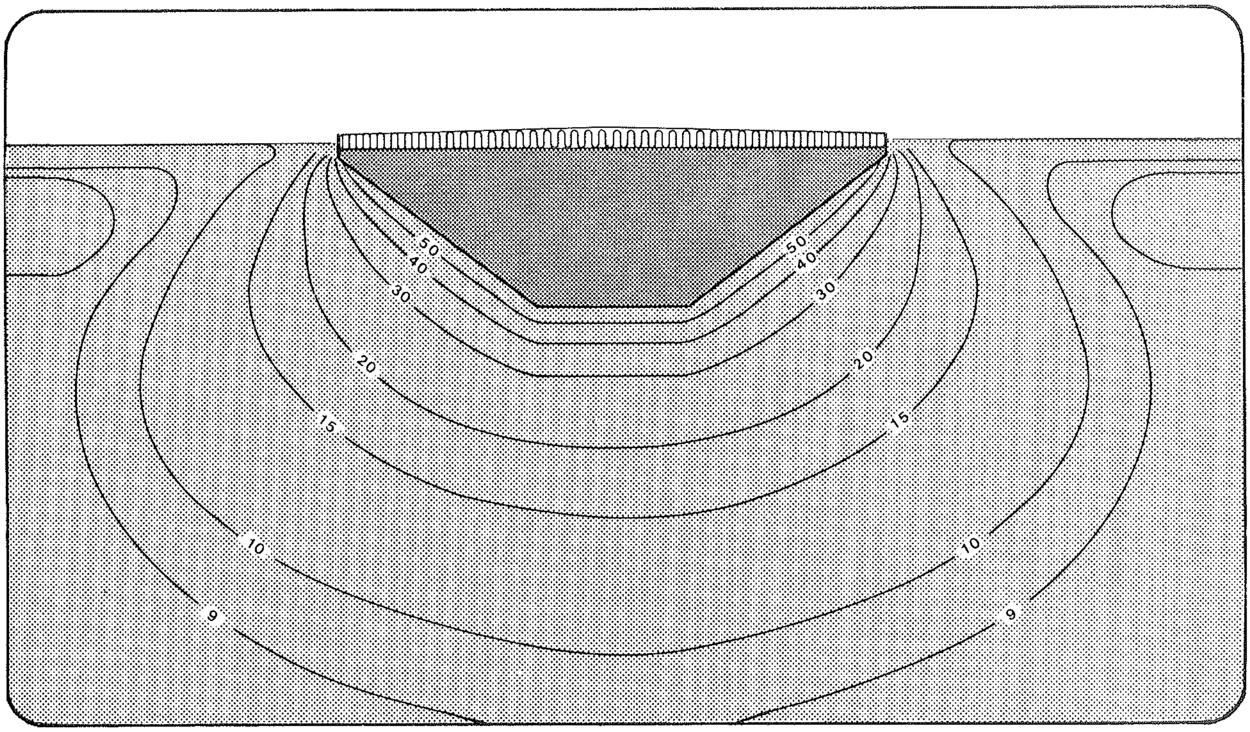
Thermal Insulation Laboratory
Technical University of Denmark

SEASONAL HEAT STORAGE IN UNDERGROUND WARM WATER STORES

Construction and testing of a 500 m³ store

KURT KIELSGAARD HANSEN
PREBEN NORDGAARD HANSEN
VAGN USSING

Meddelelse nr. 134 July 1983



6. CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

The design and construction of a 500 m^3 warm water pit was carried out with the highest priority being placed on securing accuracy in the testing of the efficiency of the pit during the pilot operations. Thus the details of this design cannot be taken as the technical and economical optimum for future full scale pits.

To simplify the comparison between the measured thermal behaviour of the pit and the numerical and analytical predictions of the performance during the pilot operations, the pit was dug into the ground completely, thus disregarding the normal procedure of securing dirt balance by placing excavated dirt as embankments.

The design and construction procedures have given no reason for changing of future facilities constructed for the same purpose.

A good agreement obtained during the testing between numerical and analytical predictions and measurements seems to indicate that the procedure followed during installation of the measuring points has been satisfactory.

Any future pilot plant and some of the first commercial applications should perhaps be equipped with "chains" of thermocouples for temperature monitoring. The chains should be safeguarded against moisture movements in the vertical holes drilled for placing of the measuring chains.

Continued observations during the coming year are expected to document the continued decrease in thermal losses predicted by the analytical studies of the operations.

The minor unforeseen difficulties arising during installation of the floating "gasket", which were designed to almost prevent evaporation and excessive heat losses along the joint between the lid and the concrete edge of the pit, are not expected to occur in full scale pits. The lid on these pits should be fully fastened to the edge of the pit, thus making the warm water, stored in the pit, part of a "closed" system for energy transmission.

It is recommended that development of large low-cost seasonal storages will be speeded up by coordination of the research and development in this field inside the solar energy R&D programme with the work clearly called for inside the energy conservation programme, as it is apparent, that energy storage from 24 hour periods up to 2000 hour periods based on uninsulated water pits can easily be made economically feasible. The results from this coordinated effort will advance the date, when solar energy can be applied economically in district heating systems.

Short term storage (24 hours) demands very high charge- and discharge effects. The influence of such high effects on the stability of the thermocline must be studied in relation to different geometrics of the pits and different inlet structures.

Daily charge- and discharge operations demand high resistance of the soil interface towards pit water. Ways to achieve low-cost protection of the pit water against soluble pit materials must be further studied.

Finally experiments with large water pits with insulated embankments must be studied. Insulation materials applied to the soil interface tend to be too expensive, but inorganic insulation materials built into the pit walls and maybe even into the bottom of the pit would be of importance if sufficient low cost of construction can be obtained.

7. REFERENCES

[1] Dansk Geoteknisk Institut: Lyngby-Tårbæk. Nordvej. Bassin for sæsonlagring af varmt vand. Geoteknisk rapport no.1 med bilag 1-8. October 1982.

[2] The Royal Norwegian Council for Scientific and Industrial Research and the Public Roads Administration's Committee on FROST ACTION IN SOILS, No.1-17. Oslo 1970-76.

[3] Balstrup,T.: Varmepumpeanlæg - Varmeovergangsforhold i jord, (Heat pumps - heat flows in soil). Teknologisk Institut, København, 1977.

[4] Hansen,K.K. and Hansen,P.N.: Seasonal Heat Storage in Underground Warm Water Stores - Construction and Testing of a 500 m^3 Store. In Solar Energy Applications to Dwellings - Solar Energy R&D in the European Community, Series A, Vol.2, pp 404-412. (Ed.W.Palz and C.den Ouden). D.Reidel Publishing Company. 1983.

[5] Hansen,P.N., Hansen,K.K. and Ussing,V.: Seasonal Heat Storage in Underground Warm Water Stores - Construction and Testing of a 500 m^3 Store. In Solar Energy Applications to Dwellings - Solar Energy R&D in the European Community, Series A, Vol.3. D.Reidel Publishing Company. 1983. (To be published).

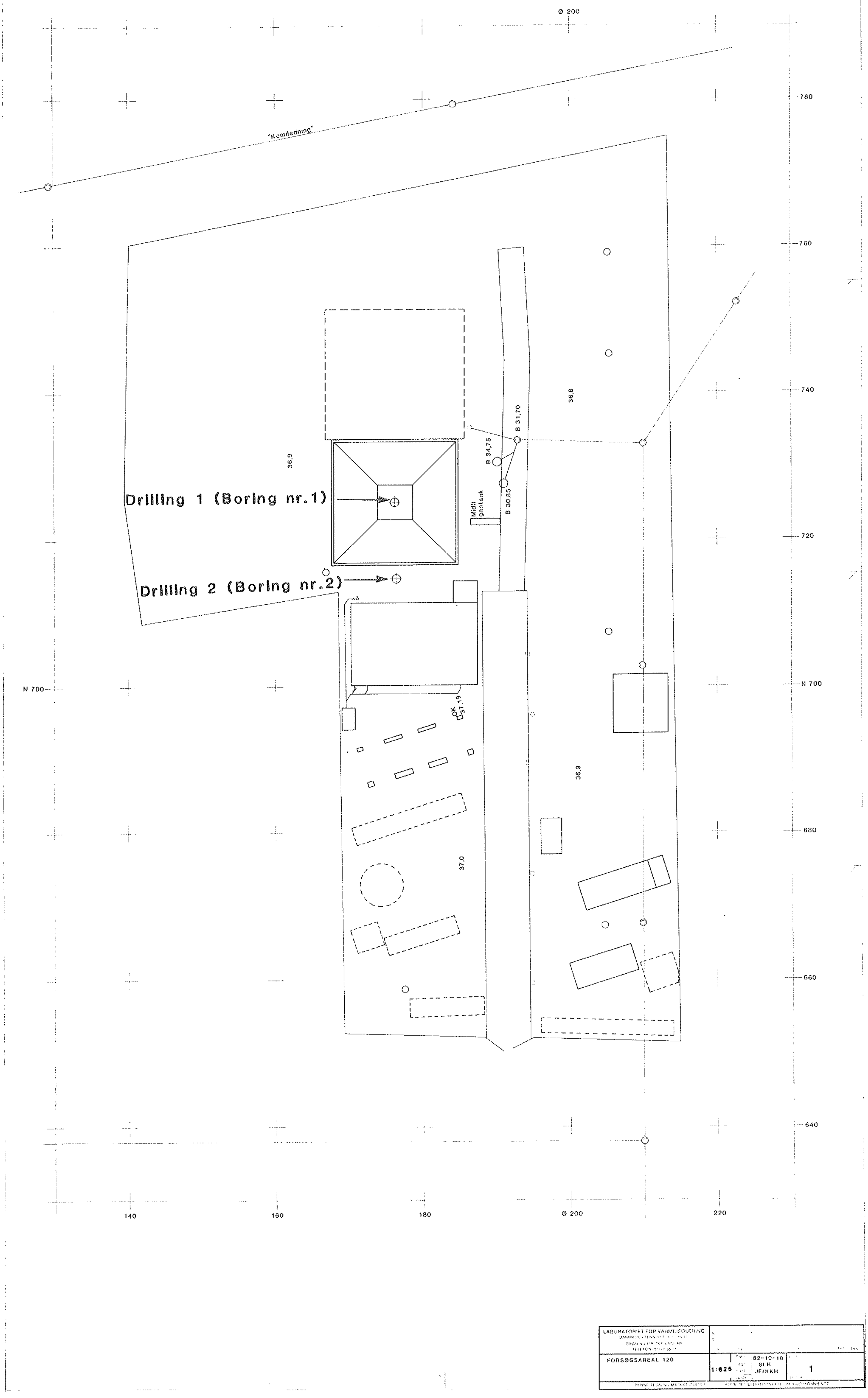
[6] Ussing,V., Hansen,K.K. and Hansen,P.N.: Seasonal Heat Storage in Underground Warm Water Stores - Dimensioning and planning of a full size store. Final report. Thermal Insulation Laboratory, Technical University of Denmark. 1983. (To be published).

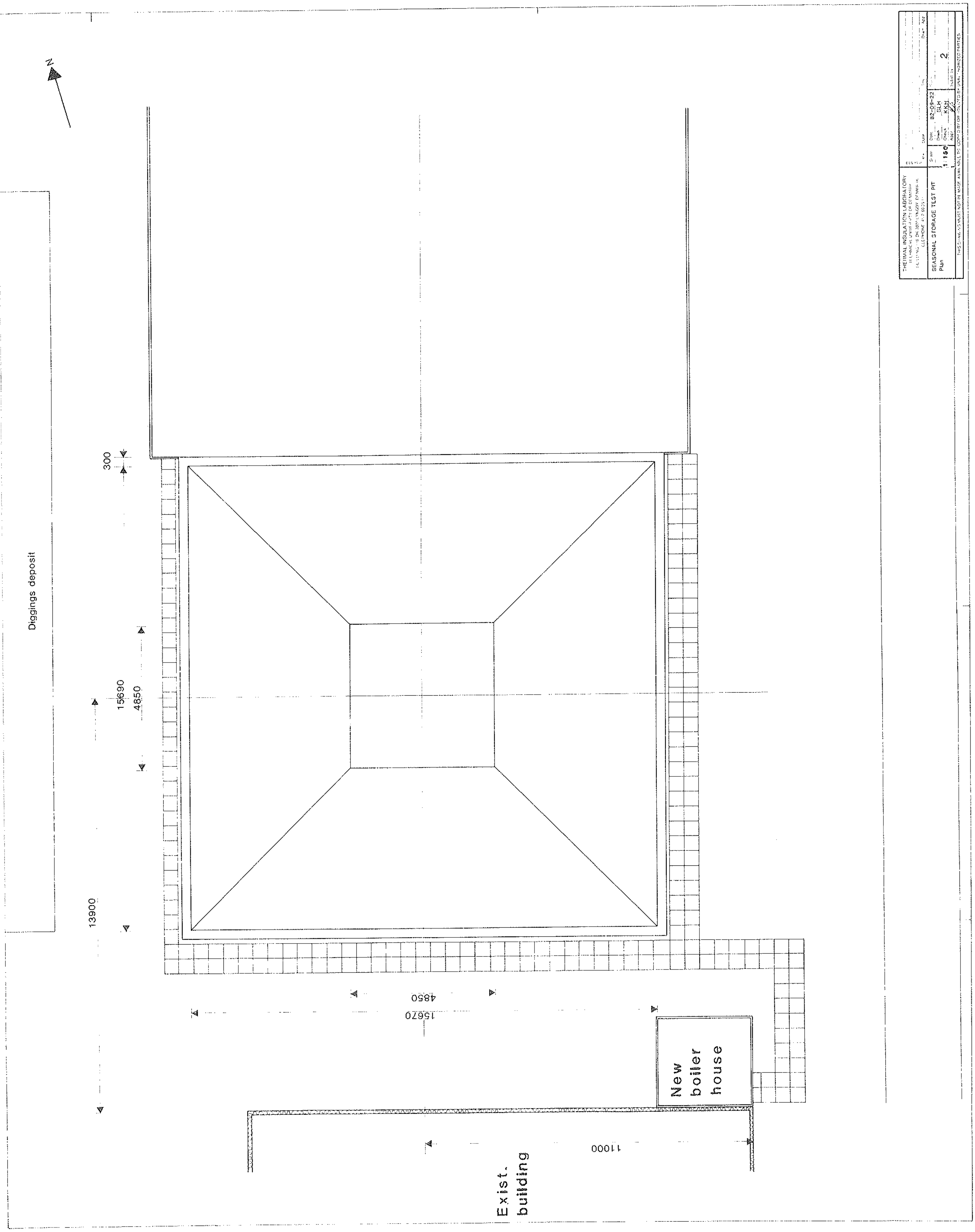
[7] Hansen,P.N.: Analytical Description of the Heat Losses from Underground Thermal Seasonal Heat Stores. Paper presented at the U.S. Department of Energy Conference "Seasonal Thermal Energy Storage", October 19-21,1981, Seattle, Washington, U.S.A.

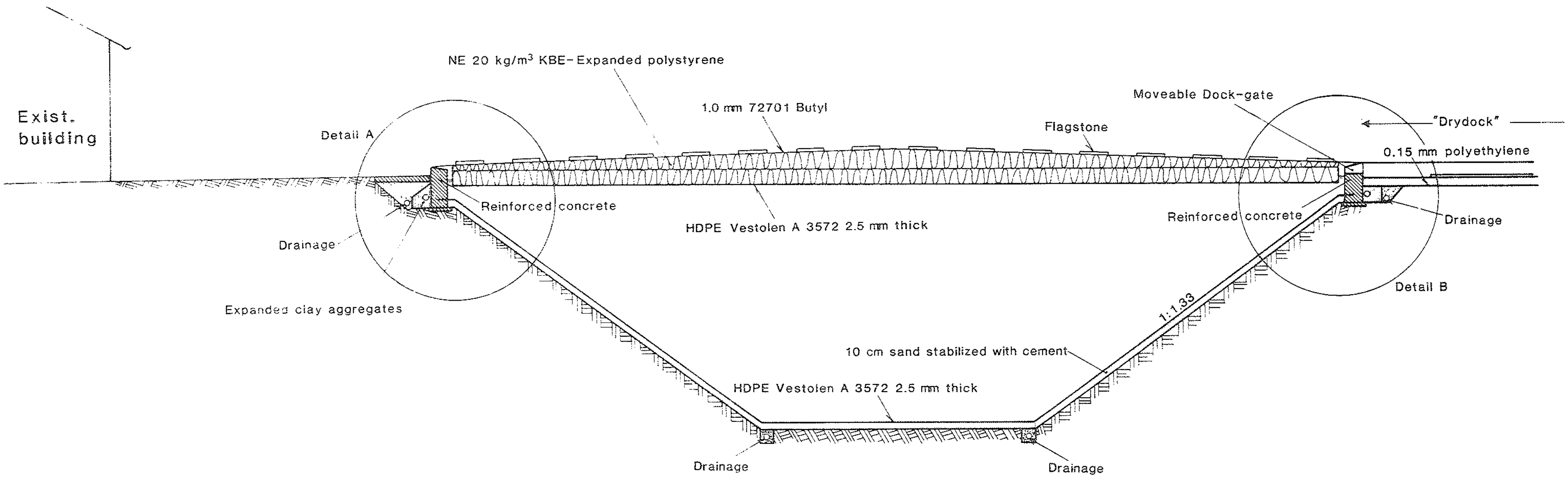
Appendix 1

The drawings for the Seasonal Storage Test Pit

No.	Title
1	Forsøgsareal 120 (test are 120)
2	Plan
3	Section
4	Detail A
5	Detail B
6	Water Level Control System, Plan
7	Drain and Sewage Pipes, Plan
10	Charge System, Plan
11	Diagram, Pipe System
12	Charge System, A
13	Charge System, B
14	Charge System, C
20	Location Plan, measuring chains
21	Section A-A showing location of measuring points, Row 1
22	Section B-B and C-C showing location of measuring points, Row 2
23	The grid points, Plan
24	Part of grid points, Plan
25	The grid points. Crosssection D-D (Row 1)
26	Part of grid points. Crosssection D-D (Row 1)
27	The grid points. Crosssection E-E (Row 2)
28	Part of grid points. Crosssection E-E (Row 2)


Ø 200
"Kemiledning"
780
760
740
720
N 700
680
660
640
140
160
180
Ø 200
220
36,9
36,8
36,9
37,0
B 31,70
B 34,75
B 30,85
Midlt gastank
OK 37,19
Drilling 1 (Boring nr.1)
Drilling 2 (Boring nr.2)
LABORATORIET FOR VARMEISOLERING
FORSØGSAREAL 120
1:625
82-10-18
SLH
JF/KKH
1


N
Diggings deposit
300
15690
4850
13900
4850
15670
New boiler house
11000
Exist. building
THERMAL INSULATION LABORATORY
SEASONAL STORAGE TEST PIT
Plan
Scale 1:100
Date 82-09-22
Drwn SLH
Check KKH
2

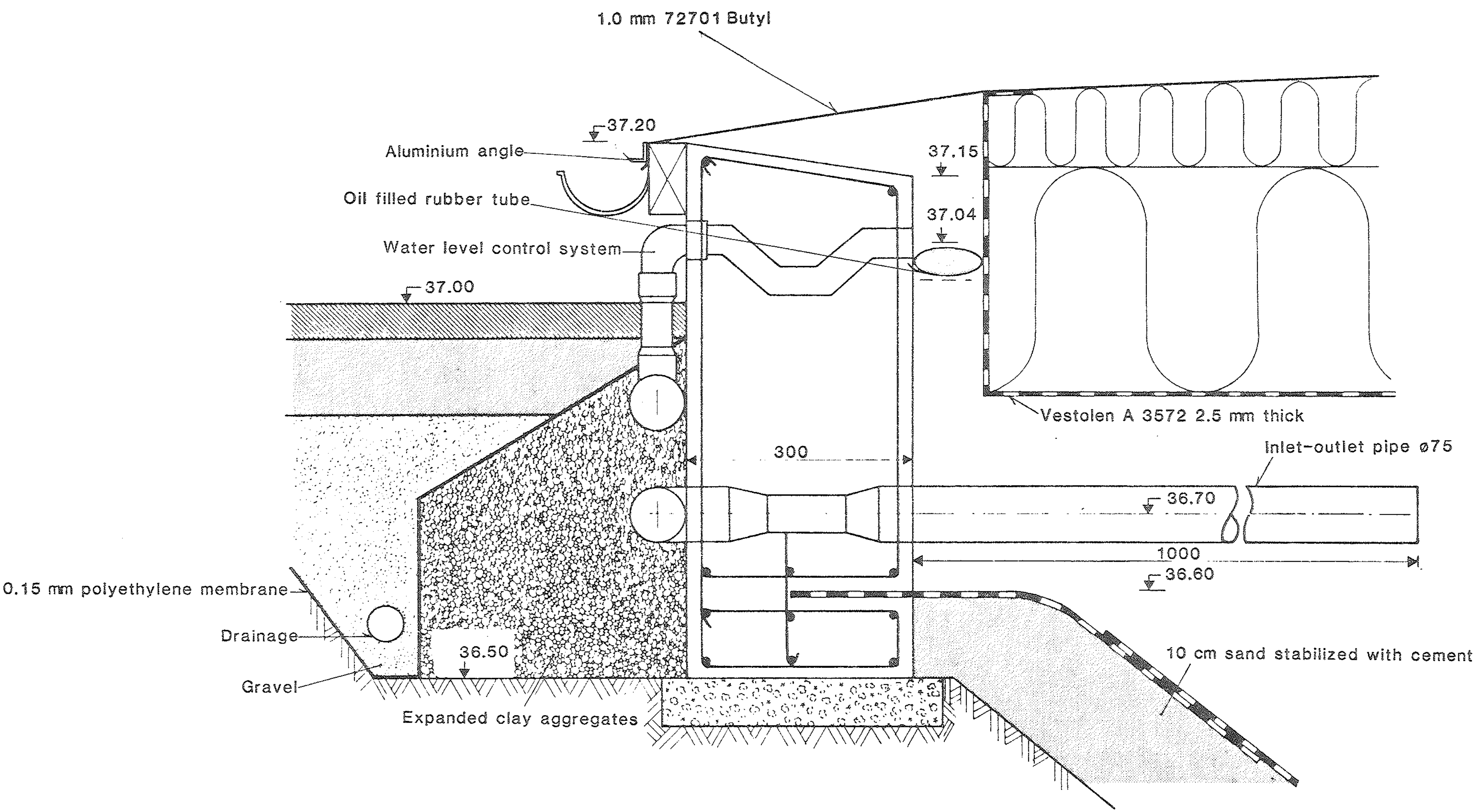


NOTE:

NE Non extinguishing
HDPE High density polyethylene

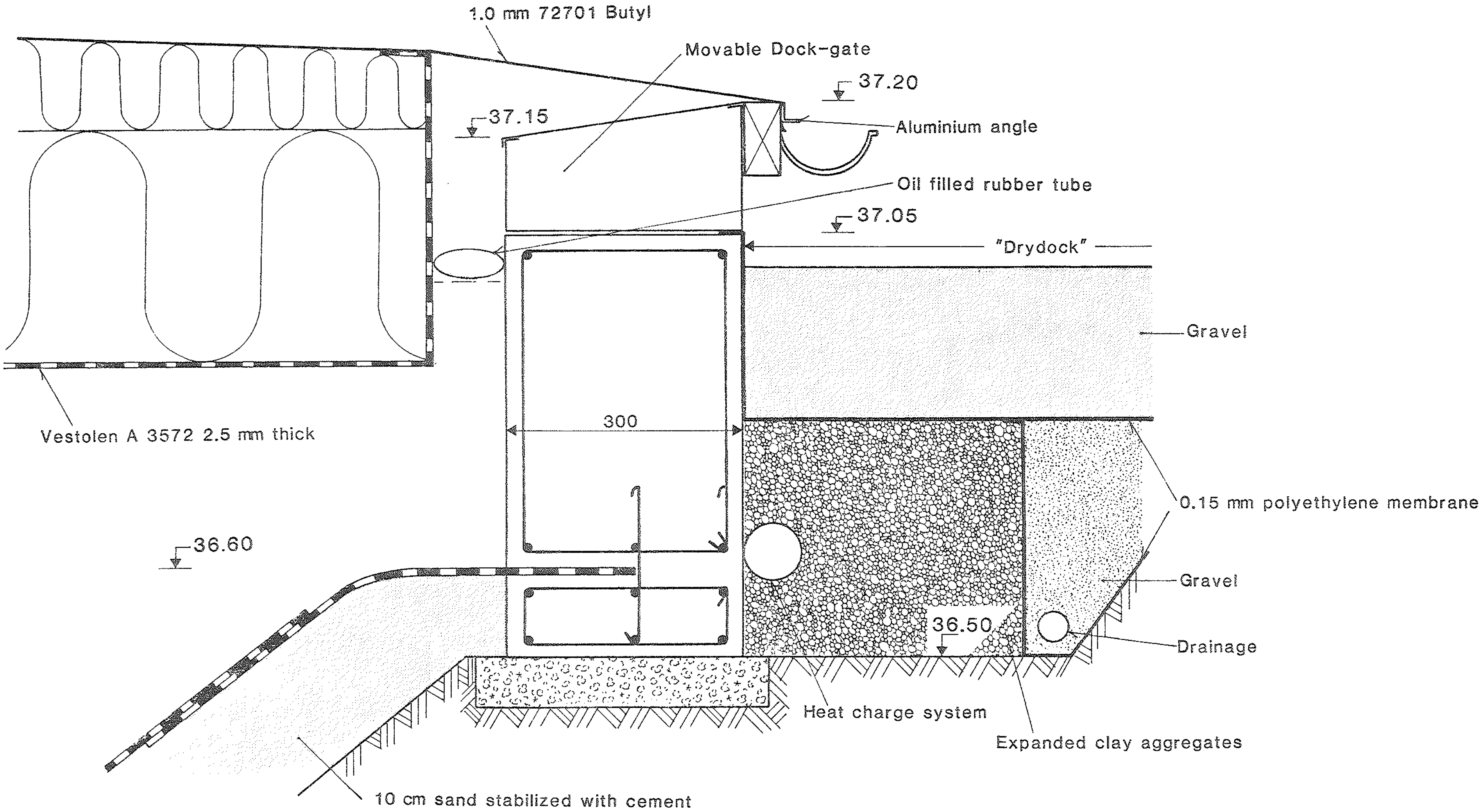
THERMAL INSULATION LABORATORY TECHNICAL UNIVERSITY OF DENMARK BUILDING 118 DK-2800 LYNGBY DENMARK TELEPHONE 45-2-88 35 11	Revised: Mrk	Date	Text	D:wn / Appr
SEASONAL STORAGE TEST PIT Section	Scale 1:100	Date 82-09-27 Drwn SLH Check KKH Appr	Subst of 3 Subst by	

THIS DRAWING MUST NOT BE MADE AVAILABLE TO, COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES

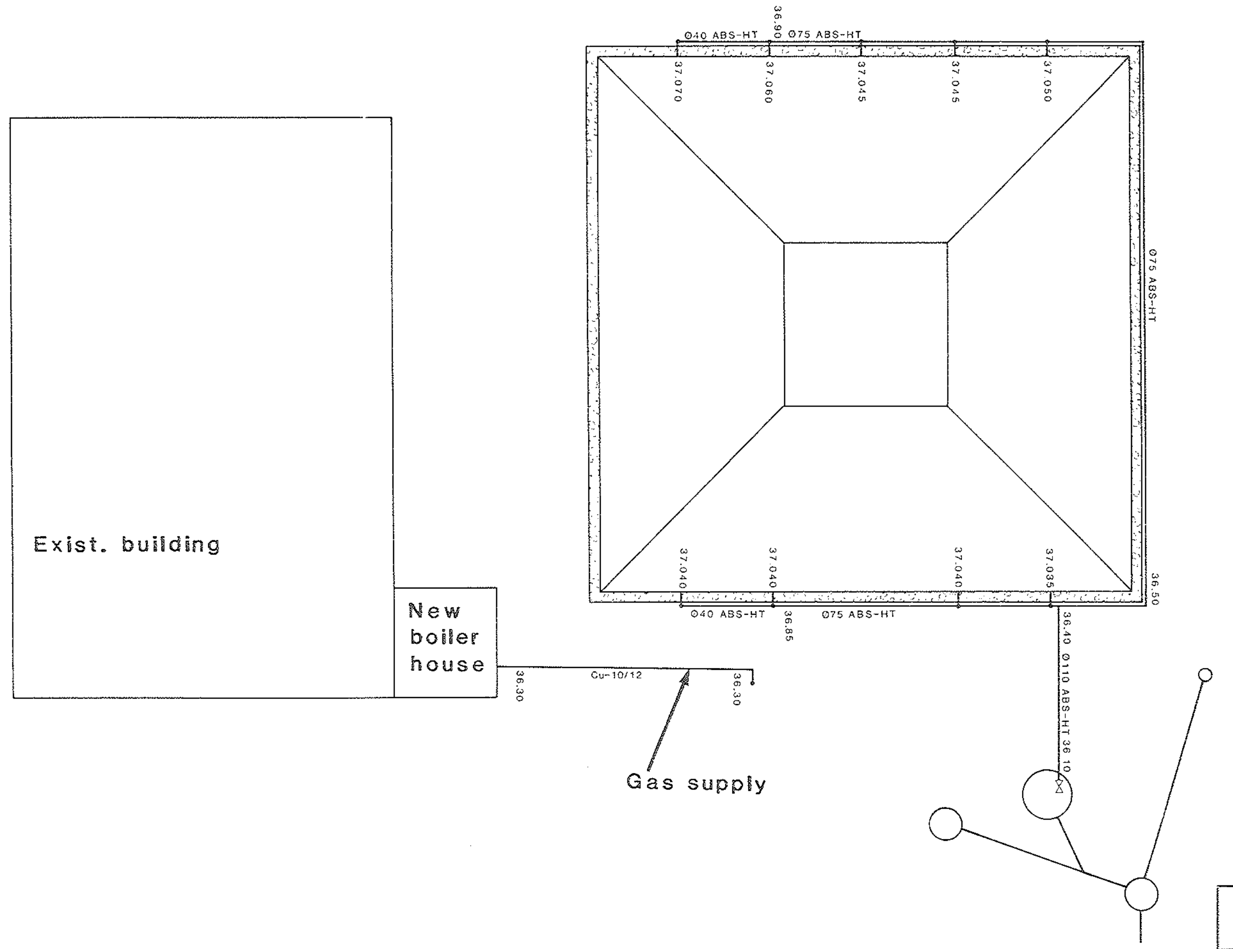


THERMAL INSULATION LABORATORY TECHNICAL UNIVERSITY OF DENMARK BUILDING 118, DK-2800 LYNGBY, DENMARK TELEPHONE 45-2-88 35 11	Revised	Mrk. Date		Text	Drwn	Appr
SEASONAL STORAGE TEST PIT Detail A	Scale 1:7.5	Date Drwn. Check Appr.	82-10-11 SLH KKH	Subst. of 4 Subst. by		

THIS DRAWING MUST NOT BE MADE AVAILABLE TO, COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES



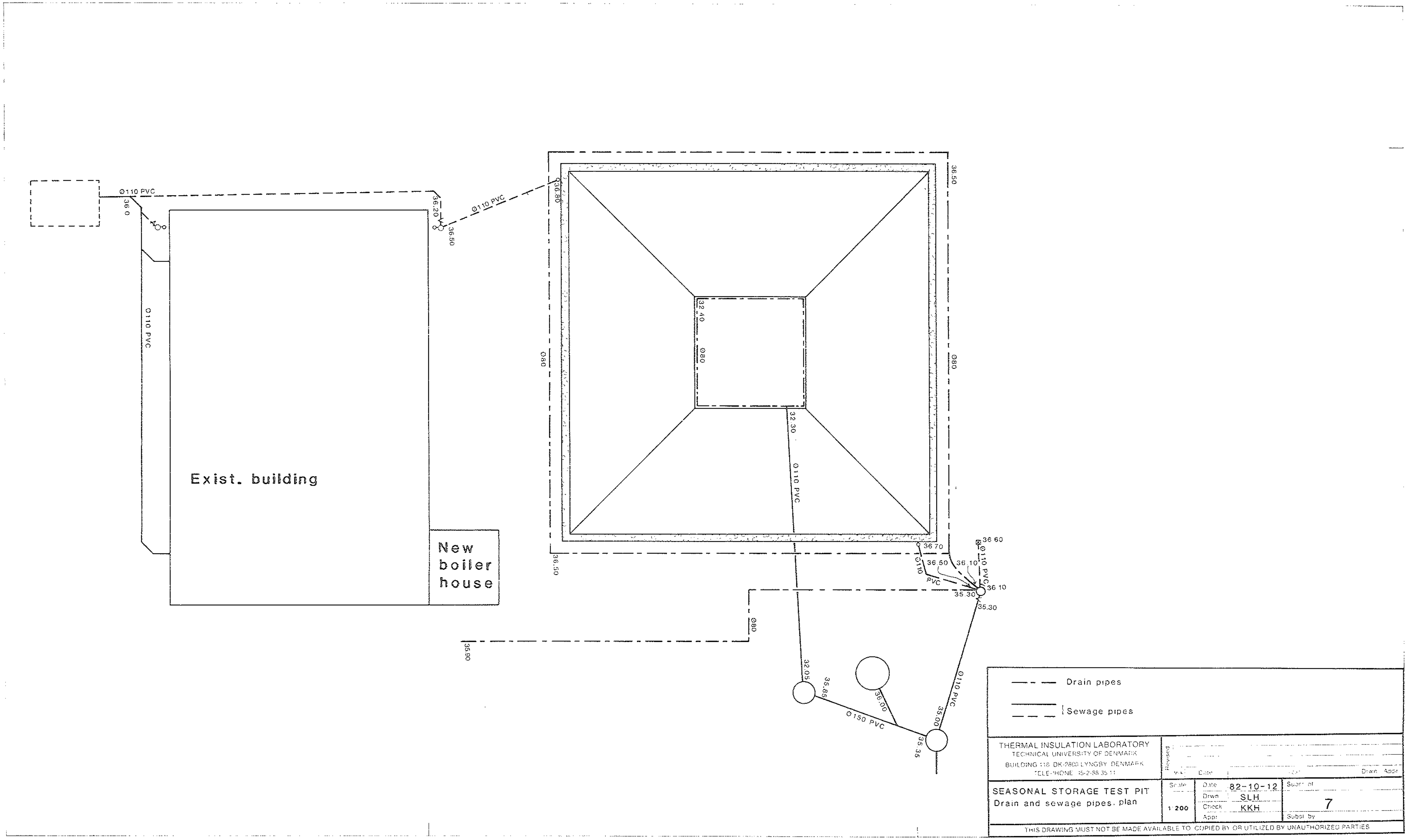
THERMAL INSULATION LABORATORY TECHNICAL UNIVERSITY OF DENMARK BUILDING 118, DK-2800 LYNGBY, DENMARK TELEPHONE 45-2-88 35 11	Revised Mrk	Date	Text	Drwn	Appr
SEASONAL STORAGE TEST PIT Detail B	Scale 1:7.5	Date 82-09-29 Drwn. SLH Check KKH Appr.	Subst. of 5 Subst. by		

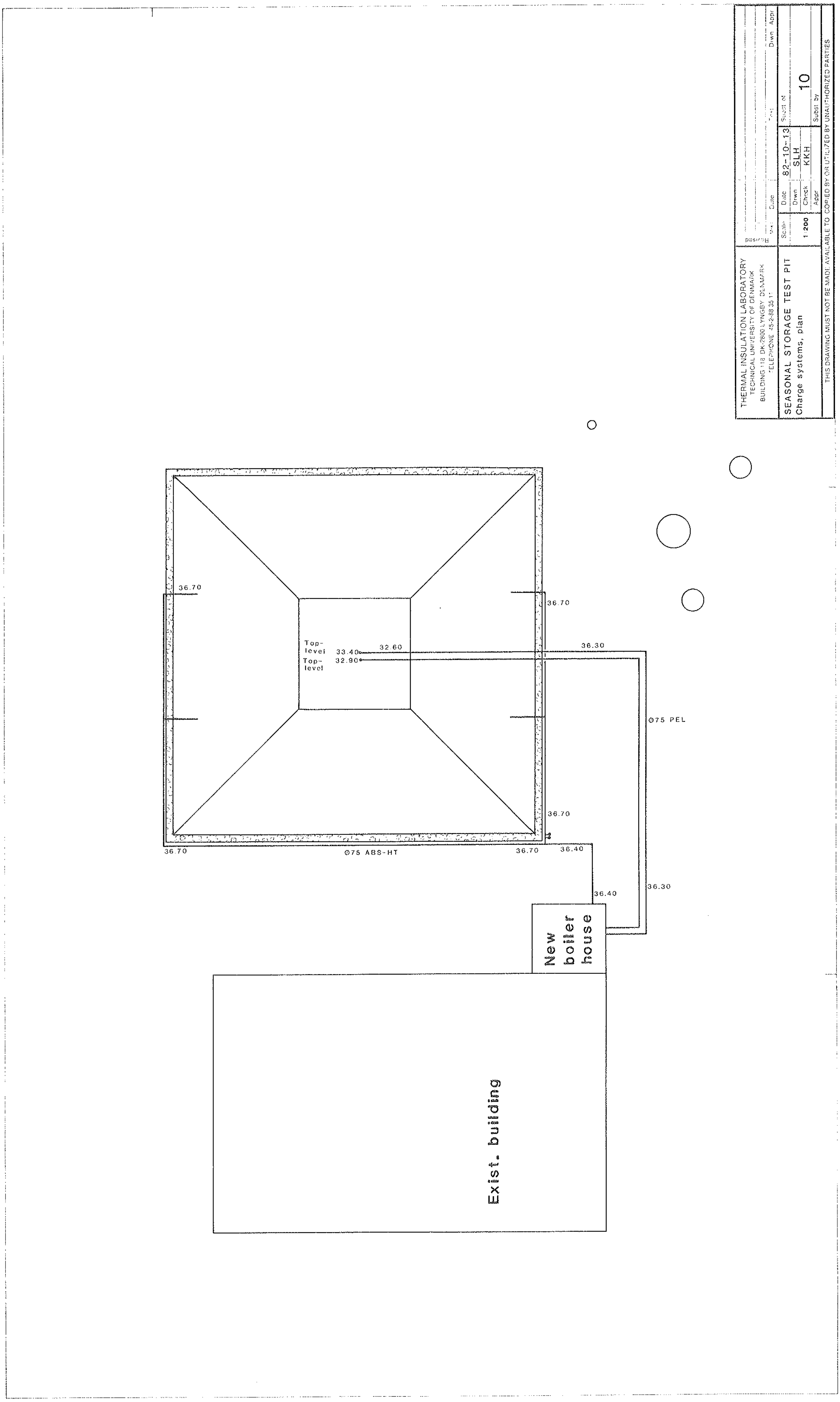


THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 118 DK 2800 LYNGBY DENMARK
TELEPHONE 45-2-88 35 11

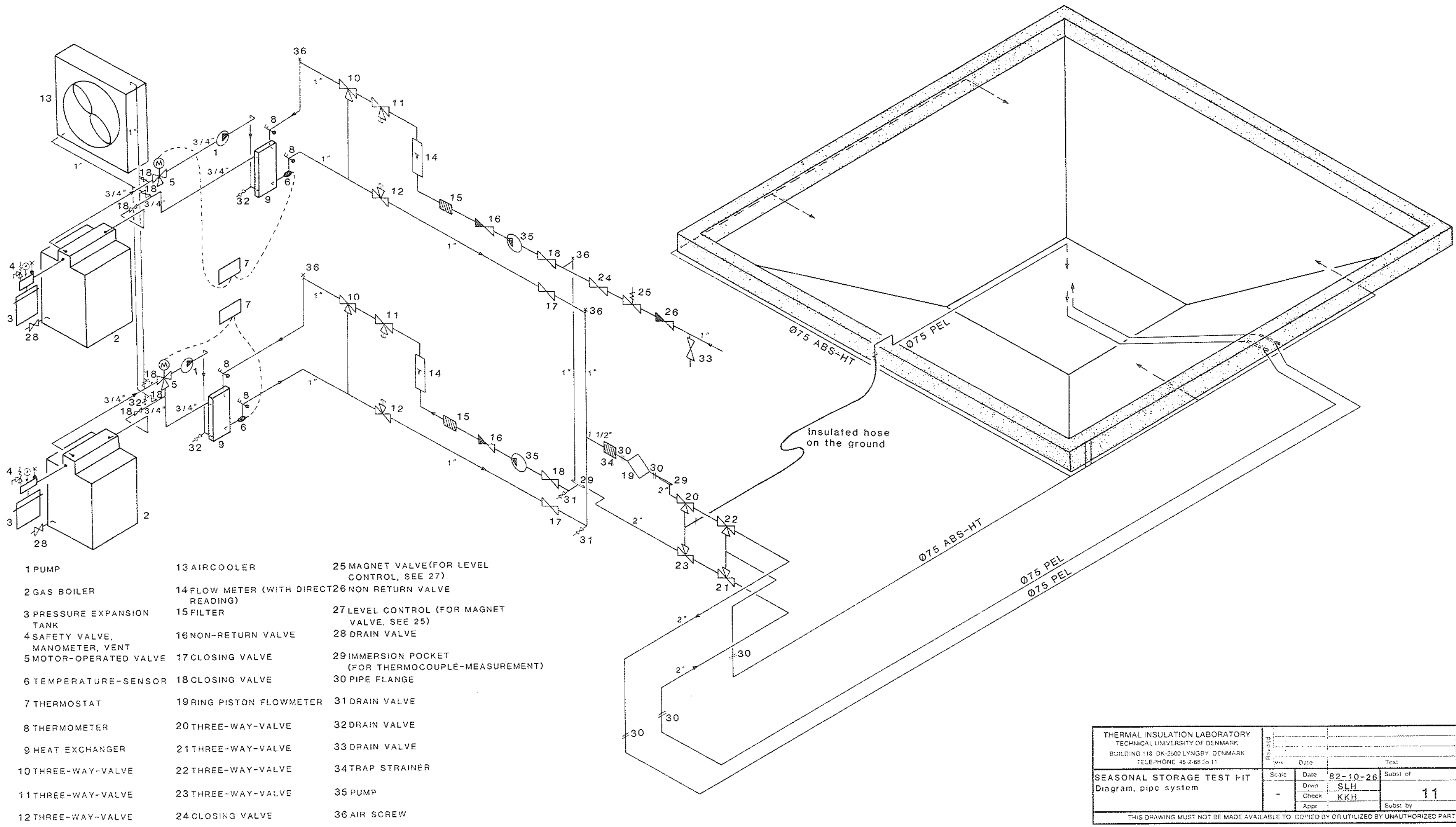
SEASONAL STORAGE TEST PIT
Water level control system, plan

Scale	Date	82-10-13	6
1:200	Drwn	SLH	
	Check	KKH	
	Appr		


Exist. building
New boiler house
Ø110 PVC
Ø80
Ø150 PVC
36.80
36.50
36.20
36 0
36 70
36 60
36 50
36 10
35 30
35.30
35,00
35 35
36,00
35,85
32,05
32 30
32 40
35.90
Drain pipes
Sewage pipes
THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
SEASONAL STORAGE TEST PIT
Drain and sewage pipes, plan
Scale 1:200
Date 82-10-12
Drwn SLH
Check KKH
7
THIS DRAWING MUST NOT BE MADE AVAILABLE TO, COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES



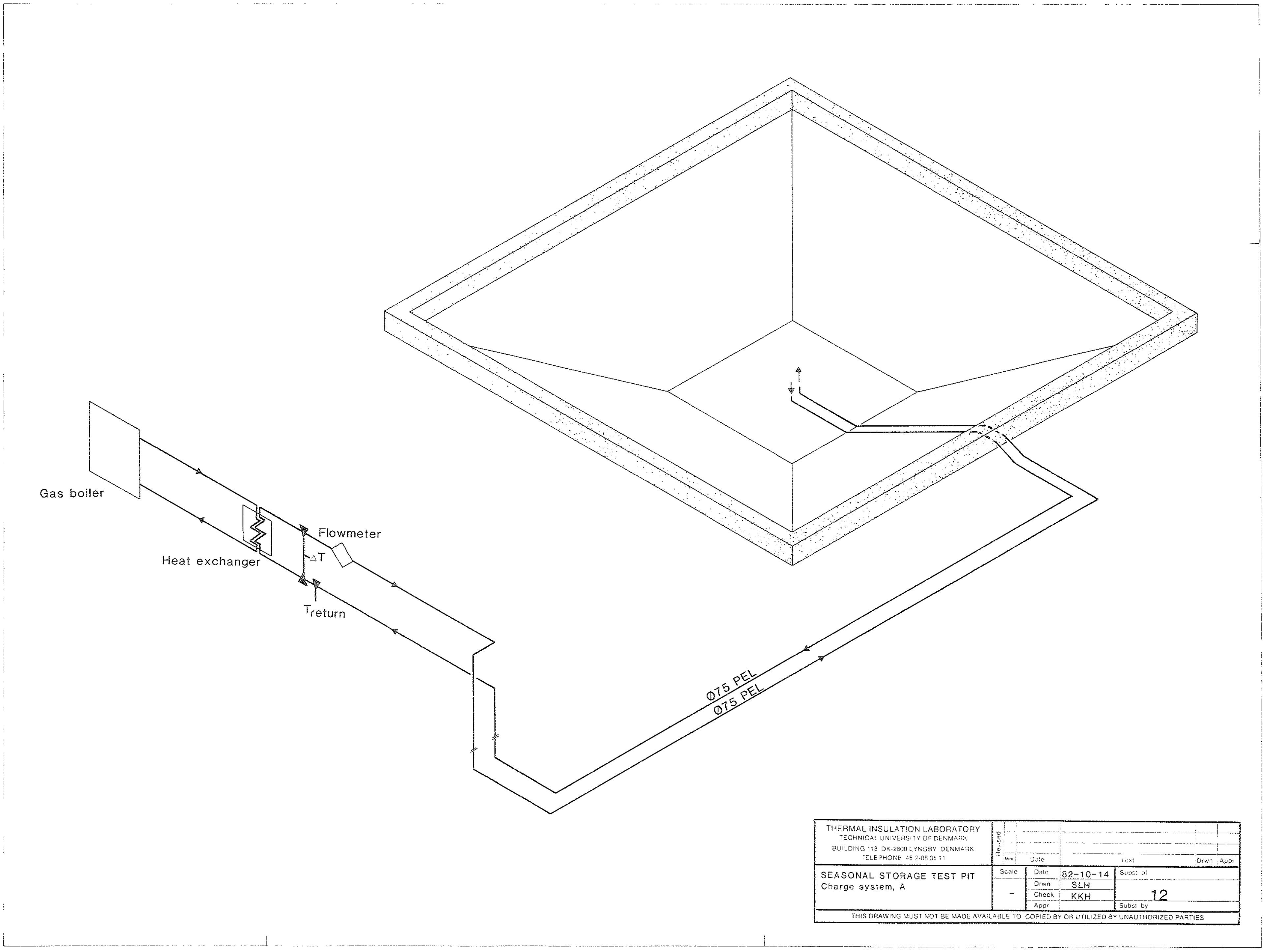
THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
SEASONAL STORAGE TEST PIT
Charge systems, plan
Scale 1:200
Date 82-10-13
Drwn SLH
Check KKH
Sheet of 10
THIS DRAWING MUST NOT BE MADE AVAILABLE TO COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES
36.70
36.70
Top-level 33.40
Top-level 32.90
32.60
36.30
Ø75 PEL
36.70
36.70
Ø75 ABS-HT
36.70
36.40
36.40
36.30
New boiler house
Exist. building

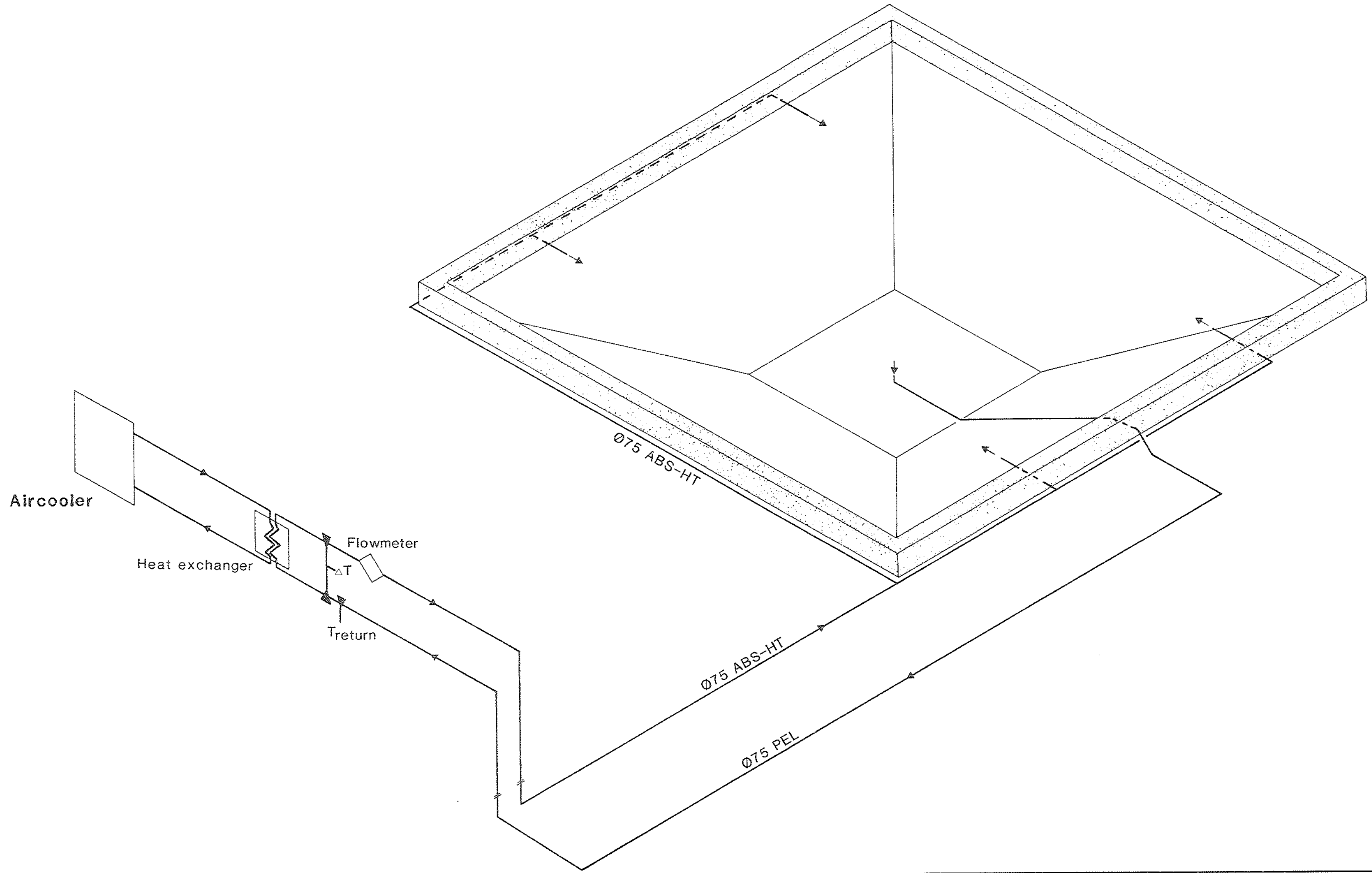


THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 118 DK-2800 LYNGBY DENMARK
TELEPHONE 45-2-8835 11

SEASONAL STORAGE TEST PIT
Diagram, pipe system

Scale	Date	82-10-26	Subst of
-	Drwn	SLH	11
	Check	KKH	
	Appr		Subst by


Gas boiler
Heat exchanger
Flowmeter
ΔT
Treturn
Ø75 PEL
Ø75 PEL
THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 118 DK-2800 LYNGBY DENMARK
TELEPHONE 45 2-88 35 11
SEASONAL STORAGE TEST PIT
Charge system, A
Scale -
Date 82-10-14
Drwn SLH
Check KKH
Appr
12
THIS DRAWING MUST NOT BE MADE AVAILABLE TO COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES

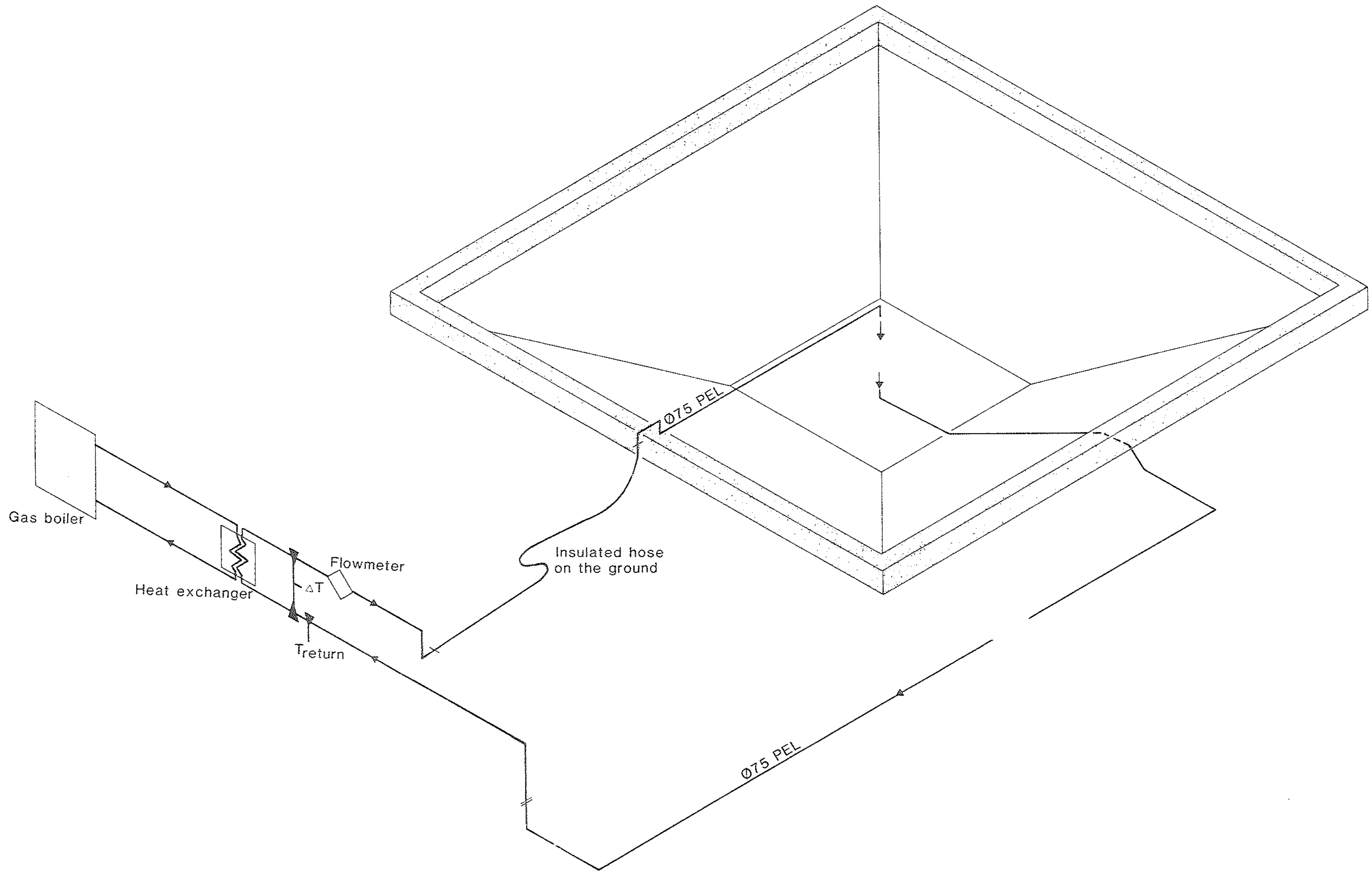


THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 118 DK-2800 LYNGBY DENMARK
TELEPHONE 45-2-88 35 11

Revised	Date	Text	Drwn	Appr

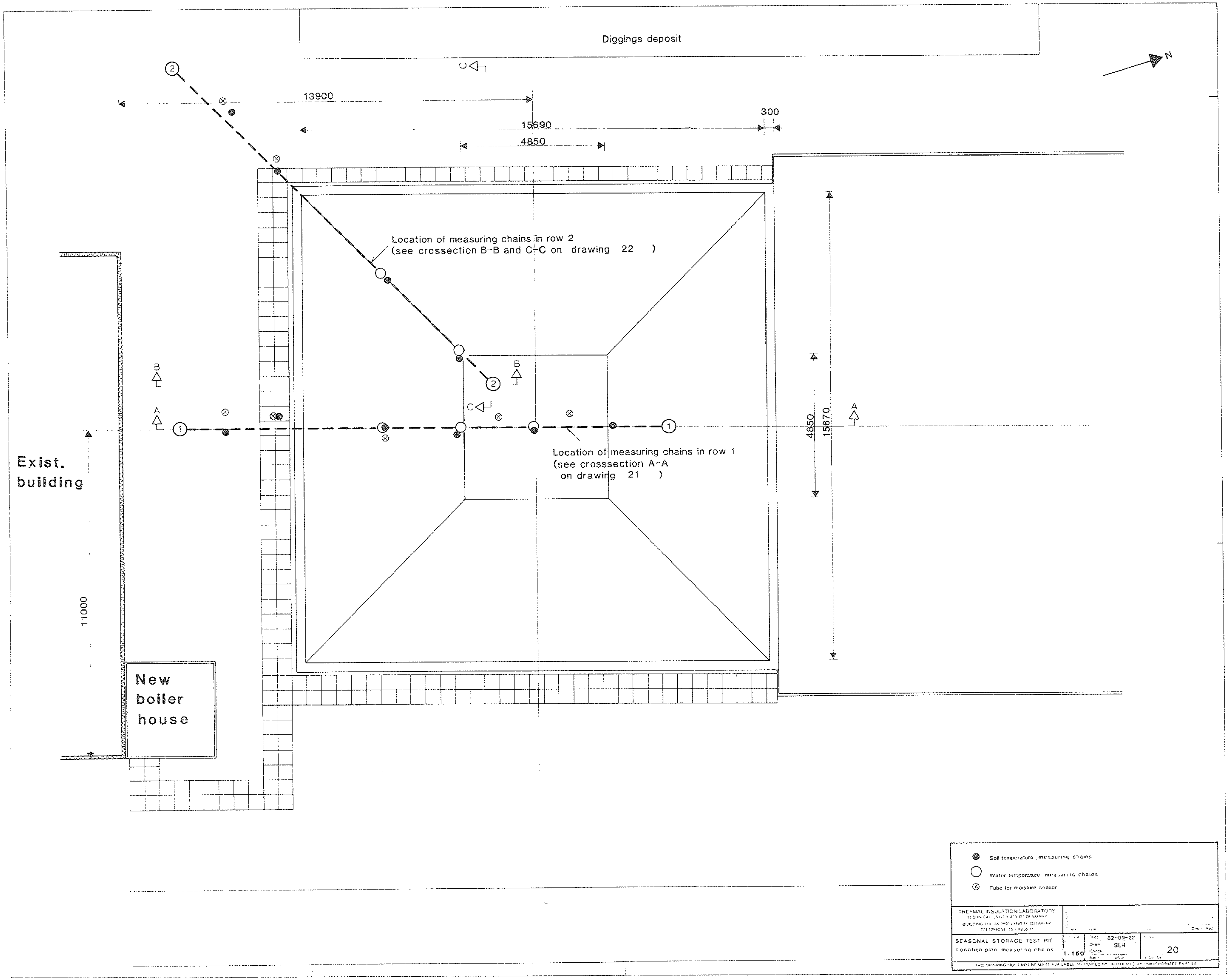
SEASONAL STORAGE TEST PIT
Charge system, B

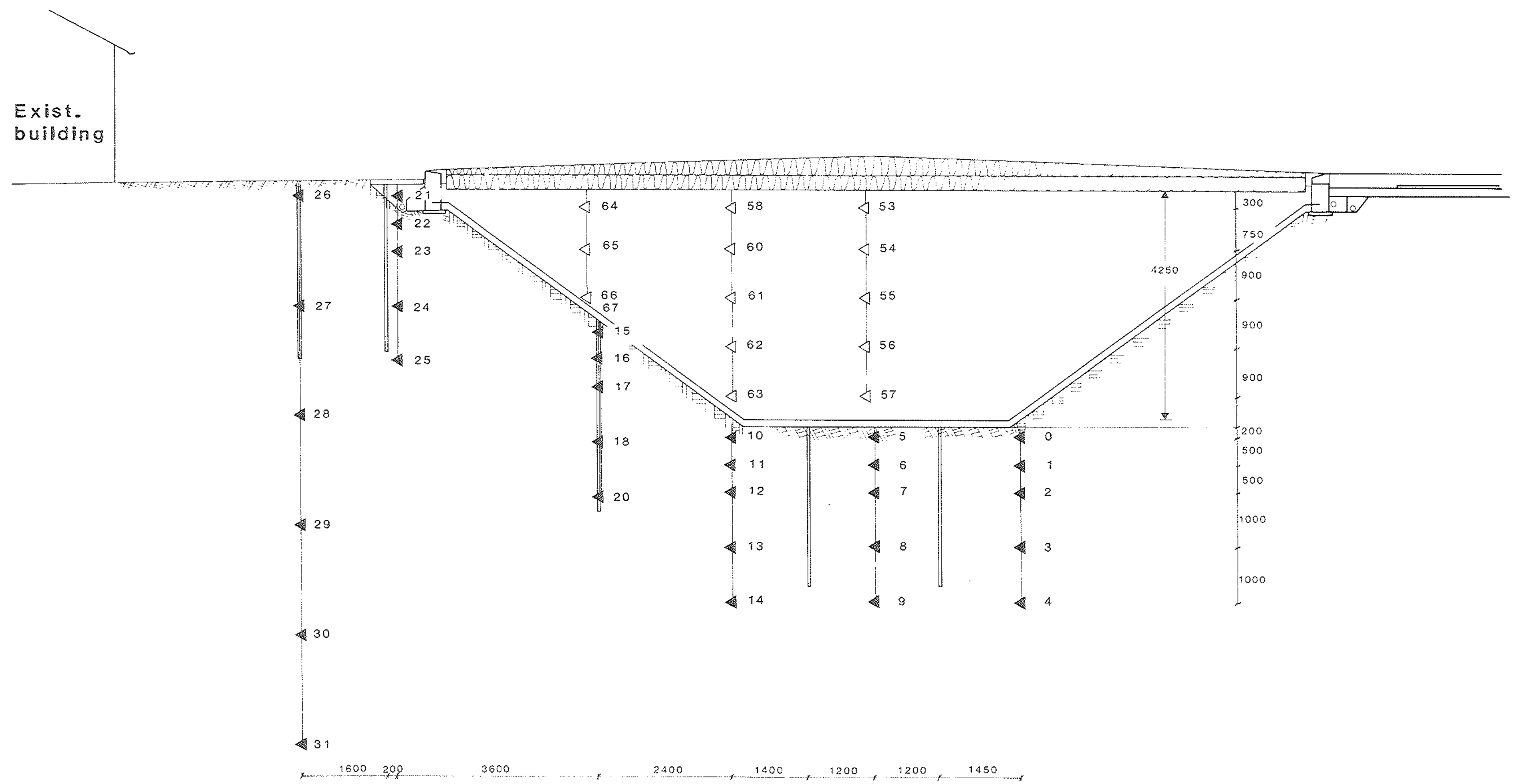
Scale			Subst of
–	Date	82-10-13	13
	Drwn	SLH	
	Check	KKH	
	Appr		Subst by



THERMAL INSULATION LABORATORY TECHNICAL UNIVERSITY OF DENMARK BUILDING 118 DK-2800 LYNGBY DENMARK TELEPHONE 45-2-88 35 11	Revised		
SEASONAL STORAGE TEST PIT Charge system, C	Scale	Date 82-10-14 Drwn SLH Check KKH Appr	Sheet of 14 Subst by

THIS DRAWING MUST NOT BE MADE AVAILABLE TO COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES


Diggings deposit
N
13900
15690
4850
300
15670
4850
11000
Location of measuring chains in row 2
(see crossection B-B and C-C on drawing 22)
Location of measuring chains in row 1
(see crosssection A-A
on drawing 21)
A
B
C
Exist.
building
New
boiler
house
Soil temperature, measuring chains
Water temperature, measuring chains
Tube for moisture sensor
THERMAL INSULATION LABORATORY
SEASONAL STORAGE TEST PIT
Location plan, measuring chains
1:150
82-09-22
SLH
20



NOTE: The members 19,39 and 59 are not shown since they are only used as references in the HEWLETT PACKARD 3054A data logger system

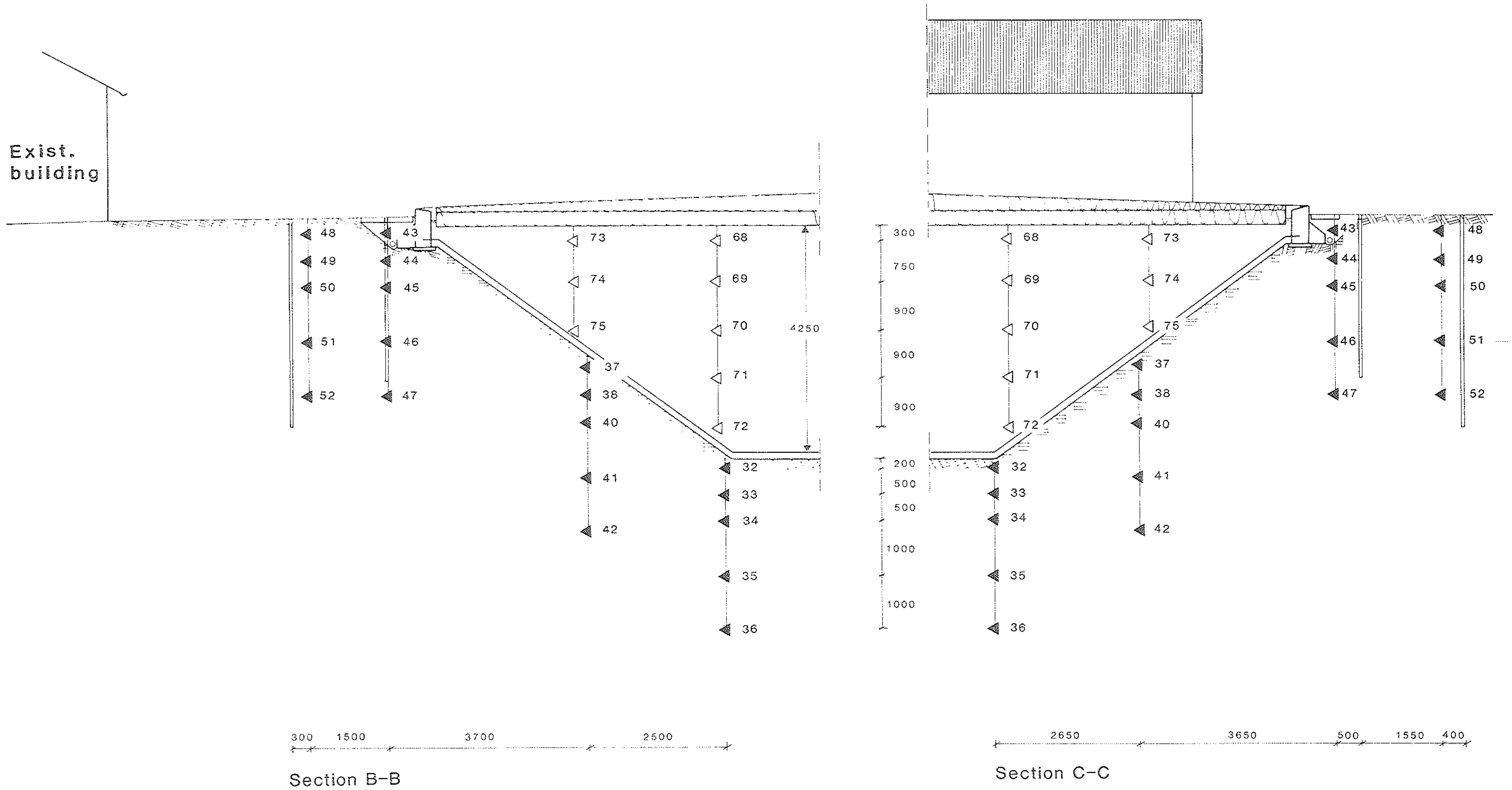
Soil temperature
Water temperature
number indicates reference No. in the HEWLETT PACKARD 3054A data logger system

Tube for moisture sensor

THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 119 DK 2800 LYNGBY DENMARK
TELEPHONE 45-2-88 35 11

SEASONAL STORAGE TEST PIT Section A-A showing location of measuring points, Row 1	Scale 1:125	Date 82-09-27 Drwn SLH Check KKH Appr	21

THIS DRAWING MUST NOT BE MADE AVAILABLE TO, COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES



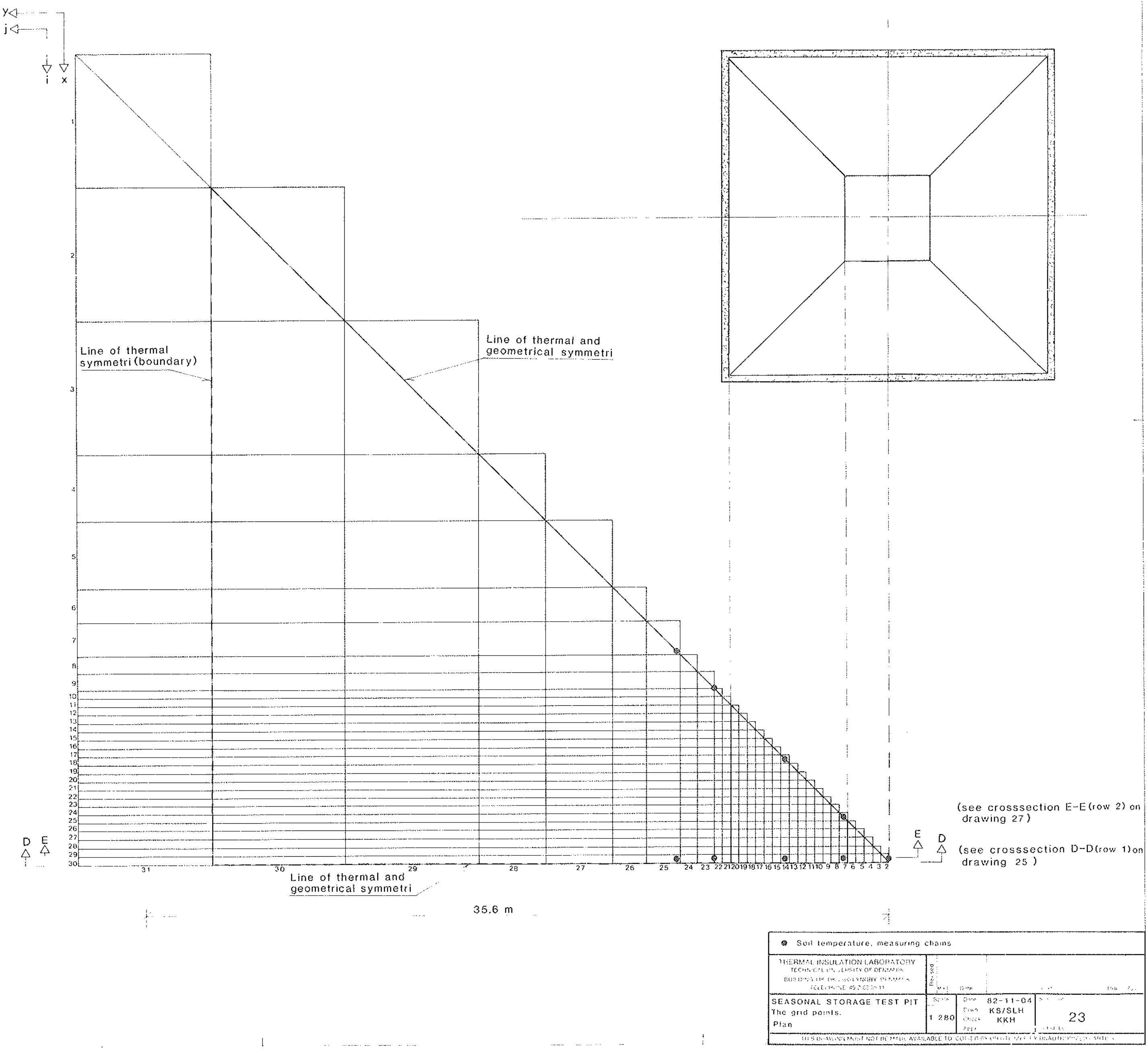
NOTE: The members 19,39 and 59 are not shown since they are only used as references in the HEWLETT PACKARD 3054A data logger system

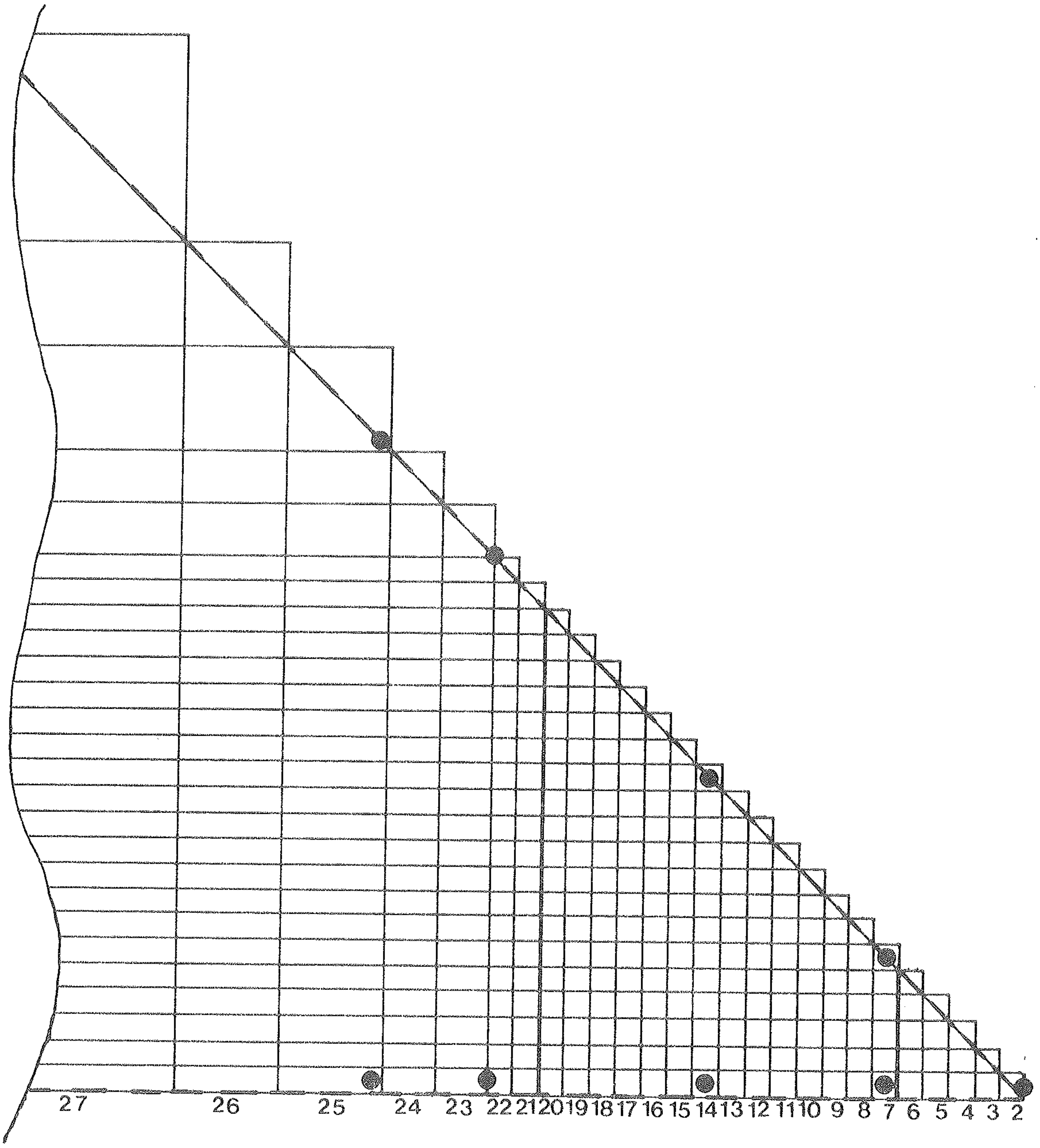
Soil temperature	number indicates reference No. in the
Water temperature	HEWLETT PACKARD 3054A data logger system
Tube for moisture sensor	

THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 118 DK 2800 LYNGBY DENMARK
TELEPHONE 45 2 88 35 11

SEASONAL STORAGE TEST PIT
Sections B-B and C-C showing location of measuring points.
Row 2

Scale			Subst of
1:125	Date	82-10-07	
	Drwn	SLH	22
	Check	KKH	
	Appr		Subst by


y
j
i
x
Line of thermal symmetri (boundary)
Line of thermal and geometrical symmetri
Line of thermal and geometrical symmetri
35.6 m
(see crosssection E-E(row 2) on drawing 27)
(see crosssection D-D(row 1)on drawing 25)
Soil temperature, measuring chains
THERMAL INSULATION LABORATORY
SEASONAL STORAGE TEST PIT
The grid points.
Plan
1 280
82-11-04
KS/SLH
KKH
23

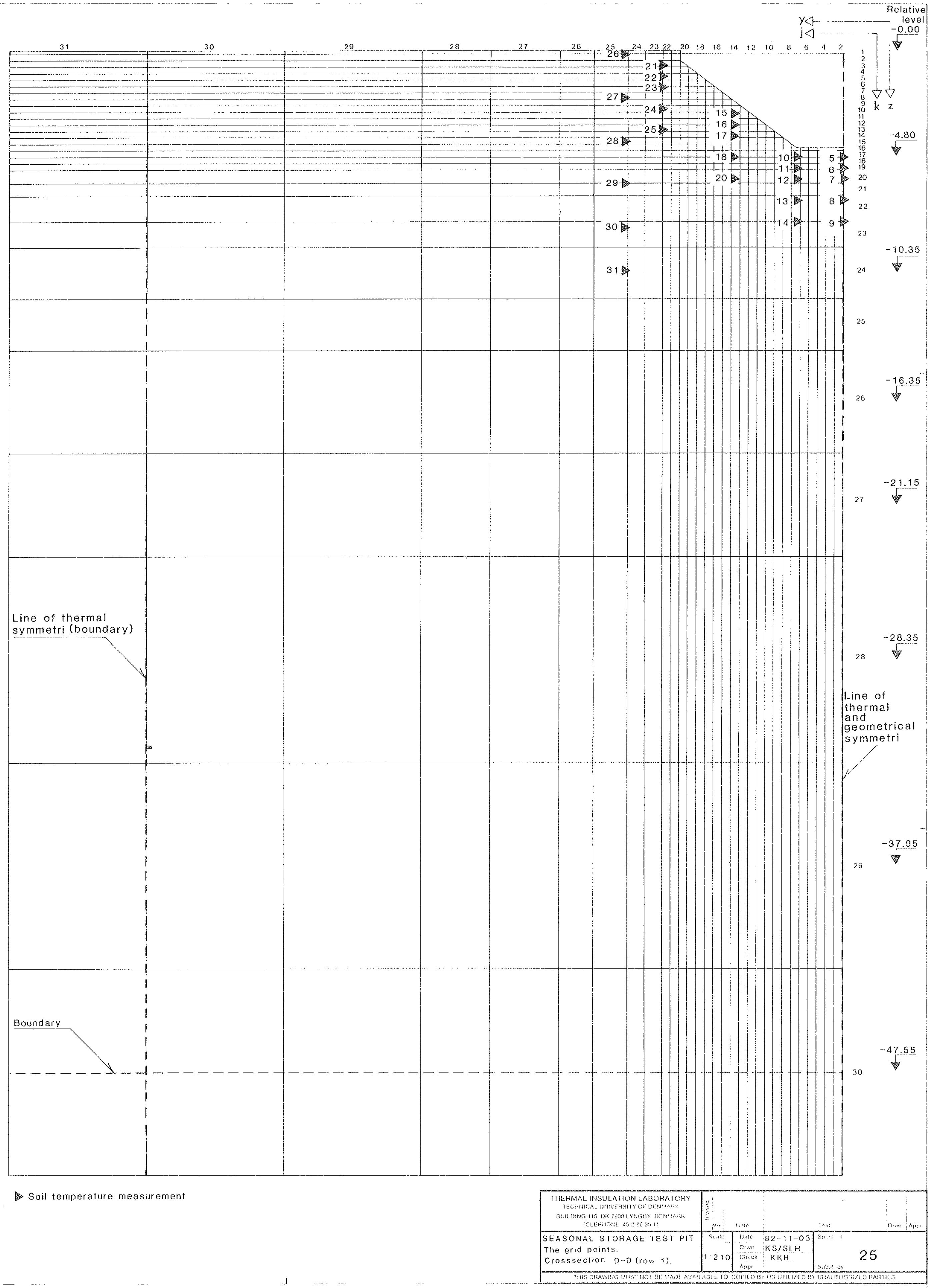


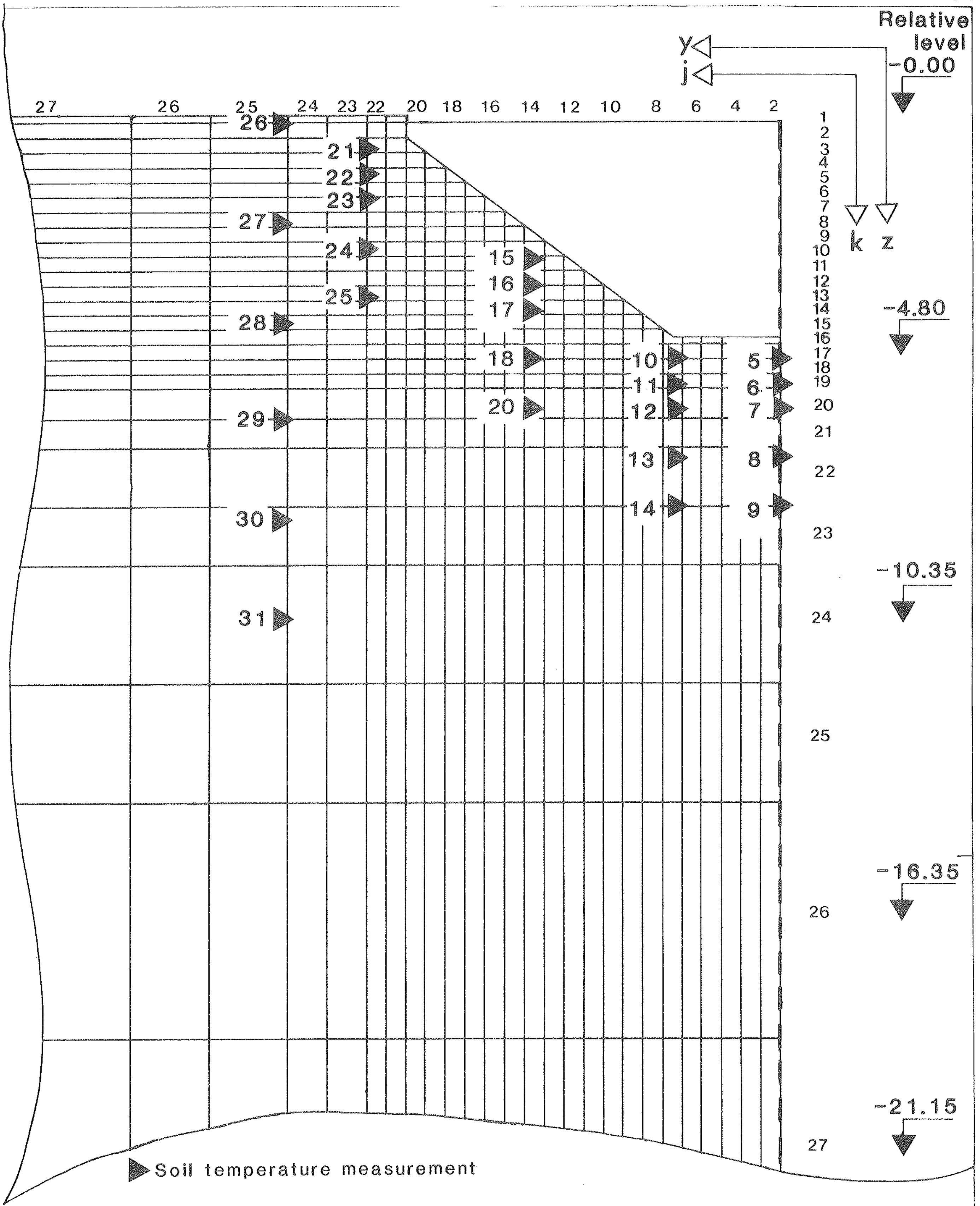
● Soil temperature, measuring chains

THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 118, DK-2800 LYNGBY, DENMARK
TELEPHONE 45-2-88 35 11

Revised Mrk.	Date	Text	Drwn.	Appr.

SEASONAL STORAGE TEST PIT Part of grid points. Plan	Scale: 1:100	Date	83-07-06	Subst. of
		Drwn.	SLH	24
		Check	KKH	
		Appr.		Subst. by


Relative level
y
j
k z
-0.00
-4.80
-10.35
-16.35
-21.15
-28.35
-37.95
-47.55
31 30 29 28 27 26 25 24 23 22 20 18 16 14 12 10 8 6 4 2
26 21 22 23 27 24 25 28 29 30 31
15 16 17 18 20
10 11 12 13 14
5 6 7 8 9
Line of thermal symmetri (boundary)
Line of thermal and geometrical symmetri
Boundary
Soil temperature measurement
THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 118 DK 2800 LYNGBY DENMARK
TELEPHONE 45 2 88 35 11
SEASONAL STORAGE TEST PIT
The grid points.
Crosssection D-D (row 1).
Scale 1:210
Date 82-11-03
Drwn KS/SLH
Check KKH
Appr
25
THIS DRAWING MUST NOT BE MADE AVAILABLE TO, COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES

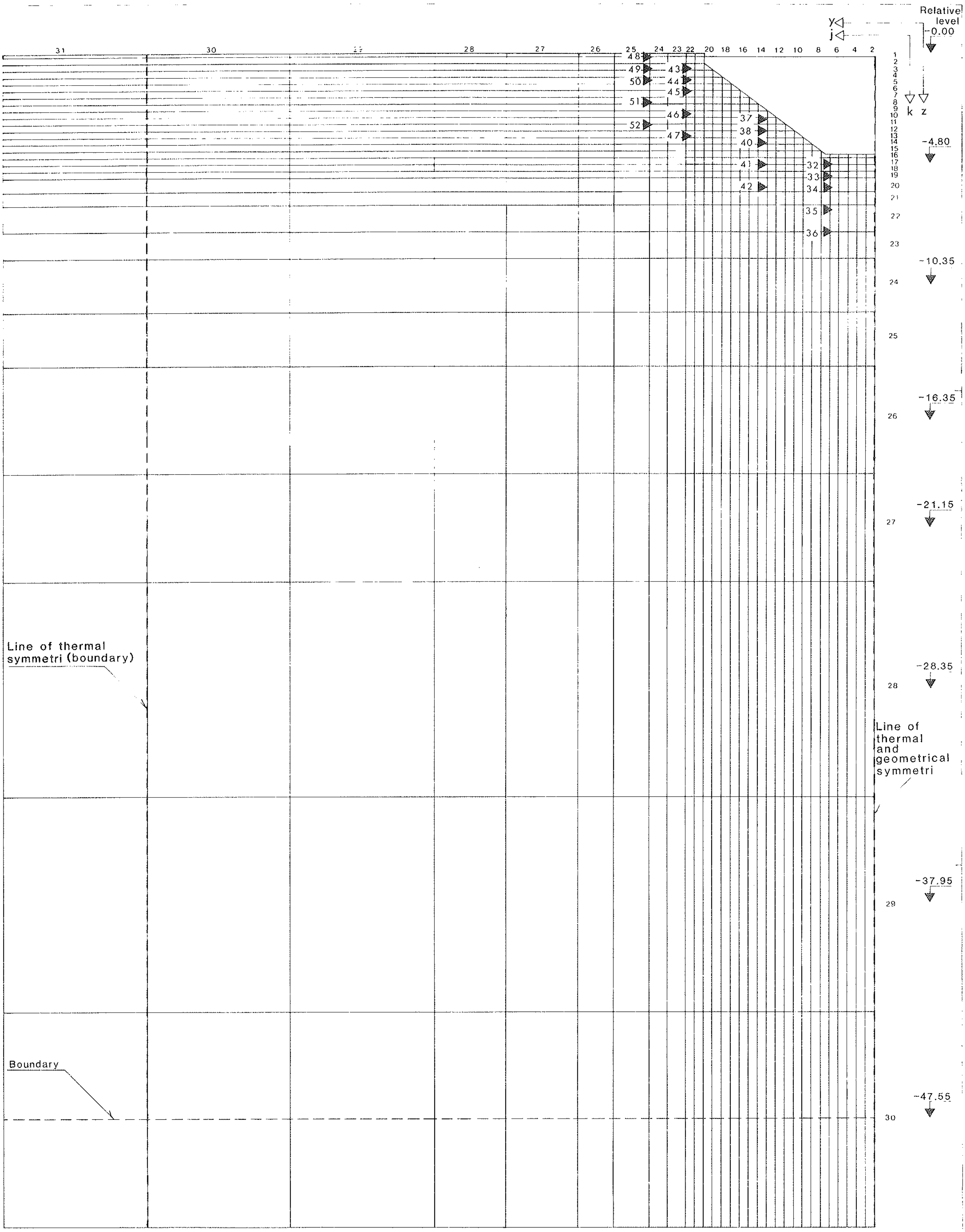


THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK
BUILDING 118, DK-2800 LYNGBY, DENMARK
TELEPHONE 45-2-88 35 11

Revised	Mrk.	Date	Text	Drwn.	Appr.

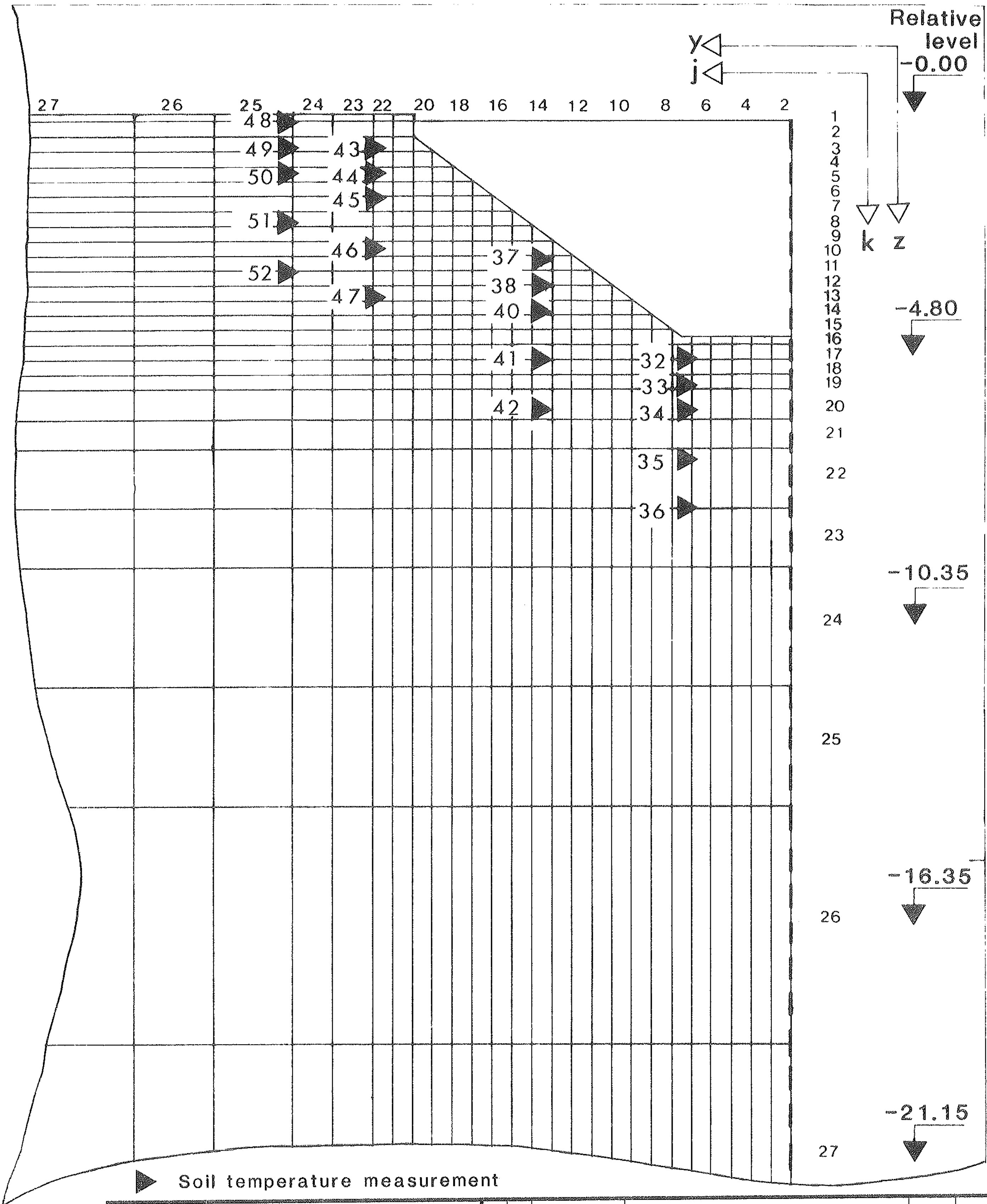
SEASONAL STORAGE TEST PIT
Part of grid points.
Crosssection D–D (row 1)

Scale			Subst. of
1:100	Date	83-07-11	26
	Drwn.	SLH	
	Check	KKH	
	Appr.		Subst. by



▶ Soil temperature measurement

THERMAL INSULATION LABORATORY TECHNICAL UNIVERSITY OF DENMARK BUILDING 118 DK-2800 LYNGBY DENMARK TELEPHONE 45-2-88 35 11	Revised	Date	Text	Drwn Appr
SEASONAL STORAGE TEST PIT The grid points. Crosssection E-E (row 2).	Scale 1:210	Date 83-03-15 Drwn KS/SLH Check KKH Appr	Subst. of 27 Subst. by	



▶ Soil temperature measurement

THERMAL INSULATION LABORATORY TECHNICAL UNIVERSITY OF DENMARK BUILDING 118, DK-2800 LYNGBY, DENMARK TELEPHONE 45-2-88 35 11	Revised	Mrk.	Date	Text	Drwn. / Appr.
SEASONAL STORAGE TEST PIT Part of grid points. Crosssection E-E (row 2)	Scale 1:100	Date	83-07-06	Subst. of	
		Drwn.	SLH	28	
		Check	KKH		
		Appr.		Subst. by	

THIS DRAWING MUST NOT BE MADE AVAILABLE TO, COPIED BY OR UTILIZED BY UNAUTHORIZED PARTIES

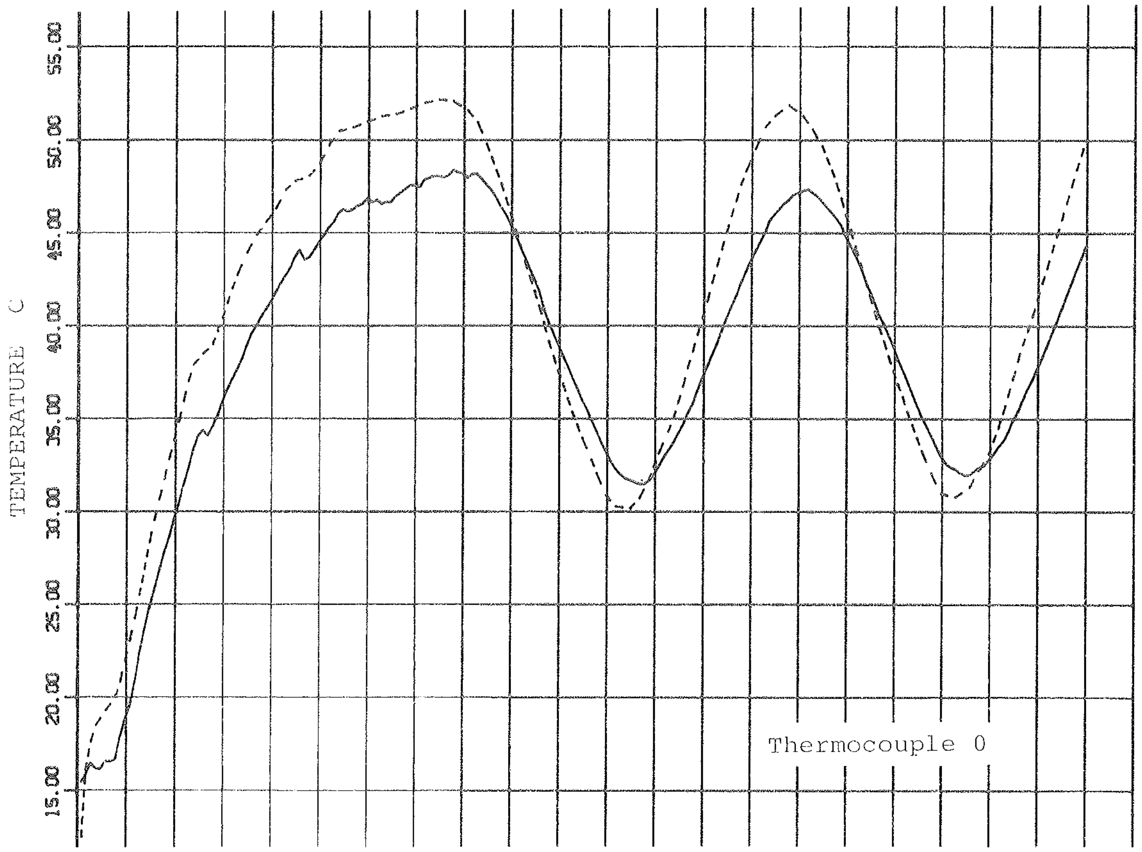
Appendix 2

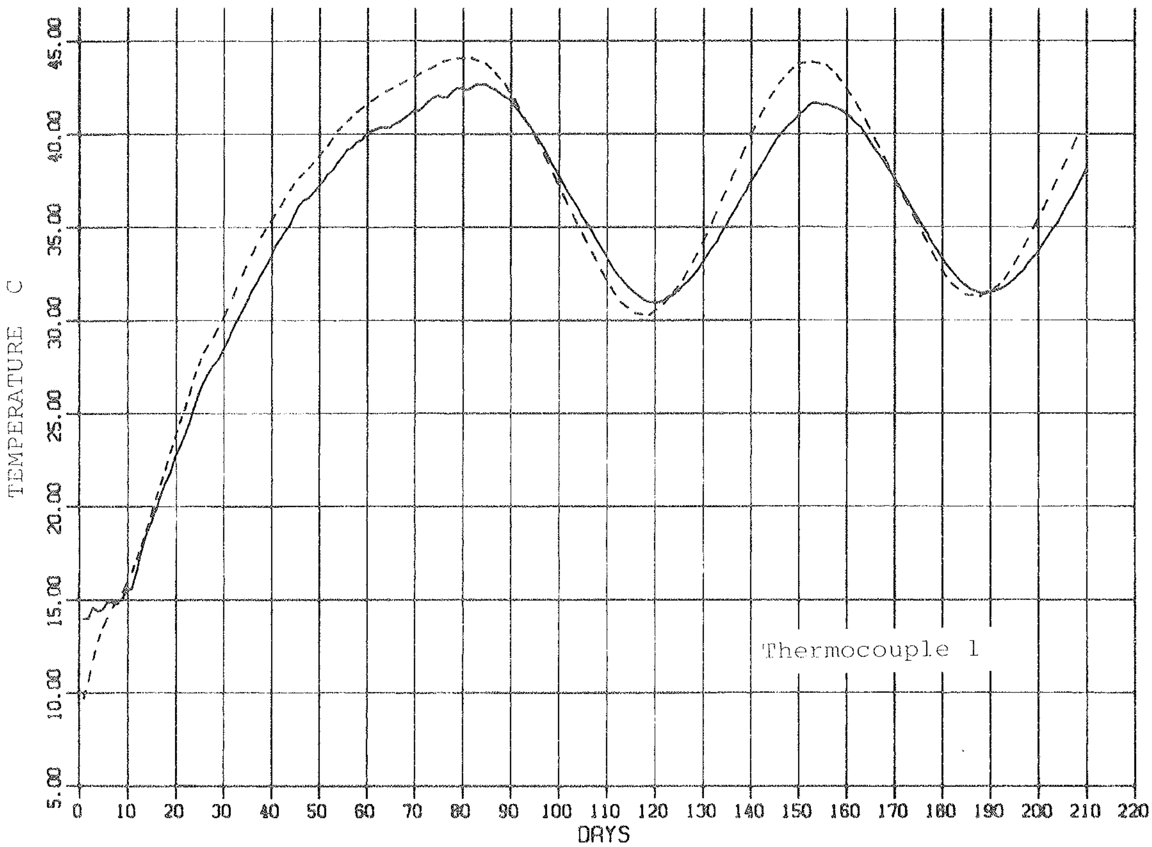
The temperatures on the different thermocouple location (the thermocouple locations are indicated on the drawings 21 and 22).

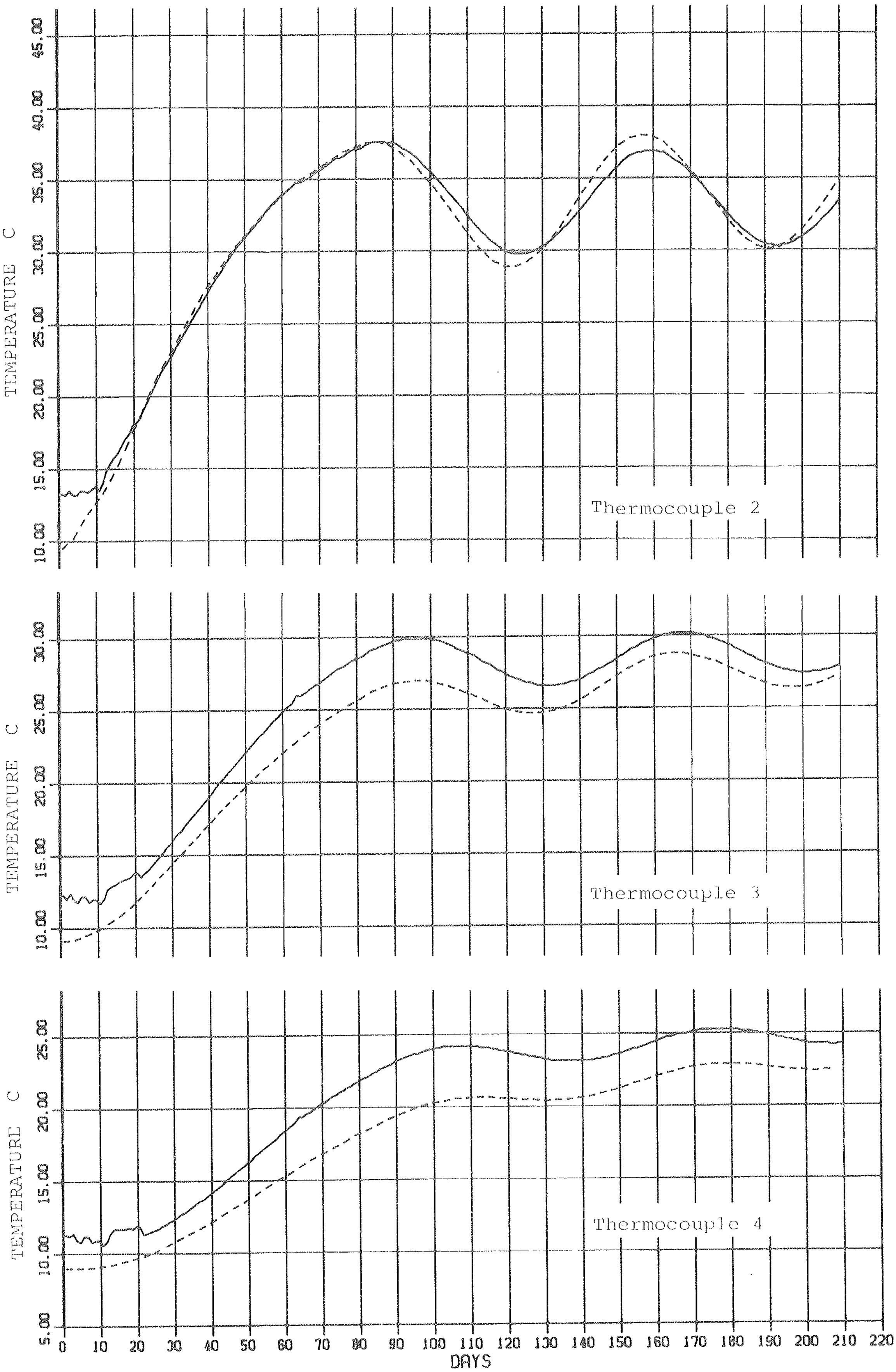
Note:

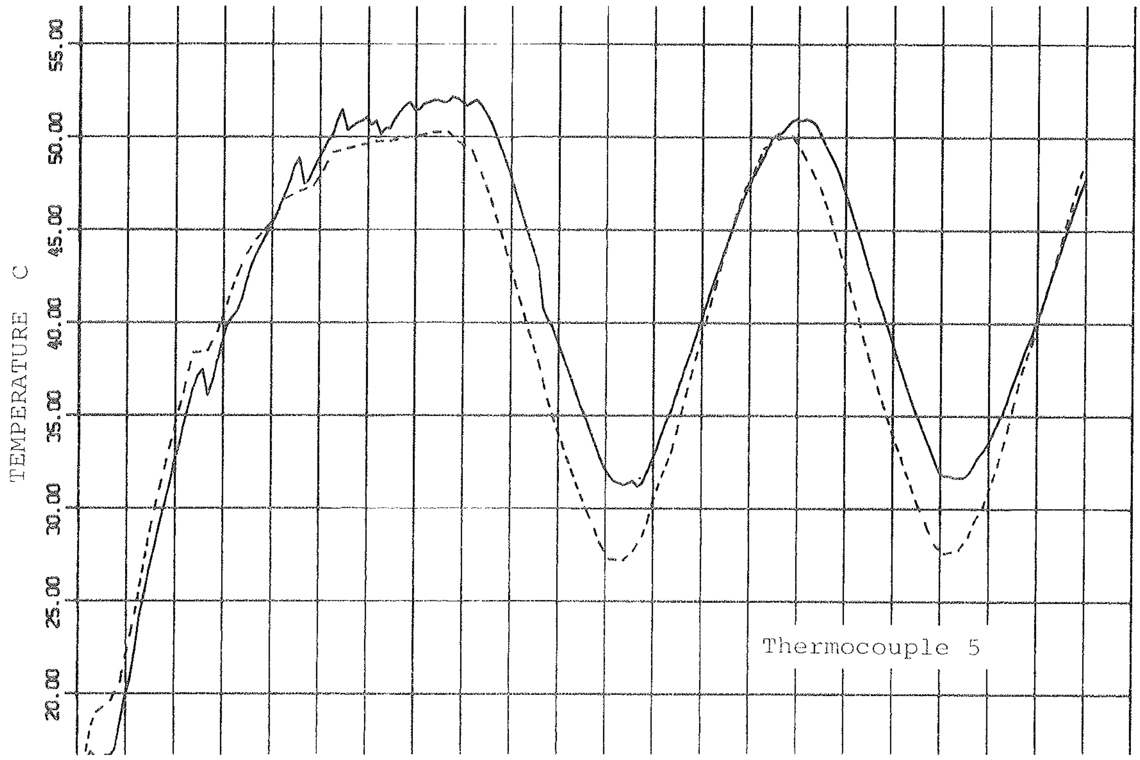
———— Measured temperature

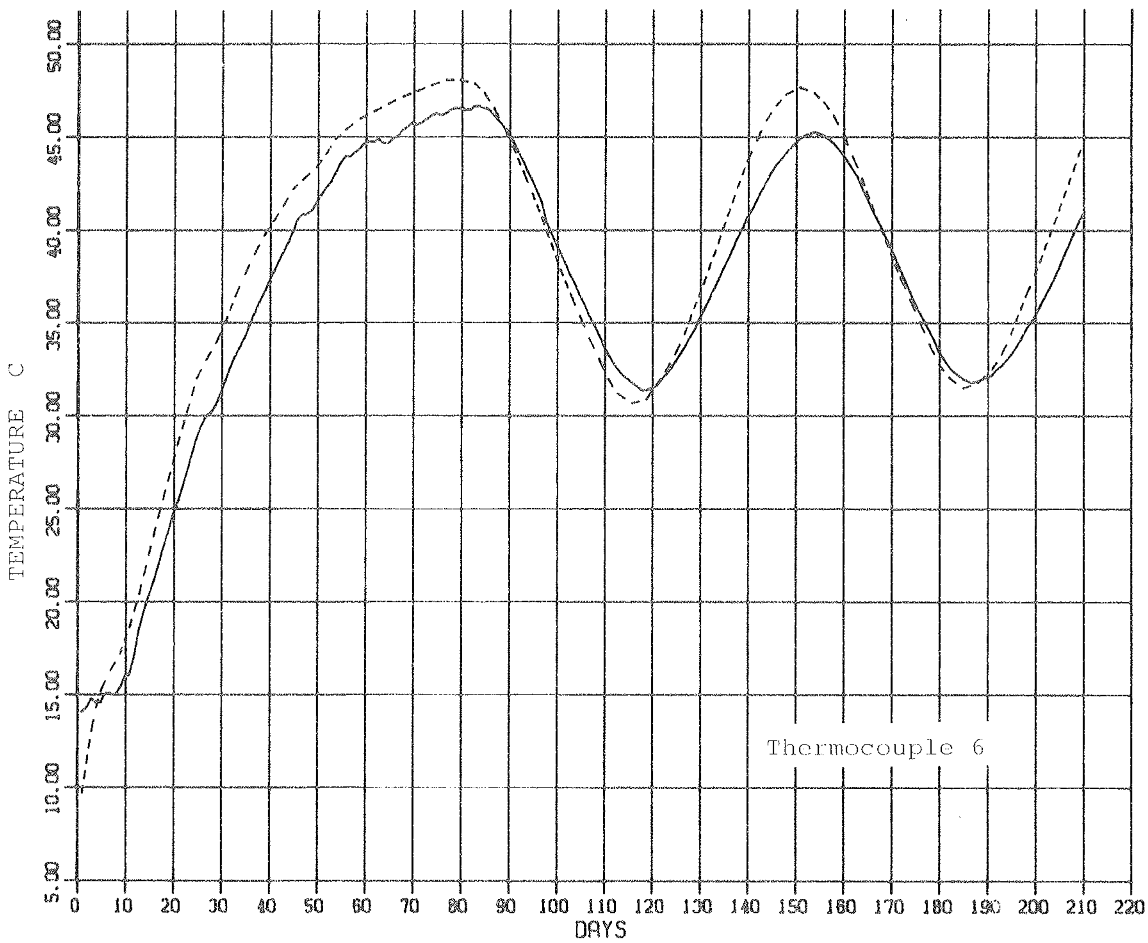
------- Calculated temperature. The thermal properties of the soil used are $\lambda = 1.6$ W/m^{0}C and $\alpha = 22$ m^2/yr.

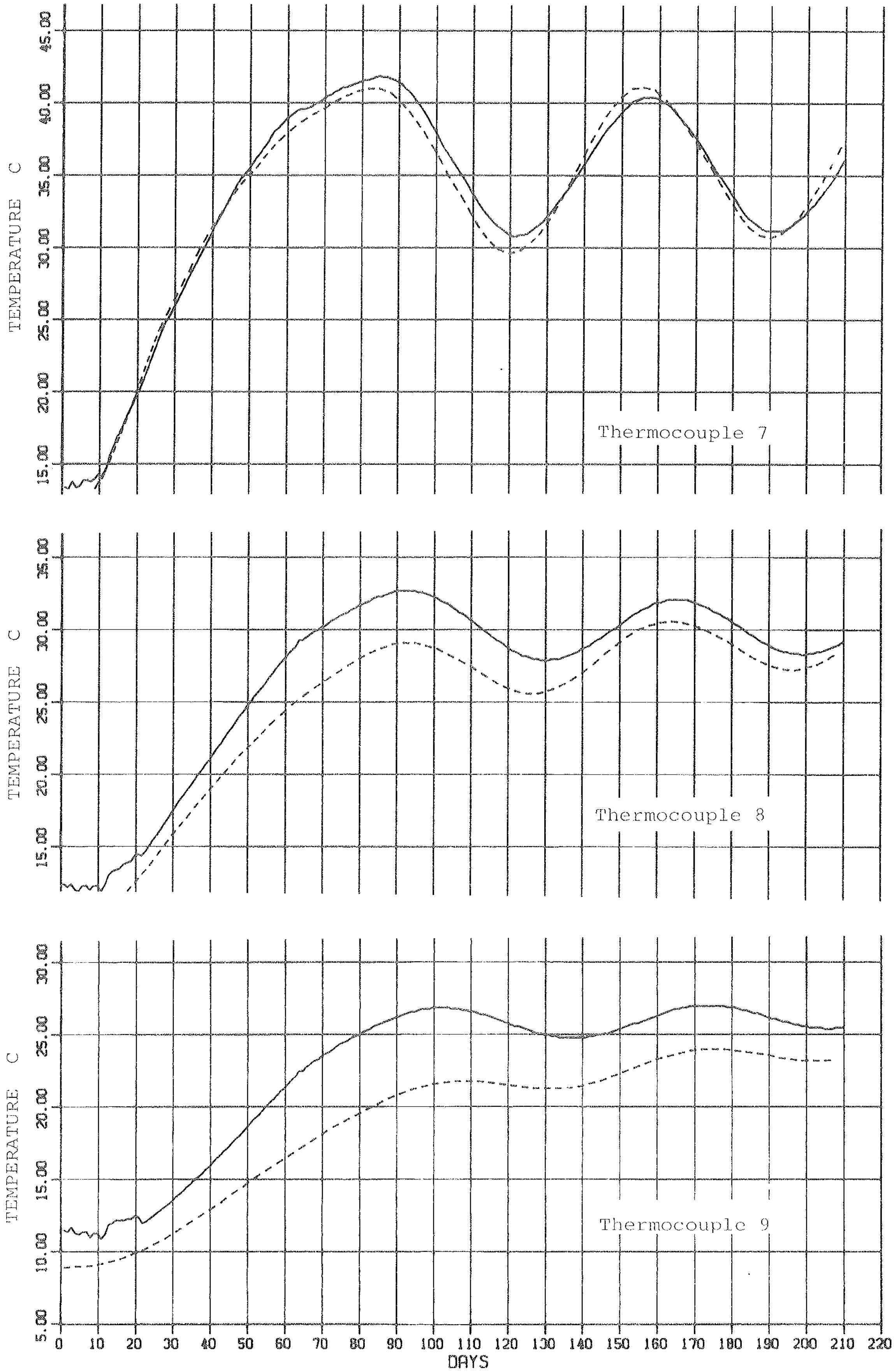

TEMPERATURE C
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
Thermocouple 0

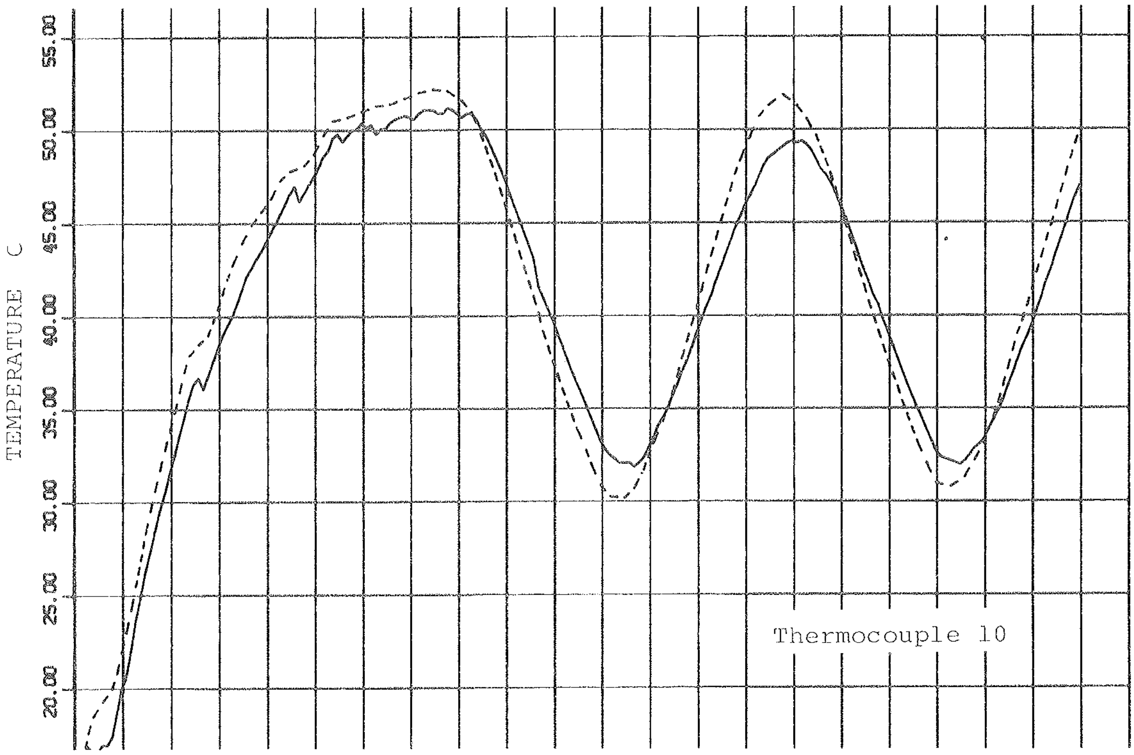

TEMPERATURE C
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS
Thermocouple 1

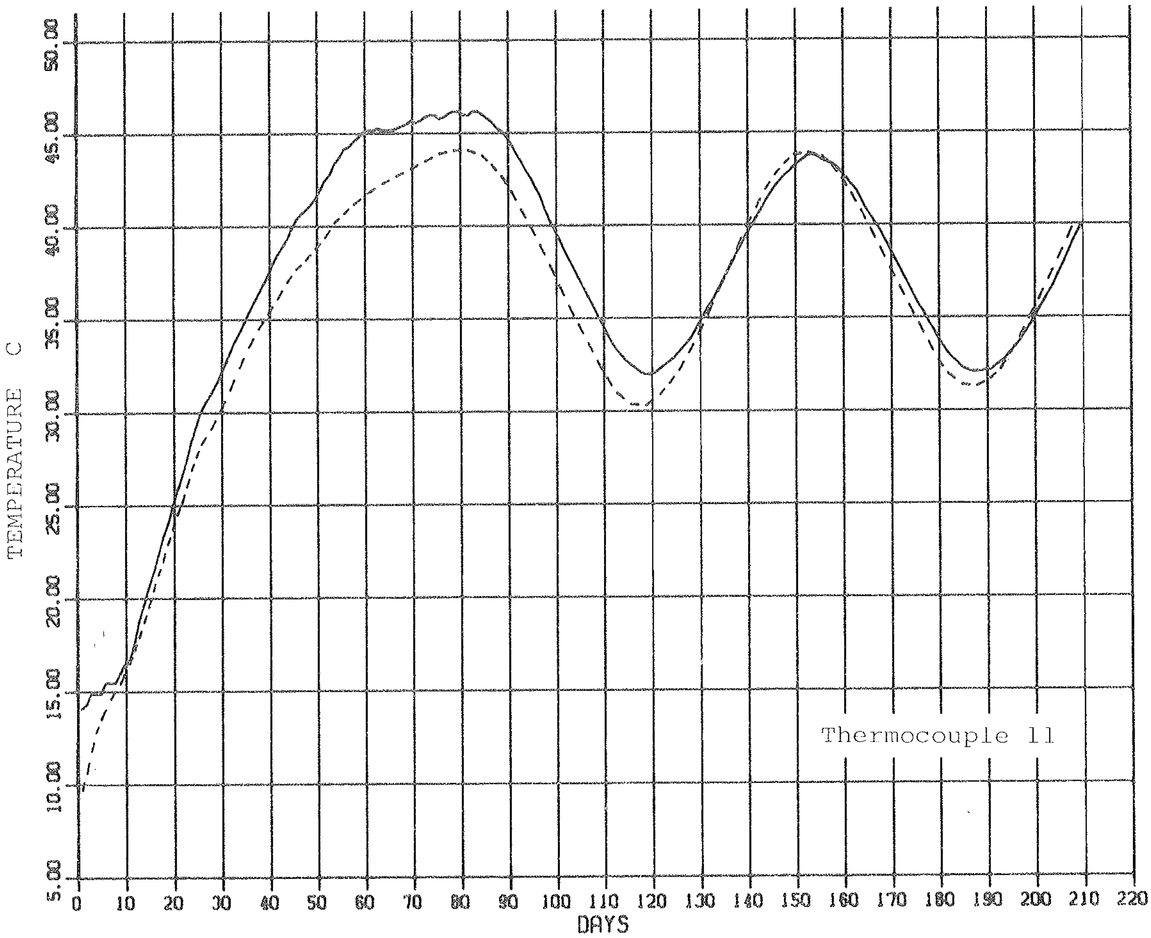

TEMPERATURE C
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
Thermocouple 2
TEMPERATURE C
10.00
15.00
20.00
25.00
30.00
Thermocouple 3
TEMPERATURE C
5.00
10.00
15.00
20.00
25.00
Thermocouple 4
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

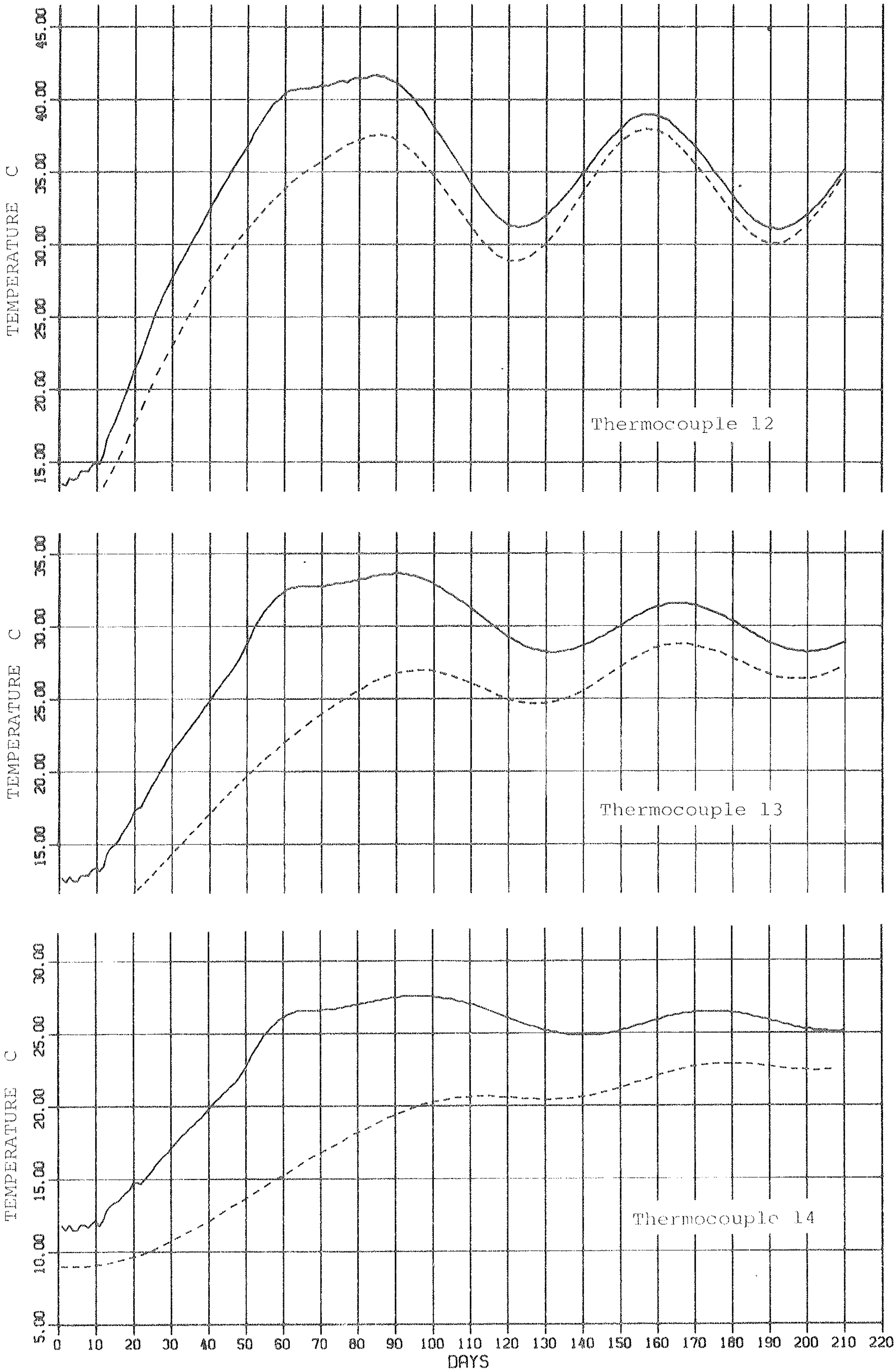

TEMPERATURE C
55.00
50.00
45.00
40.00
35.00
30.00
25.00
20.00
Thermocouple 5

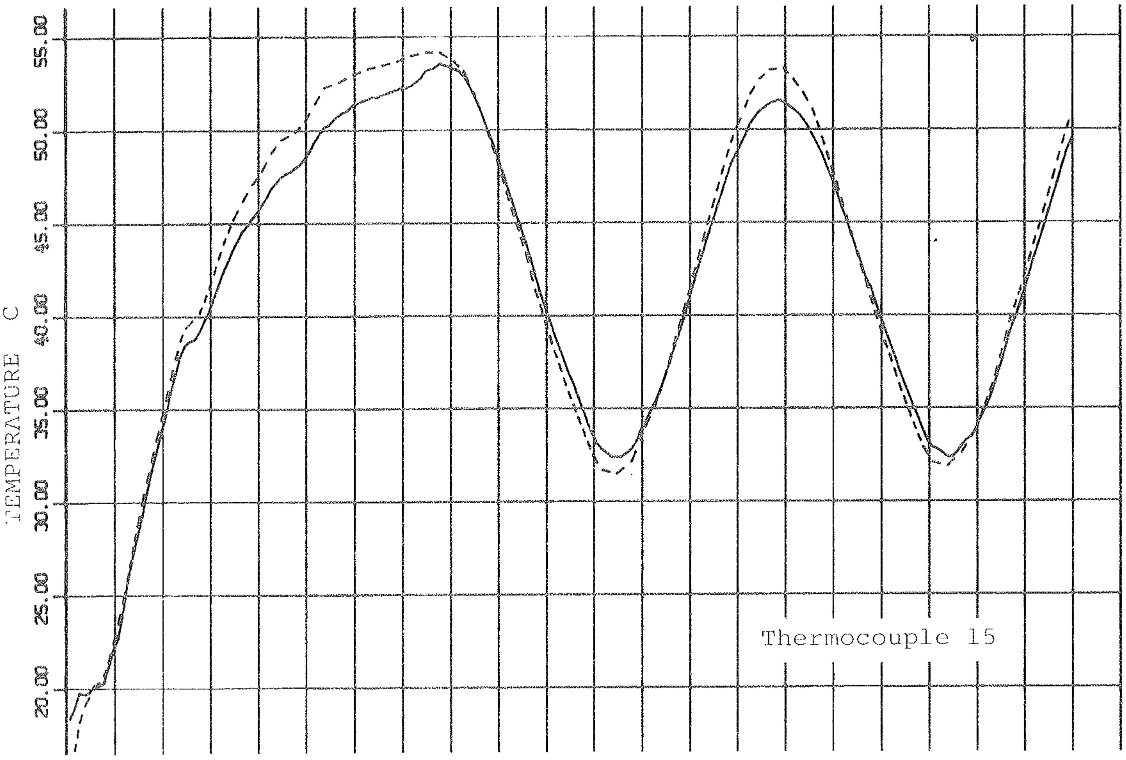

TEMPERATURE C
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
DAYS
Thermocouple 6

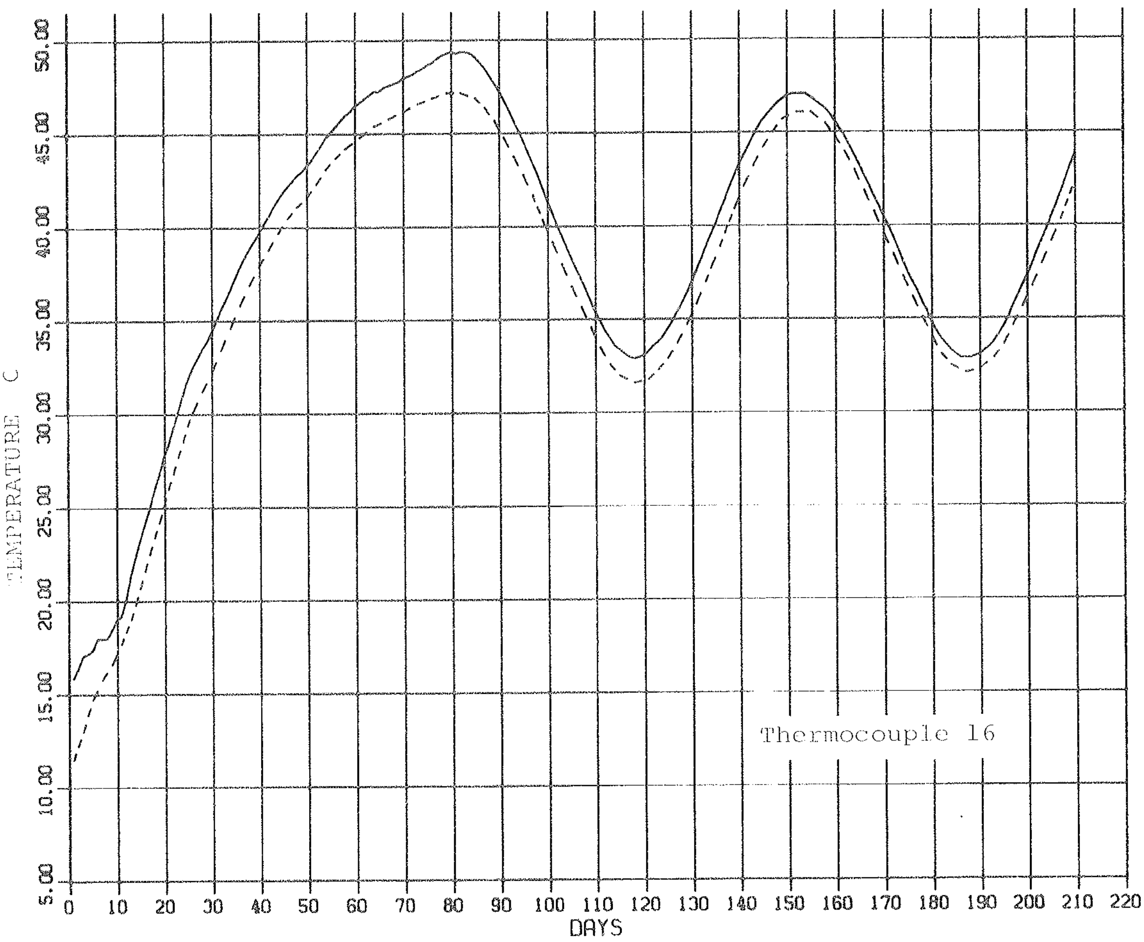

TEMPERATURE C
45.00
40.00
35.00
30.00
25.00
20.00
15.00
Thermocouple 7
TEMPERATURE C
35.00
30.00
25.00
20.00
15.00
Thermocouple 8
TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 9
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

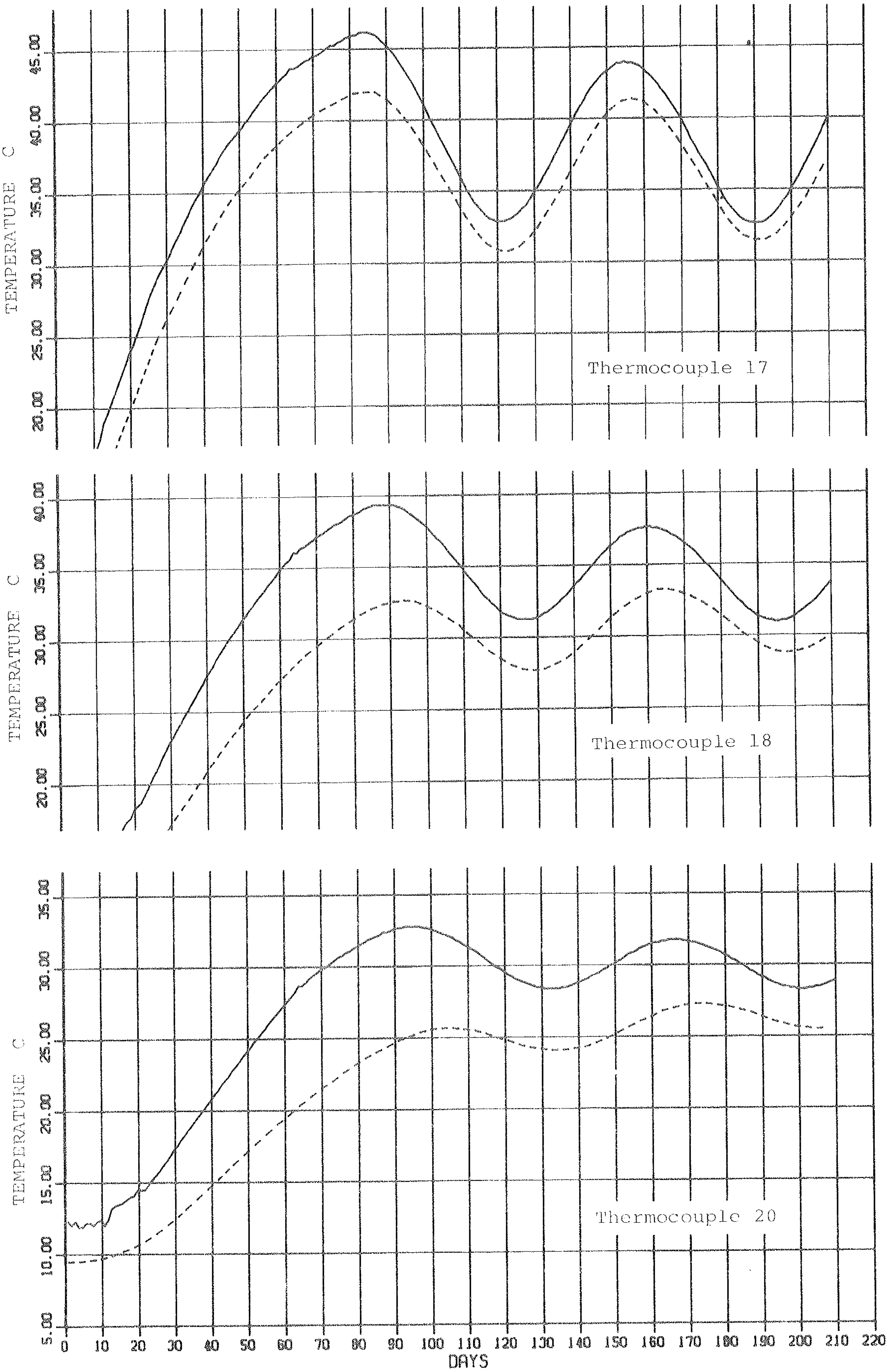

TEMPERATURE C
55.00
50.00
45.00
40.00
35.00
30.00
25.00
20.00
Thermocouple 10

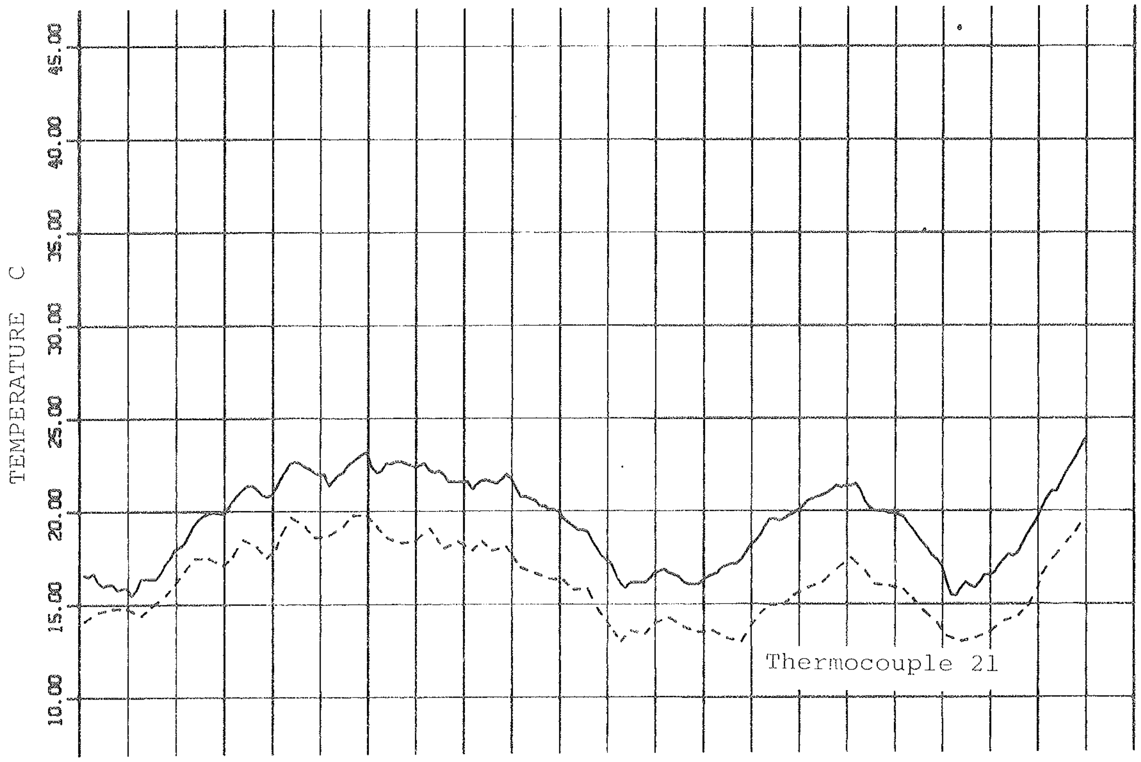

TEMPERATURE C
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 11
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

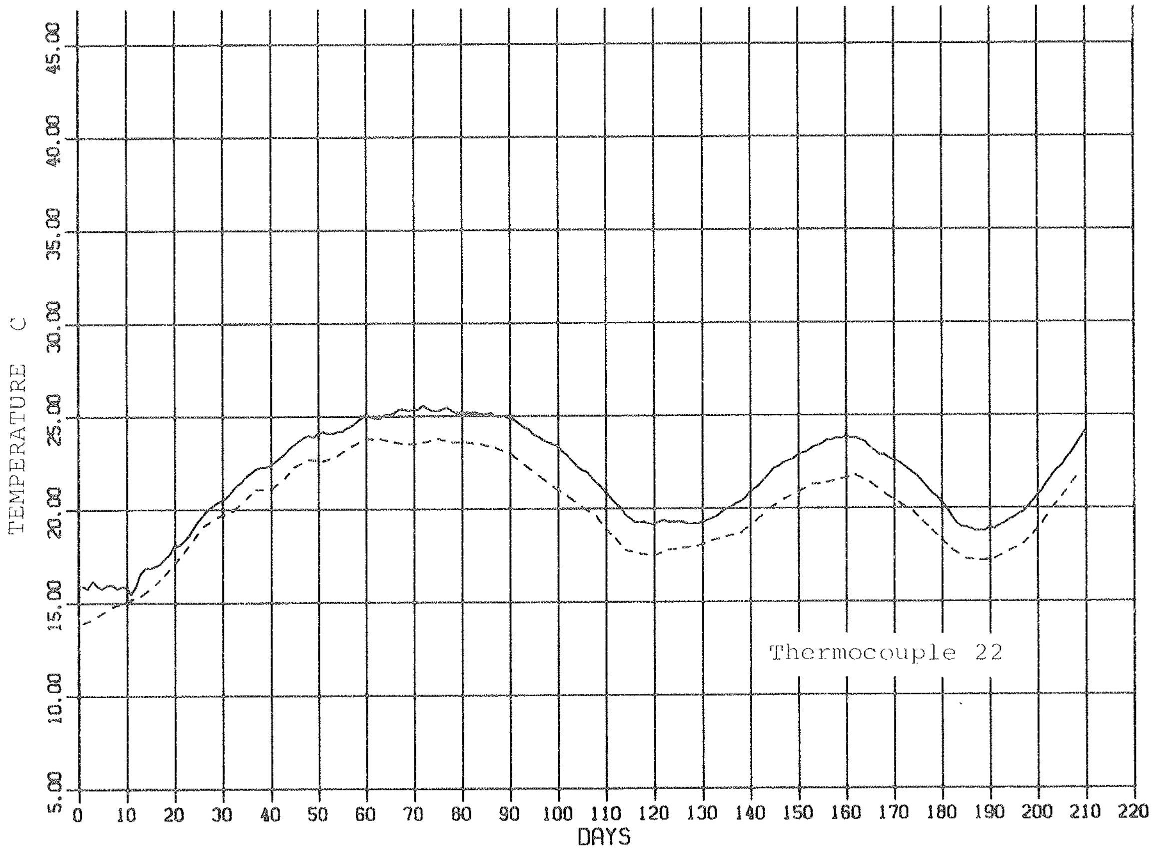

TEMPERATURE C
45.00
40.00
35.00
30.00
25.00
20.00
15.00
Thermocouple 12
TEMPERATURE C
35.00
30.00
25.00
20.00
15.00
Thermocouple 13
TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 14
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

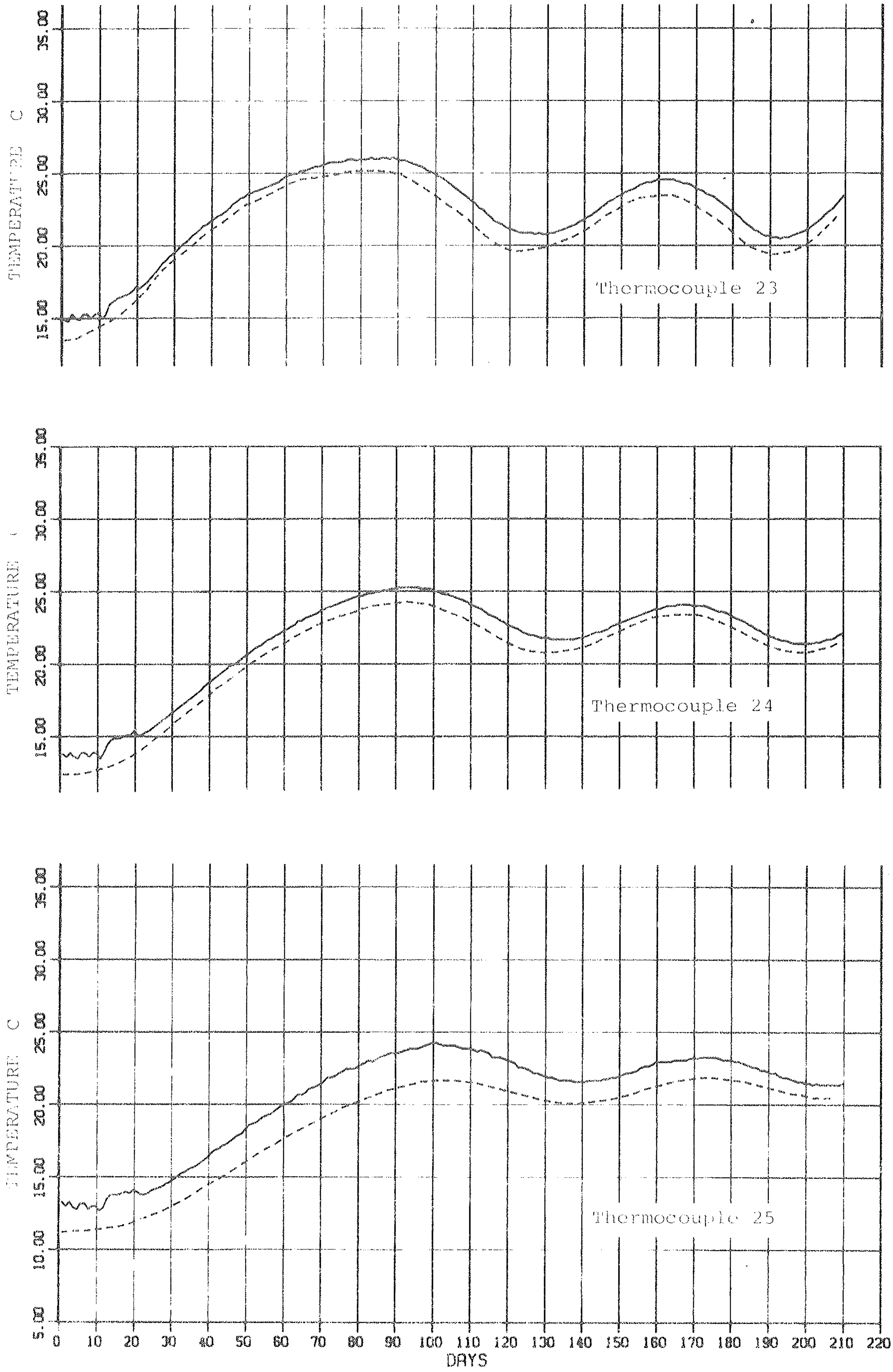

TEMPERATURE C
55.00
50.00
45.00
40.00
35.00
30.00
25.00
20.00
Thermocouple 15

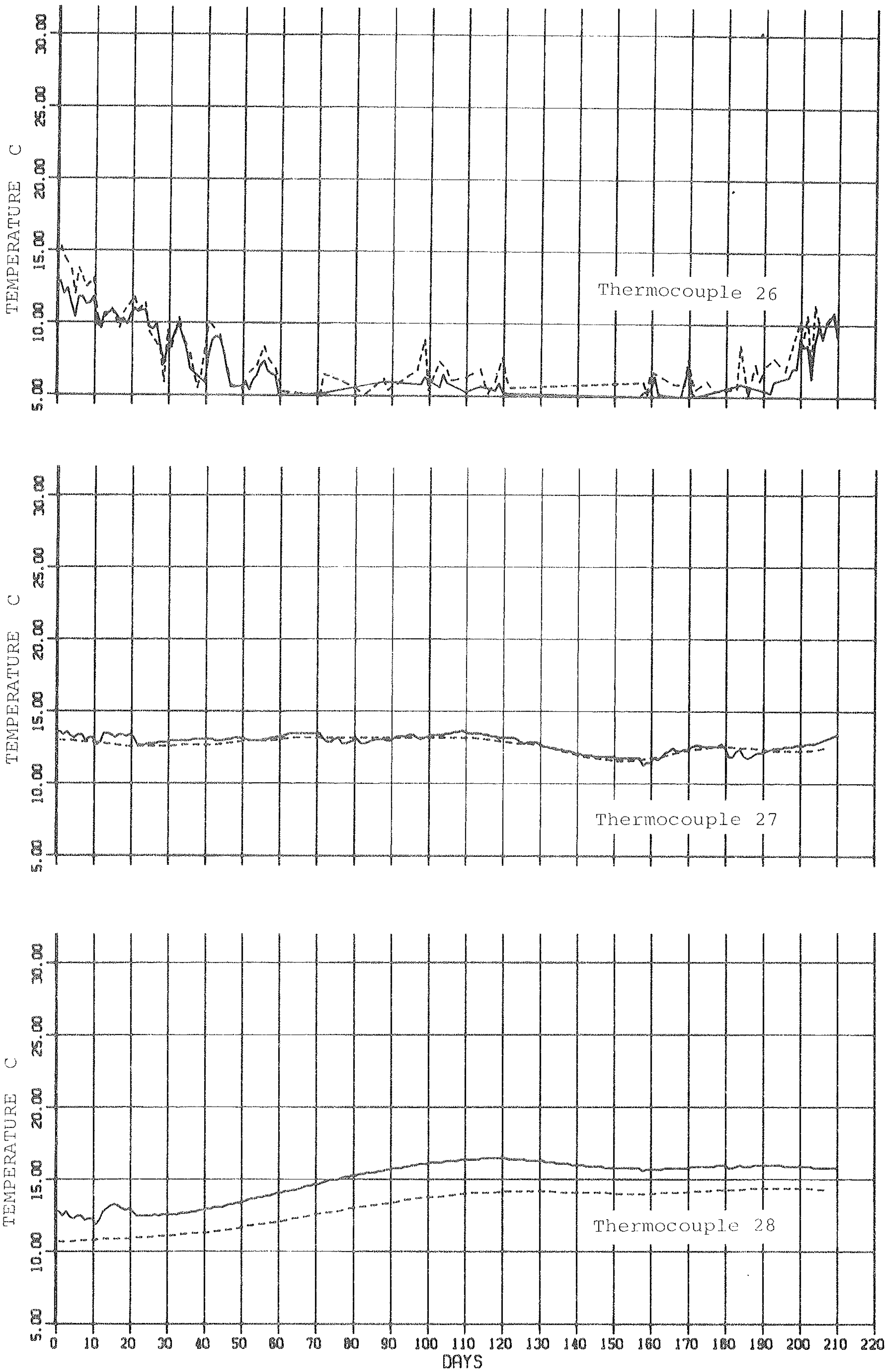

TEMPERATURE C
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS
Thermocouple 16

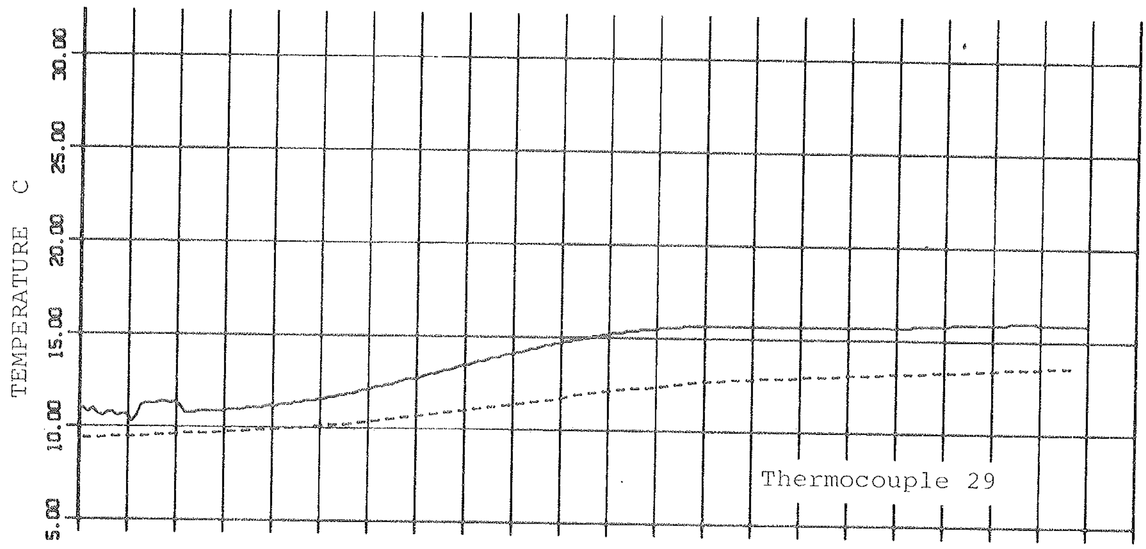

TEMPERATURE C
45.00
40.00
35.00
30.00
25.00
20.00
Thermocouple 17
TEMPERATURE C
40.00
35.00
30.00
25.00
20.00
Thermocouple 18
TEMPERATURE C
35.00
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 20
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

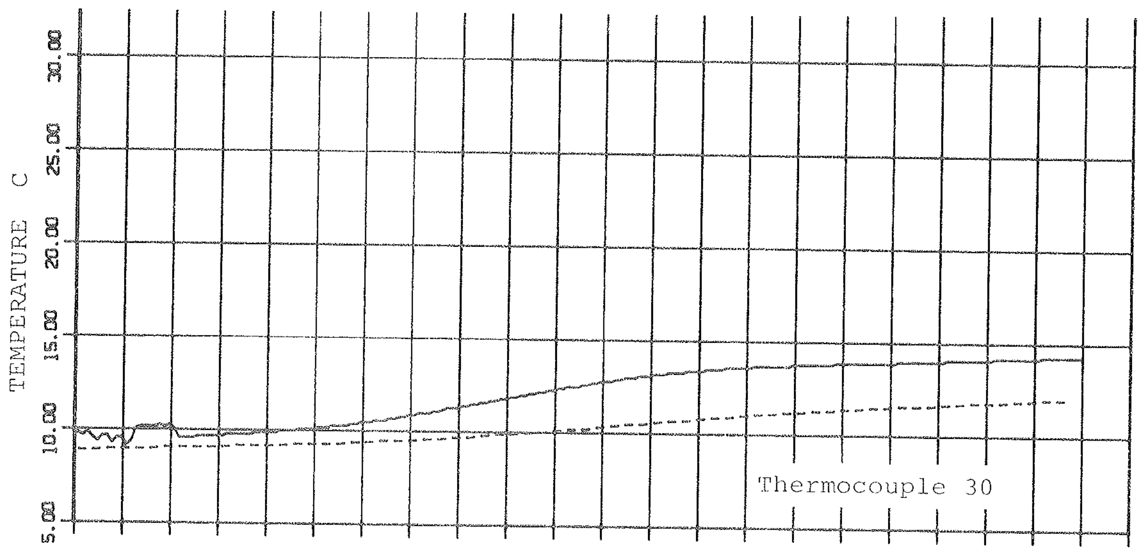

TEMPERATURE C
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
Thermocouple 21

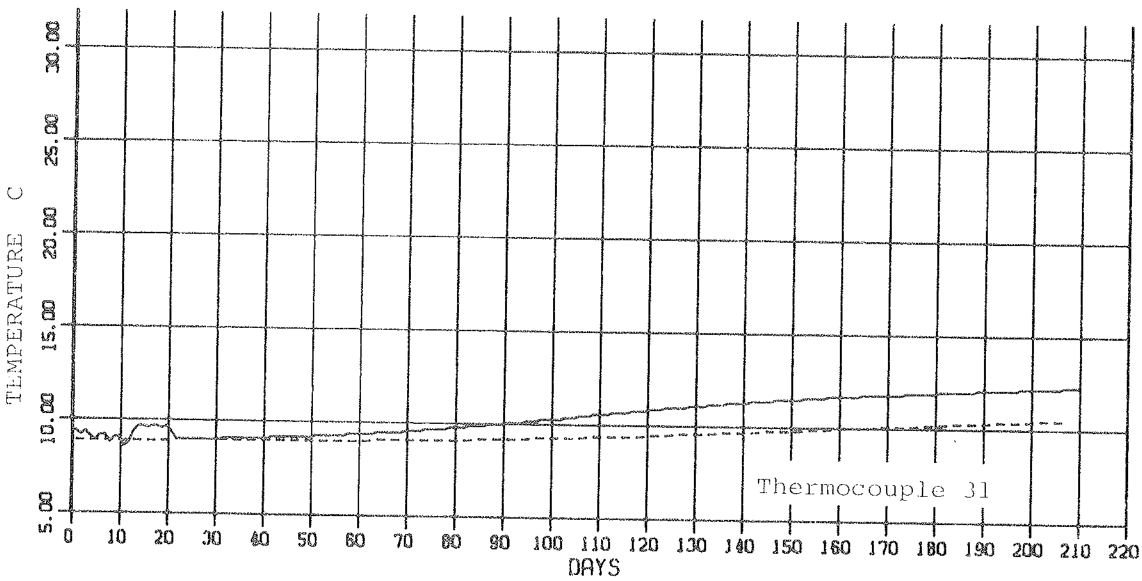

TEMPERATURE C
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
DAYS
Thermocouple 22

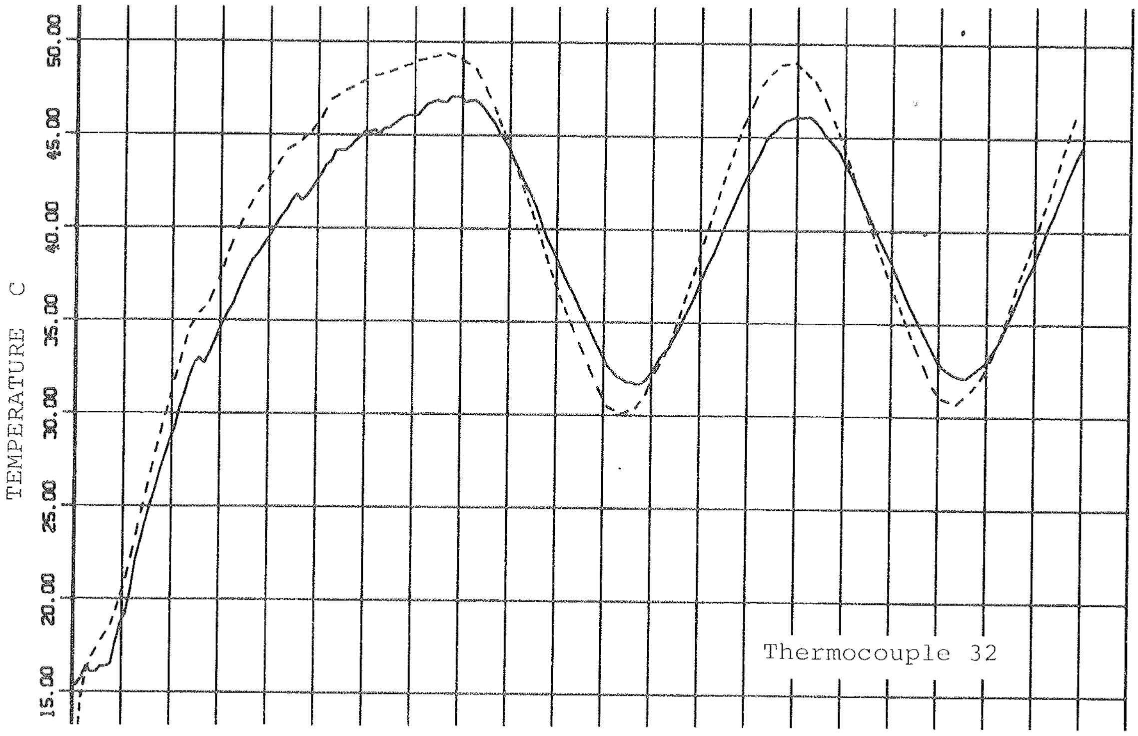

TEMPERATURE C
35.00
30.00
25.00
20.00
15.00
Thermocouple 23
TEMPERATURE C
35.00
30.00
25.00
20.00
15.00
Thermocouple 24
TEMPERATURE C
35.00
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 25
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

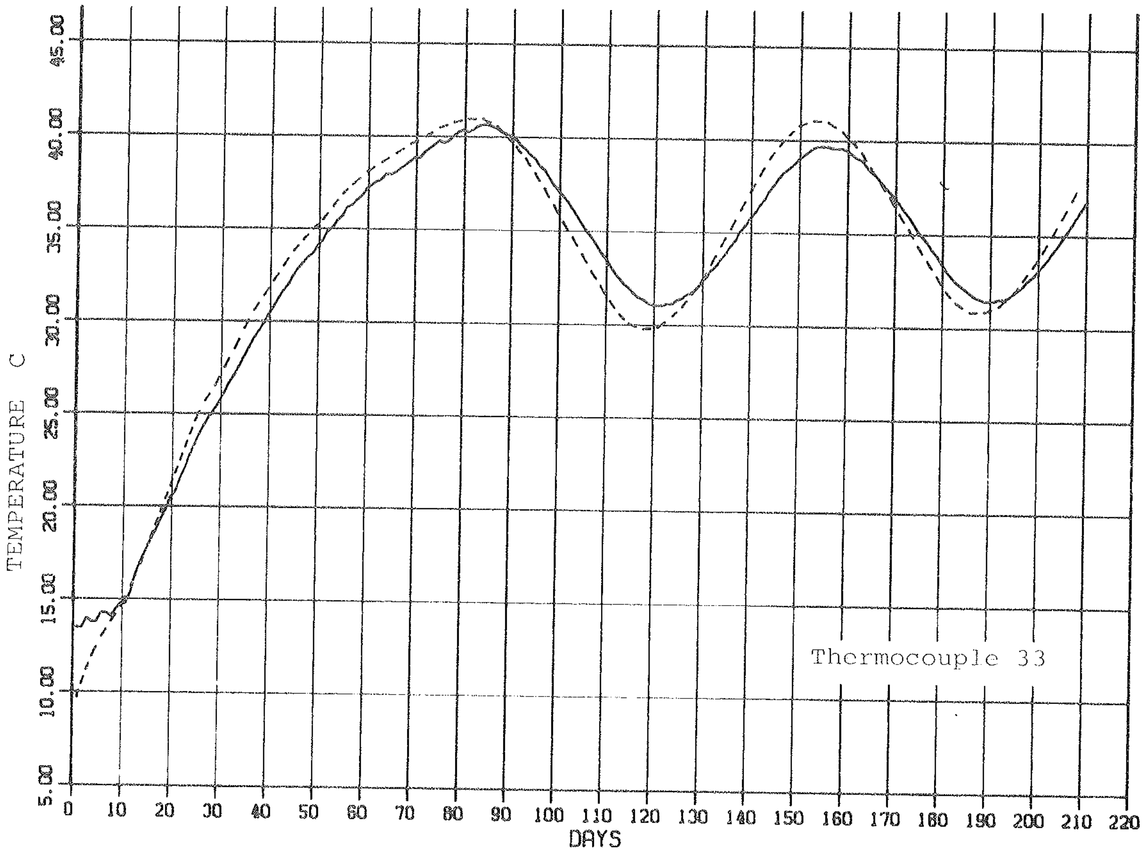

TEMPERATURE C
5.00
10.00
15.00
20.00
25.00
30.00
Thermocouple 26
Thermocouple 27
Thermocouple 28
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

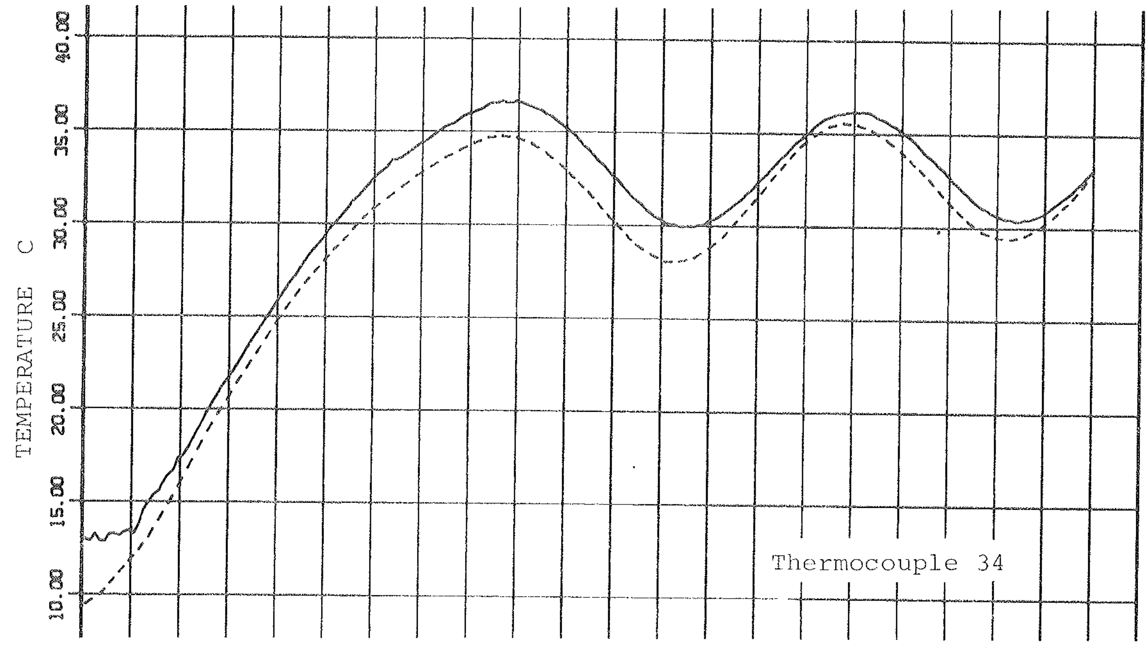

TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 29

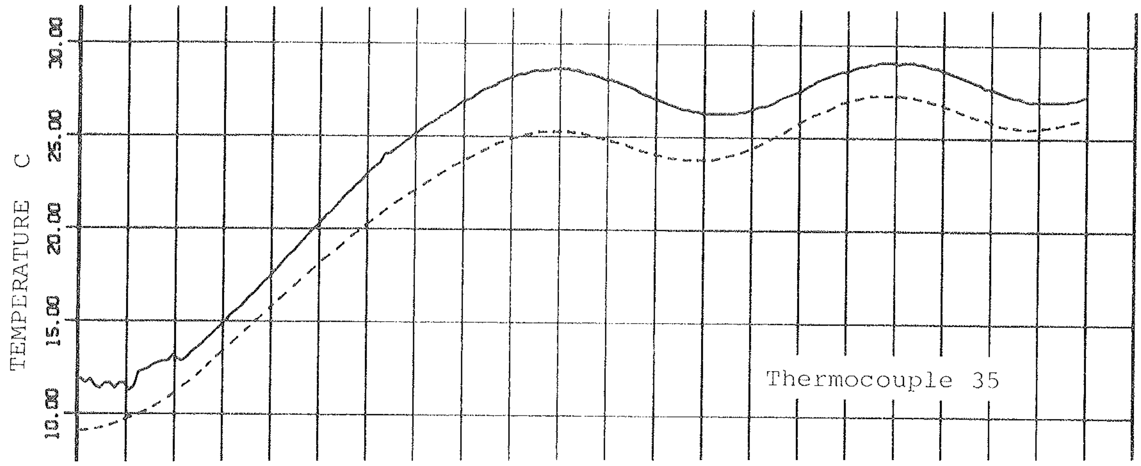

TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 30

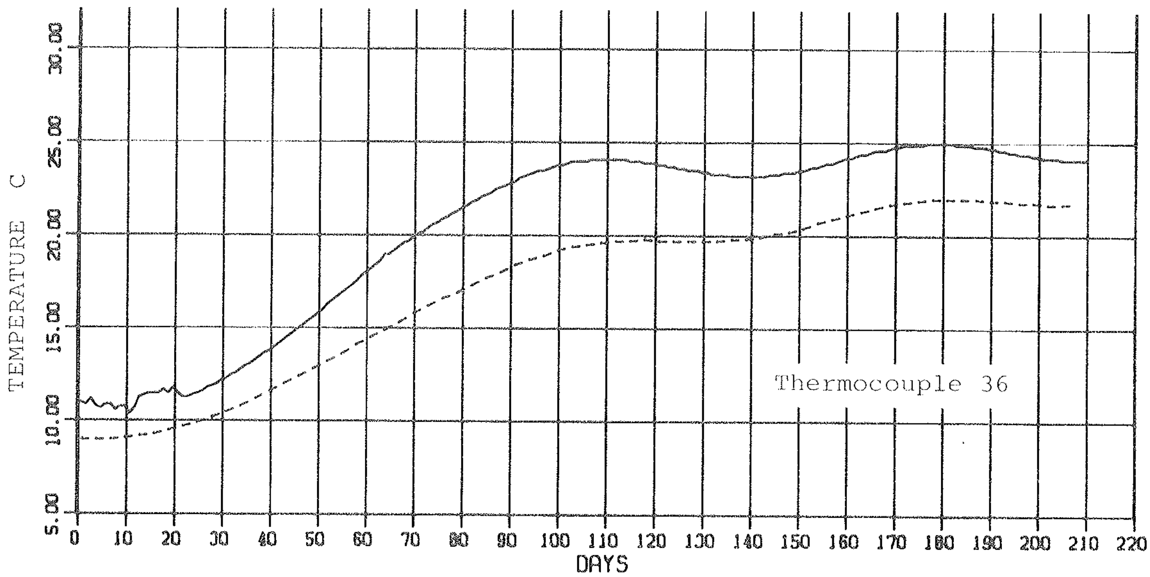

TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 31
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

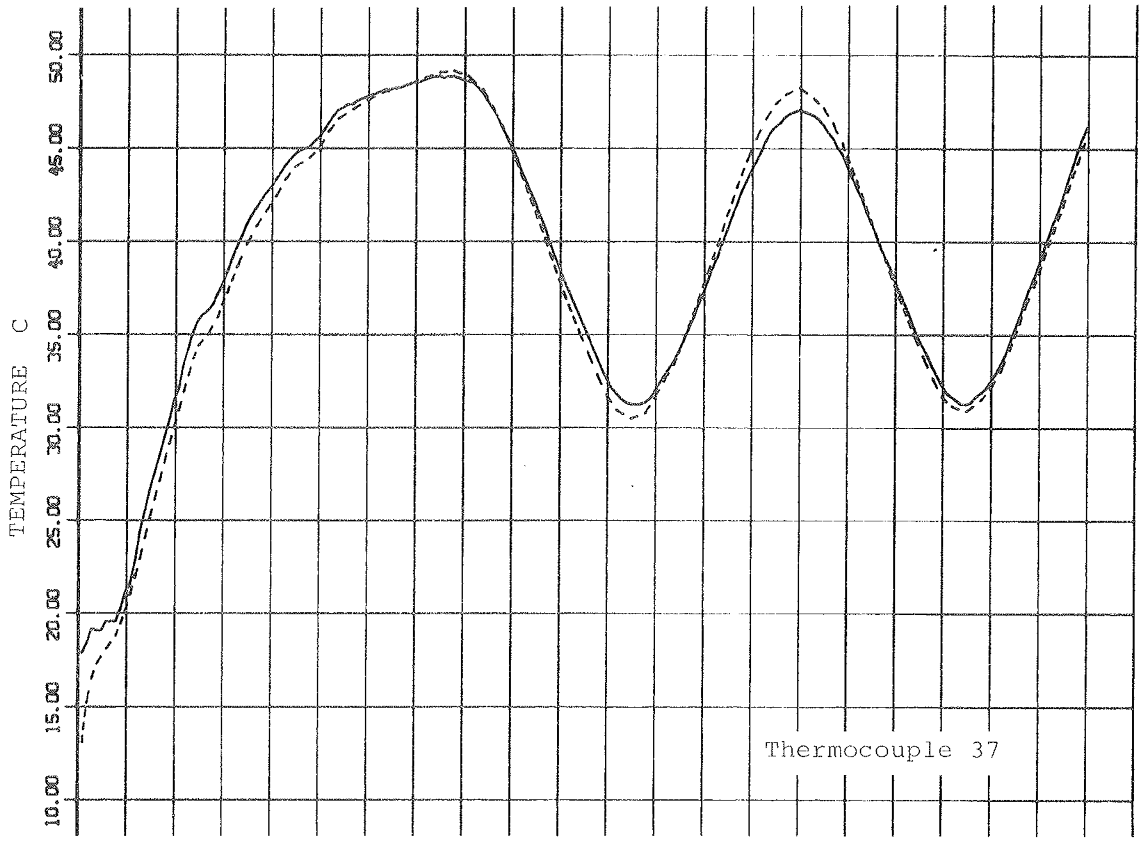

TEMPERATURE C
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
Thermocouple 32

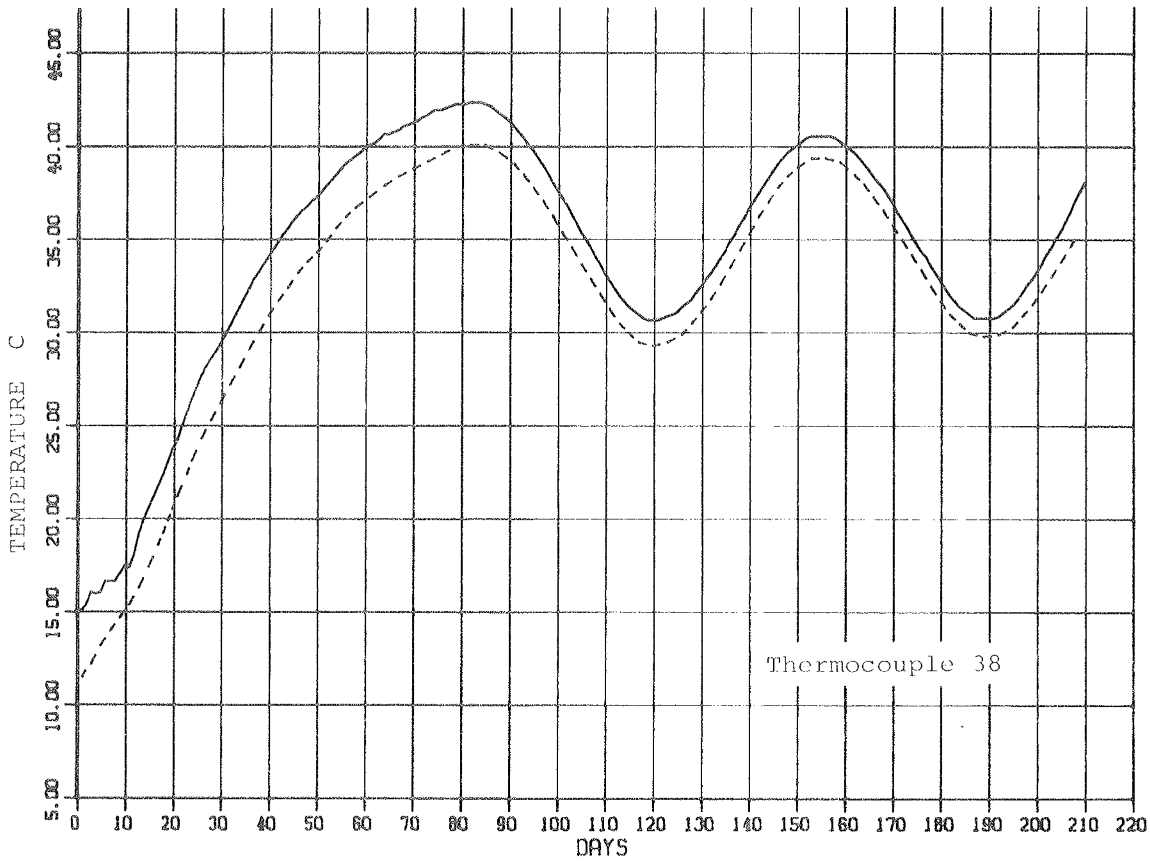

TEMPERATURE C
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
DAYS
Thermocouple 33

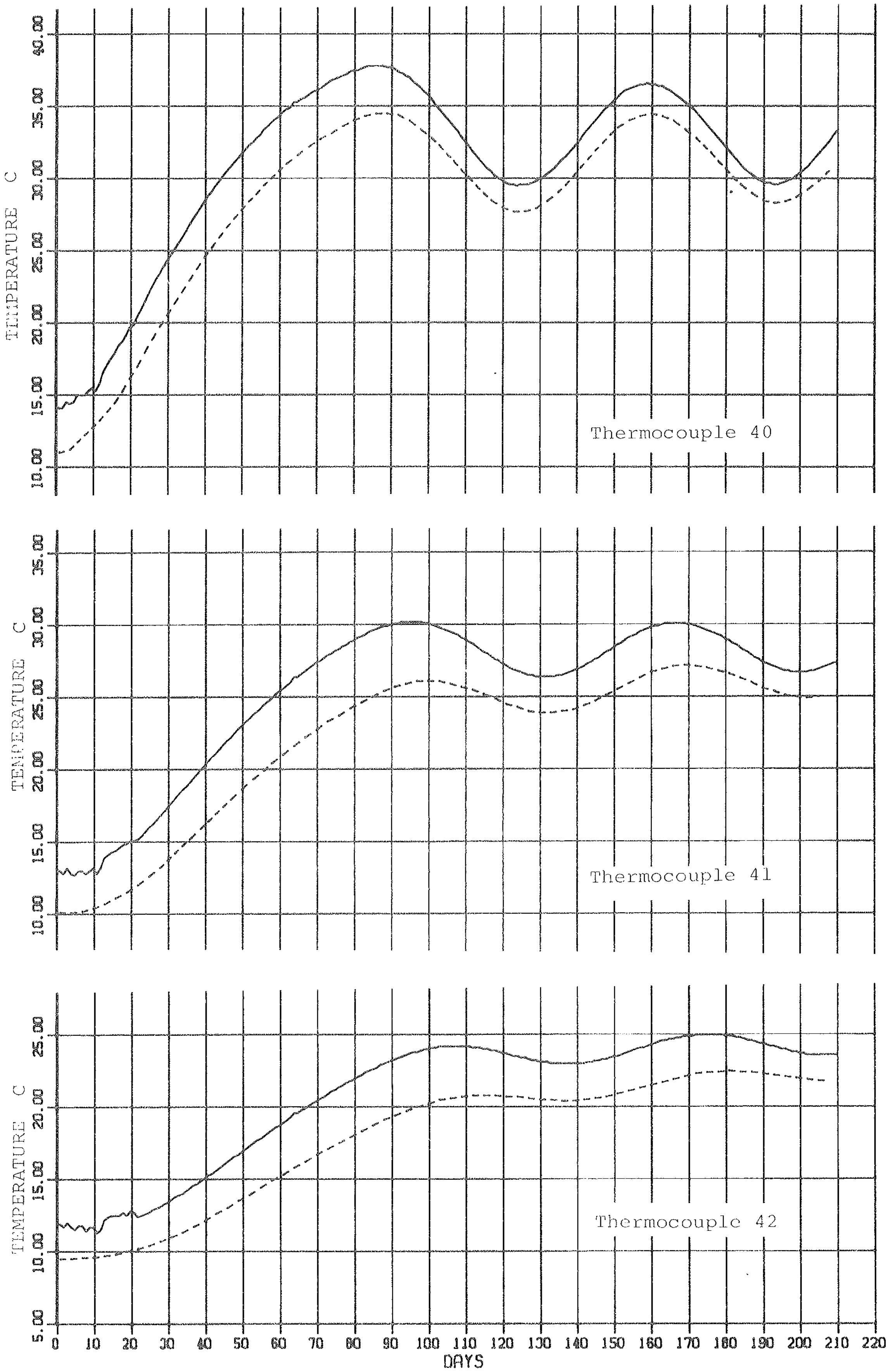

TEMPERATURE C
40.00
35.00
30.00
25.00
20.00
15.00
10.00
Thermocouple 34


TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
Thermocouple 35

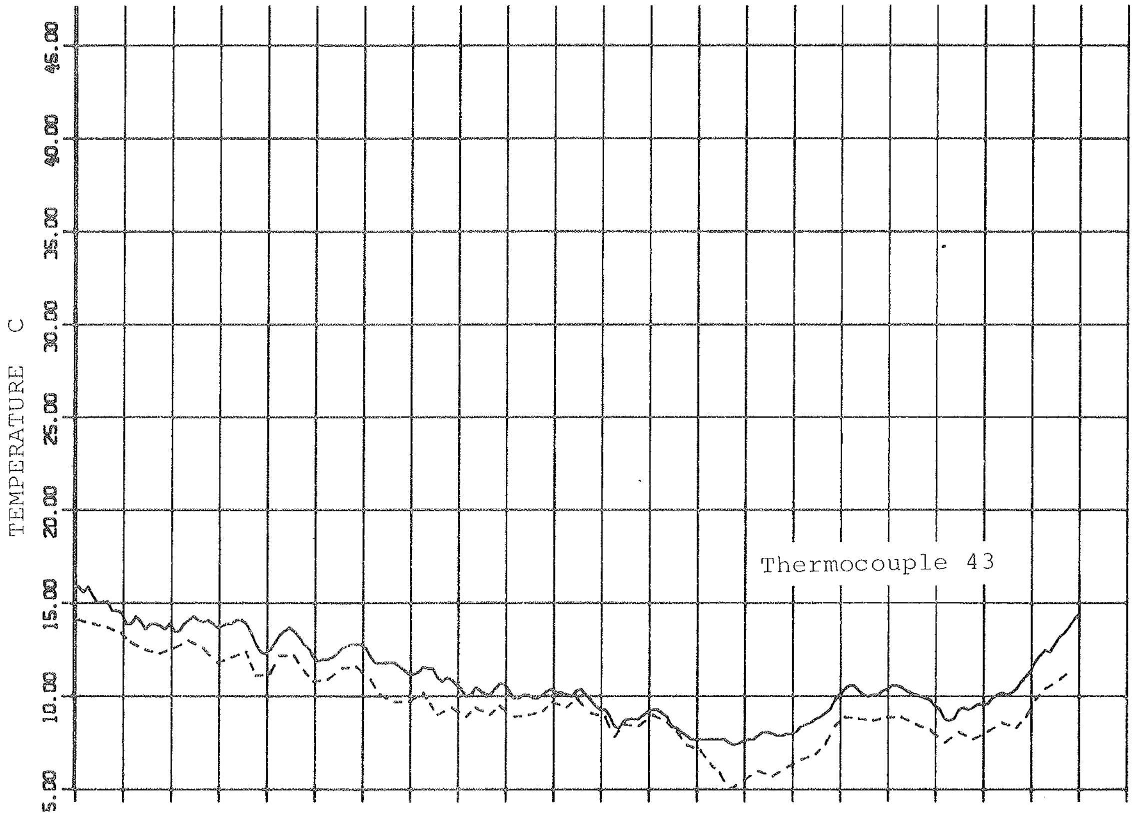

TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS
Thermocouple 36

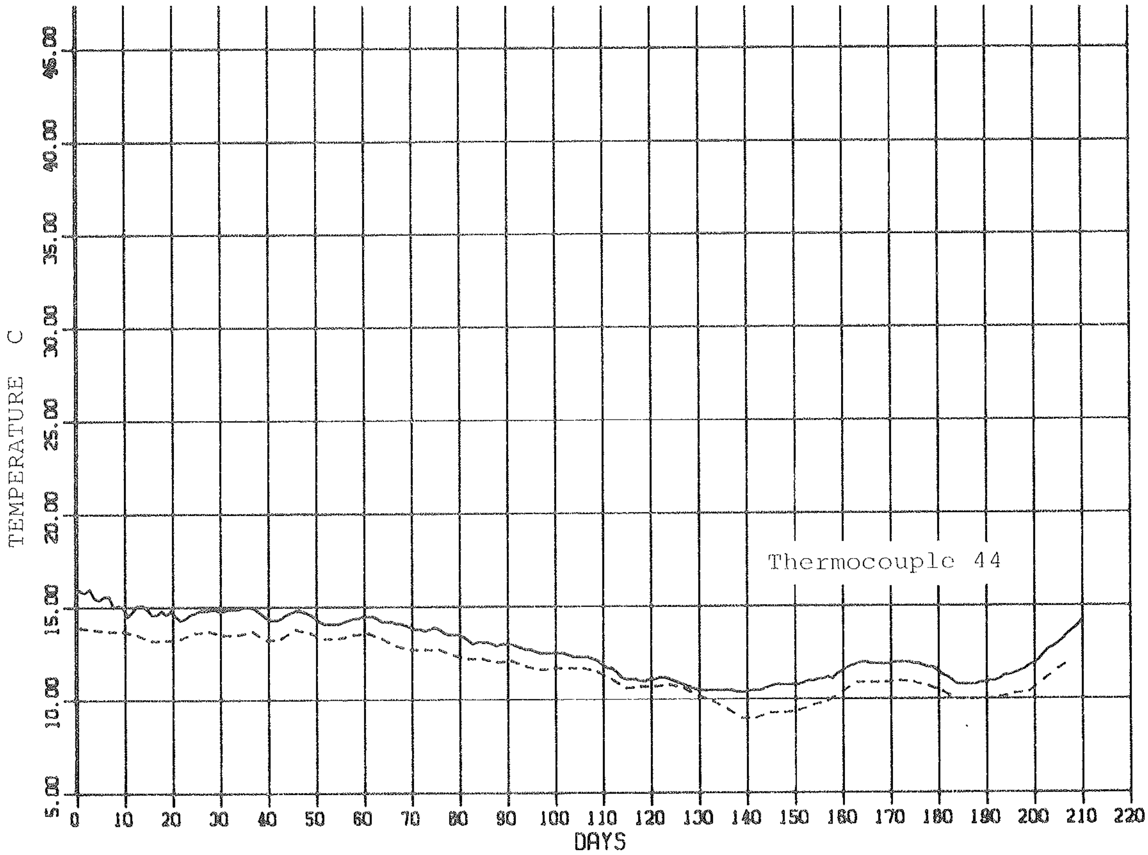

TEMPERATURE C
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
Thermocouple 37

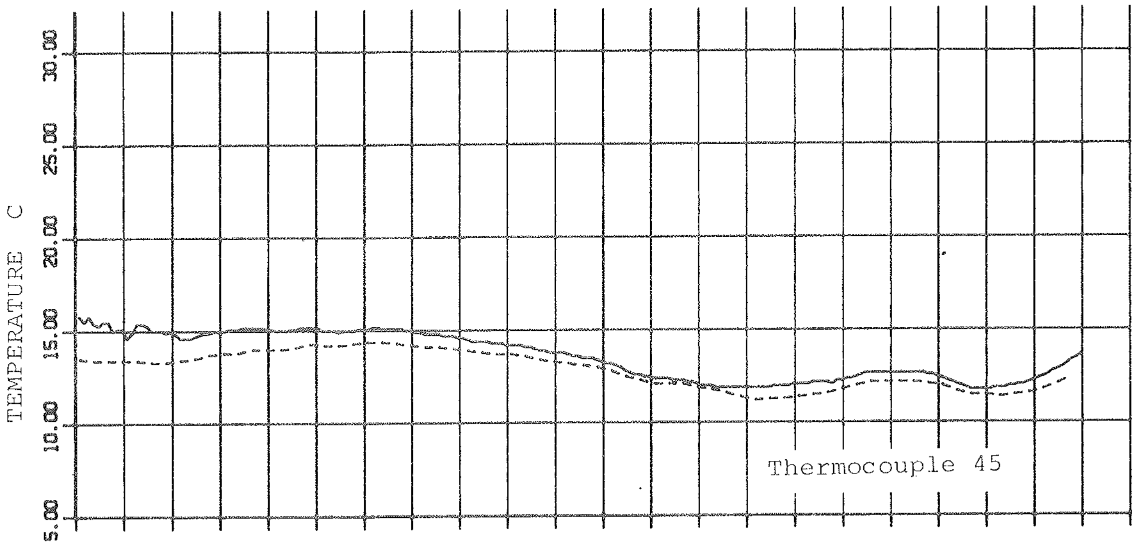

TEMPERATURE C
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS
Thermocouple 38

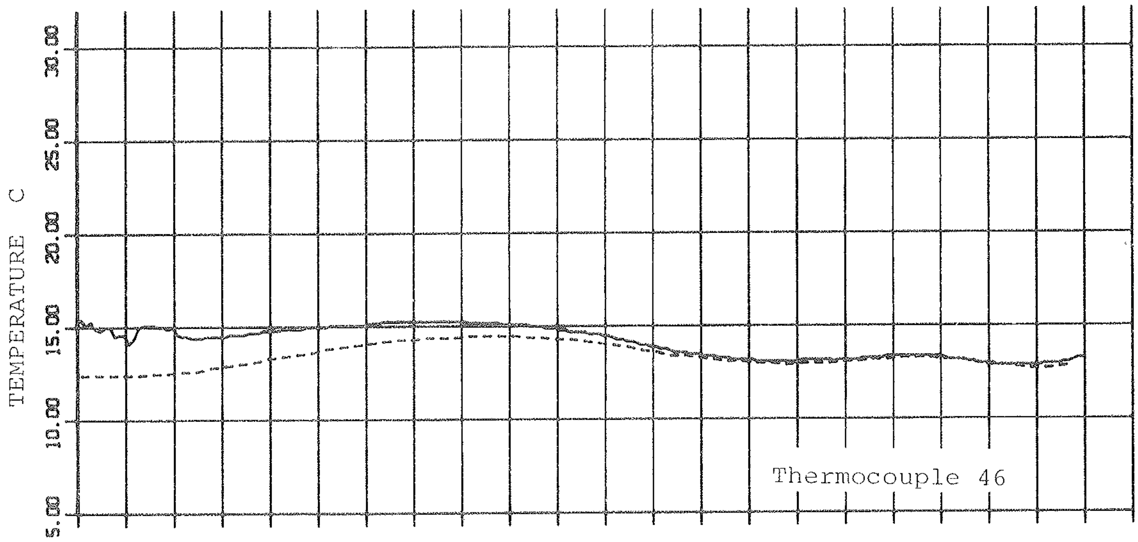


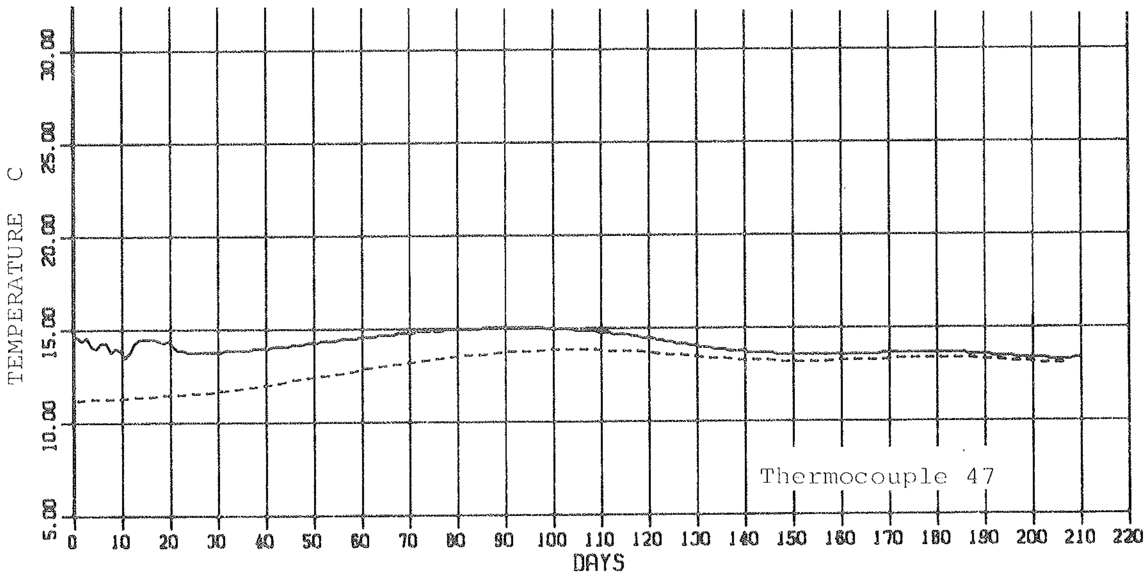
TEMPERATURE C
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Thermocouple 40
TEMPERATURE C
10.00
15.00
20.00
25.00
30.00
35.00
Thermocouple 41
TEMPERATURE C
5.00
10.00
15.00
20.00
25.00
Thermocouple 42
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

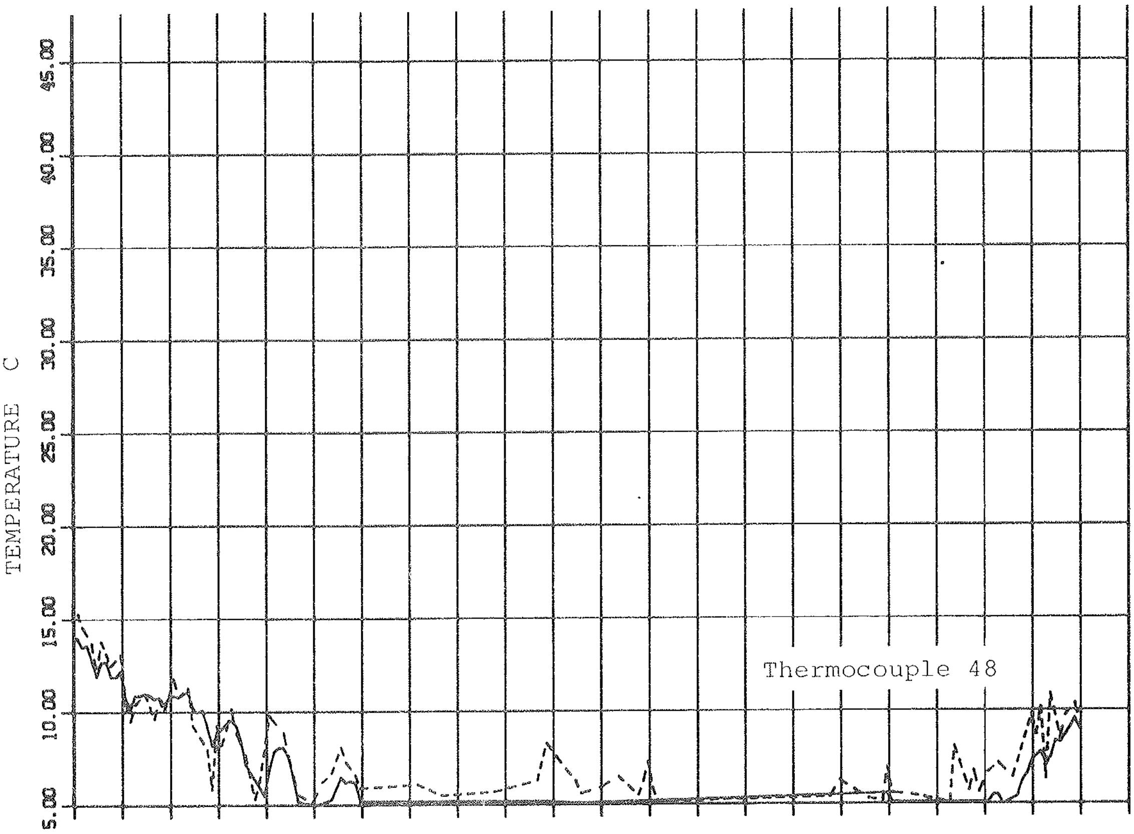

TEMPERATURE C
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 43

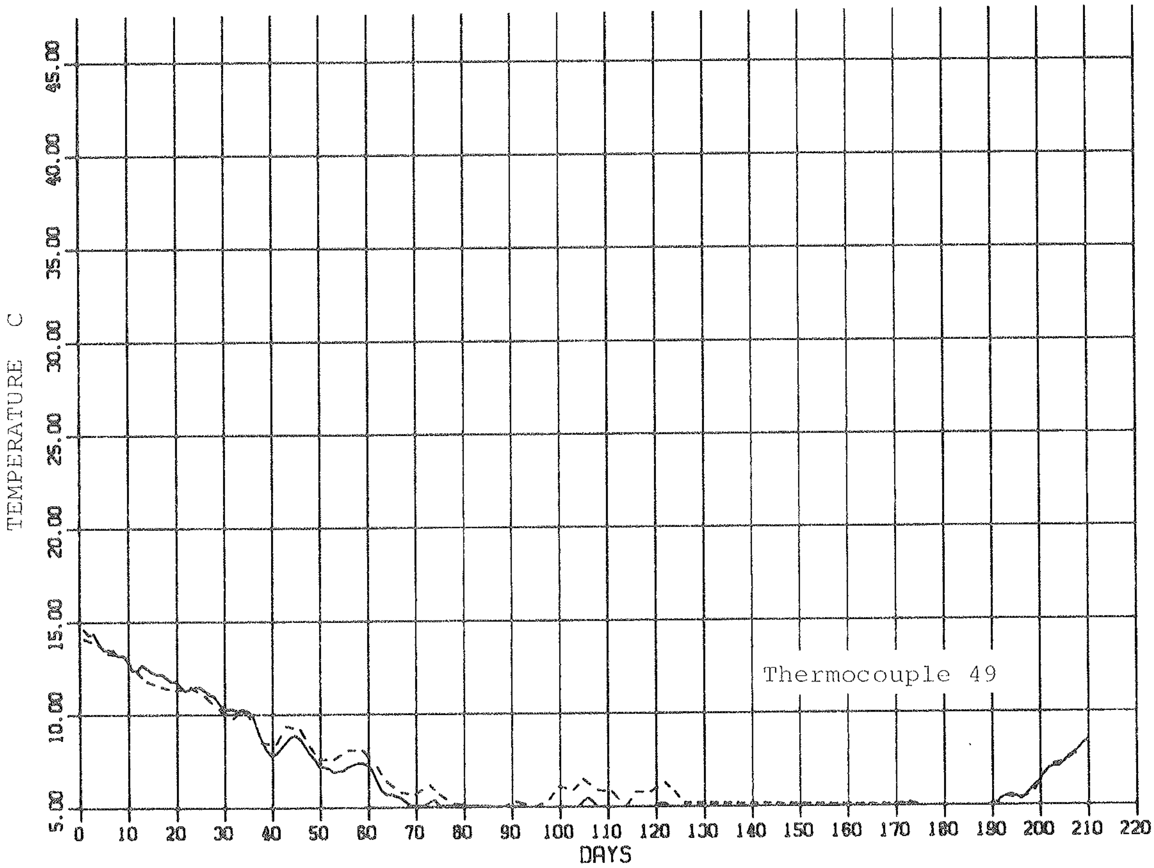

TEMPERATURE C
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 44
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

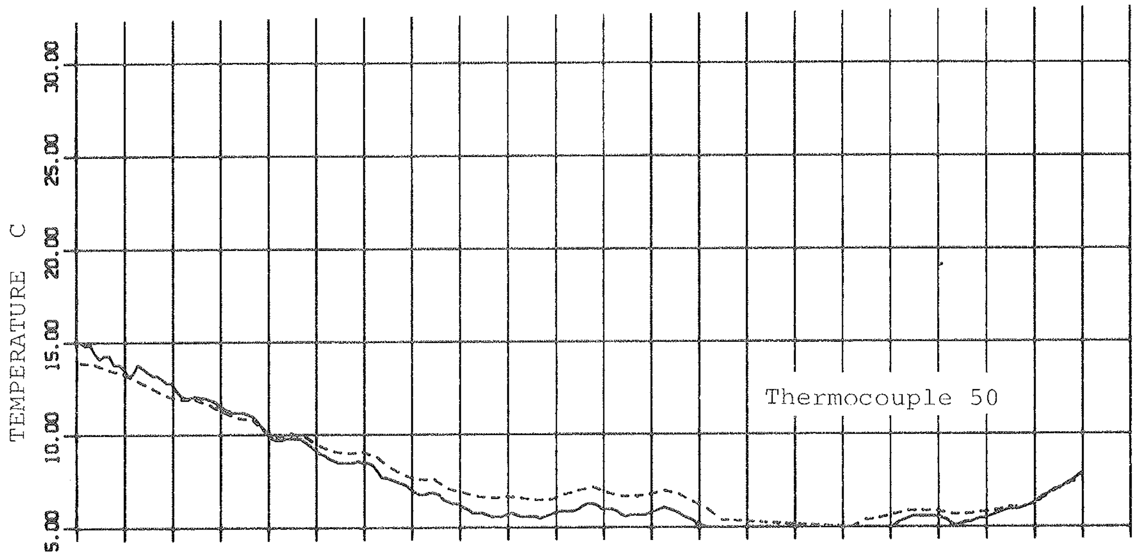

TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 45

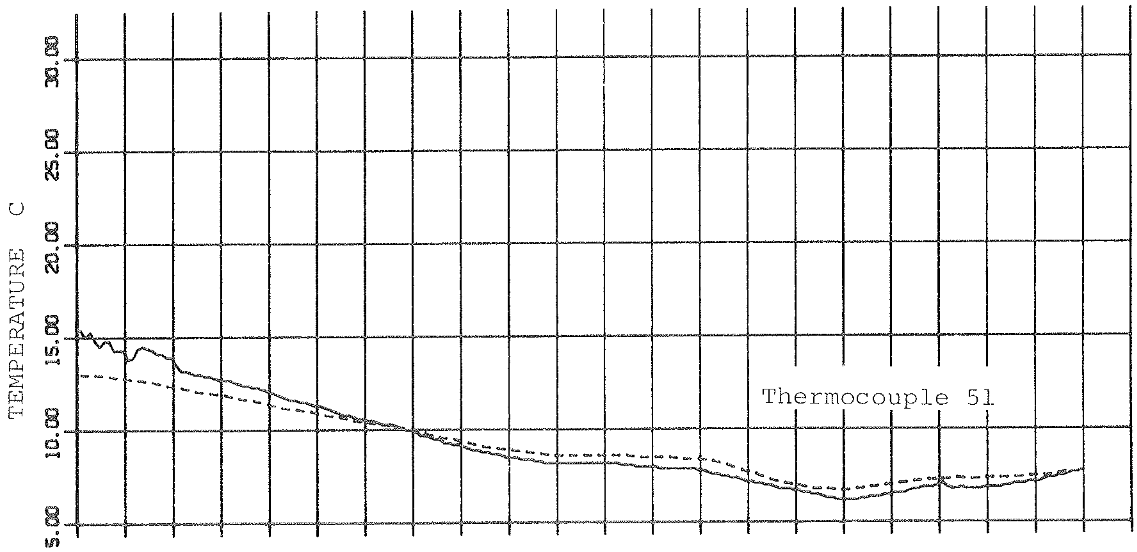

TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 46

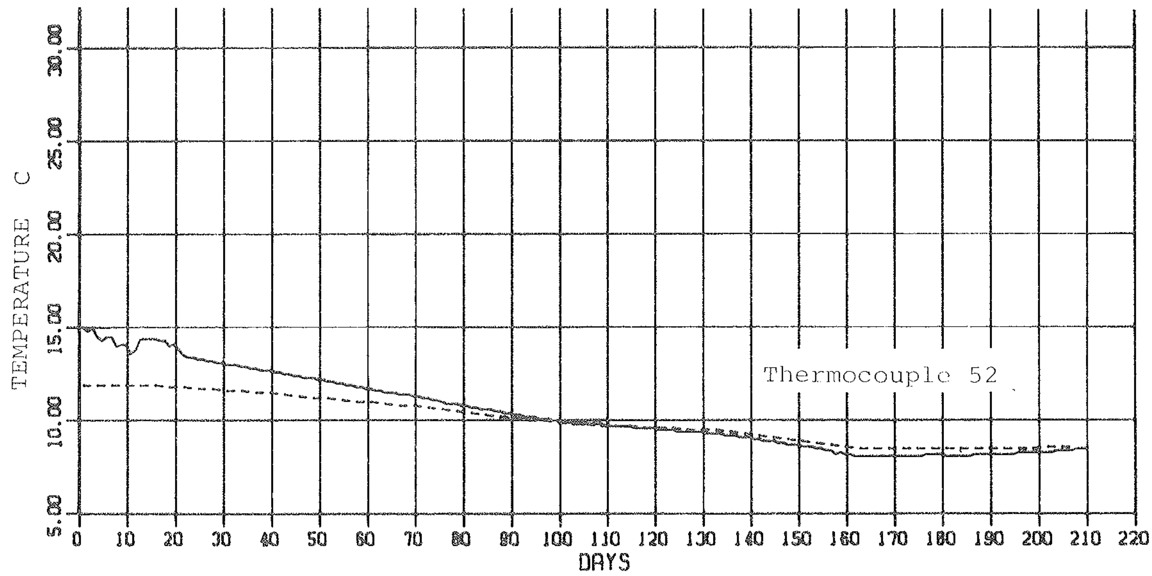

TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 47
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
DAYS


TEMPERATURE C
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
Thermocouple 48


TEMPERATURE C
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
Thermocouple 49
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
DAYS


TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 50


TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 51


TEMPERATURE C
30.00
25.00
20.00
15.00
10.00
5.00
Thermocouple 52
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
DAYS

8. ENERGIMINISTERIETS ENERGILAGRING

Projektorganisation

Styregruppe

N.O. Gram	kontorchef, Industrirådet, (formand).
S. Atlung	lektor, Fysik Kemisk Institut, DTH.
K. Delvig	civilingeniør, Miljøstyrelsen.
N. Hansen	afdelingsleder, Forsøgsanlæg Risø.
P.N. Hansen	lektor, Laboratoriet for Varmeisolering, DTH.
B.S. Jensen	afdelingsleder, Forsøgsanlæg Risø.
J. Jensen	forskningsleder, Lab. f. Energiforskning, Odense U.
K. Jensen	fuldmægtig, Energiministeriet.
J. Keller-Jacobsen	overing.,Danske Elværkers Forenings Udredningsafd.
N. Klenow	direktør, A/S Akkumulatorfabrikken LYAC.
K. Kümmel	forskningschef, Hellesen A/S.
H.C. Mortensen	direktør, Danske Fjernvarmeværkers Forening.
B. Qvale	professor, Laboratoriet for Energiteknik, DTH.
K. Sandholt	civilingeniør, Energistyrelsen.

<u>Projektmedarbejdere</u> fra

Laboratoriet for Varmeisolering, DTH:

K.K. Hansen	akademiingeniør, lic.techn.
P.N. Hansen	lektor, lic.techn.
S.L. Høgsted	programmør.
J.-E. Larsen	akademiingeniør.
O. Ravn	civilingeniør.
V. Ussing	civilingeniør (projektleder).

Thermal Insulation Laboratory
Technical University of Denmark

SEASONAL HEAT STORAGE IN UNDERGROUND WARM WATER STORES

Construction and testing of a 500 m^3 store

KURT KIELSGAARD HANSEN
PREBEN NORDGAARD HANSEN
VAGN USSING

Meddelelse nr. 134 July 1983

PREFACE

The Danish Ministry of Energy in 1979 sponsored a theoretical study of "Seasonal Storage of Heat in large Water pits". The study was carried out under the management of the Thermal Insulation Laboratory of the Technical University of Denmark, by private consultants working for the Laboratory.

The Danish Ministry of Energy in the "Energy Research-programme 82" granted funds for the construction of a 500 m^3 seasonal storage test facility and agreed to cooperate jointly with the Commission of the European Communities, who in the Solar Energy Programme placed a contract (ESA-162-DK(G)) with The Thermal Insulation Laboratory for 50% of the cost of measuring the storage efficiency during a one year test period and verifying the digital computer programme determining the storage losses during simulated operations of the facility.

This report constitutes the final report for the work undertaken for the Danish Ministry of Energy as well as for the Commission of the European Communities.

Parts of this report have been presented to the Commission of the European Communities in periodic reports (reference [4] & [5]).

July 30, 1983

for the Thermal Insulation Laboratory

Vagn Ussing
project manager

RESUME

Denne rapport omhandler projektering, udførelse, simuleret drift, målinger samt verifikation af beregningsprogram for et 500 m^3 Forsøgsvarmelager.

Hensigten med arbejdet har været at vise, at damvarmelagre, uisoleret mod jord, er anvendelige til sæsonvarmelagring. Ved at begrænse isoleringen til toppen af lageret fås en prisreduktion som er så vigtig, hvis sæsonvarmelagring skal blive økonomisk mulig.

Forsøgsvarmelageret er beliggende på Danmarks Tekniske Højskoles forsøgsareal, og projekteringen blev baseret på de geotekniske undersøgelser, der blev foretaget på stedet. Tilsvarende blev jordens termiske egenskaber bestemt for at give basis for beregningsprogrammet.

En pyramidestubformet geometri, fuldstændig nedgravet i jorden, blev valgt. Den uisolerede skilleflade mellem lager og jord blev gjort vandtæt v.hj.a. en 2,5 mm tyk membran (high density polyethylene). Det flydende isolerende låg blev konstrueret i en "tørdok" og flådet til den endelige placering. En flydende pakning forsegler låget til damvarmelagerets vægge.

Udformningen af vandtilførsel og -udtag giver mulighed for cirkulation af det totale lagervolumen på fire dage. To stk. 36 kW gaskedler og en luftkøler på ca. 30 kW gør simuleret drift af lagertemperaturen mellem 30°C og 60°C mulig.

Damvarmelageret blev anlagt på 10 uger i sommeren 1982.

Cirka 80 termoelementer blev installeret for at måle jord- og vandtemperatur på en automatisk datalogger.

I september 1982 begyndte den første opladningsperiode. For at få et indtryk af den forventede reduktion i varmetab ved mange sæsonsvingninger blev en sinusformet oplade - aflade model mellem 30°C og 60°C over en 70 dages periode anvendt. De målte

temperaturer i jorden blev sammenlignet med beregnede temperaturer og en tilfredsstillende overensstemmelse blev opnået, idet de aktuelle termiske egenskaber blev anvendt.

Den målte lagereffektivitet indikerer, at de udviklede teoretiske beregningsudtryk til bestemmelse af sæsonlagres effektivitet vil være i god overensstemmelse med de effektiviteter, som praktisk vil kunne opnås ved sæsonlagring.

ABSTRACT

This report deals with design, construction, simulated operation, measurements, computer programme verification and recommandations for "Seasonal Heat Storage in Underground Warm Water Stores, Construction and Testing of a 500 m^3 Store".

The aim of the work has been to show that warm water pits, uninsulated towards the soil are well suited for seasonal heat storage. Limiting the insulation to the top surface will contribute to a construction price reduction, which is so important, if seasonal storage shall be economically feasible.

The design work was based on the geotechnical investigations of the site selected at the laboratory test grounds on the University campus. The thermal properties were determined to form the basis of the computed analysis of the heat flows.

A truncated pyramidal geometry completely imbeded in the ground was chosen. The uninsulated store/soil interface was made waterproof by use of a 2,5 mm high density polyethylene liner. The floating insulated lid was constructed in a "dry-dock" and floated to final position. A floating gasket was installed to seal the lid to the pit walls.

The inlet- and outlet systems for water made circulation of the entire pit volume possible in four days. Two 36 kW gas boilers and an aircooler of about 30 kW made simulated operations between 30°C and 60°C possible.

The construction was carried out during 10 weeks in the summer 1982.

Approximately 80 thermocouples were installed to record soil- and water temperatures on an automatic datalogger.

In September 1982 the first charge-period was commenced. In order to get an impression of the reduction in heat loss expected by many seasonal operations a sinoidal charge-discharge pattern between 30°C and 60°C over a 70 day-periods was used.

The measured temperatures in the soil were compared with the computed temperatures and satisfactory agreement was found based on the actual thermal properties.

The storage efficiency measured indicated, that the theoretical expression developed for the seasonal storage efficiency will be in good agreement with the efficiency which will be obtained in practical work.

Table of contents

LIST OF SYMBOLS

A	Surface area of the store versus the soil	m^2
C	Heat capacity	$kWh/^{3\,0}C$
c_v	Shear strength	-
e	Porosity	-
FAK	Lineary scaling factor	-
Fo	Fourier number	-
L	Lineary dimension	m
M	Modulus, which is equal to the ratio volume of store versus surface area of the store	m
Q	Energy	kWh
S_r	Degree of saturation	-
t	Time	days,years
VOL	Volume	m^3
w	Water content based on weight	-
z	Geometry factor	-
α	Coefficient of thermal diffusivity	$m^2/year$
λ	Coefficient of thermal conductivity	W/m^0C
γ	Density	kN/m^3
η	Efficiency	-
$\Delta\nu$	Temperature amplitude in the store	^0C
ν_o	Average temperature in the store	^0C
ν_∞	Original average temperature of the soil	^0C

1. INTRODUCTION

The aim of the project has been to show that warm water pits, uninsulated against the soil, are well suited for seasonal heat storage. The fact that the use of insulation materials are limited to the top surface will result in a price reduction when comparing with pits built with insulation of the soil interface.

The project contains the following phases:

a. Detailed examination of the soil conditions on the site of the pit.

b. Determination of the thermal properties of the soil using the information from a).

c. Design of the pit using the information from a).

d. Construction of the pit.

e. Simulated operations and measurements.

f. Verification of a digital computer program for simulating the thermal behaviour of the store.

The store is situated in Lyngby on the campus of the Technical University of Denmark, see figure 1 and figure 2.

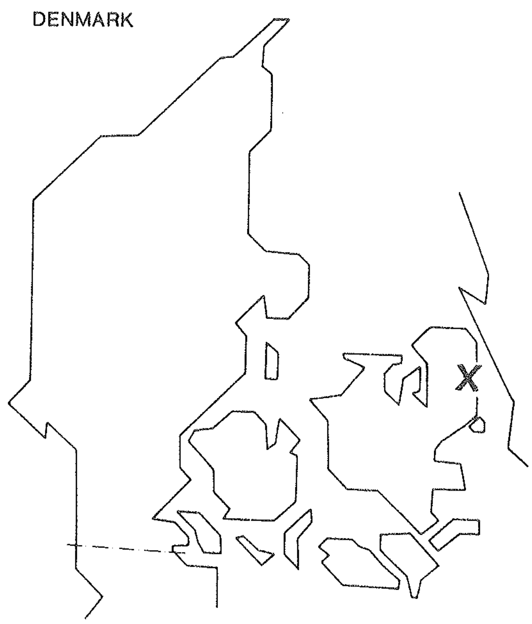


Figure 1. The location of the project.

TECHNICAL UNIVERSITY OF DENMARK

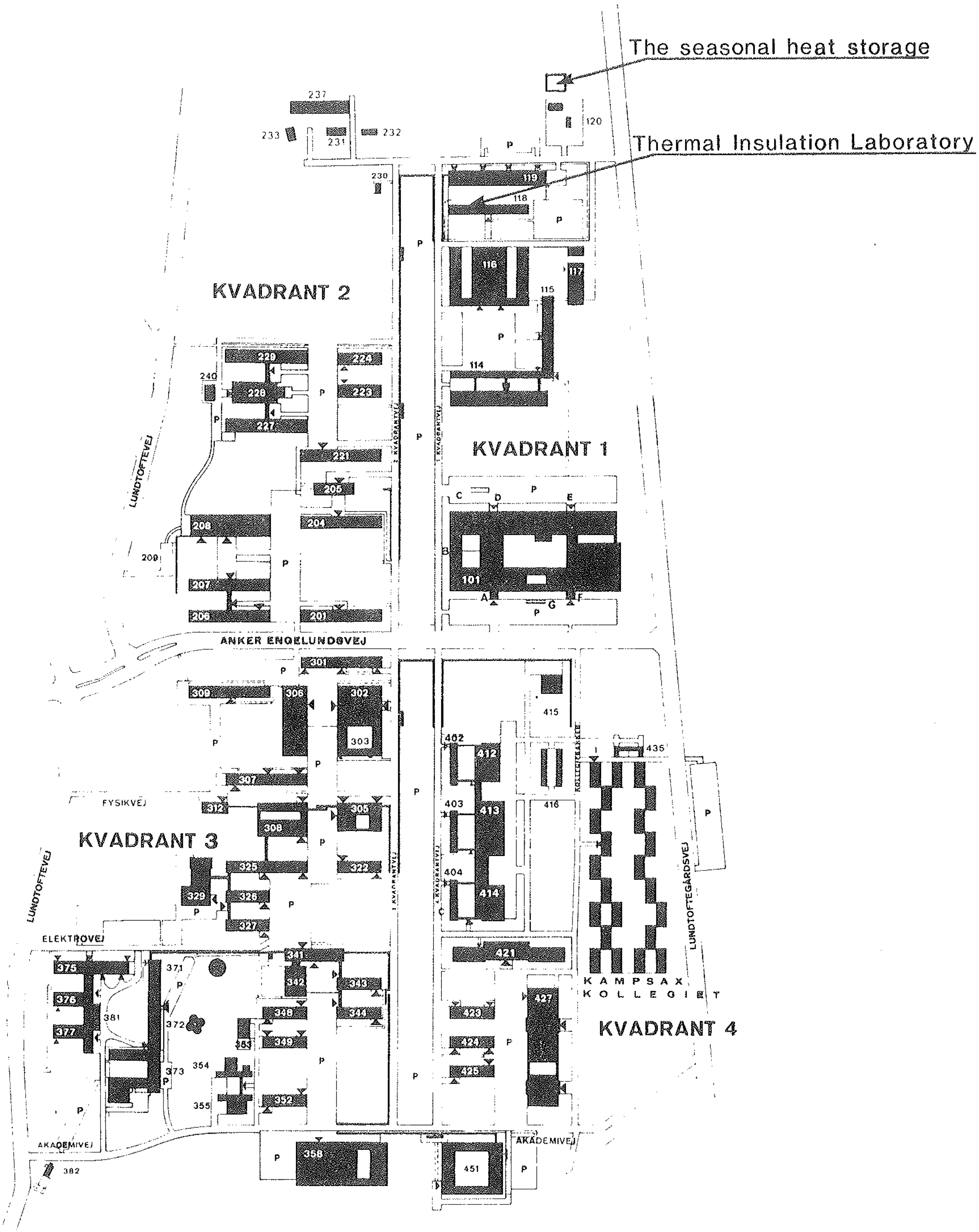


Figure 2. The location of the seasonal heat storage.

2. DESIGN AND CONSTRUCTION OF THE 500 m^3 STORAGE

2.1. Location of the 500 m^3 heat storage

The Technical University of Denmark permitted an extension of the laboratory testing grounds (area no.120) adjacent to the laboratory buildings. Fig.2 shows the test area before extension and Drawing 1 shows the extended test area.

The center of the heat storage was located 13.9 m from the north face of an existing building housing the technical installations and the measuring devices of the solar pilot test facility of the laboratory.

The edge of the heat storage is only 7.05 m from the building. Thus the measuring points for temperature in the soil nearest to the building will be slightly influenced herefrom in the second or third year of testing. This inconvenience was considered small in relation to the advantage of short electric connections from all measuring points to the datalogging equipment, which was placed in the corner of the existing building nearest to the test pit.

In order to simplify the calculations of the heat flow in the soil around the test pit, the normal design of a pit with embankments constructed from the pit excavations was abandonned for a pit with the water surface almost at the terrain level.

2.2. Examination of the soil conditions

The soil conditions was determined by the Danish Geotechnical Institute [1]. Two continuous drillings are made to collect samples for identification of the soil types in order to determine the porosity of the soil (e) in the test area. Drilling 1 and drilling 2 are shown on Drawing 1, and the drillings are made 10 m below the ground level. In drilling 1 a standpipe is installed to check the possible existence of a secondary ground water table, but nothing was found (the primary ground water is situated more than 40 m below the ground level). In drilling 2 a tube with six temperature sensors was placed. A photo of the drilling work is shown in fig.3.

In the laboratory the water content (w), the density (γ), the shear strength (c_v), the degree of saturation (S_r), the thermal properties and the grain-size distribution was determined. Determination of the thermal properties will be described in more details in the next chapter.

The results are given in fig.4 and fig.5. The soil can be described roughly as a 4-5 m thick layer of clay. Below this layer of clay is water saturated sand (different degrees of saturation). The sand is mostly "fine-grained" as shown on the grain-size distribution in fig.6 ("fine-grained" sand has more than 10% < 0.06 mm).

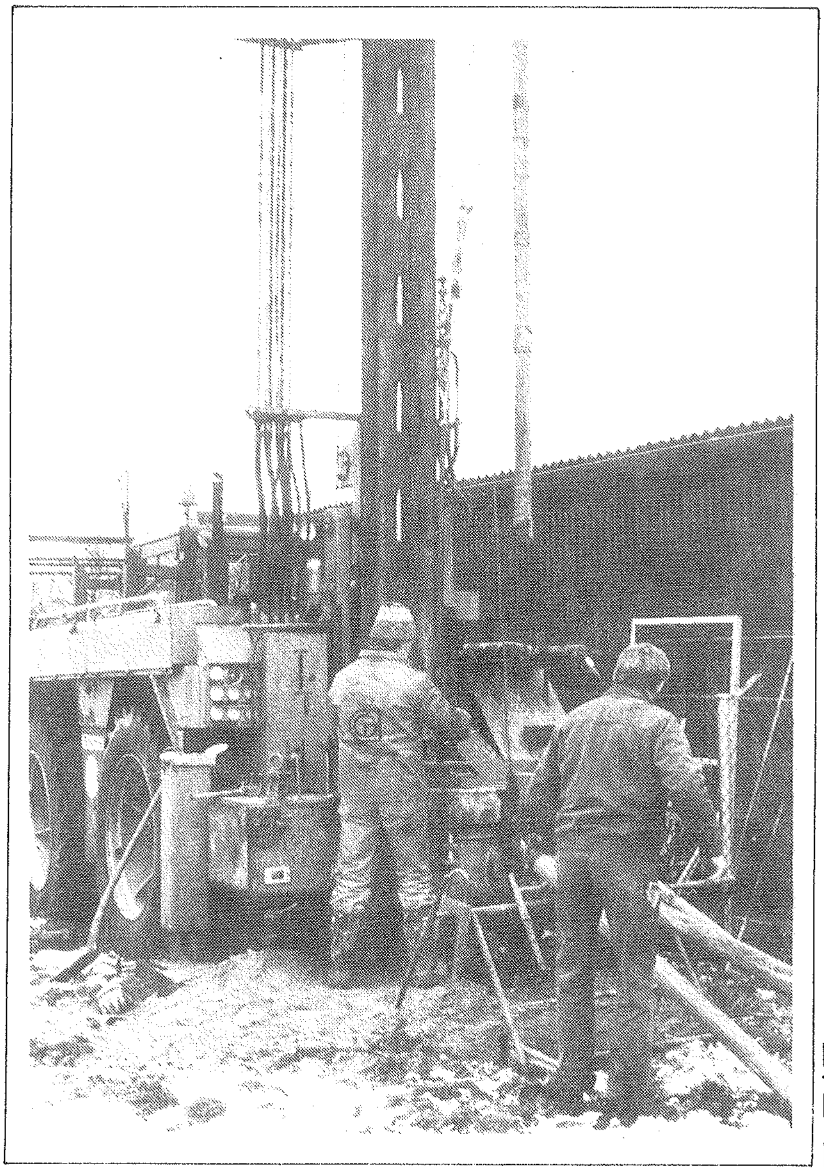
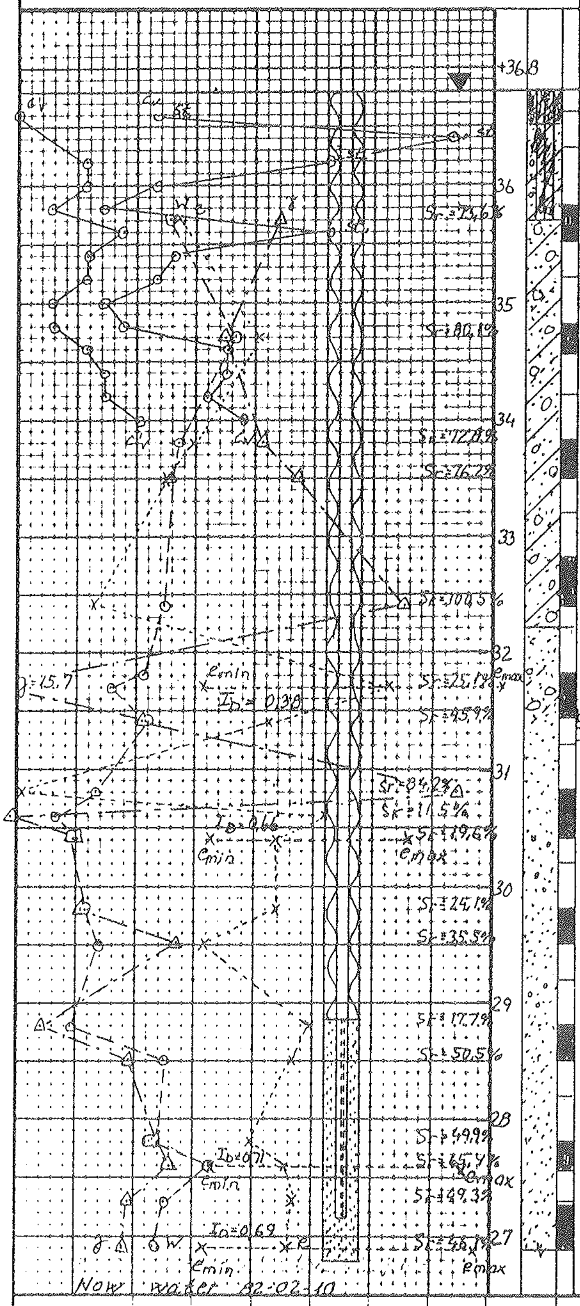


Figure 3.
Initial geotechnical investigations.

GEOLOGICAL ABBREVIATION

Deposit:				Age:	
Freshwater	F	Meltwater	Sm	Postglacial	P
Solifluction	Fl	Wash out	U	Lateglacial	S
Glacial	Gl	Aeolian	V	Glacial	G
Marine	M			Interglacial	I
Wash down	N			Tertiary	T
Top soil	O			Danien	Da
Slidedebris	Sk			Senon	Se

Strength measurements
Classification tests



Lab. No.	Soil type / Description	Deposit	Age
	Boring No. 1		
1	FILL?CLAY,mouldy,sandy,silty	O?	
2	" ? " ,sandy,slightly,gravelly w/ mouldy lumbs	"?	
3	" ? " , " , " , " - "	"?	
4	BOULDER CLAY,sandy,very silty,stony	Gl	G
5	" " , " ,rather silty,stony	"	"
6	" " , " , " " , "	"	"
7	BOULDER CLAY→MORAINE SAND,stony	"	"
8	" " ,sandy,stony	"	"
9	" " , " , "	"	"
10	SAND,well-sorted,fine	Sm	"
11	MORAINE SAND,slightly clayey,stony	Gl	"
be-low:	SAND,well-sorted,fine	Sm	"
12	" , " - " ,medium	"	"
13	" ,sorted,medium,slightly gravelly	"	"
14	" ,well-sorted,medium,slightly gravelly	"	"
15	" , " - " ,medium→fine	"	"
16	" , " - " ,medium,slightly gravelly	"	"
17	" , " - " . " , " "-"	"	"
18	" , " - " ,medium→fine	"	"
19	" , " - " , " → "	"	"
20	" , " - " , " - "	"	"
21	" , " - " , " - "	"	"

10	20	30	w	%
100	200	300	c_v, c_v	kN/m²
18	20	22	γ	kN/m³
0,4	0,6	0,8	e	

Legend and Definitions on encl. No.:

Danish Geotechnical Institute
1 Maglebjergvej, P.O.Box 119, DK 2800 Lyngby, Denmark

BORING LOG

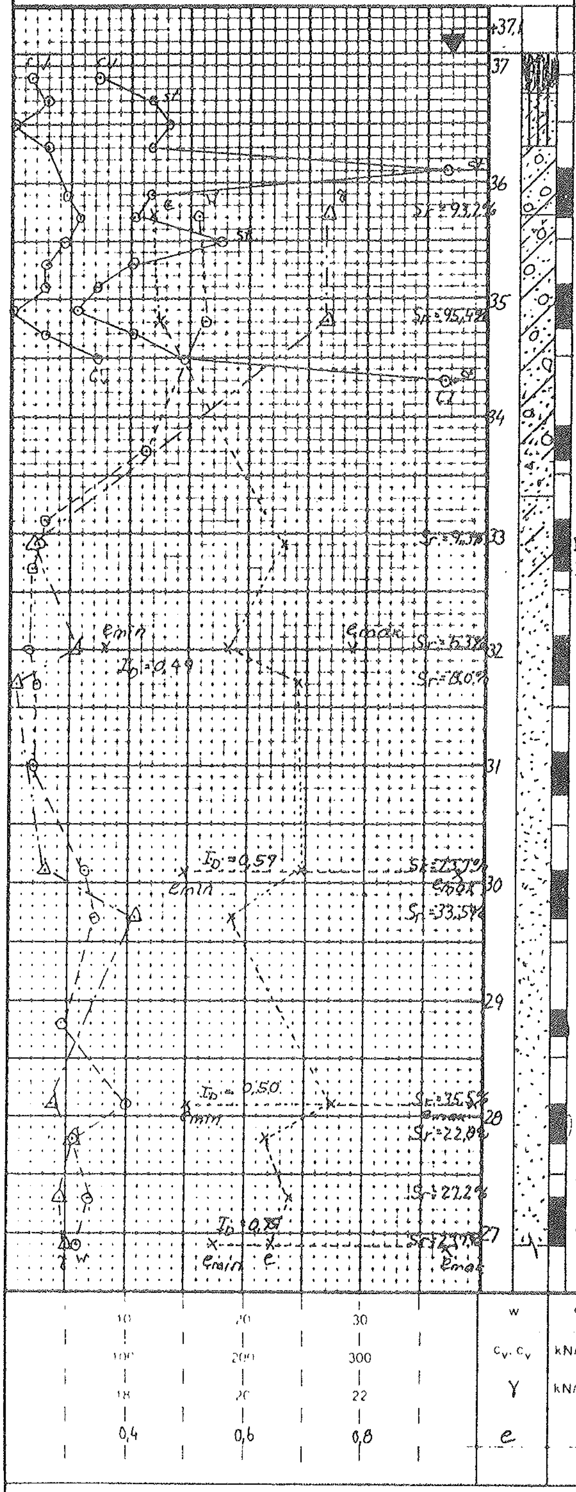
Job No.:	K 81446 Lyngby-Tårbæk
Bor. made: 82-02-09	Dess.: KS
Cont.:	Boring No.: 1
by: DGI/BEH	Appr.: JOL 82-10-04
Encl. No.:	3

Figure 4. Results of drilling 1.

GEOLOGICAL ABBREVIATION

Deposit:				Age:	
Freshwater	F	Meltwater	Sm	Postglacial	P
Solifluction	Fl	Wash out	U	Lateglacial	S
Glacial	Gl	Aeolian	V	Glacial	G
Marine	M			Interglacial	I
Wash down	N			Tertiary	T
Top soil	O			Danien	Da
Slidedebris	Sk			Senon	Se

Strength measurements
Classification tests



Lab. No.	Soil type / Description	Deposit	Age
	Boring No. 2		
22	FILL?MOULD,clayey,sandy,silty	O?	
23	" ?SAND,fine w/ silty and mouldy lumbs	"?	
24	BOULDER CLAY,sandy,stony	Gl	G
25	" " , " ,very silty,stony	"	"
26	" " , " ,stony	"	"
27	" " , " , "	"	"
28	" " , " , "	"	"
29	SAND,medium,w/lumbs of clay	Sm	"
3o	" , " ,"/ " " "	"	"
be-low:	" ,rather coarse,slightly,gravelly	"	"
31	" ,well-sorted,medium	"	"
32	" , " – " , "	"	"
33	" , " – " ,medium→ fine	"	"
34	" , " – " , " → "	"	"
35	" , " – " , " → "	"	"
36	" , " – " , " → "	"	"
37	" , " – " , " → "	"	"
38	" , " – " , " → "	"	"
39	" , " – " , " → "	"	"
40	" , " – " , " → "	"	"
41	" , " – " ,fine	"	"
42	" , " – " ,medium→ fine	"	"

Danish Geotechnical Institute
1 Maglebjergvej P.O.Box 119 DK 2800 Lyngby Denmark

BORING LOG

Job No.:	K 81446 Lyngby-Tårbæk				
Bor. made:	82-02-09	Dess.: KS	Cont.:		Boring No.: 2
by:	DGI/BEH	Appr.: JØL	82-10-04		Encl. No.: 4

Legend and Definitions on encl. No.:

Figure 5. Results of drilling 2.

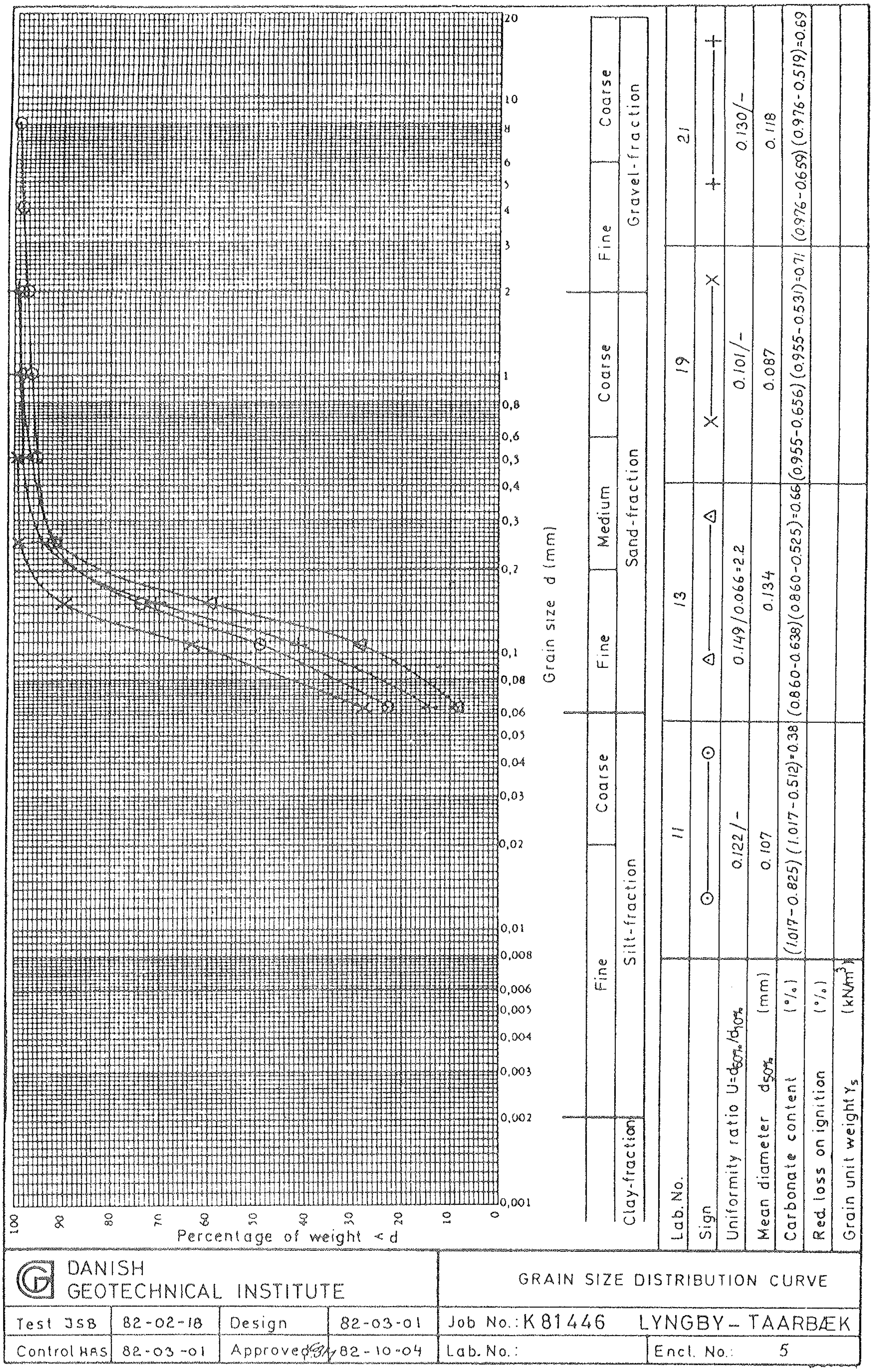


Figure 6. Grain-size distribution.

2.2.1. Determination of the thermal properties

To determine the thermal conductivity of moist soil a diagram is given in the literature [2]. The diagram is shown in fig.7 and the entry values are the quartz-content, the dry density and the degree of saturation. The easiest way to determine the quartz-content is simply to measure the thermal conductivity λ for a few samples in the laboratory by use of a "thermal-conductivity-probe" and then go "backwards" in the diagram. This is done for two samples of sand (λ measured by three different degrees of saturation ($S_r \sim 0$, 0.13 and 0.82)),and the result is a quartz-content of 75% for fine-grained (Danish ~ fint), and a quartz-content of 55% for medium-grained (Danish ~ mellemkornet). The same determination of the quartz-content is made for four samples of clay (λ measured by the natural degree of saturation ($S_r \sim 0.9$)), and the result is a quartz-content of 44%. A sketch of the "thermal conductivity-probe" is shown in fig.8.

To determine the heat capacity of moist soil a diagram is given in the literature [3]. The diagram is shown in fig.9 and the entry values are the porosity and the degree of saturation. From the knowledge of the thermal conductivity and the heat capacity, the thermal diffusivity α is found by the relation $\alpha = \lambda/C$.

The results are given in fig.10 and fig.11. The thermal conductivity lies between 0.8 W/m^0C and 2.2 W/m^0C, and the thermal diffusivity lies between 17.1 m^2/year and 26.9 m^2/year. It must be noticed that the results given in [4] has been corrected.

2.3. Excavation and water proofing

The pit with a pyramidal geometry is shown in plan on Drawing 2 and in cross section on Drawing 3. Based on the geotechnical investigation the slope of the sides of the pit was chosen as 37^0 (1:1.33). The inner dimensions in top is about 15.70 x 15.70 m and in the bottom 4.85 x 4.85 m. The depth is about 4.25 m, and these dimensions give a water volume $\simeq 540\ m^3$.

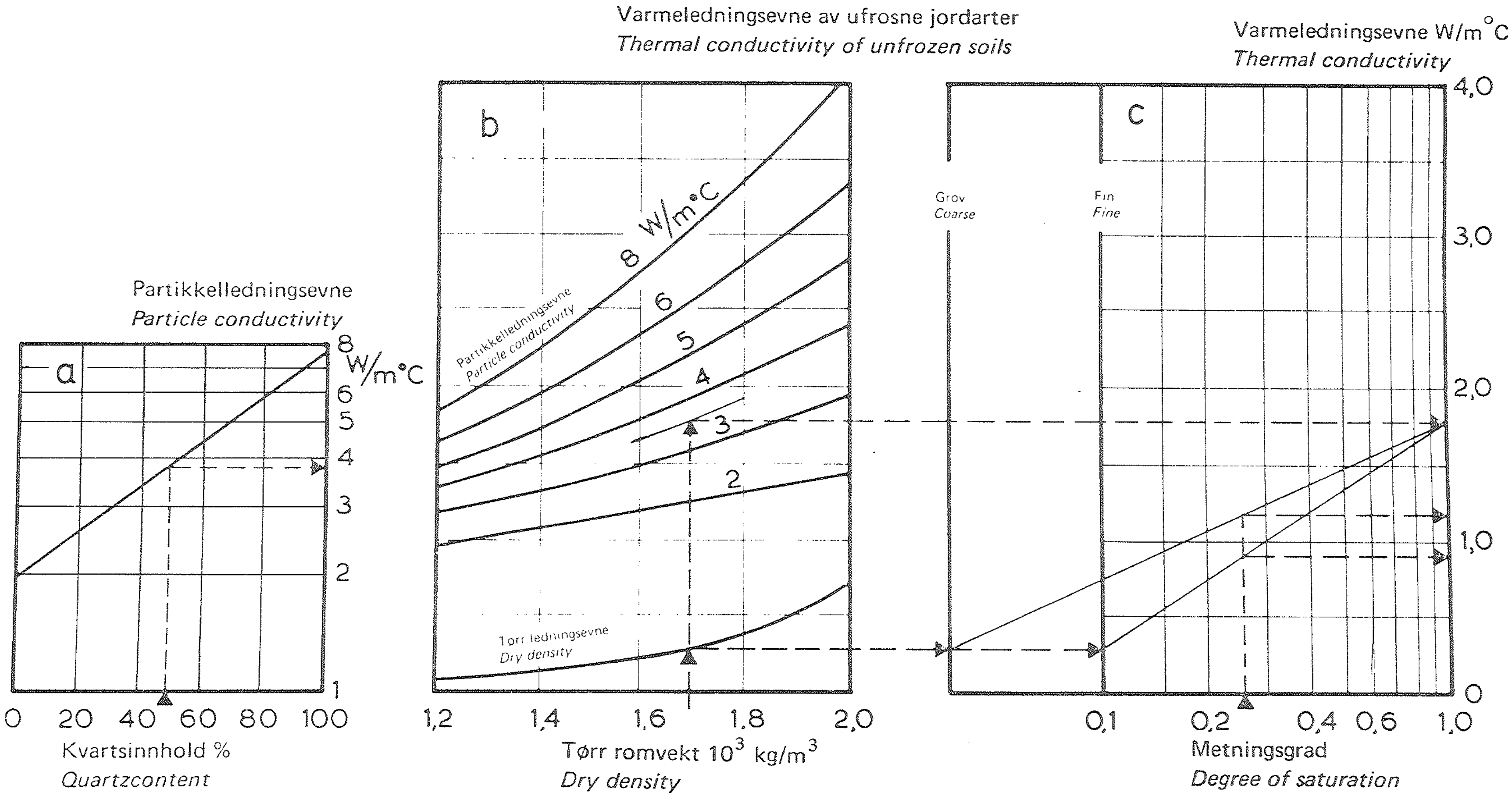


Figure 7. Thermal conductivity of unfrozen mineral soils. Reference [2].

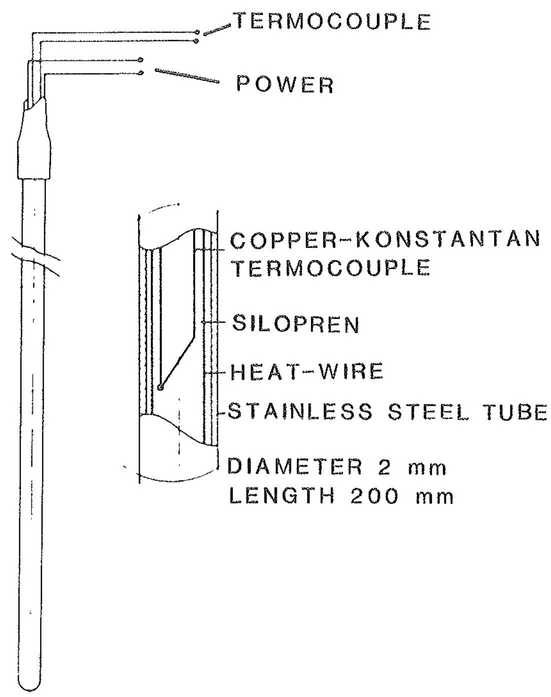
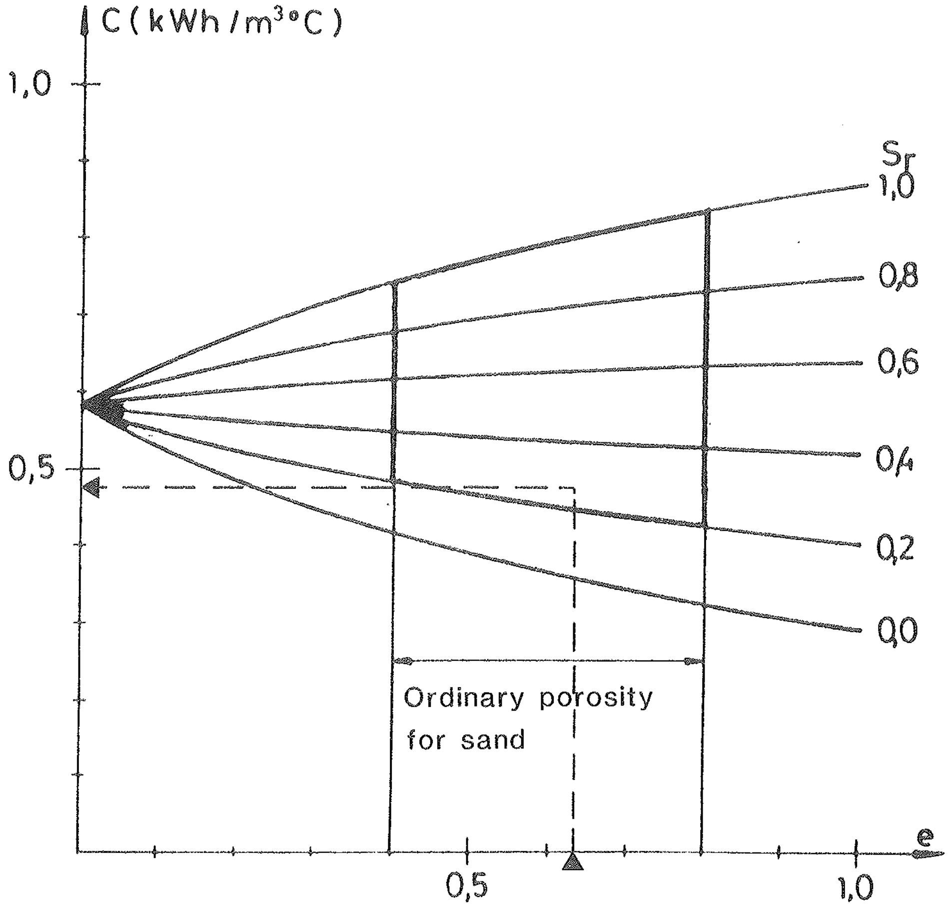


Figure 8. Sketch of a probe for measuring the coefficient of thermal conductivity.



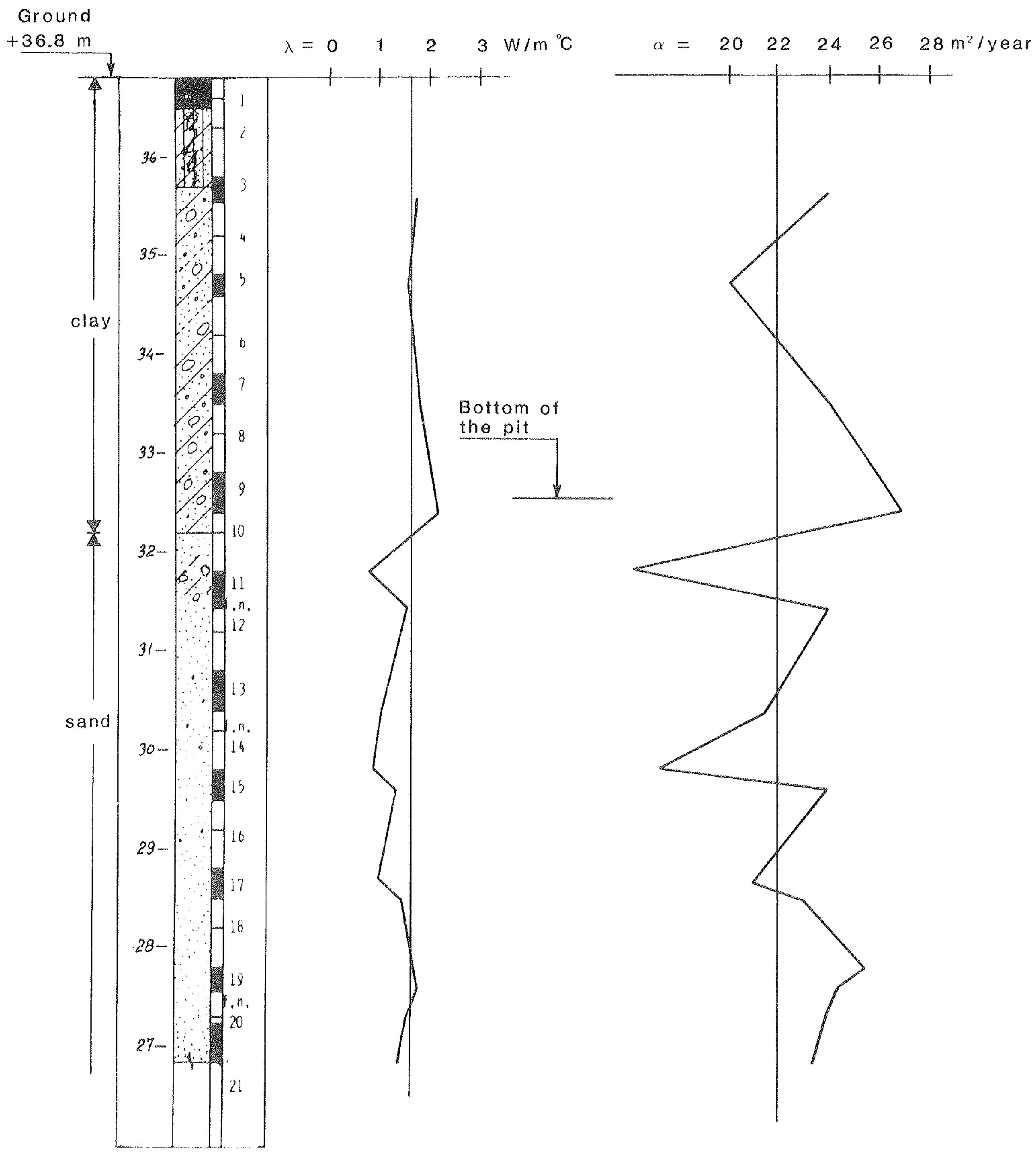
NOTE :

C is heat capacity

e porosity

S_r degree of saturation

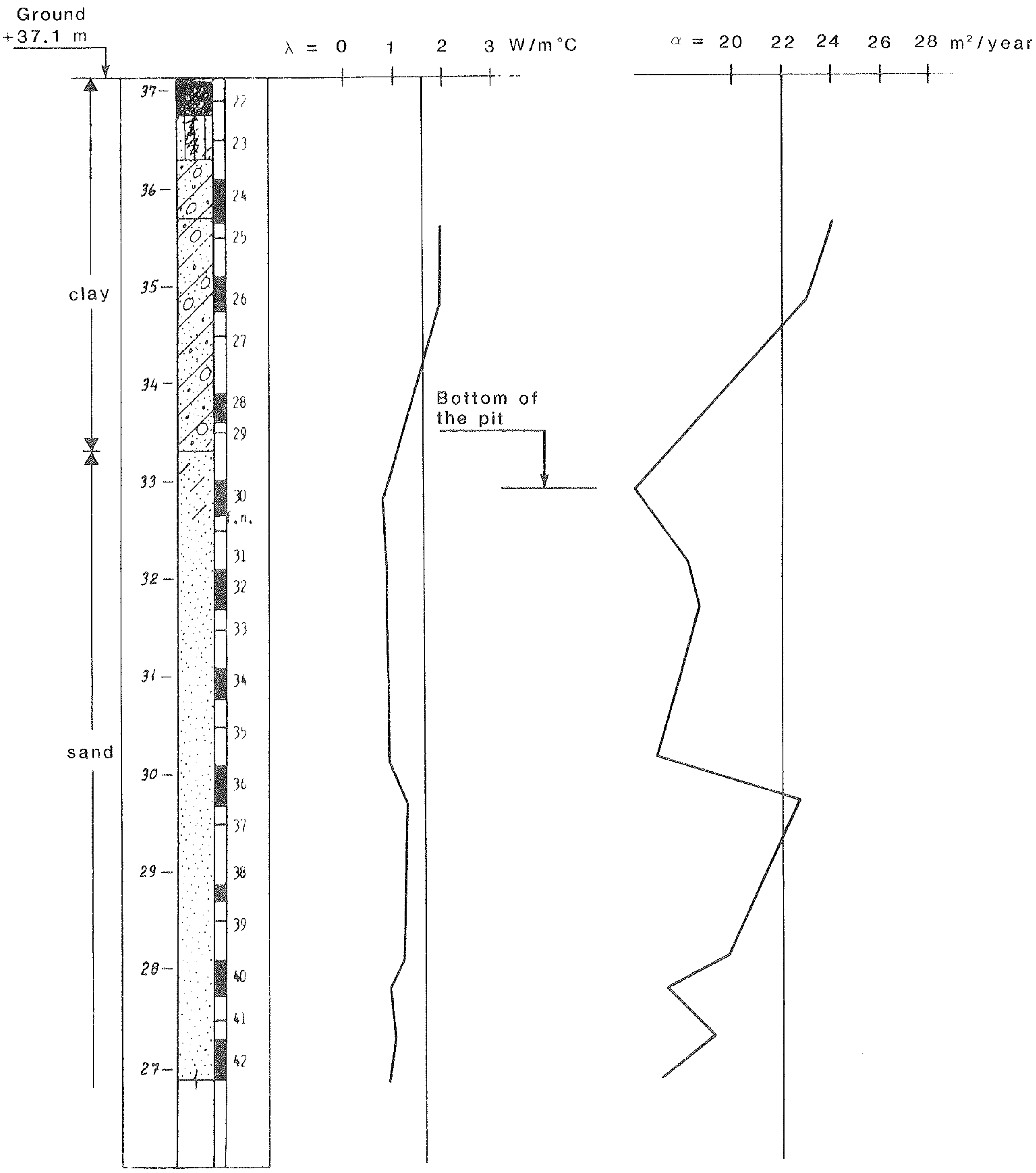
Figure 9. Determination of the heat capacity of mineral soils. Reference [3].



NOTE : λ is thermal conductivity

α is thermal diffusivity

Figure 10. The types of soil and their thermal properties. Drilling 1.



NOTE: λ is thermal conductivity

α is thermal diffusivity

Figure 11. The types of soil and their thermal properties. Drilling 2.

Building pits in clay demands drainage installations, which was arranged without serious spoiling the natural compositions of the pit walls by pressing the sewage pipe from the bottom of the neighbouring drain well to the bottom of the pit. Here the sewage pipe was connected to the drain pipes, see also Drawing 7. Behind the 0.30 m thick reinforced concrete wall at the top of the pit another drain pipe was placed in gravel to take the surface water.

To secure correct function of the test facility the store/soil interfaces are made waterproof by use of a 2.5 mm polyethelene liner supported on sand mixed with cement. Tests were made to find the optimal type of sand and the correct mixture of cement and sand (1:12). A photo of the placement of the sand is shown on fig.12 and a photo of the lining work is shown in fig.13.

The liner was produced in rolls of 10 m width and was cut in four pieces (1 piece per pit wall). After the four pieces were placed on site in the pit, they were welded together by handoperated welding machines. A photo of the welding machine is shown on fig. 14.

At the top of the pit the edge of the liner was cast into the reinforced concrete wall, see Drawing 4. In this concrete wall the water level control system (Drawing 6) and the charge systems (Drawing 10) are cast-in.

2.4. Floating lid

Adjacent to the pit a "dry dock" was constructed to make production of the floating lid possible under controlled conditions, see a photo of the "dry dock" on fig. 15.

The floating lid is heat insulated by 0.5 m polystyrene (a pyramidal geometry with 0.6 m at the center and 0.4 m at the edges) and protected against evaporation from the pit and against climatic conditions by use of a 2.5 mm polyethylene plastic bottom liner and a 1.0 mm butyl rubber liner for the topside. The rubber liner is fixed at the top of the concrete wall so the rain can run off to the

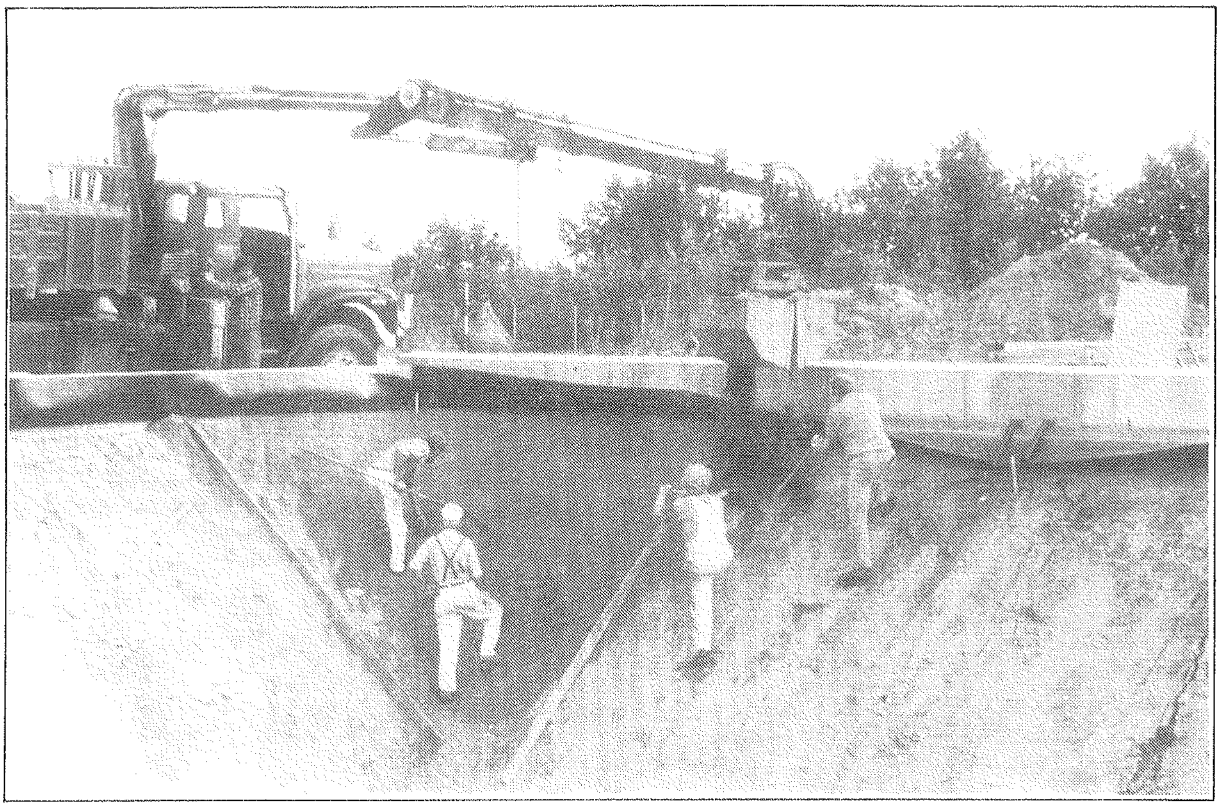


Figure 12. The laying of sand in progress.

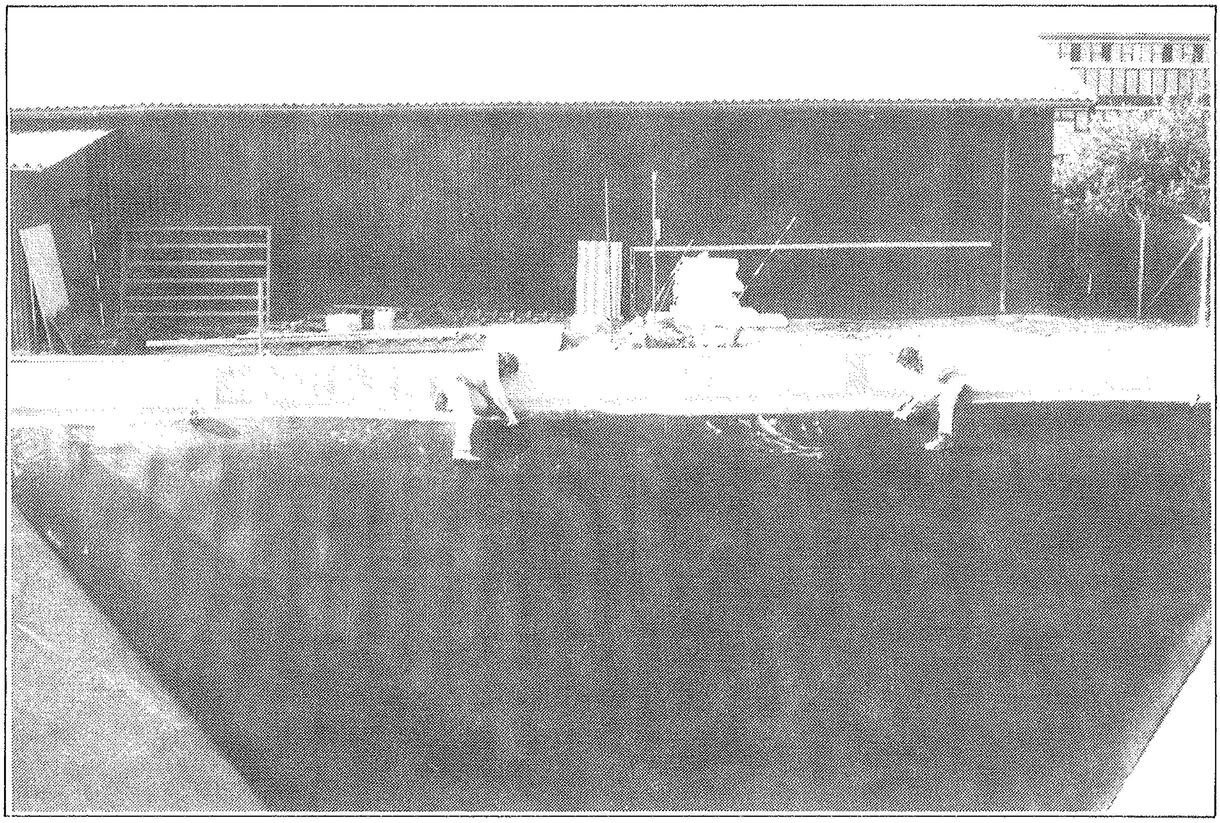


Figure 13. The lining work in progress.

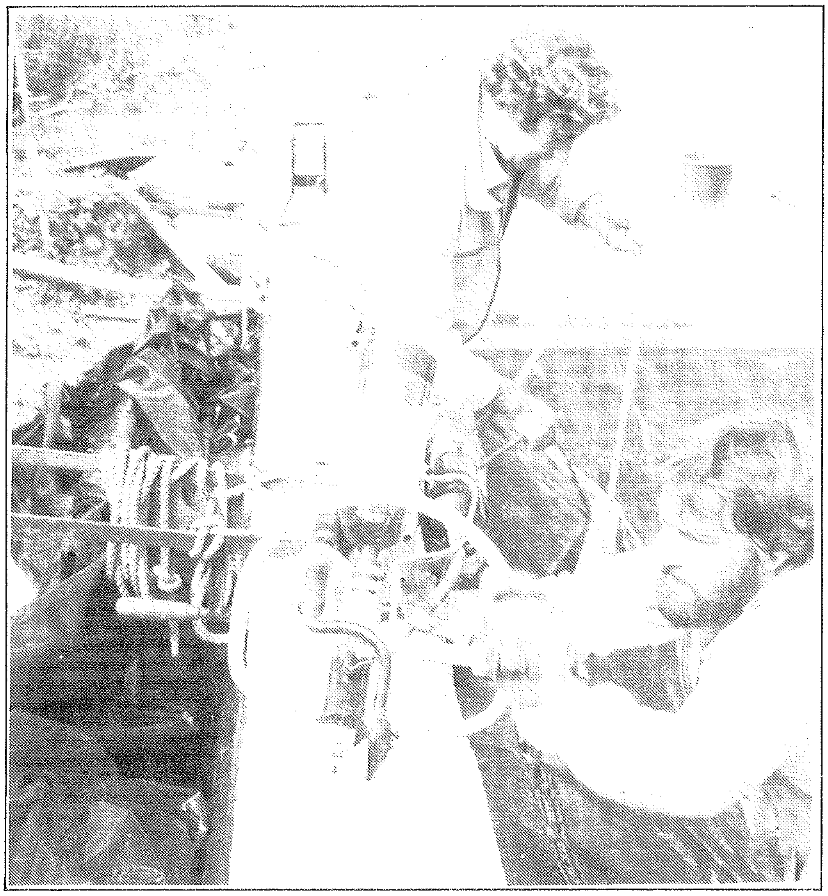


Figure 14.
The handoperated welding machine.

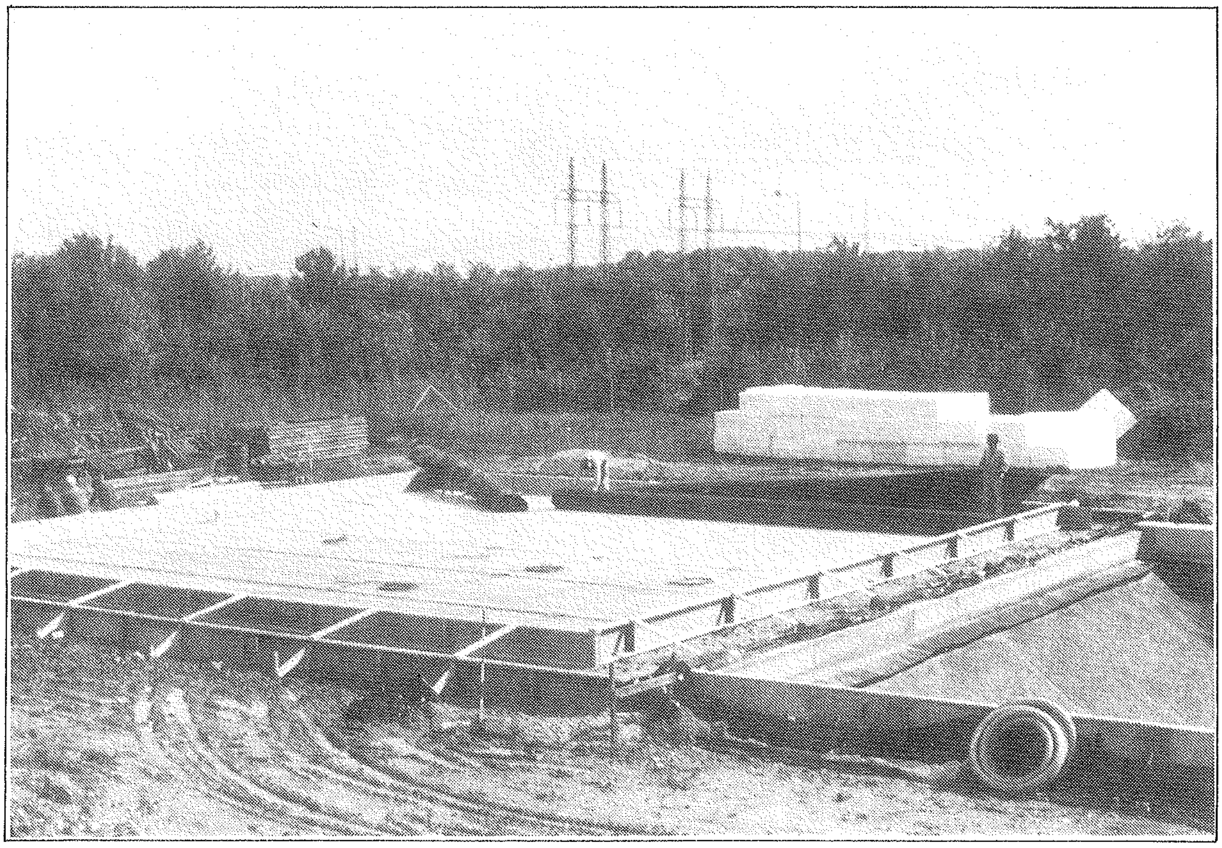


Figure 15. The "dry dock".

troughs. To secure the lid against winds about 100 flagstones were placed on the topside. To prevent evaporation and excessive heat losses along the joint between the lid and the concrete wall an oilfilled rubber tube was installed. Anyway, miner unforeseen heat losses occurred in the joint during the work with the installation of the tubes in the joints.

Exact estimates of the heat flow at the edges of the pit during the simulated operations have not been attempted.

Normal tap-water was filled into the pit from the nearest fire hydrant. When the pit was filled, the water level was raised to allow the "dry dock" to be flooded bringing the lid to float. Thus the lid could easily be floated to final position, see a photo of the floating in fig. 16. After floating the "dock gate" was fixed in place (Drawing 5).

2.5. Inlet - outlet systems

The heat input to the water of the pit is generated by two 36 kW gas boilers which are placed in a boiler house constructed adjacent to the pit. The heat exchanges, the flow meters, the valves, the piping etc. in the boiler house can be seen on Drawing 11. The pipes in the boiler house are mild steel while the pipes outside the boiler house are made of plastic. For removal of heat from the pit water an 30 kW aircooler was placed outside the boiler house (see position 13 on Drawing 11).

Three different heat inlet - outlet systems are indicated on Drawing 11 and each of them are sketched on Drawings 12, 13 and 14. In order to achieve as uniform a temperature as possible for the water in the store, the charge system A, shown on Drawing 12, has been used for heat inlet while the system B, shown on Drawing 13, has been used for heat outlet. Under normal operations system B would be used for charging and operated in reverse for discharging. The temperature of the pit water flowing from the heat exchanger is controlled by a thermostat, see position 7 on Drawing 11. The temperature-sensor, position 6, after the heat exchanger gives a signal to the thermostat which then manages the motor-operated valve, position 5. The water-flow in the pit-circuit has a maximum of 5.4 m^3/h (clean filters). During the initial heating of the test pit water (from 15°C to 60°C) it was established, that the maximum (net) heat transfer to the pit obtainable from the two boilers was 52 kW. It was also realized, that the heat loss from the test pit during a loading sequence with a charge rate of 52 kW amounted to about 17 kW. From these preliminary observations it thus could be established, that the maximum rate of change in the temperature of the pit water would correspond to around 35 kW.

A sinoidal change in temperature for the 540 m^3 of pit water between 45°C and 60°C and down to 30°C and back up to 45°C undertaken during n hours will demand a maximum rate of heat change of

$$\left(\frac{dQ}{dt}\right)_{max} = \frac{540,000 \times 15 \times 1163}{10^6} \times \frac{2\pi}{n} = \underline{\underline{\frac{59189.5}{n} \text{ kWh/h}}}$$

For $\left(\frac{dQ}{dt}\right)_{max}$ = 35 kW, n = 1691 hours or ~ 70 days.

Two simulated operations each covering a period of 70 days has been carried out after the first warm up period.

2.6. Construction period

The geotechnical drillings were done in the winter 1981/82. Based on this information the design was carried out in the spring of 1982 and the construction was started in June 1982. The construction was undertaken by a Danish contractor under daily supervision from the laboratory, and the work was completed in 10 weeks.

To facilitate the verification of the theoretical calculations the pit was dug completely into the ground, the excavated mass of dirt being deposited at the edge of the building site. A photo of the final plant, taken from the diggings deposit can be seen on fig. 17.

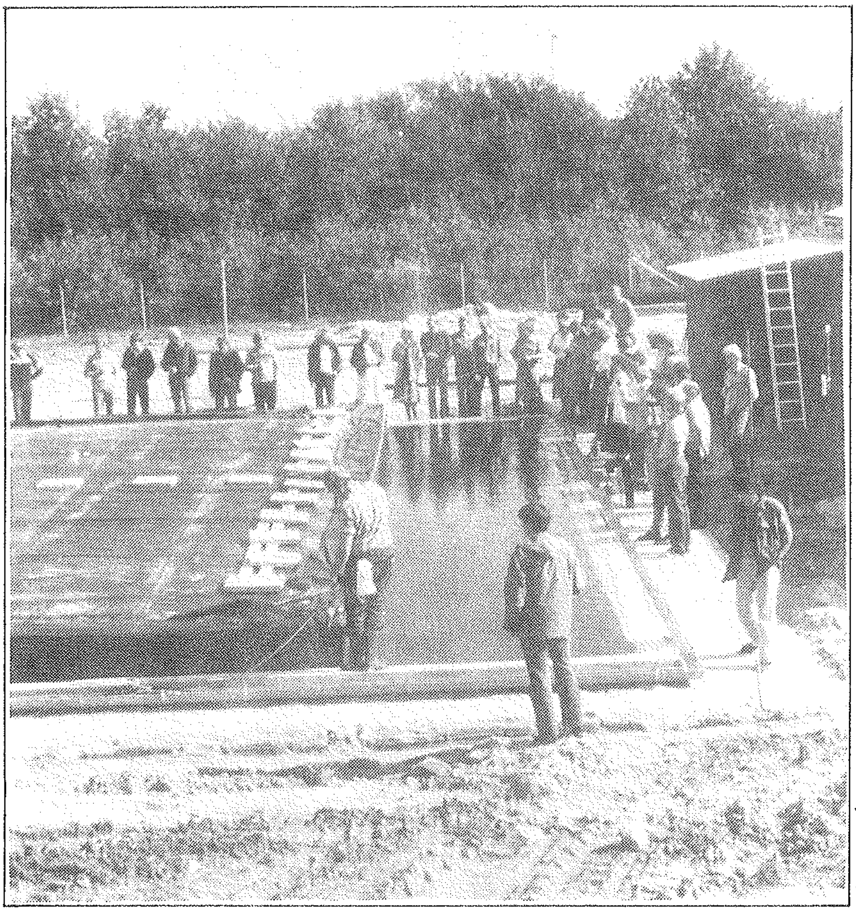


Figure 16.
Floating of the lid
to the final position.

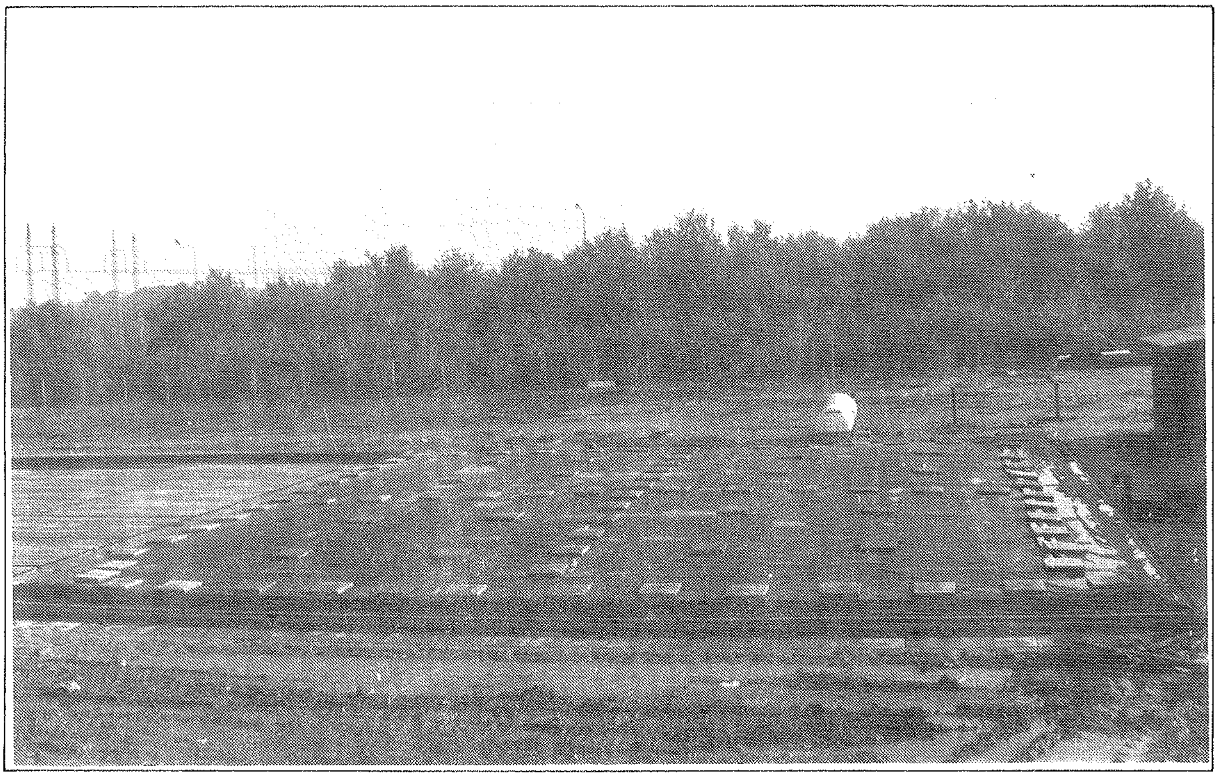


Figure 17. The final plant. The boiler house can be seen to the right.

3. TESTING USING SIMULATED LOAD

3.1. Temperature and moisture monitoring

Approximately 80 copper constantan thermocouples have been used to measure temperatures in the water and in the soil under and around the pit. The thermocouples are arranged in "chains", which are located in two planes as shown on Drawing 20 (row 1 and 2). The location of the thermocouples in the vertical planes is shown on Drawing 21 for row 1 and Drawing 22 for row 2. The chains in the soil were secured contact with the walls of the drilled hole by a dry sand filled in from the top of the hole. Another system securing against undesired vertical moisture movements in the hole will be preferred in the future.

The thermocouples in the water are fixed to a steel wire, which with a weight in the lower end has been fastened to the bottom liner of the lid.

The temperatures are scanned automatically once an hour with the Hewlett Packard 3054A datalogger system; the only temperatures, which are scanned every 2. minute are the temperature difference of the pit water in the charge/discharge pipes and the temperature of the pit water in the charge pipe. Every day the datalogger system prints all the daily mean temperatures on paper and on tape (for later transfer to our computer center). Such a daily "report" can be seen on fig.18.

It must be remarked that all the thermocouples have functioned well until now.

The moisture content in the soil was measured and reported by the Danish Geotechnical Institute (DGI) for drilling 1 and drilling 2 as well as for the vertical holes drilled for placing the measuring chains. For continuous moisture measurements in the clay 2 aluminium tubes were placed in both row 1 and row 2 just beside the pit (Drawing 21 and Drawing 22). The continuous measurements were done using a radioactive isotop, and during construction of the pit the instrument was checked against the conventional measurements made by DGI using the tubes under the pit (the 3 tubes in row 1 can be seen on Drawing 21).

DATO: 04:28:09 DAG NR. 210

	1	2	3	4	5	6
	C	C	C	C	C	C
STAVNR: 1	44.3	38.1	33.5	27.9	24.3	-
STAVNR: 2	47.7	40.9	36.1	29.2	25.5	-
STAVNR: 3	47	40	35.2	28.9	25.2	-
STAVNR: 4	49.5	43.8	39.9	33.7	28.9	-
STAVNR: 5	23.9	24.2	23.5	22.1	21.5	-
STAVNR: 6	9.2	13.4	15.8	15.9	14.3	12.3
STAVNR: 7	44.5	36.8	33.1	27.3	24.1	-
STAVNR: 8	46.2	38.1	33.3	27.4	23.6	-
STAVNR: 9	14.4	14.2	13.7	13.3	13.4	-
STAVNR: 10	9	8.5	7.9	7.8	8.5	-
STAVNR: 11	60.3	60.3	60.4	60.1	59.9	-
STAVNR: 12	60.4	60.2	60.1	60.1	59.9	-
STAVNR: 13	60.4	60.3	60.2	60.2	-	-
STAVNR: 14	60.4	60.3	60.2	60.1	60	-
STAVNR: 15	60.4	60.4	60.3	-	-	-
Tude=	9.9	7.5	7.109	8.615	Flow=84.98 l/min	

Tfrem= 68.23C DeltaT=8.814C Qdag=1230.11917kWh Qtot= 29.11MWh

Figure 18. **Example of the daily outprint from datalogger.**

A good agreement was found between the 2 methods. During the test period the continuous measurements in the clay around the pit have not shown changes in the moisture content caused by the heating of the soil.

3.2. Testing period

The first charge period started in September 1982 from a water temperature of 15°C. It took some weeks before the charging system and the datalogger system were checked.

Consequently the first temperature increase from 15°C to 25°C was not reported.

Because of the limited time being available for testing in this period, it was decided to accelerate the testing by reducing the charge/discharge cycle from 365 days to 70 days. Further it was decided to have the temperature of the water in the store as uniform as possible. The charge and discharge cycles can be seen in fig.19 where day no.1 is equal to October 1. 1982. The first long warm up period of about 45 days and the next period of about 25 days with a constant temperature of about 60.6°C show a delay caused by the finish work of the plant and control problems in the boiler house. Especially, the minor unforeseen difficulties arising during installation of the floating "gasket", which were designed to almost prevent evaporation and excessive heat losses along the joint between the lid and the concrete edge of the pit, took some extra time.

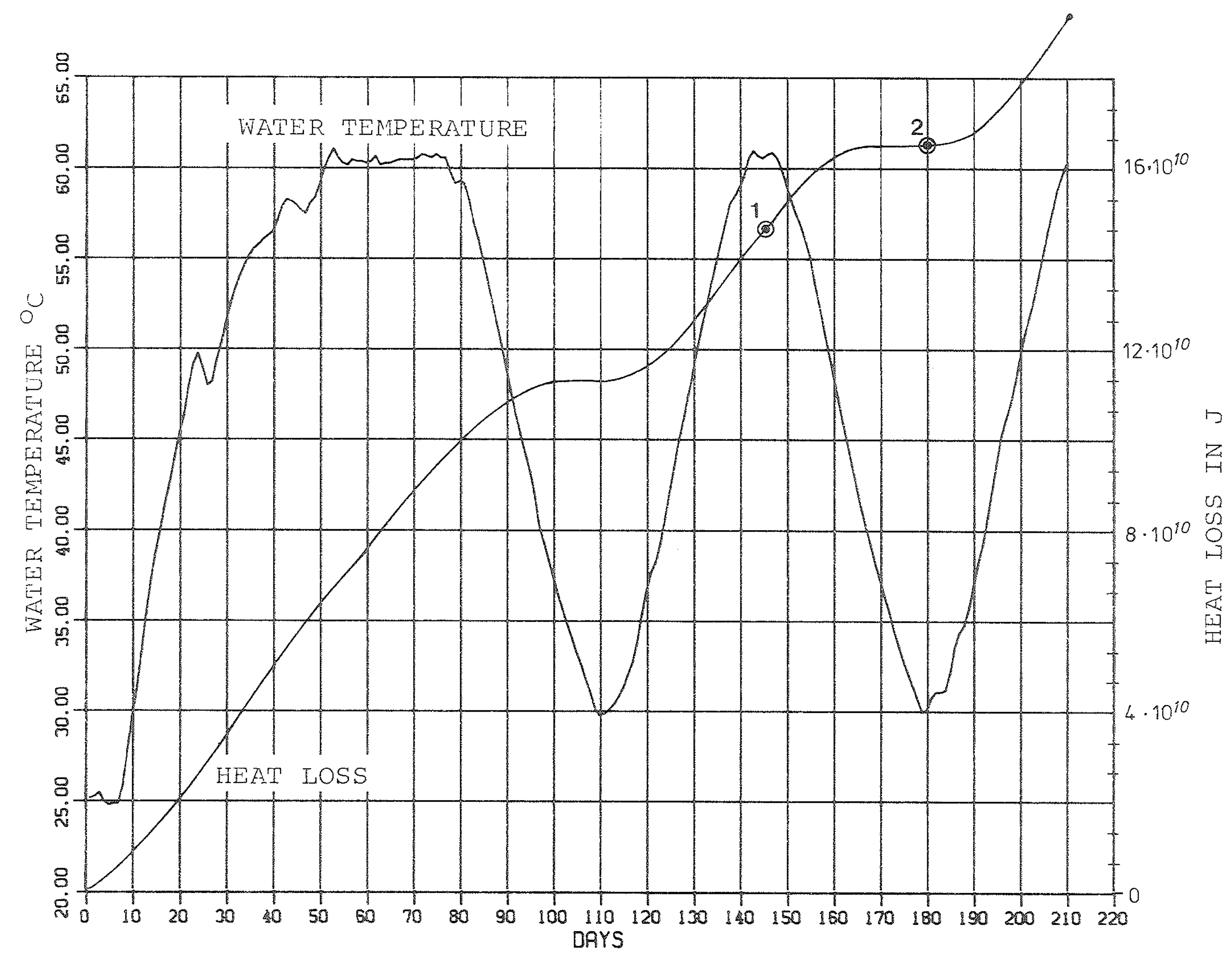


Fig. 19. The measured water temperature in the test pit and the calculated accumulated heat loss from the pit to the soil and through the insulated lid.

4. COMPUTER PROGRAMME AND VERIFICATION

4.1. Computer model

A computer program has been constructed based on the method of finite differences. The program treats the geometry of 1/8 of the pit and the surrounding soil as indicated on Drawing 23. The computer code has been constructed to be truly 3-dimensional. The enmeshment is shown on Drawings 23, 24, 25, 26, 27 and 28.

The centre points of the volume elements shown are the mesh-points used in the simulations. The computer program offers the following facilities:

- initial and boundary conditions can be specified freely,
- thermal material properties can be specified separately in every horizontal mesh point plane,
- soil temperatures in mesh points and heat loss from the pit to the soil are calculated at 6-hours time intervals,
- calculated and measured temperatures are linked in the data base to facilitate comparing,
- a yearly simulation cost of about 1.5 CPU minutes on our IBM 3033 computer.

4.2. Verification of the computer program

The procedure for determining the thermal properties of the soil has been explained in chapter 2.2.1. The values found were the following (drilling 1):

- coefficient of thermal diffusivity α = 22 m^2/yr
- coefficient of thermal conductivity λ = 1.6 W/m^0C
- coefficient of heat accumulation $\sqrt{\lambda C}$ = 3.0 $kWh/^0C\ yr^{\frac{1}{2}}$

Using these findings, measured and calculated temperatures in the soil have been compared, based on the measured water temperature in the pit (fig.19). The temperatures on the different measuring locations are shown i Appendix 2. It thus appears that the program can be used in the original form to simulate this type of a pit (No change in soil assumptions was needed. The thermal properties of the soil in drilling 2 are not used since the measuring locations here (26-31) have only registrated minor temperature changes arising from the temperature changes in the pit).

A part of the output from the computer program is the temperatures in the mesh points and this can be used to make the temperature profite through the soil. As an example the temperature profite for the day no.210 (the last day reported) is shown on fig.20.

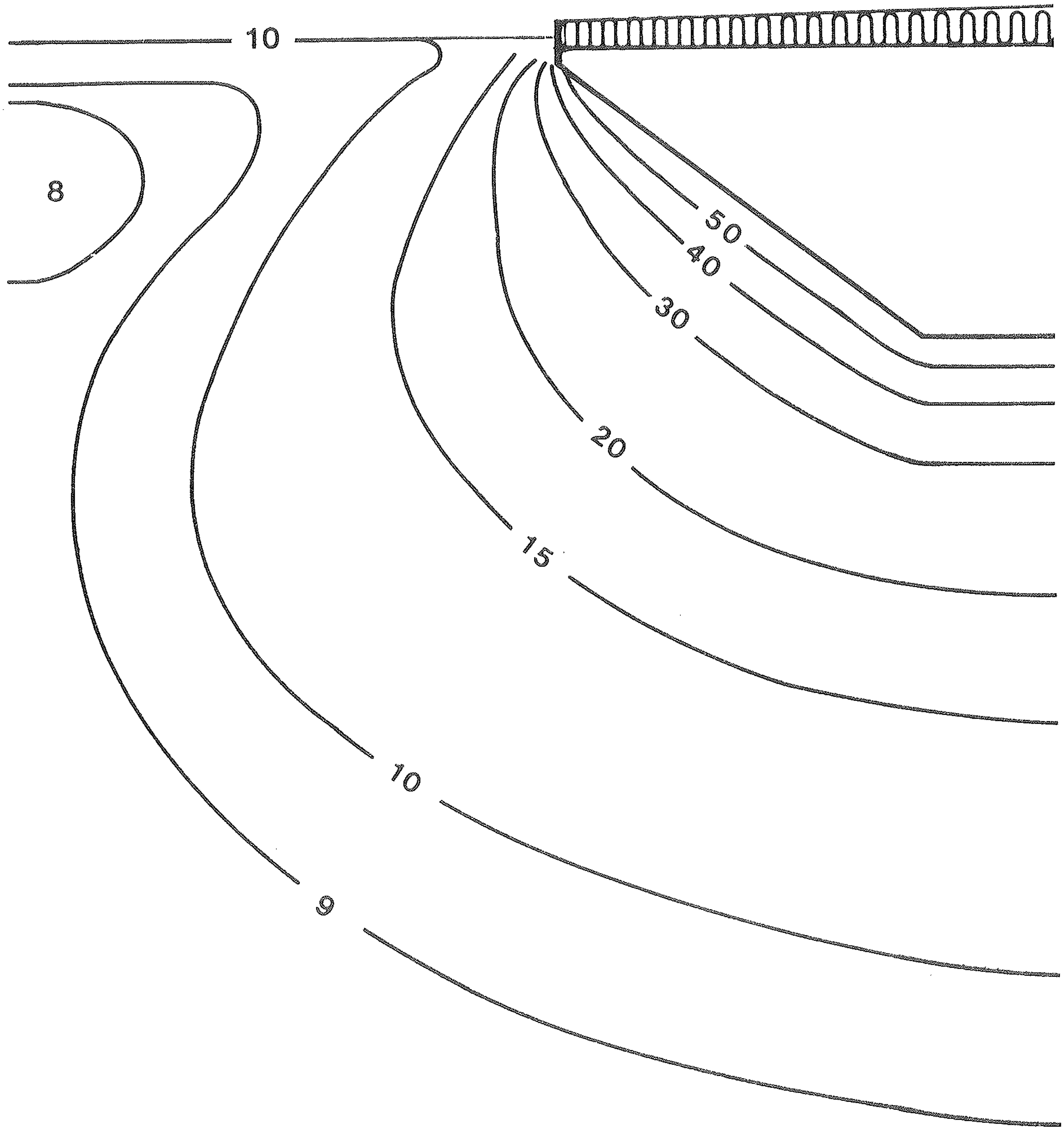


Figure 20. Temperature profile for day no. 210.
Thermocouples in row 1.

5. RESULTS

5.1. Storage efficiency

The storage efficiency in part of the period of testing is investigated. The sum of the accumulated heat loss from the pit to the soil and through the top lid by conduction is shown in fig.19. (This curve is part of the output from the computer program). The heat loss during the second discharge period from day 145 to day 180 is used (the difference between point 2 and 1 in fig.19):

$$\Delta Q_1 = 1.76 \; 10^{10} J = 4.890 \text{ kWh} \qquad (1)$$

(85% is lost to the soil and 15% through the top lid by conduction)

The heat content of the water in the pit being discharged from 60.6°C to 30°C is (water volume ≃ 540 m³):

$$\Delta Q_{acc} = 19.000 \text{ kWh} \qquad (2)$$

The cooling load measured on the air cooler during this period:

$$\Delta Q_{cool} = 11.100 \text{ kWh} \qquad (3)$$

Consequently heat losses in piping, edge transmission and evaporation losses at the edge of the lid have been:

$$\Delta Q_2 = 19.000 - 4.890 - 11.100 = 3.010 \text{ kWh} \qquad (4)$$

The major part of ΔQ_2 is an unaccounted loss due to the sealing of the lid at the edges, which has not been included in the computer calculations.

The storage efficienty:

$$\eta = \frac{\Delta C_{cool}}{\Delta Q_{acc}} = \frac{11.100}{19.000} = 58\% \qquad (5)$$

Without this unaccounted evaporation loss, the efficiency would have been:

$$\eta \simeq 74\% \qquad (6)$$

Only including the heat loss to the soil, the efficiency will be:

$$\eta' = \frac{19.000 - 4.890 \cdot 85\%}{19.000} = 78\% \qquad (6a)$$

5.2. Thermal behaviour during seasonal performance

The thermal behaviour during seasonal performance is investigated. The direct way of using the results of fig.19 goes via the Fourier number.

$$Fo = \alpha \frac{t}{L^2} \quad , \text{ where} \qquad (7)$$

α = coefficient of thermal diffusivity, t = characteristic time and L = characteristic lineary dimension of the pit.

In fig.19 the temperature cycle time from day 110 to day 180 is 70 days, which is taken as the characteristic time.

In seasonal operation t = 365 days.

Now using equation (7)

$$\alpha \frac{70 \text{ days}}{L_1^2} = \alpha \frac{365 \text{ days}}{L_2^2} \qquad (8)$$

$\Rightarrow$

$$FAK = \frac{L_2}{L_1} = \sqrt{\frac{365}{70}} = 2.283 \qquad (9)$$

FAK is the lineary scaling factor which must be applied in order to find a pit which, in seasonal operation, will manifest the efficiences of equations (5) and (6). The volume is scaled as follows:

$$VOL_{seasonal} = VOL_{70 \text{ days}} \cdot FAK^3 = 6.430 \text{ m}^3 \qquad (10)$$

To get an estimate of the efficiency in seasonal operation for large pits, the measured efficiences will be compared to the theoretical efficiencies calculated on the basis of the theory developed by P.N.Hansen [7].

The total heat loss to the soil during a 6-months discharge period in wintertime is given by equation (13) in [7]:

$$\Omega_{soil} = A \frac{\sqrt{\lambda C}}{\sqrt{\pi}} \Big(- \Delta\nu \sqrt{1 \text{ year}} + (\nu_o - \nu_\infty) \Big(\frac{\sqrt{\alpha \pi}}{zM} \tfrac{1}{2}\text{year} + 2(\sqrt{t} - \sqrt{t - \tfrac{1}{2}}) \Big) \Big) \qquad (11)$$

where

A = the surface area of the store versus the soil

$\sqrt{\lambda C}$ = the coefficient of heat accumulation of the soil

$\Delta\nu$ = the temperature amplitude in the store

ν_o = the average temperature in the store

ν_∞ = the original average temperature of the soil

t = the time in units of years

α = the coefficient of thermal diffusivity of the soil

M = the modulus, which is equal to the ratio volume of store versus surface area of the store

z = a geometry factor

Not accounting for the heat losses through the top lid the efficiency is defined by:

$$\eta' = \frac{\Delta Q_{accumulated} - \Delta Q_{soil}}{\Delta Q_{accumulated}} \qquad (12)$$

In the following it is compared if the equatation of the theory (11) and (12) will provide an efficiency comparable to equation (6a) for the store of 6.430 m^3 being discharged during seasonal operation.

Using values for the test pit (volume = 540 m^3 and surface area versus the soil = 300 m^2) one gets:

$$A = FAK^2 \cdot 300 = 1564\ m^2 \qquad (13)$$

$$M = \frac{540}{300} \cdot FAK = 4.11 \qquad (14)$$

The geometry factor is given in equation (22) in reference [7] to be z = 2.

Using equation (2) gives:

$$\Delta Q_{accumulated} = FAK^3 \cdot 19.000 = 226.100\ kWh$$

Inserting in equation (11):

$$\Delta Q_{soil} = 1564 \frac{3.0}{\sqrt{\pi}} \Big(- 15.3^0C + (45.3 - 9) \Big(\frac{\sqrt{22 \cdot \pi}}{2 \cdot 4.11} \cdot \tfrac{1}{2} + 2 \cdot (\sqrt{2} - \sqrt{1\tfrac{1}{2}}) \Big) \Big) \qquad (15)$$

$$\Delta Q_{soil} = 44.500\ kWh \qquad (16)$$

Inserting in equation (12):

$$\eta' = \frac{226.100 - 44.500}{226.100} = 80\% \qquad (17)$$

This result has to be compared with equation (6a). The agreement is seen to be very good and it can be concluded that the analytical expression in equation (11) is fit for prodicting heat losses to the soil in pit storages systems.

Further theoretical investigations will be carried through concerning the heat losses in seasonal operations for stores of volumes greater than 20.000 m^3.
This will be reported later, ref.[6].