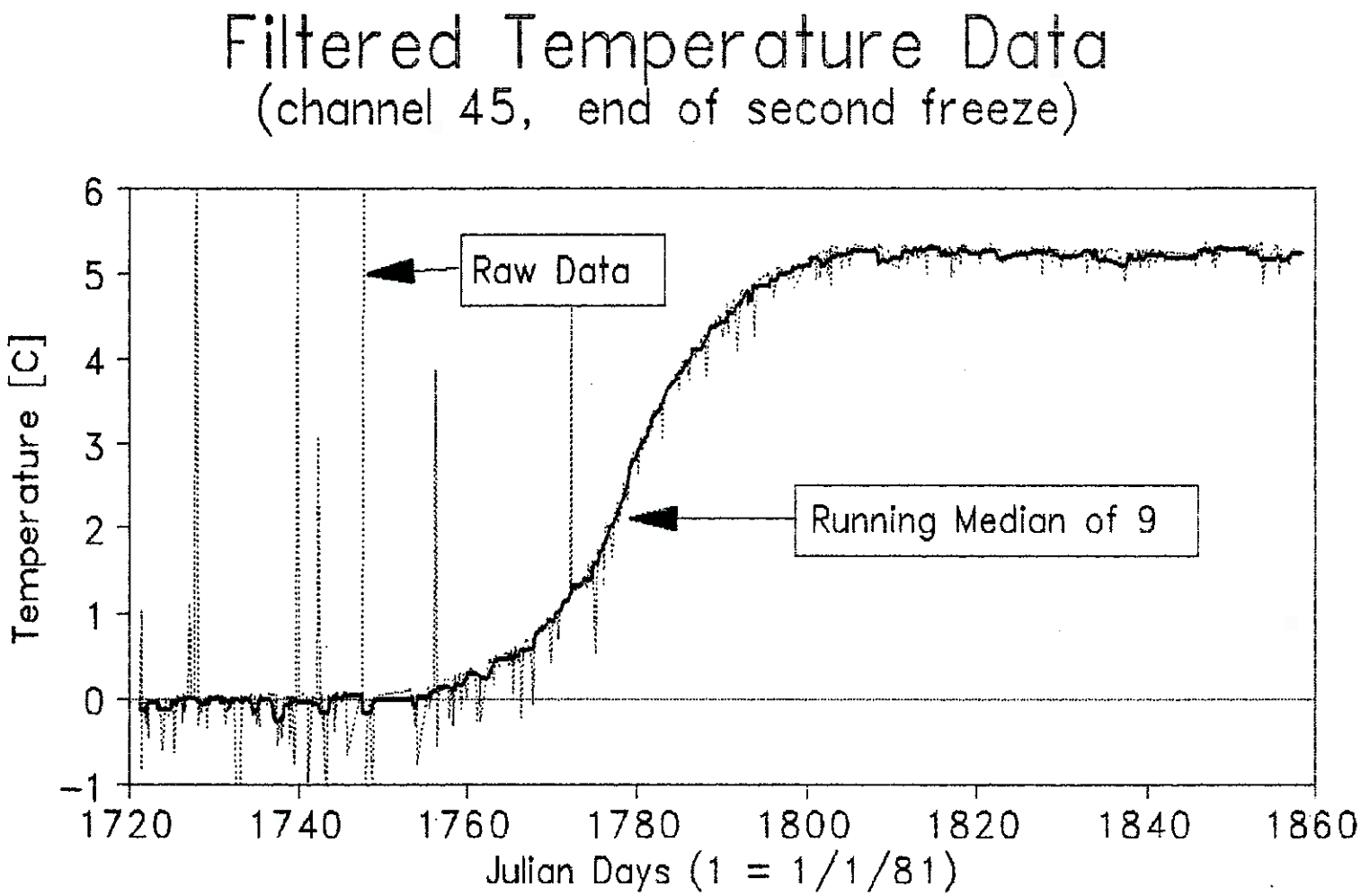
Filtered Temperature Data
(channel 45, end of second freeze)
Raw Data
Running Median of 9
Temperature [C]
6
5
4
3
2
1
0
−1
1720
1740
1760
1780
1800
1820
1840
1860
Julian Days (1 = 1/1/81)

FIGURE A1−8

APPENDIX 2 DISK DIRECTORIES

DIRECTORIES OF DATABASE DISKS

Volume is CAEN DB #1

FILE		BYTES
HVEROD1	WK1	35,229
HVEROD2	WK1	46,783
HVEROD3	WK1	28,682
HVEROD4	WK1	35,623
HVERODEX	WK1	15,548
HVRODDOC	WK1	16,754
SURF1	WK1	76,531
SURF2	WK1	122,451
SURF3	WK1	51,815
SURF4	WK1	80,393
XSECTION	WK1	16,000
HEAVE	WK1	183,576
STRAIN	WK1	119,053
GLOTZ1	WK1	57,221
GLOTZ2	WK1	118,429
GLOTZ3	WK1	26,804
GLOTZ4	WK1	31,488
PETUR3	WK1	19,584
PETUR4	WK1	42,293
19 File(s)		83,968 bytes free

Volume is CAEN DB #2

FILE		BYTES
MAG1F3	WK1	29,949
MAG1F4	WK1	26,374
MAG2F3	WK1	23,284
MAG2F4	WK1	25,140
MAG3F3	WK1	30,697
MAG3F4	WK1	27,597
MAG4F3	WK1	23,931
MAG4F4	WK1	27,084
MAG5F3	WK1	11,185
MAG5F4	WK1	13,662
MAG6F3	WK1	27,263
MAG6F4	WK1	27,693

```
MAG7F3    WK1        19,847
MAG7F4    WK1        22,506
MAG8F3    WK1        21,743
MAG8F4    WK1        21,219
MAG9F3    WK1        22,900
MAG9F4    WK1        20,429
MAG10F3   WK1        20,581
MAG10F4   WK1        25,745
MAGNTDOC  WK1         6,701
SMAGHVE3  WK1         5,301
SMAGHVE4  WK1        12,041
TEMP1F3   WK1        18,359
TEMP1F4   WK1        38,155
TEMP2F3   WK1        18,342
TEMP2F4   WK1        36,888
TEMP3F3   WK1        18,370
TEMP3F4   WK1        36,516
TEMP4F3   WK1        18,112
TEMP4F4   WK1        36,242
TEMP5F3   WK1        17,039
TEMP5F4   WK1        35,964
TEMP6F3   WK1        17,963
TEMP6F4   WK1        36,824
TEMP7F3   WK1        18,342
TEMP7F4   WK1        36,531
TEMP8F3   WK1        16,401
TEMP8F4   WK1        36,994
TEMP9F3   WK1        18,331
TEMP9F4   WK1        30,028
TEMP10F3  WK1        18,336
TEMP10F4  WK1        36,602
THRMHVE3  WK1         1,940
THRMHVE4  WK1        12,211
       45 File(s)     156,160 bytes free


VOLUME IS CAEN DB #3

     FILE          BYTES

2-PIPE    WK1       764,160
4-PIPEDT  WK1        28,082
README                  396
        3 File(s)    420,864 bytes free
```

```
VOLUME IS CAEN DB #4

     FILE          BYTES

3-PIPE   WK1        432,384
4-A      WK1        718,336
        2 File(s)       62,976 bytes free


VOLUME IS CAEN DB #5

     FILE          BYTES

1-A      WK1        381,952
1-PIPE   WK1        333,568
3-B      WK1        388,096
        3 File(s)      110,080 bytes free


VOLUME IS CAEN DB #6

     FILE          BYTES

1-B      WK1        306,304
2-A      WK1        896,128
        2 File(s)       10,752 bytes free


VOLUME IS CAEN DB #7

     FILE          BYTES

2-B      WK1        706,048
3-A      WK1        491,264
        2 File(s)       16,384 bytes free


VOLUME IS CAEN DB #8

     FILE          BYTES

4-B      WK1        580,992
4-PIPE   WK1        630,475
        2 File(s)        2,048 bytes free
```