Thermal Insulation Laboratory
Technical University of Denmark

SEASONAL HEAT STORAGE IN UNDERGROUND WARM WATER STORES

Dimensioning and planning of a full size store

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FINAL REPORT
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FORORD

I 1979 foranledigede Energiministeriet et udredningsarbejde vedrørende "Sæsonlagring af varme i store vandbassiner". Arbejdet udførtes af et rådgivende ingeniørfirma [7] under ledelse af Laboratoriet for Varmeisolering på Danmarks Tekniske Højskole.

I "Energiforskningsprogram 82" bevilgede Energiministeriet midler til anlæg af et 500 m^3 forsøgsvarmelager og indgik på, i samarbejde med The Commission of the European Communities, at afholde udgifterne i forbindelse med simuleret drift og måling af lagerets effektivitet i et år. (Kontrakt ESA-S-162-DK(G)). Arbejdet omfattede også verifikation af de opstillede EDB-programmer til bestemmelse af varmetabene i forbindelse med den simulerede drift af forsøgsanlægget. Den endelige rapport vedrørende dette projekt blev godkendt af EEC i 1983 [8].

Den i projektet vundne erfaring er blevet anvendt til at projektere et fuldskala underjordisk sæsonvarmelager. Projektet er et samarbejde mellem EEC DG XII (kontrakt ESA-S-163-DK(G)) og STVF.

Efter omhyggelig gennemgang af mulighederne for at få et fuldskala projekt gennemført, valgtes Forsyningsvirksomhederne i Esbjerg Kommune, der i et kraft-varme samarbejde med I/S Vestkraft producerer fjernvarme i Esbjerg Havn, til at fremskaffe de praktiske oplysninger, hvorpå projekteringen af et 50.000 m^3 damvarmelager kunne baseres.

Denne rapport udgør slutrapporten i det nævnte samarbejdsprojekt. Dele af rapporten er tidligere blevet præsenteret i EEC [9] og [17].

30. juni 1984
Laboratoriet for Varmeisolering
Danmarks Tekniske Højskole
Vagn Ussing
Projektleder

RESUMÉ

Denne rapport omhandler projekteringen af et "fuldskala underjordisk damvarmelager". Det har været formålet med projektet, på grundlag af de ved tidligere arbejder vundne erfaringer [8], at udføre et projekt til et fuldskala (ca. 50.000 m^3) underjordisk damvarmelager. Projektet skulle baseres på oplysninger fra et dansk fjernvarmesystem, der erklærede sig interesseret i seriøst at overveje de økonomiske fordele opnået ved projektets gennemførelse. Tidligere undersøgelser viste, at damvarmelagre ville være attraktive investeringer for fjernvarmesystemer baseret på kraft-varme forbindelser. Et fjernvarmesystem, der viste interesse i at anskaffe et damvarmelager blev udpeget, selv om dette systems nuværende behov ikke omfattede sæsonlagring men alene sigtede på forbedring af driftsøkonomien i kraftvarmeværket.

Den nødvendige kapacitet var omkring 2900 MWh, som inden for systemets temperaturgrænser kunne opnås med et damlager på 55.000 m^3.

Baseret på geotekniske undersøgelser valgtes en placering af damlageret i nærheden af kraftværket. Den valgte byggegrund var skabt ved opfyld i Vesterhavet, hvilket vil besværliggøre anlægsarbejdet noget.

Et generelt studie af damvarmelagres optimale geometri udførtes og baseret herpå, og på de geotekniske studier fra byggegrunden, valgtes projektets endelige geometri og koter.

Baseret på geotekniske studier er udførelsen af lageret beskrevet. Projektets primære princip var, at vandtætheden skulle være sikret ved lermængder i fornødent omfang, medens lagervandets kemiske stabilitet skulle sikres af plastikbeklædninger med fornøden holdbarhed. Omfattende drænsystemer har været nødvendige. Bund og sider er uisolerede.

Det svømmende låg er optimalt isoleret. Afvanding af lagets overflade nødvendiggjorde en varierende mængde grus dækket med muld og placeret på den afdækning, der beskytter låg-isoleringen mod den klimatiske fugtighed.

Lågets konstruktion er udformet med sigte på at forhindre iltindtrængning til lagervandet. Den termiske udvidelse af vandmængden er sikret ved små udbøjninger af det svømmende låg.

Projekteringen har omfattet skitsering af pumpe- og ventil-arrangementet, der er nødvendig for drift af anlægget som korttidslager.

Systemets høje effekt må erindres, når pumpestationens størrelse iagttages. Ved sæsonlagre bliver disse anlæg meget mindre.

Projektet er blevet anvendt som grundlag for et studie af anlæggets varmetab i en lang periode med fastholdt gennemsnitstemperatur.

Projektet har også dannet baggrund for et foreløbigt prisoverslag, der viser, at store underjordiske damvarmelagre med uisoleret bund og uisolerede sider samt flydende isoleret låg snart vil muliggøre priser på varmelagre, som vil vise sig interessante i forbindelse med udvikling af store solenergisystemer.

PREFACE

The Danish Ministry of Energy in 1979 sponsored a theoretical study of "Seasonal Storage of Heat in Large Water Basins". 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 [7].

The Danish Ministry of Energy in the "Energy Researchprogramme 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-S-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. Final report on this project was approved by the EEC in 1983 [8].

The experience gained in that project has been utilized to design a full size underground seasonal heat storage. The project is a joint venture between the EEC.DG XII (contract ESA-S-163-DK(G)) and the Danish Government Technical Scientific Research Council. Upon careful screening of the possibilities for realization of the project designed, the District Heating System of the Municipality of Esbjerg producing heat in cogeneration with the local power plant I/S Vestkraft in Esbjerg Harbour was selected to supply the practical parameters for the design of a 50.000 m^3 underground heat storage.

This report constitutes the final report for the work undertaken under the joint venture mentioned.

Parts of this report have been presented to the EEC in previous interim reports [9], [17].

June 30, 1984

for the Thermal Insulation Laboratory

Vagn Ussing
project manager

ABSTRACT

This report deals with the design of a "full size large underground warm water store". The aim of the work has been to use the experience gained in prior work [8] to complete the design of a full size (about 50.000 m^3) underground warm water storage. The design should be based on data obtained from a Danish District Heating System declaring an interest in a serious investigation of the economy to be gained by the construction of the designed storage. Early investigations indicated that large underground warm water stores would be an attractive investment for some of the large Danish District Heating Systems based on cogeneration. Thus a district heating system interested in building a storage pond was selected, even though the immediate need of the system does not include seasonal storage, but only short term storage for improved operational economy of the cogeneration plant.

The capacity required was about 2900 MWh which within the temperature limits of the system could be achieved by storing about 55.000 m^3 of water.

Based on geotechnical investigations a location for the pond was chosen in the vicinity of the power plant. The site selected was filled-in from the North Sea, complicating the construction to some extent.

A general study of the optimal geometry of storage ponds has been executed and based on these results and on the reports from the geotechnical studies on the site the final selection of geometry and levels were undertaken.

Based on the geotechnical studies the construction of the pond was described. The design principle was primarily, that the water tightness should be secured by clay structures of sufficient magnitude while the chemical stability of the storage water should be secured by plastic liners of satisfactory durability. Rather elaborate drainage systems were arranged. No insulation of the pond bottom or the pond walls was called for.

The floating lid on the pond was insulated to an optimal extent. Drainage of the lid surface demanded varying surcharge of gravel with topsoil placed on a liner protecting the insulation from the climatic moisture.

The construction of the lid has been arranged to maintain the elimination of air from the storage water. The thermal expansion of the water mass in the system is provided for through small deflections in the lid structure.

The project has included sketching of the pump and valve arrangements necessary for short term storage operations. The high effect of the system must be taken into account to explain the large pumpstation sketched for the daily operation of the pond. For seasonal storage this will be much smaller.

The final project has been used as a base for a study of the thermal losses to be expected over a longer period of time during a constant average temperature.

The final project has also formed a base for preliminary budget studies showing that large underground storages for warm water produced by uninsulated ponds with floating insulated lids may soon provide storages at prices interesting to future development of large solar energy systems.

Table of contents

1. INTRODUCTION

It has been the purpose of this project to design a full size (30-50.000 m^3) underground heat storage pond with un-insulated bottom and sides and an insulated floating lid. The work is based on parameters supplied by the District Heating System (DHS) most seriously indicating interest in employing the design by constructing the storage pond, assuming that the economic evaluation of the effect of the inclusion of the pond in the DHS proves advantageous.

The project contains the following phases:

- Choice of a DHS and the collection of the design data
- Determination of storage capacity
- Optimization of geometry (annex I)
- Selection of location and levels for the pond
- Geotechnical investigations (annex II)
- Construction procedures for the pond and the floating lid
- Connection of the pond to the DHS
- Operating the heat storage and determining the efficiency (annex III)
- Cost estimates
- Conclusions and recommendations.

2. CHOICE OF PROJECT

2.1. The application of large underground heat storage ponds.

Employment of solar energy for heating of buildings demands large storage facilities and seasonal storage. Only large storages have an efficiency, which will make solar systems economical for space heating. When the price of solar collectors reaches a certain low level, and the price of large seasonal storages reaches a certain low level, solar energy systems for space heating will be competitive with other systems. The perspective of this development has been described in reference [11].

As the industrialization of the supply of heating for buildings progresses, the necessity of the application of storage in the heating systems will become more obvious (see ref. [12]).

As in all storage operations in industry in general short term storages will prove easier profitable than long term storages. Thus short term heat storage has attracted attention. It appears that a major number of District Heating Systems (DHS's) based on cogeneration will benefit to a large extent by applying large underground heat storage ponds in the systems for short term storages. Some systems already apply vertical insulated steel tanks for this purpose.

The applications of large storages in cogeneration systems based on extraction turbines provide either a possible peak load generating reserve or a possibility to eliminate surplus electric power production at peak heat productions during night hours. The operational strategies made possible by large storages are so economical, that even tankstorages will be attractive. Assuming that underground storage ponds will prove considerably cheaper than steel tanks, short term storage in cogeneration links appears to promise rapid application of large underground storage ponds. Such a development may lead to a safer prognosis on the future price development for such ponds and will thus assist in judging, when solar energy will appear as an alternative in large collective heating systems.

2.2. Other storage systems

Only a limited number of underground heat storage ponds have been constructed [13], [14]. Where natural conditions allow the construction of such caverns, these have attracted considerable interest [16]. Only the maintenance of the chemical composition of the storage water may demand arrangements for rock-caverns, which tend to reduce the economic advantages otherwise so apparent.

Considerable resources have been spent on research and development of aquifer storages [15]. Again the maintenance of the chemical composition of the water in the DHS-system necessitates a separation between the storage water and the system water as well as purification arrangements for the storage water. The energy losses due to charge and discharge operations limit the economy of this type of storage to long term (seasonal) storages.

The same seems for almost the same reasons to be the case with the third major storage system: the bore-hole systems. If the system contains embedded pipe loops the only limitation on the system will be the limit placed on the charge- and discharge rate by the pump energy consumption.

It appears likely that underground heat storage ponds will be more attractive for the large collective heating systems, due to the great variety of operational strategies, which may be employed, when these ponds are used.

As a consequence hereof the project was brought to the attention of a number of large Danish District Heating Systems based on cogeneration.

2.3. The selection of a district heating system

The 30,000 - 50,000 m^3 heat storage pond should be designed based on data from a large district heating system, which would express serious interest in an early realization of the project assuming that the cost estimates proved the designed system to be advangageous in comparison with other designs.

Among the competing systems insulated new steel tanks are already in operation and serious studies have been done to renovate and insulate redundant large fuel oil tanks.

Special attention was given to systems, where part of the storage would be needed for seasonal storage. No project promising an early realization was available in sufficient size based on solar energy entirely. Most of the systems investigated had or expected to get a need for seasonal storage of heat gained from burning refuse.

Through correspondance and meetings with six of the largest district heating systems, it was established that the district heating system in the municipality of Esbjerg, located on the west coast of Jutland (figure 1), was the system most likely to establish a heat storage pond in the range between 30,000 and 50,000 m^3, immediately a competitive design was produced based on the data supplied by the system.

The district heating system in Esbjerg is part of the service rendered by "Forsyningsvirksomhederne", which is a municipal company supplying the municipality and some neighbouring ones with electricity, heat, water, bus service, radio/tv signals and street-lighting. The company served 37,000 customers in 1982 besides 160 large consumers of electricity [1]. The turnover in 1982 amounted to 42 mill. ecu. The heating sold amounted to 670.110 Gcal for 1982. "Forsyningsvirksomhederne" buys all the electricity (343 GWh) and 96,5% of the heat from "I/S Vestkraft", which holds a concession on production of electricity in the western part of Jutland. A diagram of the power station "I/S Vestkraft" is shown in figure 2.

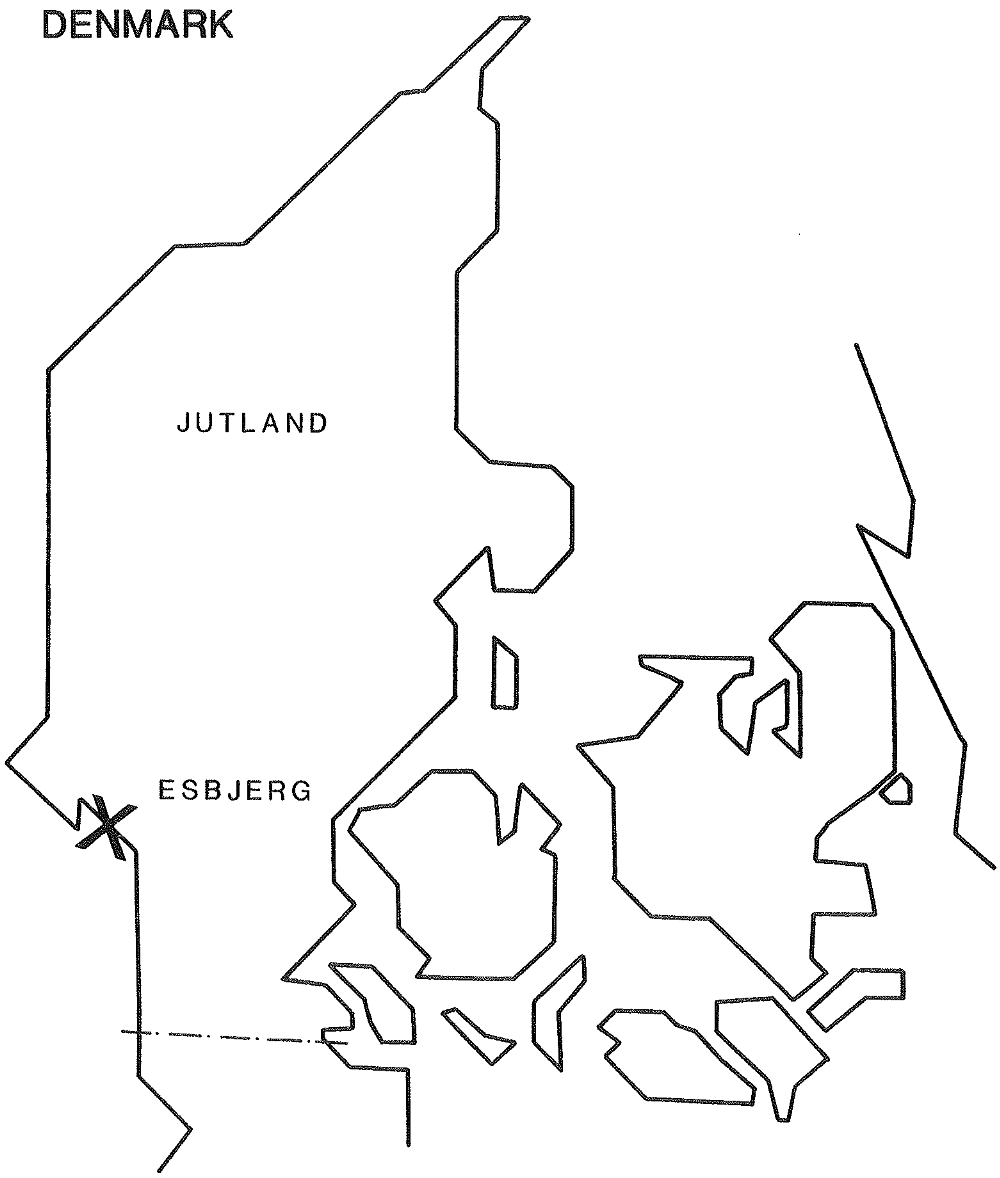
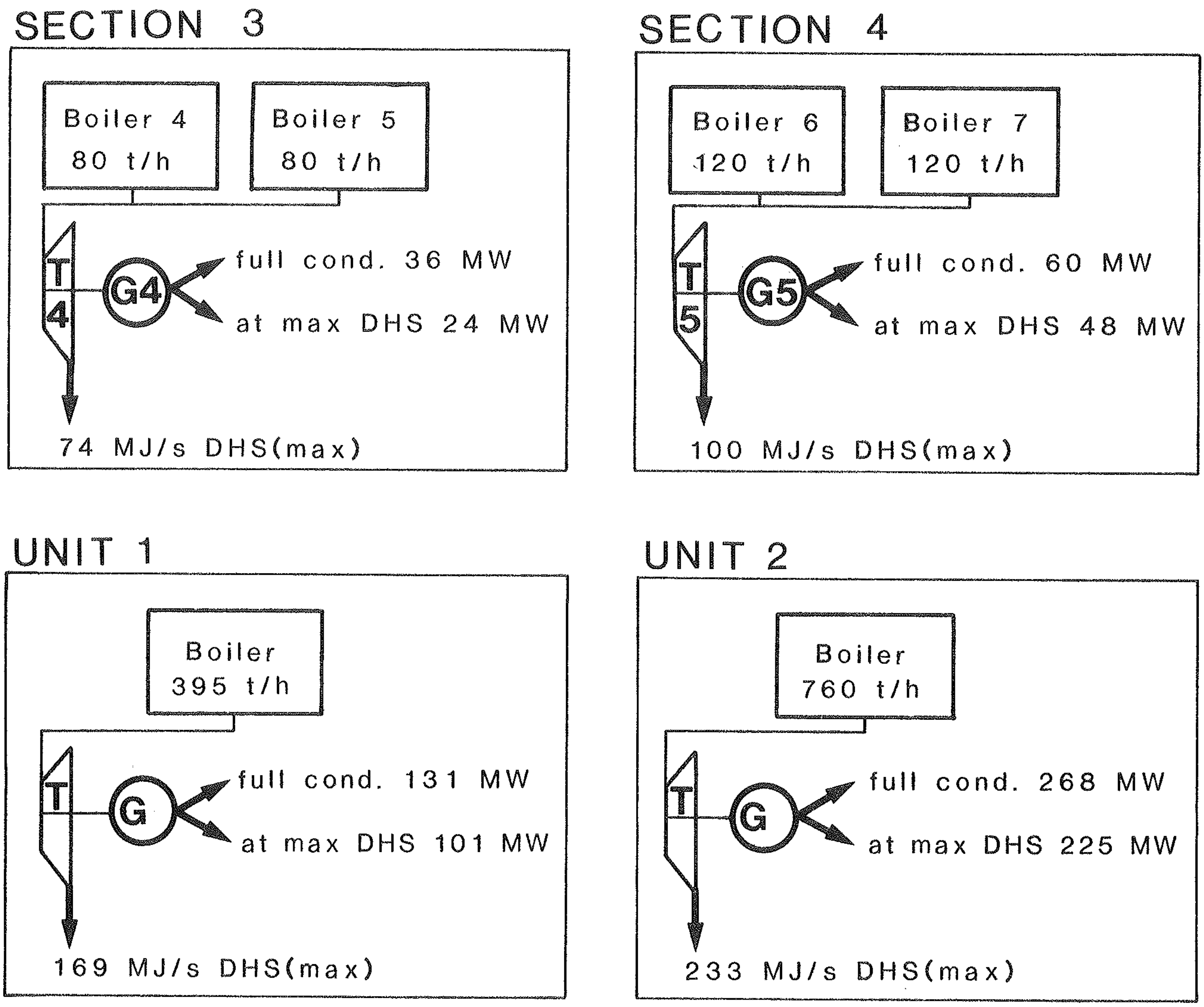


Figure 1. Esbjerg is located on the west coast of Jutland.

The municipal company as well as the power company have expressed interest in the project and the realization hereof, if the design proves competitive.

The power company has completed investigations concerning establishment of a heat storage tank in the Esbjerg system.



Note:

Rated max. electric capacity	:	495 MW
Rated max. heating capacity	:	576 MJ/s
Rated max. electric capacity at max. heating load	:	398 MW

T Turbine

G Generator

DHS District Heating System

Figure 2. POWERSTATION "I/S VESTKRAFT".

The power company owns and operates the district heating system plant in Herning based on a back pressure turbine and including a 40,000 m^3 steel tank storage.

2.4. The design data from the Esbjerg District Heating System

The most recent prognosis for the peak heating load in the Esbjerg District Heating System for 1999 (adding power station load to local peak back-up loads) shows a load of 489 MW (see figure 3). The winter load distribution over a 24 hour period has been taken from the most recent proposal for an operation model for the entire Jutland area [2]. The distribution is shown in figure 4. In order to separate the power station from the heat demand for 6 hours a storage capacity must be available. Cutting off the 3 two-hour periods from 6 o'clock to 12 o'clock demands a storage capacity of 25.42% of the 24 hour load. The 24-hour demand may be estimated as 489 MW x 24h x 1/1.045 = 11,230.62 MWh. Thus the required capacity will be 25.42% of 11,230.62 or 2854.82 MWh. For the cut-off period from 16 to 22 a storage of 25.87% of the 24-hour load will be needed, or 2905.36 MWh.

The Esbjerg District Heating System operates under a temperature variation strategy for the water in the heat transmission system as shown in figure 5.

The main part of the year a constant forward temperature is maintained by varying the flow in the system. When maximum flow rate is obtained (-2 °C ambient) the forward temperature is raised about 2,5 °C per 1 °C further fall in the ambient temperature.

The planning for 1999 is based on a temperature variation of 105/51 °C. This variation in temperature will for the heat transmission system between the power station and the underground heat storage pond be limited to 95/48 °C. From figure 5 it may be seen that 95 °C corresponds to -10.5 °C ambient. At this outside temperature the temperature variation in the transmission system is assumed to be 95/48 °C. Figure 6 shows the heat load in the system in relation to the ambient temperature. The maximum load is

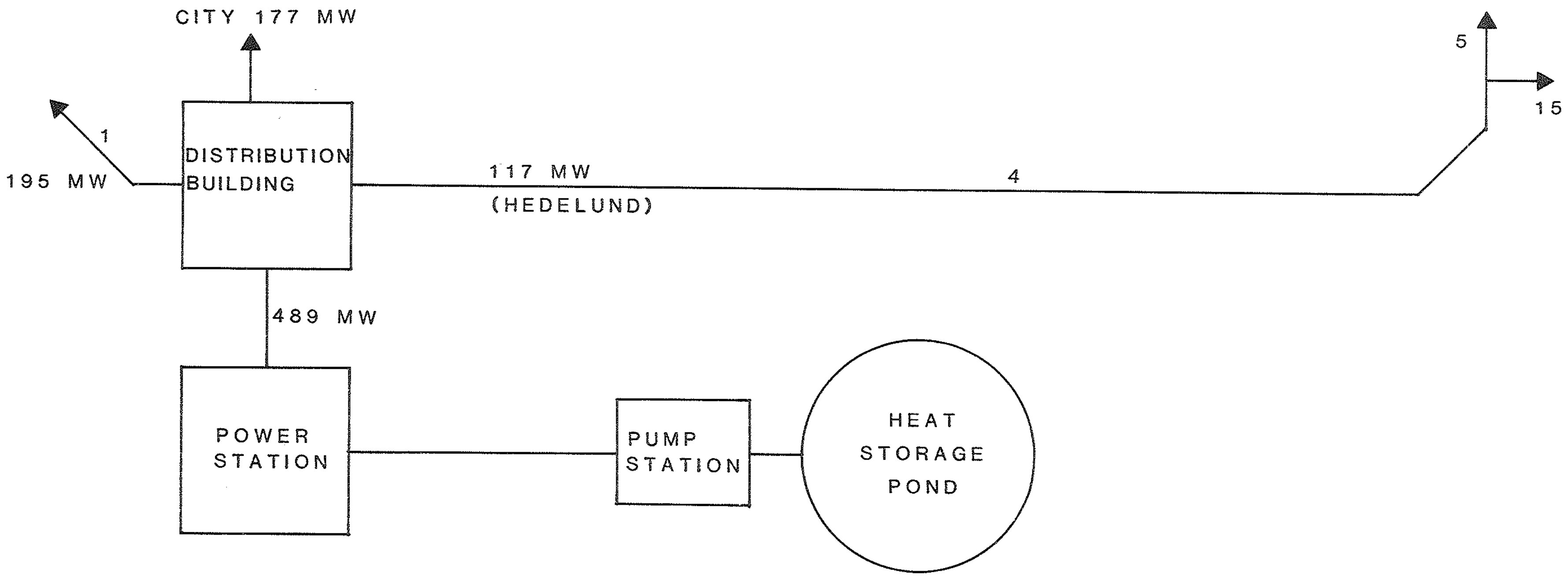


Figure 3. A part of the principal diagram for the Esbjerg District Heating System with the connection of the Heat Storage Pond. Figures for 1999.

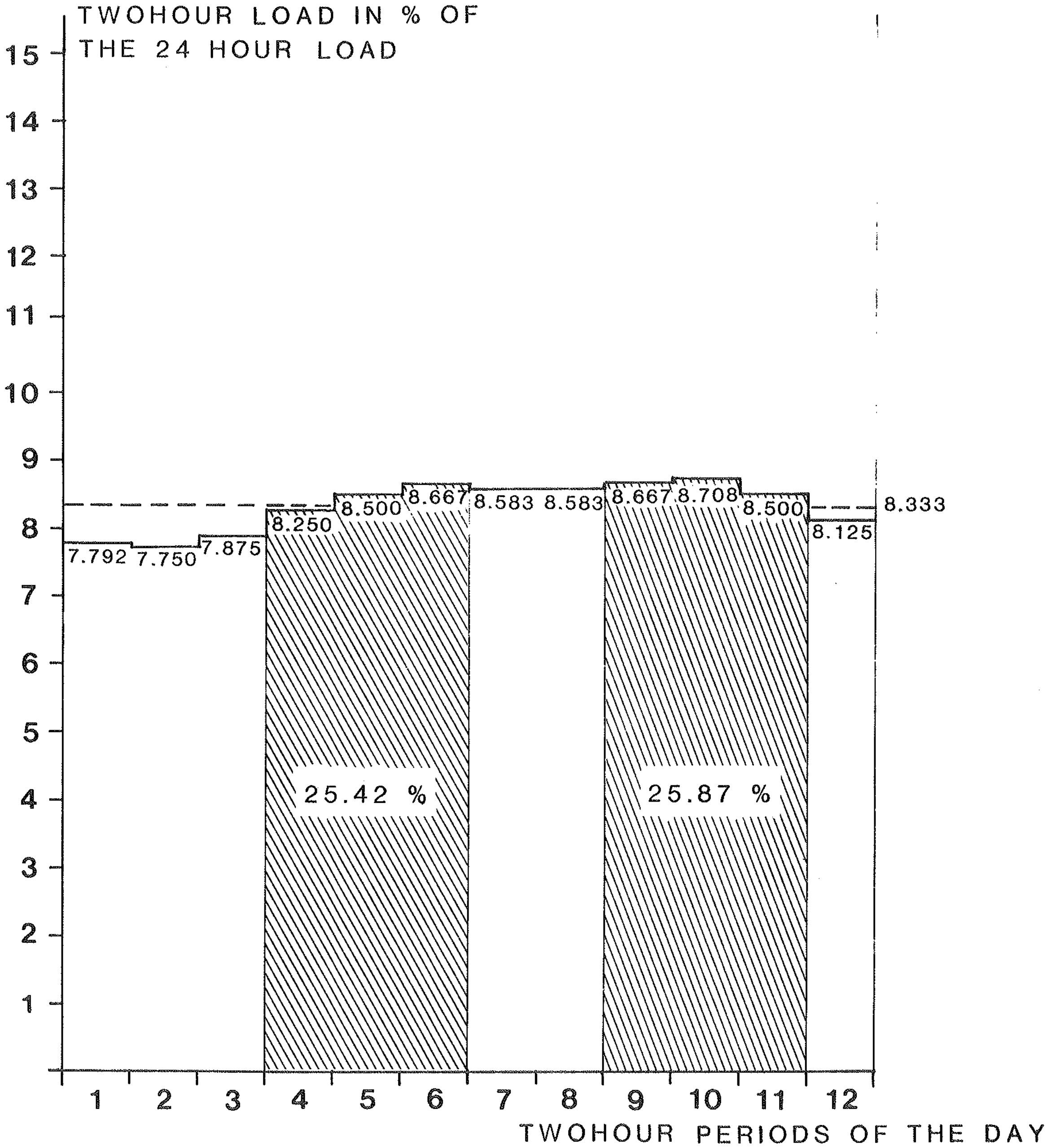


Figure 4. The heating load for a 24 hour winterday (mean value for two wintermonths). The maximum twohour load exceeds 24 hour load by 4.5%. Cutting off the 3 twohour periods from 6 o'clock to 12 o'clock demands a storage capacity of 25.42% of the 24 hour load.

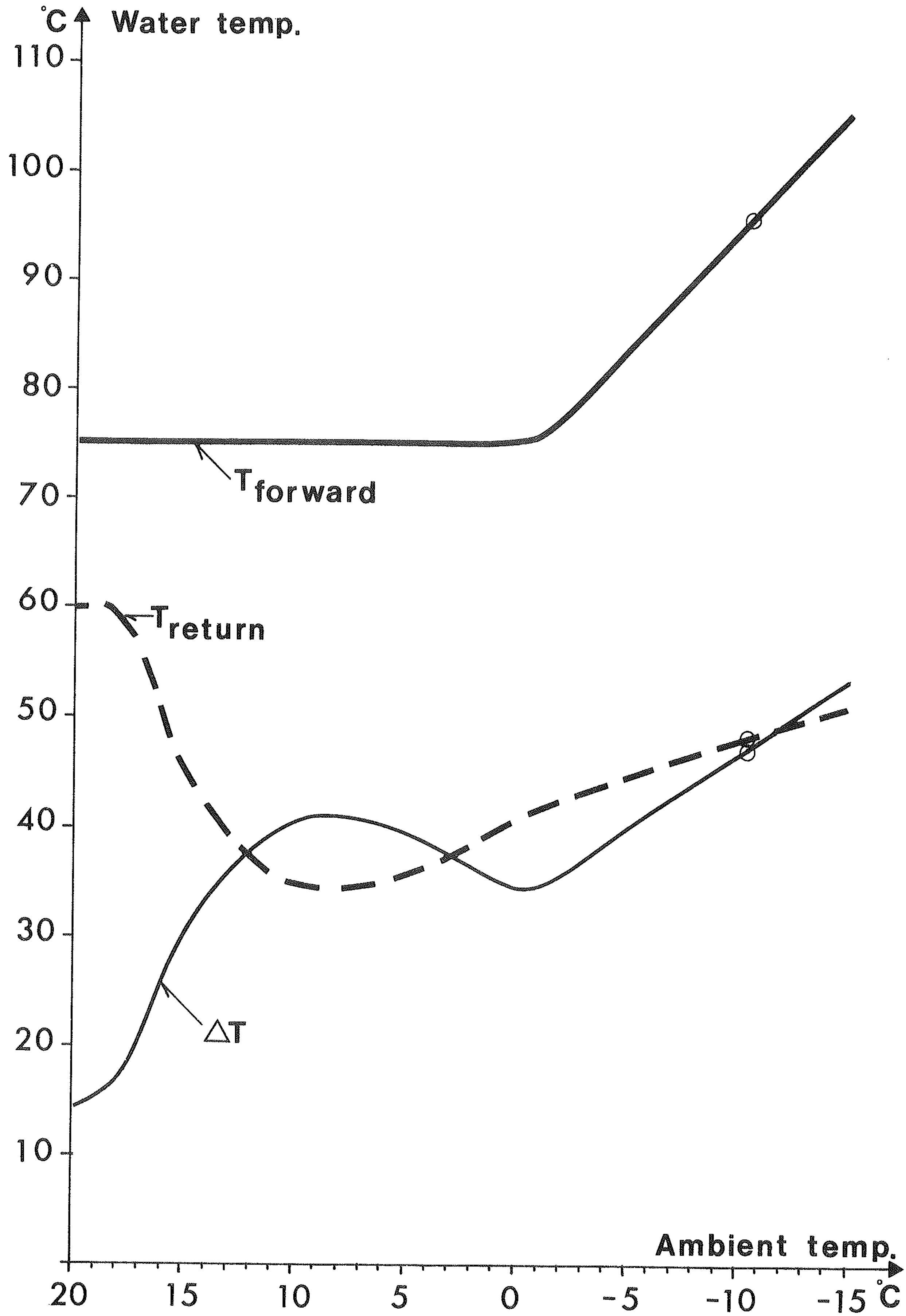


Figure 5 ΔT, forward and return water temperatures as a function of ambient temperature for the Esbjerg District Heating System. The dimensioning temperature variation is

a) 105/51 °C without storage pond.

b) 95/48 °C with storage pond and increasing circulating water volume.

Figure taken from reference[4].

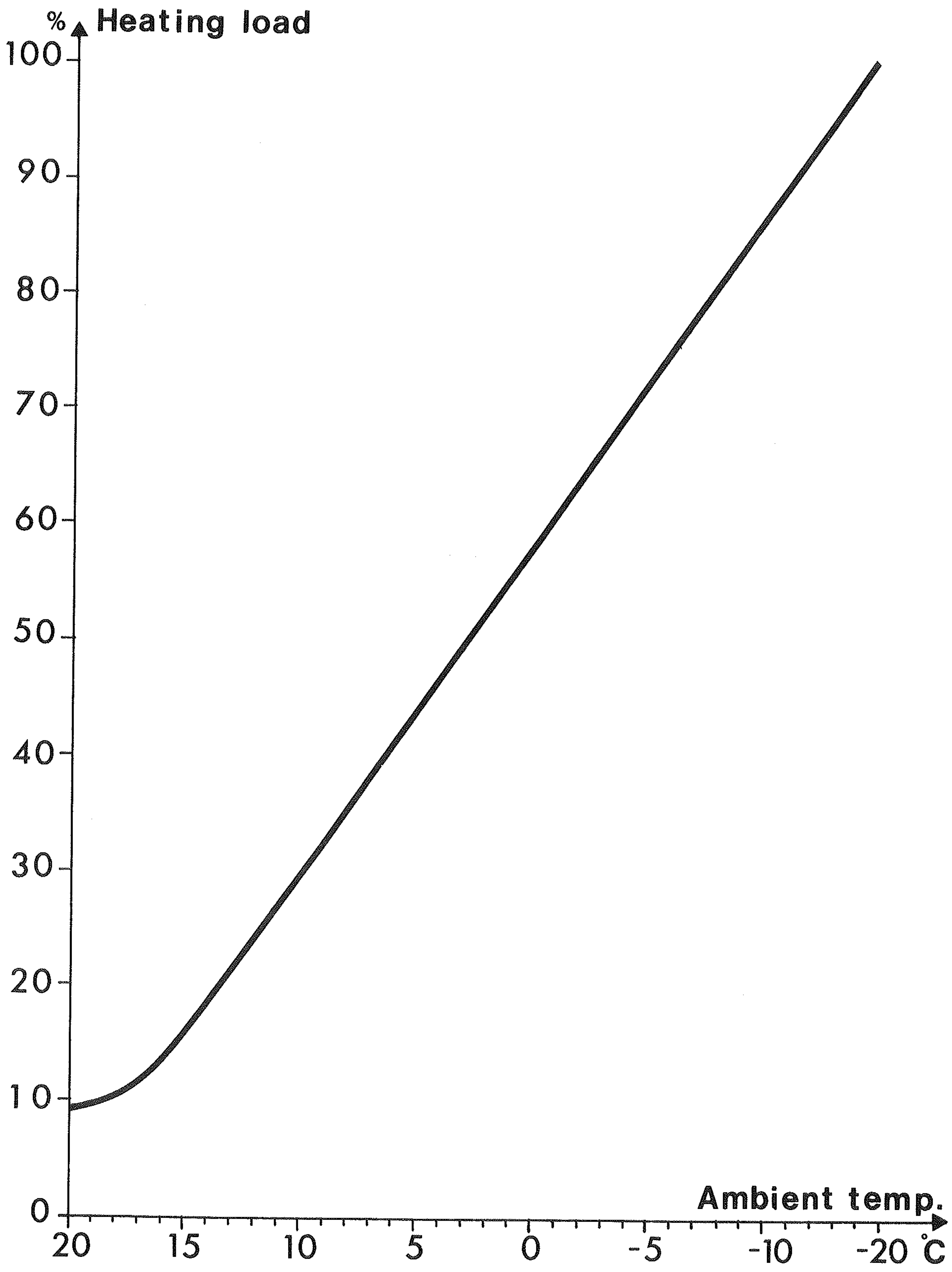


Figure 6 Heating load as a function of ambient temperature for Esbjerg District Heating System.
Figure from reference [4].

based on an ambient temperature of -15°C. An ambient temperature of -10.5°C corresponds to 87% of the capacity being needed. The load duration curve (see figure 7) indicates that loads above 87% will only occur during 75 hours corresponding to less than 2% of the yearly production. Peak load hours may be taken care of without raising the top temperature above 95°C by an increase in the circulating water volume (15%).

3. DESIGN

3.1. Determination of the storage capacity

The inclusion of a large heat storage pond in a district heating system based on cogeneration increases the number of variables in the already complicated optimization of the operation strategy for the system.

By far the most important economic advantage of operating a large heat storage pond is derived from making 6 hour cut offs in the direct heat supply possible, thus making full electric output of the power plant possible for 6 hours.

Consequently a storage capacity of 2905 MWh (as mentioned above for a 6 hour cut off from 16 to 22 on the maximum winter day) will be the design criteria.

The heat content of 1 m^3 of a pond varying in temperature between 48°C and 95°C may be estimated as follows:

$$\Delta Q = \rho_{72} \cdot c_{p,72} \cdot \Delta t \cdot k = 53.44 \text{ kWh/m}^3$$

where ρ_{72} = 976.6 kg/m^3

$c_{p,72}$ = 4,1912 kJ/kg·K

Δt = 95 - 48 = 47°C

k = $277.8 \cdot 10^{-6}$ kWh/KJ (conversion factor)

Thus the volume of the pond necessary to provide a storage capacity of 2905 MWh may be determined as:

2905000/53.44 = 54.360 m^3

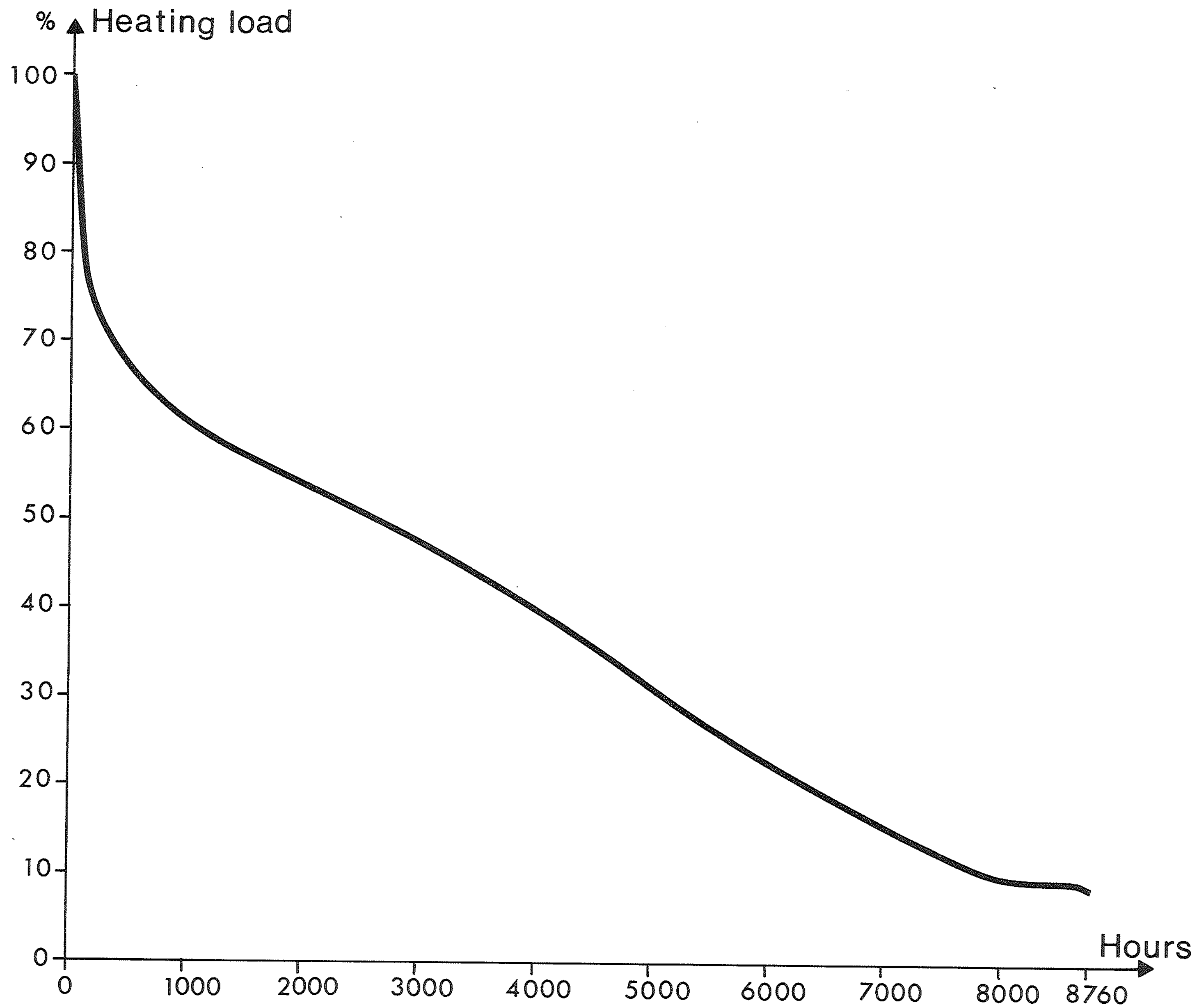


Figure 7 Load duration curve for heating load for the Esbjerg District Heating System. Figure taken from reference [4].

3.2. Selection of geometry for the pond

As a major contribution to reduction of the construction cost for large heat storage ponds, early studies [5], [6], [7] have shown, that ponds with uninsulated bottom and sides and a well insulated swimming lid may have a reasonable efficiency for seasonal as well as short time storage.

Thus the important feature of a pond design will be the area of bottom and sides compared to the volume of the pond.

In annex I the relation between the area of the soil interface and the volume of ponds of different geometries have been studied. The ratio between the soil interface of the pond and the volume of the pond (the surface coefficient) has been developed for different geometries and plotted against the volume of the pond. The study shows the surface coefficient (ω) for 4 different slopes of the sides (a = 0.5, 1.5, 2.0 and 2.5) and 4 different depths of the pond. The study is done for semisphere, segment of a sphere, cylinder, frustum of a cone and frustum of a pyramid.

The characteristic parameter R (see sketches) for the different geometries has been developed and plotted as function of the volume for different slopes.

In a supplement the module M defined as the volume over the area of the soil interface ($M = \frac{1}{\omega}$) is maximized. A slope of 0.5059 will make a minimum surface coefficient ($\omega = \frac{1}{M}$) for a truncated cone possible. This optimal slope will not be feasible from a structural point of view.

For an underground large heat storage of optimal economy the dirt dug out and the dirt build into the walls of the pond must be in balance. The depth of the pond from the original soil surface (Z) has been calculated and plotted against the volume for a truncated cone of varying depth and with varying slopes.

It appears from the geometric studies that no important increase in the surface coefficient (ω) can be obtained for depth (h) greater than $0.3 \cdot R$. Thus the geometry of the pond may be determined from the curves in annex I, as soon as the potential slope of the sides of the pond has been chosen on the basis of the geotechnical investigations on the actual building site. Figure 10 shows the final dimensions of the "Esbjerg" pond. The water content of the pond is 54.500 m^3.

3.3. Selection of location for the pond

Previous studies done by "IS Vestkraft" in Esbjerg of large tank storages obviously assumed that the storage should be placed immediately on the site of the power-station.

The site needed for an underground heat storage will be around 1 ha, which will not be availabele directly at the site of the power-station.

A part of the principal diagram of the water transmission system in the Esbjerg system may be seen in figure 3 showing the estimated capacity requirements for the year 1999.

Two locations appeared possible. The pond might be located on transmission line 4 using that newly erected double line to connect the pond with the power-station, if a geotechnically suitable location could be found. The alternative would be to pick the location nearest to the power-station offering suitable geotechnical conditions and connect the pond to the power-station via a new transmission link.

The first alternative appeared tempting as line 4 traversed an area previously used as supply for local brick works thus leaving a series of water filled clay pits. A former clay pit 2500 m from the power station was investigated (see annex II, geotechnical report 2b). The conclusion of the investigation was, that the extensive sand deposits found on the location would necessitate extensive rebuilding of the pond walls and bottom with clay from other locations and the groundwater movements would reduce the efficiency of the storage.

Besides this, the charge and discharge capacity of the storage would have to be limited to the transmission capacity of line 4. Assuming a flow two times the design flow of the transmission line 4 the max. effect of shut-off for the power plant will be only about 40% of the peak winter effect expected in 1999. Besides that the operating cost of using line 4 at a double flow rate was considered unacceptable.

Thus the search for a location as close to the power plant as possible commenced. The power station had deposited fly ash in the sea areas adjacent to the station. The industrial sites developed by the power station had been placed under the government harbour administration. An inquiry to the harbour administration resulted in an acceptance on placing the underground heat storage on the industrial site immediately east of the power station. See figure 8.

The site is traversed by 2 high-tension (150 kV) power lines and both lines have one pylon in the site, see figure 9. It has been assumed that the newly rearrangement of the location of the pylons for the 2 power lines leads to a decision that the storage pond must be located a little more than 20 m east of the pylon (No. 3) on the industrial site close to the power station. The transmission line between the power station and the pond may be shortened about 100 m if the location of the towers for the 2 power lines can be rearranged once more.

3.4. Determination of the levels of the design

As noted in annex I the levels of a pond design may be chosen with regard to a dirt balance being obtained during construction of the pond. For a pond of about 54.500 m^3 the bottom of the pond should be placed at a level of about 9.2 m below the surface of the site (+4.0) or at level -5.2 m.

For the location selected for the pond the levels can not be determined solely from the intention of obtaining dirt balance during construction. The determining factor in this case will be the level limitations placed by the 150 kV lines overhead on the height of buildings on the site, see figure 10. As an access building is required at the center of the floating lid and a sloping lid must be foreseen, the level of the pond bottom must be chosen as -9.2 m sloping 1:30 towards a center pump well in stead of -5.2 m, which would be required if only dirt balance was to be considered.

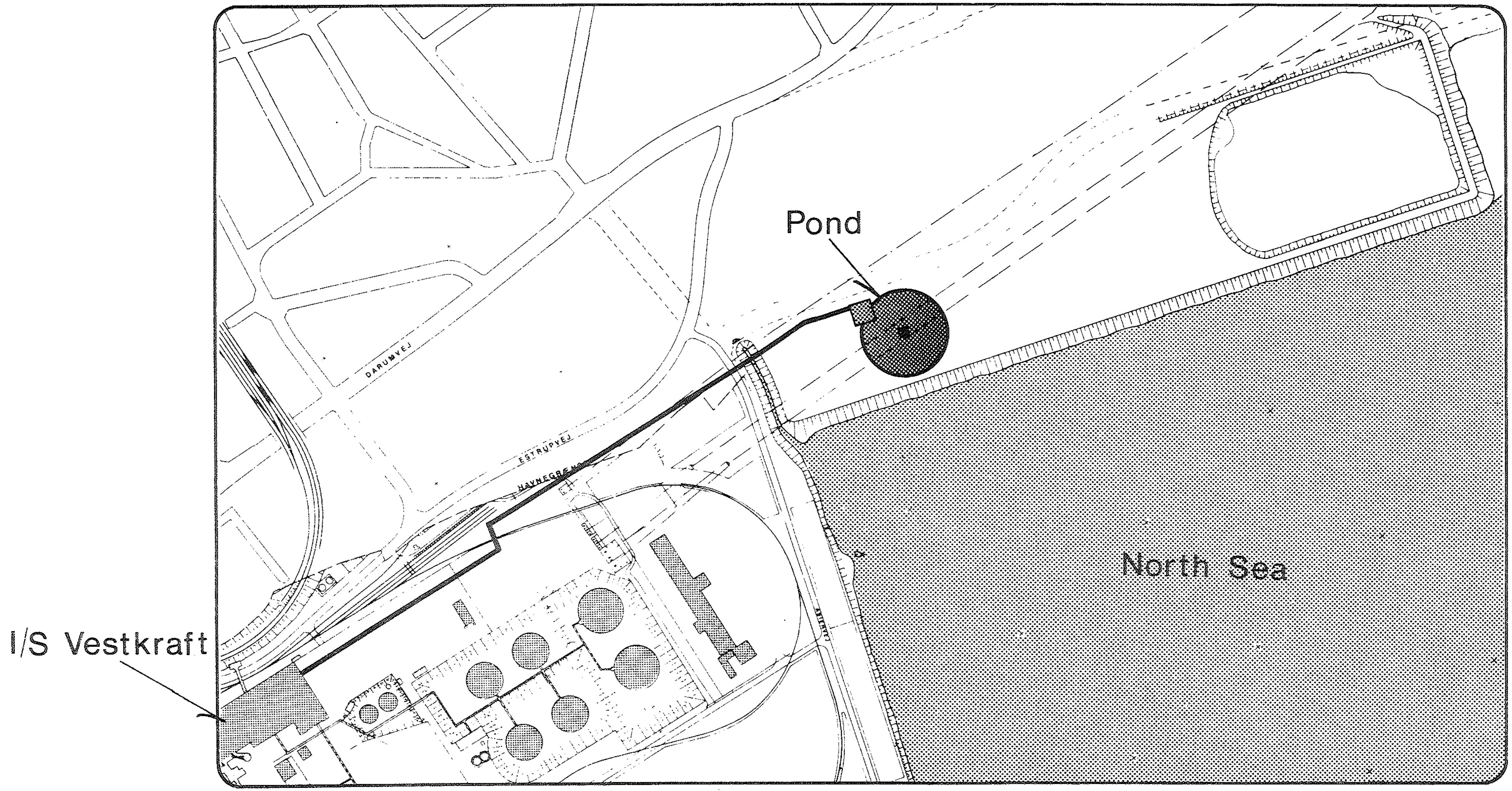


Figure 8. Final location of the pond.

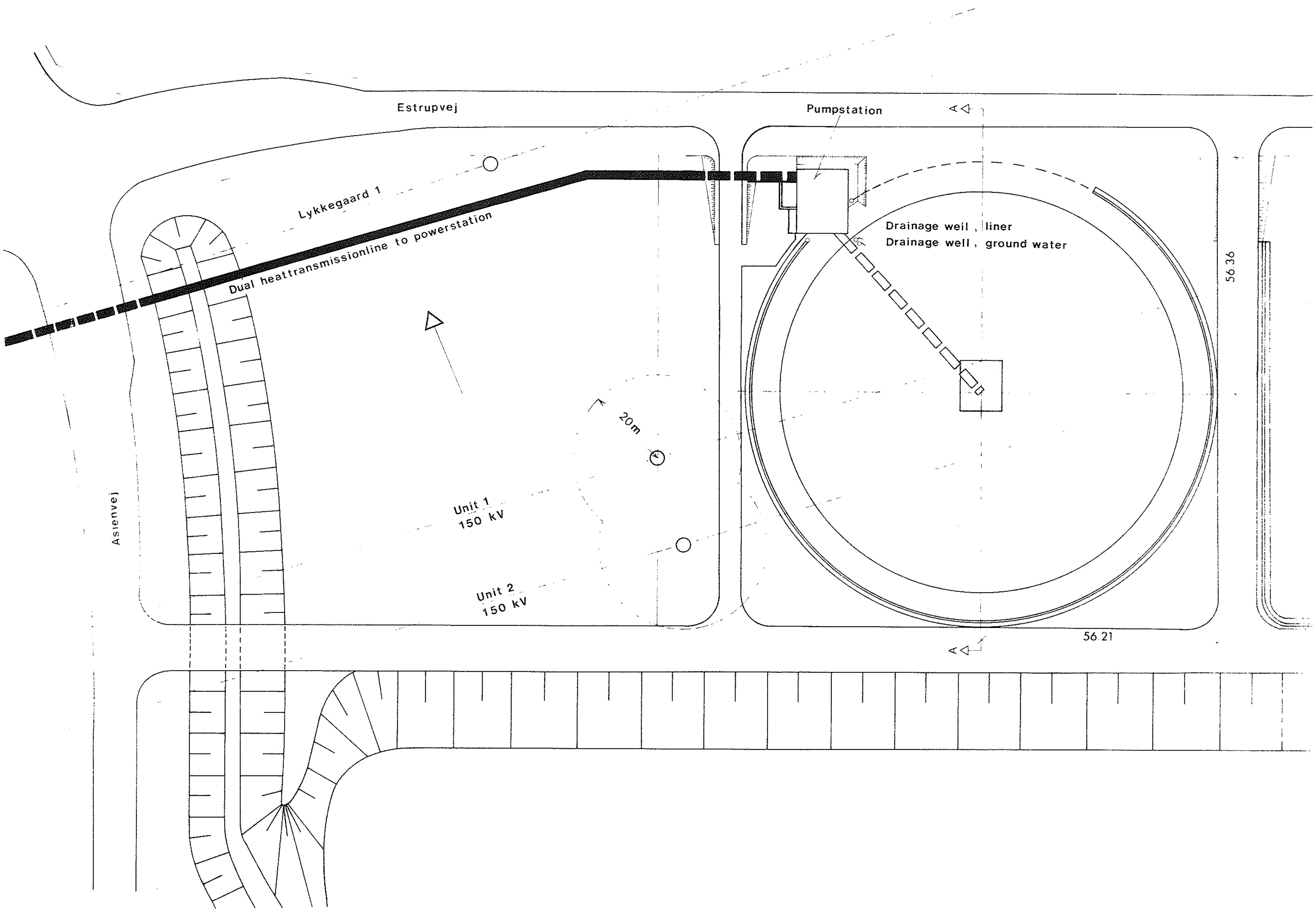


Figure 9. Esbjerg heat storage pond. Plan view.

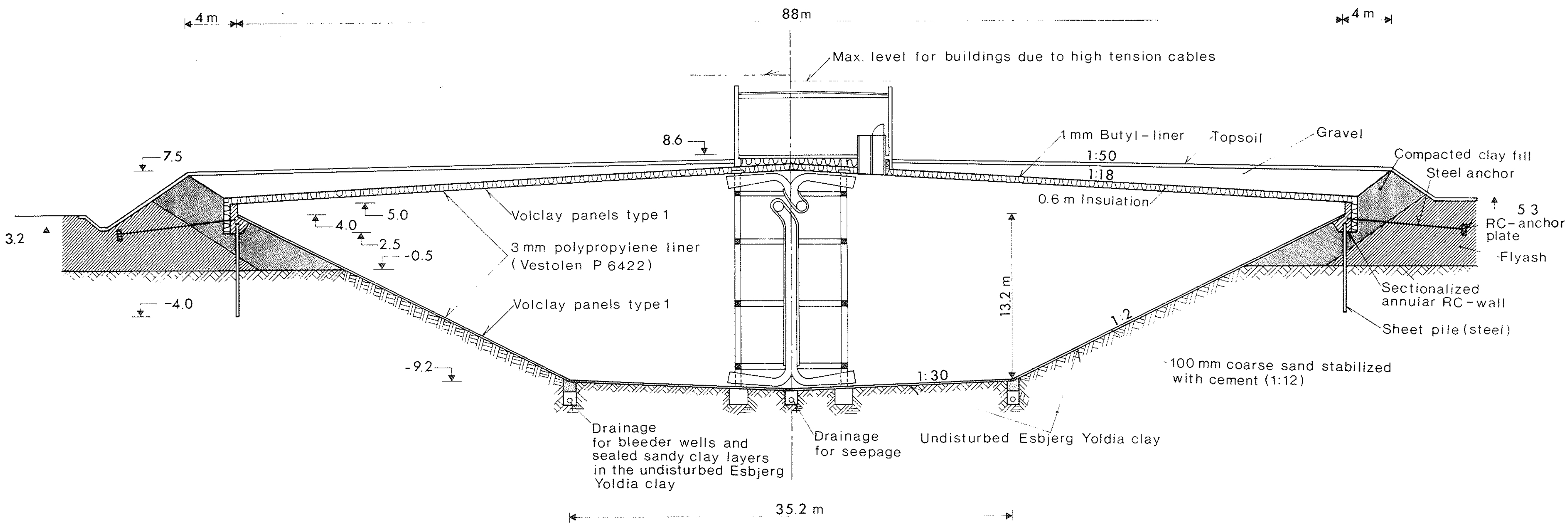


Figure 10. Esbjerg heat storage pond. Sectional view.

It will appear from the geotechnical investigations (see annex II, geotechnical report 2b) that the pond anyhow would have to be placed at the level dictated by the overhead 150 kV lines in order to get a sufficient quantity of acceptable clay for use in constructing the upper part of the pond walls, as suitable clay will only be found below the level -0.5 m. Above this level sand, fly ash and gravel will be found. Part of that dirt can be discarded at the present dump for fly ash in the vicinity. The deeper the pond is placed on this location the better will be the quality of the clay.

3.5. The geotechnical investigations

The Danish Geotechnical Institute (DGI) has been engaged as a sub-contractor handling all the geotechnical problems involved in the relation to the location and to the design on the location selected.

In annex II a resumé of the work of DGI is presented. From the resumé it appears, that particularly the following conclusions may be drawn:

1) The water tightness of the pond is based solely on the impermeability of the clay in the bottom and in the walls. The tightness of the plastic liner is disregarded.

2) If a water loss less than 43,800 m^3/year is required all sandy parts of the walls between level -4 and -6.5 m must be "plugged" by clay. Each "plug" must be drained to the "bleeder well" system to secure stability of the wall while the pond is empty.

3) The permeability of the soil must be so low ($k_{10} < 10^{-10}$ m/sec) that the ground water flow does not noticeably influence the heat flow around the pond during normal operations.

4) The stability of the empty pond is assumed possible by operating drain pumps connected to the 16 "bleeder wells". Test pumping must check this assumption before construction is started.

5) Detailed rules of construction and operation of the pond particularly needed due to the swimming lid, may be brought to include rules balancing the dirt pressure on the concrete ring wall against the water pressure from the pond content thereby reducing the required anchoring of the ring wall supported by the sheet piles. (Figure 11).

4. CONSTRUCTION

4.1. Construction of the heat storage pond

With a slope on the sides of 1.5, a truncated cone with a top diameter of 100 m is dug to level +1.0 m.

From this level a circle of 16 "bleeder wells" are dug to level -20.0 m. The diameter of this circle is 35.2 m. From the level +1.0 m a sheet piling wall with a diameter of 88 m is placed to level -4.0 m. The profile applied should be able to resist a maximum moment of 55 kNm/m. Every second sheet pile may be cut at +1.0 m and every other sheet pile at +3.8 m.

Upon completion of the sheet piling excavation of the original truncated cone to -0.5 m can proceed. All materials excavated so far are disposed of at the present fly ash dump further to the east.

Excavation from level -0.5 m may now proceed with a slope of 2.0. In case water carrying strata in the clay are discovered suction drains must be applied. The sandy seams in the clay are plugged by excavating 0.6 m in the pond wall or bottom at first. Behind the "plugs" drains connected to the "bleeder well" drain system are installed and the plug is constructed of 2 layers of 0.3 m each of unsaturated Yoldia clay compacted to >100% SP. As soon as a final clay surface has been reached, the surface is protected against saturation by 0.1 m cement stabilized sand (1:12). The pump must evacuate rain and seepage from wells.

From level -0.5 m to level +7.5 m the clay excavated in the bottom of the pond is built in and compacted to >100% SP forming a 3 m thick pond wall.

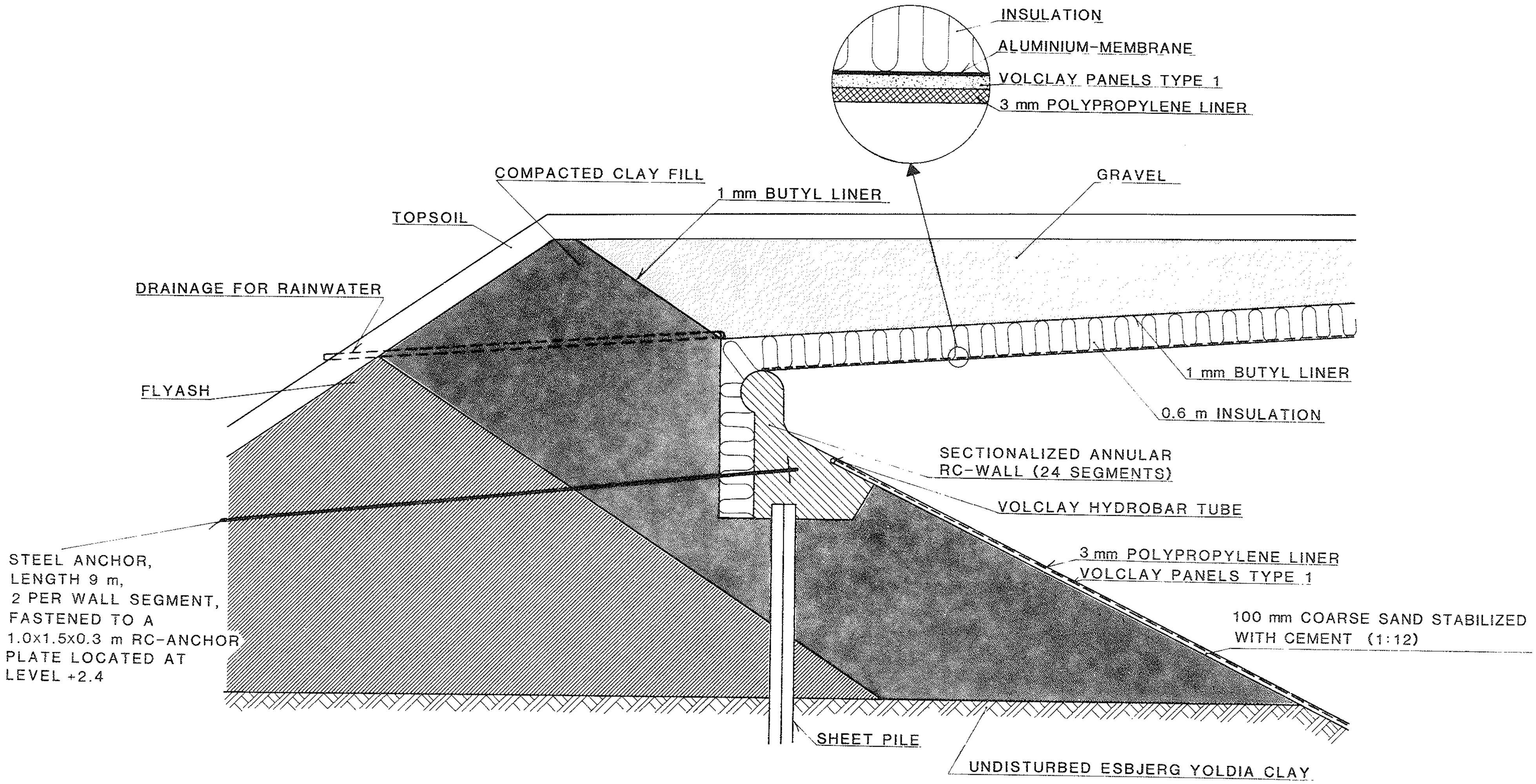


Figure 11. Joint between lid and wall.

At the level +2.5 m a reinforced concrete ring wall is cast. The joints between each segment are tightened by plastic strips (Dura joints). The steel anchors (48 anchors each capable of carrying 156 kN) and 1.0 x 1.5 x 0.3 m anchor plates are installed when the building of the pond wall reaches the appropriate level.

In the bottom of the pond foundations for 4 columns carrying the charge and discharge arrangements as well as the access building are cast. While the ring wall components are being cast, the columns and beams of the centre structure together with foundation beams for the access building are being cast. At the level of the liner placed in the bottom of the lid, a reinforced concrete ring is cast, in which the steel wires supporting the liner and the lid insulation can be anchored. At the level where the columns intersect the level of the bottom liner of the lid, liner sheets are cast into the columns.

The walls and the bottom are lined with 3 mm polypropylen installed by the manufacturer on Volclay panels. The wall and the lid liner are welded to a sheet of plastic cast into the ring wall. The steel wires in the lid are anchored in the ring wall.

Upon a rotating collapsible scaffold, the bottom liner of the lid (polypropylen 3 mm) is welded from precut parts. The liner, the Volclay panels and the insulation (10 cm mineral wool and 50 cm polystyren topped by 1 mm butyl liner) are supported by steel wires anchored in the concrete ring wall and in the ring beam on top of the columns of the centre structure. The tightness of the top liner is checked by applying air pressure to the pond volume lined with plastic before the pond is waterfilled.

As soon as the liner has been approved and all scaffolding has been dismounted and the pond surfaces have been cleaned, the filling with district heating water takes place.

When the water reaches a level equal to the top level of the ring wall, gravel is placed on the lid insulation at a rate exactly balancing the water pressure arising as the level rises over +5.0 m. The gravel load on the swimming lid is topped off by topsoil which can be seeded with grass.

Corresponding to the placement of gravel on the swimming lid, the clay walls around the pond are completed to a level corresponding to the top of the pond perimeter (+7.5 m).

Adjacent to "Estrupvej" a 2 storey pumpstation is constructed. Adjacent to the pump station drain pump wells are installed. One drain system secures that the 16 "bleeder wells" and the "plug-drains" can secure the stability of the pond, if it is not filled with water.

The other drain system secures that any seepage through the clay can be registered and controlled. The cement stabilized sand layer under the pond liner on walls and bottom will serve as the drain for this seepage and will at the same time make recording of leaks in the liner possible. The pipes for these drain systems must be installed by hydraulic methods in order to prevent disturbance in the clay layers securing the tightness of the pond.

4.2 The water tightness of the heat storage pond

The construction of artificial lakes or water reservoirs has been known for many years. A majority of these structures has the water tightness based on clay, due to the low permeability and the easy availability of this material.

According to the DGI-report (annex II) the "Yoldia" clay found on the site from level -8.5m to the bottom has a coefficient of permeability of $k_{10} \sim 10^{-10}$m/sec. The rest of the clay below level -0.5m has a coefficient of permeability of $k_{10} \sim 1 - 10 \times 10^{-9}$m/sec.

Assuming that the plugging of the earlier mentioned sandy seams in the bottom and the walls takes place as described, it can be assumed, that the loss of water from the pond can be limited to less than 1000 m^3 per year. The yearly loss of water in the district heating system at present exceeds 200,000 m^3 per year. [1]

The clay walls of the pond are carried to the level +7.5 m in order to secure that leaks in the floating lid may be contained. The gravel load on the floating lid is drained through the clay walls of the pond to ditches providing drainage for the surface run-off from the top of the lid during winter seasons.

4.3 Maintenance of the quality of the pond water

The heat storage pond is operated as a direct link in the district heating system. Thus the water stored in the pond is the water circulated in the heating system. In the present Esbjerg-system great care is shown in order to maintain the quality of water circulating in the district heating system at a level minimizing corrosion.

As a consequence the entire soil interface must be protected by a liner capable of preventing a change in the chemical composition of the storage medium.

In the previous work ("Seasonal Heat Storage in Underground Warm Water Stores, Construction and testing of a 500 m^3 store (ESA-S-162-DK(G)) [8] experience with plastic liner has been gained. The 500m^3 storage has been operated between 30-80^{o}C for almost two years without any mishaps on the part of the high density polyethylene liner (2.5mm thick). (See also [10]).

In the present project the temperature range is raised to 48-95^{o}C. This factor has led the manufacturer of the plastic liner to recommend a change from high density polyethylene to a special polypropylene liner (Vestolen P6422 or similar). The change will make certain that the durability of the liner inside the temperature range of operations (48-95^{o}C) will be satisfactory (5 year-guarantee and 15-20 years estimated life time).

In order to eliminate the risk of failure of the tightness of the polypropylene liner a layer of "Volclay" panels are placed immediately under the liner (in the lid immediately above the liner). A crack in the plastic liner will thus automatically be tightened up by the swelling of the "Volclay" [14].

Small cracks in the plastic liner are not assumed to interfere with the quality of the pond water.

4.4 The floating lid of the heat storage pond

The considerations taken into account during the design of the floating lid are:

a) The drainage of the lid surface

b) The thermal expansion of the water volume of the entire DHS

c) The optimal insulation of the lid surface and the top edge of the pond wall

d) The water tightness and the moisture transmission of the lid

e) The ozygen penetration into the lid

f) The construction problems

The basic requirement of the design of the floating lid was to secure, that no air could come into contact with the system water during operation of the storage. A second requirement was that the top surface of the lid should secure natural run off for melting snow during periods where the topsoil is frozen.

These requirements led to the following design details. The bottom liner of the lid must be fastened to the liner protecting the pond wall thus forming a closed storage system. The lid liner and the insulation with dirt cover must be flexible to allow the volumetric expansion of the system water during temperature variations (48 - 95°C). The lid liner is fixed in an inflexible way at the center of the lid due to the access building and the diffusors there. The lid liner between the center access structure and the top edge of the pond wall (39,0 m) must be able to bulge about 0.45m, when the storage temperature is raised from 48°C to 95°C. The volume expansions during the initial filling and heating of the storage is taken care of through the water production facility at the power plant. The thermal expansion of the liner secures, that the stresses induced in the liner by the "bulging", does not reach the non-elastic region for the plastic employed.

To secure a slope of 1:50 on the top surface of the lid a slope of 1:18 on the bottom liner of the lid has been chosen. The 2.5m water pressure at the edge of the lid thus provided, is counterbalanced by an extra amount of gravel on the insulation. The surcharge of gravel and top soil on the lid thus varies from 1.9m at the edge of the lid to 0.5m at the access building.

The optimal insulation of the floating lid was based on the assumption that polystyren should only be applied at points where the operational temperatures were limited to 80^{o}C. Points with temperatures above that level should be insulated with mineral wool slabs. The insulation price was estimated at 400kr/m^3, the heat loss was estimated to cost 250kr/MWh and the interest rate was set at 7%. The optimal thickness of the insulation thereby came out to be slightly less than 60cm and selecting 60cm the thickness of the mineral wool must be taken as 10cm to secure that the polystyren does not exceed 80^{o}C during storage operations.

Turning now to the water tightness and the vapour transmission, it should first be recalled, that the overall security for containing the storage water is provided by the clay walls being built to the level corresponding with the top water level of the pond. Thus the plastic liner again primarily provides chemical separation between the system water and the structural materials in the lid. Any minor leak in the liner will not endanger the chemical composition of the storage water.

The operation of the 500m^3 test facility at the Technical University of Denmark [8] has indicated, that the moisture content in the insulation of the floating lid can be kept sufficiently low, if the moisture protection of the insulation towards the outside climatic moisture is undertaken with a liner having a resistance against diffusion considerably smaller than the resistance of diffusion of the bottom liner of the lid. Experience has shown, that 2.5mm high density polyethylene has a resistance sufficiently above a liner made of 1mm of butyl, which has been applied for protection of the insulation from climatic moisture.

The protection of the water of the storage from oxygen pollution is important in order to prevent corrosion in the DHS. Oxygen appears to be able to penetrate the different liners used in the construction of the pond. The clay walls must, however, be judged as giving a sufficient protection against oxygen penetration through the sides of the pond. As the water volume is exchanged several times a year only the possible penetration of oxygen through the lid must be given attention. To safeguard against possible penetration by oxygen through the top soil and gravel on the insulation of the lid an aluminium membrane laminated on the topside of the Volclay panels, which are placed directly on the bottom liner of the lid, must be provided.

The construction of the large floating lid poses some problems. The floating lid is fastened to the edge beam on the pond wall and to the access building constructed on a center tower in the pond.

In order to create a closed vessel for storage of water the bottom liner of the lid must be suspended between the center support and the edge beam. In order to be able to weld the pre-cut liner pieces together to form a suspended cover over the empty pond, a rotating scaffold must be constructed in the pond. In order to secure that the liner can carry its own weight plus the weight of the Volclay panels and insulation with butyl liner steel wire reinforcement is strung between the edge beam and the center structure.

Upon completion of the suspended bottom liner of the lid, cleaning of the internal pond surfaces is undertaken and the rotating scaffold is removed through the access openings in the center structure.

After completion of this work the pond is filled with water (produced by the power plant) to the level +5.0m. When the water has reached level +5.0m the completion of the floating lid starts. From the edge beam drainage pipes, gravel and top soil is placed on the butyl liner (on top of the polystyrene insulation) at a rate corresponding to the rate with which the water level is raised above the level +5.0m. Care is taken to secure drainage of rainwater during construction. The rainfall on the finished part of the lid is drained through the clay walls of the pond to the ditch at the foot of the slope from the edge of the lid.

It should be noted that this rather difficult construction process must be reversed if decision is ever taken to empty the pond. All topsoil and gravel as well as clay must be removed to level +5.0m in case the pond must be emptied for water.

4.5 Connecting the pond to the DHS

In a district heating system based on cogeneration the storage will preferably be placed at the power plant. This is also the case at the cogeneration plants which are already employing tank storage. As mentioned earlier the location of a large pond storage may not be possible directly at the power plant. In Esbjerg the storage had to be placed about 600 m from the power plant in order to secure space for the pond (see fig. 8).

The DHS in Esbjerg operates at a pressure of 6 bar. The storage is operated at about 0.85 bar. Thus charging the pond necessitates allowing the hot water from the power plant to enter the pond through a reducing valve, while a pump system returns the same amount of pond water to the power plant at 6 bar pressure.

Fig. 12 and fig. 13 show the principal diagrams for the discharge and charge of hot water.

One of the four pumps shown must be variable in performance allowing exact balance of the quantities of water moving in and out of the storage. The maximum capacity of the pumping station is 9,000 m^3/h.

The four following figures will show the pump station: Fig. 14 shows a diagram of the pipe system in the basement, fig. 15 and fig. 16 show the planviews of the basement and the ground floor, and fig. 17 shows a section of the building.

4.6 Securing proper stratification during charge- and discharge operations.

In order to be able to utilize the full storage capacity during 6 hours the charge- and discharge arrangements must allow movement of 2.5 m^3/sec. in or out of the storage.

Several of the tank storages already in operation have been built with diffusors allowing a maximum speed in the diffusor opening of 0.08 m/sec. Taking this speed as a criteria for the maintenance of proper stratification the opening of the diffusors must be 31.25 m^2. Taking the diameter of the diffusors as 10.00 m the opening of the diffusor must be about 1.0 m.

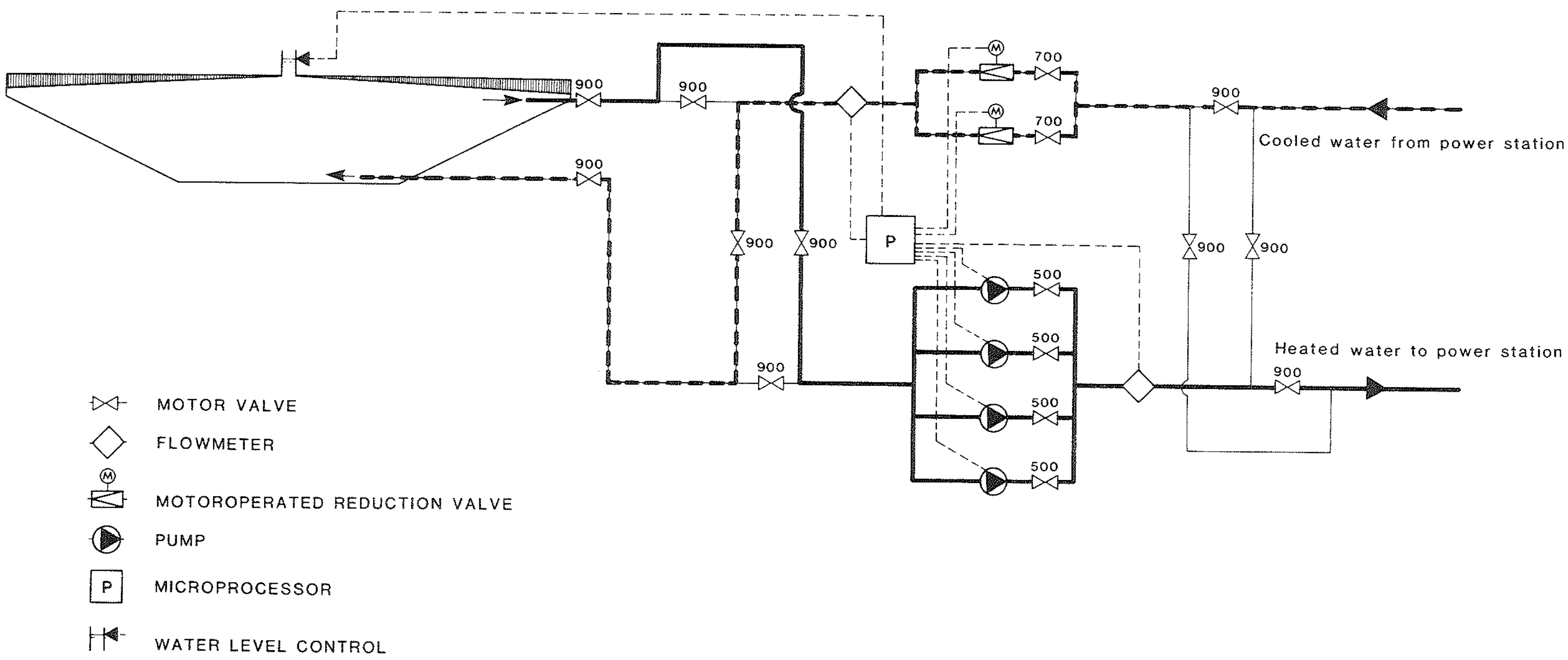


Figure 12. Pond connection to power station during discharge operation.

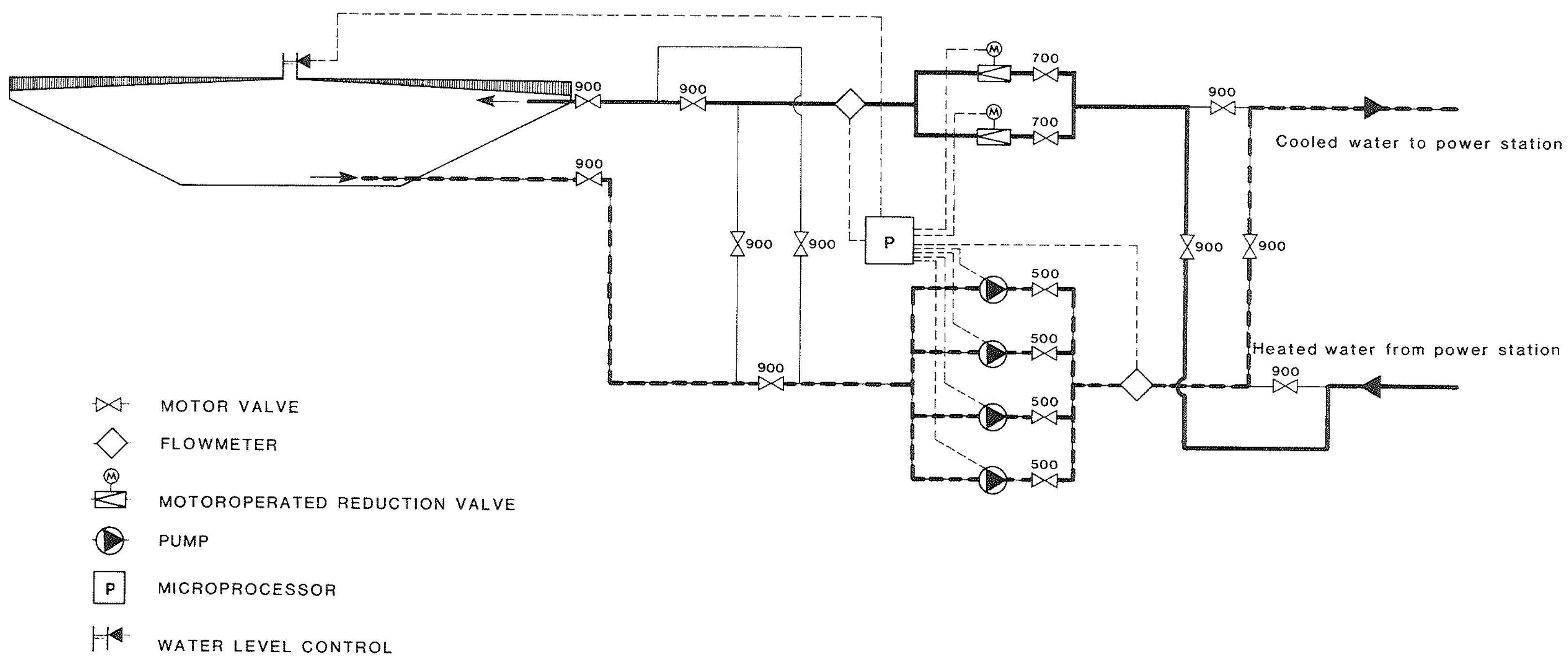


Figure 13. Pond connection to power station during charge operation.

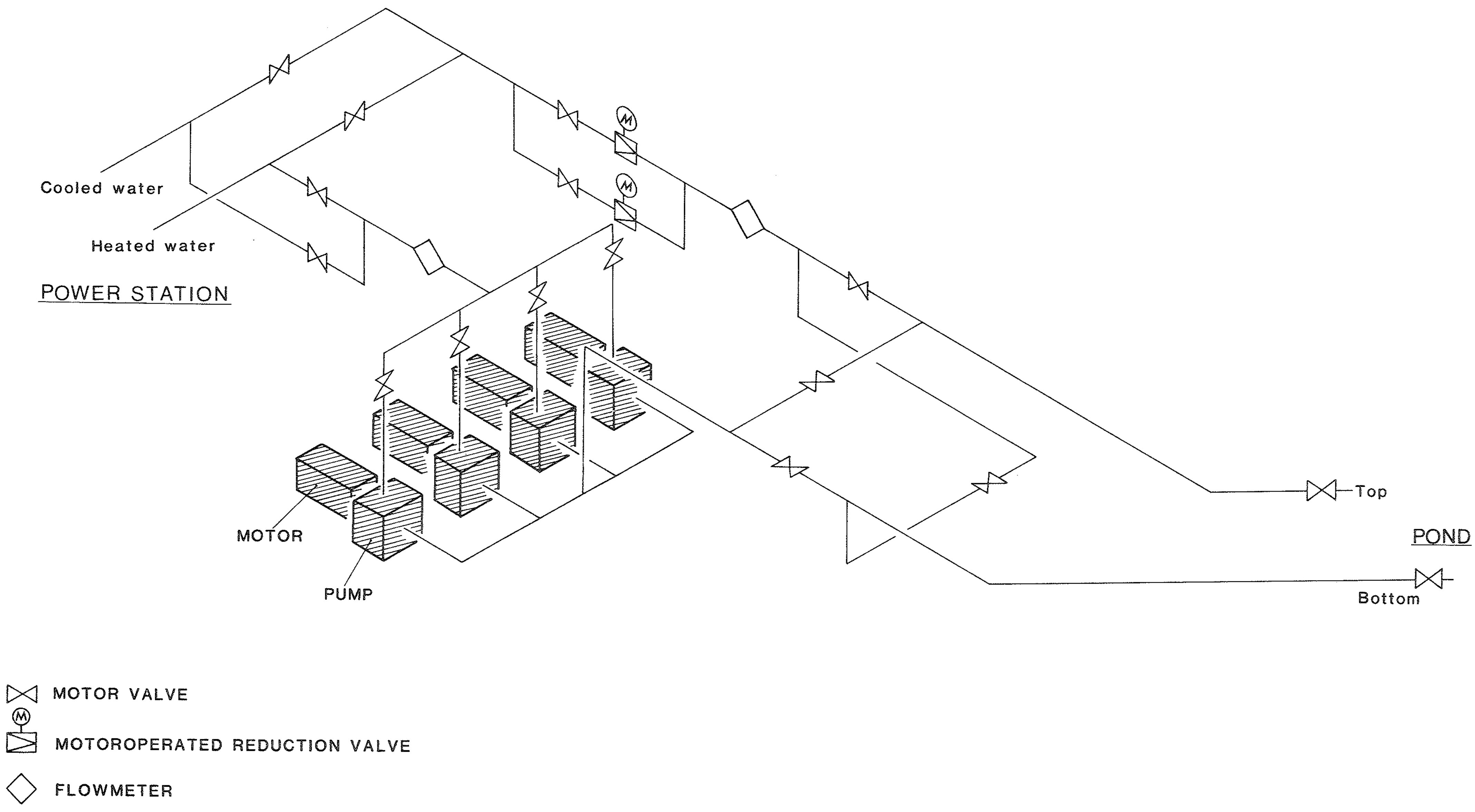


Figure 14. Pumpstation. Diagram of the pipe system.

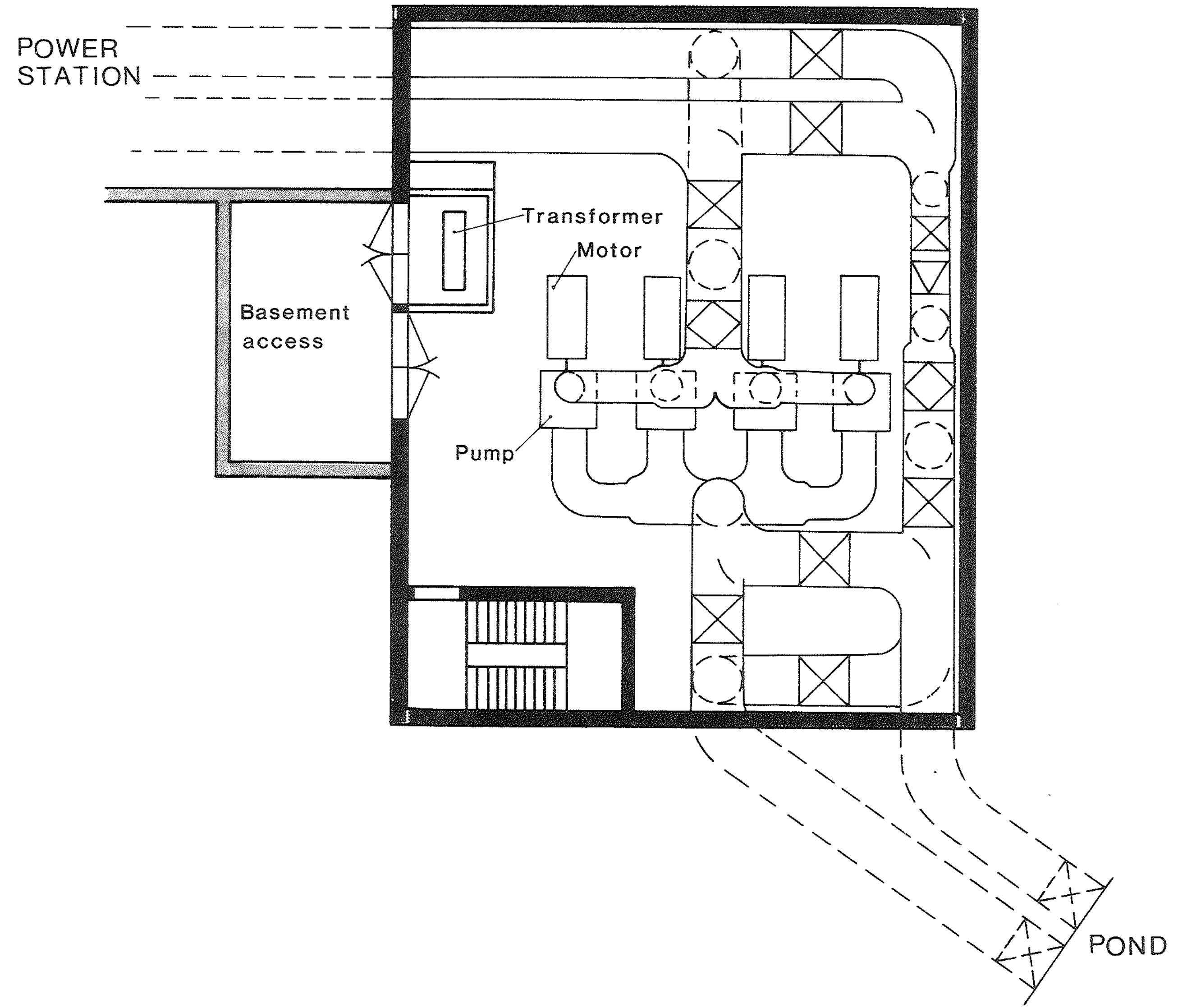


Figure 15. Pumpstation. Basement, plan.

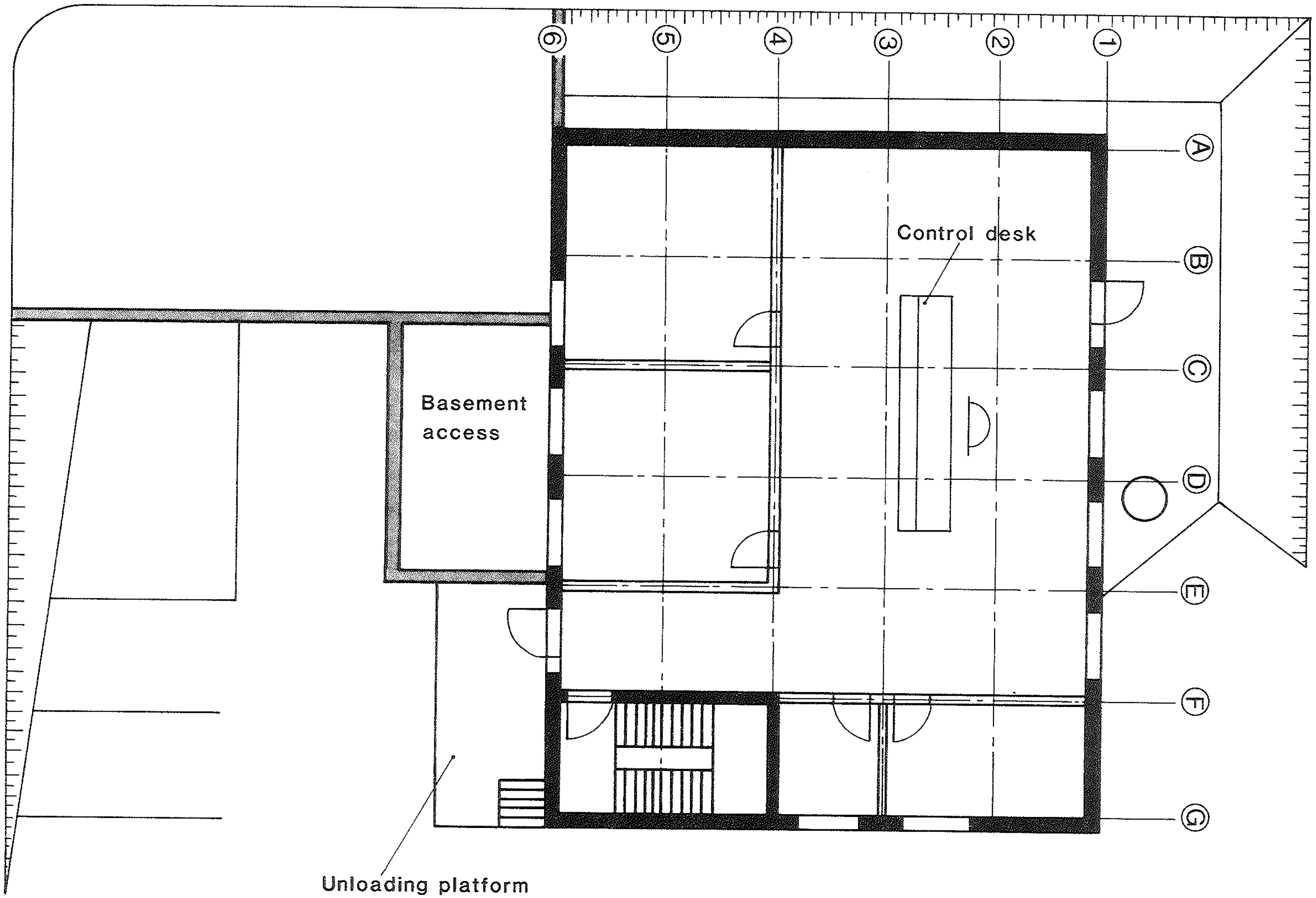


Figure 16. Pumpstation. Ground floor, plan.

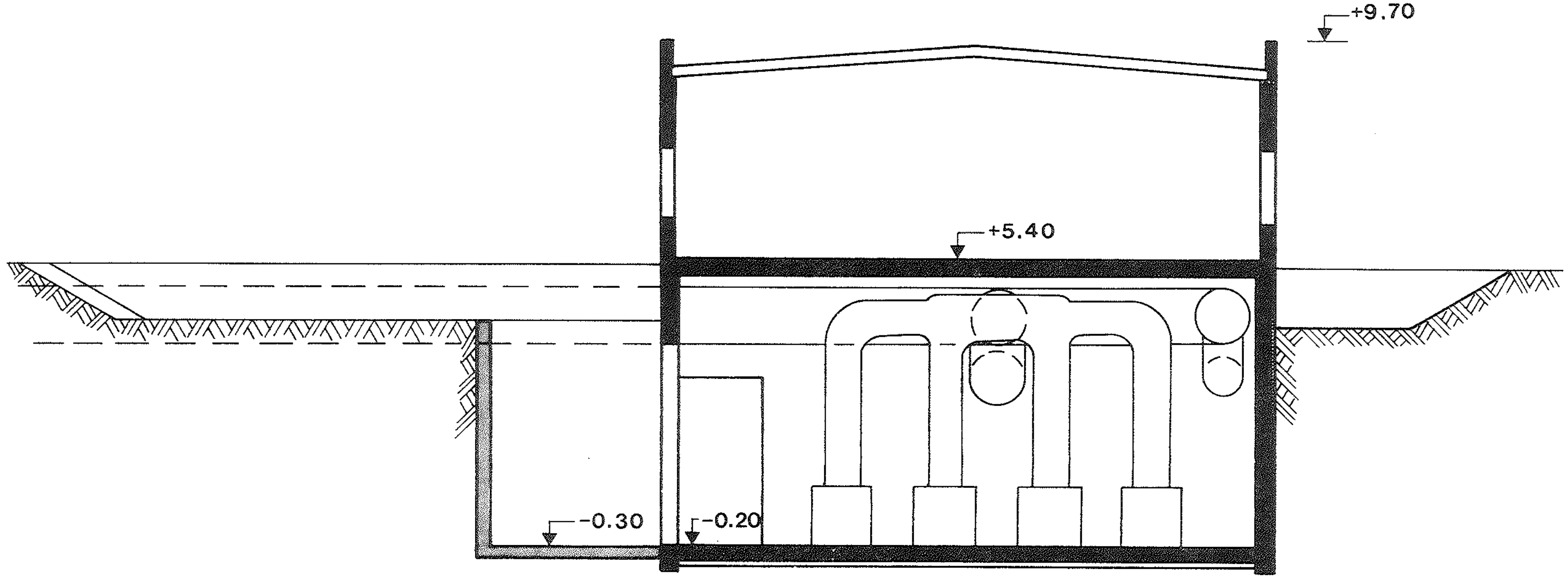


Figure 17. Pumpstation. Section.

The diffusors must be mounted on the tower structure in the centre of the pond. Vertical cross walls in the diffusors guide the water flow past the four columns of the centre structure without creating whirls.

The charge- and discharge pipelines from the pumping station enter the pond through the edge beam. The pipelines are insulated to prevent heat losses.

5. OPERATION

5.1. Thermal calculations in relation to the operations of a 50,000 m^3 underground heat storage

Annex III describes a computer programme called "TAB" designed to make heat loss calculations of the pond indicated on drawing 121 for different operational strategies simple. Examples of heat loss and temperature distribution in the soil are shown for the forth year of operation.

5.2. Operation and maintenance of the storage pond

The prime operational concern is, as already mentioned, to maintain a constant content of water in the pond. Sufficient "back-up" arrangements must be available in case the pipes to the power-station are interrupted. Auxiliary water supply must be arranged.

In order to facilitate the control of leakage two separate drainage systems have been proposed. Any flow of water through the clay in the bottom and the sides towards the pond is interrupted and drained by the 10 cm stopgraded sand-cement layer. This layer also collects any minor leakage from the Volclay-panels. The pump well for draining the sand-cement layer is placed in the clay wall near the pump station in order to secure that the drain system does not endanger the overall water tightness of the pond. The pipe connections to this well are executed by pressing the pipes hydraulicly through the pond walls.

The drains of the sandy seams behind the clay "plugs" in the bottom and in the walls are connected to another pump well also placed in the vicinity of the pump station in the clay pond wall.

This drain arrangement is only foreseen used after completion if the lid has been removed and a decision to empty the pond has been taken. During construction of the pond this drain system is operated at a rate allowing the water table around the pond to be lowered to a level sufficiently low to secure the structural stability of the pond bottom and sides. The level will have to be determined by detailed geotechnical investigations when construction starts.

6. ESTIMATE

6.1. Estimated construction cost of the storage pond

The construction cost can be split into three main groups:

Construction costs related only to seasonal storage pond

Construction costs related only to short term storage

Construction cost related only to the particular location

The preliminary estimate contains a number of rather unconventional contracting operations. Thus the accuracy of this preliminary estimate may be expected to be uncertain. It will, however, appear that for short term storage the lack of accuracy should be of minor importance, as the margin is very wide towards the cost of competing systems for short term storages.

As soon as a number of profitable short term storages have been constructed and the construction costs have been accounted for, a serious estimate for the price development for future seasonal storages may be possible.

A first estimate (in ECU) for the present design may be as follows: (1983 prices).

ECU	Seasonal storage	Short time storage	Local conditions	Total cost
A. Design Investigation inspection	204,000	59,000	67,000	330,000
B. Storage construction	1020,000	-	70,000	1090,000
C. Connection to DHS	70,000	300,000	300,000	670,000
D. Filling & heating	80,000	-	-	80,000
E. Misc.	19,000	5,000	6,000	30,000
Total	1393,000	364,000	443,000	2200,000
Cost per m^3	25,56	6,68	8,13	40,37
Cost per kWh capacity	.48	.13	.15	.76

The total cost of the short term storage is 40.37 ECU/m^3. The corresponding steel tank will most likely cost double the amount [11]. Renovation of existing steel tanks will very likely cost something similar, assuming that a 50,000 m^3 tank was availabl Smaller tanks will very likely cost more.

The cost of the seasonal storage is estimated at 25,50 ECU/m^3. After completion of a number of short term storages a more secure estimating of seasonal storages may be undertaken. A reduction up to 30% seems not unlikely. The preliminary estimate seems in good agreement with earlier reports [11].

As experience is gained by construction of a number of short term large underground heat storage ponds the construction cost for seasonal storage ponds can be assumed to be reduced to an extent, which may bring the underground storage ponds to a price level comparable with the price level of aquifer storages [15].

7. CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

The dimensioning and planning of a full size underground warm water store has led to the conclusion, that a rapid development in the construction experience relating to uninsulated underground heat storages with insulated floating lids may be anticipated, due to the economic advantages expected in district heating systems (DHS) based on cogeneration using underground ponds for short term storages.

When a number of large underground storages have been built for short term storage purposes, the experience gained in the construction may lead to a reduction in construction cost of great importance to the future development of large district heating systems based on seasonal storage of solar energy.

The need for short term as well as seasonal storage in large district heating systems very often exceeds 100,000 m^3 which appears to be the practical limit today for steel storage tanks.

The underground storage ponds appears to serve a large DHS in a more flexible way than aquifers and bore-hole storages because a pond may be equipped to function economically for all lengths of storage time.

It seems highly recommendable, that further prototype designs for large underground heat storages should be made in order to initiate a wide application of more efficient production strategies in large DHS' based on waste heat or solar energy.

Future research appears to be needed concerning the liners used in the pond, as they represent a major item in the total construction cost.

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LARGE HEAT STORAGES

THE RATIO BETWEEN THE AREA OF THE SOIL INTERFACE OF THE HEAT STORAGE PIT AND THE VOLUME OF THE PIT DERIVED FOR DIFFERENT GEOMETRIES

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THE RATIO BETWEEN THE AREA OF THE SOIL INTERFACE OF THE HEAT STORAGE PIT AND THE VOLUME OF THE PIT DERIVED FOR DIFFERENT GEOMETRIES

Summary

The ratio between the area of the soil interface of the heat storage pit and the volume of the pit (the surface coefficient) is derived for different geometries and recorded as a function of the volume. The depth is varied (4 curves) for each of the slopes a = 0.5, 1.5, 2.0, 2.5.

The characteristic parameter R (see drawings) is derived for different geometries and recorded as a function of the volume.

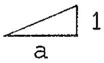
For the frustum of a cone and the frustum of a pyramid appendix 1 shows,

1) The optimal depth can be found for a selected slope and volume,

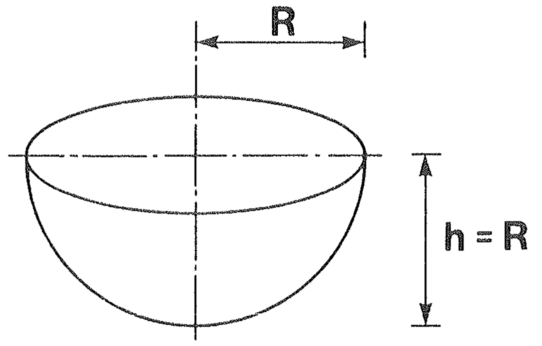
2) The slope which has the lowest surface coefficient is $a = 1/1,9767 \simeq 0,5$.

The distance from the surface of the ground, Z, is drawn for a pit shaped like a frustum of a cone when dirt-balance is required. The removed dirt is deposited around the excavated hole.

Notation

A	Constant	[m]
B	Constant	$[m^2]$
C	Constant	$[m^3]$
M	Module = $1/\omega$	[m]
O	Soil interface	$[m^2]$
R	Characteristic parameter, see drawings	[m]
V	Volume of the pit	$[m^3]$
Z	Distance from ground surface	[m]
a	Slope 	[-]
b	Constant	[-]
c	Half a length of the side	[m]
e	Radius	[m]
h	Depth	[m]
k	Constant	[m]
k_1	Constant	[m]
p	Constant	$[m^2]$
q	Constant	$[m^3]$
r	Radius	[m]
s	Length of the side	[m]
x	= $1/a$	[-]
y	Variable	[m]
α	Coefficient	[-]
β	Height of the embankment above ground surface	[m]
ω	Surface coefficient = $1/M$	$[m^{-1}]$

A Semisphere



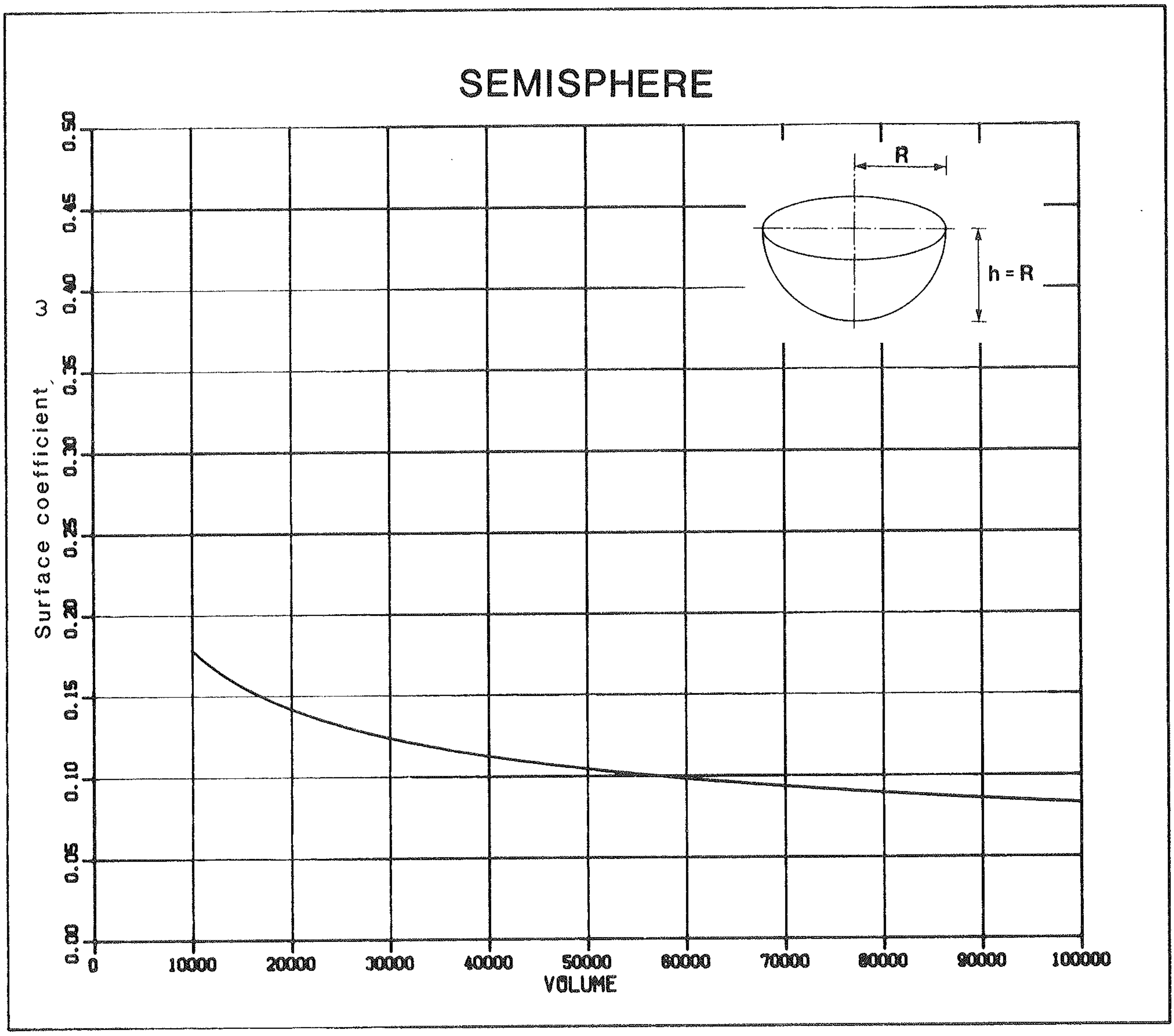
$$O = 2\pi R^2$$

$$V = \frac{2\pi R^3}{3}$$

$\Rightarrow$

$$R = \sqrt[3]{\frac{3V}{2\pi}} = 0,782 \cdot V^{1/3}$$

$$\omega = \frac{O}{V} = \frac{2\pi R^2}{\frac{2}{3}\pi R^3} = 3,836 \cdot V^{-1/3}$$


SEMISPHERE
Surface coefficient, ω
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
R
h = R
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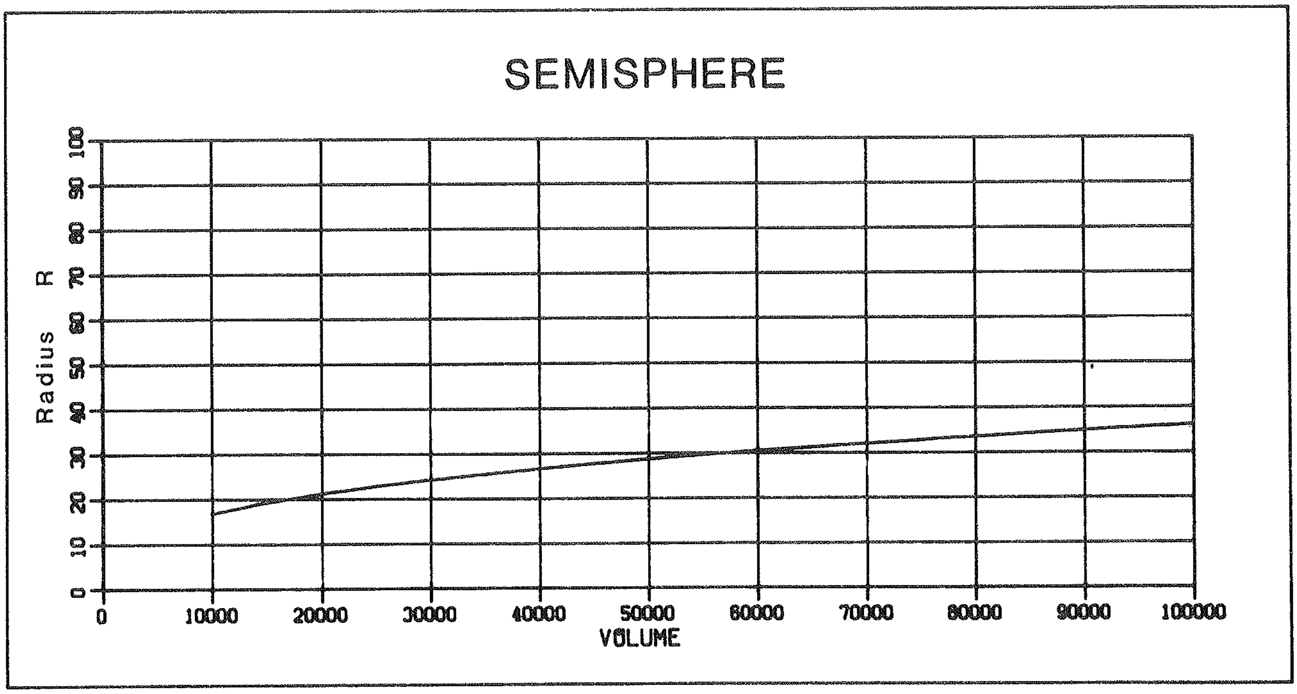
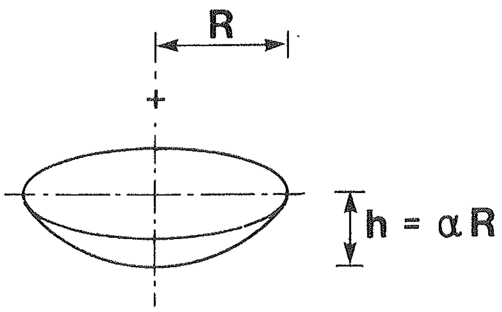
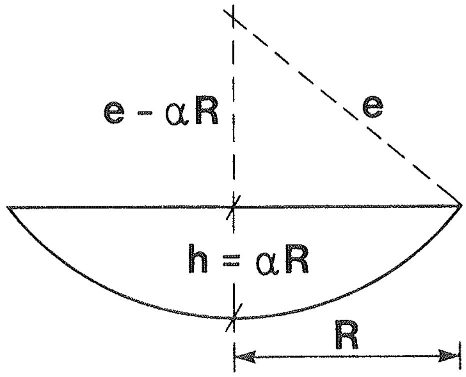
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME


SEMISPHERE
Radius R
0
10
20
30
40
50
60
70
80
90
100
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME

B Segment of a sphere





$$O = 2\pi R \frac{\alpha^2 + 1}{2\alpha} \alpha R$$

$$= \pi R^2 (\alpha^2 + 1)$$

$$V = \frac{\pi R \alpha}{6} (3R^2 + R^2 \alpha^2)$$

$$= \frac{\pi R^3 \alpha}{2} (1 + \frac{\alpha^2}{3})$$

$\Rightarrow$

$$R = \sqrt[3]{\frac{2V}{\pi\alpha(1 + \frac{\alpha^2}{3})}} = 0{,}860 \cdot \frac{V^{1/3}}{\sqrt[3]{\alpha(1 + \frac{\alpha^2}{3})}}$$

$$\omega = \frac{\pi R^2 (\alpha^2 + 1)}{\frac{\pi R^3 \alpha}{2} (1 + \frac{\alpha^2}{3})}$$

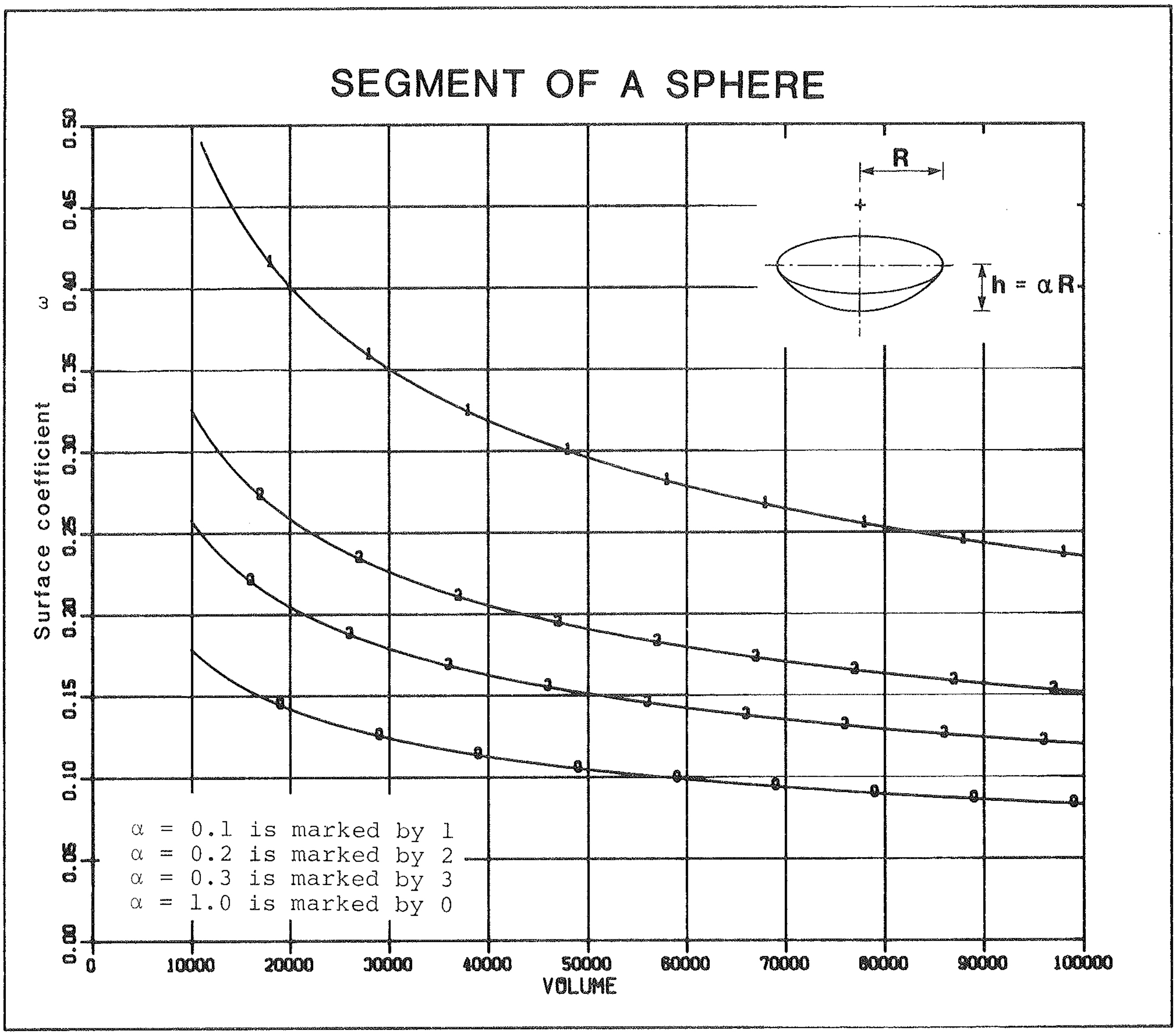
$$= \frac{2}{R} \cdot \frac{\alpha^2 + 1}{\alpha(1 + \frac{\alpha^2}{3})}$$

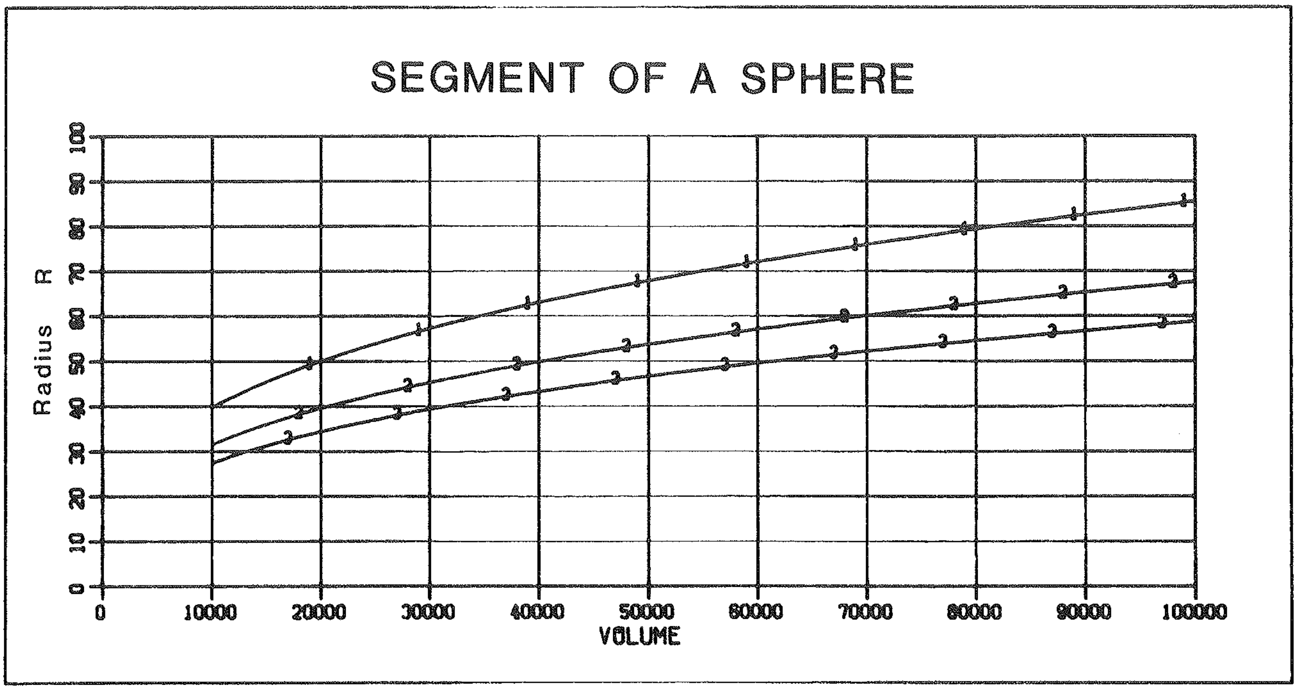
$$= \frac{2 \cdot \sqrt[3]{\frac{\pi}{2}} \cdot (\alpha^2 + 1)}{\alpha^{2/3} (1 + \frac{\alpha^2}{3})^{2/3}} \cdot V^{-1/3}$$

$$(e - \alpha R)^2 + R^2 = e^2$$

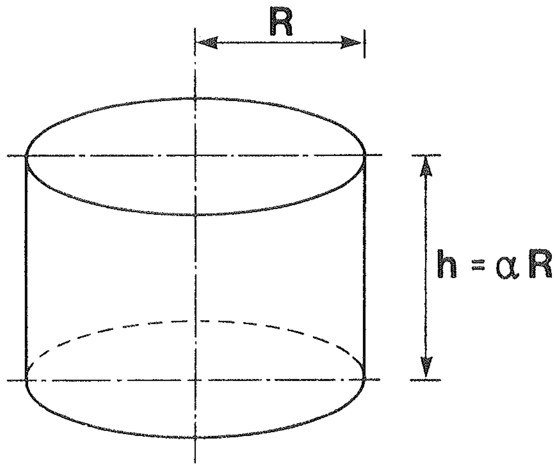
$\Rightarrow$

$$e = R \frac{\alpha^2 + 1}{2\alpha}$$


SEGMENT OF A SPHERE
R
h = αR
Surface coefficient ω
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 1.0 is marked by 0
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME


SEGMENT OF A SPHERE
Radius R
0
10
20
30
40
50
60
70
80
90
100
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME

C Cylinder



$$O = 2\pi\alpha R^2 + \pi R^2$$

$$V = \pi\alpha R^3$$

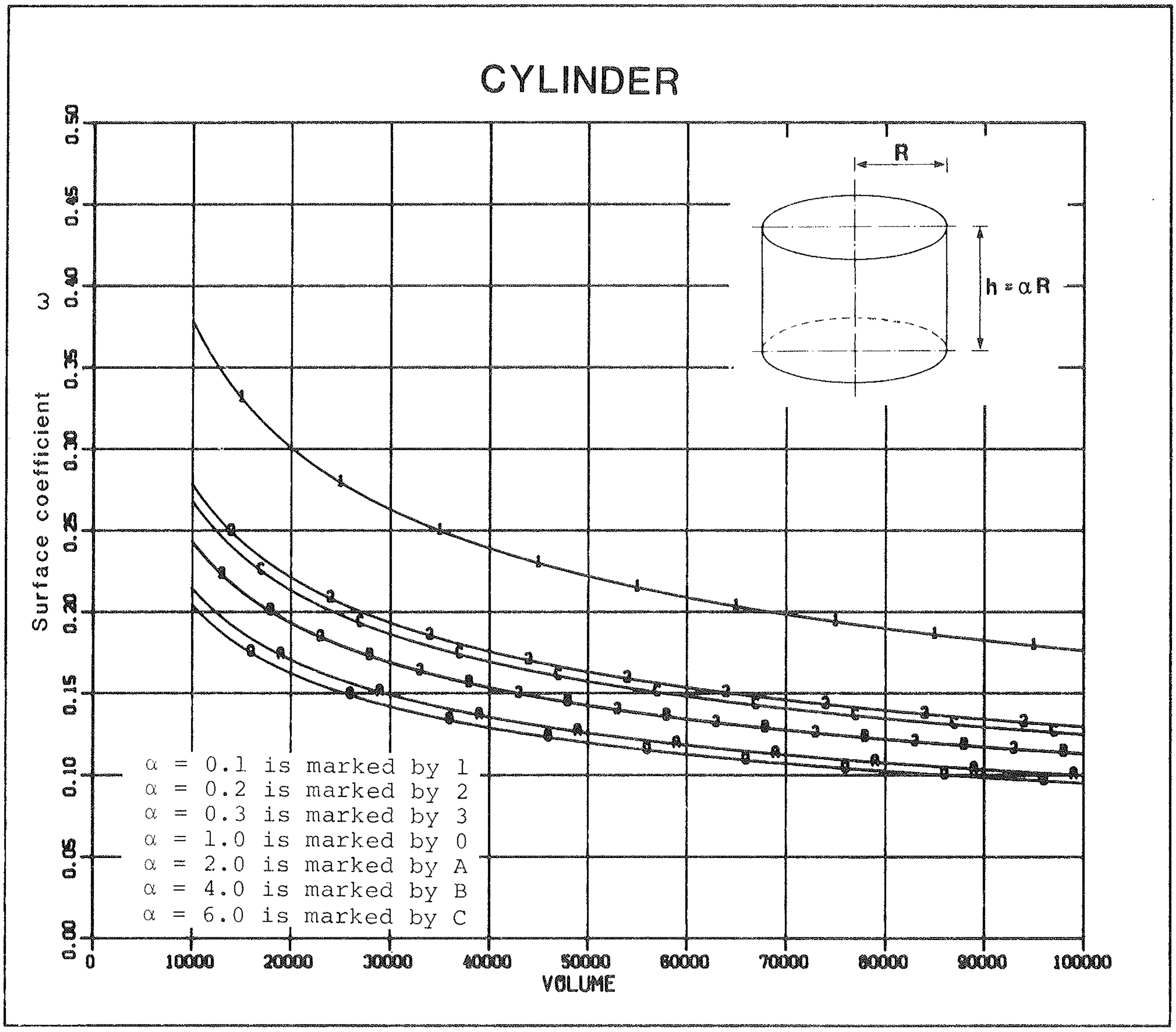
$\Rightarrow$

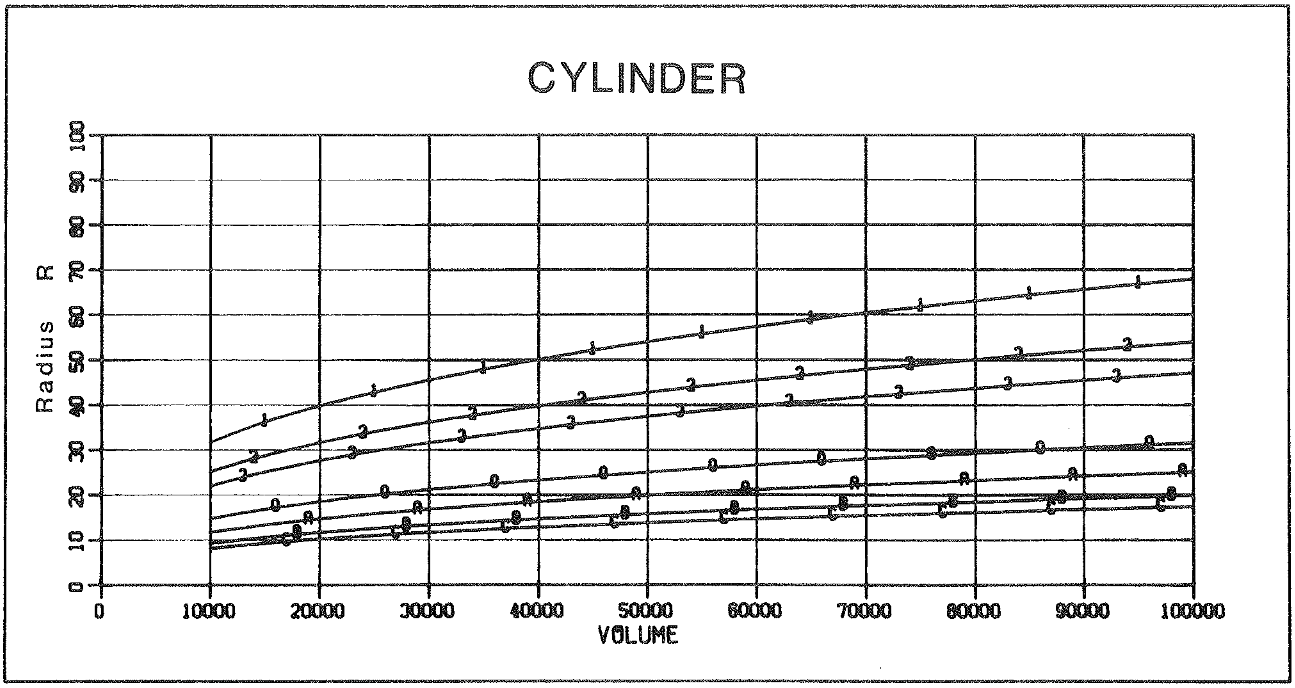
$$R = \sqrt[3]{\frac{V}{\pi\alpha}} = 0,683 \cdot \left(\frac{V}{\alpha}\right)^{1/3}$$

$$\omega = \frac{O}{V} = \frac{2\pi\alpha R^2 + \pi R^2}{\pi\alpha R^3}$$

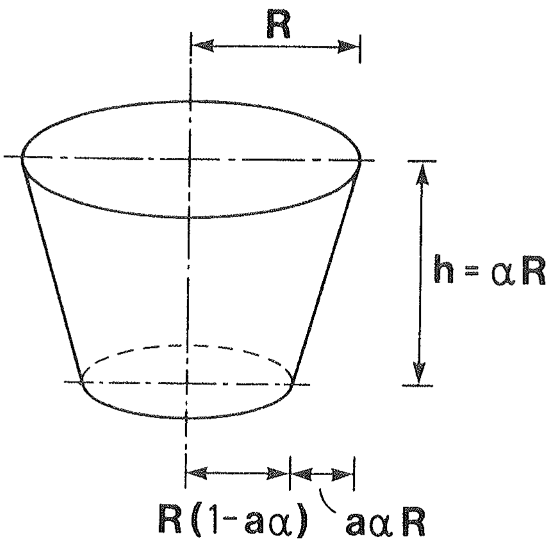
$$= \frac{2\alpha + 1}{\alpha R}$$

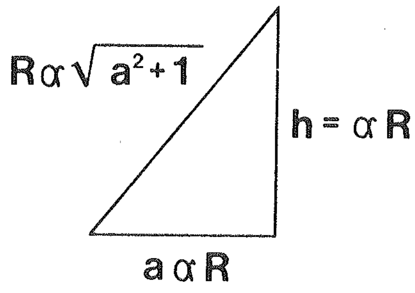
$$= \frac{\sqrt[3]{\pi}\,(2\alpha + 1)}{\alpha^{2/3}} \quad V^{-1/3}$$


CYLINDER
Surface coefficient ω
VOLUME
R
h = αR
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 1.0 is marked by 0
α = 2.0 is marked by A
α = 4.0 is marked by B
α = 6.0 is marked by C


CYLINDER
Radius R
VOLUME

D Frustum of a cone





$$O = \pi \cdot R\alpha \sqrt{a^2 + 1} \cdot (R + R(1 - a\alpha)) + \pi (1 - a\alpha)^2 R^2$$

$$= \pi R^2 (\alpha \sqrt{a^2 + 1} \cdot (2 - a\alpha) + (1 - a\alpha)^2)$$

$$V = \frac{\pi\alpha R}{3} (R^2 + R^2 - a\alpha R^2 + R^2 (1 - a\alpha)^2)$$

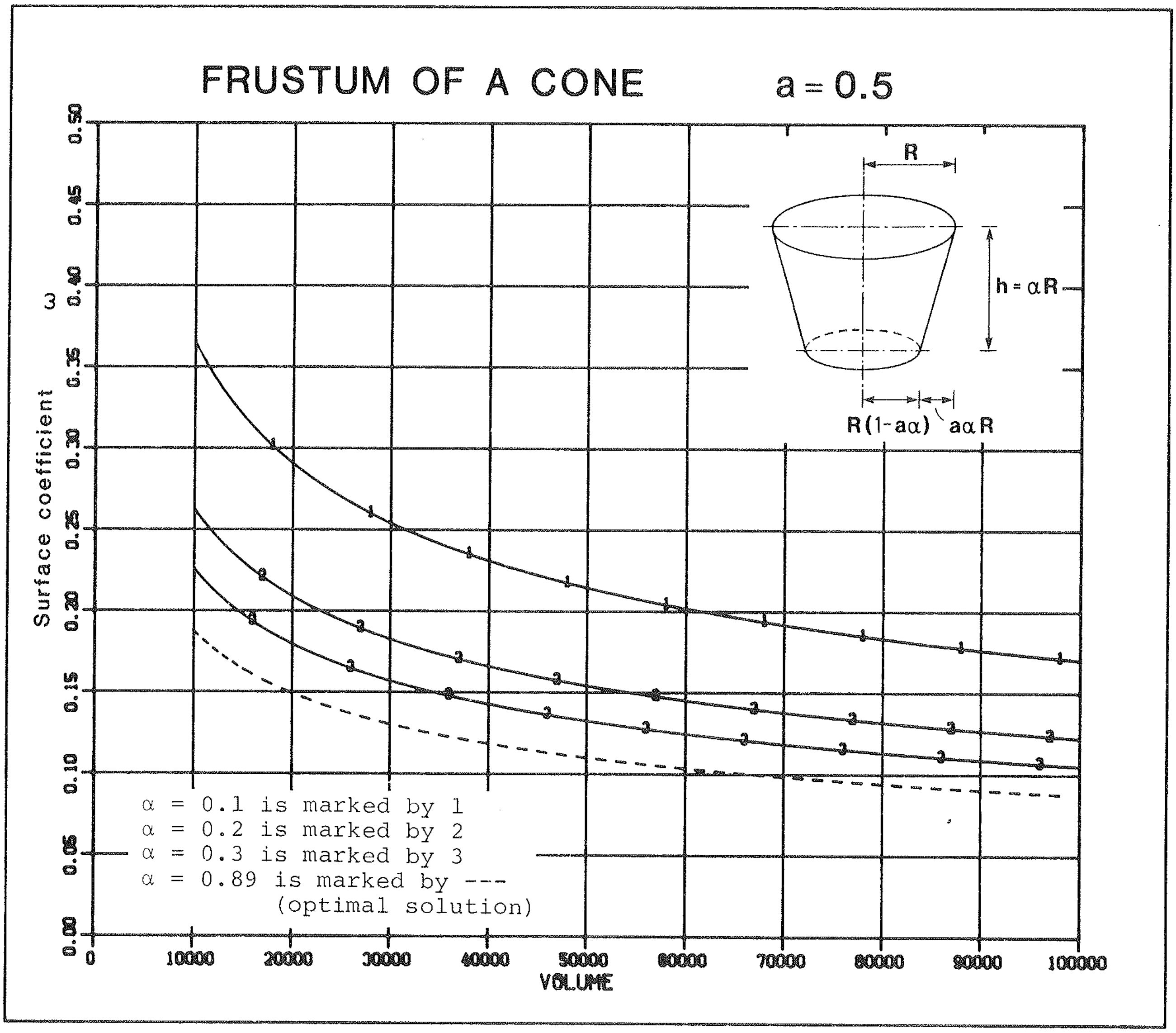
$$= \pi\alpha R^3 (1 - a\alpha + \frac{\alpha^2 a^2}{3})$$

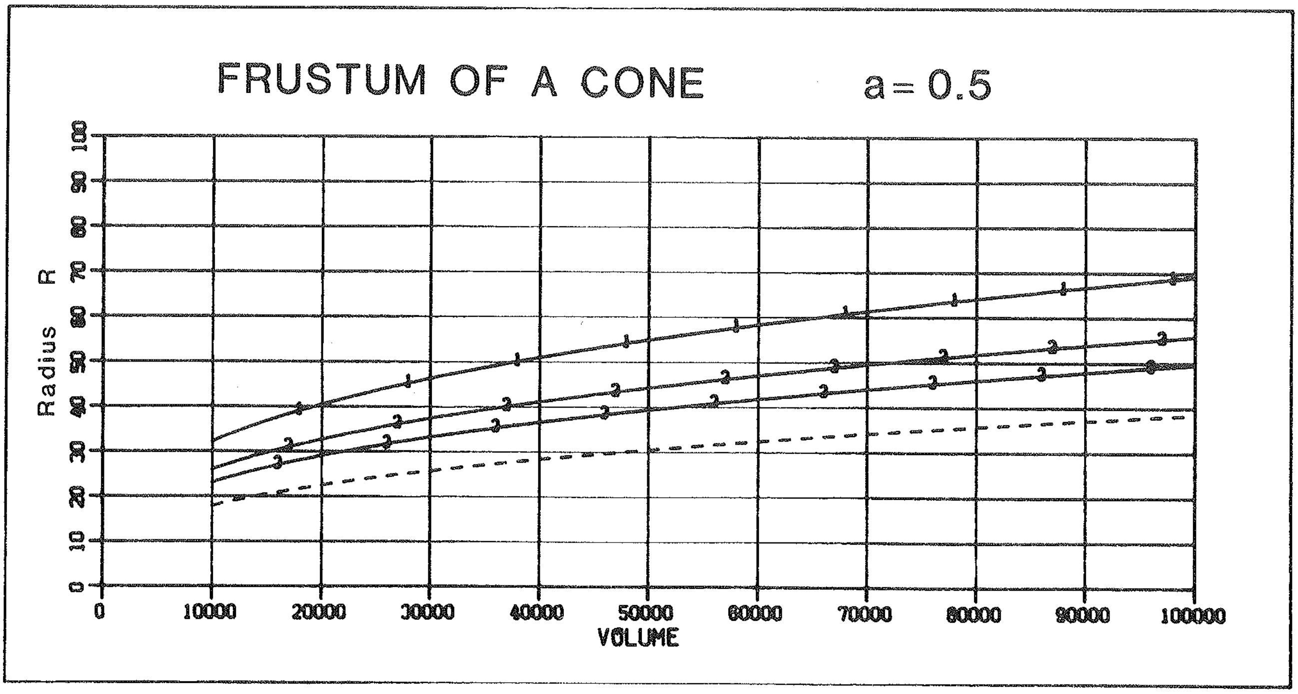
$\Rightarrow$

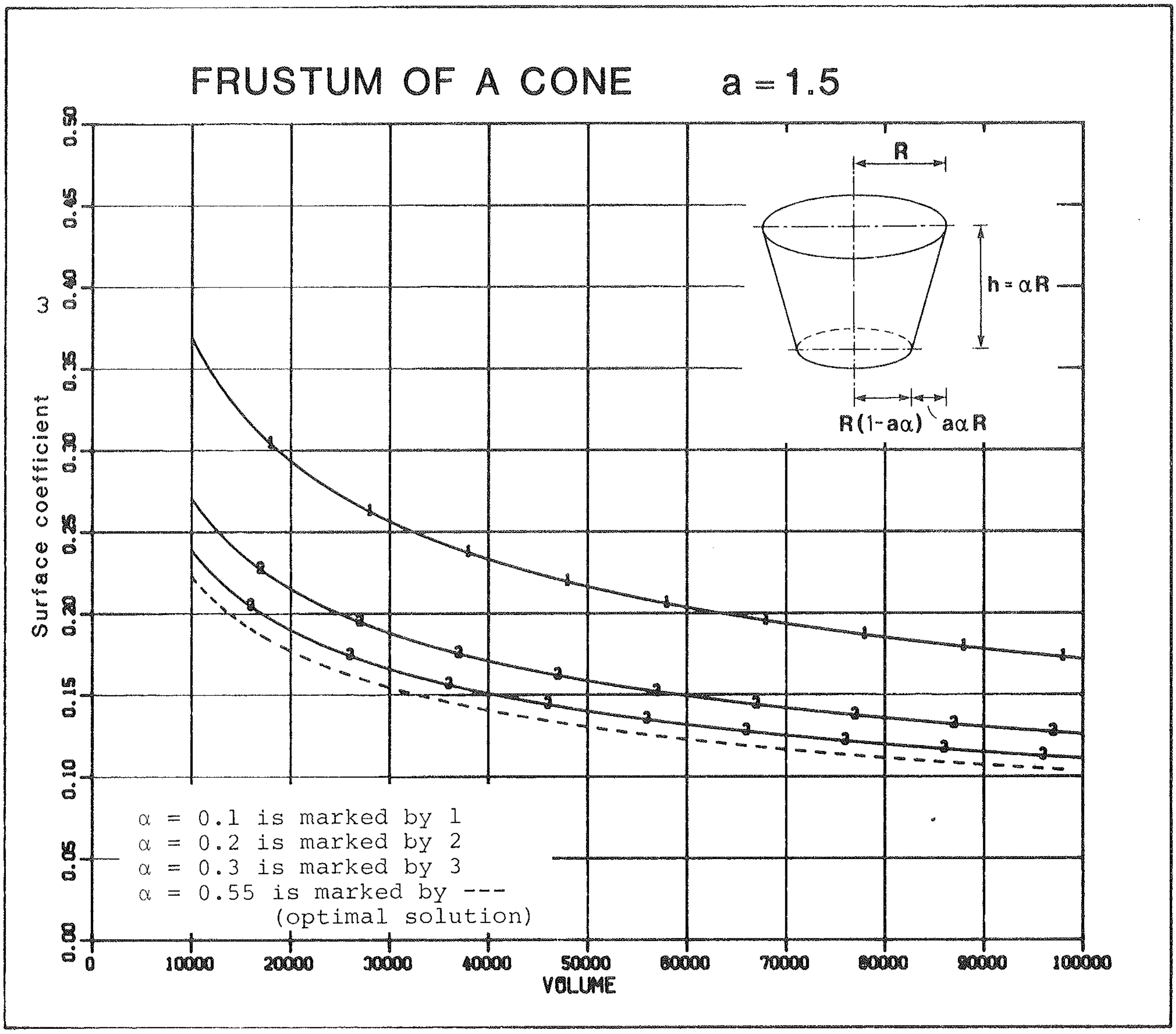
$$R = \sqrt[3]{\frac{V}{\pi\alpha (1 - a\alpha + \frac{\alpha^2 a^2}{3})}} = 0{,}683 \cdot \frac{V^{1/3}}{\sqrt[3]{\alpha (1 - a\alpha + \frac{a^2\alpha^2}{3})}}$$

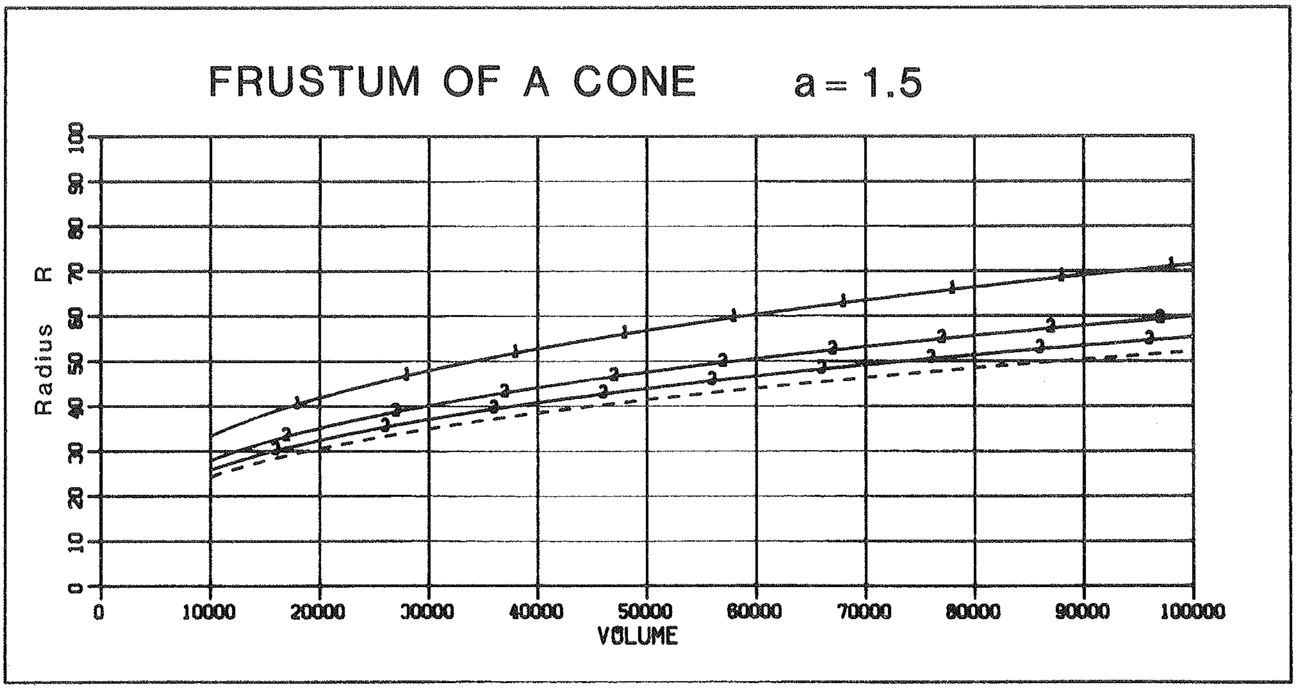
$$\omega = \frac{O}{V} = \frac{\pi R^2 (\alpha\sqrt{a^2 + 1} \cdot (2 - a\alpha) + (1 - a\alpha)^2)}{\pi\alpha R^3 (1 - a\alpha + \frac{\alpha^2 a^2}{3})}$$

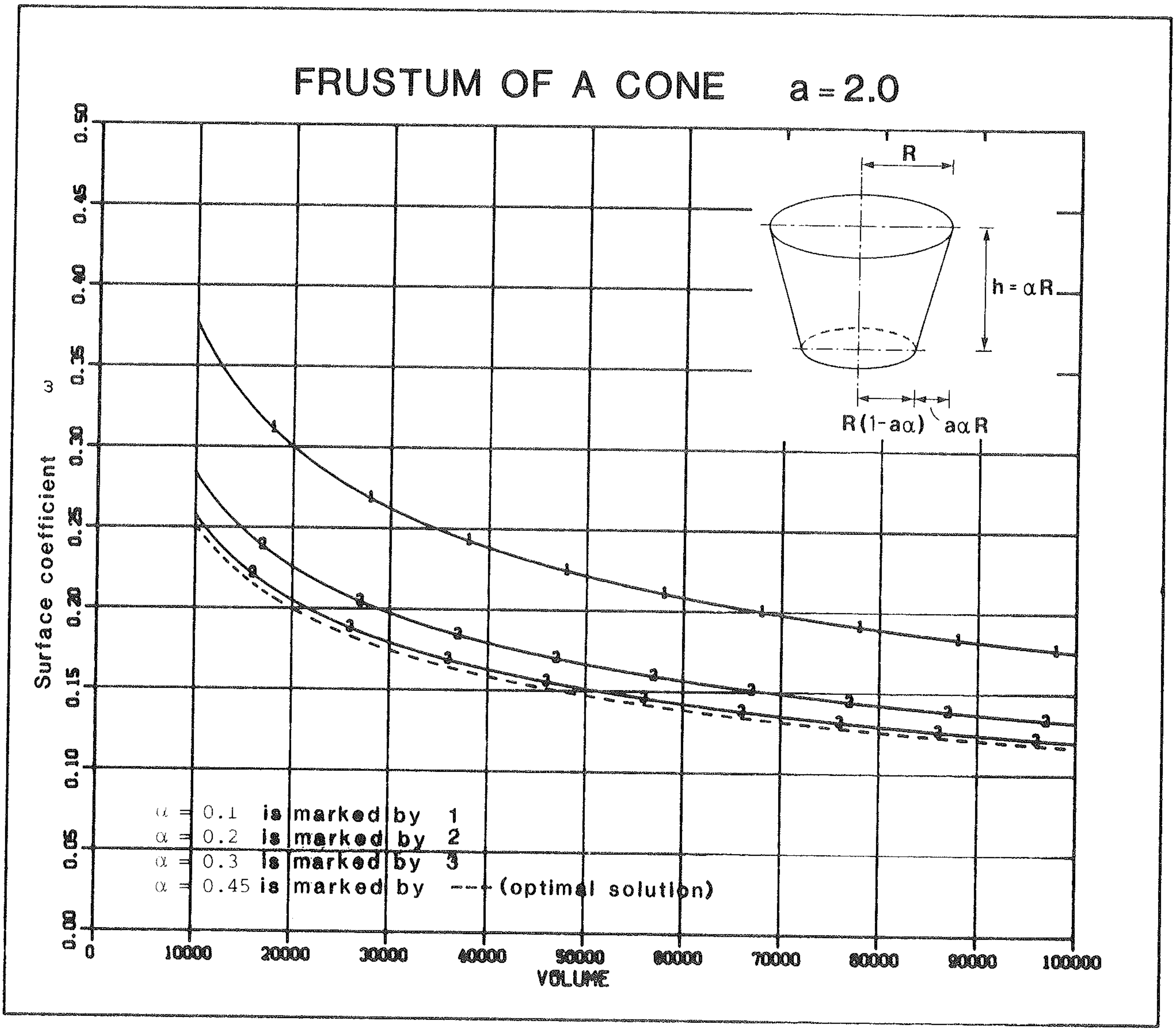
$$= \frac{\sqrt[3]{\pi} (\alpha\sqrt{a^2 + 1} \cdot (2 - a\alpha) + (1 - a\alpha)^2)}{\alpha^{2/3} (1 - a\alpha + \frac{\alpha^2 a^2}{3})^{2/3}} \cdot V^{-1/3}$$

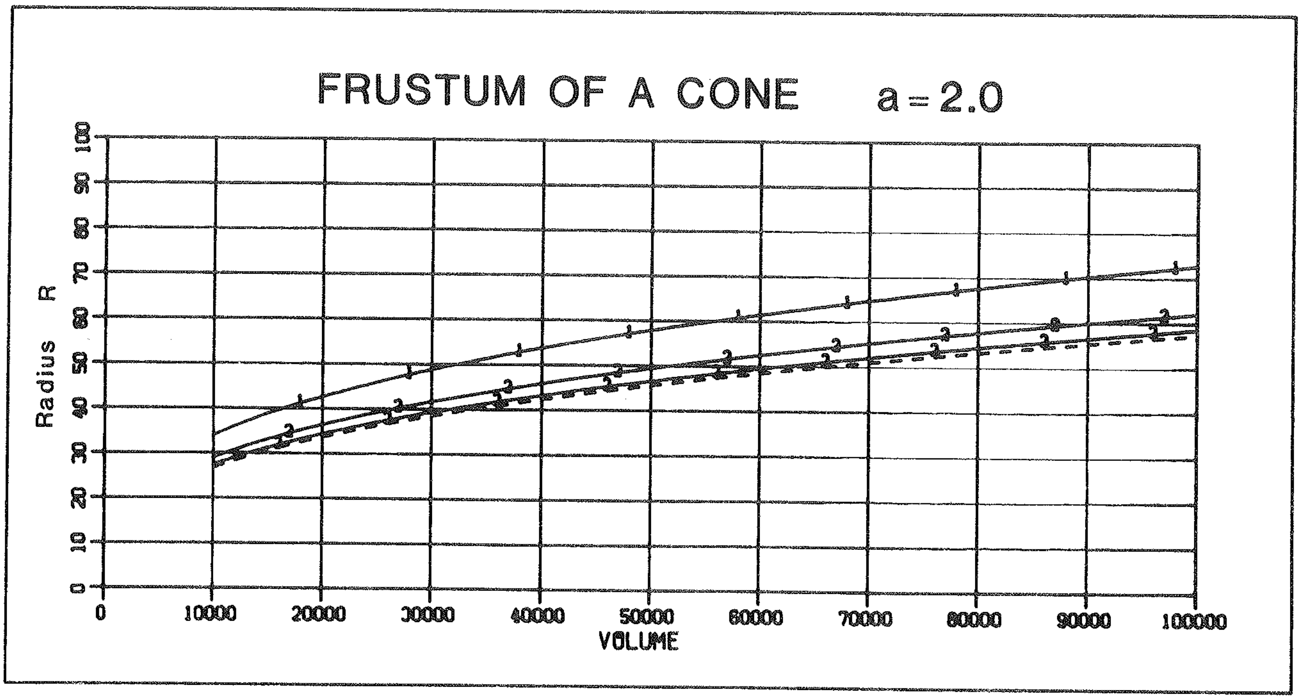

FRUSTUM OF A CONE
a = 0.5
R
h = αR
R(1-aα)
aαR
Surface coefficient ω
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.89 is marked by ---
(optimal solution)

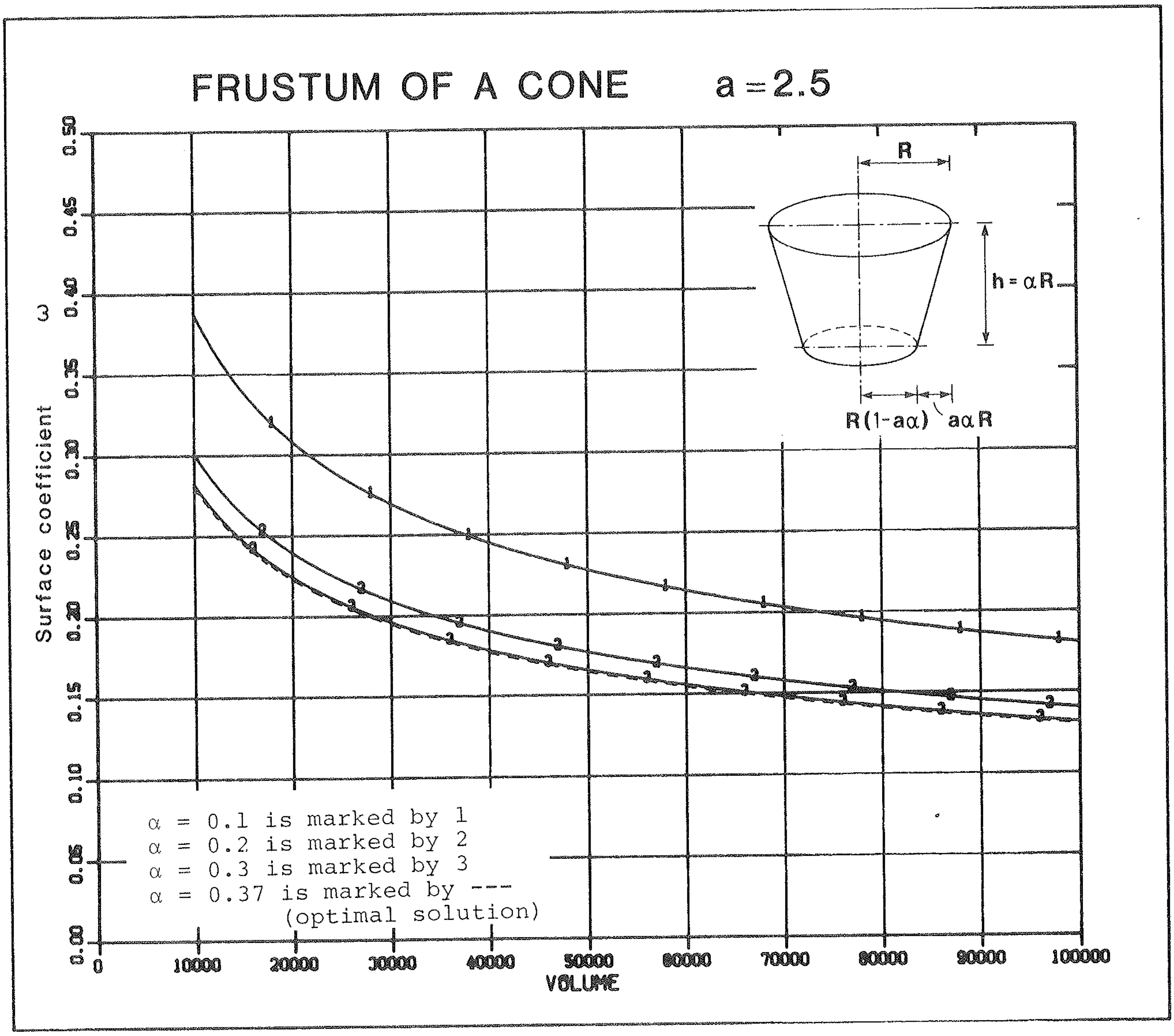

FRUSTUM OF A CONE
a = 0.5
Radius R
0
10
20
30
40
50
60
70
80
90
100
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME

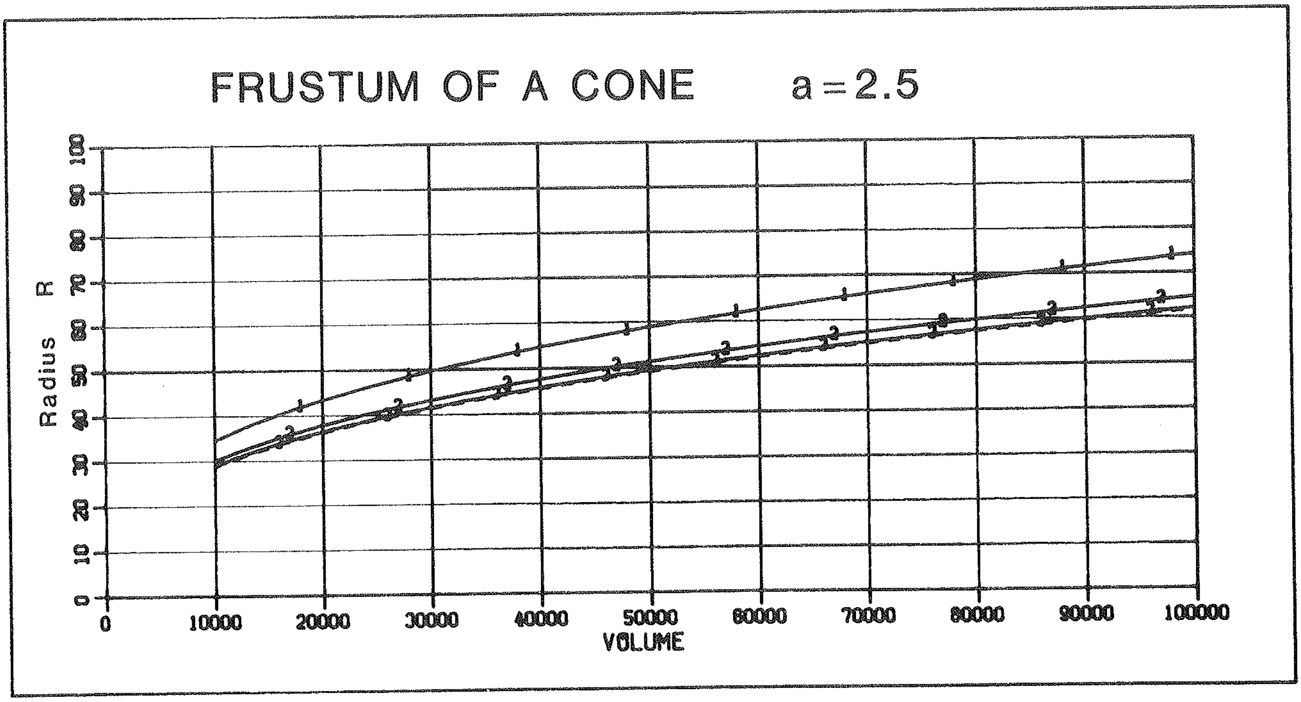

FRUSTUM OF A CONE a = 1.5
Surface coefficient ω
VOLUME
0 10000 20000 30000 40000 50000 60000 70000 80000 90000 100000
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50
R
h = αR
R(1-aα)
aαR
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.55 is marked by ---
(optimal solution)


FRUSTUM OF A CONE a = 1.5
Radius R
VOLUME
0 10000 20000 30000 40000 50000 60000 70000 80000 90000 100000
0 10 20 30 40 50 60 70 80 90 100

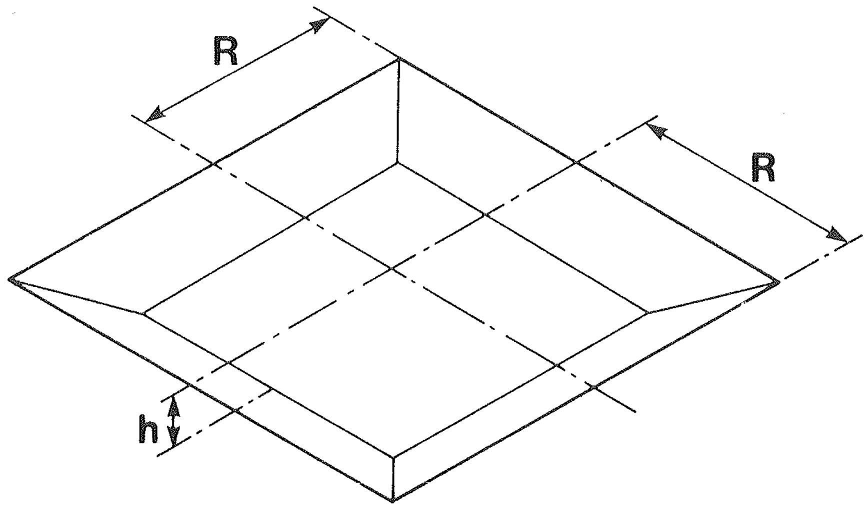

FRUSTUM OF A CONE a = 2.0
R
h = αR
R(1-aα)
aαR
Surface coefficient
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.45 is marked by --- (optimal solution)
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME

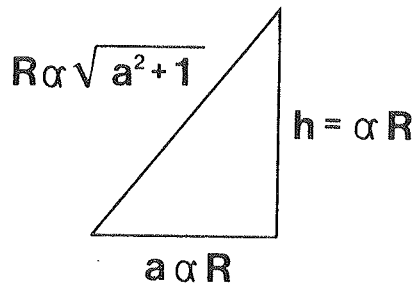

FRUSTUM OF A CONE a = 2.0
Radius R
0
10
20
30
40
50
60
70
80
90
100
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME


FRUSTUM OF A CONE a = 2.5
Surface coefficient ω
VOLUME
R
h = αR
R(1-aα)
aαR
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.37 is marked by ---
(optimal solution)


FRUSTUM OF A CONE a = 2.5
Radius R
VOLUME

E Frustum of a pyramid





$$O = 4\ \frac{2R(1 - a\alpha)\ +\ 2R}{2}\ R\alpha\sqrt{a^2 + 1}\ +\ (2R(1 - a\alpha))^2$$

$$= 4R^2\ ((2 - a\alpha)\,\alpha\sqrt{a^2 + 1} + (1 - a\alpha)^2\ )$$

$$V = \frac{\alpha R}{3}\ (4R^2\ +\ 4(R - a\alpha R)^2\ +\ 2R(2R - 2a\alpha R))$$

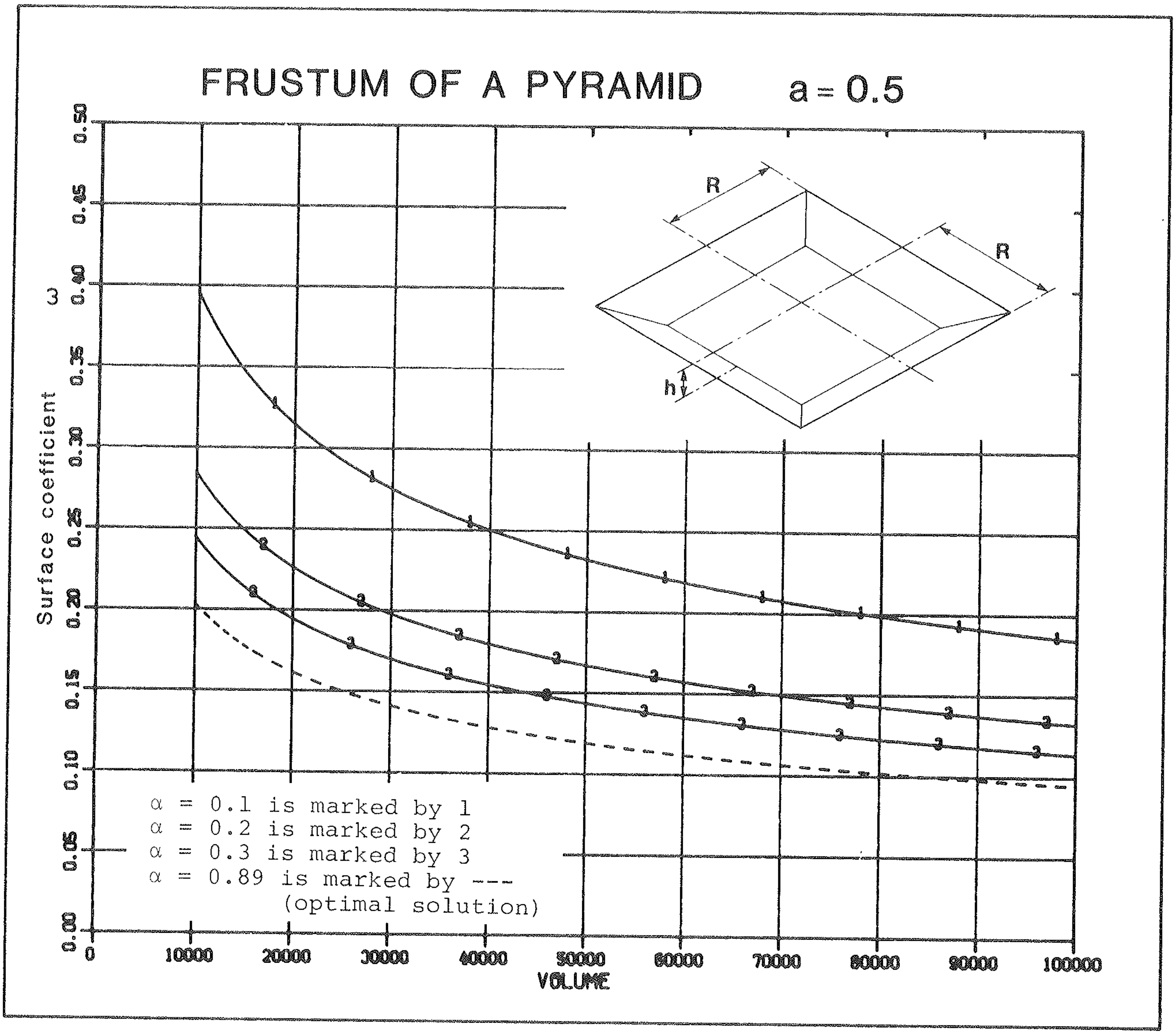
$$= 4\alpha R^3\ (1 - a\alpha\ +\ \frac{\alpha^2 a^2}{3})$$

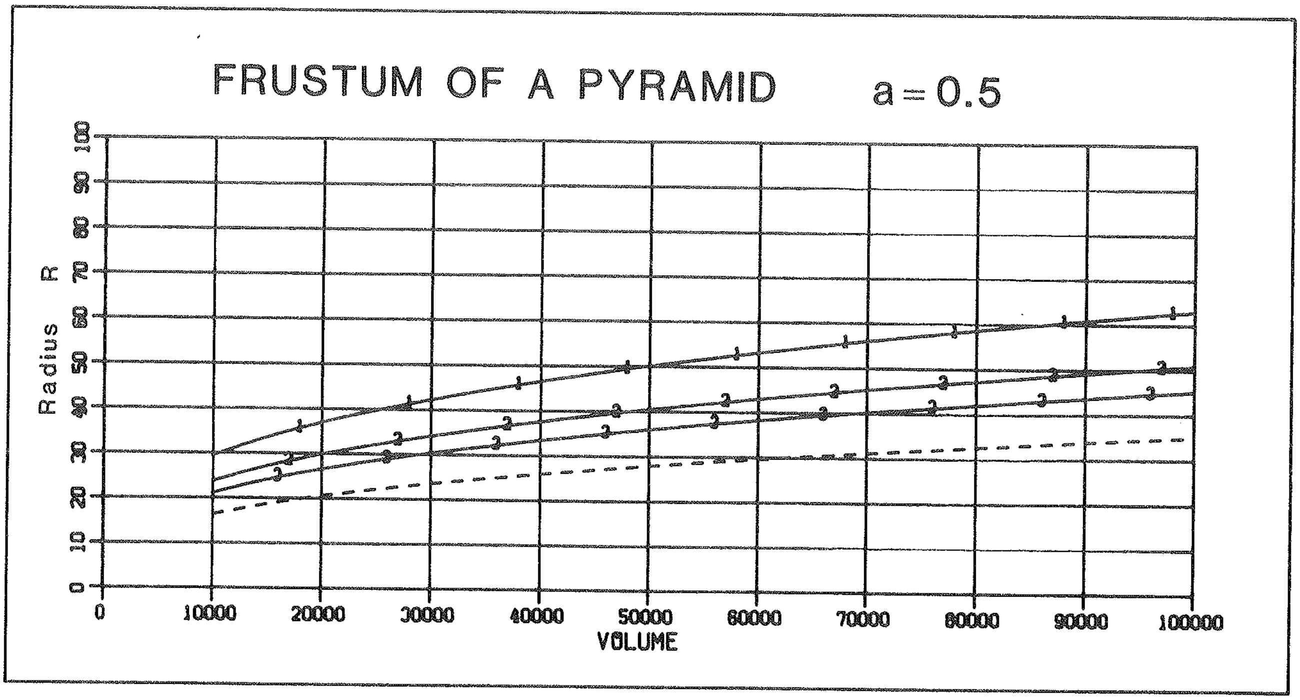
$\Rightarrow$

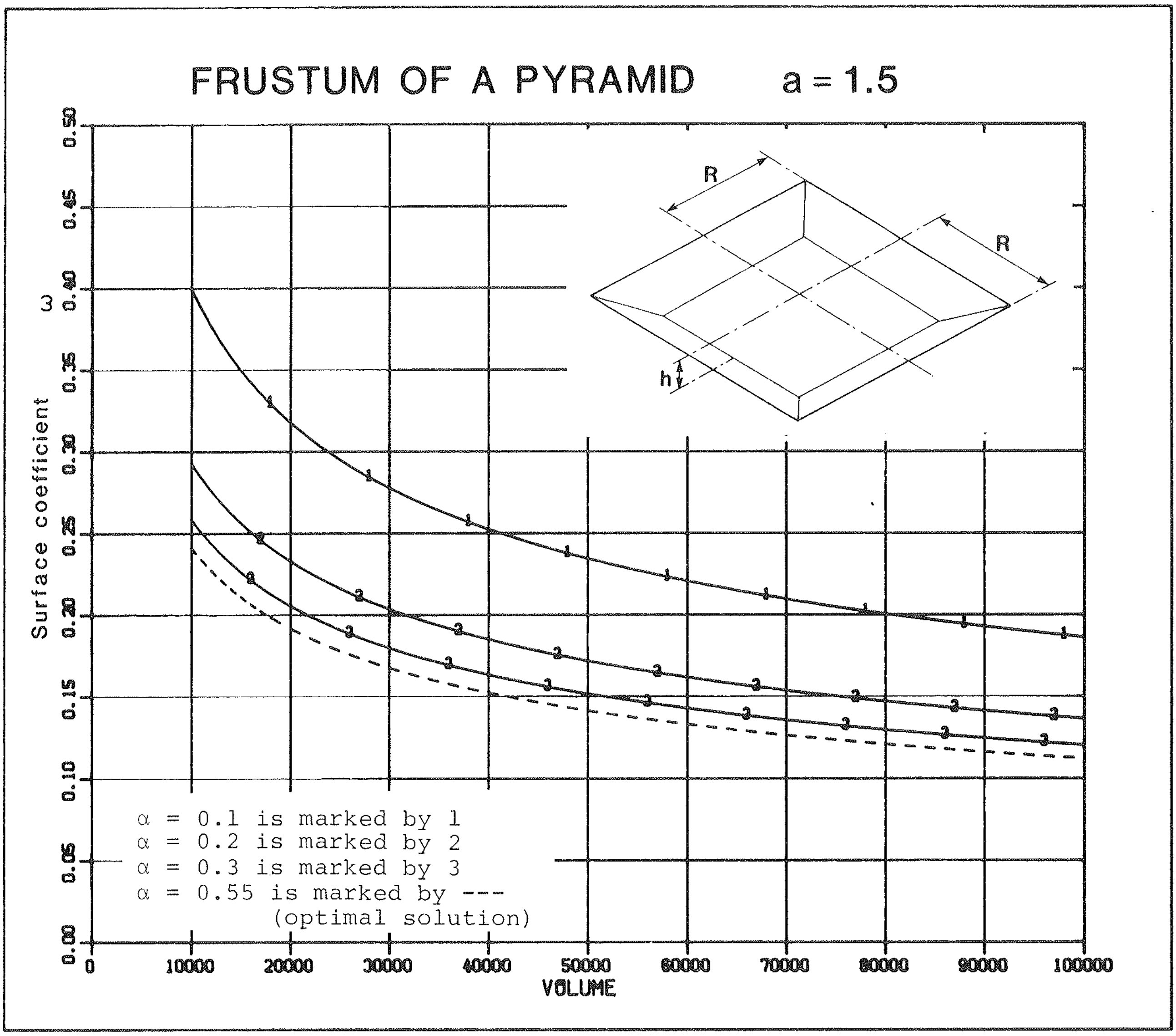
$$R = \sqrt[3]{\frac{1}{4}\cdot\frac{V}{\alpha(1 - a\alpha\ +\ \frac{a^2\alpha^2}{3})}} = 0{,}623\ \frac{V^{1/3}}{\sqrt[3]{\alpha(1 - a\alpha\ +\ \frac{a^2\alpha^2}{3})}}$$

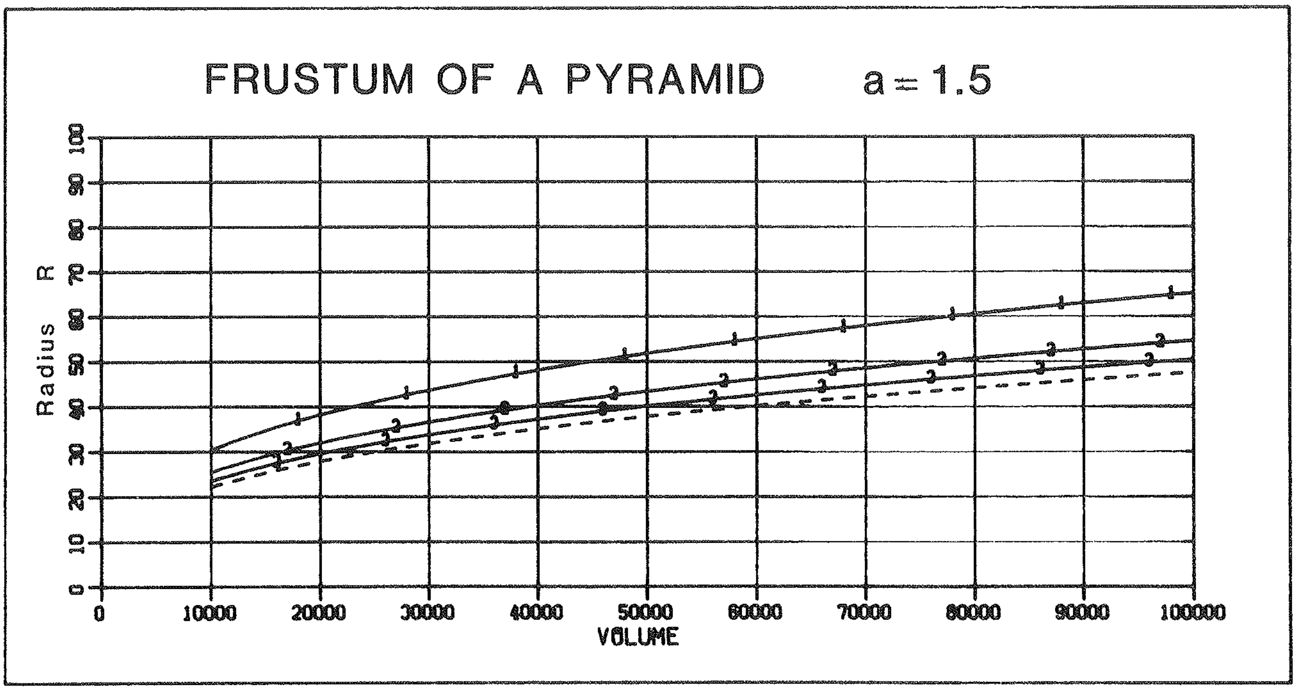
$$\omega = \frac{4R^2((2 - a\alpha)\,\alpha\sqrt{a^2 + 1} + (1 - a\alpha)^2\ )}{4\alpha R^3(1 - a\alpha\ +\ \frac{a^2\alpha^2}{3})}$$

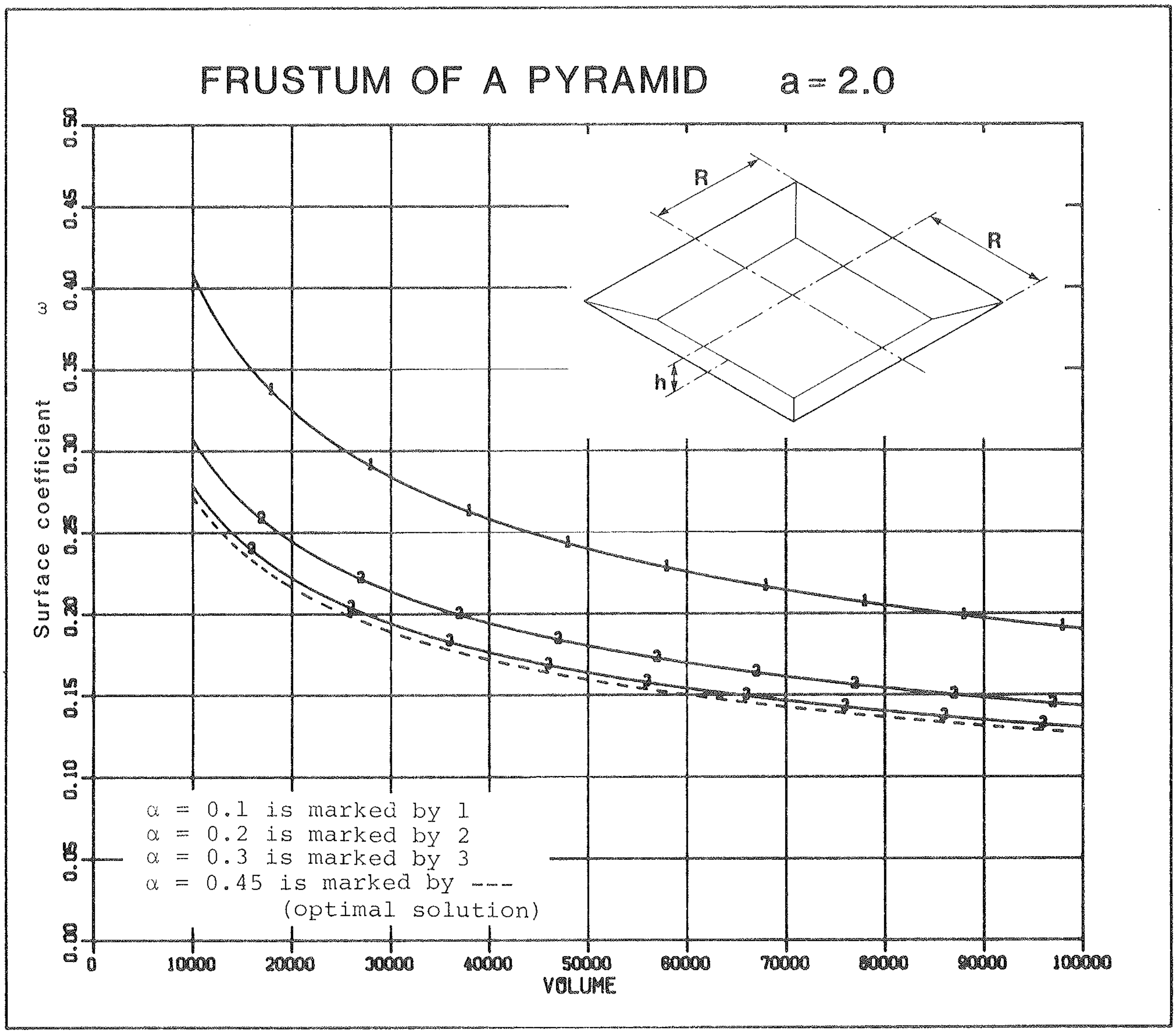
$$= \frac{\sqrt[3]{4}\cdot(\alpha\sqrt{a^2 + 1}\cdot(2 - a\alpha)\ +\ (1 - a\alpha)^2\ )}{\alpha^{2/3}\ (1 - a\alpha\ +\ \frac{\alpha^2 a^2}{3})^{2/3}}\cdot V^{-1/3}$$

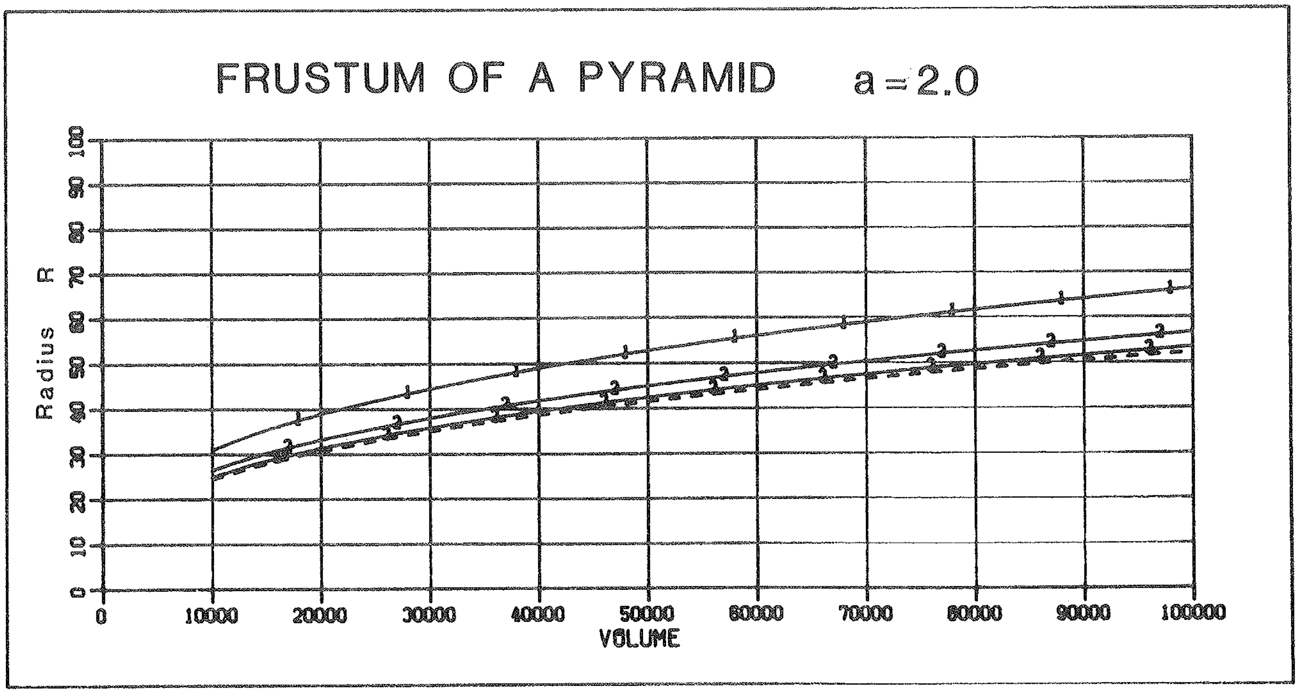

FRUSTUM OF A PYRAMID a = 0.5
Surface coefficient ω
R
R
h
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.89 is marked by ---
(optimal solution)
VOLUME

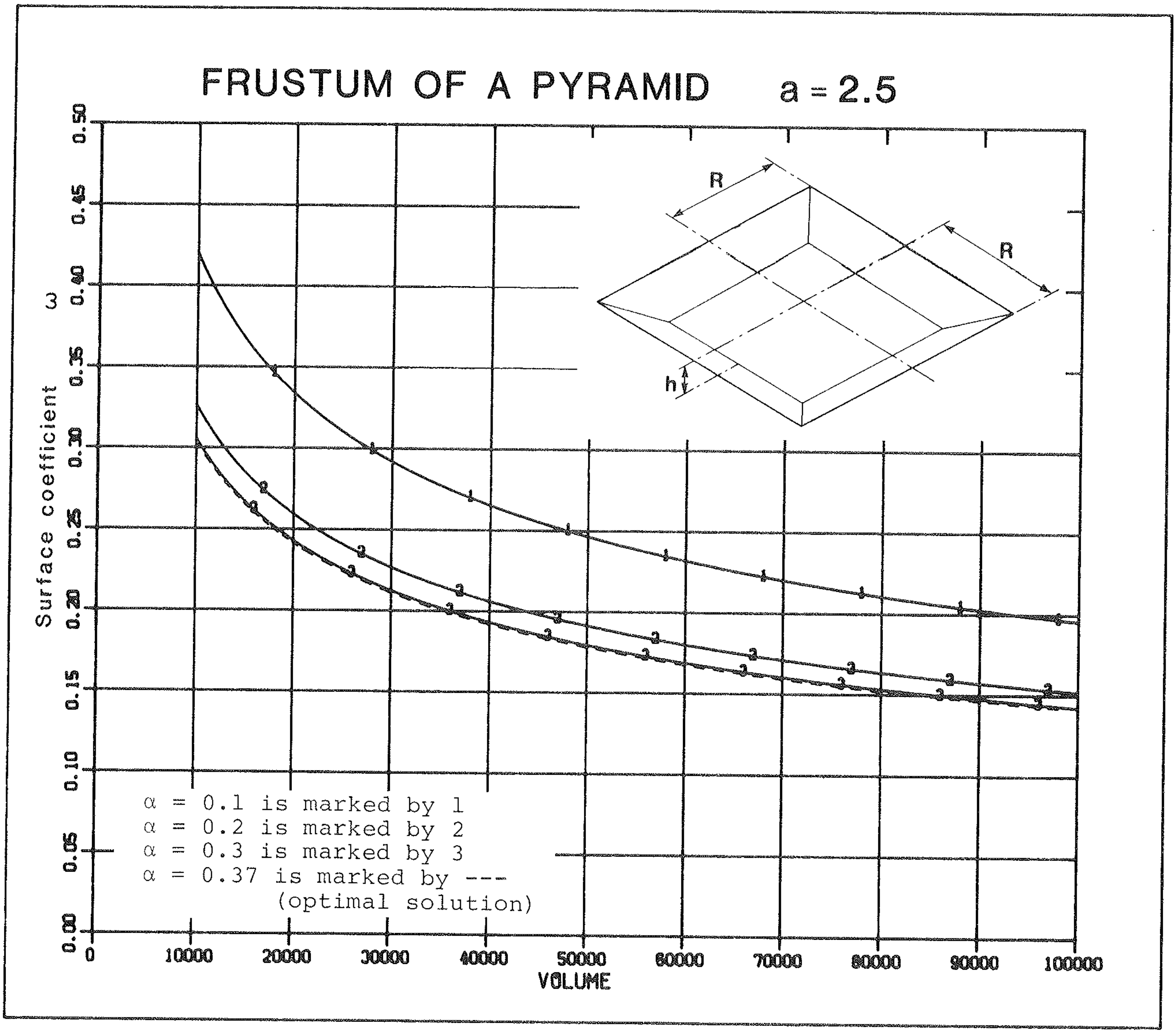

FRUSTUM OF A PYRAMID a = 0.5
Radius R
VOLUME

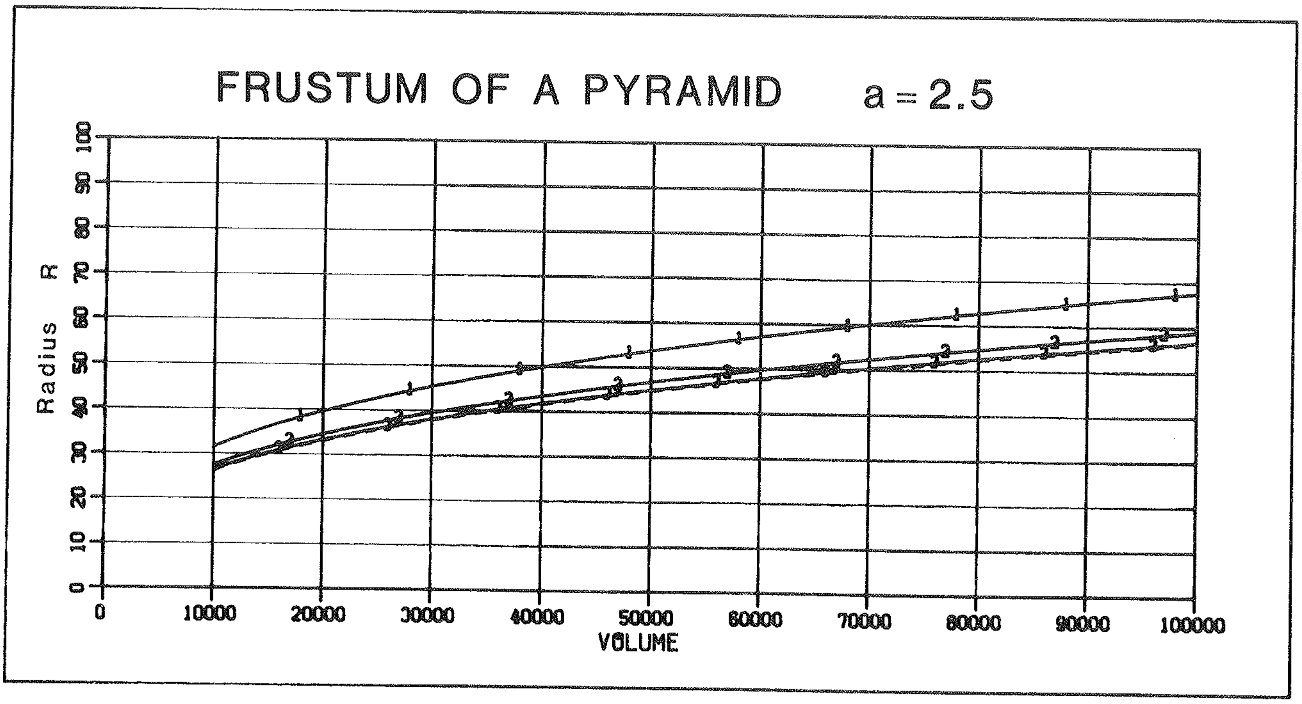

FRUSTUM OF A PYRAMID a = 1.5
R
R
h
Surface coefficient ω
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.55 is marked by ---
(optimal solution)
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME


FRUSTUM OF A PYRAMID a = 1.5
Radius R
0
10
20
30
40
50
60
70
80
90
100
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME

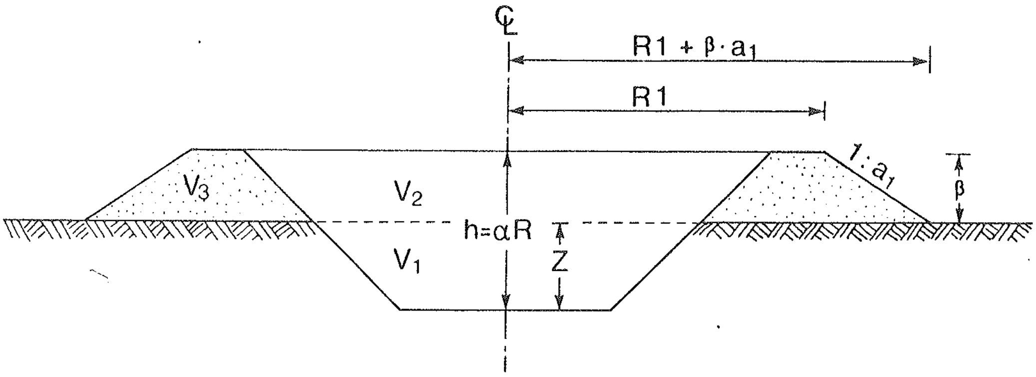

FRUSTUM OF A PYRAMID a = 2.0
Surface coefficient ω
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME
R
R
h
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.45 is marked by ---
(optimal solution)


FRUSTUM OF A PYRAMID a = 2.0
Radius R
0
10
20
30
40
50
60
70
80
90
100
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME


FRUSTUM OF A PYRAMID a = 2.5
R
R
h
Surface coefficient ω
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.37 is marked by ---
(optimal solution)
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME


FRUSTUM OF A PYRAMID a = 2.5
Radius R
0
10
20
30
40
50
60
70
80
90
100
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
VOLUME

DIRT-BALANCE FOR THE FRUSTUM OF A CONE



From $V = V_2 + V_3$ (and $V = V_1 + V_2$) follows

$$V = \frac{\pi \cdot \beta}{3} \left((R1 + \beta \cdot a_1)^2 + (R1 + \beta \cdot a_1) R1 + R1^2 \right)$$

⇒

$$\frac{3V}{\pi} = 3 \cdot \beta \cdot R1^2 + \beta^3 \cdot a_1^2 + 3 \cdot \beta^2 \cdot R1 \cdot a_1$$

⇒

$$0 = \beta^3 + \frac{3 \cdot R1}{a_1} \beta^2 + \frac{3 \cdot R1^2}{a_1^2} \beta + \left(- \frac{3 \cdot V}{\pi \cdot a_1^2} \right)$$

This equation can be solved by manual with

$$A = \frac{3 \cdot R1}{a_1}$$

$$B = \frac{3 \cdot R1^2}{a_1^2}$$

$$C = - \frac{3 \cdot V}{\pi \cdot a_1^2}$$

Substituting $\beta = y - \frac{A}{3}$ we obtain

$$0 = y^3 + p \cdot y + q$$

with

$$p = B - \frac{1}{3} \cdot A^2 = \frac{3 \cdot Rl^2}{a_1^{\ 2}} - \frac{1}{3} \left(\frac{3 \cdot Rl}{a_1}\right)^2 = 0$$

$$q = C + \frac{2}{27} \cdot A^3 - \frac{1}{3} \cdot AB$$

The solution of the equation $y^3 + g = 0$ is

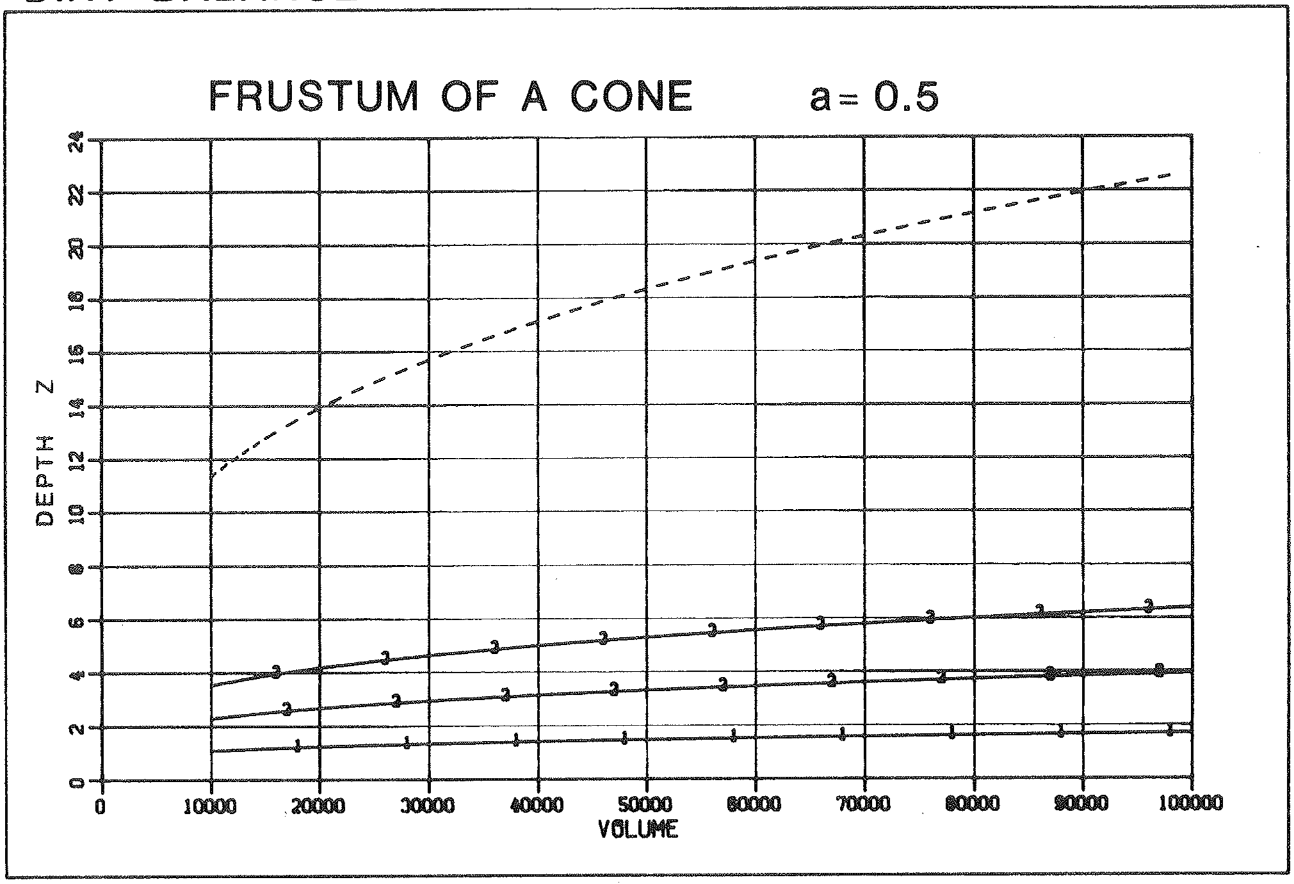
$$y = \sqrt[3]{-q}$$

and $\beta = y - \frac{A}{3} = \sqrt[3]{-q} - \frac{A}{3}$

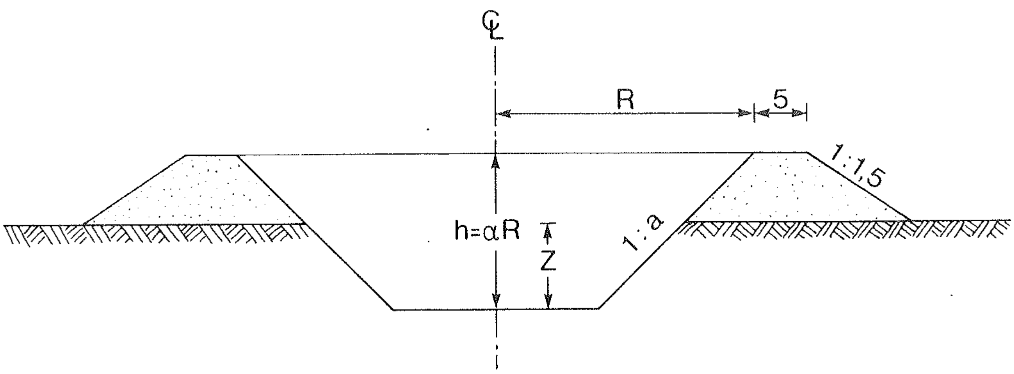
As Z is concerned, we have

$$Z = \alpha R - \left((-q)^{1/3} - \frac{A}{3}\right) = \alpha R + \frac{A}{3} - (-q)^{1/3}$$

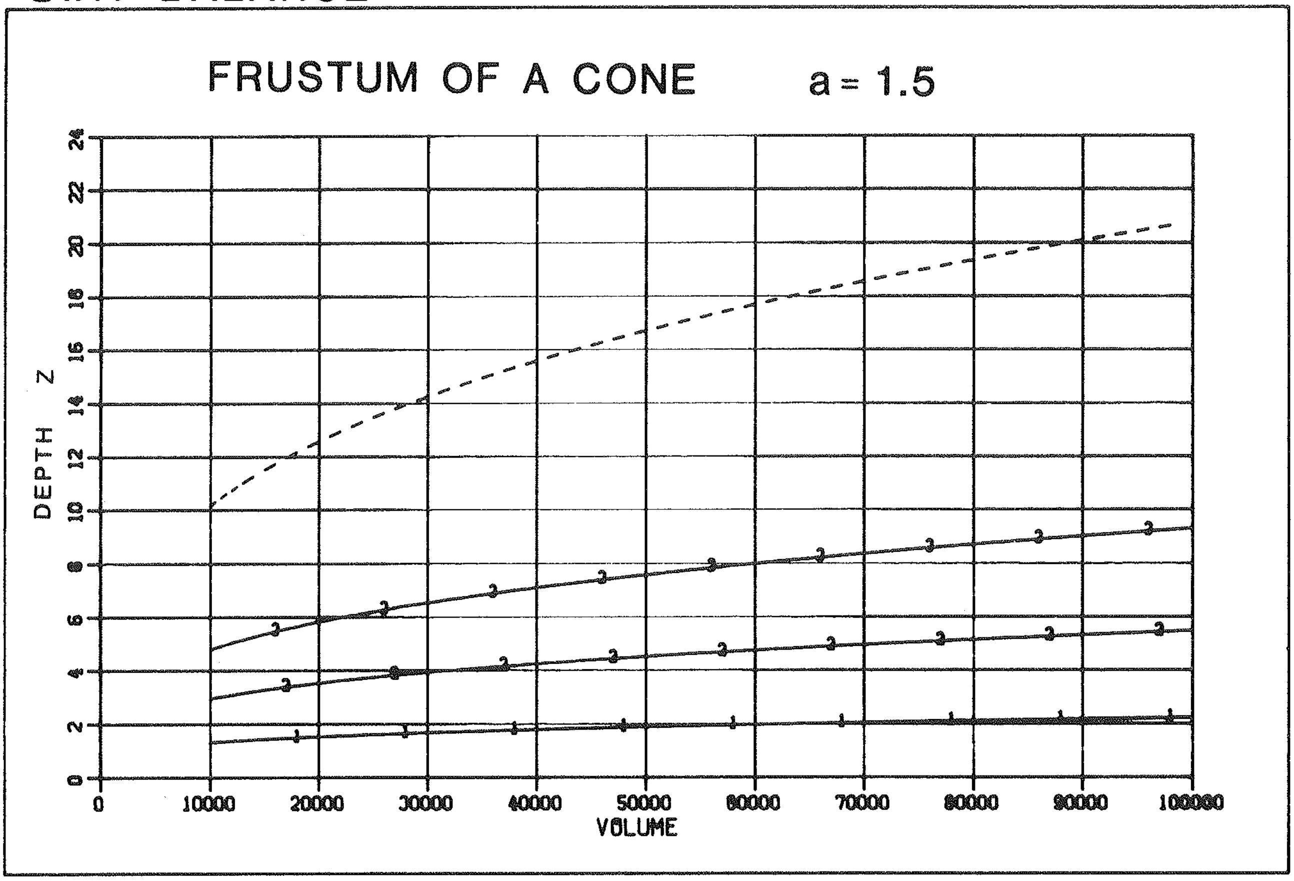
DIRT-BALANCE



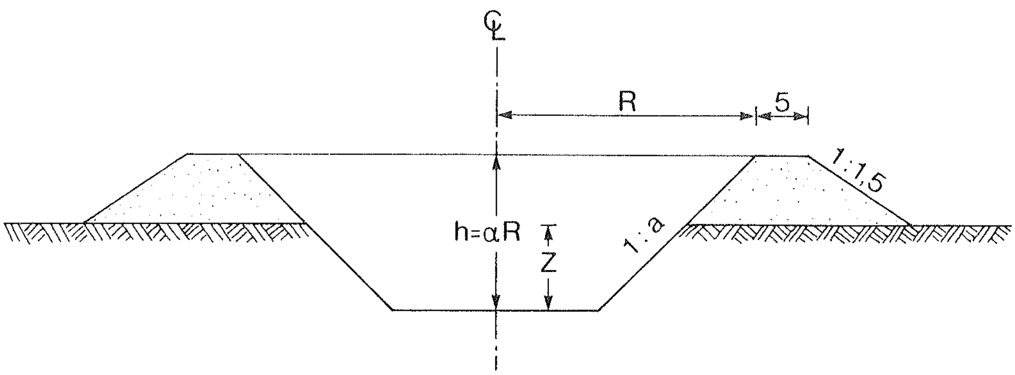
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.89 is marked by ---
(optimal solution)



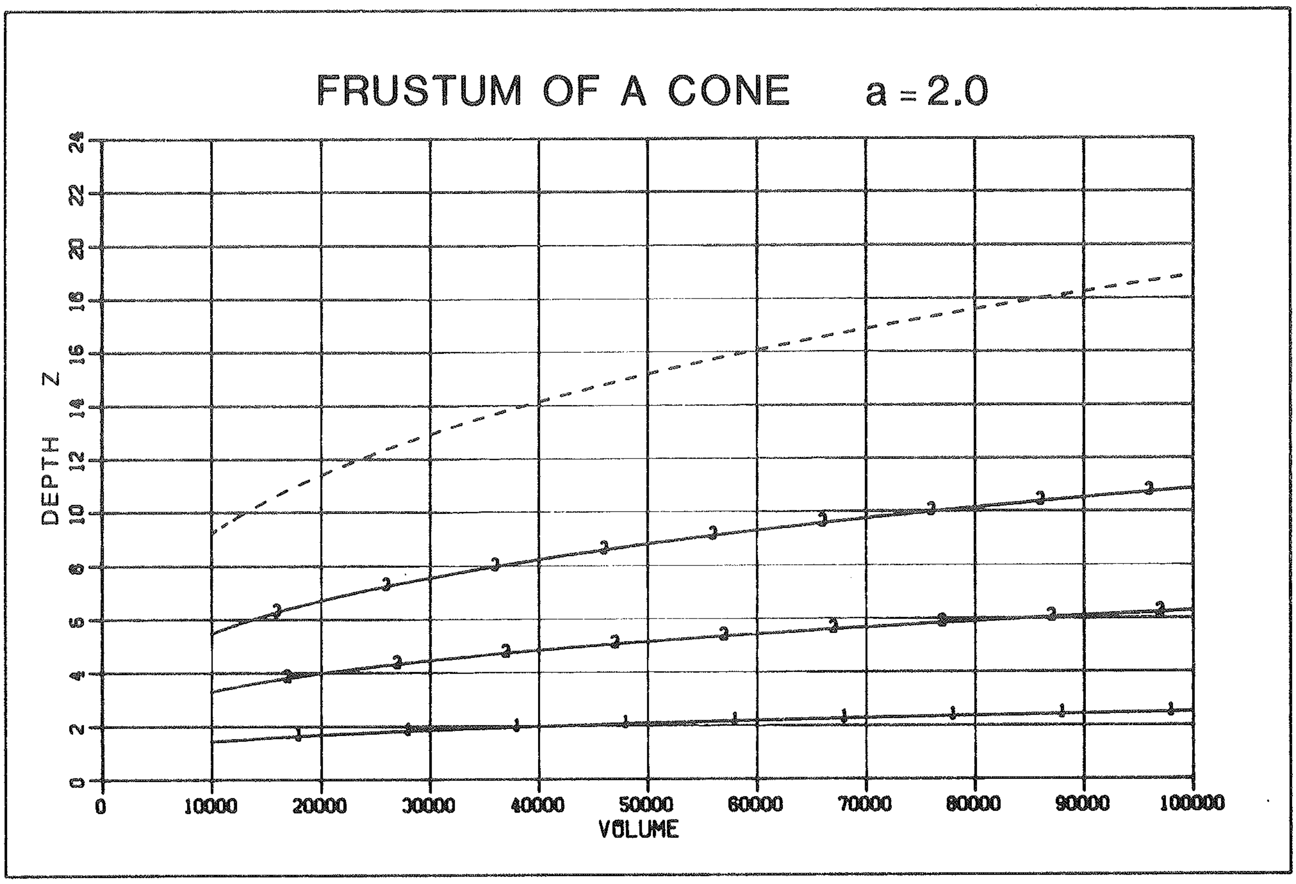
DIRT-BALANCE



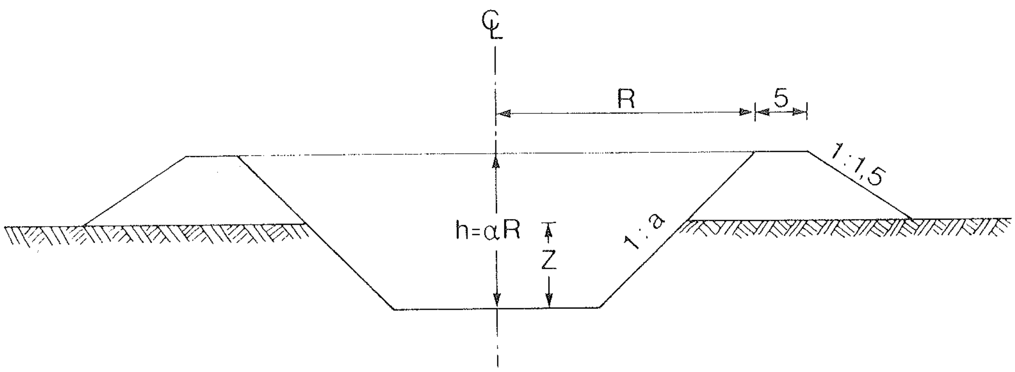
α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.55 is marked by ---
(optimal solution)



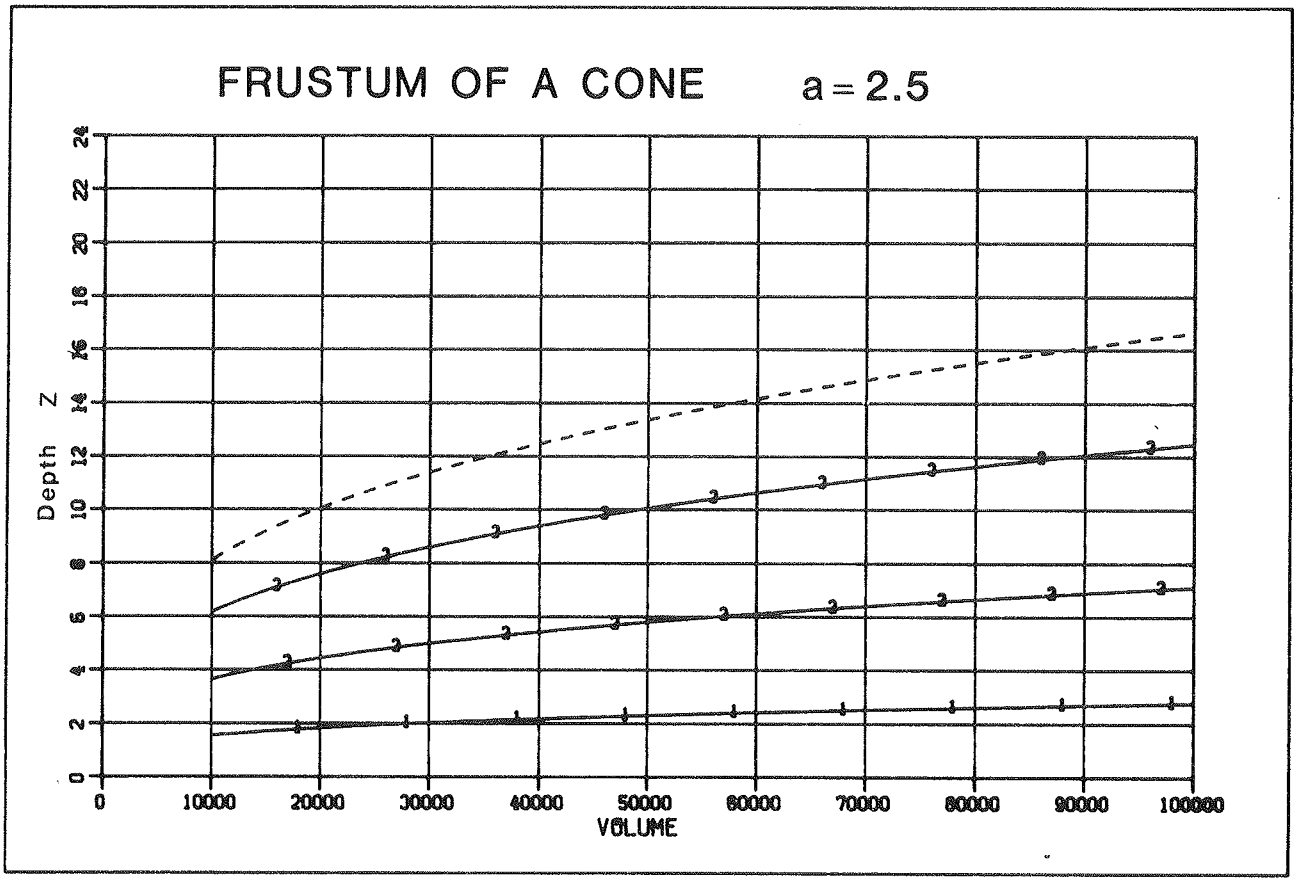
DIRT - BALANCE



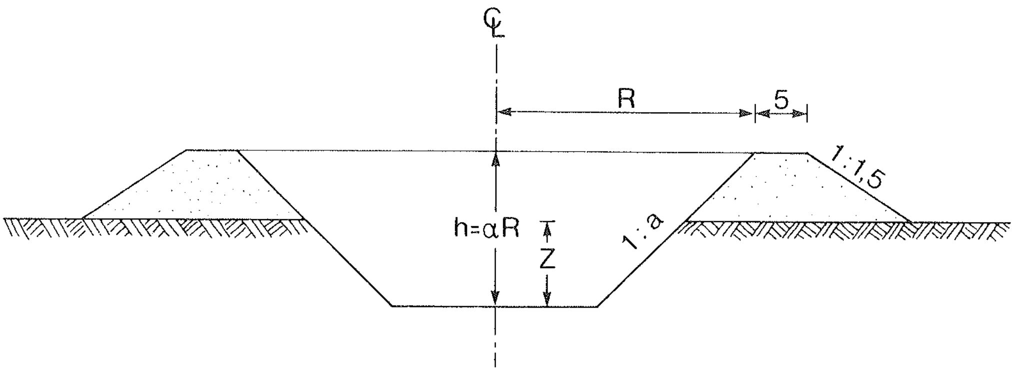
α = 0,1 is marked by 1
α = 0,2 is marked by 2
α = 0,3 is marked by 3
α = 0,45 is marked by ---
(optimal solution)



DIRT-BALANCE



α = 0.1 is marked by 1
α = 0.2 is marked by 2
α = 0.3 is marked by 3
α = 0.37 is marked by ---
(optimal solution)



APPENDIX 1

In this appendix the module M is defined as

$$M = \text{module} = \frac{\text{volume}}{\text{soil interface}} = \frac{V}{O} = \frac{1}{\omega} = \frac{1}{\text{surface coefficient}}$$

I)

Choosing $x = 1/a$ M is maximum when

$$b = \frac{R}{r} = \frac{R}{c} = \frac{\sqrt{1 + x^2}}{\sqrt{1 + x^2} - 1}$$

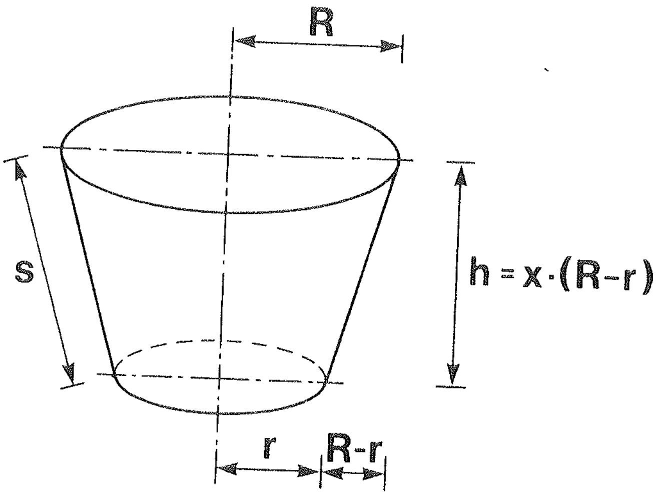
II)

The x-value obtaining the highest M-value is

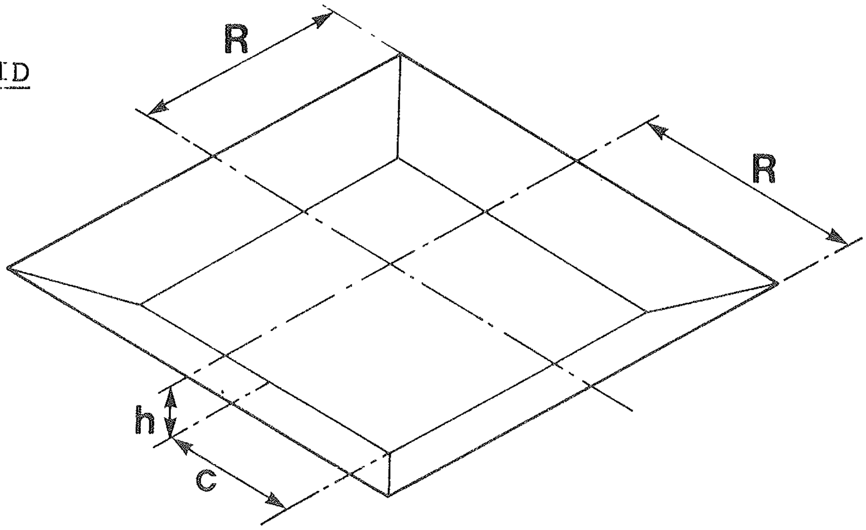
$$x = \sqrt{\frac{14}{9} + \frac{\sqrt{448}}{9}} \simeq 1{,}9767$$

The following calculations are carried out for a frustum of a cone. However, as the terms of M for a frustum of a cone and for a frustum of a pyramid are identically but one constant the calculations will also apply for a frustum of a pyramid.

FRUSTUM OF A CONE



FRUSTUM OF A PYRAMID



Referring to I:

$$b = \frac{R}{r} \Rightarrow R = r \cdot b$$

$$h = x \cdot (R - r)$$

$$s = \sqrt{(R - r)^2 + h^2} = \sqrt{(R - r)^2 + x^2 (R - r)^2}$$

$$= (R - r)\sqrt{1 + x^2}$$

Volume:

$$V = \frac{\pi \cdot h}{3} (R^2 + Rr + r^2)$$

$$= \frac{\pi}{3} x (R - r) \cdot (R^2 + Rr + r^2)$$

$$= \frac{\pi}{3} xr (b - 1) \cdot (b^2 r^2 + br^2 + r^2)$$

$$= \frac{\pi}{3} xr^3 \cdot (b^3 - 1)$$

$\Rightarrow$

$$r = \frac{V^{1/3}}{(\frac{\pi}{3} x (b^3 - 1))^{1/3}}$$

Soil interface:

$$O = \pi r^2 + \pi s (R + r)$$

$$= \pi (r^2 + (R + r)(R - r)\sqrt{1 + x^2})$$

$$= \pi (r^2 + (R^2 - r^2)\sqrt{1 + x^2})$$

$$= \pi (r^2 + (b^2 r^2 - r^2)\sqrt{1 + x^2})$$

$$= \pi r^2 (1 + (b^2 - 1)\sqrt{1 + x^2})$$

$$\frac{V}{O} = \frac{\frac{\pi}{3} x\ r^3 \cdot (b^3 - 1)}{\pi r^2\ (1 + (b^2 - 1)\sqrt{1 + x^2})} \Rightarrow$$

$$\frac{V}{O} = \frac{\frac{1}{3} x\ r\ (b^3 - 1)}{1 + (b^2 - 1)\sqrt{1 + x^2}} \Rightarrow$$

$$\frac{V}{O} = \frac{\frac{1}{3} x \left(\frac{V}{\frac{\pi}{3} x\ (b^3 - 1)}\right)^{1/3} (b^3 - 1)}{1 + (b^2 - 1)\sqrt{1 + x^2}} \Rightarrow$$

$$\boxed{\frac{V}{O} = \frac{(1/3)^{2/3} \cdot x^{2/3} \cdot \pi^{-1/3} \cdot V^{1/3} \cdot (b^3 - 1)^{2/3}}{1 + (b^2 - 1)\sqrt{1 + x^2}}}$$

When the slope a is given the maximum V/O value for the relation between volume and soil interface can be found by differentiation and assumed equal to zero. As x is a constant the equation can be simplified to

$$\frac{V}{O} = \frac{k \cdot (b^3 - 1)^{2/3}}{1 + (b^2 - 1)\sqrt{1 + x^2}} \quad \text{, with } k = (1/3)^{2/3} \cdot x^{2/3} \cdot \pi^{-1/3} \cdot V^{1/3} = \text{constant value}$$

When $\frac{\partial (V/O)}{\partial b}$ is equal to O, the differential equation is:

$$\frac{\partial (V/O)}{\partial b} = \frac{2/3 \cdot (b^3 - 1)^{-1/3} \cdot 3\, b^2}{1 + (b^2 - 1)\sqrt{1 + x^2}} - \frac{(b^3 - 1)^{2/3} \cdot 2b\sqrt{1 + x^2}}{(1 + (b^2 - 1)\sqrt{1 + x^2})^2} = 0$$

$\Rightarrow$

$$\frac{b}{1 + (b^2 - 1)\sqrt{1 + x^2}} - \frac{(b^3 - 1)\sqrt{1 + x^2}}{(1 + (b^2 - 1)\sqrt{1 + x^2})^2} = 0$$

$\Rightarrow$

$$b + (b^3 - b)\sqrt{1 + x^2} - b^3\sqrt{1 + x^2} + \sqrt{1 + x^2} = 0$$

$\Rightarrow$

$$b \cdot (1 - \sqrt{1 + x^2}) + \sqrt{1 + x^2} = 0$$

$\Rightarrow$

$$\boxed{b = \frac{\sqrt{1 + x^2}}{\sqrt{1 + x^2} - 1}}$$

Referring to II: The x-value which gives highest M-value.

The starting point is the following equation from I:

$$\frac{V}{O} = \frac{(1/3)^{2/3} \cdot x^{2/3} \cdot \pi^{-1/3} V^{1/3} \cdot (b^2 - 1)^{2/3}}{1 + (b^2 - 1)\sqrt{1 + x^2}}$$

Substituting $\sqrt{1 + x^2}$ by y we have

$$y = \sqrt{1 + x^2} \Rightarrow y^2 = 1 + x^2 \Rightarrow x = (y^2 - 1)^{\frac{1}{2}}$$

and

$$b = \frac{y}{y - 1} = \frac{\sqrt{1 + x^2}}{\sqrt{1 + x^2} - 1}$$

Inserting this value

$$\frac{V}{O} = \frac{(\frac{1}{3})^{2/3} ((y^2 - 1)^{1/2})^{2/3} \pi^{-1/3} V^{1/3} (\frac{y^3}{(y - 1)^3} - 1)^{2/3}}{1 + (\frac{y^2}{(y - 1)^2} - 1) y}$$

$$= \frac{k_1 \cdot (y^2 - 1)^{1/3} \cdot (3y^2 - 3y + 1)^{2/3}}{3y^2 - 3y + 1}$$

$$= k_1 (\frac{y^2 - 1}{3y^2 - 3y + 1})^{1/3}$$

$\Rightarrow$

$$(\frac{V}{O})^3 = k_1^{\ 3} \frac{y^2 - 1}{3y^2 - 3y + 1} \text{, with}$$

$$k_1 = (\frac{1}{3})^{2/3} \pi^{-1/3} V^{1/3} = \text{constant value}$$

The maximum relation between volume and soil interface can once again be found by differentation and assumed equal to 0:

$$\frac{\partial (V/O)}{\partial y} = 0$$

$\Rightarrow$

$$\frac{\partial (V/O)}{\partial y} = \frac{2y}{3y^2 - 3y + 1} + \frac{(-y^2 + 1)(6y - 3)}{(3y^2 - 3y + 1)^2} = 0$$

$\Rightarrow$

$$-3y^2 + 8y - 3 = 0$$

$\Rightarrow$

$$y = \frac{4}{3} \pm \frac{\sqrt{7}}{3}$$

Where $y = \sqrt{x^2 + 1}$ we have

$$x^2 + 1 = y^2$$

$\Rightarrow$

$$x^2 + 1 = \left(\frac{4}{3} \pm \frac{\sqrt{7}}{3}\right)^2$$

$\Rightarrow$

$$x = \sqrt{\frac{14}{9} \underset{(-)}{+} \frac{\sqrt{448}}{9}} = 1{,}9767$$

Frustum of a cone + Frustum of a pyramid

Appendix 1 shows:

I)

When a is chosen ω is minimum i.e. optimum solution, when

$$\frac{r}{R} = \frac{R(1 - a\alpha)}{R} = \frac{\sqrt{1 + \frac{1}{a^2}} - 1}{\sqrt{1 + \frac{1}{a^2}}}$$

$\Rightarrow$

$$\alpha = \frac{1}{a} \cdot \left(1 - \frac{\sqrt{1 + \frac{1}{a^2}} - 1}{\sqrt{1 + \frac{1}{a^2}}}\right)$$

II)

The a-value which has the lowest ω is

$$a = \frac{1}{x} \simeq 0{,}5059$$

with $x = \sqrt{\frac{14}{9} + \frac{\sqrt{448}}{9}} \simeq 1{,}9767$

GEOTECHNICAL INVESTIGATIONS
FOR UNDERGROUND HEAT STORAGE

BY

DANISH GEOTECHNICAL INSTITUTE

MARCH 1984

Danish
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Annex II

Your ref. Our ref. K82390 CBM/BEL Date 1984-02-29

Esbjerg. Heat storage in large reservoirs.
Geotechnical report No 2b and enclosures Nos 1a - 11a.

1. Summary

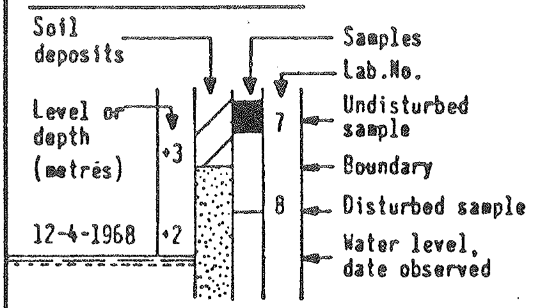
In connection with considerations of placing a 50.000 m^3 warm water store in the vicinity of the power station at Esbjerg, a boring 17.5 m deep was first made at a former clay pit approx. 2500 m from the power station. The results of this boring - which are attached to the report as enclosures Nos 10a - 11a - showed at 4-meter sand layer from 9 to 13 meters below ground level. This fact, combined with the considerations of the operation technology of the warm water store, resulted in the investigations mentioned below with regard to positioning of the store at a distance of approx. 500 m from the power station. In this new position - which can be seen at enclosure No 1 - a boring 22 m deep has been made for illustration of soil and water level conditions by excavation down to level approx.-9.2 in Esbjerg's Yoldia clay. The results of this boring can be seen in enclosures Nos 3a - 5a.

The boring shows that the clay contains a few sand embedments, which will necessitate either an enclosing sheet pile or a provisional lowering of the ground water level during performance of the work, just as the deep excavation will make construction of bleeder wells necessary.

LEGEND FOR DEPOSITS:

Stones (60 mm)	Clayey stony sand (moraine sand)	Top soil	Fill
Gravel (2 mm)	Sandy stony clay (boulder clay)	Peat	Organic silt
Sand (0,06 mm)	Silty sand	Peaty organic silt, Mud	
Silt (0,002 mm)	Limestone or chalk	Organic silt, Mud	
Clay	Rock	Shells	

LEGEND FOR BORING LOGS:



LEGEND FOR SITE PLANS:

- Boring with soil sampling
- Test pit with soil sampling
- Test pit
- Weighted drill point sounding
- Static sounding
- Dynamic sounding
- Vane test
- Loading test
- Settlement observations
- Pore pressure measurement

DEFINITIONS:

Water content	w	= Weight of water in per cent of weight of solids.
Liquid limit	w_L	= Water content at the transition from liquid to plastic state.
Plastic limit	w_P	= Water content at the transition from plastic to semi-solid state.
Plasticity index	I_P	= $w_L - w_P$.
Void ratio	e	= Ratio of volume of voids to volume of solids.
Porosity	n	= - - - - - - - - total.
Degree of saturation	S_r	= Degree of saturation in volume of voids.
Max. void ratio	e_{max}	= Void ratio of soil in loosest state by standard laboratory test.
Min. void ratio	e_{min}	= Void ratio of soil in densest state by standard laboratory test.
Density index	I_D	= Relative density = $(e_{max} - e)/(e_{max} - e_{min})$.
Bulk density (kN/m^3)	γ	= Ratio of total weight to total volume.
Unit weight (kN/m^3)	γ_s	= Mean unit weight of solid constituents.
Organic content	gl	= Weight loss by long time glowing, in per cent of original dry weight.
Lime content	ka	= Weight of $CaCO_3$ in per cent of original dry weight.
Vane strength (kN/m^2)	c_v	= Undrained shear strength measured by vane test in undisturbed deposits.
Vane strength (kN/m^2)	c'_v	= Undrained shear strength measured by vane test (remoulded, 10×360^0).

S : Grain size analysis
SP : Standard Proctor test
K : Consolidation test
T_1 : Unconfined compression test
T_3 : Triaxial test

} Referring from boring logs to special enclosures.

c_v and c'_v (from vane tests) are not valid directly when testing:

a. Sand, silt, or soils with large contents of these fractions,
b. Fissured clay (e.g. Little Belt Clay, Septarian Clay).

THE DANISH GEOTECHNICAL INSTITUTE | LEGEND AND DEFINITIONS

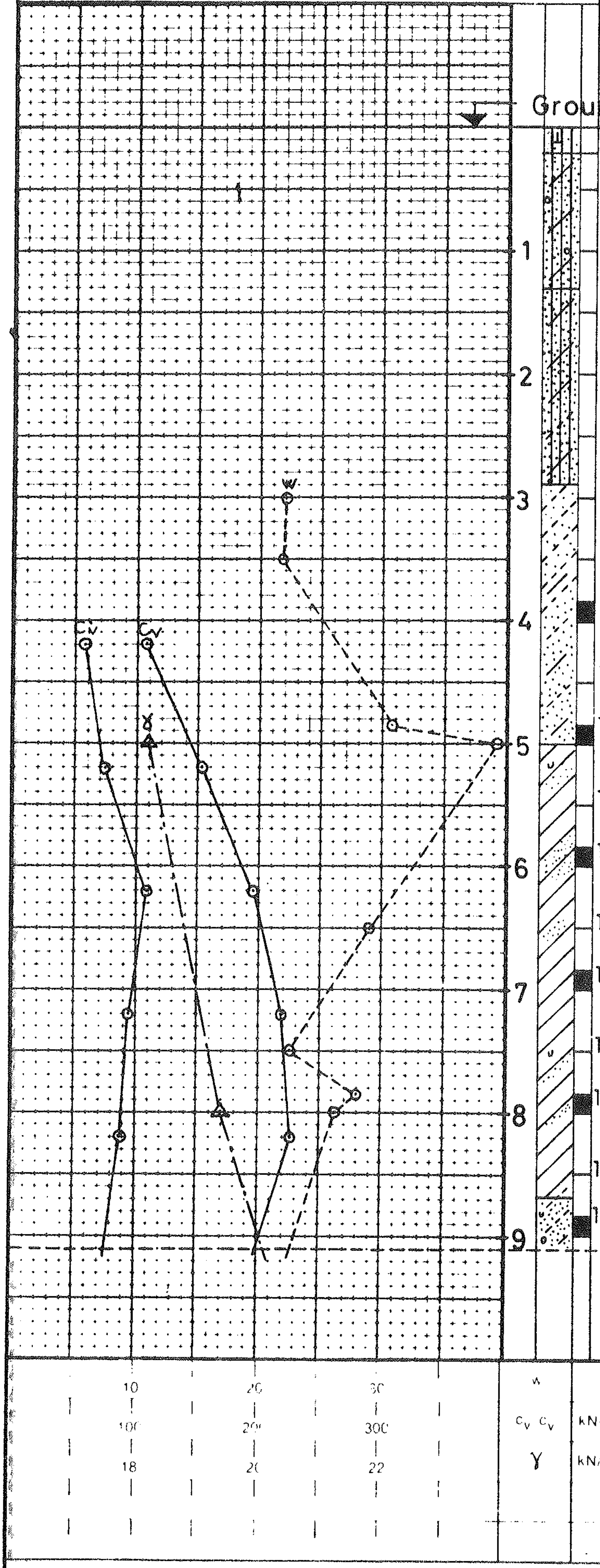
Ref.: K 92330

GEOLOGICAL ABBREVIATION

78

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	D
Slidedebris	Sk			Senon	S

Annex II



Lab. No.	Soil type / Description	Deposit	Age
	Boring No. 1		
1	FILL:Topsoil,sandy w/roots		
2	" :SAND,fine,clayey,slightly gravelly		
3	" : " " " ,w/topsoil		
4	" : " " ,w/clayey topsoil		
5	" : " " ,clayey w/topsoil and roots		
6	" : " " ,silty,clayey		
7	SILT,sandy w/ferrous sulphide and micaceous clay	M	G[1]
8	" ,clayey,sandy w/ferrous sulphide	"	"
9	SAND,very fine,silty w/lumbs of clay and w/fer. sulp. and mic.clay	"	"
10	" ,very fine,silty,w/lumbs of clay and w/fer. sulp. and mic.clay	"	"
11	CLAY,fat w/fer.sulp.,mic.clay and fragments of shells	"	"
12	" ,fat w/fer.sulp. and mic.clay	"	"
13	" , " " " " " " and SAND,fine	"	"
14	" , " " " " " " " " "	"	"
15	" , " " " " " "	"	"
16	" , " " " " " " ,and sandy streaks	"	"
17	" , " " " " " " " " "	"	"
18	" ,rather fat w/fer.sulp. and mic.clay and fine sand	"	"
19	SAND,fine,silty w/fer.sulp. and mic.clay and SAND,clayey,silty	"	"

to be continued

Danish Geotechnical Institute
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BORING LOG

Job No.: K82390 ESBJERG			
Bor. made: 83-03-28/29	Dess.: LTE.	Cont.:	Boring No.: 1
by: AC/JC	Appr.: CBK	84-02-07	Encl. No.: 10a

Legend and Definitions on encl. No.:

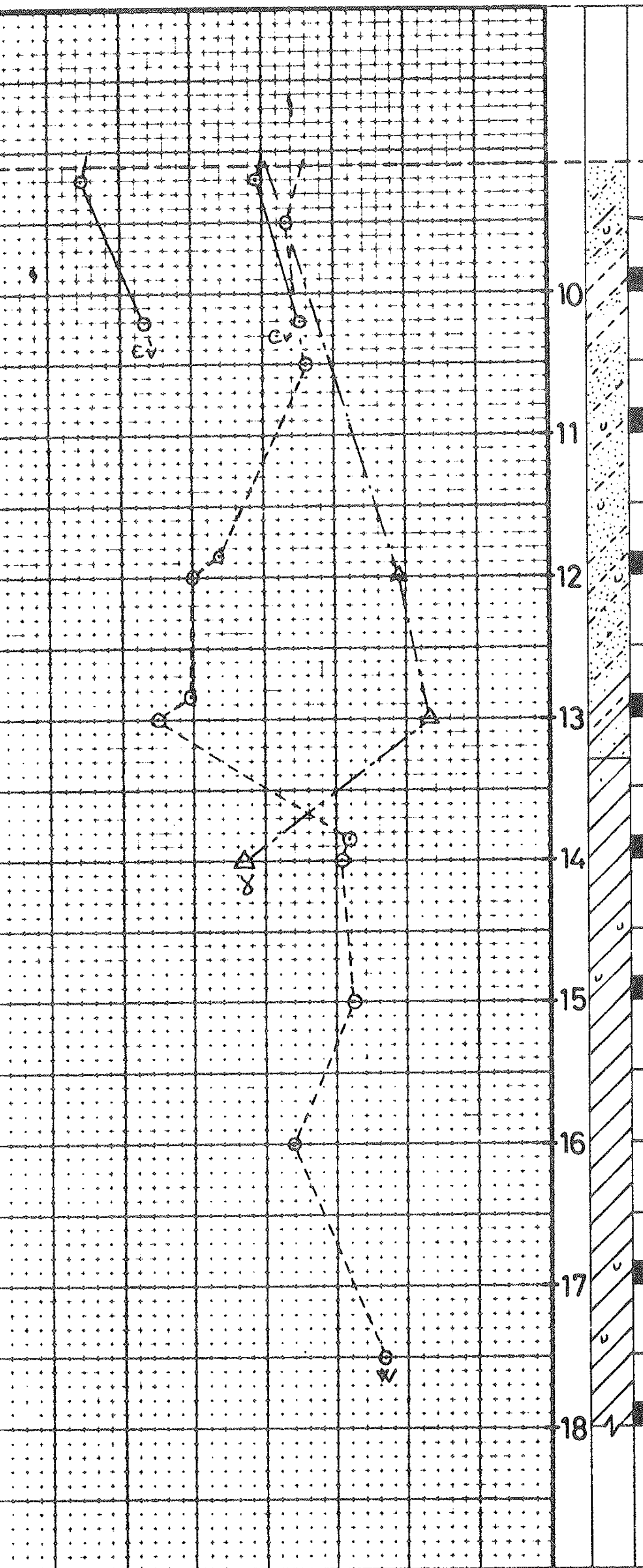
EOLOGICAL ABBREVIATION

Annex II

Deposit: Freshwater F, Solifluction Fl, Glacial Gl, Marine M, Wash down N, Top soil O, Slidedebris Sk, Meltwater Sm, Wash out U, Aeolian V

Age: Postglacial P, Lateglacial S, Glacial G, Interglacial I, Tertiary T, Danien Da, Senon Se

trength measurements
lassification tests



Boring No. 1, continued

Lab. No.	Soil type / Description	Deposit	Age
20	SAND, very fine, slightly clayey w/ferrous sulphide and micaceous clay	M	G[1)]
21	SILT, sandy w/fer.sulp. and sandy streaks	"	"
22	SAND, very fine w/fer.sulp. and organic contents	"	"
23	" " " " " and mic.clay	"	"
24	" " " " " " " "	"	"
25	" " " and SILT w/fer.sulp.and mic.clay	"	"
26	" " " w/fer.sulp.and mic.clay and organic contents	"	"
27	CLAY, silty, sandy w/mic.clay	"	"
28	" , rather fat w/mic.clay	"	T[2)]
29	" " " " "	"	"
30	" " " " "	"	"
31	" " " " "	"	"
32	" " " " "	"	"
33	" " " " "	"	"
34	" " " " "	"	"
35	" " " " "	"	"
36	" " " " "	"	"
37	" " " " "	"	"

1) Esbjerg Yoldia-clay. Flake?
2) Micaceous clay. Flake?

10	20	30	w			
100	200	300	c_v C_v	kN/m²		
18	20	22	γ	kN/m³		

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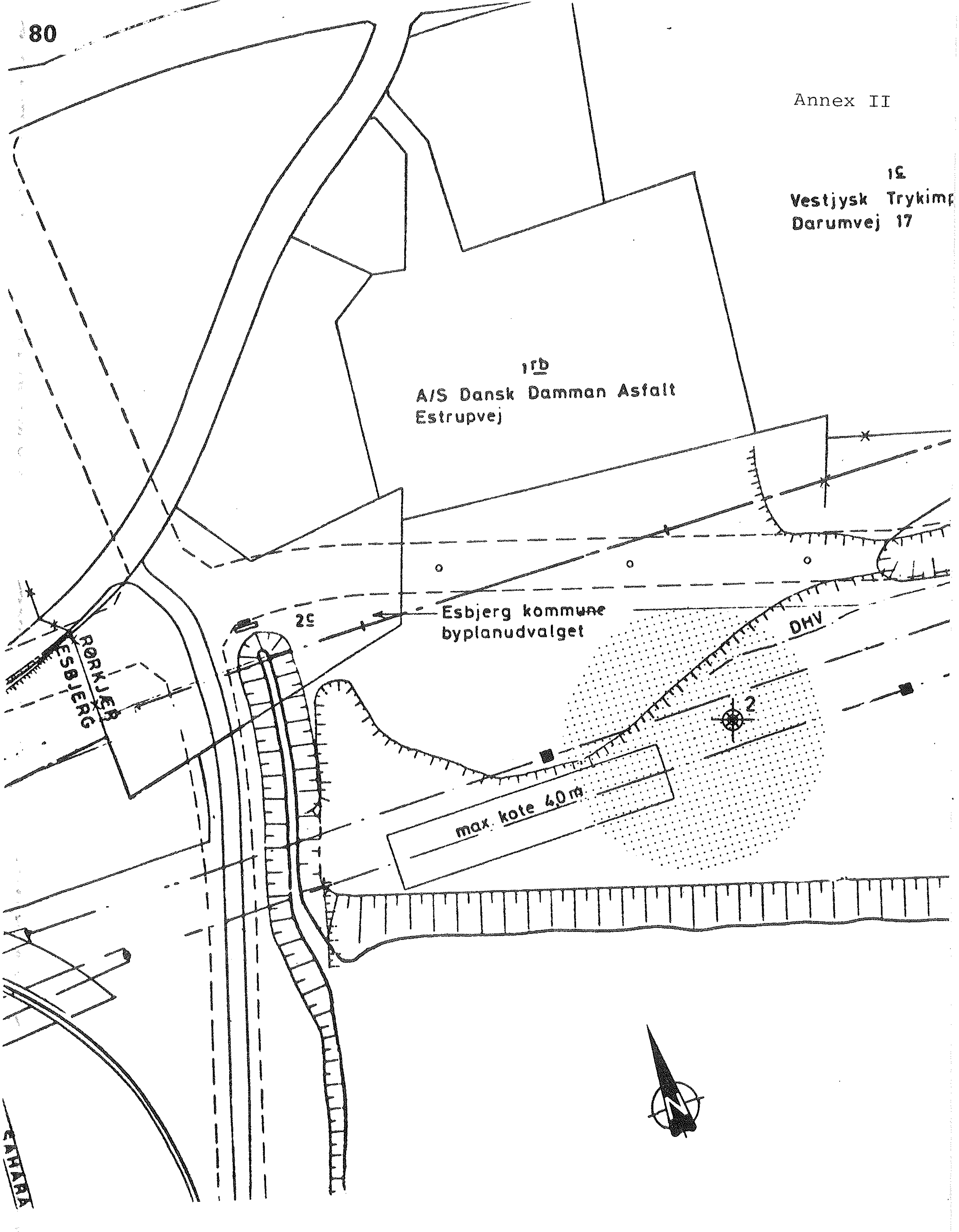
BORING LOG

Job No.: K82390 ESBJERG

Bor. made: 83-03-28/30 | Dess.: LTE. | Cont.: | Boring No.: 1
by: AC/JC | Appr.: GSM 84-02-07 | Encl. No.: 11a

Legend and Definitions on encl. No.:

Annex II



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K82390 Esbjerg

SITE PLAN 1:2000

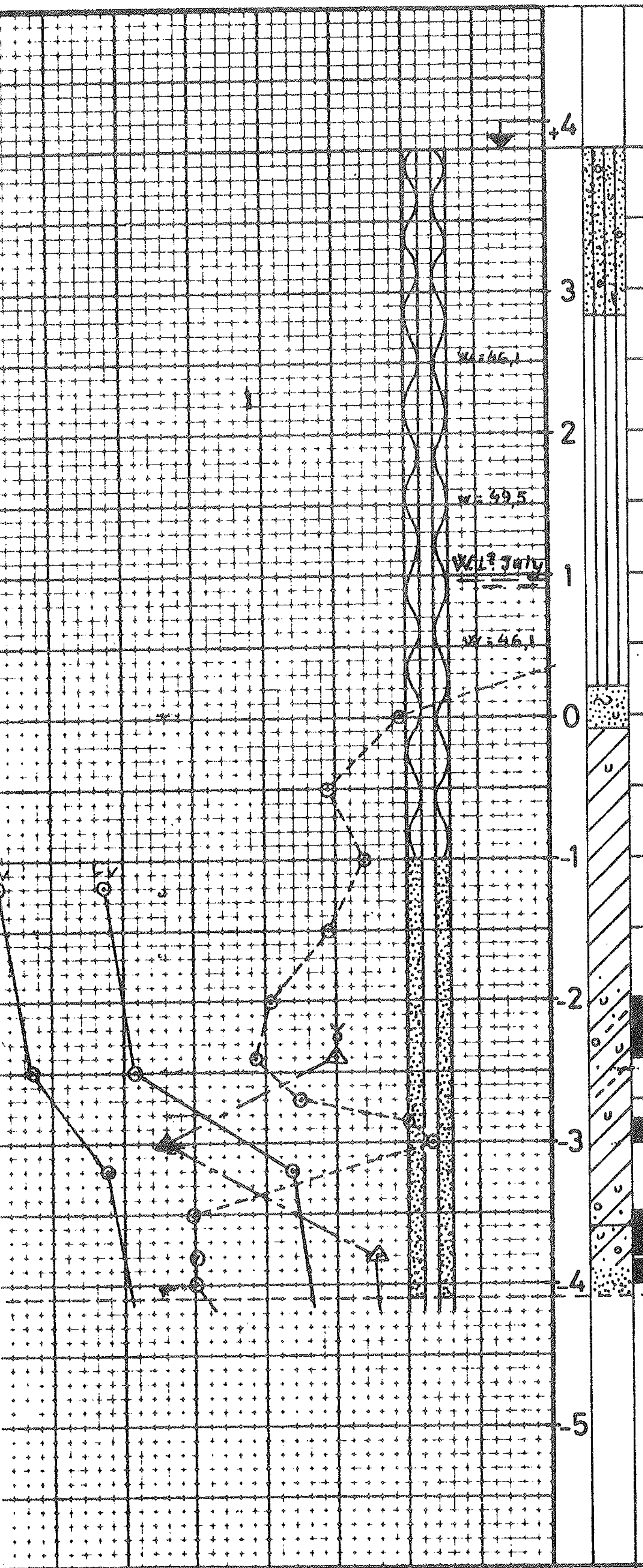
DRAWN BY LTE.	CHECK BY	APPR BY GBy	
DATE 83-11-24	DATE	DATE 83-12-06	ENCL NO 1a

GEOLOGICAL ABBREVIATION

Annex II

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



Level ~~Depth~~	Lab. No.	Soil type / Description	Deposit	Age
+4		Boring No.2		
	38	FILL: Sand, fine, sorted w/gravel and fragments of shells		
3	39	" " " gravelly w/roots		
	40	" Flyash		
2	41	" "		
	42	" "		
1	43	" "		
	44	" "		
0	45	SAND, fine w/organic contents, fragments of shells and ferrous sulphide	M	P
	46	CLAY, rather fat w/fragm. of shells and micaceous clay	Flake °)	G
-1	47	" " " w/lumps of ferrous sulp. and mic.clay	"	"
	48	" "/"	"	"
-2	49	" " " slightly sandy and gravelly w/ fragments of shells	"	"
	f.n.	" silty w/micaceous clay	"	"
	50	" " w/lumps of fer.sulp.and shells	"	"
-3	51	" fat w/micaceous clay	"	"
	52	" "	"	"
	f.n.	CLAY, sandy w/flint and fragments of shells	LM x)	"
-4	53	" " w/ "		
	f.n.	SAND, fine, sorted, slightly clayey	"	"
-5				

°) Esbjerg Yoldia... clay

x) LM: local moraine lithology ...

to be continued

w	°/o
c_v, c_v	kN/m²
γ	kN/m³

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BORING LOG

Job No.: K82390 Esbjerg			
Bor. made: 83-07-21	Dess.: LTE.	Cont.:	Boring No.: 2
by: AC/JL	Appr.: [signature]	83-12-01	Encl. No.: 3a

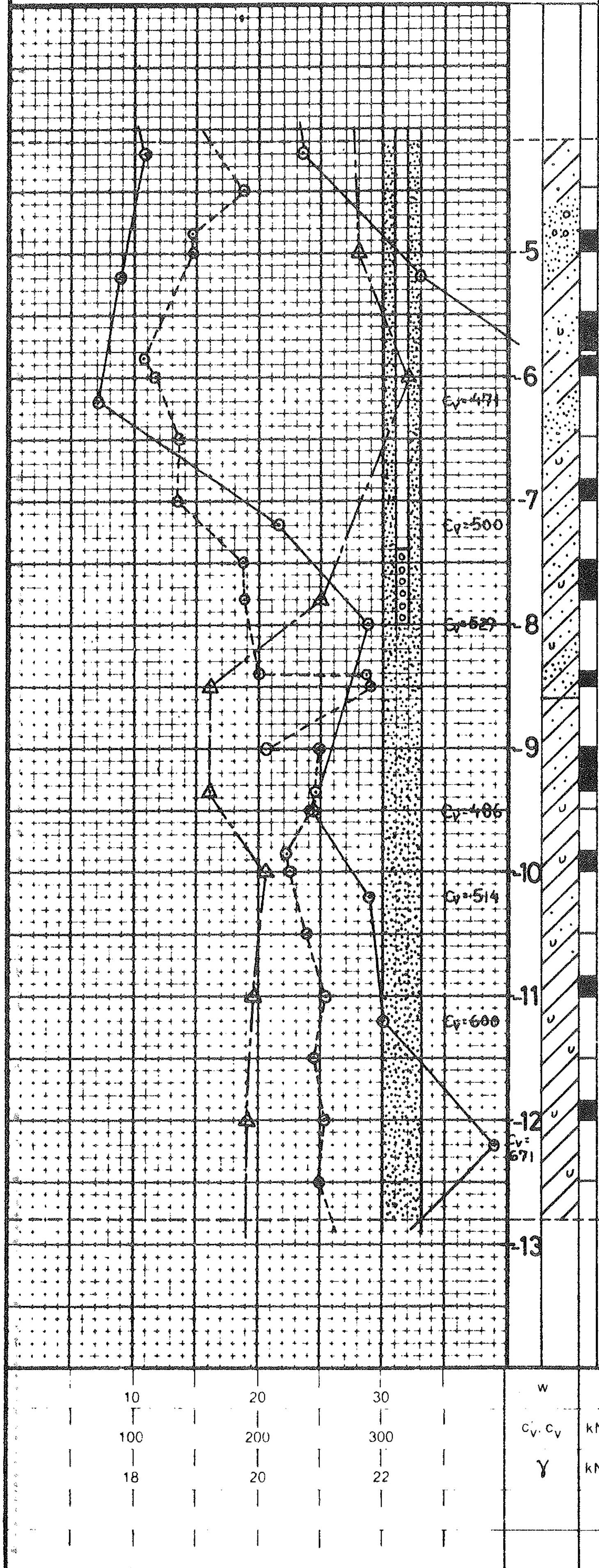
Legend and Definitions on encl. No.: 2

GEOLOGICAL ABBREVIATION

82

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

Annex II



Lab. No.	Soil type / Description	Deposit	Age
	continued Boring No.2		
54	CLAY, fat w/streaks of sand, very fine	LM	G
55	SAND, fine, sorted w/clayey lumps and coarse sand	"	"
f.n.	CLAY, rather fat, slightly sandy w/coarse sand and mic.clay	"	"
56	SAND, fine, sorted	"	"
57	CLAY, sandy w/mic.clay	"	"
f.n.	SAND, clayey "	"	"
58	CLAY, sandy, rather fat w/flint and mic.clay	"	"
59	" , very sandy w/fragment of shells	"	"
60	" " " and SAND	"	"
f.n.	" , sandy, rather fat w/frag.of shells	"	"
61	" " w/SAND and fragments of shells	"	"
62	" " /fat, fissured	"	"
63	" , fat	Flake	"
f.n.	" rather fat w/coarse sand	"	"
64	" , fat w/fragments of shells	"	"
65	" , " " " and mic.clay	"	"
66	" , rather fat	"	"
67	" , fat, fissured	"	"
68	" " w/fragments of shells	"	"
69	" " " "	"	"
70	" " " "	"	"
	to be continued		

Danish Geotechnical Institute

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BORING LOG

Job No.: K82390 Esbjerg			
Bor. made: 83-07-21	Dess.: LTE.	Cont.:	Boring No.: 2
by: AC/JL	Appr.: [signature]	83-12-01	Encl. No.: 4a

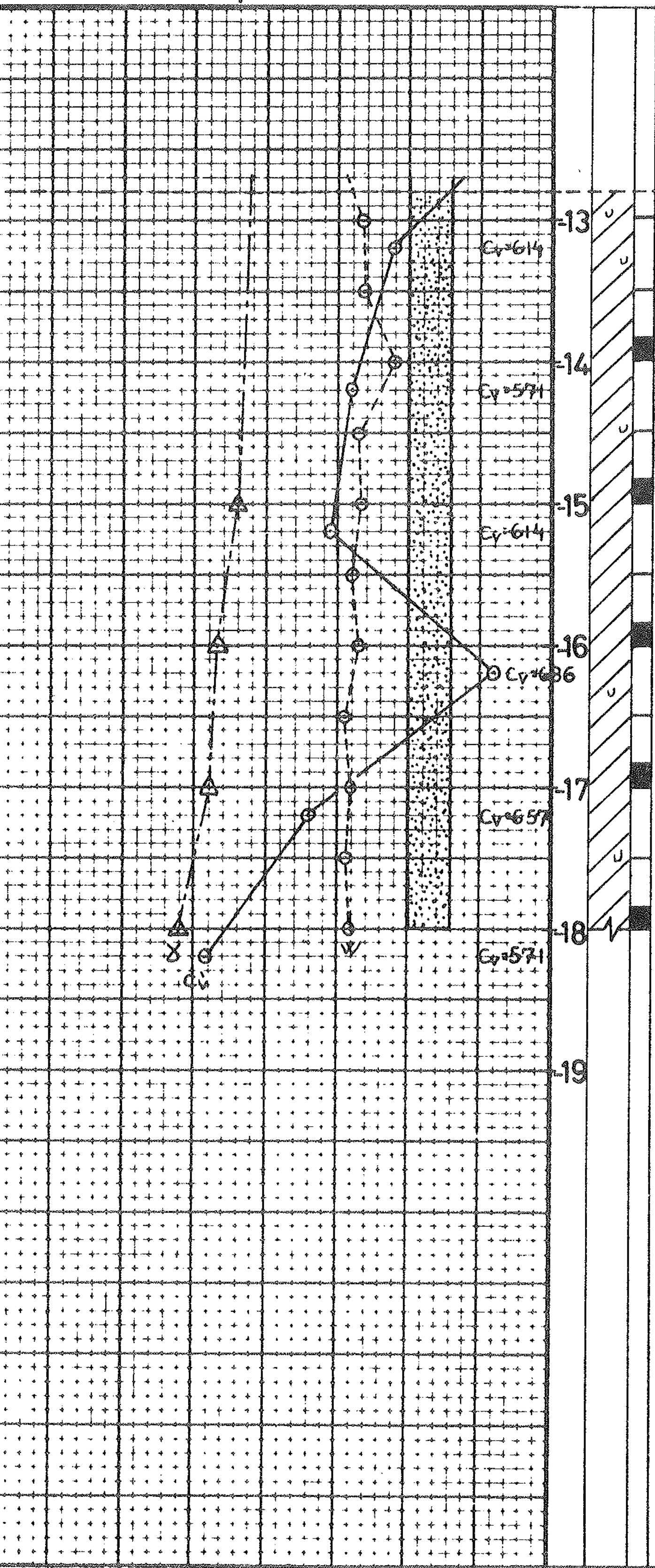
Legend and Definitions on encl. No.: 2

GEOLOGICAL ABBREVIATION

Annex II

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



Level	Lab. No.	Soil type	Description	Deposit	Age
		Continued Boring No.2			
-13	71	CLAY, fat w/fragments of shells		Flake	G
	72	" " " "		"	"
-14	73	" "		"	"
	74	" " " "		"	"
-15	75	" " w/micaceous clay		"	"
	76	" " ,laminated		"	"
-16	77	" "			
	78	" " w/fragment of shell		"	"
-17	79	" " slightly laminated		"	"
	80	" " w/fragment of shell		"	"
-18	81	" " slightly laminated		"	"

	10		20		30		w	%
	100		200		300		c'v, cv	kN/m²
	18		20		22		γ	kN/m³

Legend and Definitions on encl. No.: 2

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BORING LOG

Job No.: K82390 Esbjerg			
Bor. made: 83-07-21	Dess.: LTE.	Cont.:	Boring No.: 2
by: AC/JL	Appr.: GH	83-12-01	Encl. No.: 5a

Both ordinary classification tests and standard proctor tests as well as determination of the thermal conductivity have been made on the material sample drawn, and on the basis of this and our general experience, a set of dimensioning parameters are stated, confer enclosures Nos 6a - 8a. A computation has been made of an enclosing sheet pile which also constitutes the foundation for the surrounding wall. The results of this are given in subsection 4.2.

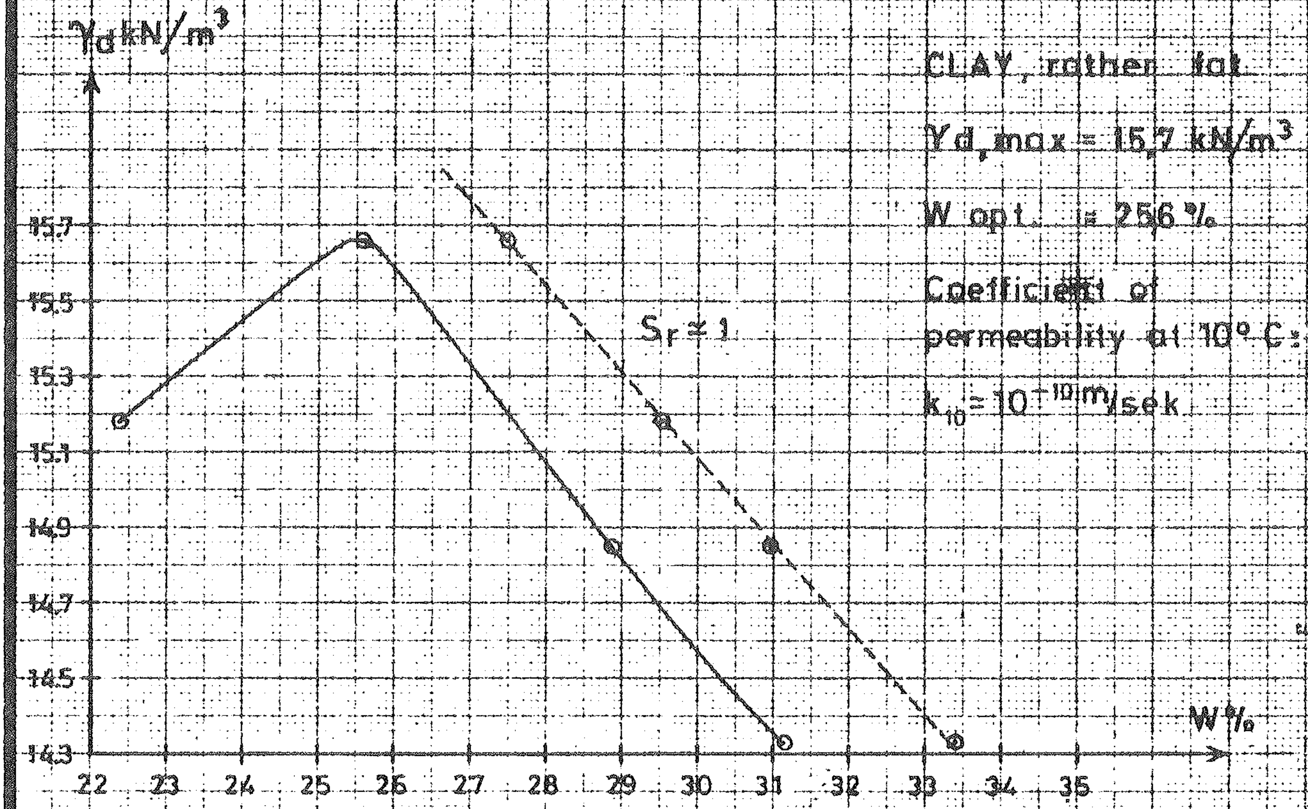
On the basis of the registered profile, the liquid loss has been computed on the assumption of heavy leaks in the membrane, almost corresponding to an unlined reservoir, confer section 5.

2. Ground and water level conditions

The boring made shows that from ground level at +4 there is approx 1 m sand fill deposited on 2.5 m flyash. Below these layers of fill there is a thin marine sand layer approx around level 0. This layer is underlaid by Esbjerg Yoldia clay consisting of a rather fat clay with shell fragments. Between levels approx -3.5 and -8.5 there is a rather fat clay with sand embedments, whereafter a homogeneous rather fat clay is present again down to the bottom of the boring.

Adjacent borings - which have been made in connection with other projects - have shown deposits of micaceous clay in the area, and the total investigations seem to indicate that the deposits are oblique (raised flakes) so that the depth to the upper and lower side of the encountered sand embedments may vary.

The area faces the harbour area directly, and so the water level will depend on the sea level, especially in connection with flow through the sand layer encountered around level 0. Previous investigations show that it will also be necessary to expect a secondary water level at level approx +2.



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K82390 ESBJERG

Standard proctor test on Lab. No.
46, 47, 48, 50, 63, 64, 66, 70 and 71.

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DATE 83-12-05	DATE	DATE 83-12-06	ENCL NO 6a

Thermal conductivity

DGI Lab. No.		w (%)	γ (kN/m^3)	e	n	S_r	$\bar{\lambda}$ (W/mK)
40+41	Flyash	39.2	14.6	1.20	0.54	0.75	0.88
43+44	Flyash	46.8	14.1	1.39	0.58	0.77	0.86
49	Esbjerg Yoldia-clay	19.3	21.0	0.508	0.34	1.01	1.87
52	Esbjerg Yoldia-clay	15.1	21.5	0.418	0.29	0.96	2.25
56	Sand	14.7	21.6	0.409	0.29	0.95	2.79
57	Local moraine lithology	11.6	22.4	0.322	0.24	0.96	2.70
60	Local moraine lithology	18.8	21.0	0.498	0.33	1.00	2.02
65	Esbjerg Yoldia-clay	22.3	20.1	0.613	0.38	0.97	1.82
73	Esbjerg Yoldia-clay	28.9	19.0	0.801	0.45	0.96	1.50
81	Esbjerg Yoldia-clay	25.9	18.8	0.773	0.44	0.89?	1.45

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Strength parameters

Level	Soil deposit	φ°	c kN/m²	c_u kN/m²
+ 4				
	Fill: Sand	34°	0	0
+ 2.8				
	" : Flyash	30°	0	?
+ 0.2				
	Sand, marine	34°	0	0
+ 0.1				
	Clay, rather fat	26°	(40)→0	0.5 × c_v ~50 á 100
- 3.6				
	Local moraine/	30°	(20)→0	~ 200
	Sand	38°	0	0
- 8.6				
	Clay, rather fat	26°	(40)→0	0.5 × c_v $\gtrsim$ 250

Parameters given are based at the experience at DGI.

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3. Project

The present sketch project comprises establishment of a 50,000 m^3 warm water store in the position shown at enclosure No 1a. The basic design is shown on enclosure No 9a.

It is the idea to construct the warm water store as a double truncated cone with a maximum diameter of approx 44 m, the bottom at level approx -9.2, a water level at the periphery at level +5, and with a membrane laid on a cement-stabilized draining sand layer on the sides of the reservoir as well as a roof consisting of a polypropylene membrane (Vestolen P6422), insulation covered with butyl cloth and covering soil. Membrane and butyl cloth are fixed to an annular concrete foundation grouped on compressed Yoldia clay fill and supported by a sheet pile. The annular foundation is made with expansion joints. The sloping sides of the reservoir are made with gradient 2.

4. Excavation. Pit.

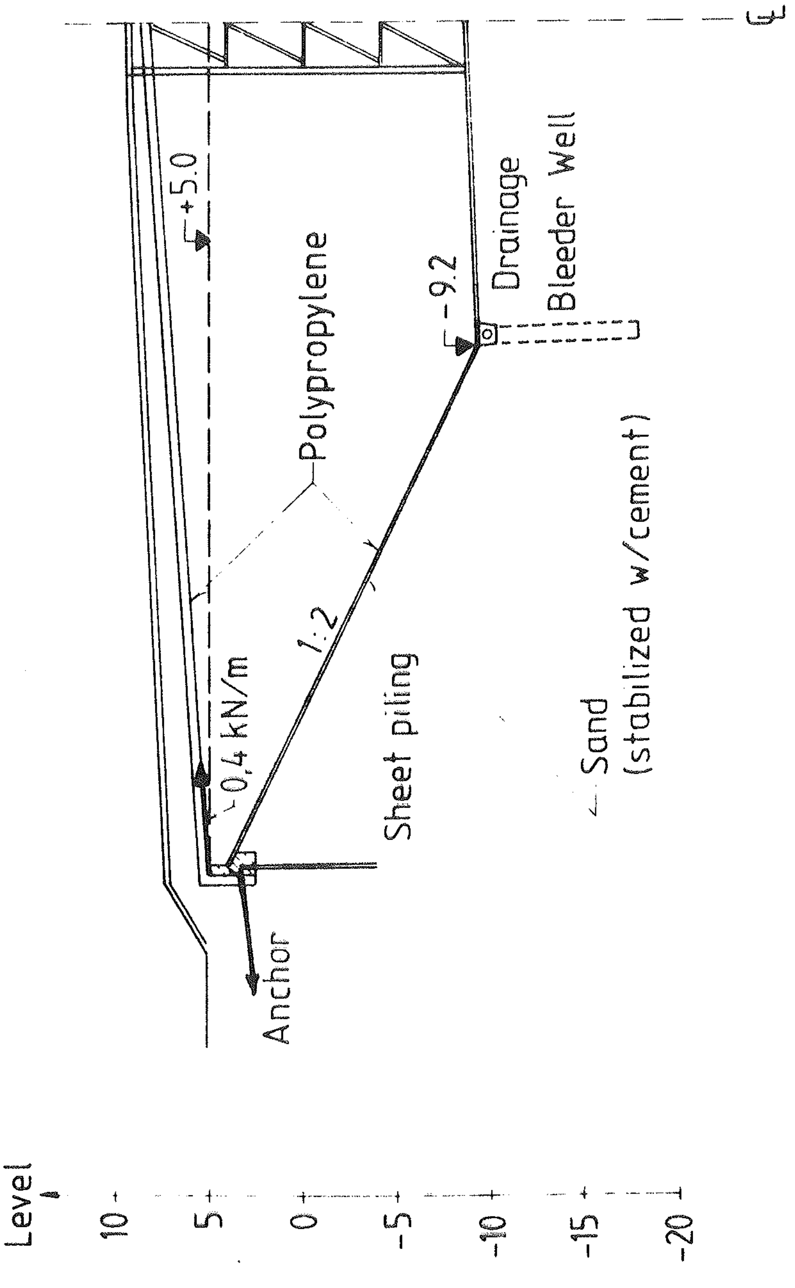
4.1 Stability and keeping excavation dry

Establishment of drains and membrane in the reservoir bottom and sides will be conditional on stability and keeping the excavation dry.

A gradient of 2 will just offer security against stability rupture at the construction stage, on condition that uncontrolled discharge of water to the building pit or build-up of water pressure behind the sides of the building pit is not permitted.

In order to ensure stability and dryness of the excavation we recommend that

- bleeder wells should be established in the excavation bottom,



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Cross section
Outline plan 1 : 400

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- a provisional lowering of the ground water level should be established to the necessary extent in (semi-) permeable deposits along the periphery of the excavation,
- carpet drains should be laid concurrently with the excavation work, and that
- water influx from bleeder wells and carpet drains should be pumped out.

In order to secure the vertical stability and as a protection against soaking of the bottom, bleeder wells should be made from level +1 down to level approx -20. The wells shall only be kept from level -9 to -20 in the final construction.

With a view to lowering of the water level in the sandy clay layers which in boring 2 are found from level -3.5 to -8.5, it is recommended that a system of well points with tips down to approx -5 to -10 should be established to the extent which might be deemed necessary during excavation. These systems should be established by vacuum and serve to procure the necessary stability and dryness of the slopes during establishment of drain layers and membrane.

As a protection against local soaking and stability failure it is recommended that the permanent drainage layer should be laid concurrently with the excavation work. Where sandy clay layers are encountered, further sealing of these can - besides the membrane - be carried out by replacing the layers with compressed Yoldia clay during which work a drain should be established for connection to the pump sump of the bleeder wells. The extent of such a replacement must be determined by inspection concurrently with the excavation. Sealing must be done with homogeneous unsoaked Yoldia clay to be built in in at least two 0.25 m layers and compressed effectively which ensures integration to min 100 % SP. If replacements are carried out in the sides of the excavation (for reduction of the water permeability of the reservoir wall), drainage layers should be built in to give protection against build-up of water pressure during the period before the reservoir is filled with water or during subsequent drainage of the reservoir.

5.2 Bordering

A sheet pile is to be rammed for bordering of the building pit during excavation below level +1 with a view to cutting off water influx in the sand layer around level 0 and as a foundation for the concrete ring to which the membranes are fixed. Computation of such a sheet pile according to the strength parameters given in section 4 and in the position shown in enclosure No 9a shows that steel piles with tip level at -4.0 and a design maximum moment of 55 kNm/m must be used, this sheet pile being anchored at the same time by ground anchors which must be able to take up a pull of 200 kN/m.

5.3 Permanent drainage

Considering the possibility of future drainage of the reservoir, it must be built up with a drainage layer under the membrane so that it can be ensured during drainage of these layers that an upward water pressure will not be established on the membrane.

As a protection against any reservoir water leaking out being mixed with ground water leaking in, it is recommended that a double drainage system with an intermediate membrane should be established. Hereby the possibility is preserved of identifying leakage through the reservoir membrane through observations in the upper drainage system.

6. Liquid loss

With a warm water store as sketched in enclosure No 9a, an outside mean water level at level +1, and a computation based on a coefficient of permeability of

$k_{10} \sim 10^{-10}$ m/sec above level -4 (enclosing sheet pile)

$k_{10} \sim 10^{-9}$ m/sec from level -4 to -6.5 for 60 % clay

$k_{10} \sim 5 \cdot 10^{-5}$ m/sec from level -4 to -6.5 for 40 % sand

$k_{10} \sim 10^{-8}$ m/sec from level -6.5 to -8.5

$k_{10} \sim 10^{-10}$ m/sec from level -8.5 and downwards

we have carried out a computation of liquid loss on the assumption of an unlined reservoir. This computation shows that at 10°C there will be an efflux of 1 - 1.5 m^3/h and with a correction to 70°C an efflux of 3 - 5 m^3/h.

A general requirement for a liquid loss < 1 % of the volume on an annual basis can, therefore, only be satisfied with a tight membrane or another sealing of the sides between levels -4 and -6.5 (to -8.5) which in the above-mentioned computation account for 98 % of the leakage.

DANISH GEOTECHNICAL INSTITUTE - DGI
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H.Kryger Hansen

Engineer in charge: C.Bæk-Madsen

Annex II

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Lyngby,
1984-03-22

Esbjerg. Heat storage in large reservoirs.
Appendix to geotechnical report No 2b.

Instructions for the bordering of the building pit - as given in section 4 - can be changed to a design maximum moment of 55 kN/m and tip level at -4.0 in connection with a lower anchor pull of 27 kN/m. The lower pull can be taken into account on the assumption that the surrounding ground level must not exceed level +5 under draining off the reservoir.

Computation of an anchor plate shows that a concrete plate with dimensions 1.0 m wide, 1.5 m heigh and 0.3 m thick has to be placed per 6.5 m at level +2 and with the point of attach for the anchor at level +2.75.

DANISH GEOTECHNICAL INSTITUTE - DGI
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SEASONAL STORAGE PILOT PIT

TAB - A PROGRAMME

FOR THERMAL CALCULATIONS

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VAGN USSING

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NOVEMBER 1983

1. INTRODUCTION

The aim of this report has been to give the principles of the thermal calculations for the surrounding soil of the 50.000 m^3 pit which is only thermally insulated at the floating top cover.

The model is made in cylindrical coordinates and an explicit finite-difference technique is used in the numerical calculations.

The model can calculate the temperatures in the different depths in the surrounding soil as a function of time together with the calculations of the heat loss through the bottom, the sides and the insulated top of the pit. A flow diagram for a general view of the programme is shown on Figure 1.

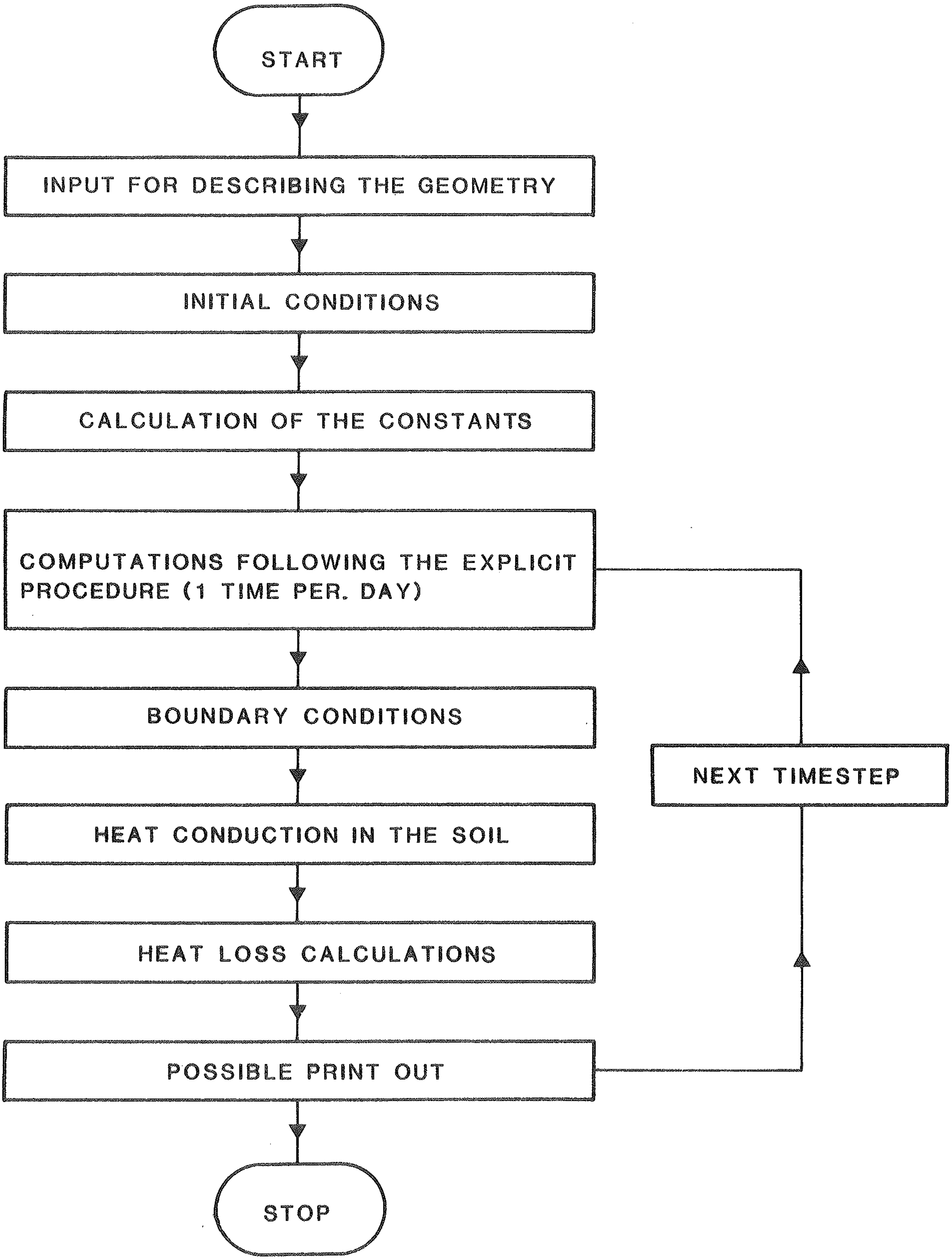


Figure 1. A flow diagram for a general view of the programme.

2. NUMERICAL SIMULATION OF HEAT CONDUCTION IN SOIL.

The starting point is the linear partial differential equation of parabolic type (Fourier's law of heat conduction) which in cylindrical coordinates looks like:

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} = \lambda \cdot \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T}{\partial r} \right) + \lambda \cdot \frac{\partial^2 T}{\partial z^2} \qquad (1)$$

Where T denotes temperature and λ, ρ, c_p are the thermal conductivity, density and specific heat.

When using a finite-difference technique to solve a partial differential equation, a network of grid points is first established throughout the soil volume, see the drawings 120, 121 and 122 (on the drawings 121 and 122 the grid point is the center of the shown area). As showed on the drawings the spacing of the grid points is most dense in the embankment of the pit where the spacing is Δr = 0,75 m and Δz = 0.5 m. Down through the soil and farther away from the embankment the spacing is increased.

The initial conditions in the grid points plus the associated boundary must be known.

The calculations are made as follows. The unknown temperature in a grid point (i,j) on time level $t = t_1 + \Delta t$ is calculated using the known temperatures in the grid point itself (i,j) and the four surrounding elements on time level $t = t_1$, using equation (1) may be developed as follows:

$$\text{vol} \cdot \rho \cdot c_p \cdot \frac{\partial T}{\partial t} = \frac{\Delta T_1}{R_1} + \frac{\Delta T_2}{R_2} + A_3 \cdot \frac{\Delta T_3}{M_3} + A_4 \cdot \frac{\Delta T_4}{M_4} \qquad (2)$$

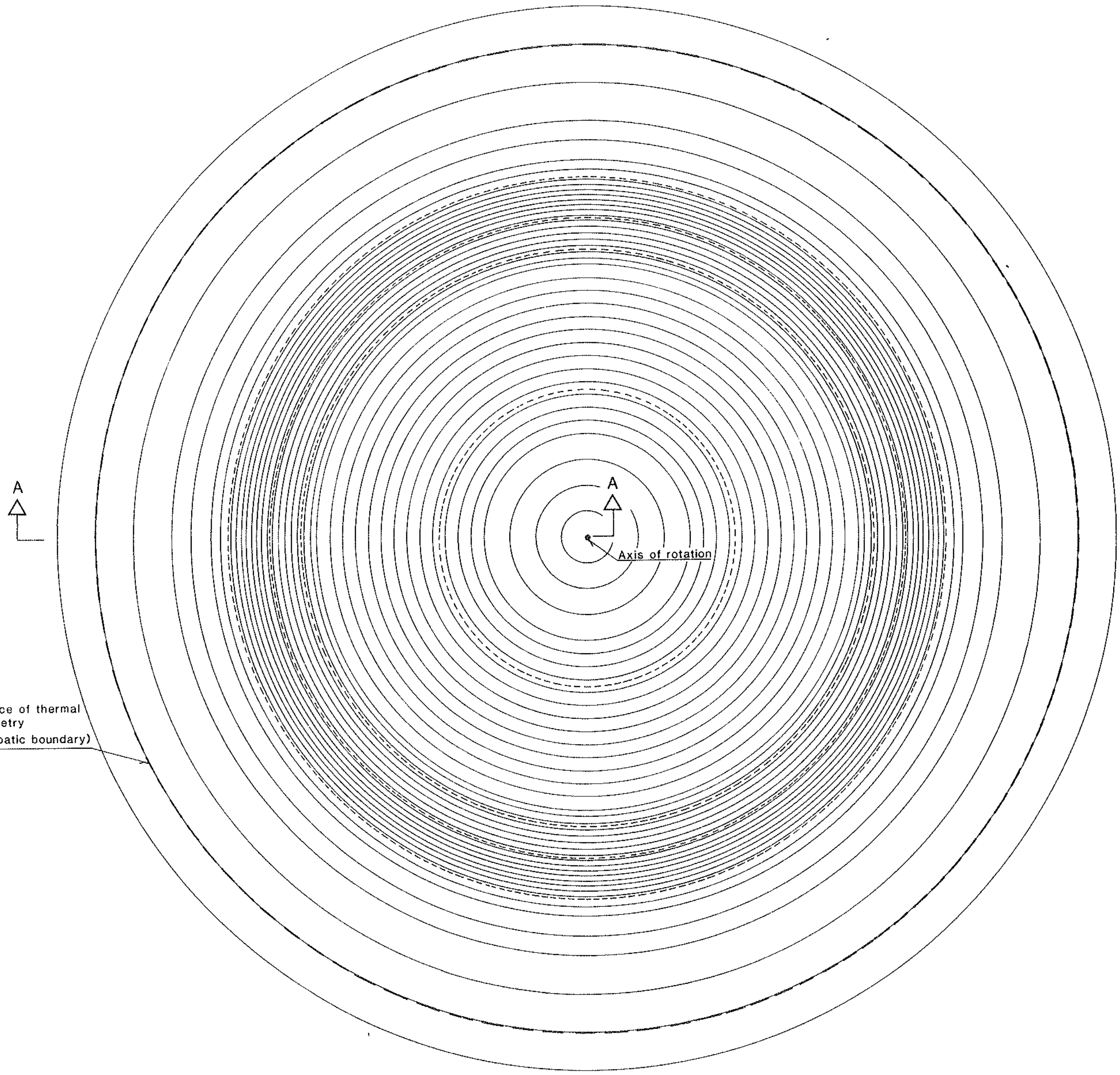
Equation (2) tells: The change per timestep in the temperature of the volume of the annulus is equal the sum of the heat-fluxes through the surfaces of the volume.

This equation (2) will be explained by use of Figure 2. describing the volume of the annulus as:

$$\text{vol} = \pi \cdot \left((r + \frac{\Delta r}{2})^2 - (r - \frac{\Delta r}{2})^2 \right) \cdot \Delta z$$

$$= 2 \cdot \pi \cdot r \cdot \Delta r \cdot \Delta z \qquad (3)$$

equation (2) can be described as follows in the grid point (i,j):



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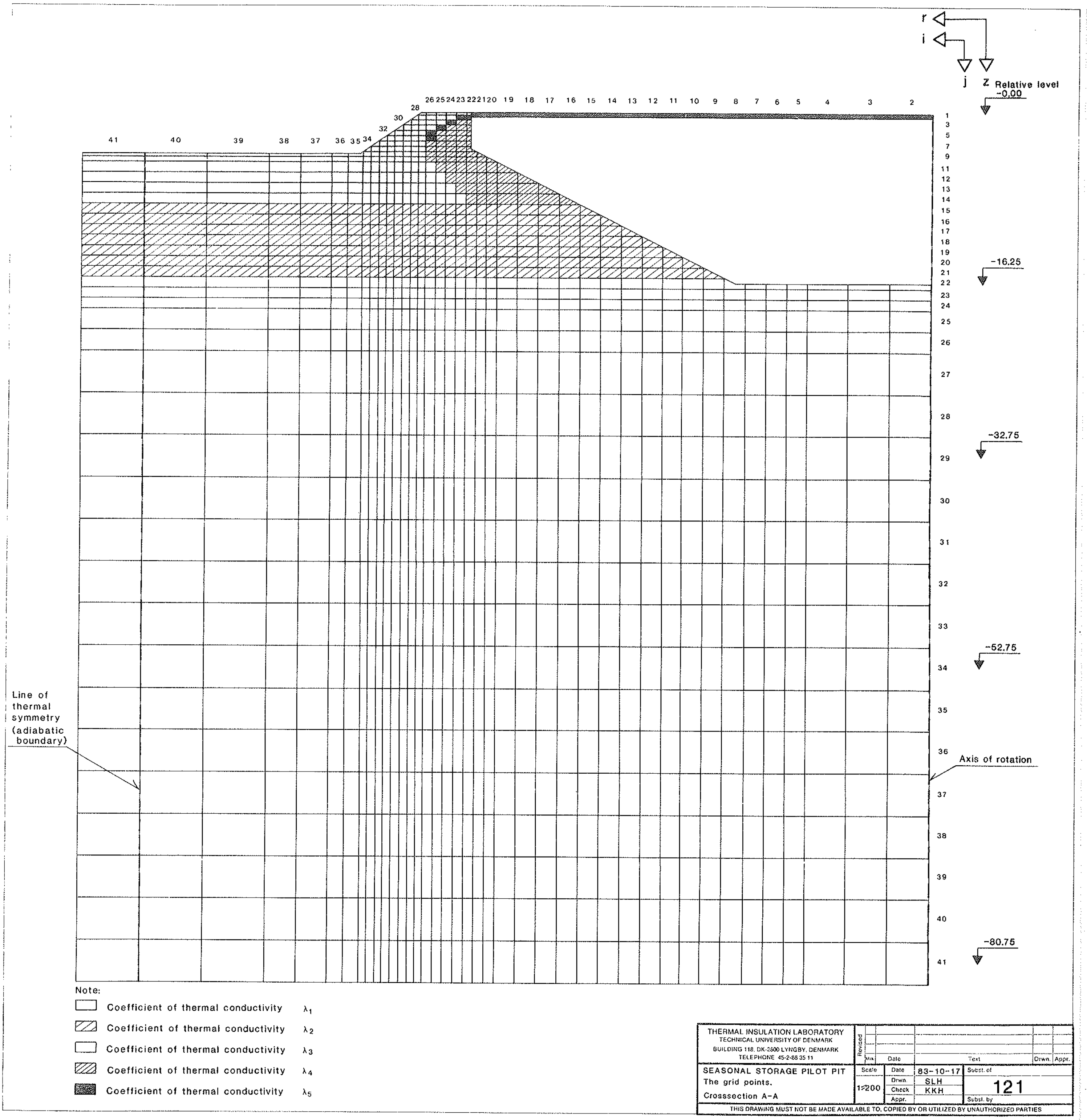
SEASONAL STORAGE PILOT PIT The grid points. Plan	Scale 1:400	Date Drwn Check Appr.	83-10-17 SLH KKH	Subst. of 120 Subst. by		


r
i
j
z
Relative level
-0.00
-16.25
-32.75
-52.75
-80.75
Line of thermal symmetry (adiabatic boundary)
Axis of rotation
Note:
Coefficient of thermal conductivity λ_1
Coefficient of thermal conductivity λ_2
Coefficient of thermal conductivity λ_3
Coefficient of thermal conductivity λ_4
Coefficient of thermal conductivity λ_5
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SEASONAL STORAGE PILOT PIT
The grid points.
Crosssection A-A
Scale 1:200
Date 83-10-17
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121
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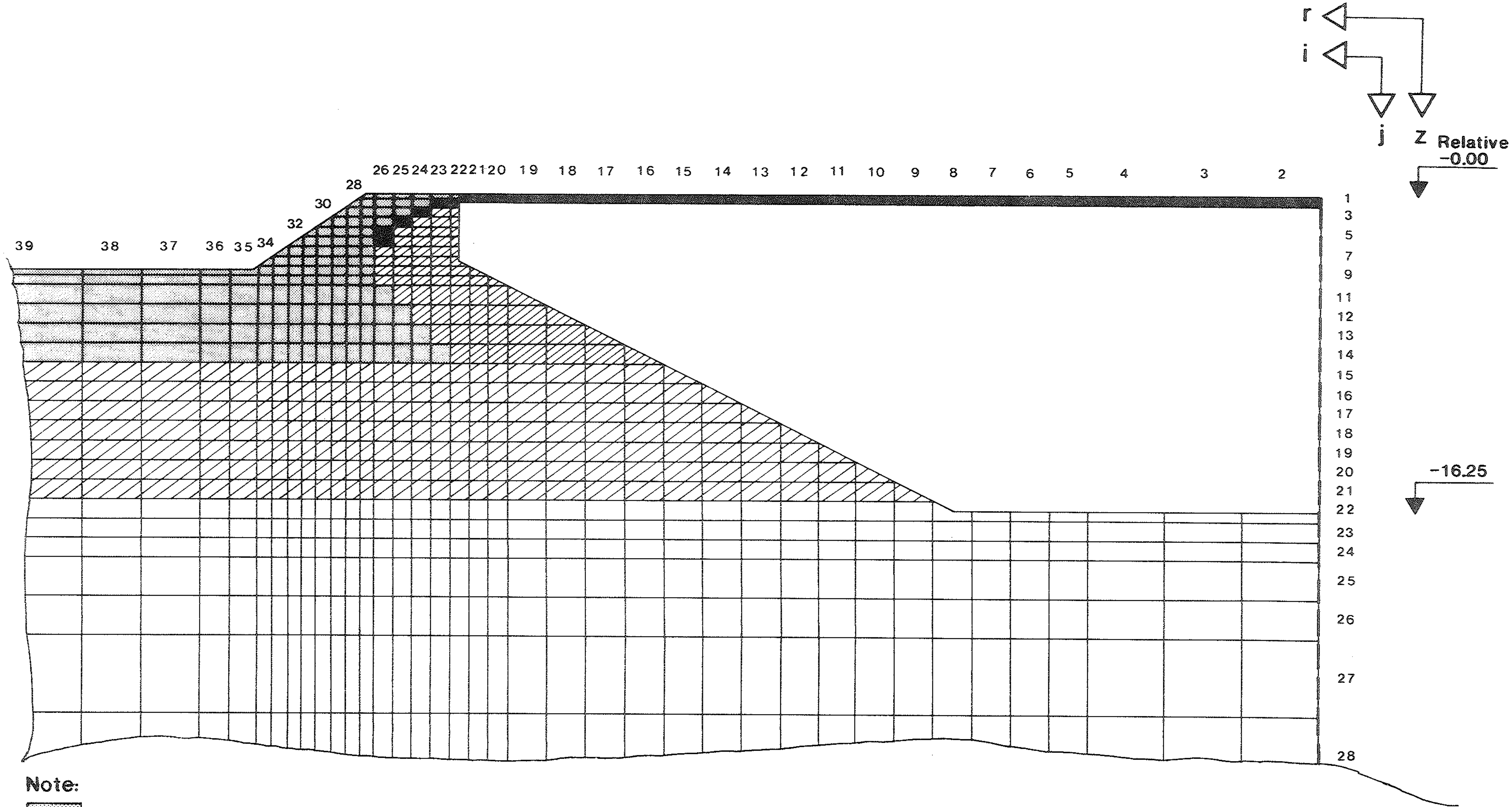

Note:

- Coefficient of thermal conductivity λ_1
- Coefficient of thermal conductivity λ_2
- Coefficient of thermal conductivity λ_3
- Coefficient of thermal conductivity λ_4
- Coefficient of thermal conductivity λ_5

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SEASONAL STORAGE PILOT PIT
Part of grid points.
Crosssection A-A.

Scale			
	Date	83-10-18	Subst. of
	Drwn.	SLH	122
	Check	KKH	
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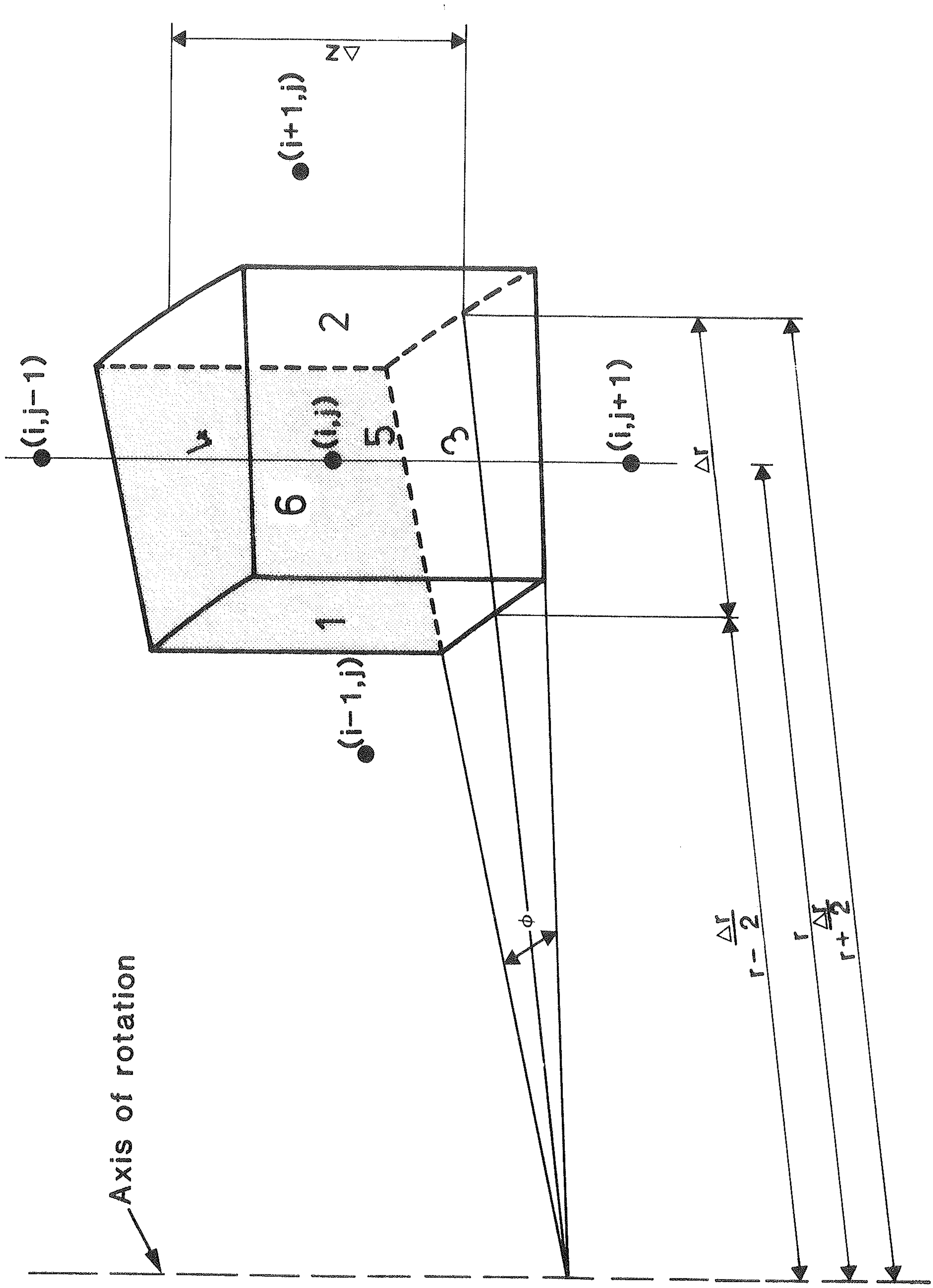


Figure 2. Part of a volume element (equal annulus for $\phi = 2\pi$).

$$2\cdot\pi\cdot r\cdot\Delta r\cdot\Delta z\cdot\rho\cdot c_p\cdot\frac{\partial T}{\partial t} =$$

$$\frac{T_{i-1} - T_i}{R_{i-1} + R_i} + \frac{T_{i+1} - T_i}{R_i + R_{i+1}} + 2\cdot\pi\cdot r\cdot\Delta r\cdot\left(\frac{T_{j-1} - T_j}{M_{j-1} + M_j} + \frac{T_{j+1} - T_j}{M_{j+1} + M_j}\right) \qquad (4)$$

In this equation (4) R_{i-1} and R_i are the thermal resistance in half of the elements (i-1,j) and (i,j) respectively:

$$R_{i-1} = \frac{\ln\left((r_i - \frac{\Delta r_i}{2}) / (r_i - \Delta r_i)\right)}{2\cdot\pi\cdot\lambda_{i-1}\cdot\Delta z}$$

$$= \frac{\ln\left((r_i - \frac{\Delta r_i}{2}) / r_i - (r_i - r_{i-1})\right)}{2\cdot\pi\cdot\lambda_{i-1}\cdot\Delta z}$$

$$= \frac{\ln\left((r_i - \frac{\Delta r_i}{2}) / r_{i-1}\right)}{2\cdot\pi\cdot\lambda_{i-1}\cdot\Delta z} \qquad (5)$$

$$R_i = \frac{\ln\left(r_i / (r_i - \frac{\Delta r_i}{2})\right)}{2\cdot\pi\cdot\lambda_i\cdot\Delta z} \qquad (6)$$

For the pair of thermal resistances $R_i + R_{i+1}$ the same equations (5) and (6) are used again with R_i replaced for R_{i-1} in equation (5) and R_{i+1} replaced for R_i in equation (6).

Drawn together equation (4) becomes:

$$HO_{i,j}\ (TN_{i,j} - T_{i,j}) = HX_{i,j}\cdot(T_{i-1,j} - T_{i,j}) + HX_{i+1,j}\cdot(T_{i+1,j} - T_{i,j})$$
$$+ HY_{i,j}\cdot(T_{i,j-1} - T_{i,j}) + HY_{i,j+1}\cdot(T_{i,j+1} - T_{i,j}) \qquad (7)$$

where

$$HO_{i,j} = 2\cdot\pi\cdot r\cdot\Delta r\cdot\Delta z\cdot\rho\cdot c_p/\Delta t \qquad (8)$$

and

$$HX_{i,j} = \frac{1}{R_{i-1} + R_i} \qquad (9)$$

$$HX_{i+1,j} = \frac{1}{R_i + R_{i+1}} \qquad (10)$$

$$HY_{i,j} = \frac{2\cdot\pi\cdot r\cdot\Delta r}{M_{j-1} + M_j} \qquad (11)$$

$$HY_{i,j+1} = \frac{2 \cdot \pi \cdot r \cdot \Delta r}{M_{j+1} + M_j} \qquad (12)$$

where M_{j-1} , M_j , M_{j+1} are the vertical resistances in half of the elements (i,j+1), i,j) and (i,j+1) respectively.

See also Figure 3. In the programme the final expression to calculate $TN_{i,j}$ (e.g. $T_{i,j}^{t_1 + \Delta t}$) explicit looks like:

$$TN_{i,j} = T_{i,j} + HS/HO_{i,j} \qquad (13)$$

where HS is the right side of equation (7).

In this way all the "new" temperatures in the internal grid points are calculated. By use of the now calculated temperatures on time level $t = t_1 + \Delta t$ the temperatures on time level $t = t_1 + 2 \cdot \Delta t$ can be calculated in the same way etc.

In [1] it is shown that the calculations will be stable when the following stable condition is fulfilled:

$$\Delta t_s \leq \frac{1}{\frac{2 \cdot \lambda}{\rho \cdot c_p}\left(\frac{1}{(\Delta r)^2} + \frac{1}{(\Delta z)^2}\right)} \qquad (14)$$

Substituting in equation (14)

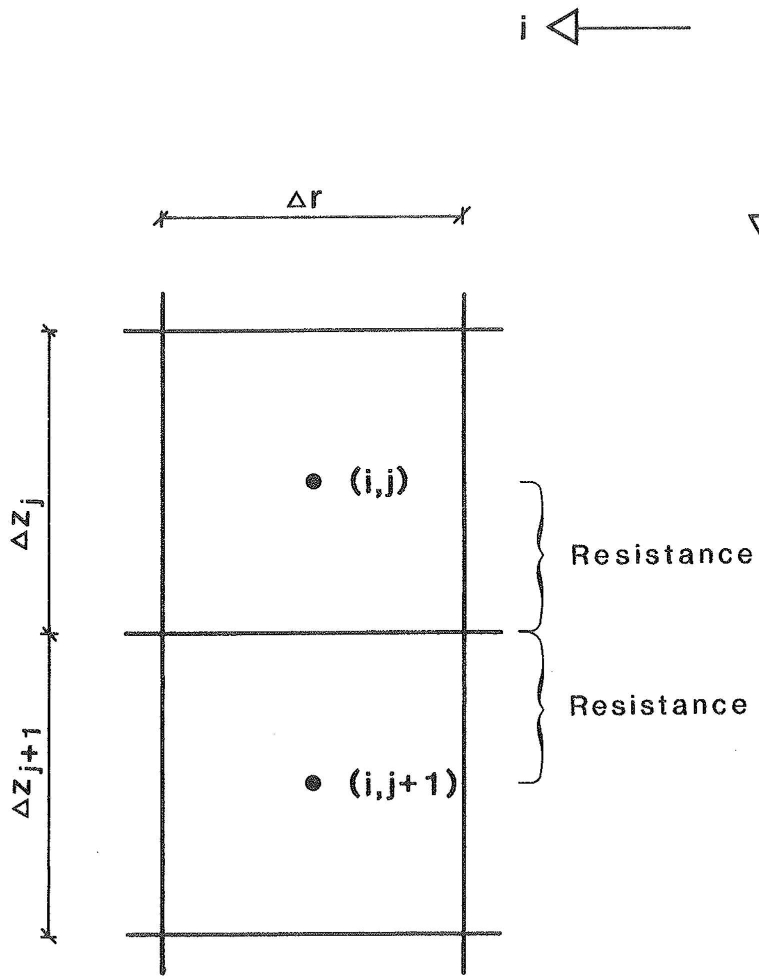
$$\Delta t = \frac{1}{\frac{2 \cdot 2,35}{2.6 \cdot 10^6}\left(\frac{1}{(0,75)^2} + \frac{1}{(0,5\ )^2}\right)} \qquad (15)$$

$$= 9,57 \cdot 10^4 \text{ sec} = 0,0030 \text{ year}$$

If the calculations are done once per day

$$\Delta t_s = \frac{1}{365} = 0,0027 \text{ year} \qquad (16)$$

When $\Delta t_s < \Delta t$ it is clear the one calculation per day is enough to secure stable calculations.



$$M_j = \frac{\Delta z_j}{2 \cdot \lambda_j}$$

$$M_{j+1} = \frac{\Delta z_{j+1}}{2 \cdot \lambda_{j+1}}$$

Figure 3. The resistance between 2 elements.

3. INITIAL AND BOUNDARY CONDITIONS.

3.1 Initial conditions

The initial temperatures in the grid points are all set to 10°C. This initial condition has no importance after the first half year calculation.

3.2 Boundary conditions

3.2.1 Soil surface

The temperatures in the grid points which separate air and soil follow the temperature of the outside air as a cosine-function:

$$T_{amb} = T_o + \Delta T \cos(\omega \cdot t - \phi) \qquad (17)$$

With a wavelength of 1 year the period is $\omega = 2\pi$. ϕ is the phasedisplacement which depends on the starting time of the year, T_o is the mean value and ΔT the temperature amplitude of the outside air. Here is used $T_o = 8.9°C$ and $\Delta T = 9.2°C$.

3.2.2 Grid points in the soil

The vertical axis of rotation is a line of thermal symmetry. The outside vertical boundary is also a plane of thermal symmetry. Downwards a heat sink with constant temperature is placed.

4. HEAT LOSS CALCULATIONS.

The heat loss calculations are made each timestep for the bottom, the sides and the top cover separately.

4.1 Bottom

The expression to calculate the heat loss through the bottom looks like for an element at the bottom interface:

$$LOSSB = \frac{\pi \cdot \lambda \cdot \Delta r \cdot \left(T_{i,jc+1} - T_{i,jc}\right) \cdot \Delta t}{\Delta z} \qquad (18)$$

where jc is shown on figure 7.

4.2 Side

The expression to calculate the heat loss through a side element has two parts. The first part of the expression is related to the heat loss through the horizontal part of an element at the side interface and the second part of the expression is related to the vertical part of the element:

$$\text{LOSSI} = \frac{\pi \cdot \lambda \cdot \Delta r \cdot \left(T_{i,j+1} - T_{i,j}\right) \cdot \Delta t}{\Delta z} + \frac{2 \cdot \pi \cdot r \cdot \Delta z \cdot \lambda \cdot \left(T_{i+1,j} - T_{i,j}\right) \cdot \Delta t}{\Delta r} \qquad (19)$$

4.3 Top cover

The insulation material in the top cover has a constant thickness of 0.5 m and a thermal conductivity of 0.04 W/m^{0}C. The top cover is calculated as one single element:

$$\text{LOSST} = \frac{\pi \cdot L^2 \cdot 0.04 \cdot (T_{store} - T_{amb}) \cdot \Delta t}{0.5} \qquad (20)$$

4.4 Example on heat loss calculation

The three components of the heat loss are then added to give a total heat loss. Figure 4 shows a calculation through 4 years with a constant temperature of the stored water of 73^{0}C.

In the calculation the four soil types and the thermal insulation material in the embankment have the following thermal properties:

	thermal conductivity λ W/m^{0}C	heat capacity $\rho \cdot c_p$ J/m$^{3\,0}$C
soil 1	0.88	$2.6 \cdot 10^6$
soil 2	2.35	$2.6 \cdot 10^6$
soil 3	1.60	$2.6 \cdot 10^6$
soil 4	2.35	$2.6 \cdot 10^6$
insulation 5	0.05	$1.1 \cdot 10^5$

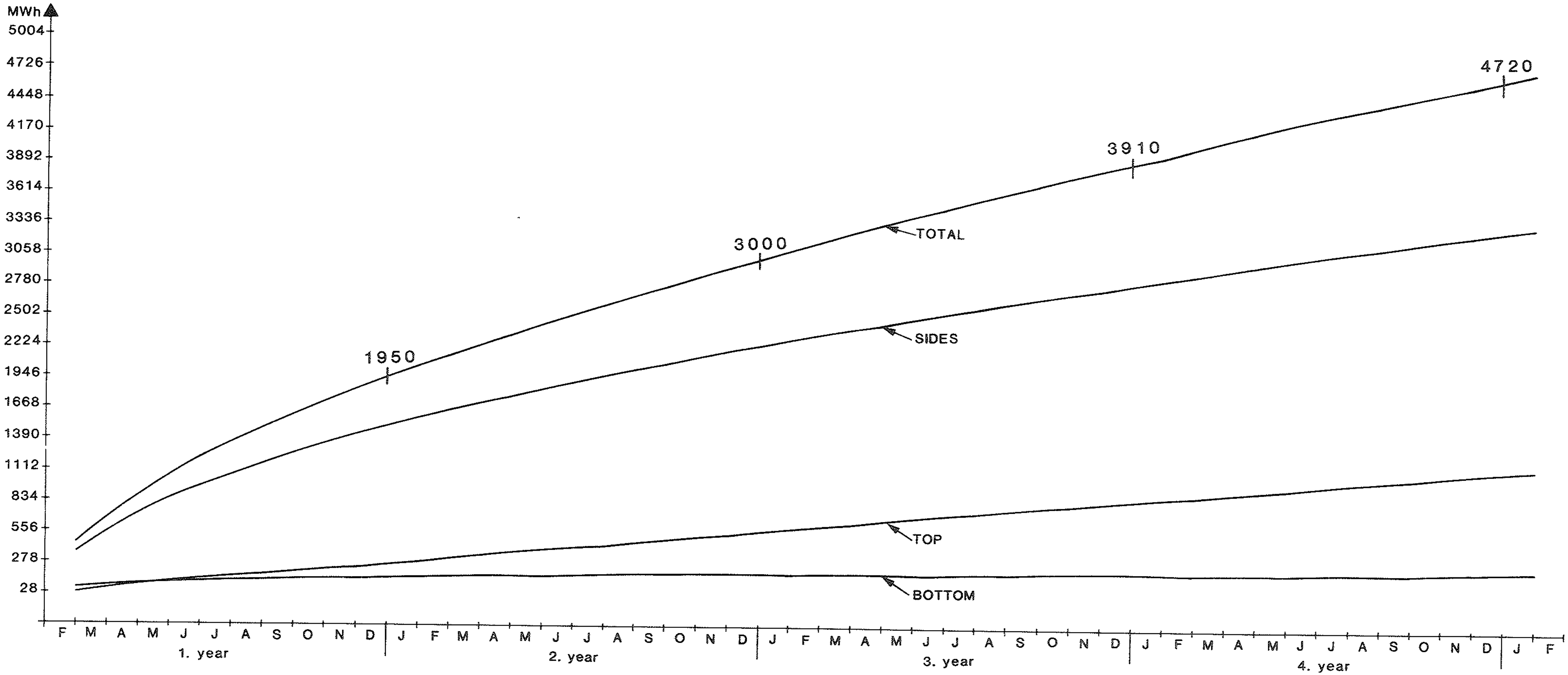


Figure 4. The accumulated heat loss through the bottom, the sides, the top and total for a period of 4 years for a 50,000 m^3 pit. The temperature of the stored water is 73 °C (constant).

The results from Figure 4 of the 4. year are shown in Figure 5. The percentage heat loss of the maximum theoretical heat content is shown as a function of days, and it can be seen that only about 12% is lost after 3 months (120 days).

INPUTDATA

A print out of the inputdata is shown in Figure 6. The inputdata give the inner and outer boundary of the embankment, the soil material number, and the spacings Δr and Δz. In Figure 8 is shown a print out of the inputdata giving the position of the different materials accordind to the drawings 121 and 122.

OUTPUT.

As an example a print out of the output is shown on Figure 9.

A part of the output is the temperature in the grid points and this can be used to make the temperature profile through the soil. As an example the temperature profile for the last day of the 4. year is shown on figure 10.

7. LITERATURE

[1] Hansen, Preben Nordgaard: Termiske beregningsmetoder. LfV, DTH. 1978.

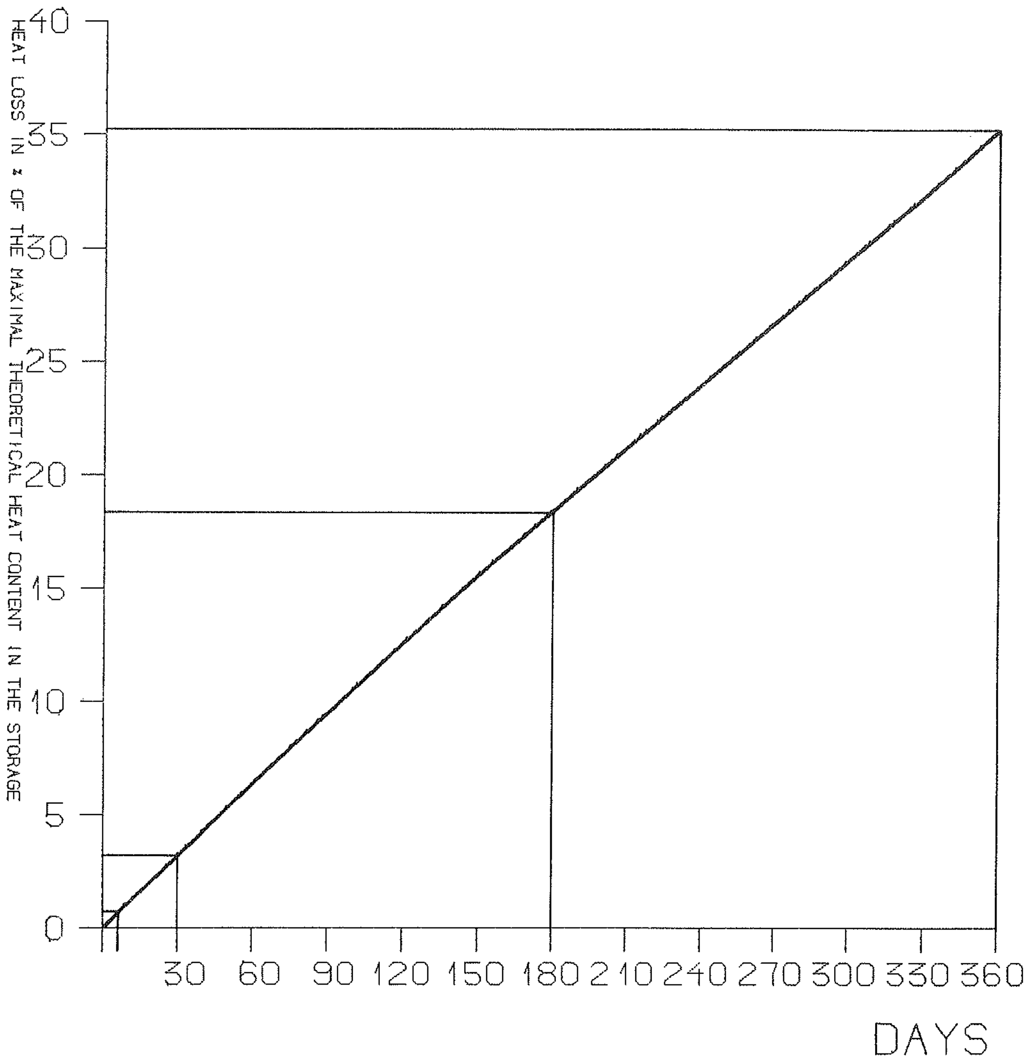


FIGURE 5. THE PERCENTAGE HEAT LOSS OF THE MAXIMAL THEORETICAL HEAT CONTENT BASED ON A TEMPERATURE SPAN OF 44°C FOR A 50,000 m³ PIT. THE TEMPERATURE OF THE STORED WATER IS 73°C (CONSTANT), AND THE PERIOD IS THE 4. YEAR.

I

I1( )	I2( )	Soil material no.	Δr	Δz
23	26	1	4.00	0.50
23	27	1	4.00	0.50
23	28	1	4.00	0.50
23	29	1	4.00	0.50
23	30	1	2.00	0.50
23	31	1	2.00	0.50
23	32	1	2.00	0.50
23	33	1	2.00	0.50
22	34	1	2.00	0.50
21	40	1	2.00	0.50
20	40	1	2.00	1.00
19	40	1	2.00	1.00
18	40	1	2.00	1.00
17	40	1	2.00	1.00
16	40	2	2.00	1.00
15	40	2	2.00	1.00
14	40	2	2.00	1.00
13	40	2	2.00	1.00
12	40	2	2.00	1.00
11	40	2	1.00	1.00
10	40	2	1.00	1.00
9	40	3	1.00	1.00
2	40	3	1.00	1.00
2	40	3	1.00	1.00
2	40	3	1.00	2.00
2	40	3	1.00	2.00
2	40	3	0.75	4.00
2	40	3	0.75	4.00
2	40	3	0.75	4.00
2	40	3	0.75	4.00
2	40	3	0.75	4.00
2	40	3	0.75	4.00
2	40	3	0.75	4.00
2	40	3	0.75	4.00
2	40	3	1.50	4.00
2	40	3	1.50	4.00
2	40	3	3.00	4.00
2	40	3	3.00	4.00
2	40	3	6.00	4.00
2	40	3	6.00	4.00
2	40	3	6.00	4.00

II

i-no.	j-no.	Material no.
23	2	5
22	2	5
24	3	5
25	4	5
26	5	5
26	6	5
26	7	4
26	8	4
26	9	4
26	10	4
25	5	4
25	6	4
25	7	4
25	8	4
25	9	4
25	10	4
25	11	4
24	4	4
24	5	4
24	6	4
24	7	4
24	8	4
24	9	4
24	10	4
24	11	4
24	12	4
23	3	4
23	4	4
23	5	4
23	6	4
23	7	4
23	8	4
23	9	4
23	10	4
23	11	4
23	12	4
23	13	4
22	3	4
22	4	4
22	5	4
22	6	4
22	7	4
22	8	4
22	9	4
22	10	4
22	11	4
22	12	4
22	13	4
22	14	4
21	9	4
21	10	4
21	11	4
21	12	4
21	13	4
21	14	4
20	10	4
20	11	4
20	12	4
20	13	4
20	14	4
19	11	4
19	12	4
19	13	4
19	14	4
18	12	4
18	13	4
18	14	4
17	13	4
17	14	4
16	14	4

Figure 6. Input data. I1( ) and I2( ) is the inner and outer bound of the embankment, see figure 7. The input data II follow I and describe only the position of the soil material 4 and the insulation material 5.

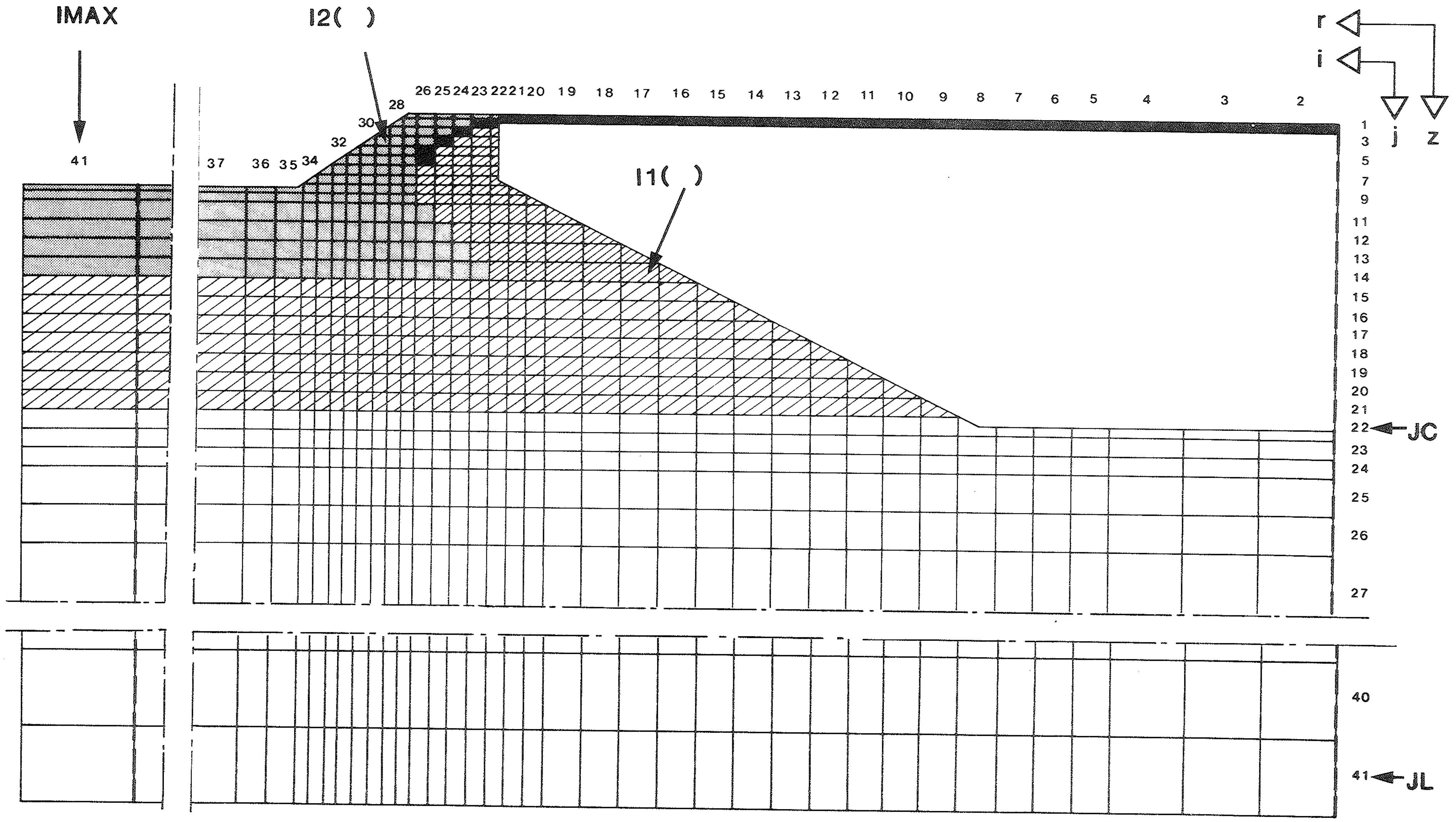


Figure 7. Denomination of some elements used in the input data and in the computer programme.

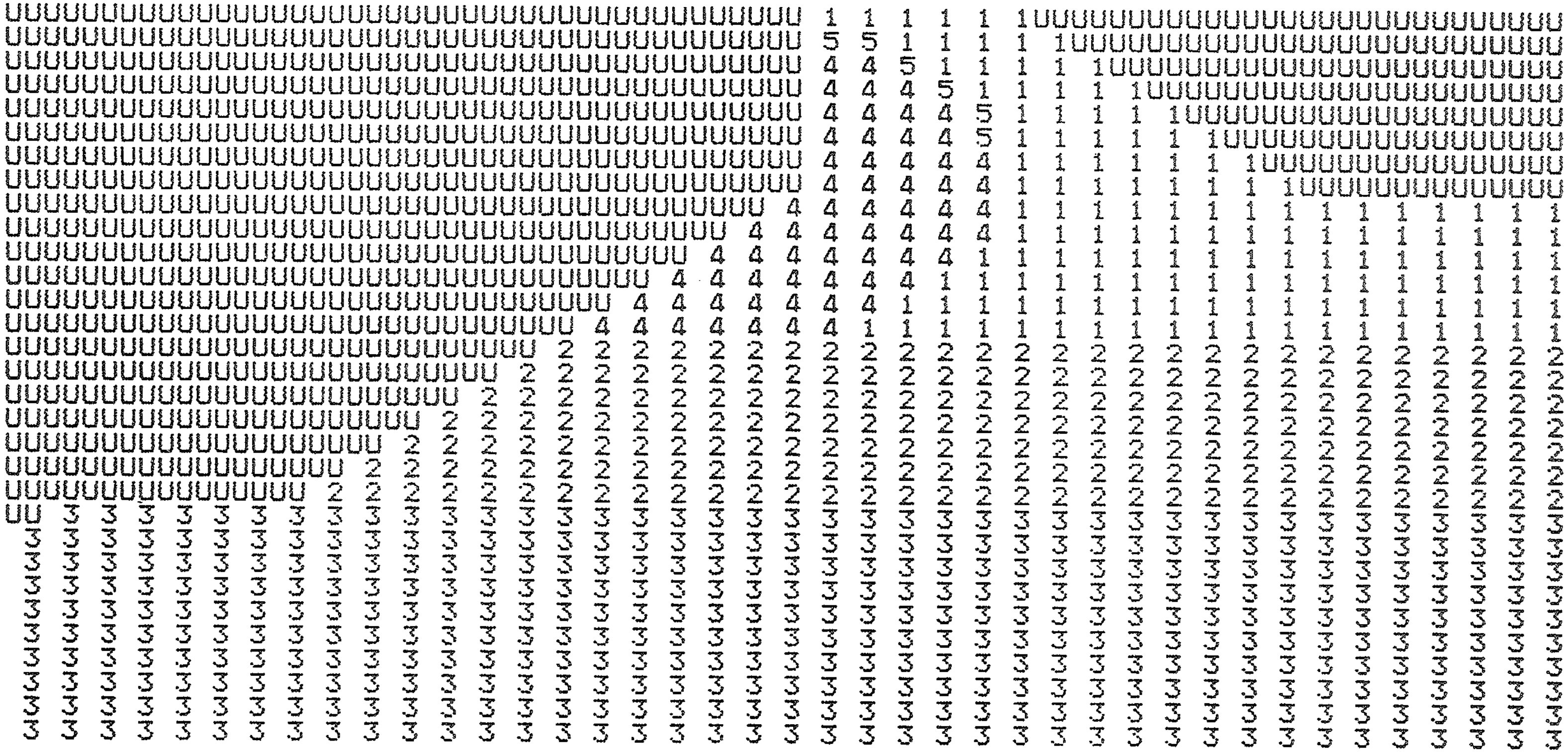


Figure 8. A print out of the input data showing the position of the different materials according to the drawings 121 and 122.

```
TIME        HEAT LOSS IN JOULE THROUGH
(4 years)   BOTTOM         SIDES          TOP            BOTTOM+SIDES   TOTAL

   4.02766  -0.89516E 12   -0.13092E 14   -0.43247E 13   -0.13987E 14   -0.18312E 14
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 0.3UUUUUUUUUUUUUUUUUUUUUUUUUUU
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 73.0 13.2 0.3UUUUUUUUUUUUUUUUUUUUUU
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 73.0 25.2 6.0UUUUUUUUUUUUUUUUUUUUUU
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 73.0 30.3 11.3UUUUUUUUUUUUUUUUUUUUU
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 73.0 43.0 15.9 0.3UUUUUUUUUUUUUUUUU
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 73.0 44.3 20.1 4.9UUUUUUUUUUUUUUUUU
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 73.0 45.6 24.0 8.9UUUUUUUUUUUUUUUUU
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 73.0 46.4 26.8 12.2 0.3UUUUUUUUUUUU
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 69.6 47.0 28.7 14.8 4.5 0.3 0.3
UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU 67.5 47.3 29.8 16.6 7.6 2.5 2.2
UUUUUUUUUUUUUUUUUUUUUUUUUUUUU 73.0 63.3 47.9 31.0 20.1 13.3 7.6 6.3
UUUUUUUUUUUUUUUUUUUUUUUUUUUUU 67.7 59.2 46.3 31.2 22.6 17.6 11.8 9.2
UUUUUUUUUUUUUUUUUUUUUUUUUUUUU 63.2 55.6 42.9 30.8 24.0 20.1 14.2 10.4
UUUUUUUUUUUUUUUUUUUUUUUU 73.0 59.2 52.0 39.4 30.1 24.8 21.7 15.7 10.6
UUUUUUUUUUUUUUUUUUUUUUUU 70.0 55.6 48.0 37.1 29.6 25.3 22.5 16.4 10.6
UUUUUUUUUUUUUUUUUUUUUUUU 67.2 52.4 45.1 35.8 29.2 25.3 22.8 16.7 10.5
UUUUUUUUUUUUUUUUUUU 73.0 64.6 49.7 42.7 34.6 28.7 25.2 22.8 16.9 10.5
UUUUUUUUUUUUUUUUUUU 71.1 62.2 47.2 40.6 33.4 28.2 25.0 22.8 17.0 10.5
UUUUUUUUUUUUUUUUUUU 69.2 60.1 45.1 38.9 32.3 27.6 24.7 22.6 17.0 10.4
UUUUUUUUUUUUUU 73.0 67.6 58.2 43.3 37.4 31.4 27.0 24.3 22.4 17.0 10.4
UUUUUUUUUUUUUU 71.7 66.0 56.4 41.7 36.1 30.5 26.4 23.9 22.1 16.9 10.4
73.0 73.0 73.0 70.2 64.3 54.6 40.1 34.7 29.5 25.7 23.4 21.7 16.7 10.4
71.7 71.7 71.4 68.5 62.4 52.6 38.5 33.3 28.5 25.0 22.8 21.3 16.5 10.4
70.5 70.4 70.0 66.9 60.7 51.0 37.1 32.2 27.6 24.3 22.3 20.8 16.3 10.4
66.8 66.5 65.7 62.5 56.3 46.8 33.8 29.4 25.5 22.7 21.0 19.7 15.8 10.4
62.2 61.7 60.7 57.4 51.2 42.3 30.5 26.7 23.3 20.9 19.5 18.4 15.1 10.4
49.4 48.6 47.3 44.3 39.1 32.1 23.5 20.8 18.6 17.1 16.2 15.5 13.4 10.3
35.1 34.3 33.2 30.9 27.3 22.7 17.4 15.9 14.6 13.8 13.3 12.9 11.8 10.2
24.2 23.6 22.8 21.4 19.2 16.6 13.7 12.9 12.2 11.8 11.6 11.4 10.9 10.1
16.3 16.0 15.6 14.9 13.9 12.7 11.5 11.2 10.9 10.7 10.6 10.6 10.3 10.0
10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0
```

B-CENTER VED DANMARKS TEKNISKE HØJSKOLE

Figure 9. Example on the output. Only one third of the calculated temperatures down through the soil are printed.

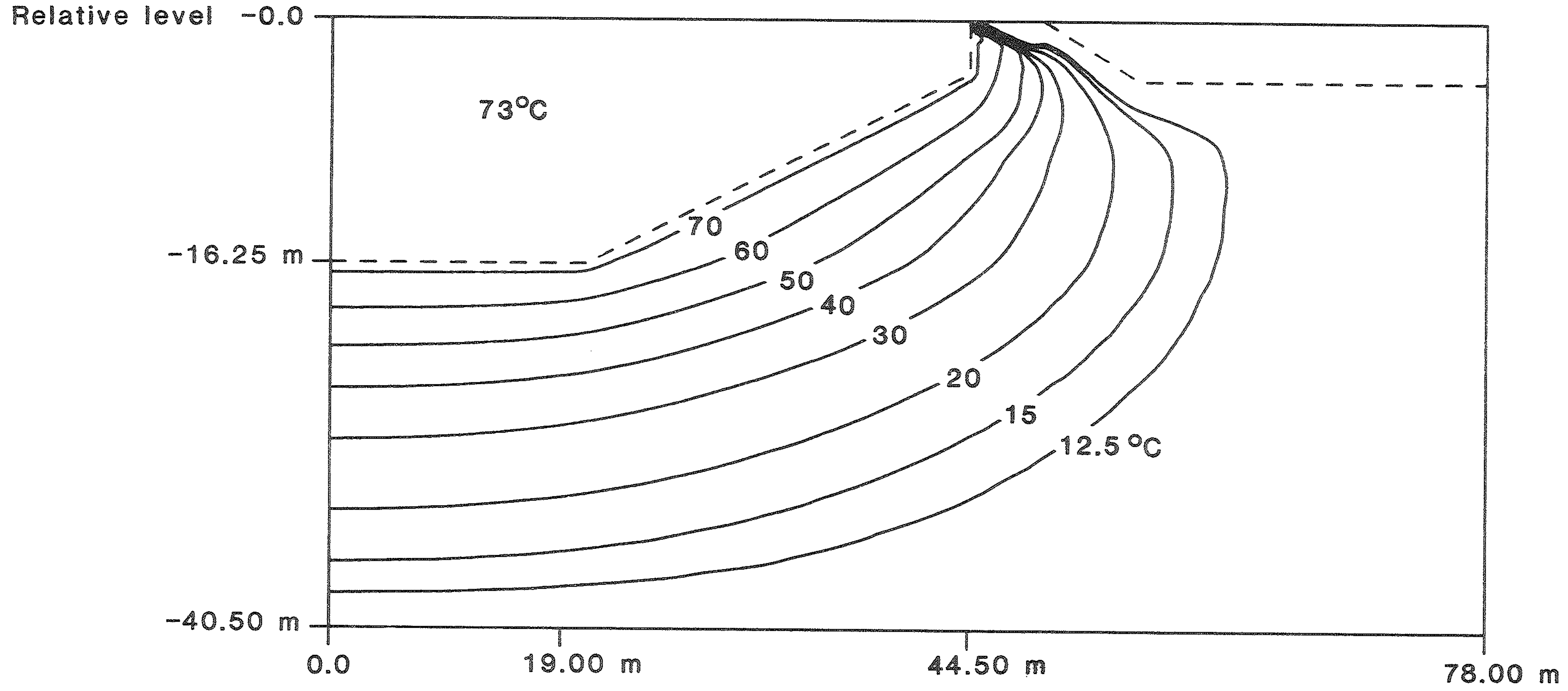


Figure 10 The temperature profile through the soil for the last day of the 4. year.