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# A BOREHOLE HEAT STORE IN ROCK

## Pilot trials in Luleå and preliminary design of a full-scale installation

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CONTENTS

# FOREWORD

The borehole heat store in rock project has comprised system and thermal engineering field trials and their assessment, together with preliminary design of an experimental and demonstration installation to be built at the University of Luleå. The work has covered a wide range of cross-disciplinary fields. The positive attitude and active participation of the Luleå Energy Authority has played an important part, not least when seen in the perspective of the emphasis of the project on producing an experimental and pilot installation.

The following personnel have participated in the work:

| | | |
|---|---|---|
| Sören Andersson, | AIB, Stockholm | Project leader |
| Bo Nordell, | LUH*, Water Resources Engineering | Research leader |
| Alf Johansson | LUH, " | Fittings and equipment |
| Kurt Leijon | LUH, " | Instrumentation system |
| Roger Hermansson, | LUH, Physics | Measurements |
| Göran Säwe | LUH, " | Measurements |
| Björn Lindahl | LUH, Ecology | Ecology |
| Tomas Åbyhammar | AIB, Stockholm | Preliminary design |
| Lars Ljung | AIB, " | Preliminary design |
| Anders Eriksson, | AIB, " | Preliminary design |
| Anders Forsén | Swedish Energy Systems AB | Preliminary design |

Other work, forming part of the overall project, has been carried out by:

- Johan Claesson, Göran Hellström and Per Eskilson, University of Lund, Department of Mathematical Physics, concerning mathematical design models and assessment of measured data.
- Tommy Claesson and Bo Ronge, Chalmers University of Technology, Department of Geology, concerning water chemistry and solubility experiments.
- Bengt Ludvig, University of Luleå, Division of Rock Mechanics, concerning the geology of the store area.
- Roger Lindfors and Gustaf Lindqvist, University of Luleå, Division of Soil Physics, concerning determination of rock properties and seismic measurements.
- Eva Cassel, University of Luleå, Division of Water Resources Engineering, concerning water analyses.
- Sven Knutsson and Sven Juhlin, University of Luleå, Division of Soil Mechanics, concerning determination of soil properties.

* University of Luleå

Civil engineering and installation works have been carried out by:

- Gällivare Berg och betongborrning AB (Gällivare Rock and Concrete Drilling Co. Ltd.) - core drilling.
- Luleå kommun, gatukontoret (Luleå town council, highways department) - drilling for groundwater observation holes.
- Älvsby Bergentreprenader AB (Älvsby Rock Contractors Ltd.) - drilling of trial holes and temperature measurement holes.
- Svetstjänst AB (Welding Services Ltd.) - installed fittings etc.

The work was carried out between March 1981 and April 1982.

May, 1982

AIB - ALLMÄNNA INGENJÖRSBYRÅN AB
Energy and process technology
STOCKHOLM

University of Luleå
Division of Water
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LULEÅ

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Bo Nordell

SUMMARY

## General

Results from several theoretical analyses and practical trials, either completed or in progress, indicate that borehole heat stores in rock, as shown below in Figure A, can be a competitive alternative to other means of large-scale heat storage. The field trials described in this report, together with such existing results, indicate that the borehole heat store has now reached the stage where it can be regarded as suitable for testing in an experimental and demonstration installation on a larger scale.

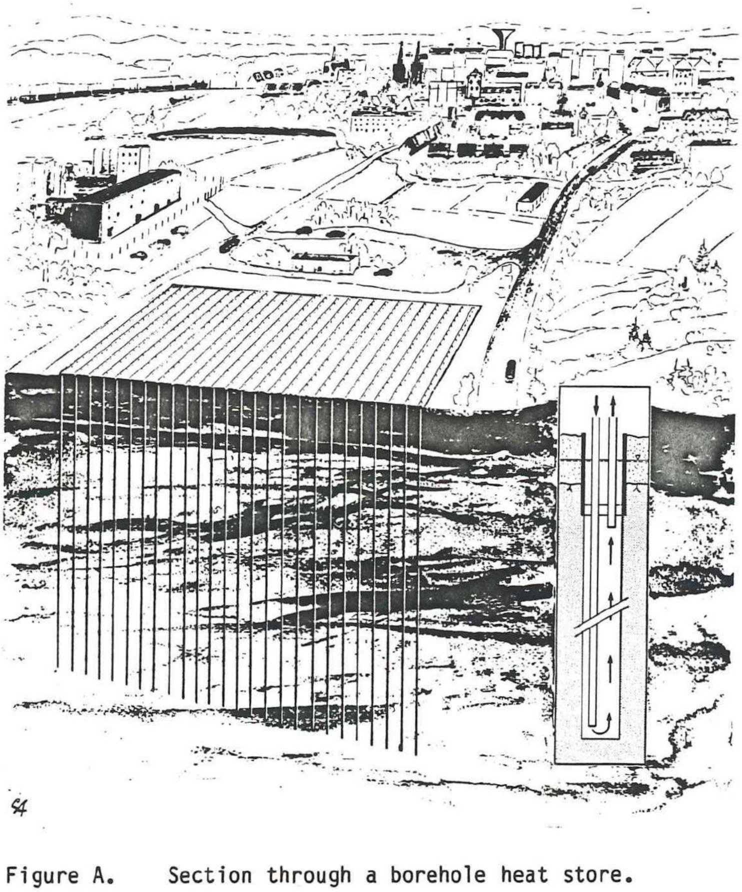



Figure A. Section through a borehole heat store.

## The trial installation

The field trials described in this report have related to seasonal storage of heat in a borehole heat store. The trials have been carried out in a store consisting of 19 storage holes and 10 temperature monitoring holes. The diameter of the storage holes was 52 mm, spaced 1.3 m apart. All holes were 21 m deep, of which the upper 6 m passed through the overlying earth, with 15 m in the bedrock below. Each storage borehole contained two polyethylene hoses, one extending to the bottom of the hole and one extending only part-way down, of 16 mm internal diameter and 2 mm wall thickness. The storage holes were unlined. A plan of the store, and section through a borehole, are shown in Figure B.

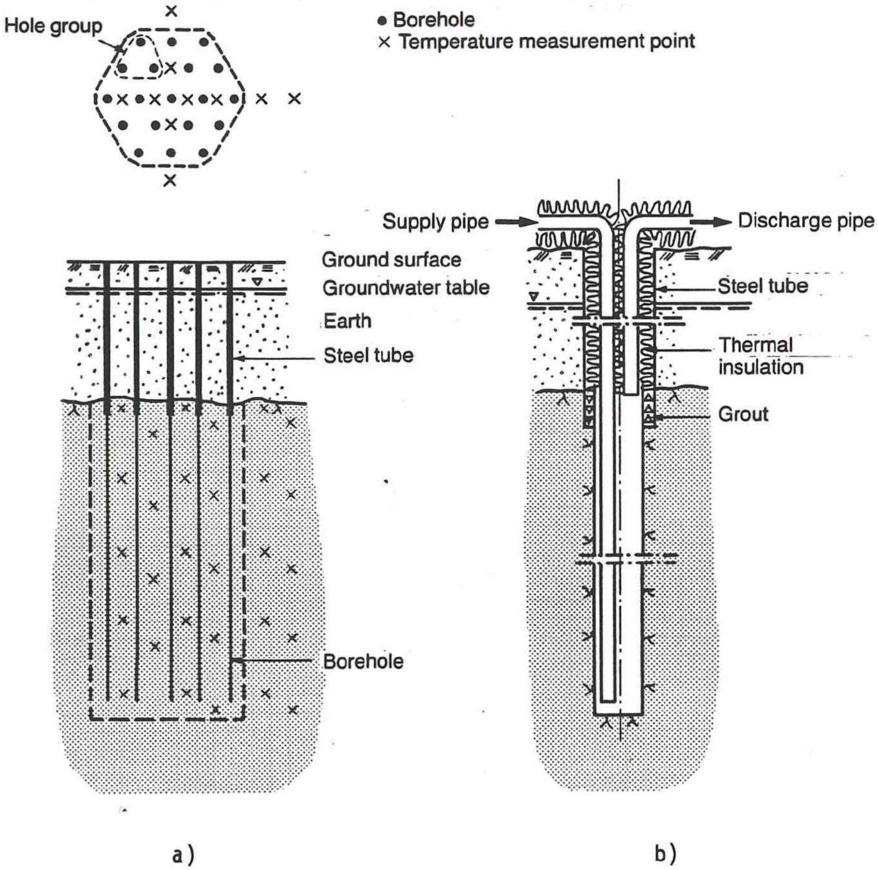



Figure B a) Plan and section through the experimental store.
b) Section through a borehole, showing insulation and hoses.

The trials store was charged with heat supplied through a heat exchanger connected to an existing nearby hot water boiler plant connected to the Luleå district heating system. Heat abstracted from the store was dissipated by cooling water from a nearby fire hydrant.

The circulation system in the store comprised six groups, each of three holes, connected in parallel. The centre hole was connected separately in parallel with the six other groups. Circulation through the store was provided by pump pressure and siphon action between the holes.

Initial surveys were carried out, in connection with the search for a suitable site for the trials, and included geological mapping and seismic investigations. When the final choice of site had been made, investigations were complemented by observations of such other parameters as groundwater height, permeability measurements, core drilling and determination of physical data for the rock and overburden.

In parallel with the heat store trials, solubility analyses of rock from the heat store have been carried out in an autoclave.

## Results of the trial

Five annual cycles were simulated during the trials, each as follows:

| | |
|---|---|
| Charging | 10 days |
| Rest | 4 days |
| Abstraction | 6 days |
| Rest | 4 days |
| Total | 24 days |

If the behaviour of a small-scale store, operating on a 24-day cycle, is to model the thermal processes in a full-scale store over a period of a year, it is necessary to scale down the store in the proportion $\frac{24}{365}$, i.e. 1:3.9. This means that the pilot store, with a volume of 400 $m^3$, can be regarded as part of a full-scale store, reduced by a longitudinal factor of 3.9.

The temperatures measured in the rock during the trials, both within and outside the periphery of the store, showed good agreement with theoretical results derived from a three-dimensional mathematical model developed at the University of Lund. This can be seen, for example, in Figure C, where continuous temperature measurements of the rock and circulating water are indicated by continuous lines, with the nearby dots etc. indicating the corresponding theoretical values.

Apart from certain initial problems, which were quickly overcome, all parts of the system have operated without trouble.

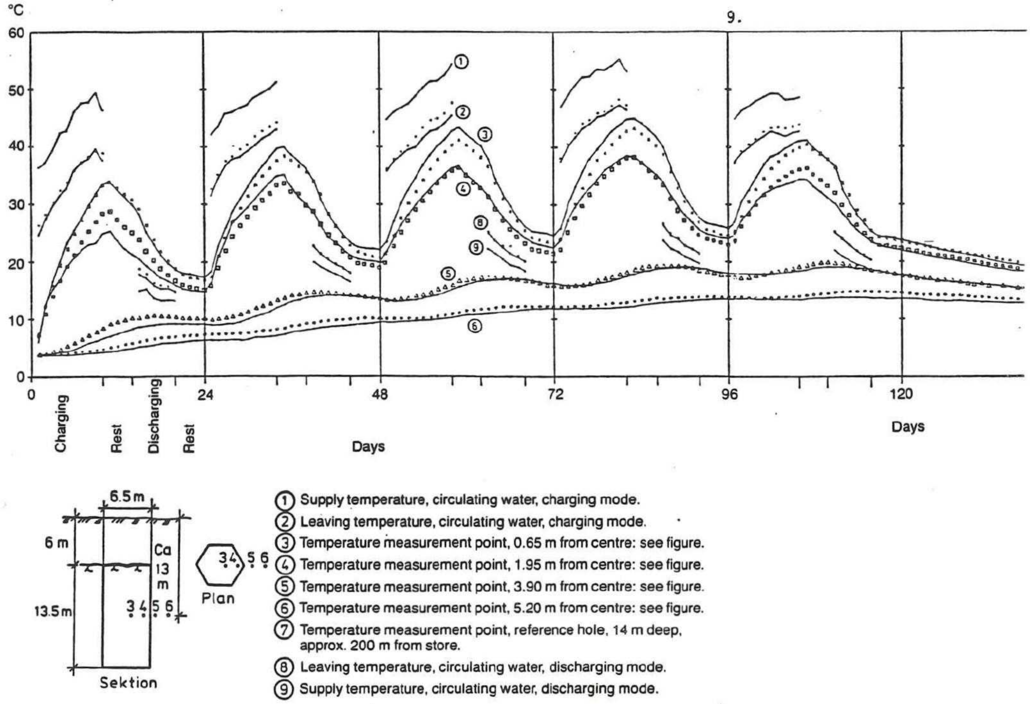



Figure C. As-measured temperatures (continuous lines) and corresponding theoretical temperatures (point plots).

## Experimental and demonstration installation

The project has also included preliminary design of a borehole store intended as an experimental and demonstration installation. It is the intention that the store should be used during the summer for storage of excess heat from the combined heat and power station in Luleå. During the winter, heat would be abstracted from the store and used to supply one of the blocks of buildings at the University of Luleå. The store would have a thermal capacity of 2.2 GWh, and operate with an open circulation system.

# 1. INTRODUCTION

## 1.1 Storage requirements

Large-scale heat storage may be needed in connection with solar heating or waste heat installations, or as a means of levelling out load variations on district heating systems. A seasonal heat store, for example, can enable system boiler capacity to be reduced and utilization time increased. Such stores can also improve the economic operating conditions of heat pumps, e.g. when abstracting heat from the upper layers of the ground or from water. In extreme cases, large-scale heat stores could also be envisaged for seasonal storage of heat produced by cheap surplus electricity during the spring and summer.

An estimate of the amount of thermal storage capacity likely to be required in Sweden by 1990 was presented at a working seminar (1) arranged by the Committee for Underground Construction of the Royal Swedish Academy of Engineering Sciences, and held in Älvkarleby in March 1981, and was as shown in the table below:

| Type of store | Capacity, TWh | Volume, $10^6$ $m^3$ | Number |
|---|---|---|---|
| Rock cavern | 1.0-1.5 | 20-30 | 40-60 |
| Borehole store | 0.5-1.5 | 20-40 | 20-40 |
| Excavated pit store | 0.5-1.5 | 20-35 | 50-70 |
| Storage in peat or clay | 0.5-1.0 | 25-35 | 100-200 |
| Other | 0.5-1.0 | - | - |
| | 3.0-6.5 | | 210-370 |

However, it was felt that the true need for storage capacity up to 1990 would be considerably less than the 3.0-6.5 TWh shown in the table above. It was felt that it would be unlikely that more than 1-3 TWh of storage capacity would be built before 1990, although even this lower rate of production might be still further reduced as a result of limited civil engineering and building capacity for certain types of store.

However, it is apparent that even a low rate of building would require a considerable amount of work in terms of development and building of seasonal heat stores.

## 1.2 Development status

### 1.2.1 General

In general, it is difficult to make economic and technical comparisons between different types of heat store. The store is merely one element among several in a heating system, and overall system aspects are often so complex that it is not possible to make general assessments. A further complication is introduced by the fact that, for a number of methods, heat storage technology is only at an early stage, while other methods have already been demonstrated in practice. It is therefore necessary to proceed with caution when attempting to assess the expected economic and technical performance of various methods.

### 1.2.2 The borehole heat store

The borehole heat store in rock has been studied in general theoretical terms by workers such as Johansson, B. & Nordell, B., 1980 (2), Andersson, S., Eriksson, A. and Tollin, J., 1981 (3) and Kadesjö, H. and Sintorn, J., 1981 (4). Advanced mathematical design models have been developed at the University of Lund, by Johansson, M. and Claesson, J., 1979 (5), and by Hellström, G., 1981 (6).

For the Södertuna project, AIB is at present investigating how the operating strategy of a borehole heat store might be matched to the requirements of a larger residential area, 80% of the heat to which is provided by solar energy. AIB is also investigating how a borehole heat store could be used in combination with heat pumps abstrating heat from a lake. Industriplanering - Anders Forsén and the University of Luleå - are investigating the use of a borehole heat store for seasonal storage of waste heat from process industries.

Practical trials of a borehole heat store for a detached house, operating a low temperatures, have been carried out in Sigtuna by Platell, O. and Wikström, H., 1981 (7).

Full-scale trials in three 110 m deep boreholes are being carried out at present by the Swedish State Power Board development laboratories at Älvkarleby. The work is being performed jointly by the Swedish State Power Board and AIB, and is concerned primarily with practical aspects of system design and installation as applied to closed circulation systems.

Field trials and system studies have been carried out at the University of Luleå in conjunction with Svenska Energi System AB and AIB. This work, which is described in this report, has included simulation of five annual cycles in a 1:4 scaled-down store having an open circuit circulation system.

Results from the above-mentioned studies and practical trials indicate that the borehole heat store can be a competitive alternative to other large-scale storage systems, as demonstrated by Andersson, S., Eriksson, A. and Nordell, B., 1981 (8). The borehole heat store should therefore now be regarded as having reached the stage at which it can be tested in a demonstration and experimental installation on a larger scale.

# 2. GENERAL DESIGN AND FEATURES OF THE BOREHOLE HEAT STORE

## 2.1 Operating principles

The operating principle of the borehole heat store has been described in detail by earlier workers, e.g. (2) and (3). To avoid unnecessary repetition, the following is therefore only a very brief description of the main features and principles.

Operation of a borehole heat store is based on the thermal conduction and thermal capacity of bedrock. Heat is transferred to or from the rock by means of water, circulating through a large number of boreholes, as shown in Figure 2.1.

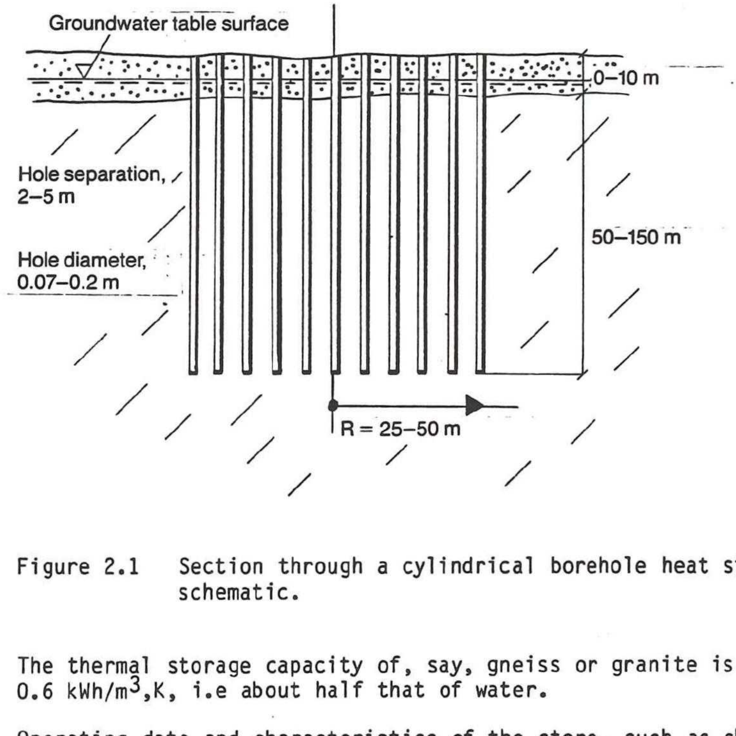


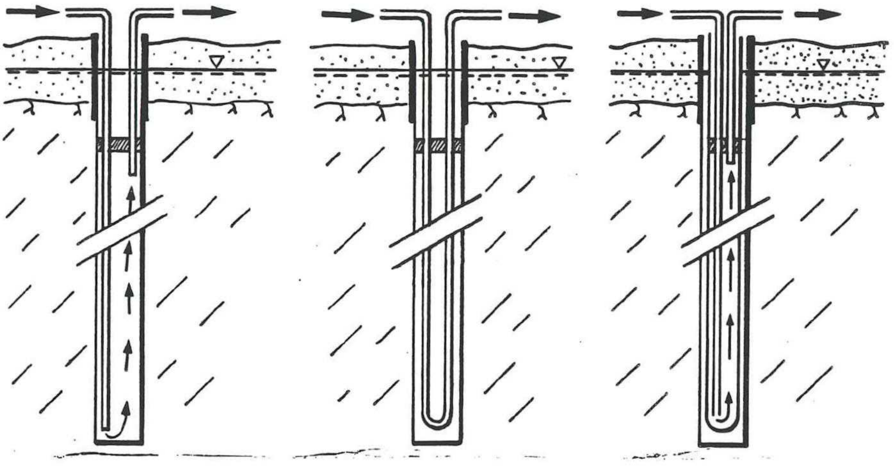

Figure 2.1 Section through a cylindrical borehole heat store - schematic.

The thermal storage capacity of, say, gneiss or granite is about 0.6 kWh/m$^3$,K, i.e about half that of water.

Operating data and characteristics of the store, such as charge and discharge power capacities, energy capacity and temperature efficiency, are determined by parameters such as borehole separation, borehole diameter, store size, operating strategy and other factors, (2), (3) and (5).

## 2.2 The circulation system

The heat transfer medium (water) is circulated through the boreholes in an open or closed system, as shown in Figure 2.2. Boreholes can be connected in parallel or in series, either individually or in groups.



a) b) c)

Figure 2.2 Circulation systems:
a) open system: b) and c) closed systems

The borehole may also be fitted with a liner, grouted and/or expanded against the borehole wall. This method gives excellent heat transfer to and from the rock, but involves high civil engineering costs. Very thin liners can easily be crushed by hydrostatic pressure if the borehole is emptied of water.

The following field trials, as described in this report, have been carried out using an open circulation system as shown in a) in Figure 2.2.

## 2.3 The size and shape of the store

Apart from optionally at the ground surface, a borehole heat store has no artificial thermal insulation. It is therefore important that the volume of the store should be sufficiently large to reduce thermal losses to a sufficiently low proportion to give acceptable energy and temperature efficiencies.

It is not generally possible to define any minimum 'economic' size of store. However, it can be said that it is unlikely that store size should be less than about 100 000 $m^3$ - at least, not when the store is intended to operate at high temperatures.

Store efficiency is also influenced by the shape of the store. However, for larger sizes of store, modest departures from minimum peripheral envelope area have no practical effect.

Figure 2.3 shows the size of store necessary as a function of the number of detached houses to receive heat from the store.

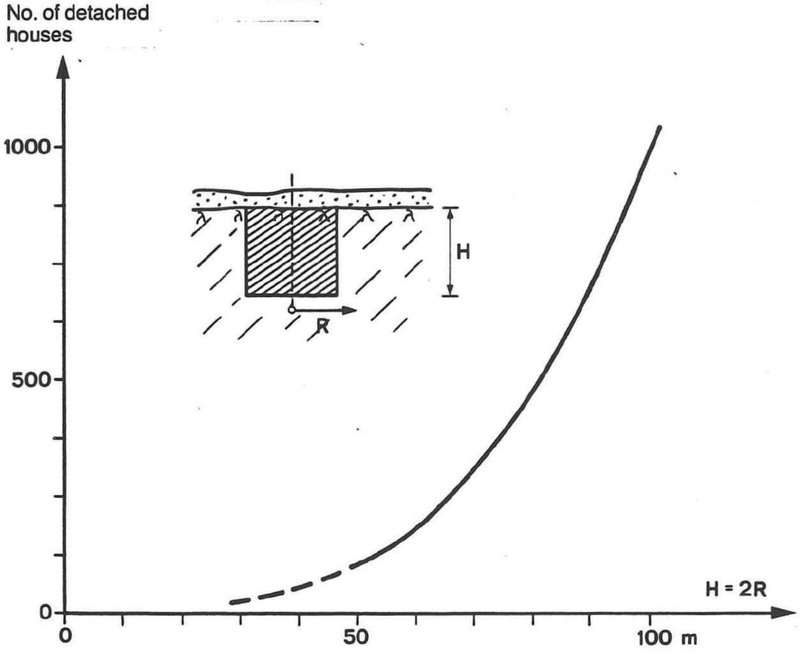



Figure 2.3 Store size as a function of storage capacity (expressed as number of detached houses constituting the load) for an assumed effective temperature difference of 35 K between charge and discharge store temperatures.

## 2.4 Operating strategies

Different operating strategies can be used for both charging and discharging. In the simplest case the entire store volume is (in principle) charged or discharged simultaneously. Equal flows of water at the same temperature are pumped through all boreholes.

Another operating strategy, providing higher temperature and energy efficiencies, charges the store radially outwards from the centre. Discharge is in the reverse direction, starting from the peripheral elements of the store. In principle, this involves series connection of the boreholes, with water passing from one borehole to the next in a radial direction. Practical application of this strategy can be implemented by dividing the store into a number of concentric temperature zones, as shown in Figure 2.4.

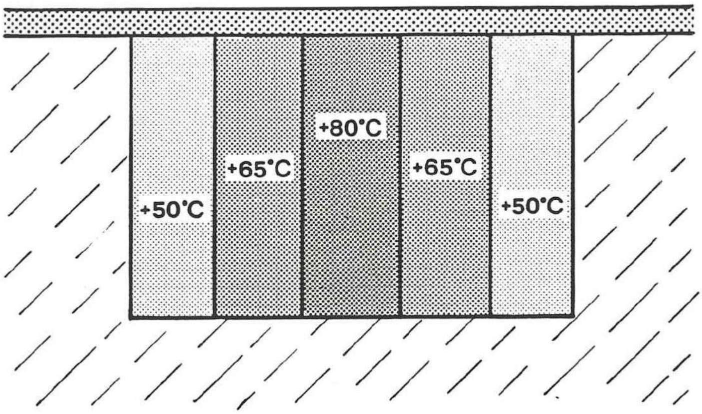



Figure 2.4 Temperature zones in a cylindrical borehole heat store, shown in section.

Any operating strategy that requires or permits utilization of more or less distinct temperature zones calls for a very large store volume (= many boreholes). In a smaller store, radial series connection of boreholes would result only in a uniform drop in temperature from the centre of the store and radially outwards. Nevertheless, even with very small stores, this operating strategy reduces store losses and so results in improved temperature and energy efficiencies, as shown in Figure 2.5.

The diagram on the following page is based on the following conditions:

- ---o--- all boreholes connected in parallel.
- ---x--- store divided up into four series-connected zones, each having the same number of boreholes.
- The store is in its fifth annual cycle.
- Borehole separation: 4 m.
- Coefficient of thermal conductivity, $\lambda$ = 3.5 W/m,K.
- Storage cycle:

  3 months' charging at constant temperature of +70 °C:

  3 months' rest:

  3 months' abstraction at constant 10 K above supply water temperature:

  3 months' rest.

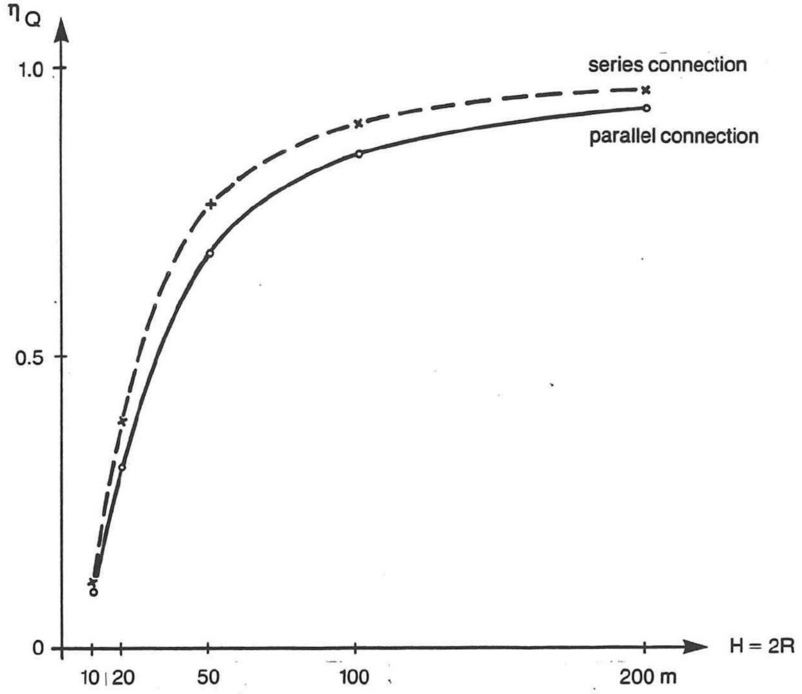



Figure 2.5 Energy efficiency as a function of store size and operating stragegy.

Figure 2.6 shows how energy efficiency varies with variation in four parameters: the coefficiency of thermal conductivity of the rock, $\lambda$, the distance between boreholes, d, the depth of the store, H (= 2R), and the relative circulating flow, expressed as $\frac{Q_f}{4\pi R^2 H}$.

Basic assumptions in establishing the reference conditions have been:

$H = 2R = 100$ m
$\lambda = 3.5$ W/m,K,
$d = 4$ m
$Q_f = 5 \times 10^{-8}$ $s^{-1}$.

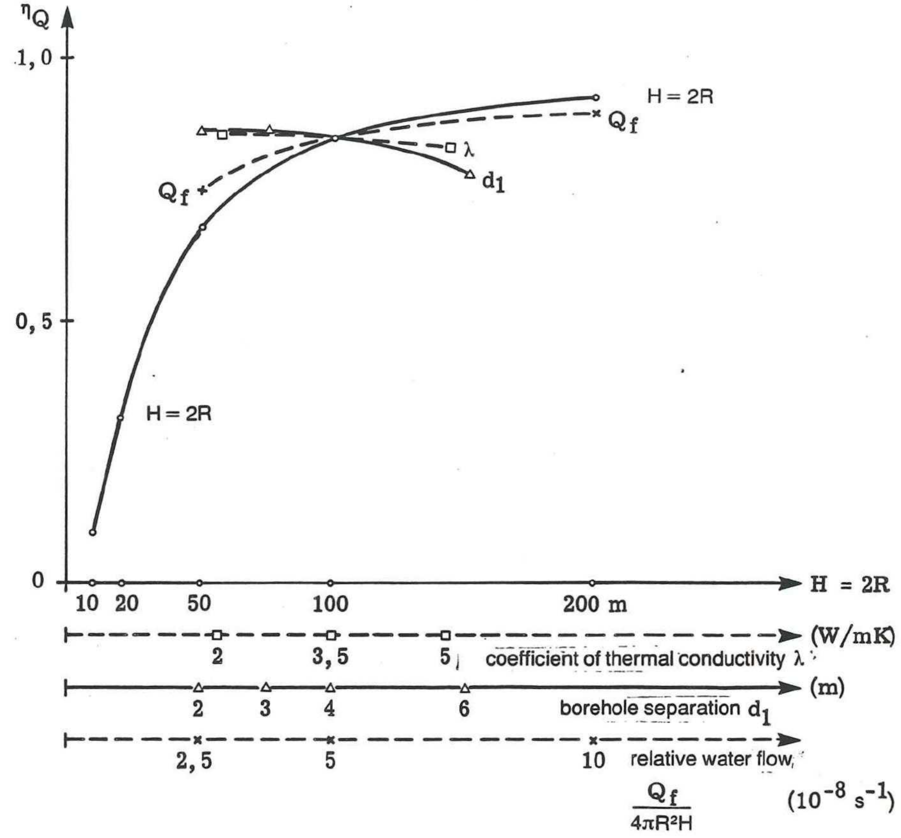



Figure 2.6 Energy efficiency as a function of four different parameters: only one parameter being varied at a time for each curve.

Reference values: 2R = H = 100 m, λ= 3.5 W/m,K, d = 4 m and $Q_f$ = $5 \times 10^{-8}$ $s^{-1}$.

The diagram above is based on the following assumptions:

- All boreholes connected in parallel.
- That the heat store is in its fifth annual operating cycle.
- Storage cycle:

  3 months' charging at constant temperature of +70 °C:

  3 months' rest:

  3 months' abstraction at constant 10 K above supply water temperature:

  3 months' rest.

# 3. THE EXPERIMENTAL STORE

## 3.1 Siting

In a project entitled 'Development of Technology for Energy Storage in the Ground' (9), and financed by the Fund for Northern Sweden and the Norrbotten Delegation, the borehole heat store was noted as a technically and economically interesting method of storage. As the project had a commercial slant, and as it seemed probable that suitable rock conditions for borehole heat stores should be available over much of the country, work was started on a store of this type.

A suitable trials site was found to the north of the University of Luleå, about 200 m from the nearest buildings. Some of the important factors in determining a choice of site were:

- generally favourable geological and topographical indications:
- closeness to an existing district heating system:
- closeness to the University and its technical facilities, and
- ability to continue the work in future stages, establishing an experimental and demonstration store, from which parts of the University could be provided with heat.

The 19 circulation holes and 10 observation holes that formed the basis of the scaled-down experimental store had also been drilled on the site as part of the work of the project mentioned in the first paragraph.

## 3.2 A description of the store and its method of operation

The experimental store consists of 19 boreholes, 52 mm in diameter, for heat supply and abstraction, and 10 smaller boreholes for temperature monitoring. All boreholes are 21 m deep, of which the upper 6 m pass through earth and the lower 15 m are in rock. A liner protects the borehole where it passes through the earth layers, and continues down about 0.2 m into the rock, where it is grouted in position. After completion of this part of the hole, the rest of the hole was drilled down through the liner and cement plug (see Figure 3.1).

Two 20/16 mm polyethylene hoses have been inserted into each of the larger holes. One extends down to a depth of 13 m below the upper surface of the rock, while the other reaches down to only just below the rock/soil interface. The bottom of the borehole, i.e. between 13 m and 15 m below the rock interface, is intended to act as a sump for the collection of sludge and stones etc.

The larger boreholes have been positioned at the corners of equilateral triangles with a side length (i.e. = borehole separation) of 1.3 m. The temperature measurement holes have been drilled between the store holes and outside the body of the store (see Figure 3.1).

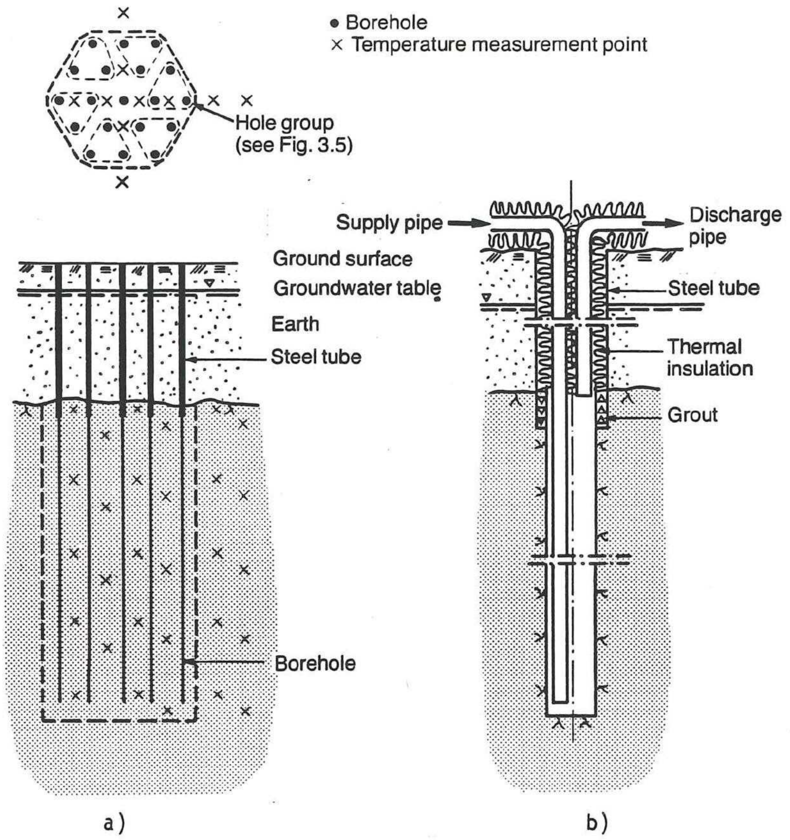



Figure 3.1 a) Plan and section through the experimental store.
b) Section through a borehole, showing insulation and hoses.

Dimensional analysis of the general thermal conductivity equation indicates that the physical length and time scales of the model and of a full-size store are governed by the relationship:

$$\frac{l}{l_1} = \sqrt{\frac{T}{T_1}}$$

If the behaviour of a small-scale store, operating on a 24-day cycle, is to model the thermal processes in a full-scale store over a period of a year, it is necessary to scale down the store in the proportion $\frac{24}{365}$, i.e. 1:3.9. This means that the borehole separation of 1.3 m used here would correspond to a full-scale separation of 5.1 m, while the model volume of 400 $m^3$ would correspond to a full-scale store volume of 24 000 $m^3$.

The trials store was charged with heat supplied through a heat exchanger connected to an existing nearby 3 MW hot water boiler plant connected to the Luleå district heating system. Heat abstracted from the store was dissipated by cooling water from a nearby fire hydrant. The main features of the installation, and a view of the general appearance, are shown in Figures 3.2 and 3.3.

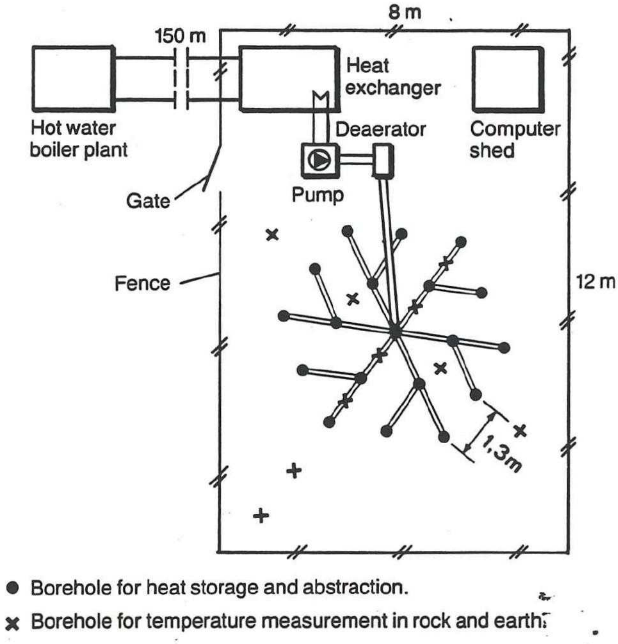



Figure 3.2 Plan and main features of the trial installation.

The circulation system of the heat store consisted of six groups of holes, each containing three boreholes, connected in parallel. The centre hole was separately connected in parallel with the six groups.

The centre borehole, and each of the groups of holes, was connected via a deaerator and flow distributor to the pump and heat exchanger, as shown in Figure 3.5.

The circulation system was developed experimentally and tested in laboratory trials, as shown in Figure 3.4.

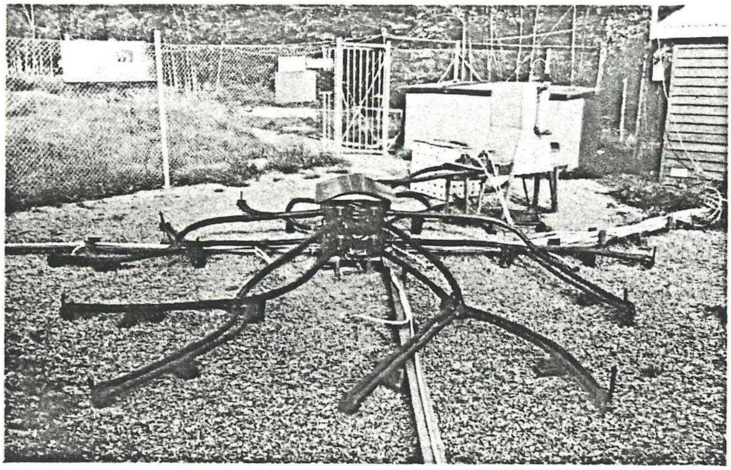


Figure 3.3 General view of the trials site.

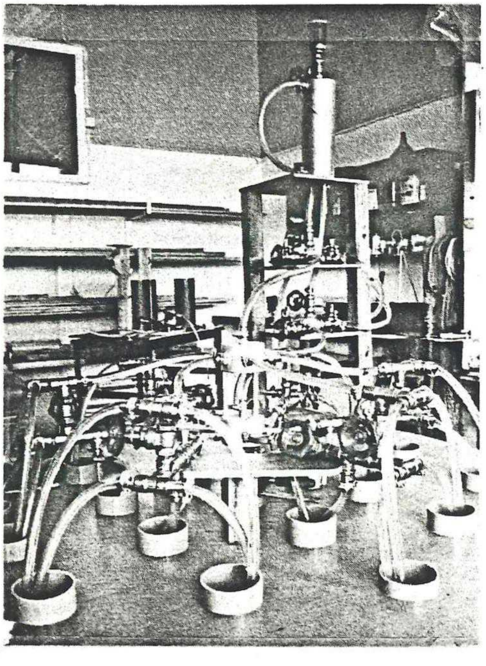


Figure 3.4 Test arrangement of the circulation system.

As shown in Figure 3.5, circulation in the store is based on siphon action. This has the considerable advantage that the flow between boreholes is controlled automatically, with no risk of any borehole becoming over-full. However, it is essential that no air or gas pockets accumulate and break the siphons. To prevent this, and to enable circulation to be easily started, air baffles have been incorporated in some of the branch pipes in the form of special restriction washers (see Figures 3.5 and 3.6). These washers reduce the flow to some few per cent of the total flow through the siphon.

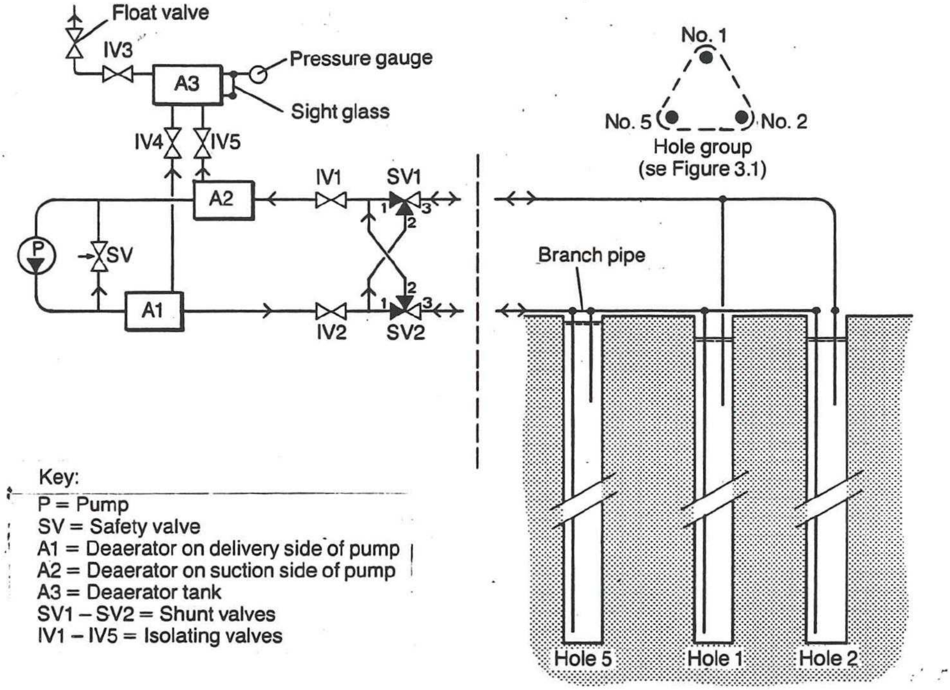



Figure 3.5 Diagram of deaeration and circulation systems.

The difference in level between the water surfaces in the boreholes, varying from about 10 to 30 cm, provides a driving force for water flow through the natural cracks in the rock. When the store is being charged, groundwater level is highest at the centre of the store, giving rise to a flow towards the periphery. When heat is being abstracted, the direction of flow is reversed, producing a flow through the fissures in the rock towards the centre of the store. These flows increase the charging and discharge power capacities of the store, as the heat transported by the groundwater augments the heat flow through the rock by conductivity.

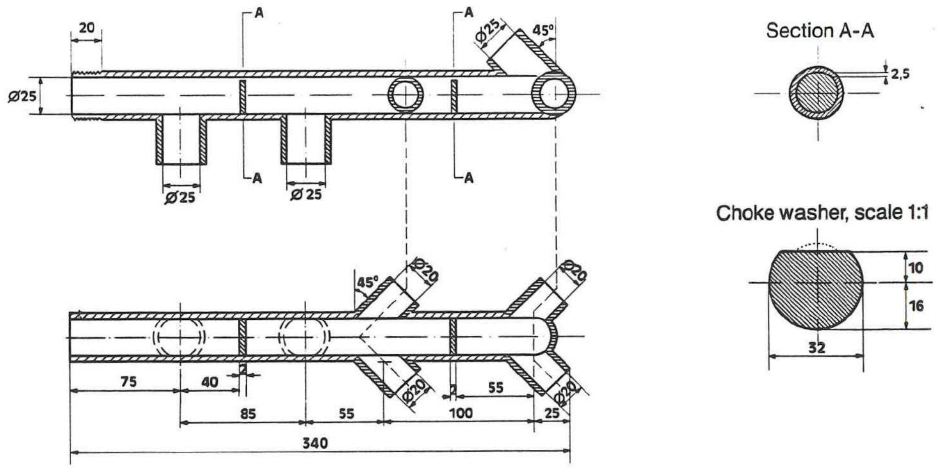



Figure 3.6 Branch pipe with air baffle. (See also Figure 3.5.)

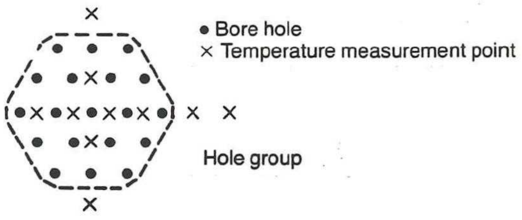
## 3.3 The instrumentation system

### 3.3.1 Instrumentation points

61 temperatures have been recorded hourly throughout the trials. Flow measurements have been made continuously, using pulse counters. Flows and temperatures have been measured in the distribution header between the store and the heat exchanger, and have thus recorded the total energy flow to and from the store. Ground temperatures have been measured in the rock and in the soil body above, both within the envelope of the store and outside it, using temperature sensors in separate temperature measurement holes, as shown in Figure 3.7. After the sensors had been installed, the holes were filled with sand in order to prevent thermal convection.

During operation, temperature measurements were also made in the charge/discharge holes by means of sensors fitted to steel measuring tapes. Temperatures were also measured in a reference borehole not affected by the heat of the store.

Finally, groundwater levels in the store and outside it were measured using a electric lamp circuit depth indicator.



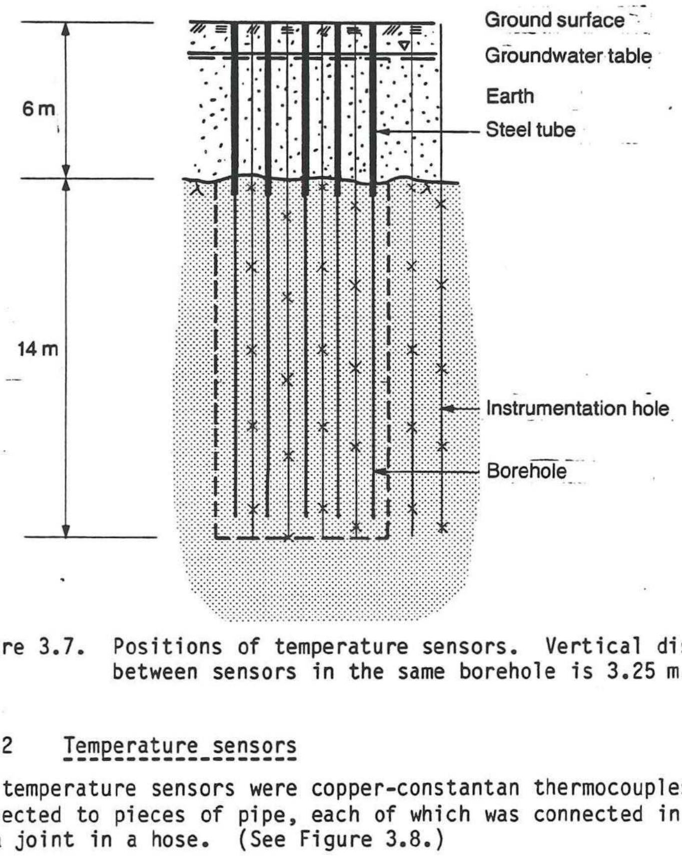




Figure 3.7. Positions of temperature sensors. Vertical distance between sensors in the same borehole is 3.25 m.

### 3.3.2 Temperature sensors

The temperature sensors were copper-constantan thermocouples connected to pieces of pipe, each of which was connected in turn as a joint in a hose. (See Figure 3.8.)

This method of fitting and encapsulating the temperature sensors, as used in the trials, was found to be very reliable, and all temperature sensors have worked without any trouble. This is wocth noting, as other instrumentation projects often refer to difficulties experienced in making measurements of this sort.

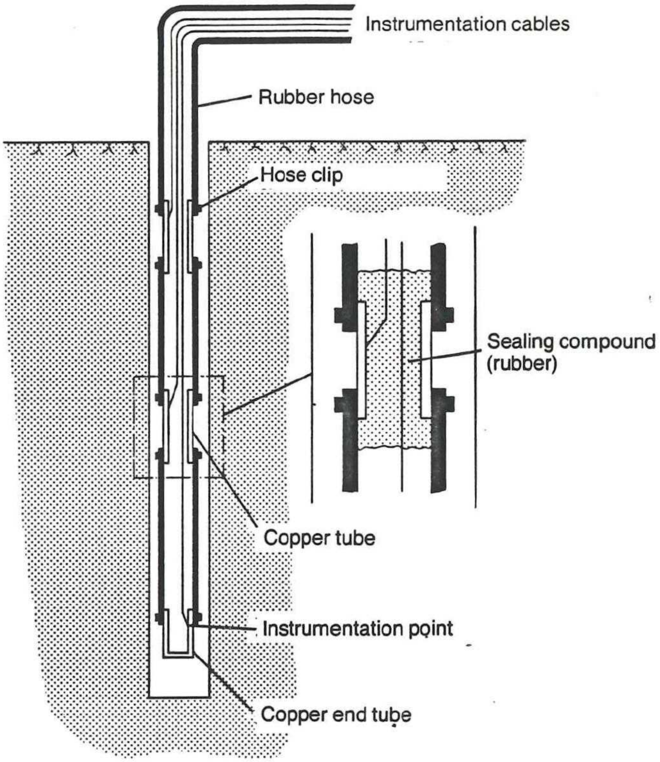



Figure 3.8 Encapsulation and positioning of the temperature sensors in a borehole. After installation of the sensors, boreholes were filled with sand.

### 3.3.3 Data acquisition and recording

A ZAMPO Z80 microcomputer, with two floppy disc units and a screen, has been used for data acquisition and processing. Software has included several programs, which have enabled performance of the store to be monitored. The programs can, for example, display measured values on the screen from any particular time, past or present, or print out measured values for any instrumentation point for any given period.

Figure 3.9 is a schematic diagram of the logging and data processing system.

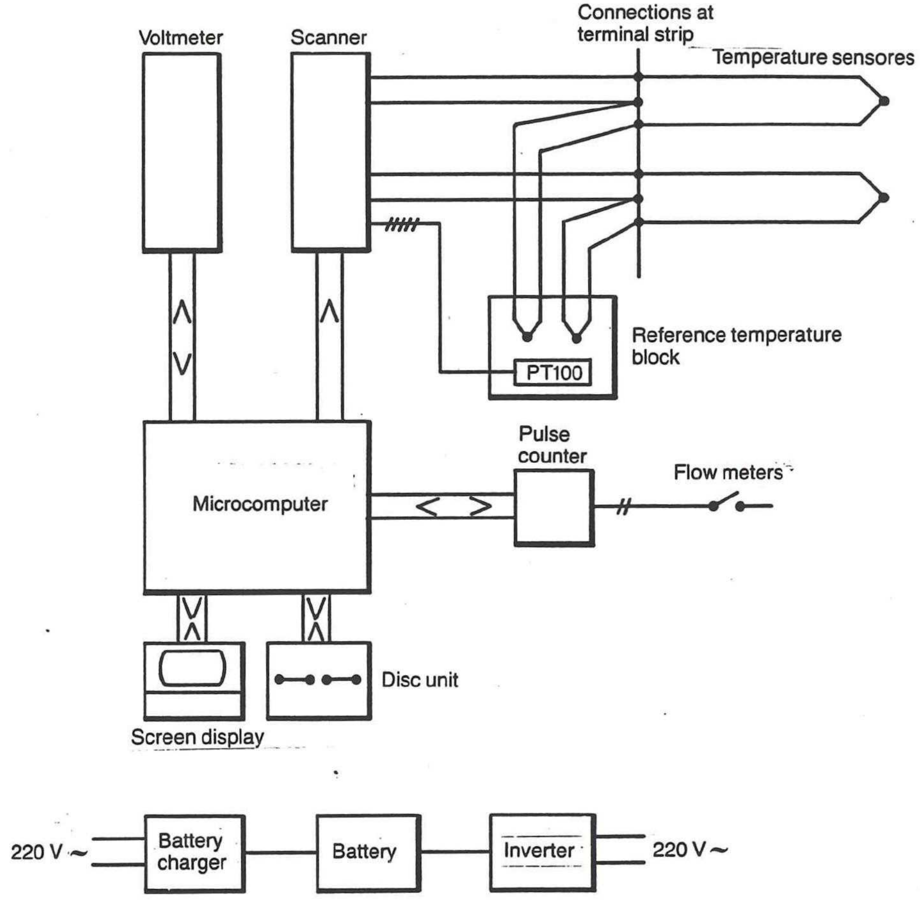



Figure 3.9 Schematic diagram of data acquisition and processing system.

## 4 PRELIMINARY INVESTIGATION

### 4.1 General

Various investigations, including geological mapping and seismic studies, were carried out prior to determining the site for the trials store, as shown in Figure 4.1.

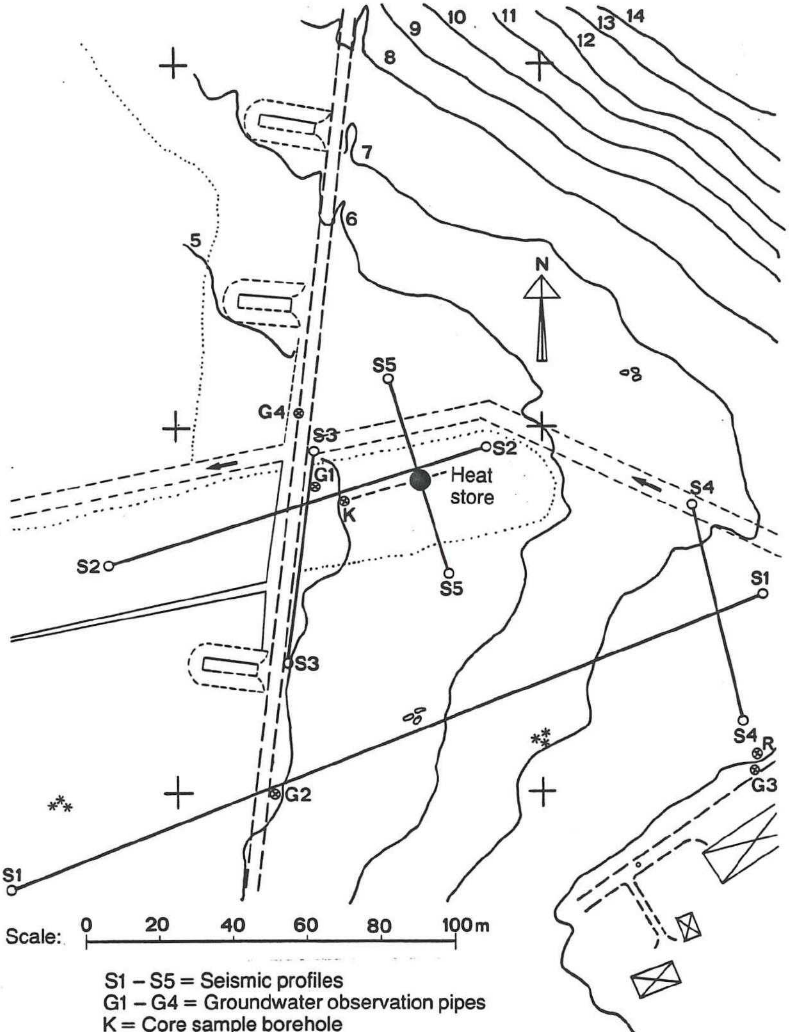



Figure 4.1 A map of the area around the heat store.

When the site had been decided upon, further investigations were carried out, including groundwater observations, core drilling, permeability measurement and determination of the properties and thermal characteristics of the rock and soil cover. Solubility analyses of rock material from the store site have also been carried out in an autoclave while the heat storage trials were in progress. Initial ecological observations and investigations have also been made.

## 4.2 Geological mapping

The bedrock in the store area consists of folded medium-grained gneiss, with an overburden consisting primarily of silty clay of sulphide soil type. There is no exposed rock in the immediate vicinity of the store site. However, the rock is exposed in a ditch that has been blasted 80 m south-west of the site, and it can be seen that there is a considerable amount of shale running through the gneiss, aligned N5/74°W.

The gneiss has been converted to igneous rock on Porsø hill, about 400 m north of the store site. The strike of the shale here is N65E, with a dip of between 65N and the vertical.

Further details of the geological mapping have been described by Ludvig, B., 1981 (10).

## 4.3 Seismic investigations

Five seismic measurement profiles (Figure 4.2) were carried out in order to determine the depth of soil cover and to detect the presence of any fracture zones.

The seismic profiles indicate that the depth of soil cover in the area of the store ranges between 5 m and 10 m, and that there are no larger fracture zones running through the store site. Subsequent drillings have shown good agreement with the depths of soil cover indicated by the seismic investigation.

## 4.4 Groundwater observations

Four observation holes, G1, G2, G3 and G4 (Figure 4.1) were drilled for groundwater observations. The differences between the groundwater table level in the four holes, taken together with the depth of soil cover, indicate a direction of flow of groundwater as shown in Figure 4.3, with an as-measured gradient of about 2 ‰.

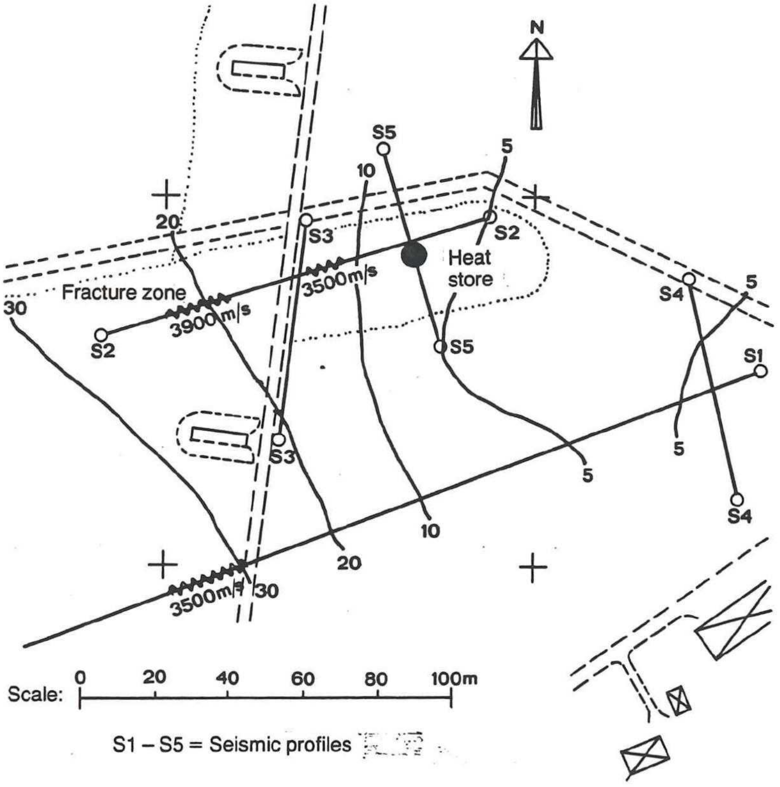



Figure 4.2 Seismic profiles at the trials site. Isolines indicate thickness of soil cover.

## 4.5 Core drilling

A 48 m long core borehole with a 32 mm core was drilled 23 m west of the store, parallel to seismic profile no. 2 and angled away from the vertical such that it passed through the proposed site of the store. See Figure 4.1.

Core orientation was carried out during drilling using an Atlas Copco core orientator. Core mapping was performed, indicating the positions and types of cracks: Ludvig, B., 1981 (10).

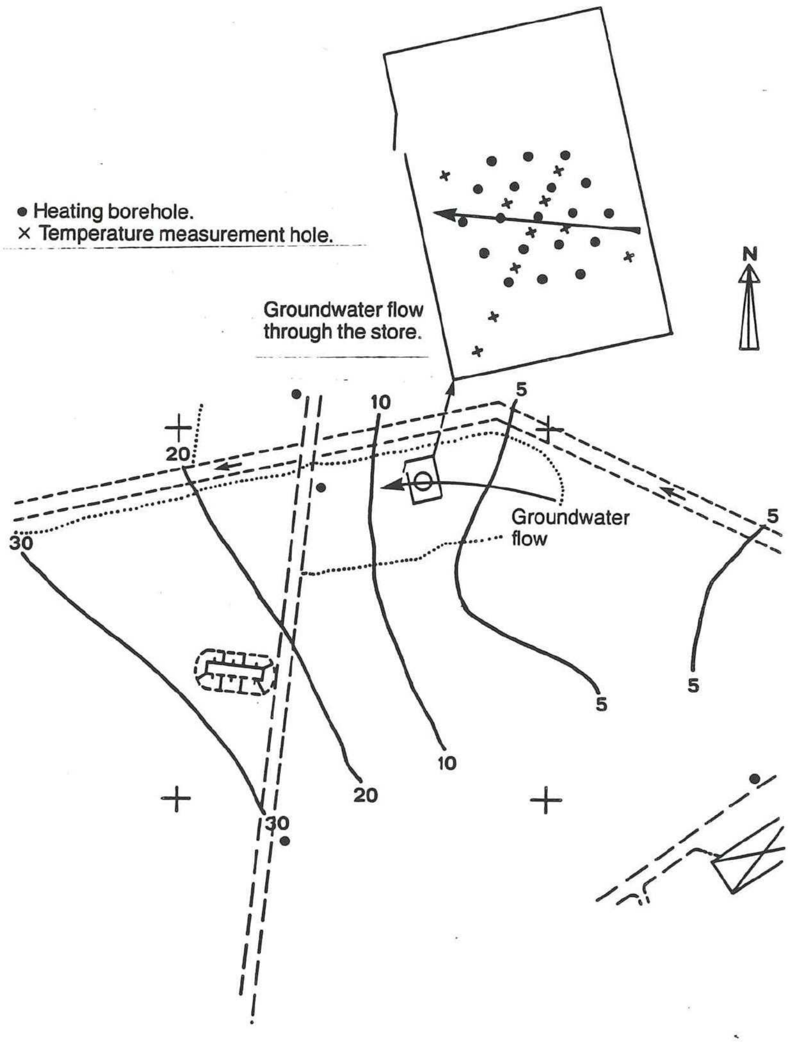



Figure 4.3 Direction of groundwater flow in the store area. Isolines indicate thickness of soil cover.

The types of rock in the core consisted primarily of grey, medium-grain gneiss. Twelve shear zones, with a total width of 2.7 m, intersect the core hole. The majority of these shear zones have been formed as a result of cracking along the shale planes. These planes run in a direction N30E, with vertical dip. The shear zones contain clay mineral and biotite layers, and can therefore be assumed to be reasonably permeable.

Figure 4.4 is a vertical section through the core hole, with the fracture zones encountered by the core extrapolated to the rock surface. Apart from one fracture zone with a width of 55 cm, no fracture zones encountered and assumed to cut through the body of the heat store exceed 10-12 cm in width.

None of the wide fracture zones indicated by the seismic measurements were encountered by the core hole. This reinforces the geological interpretation that dominant fracture and crushed zones tend to follow the shale planes which dip steeply and strike in an NS-NNE direction.

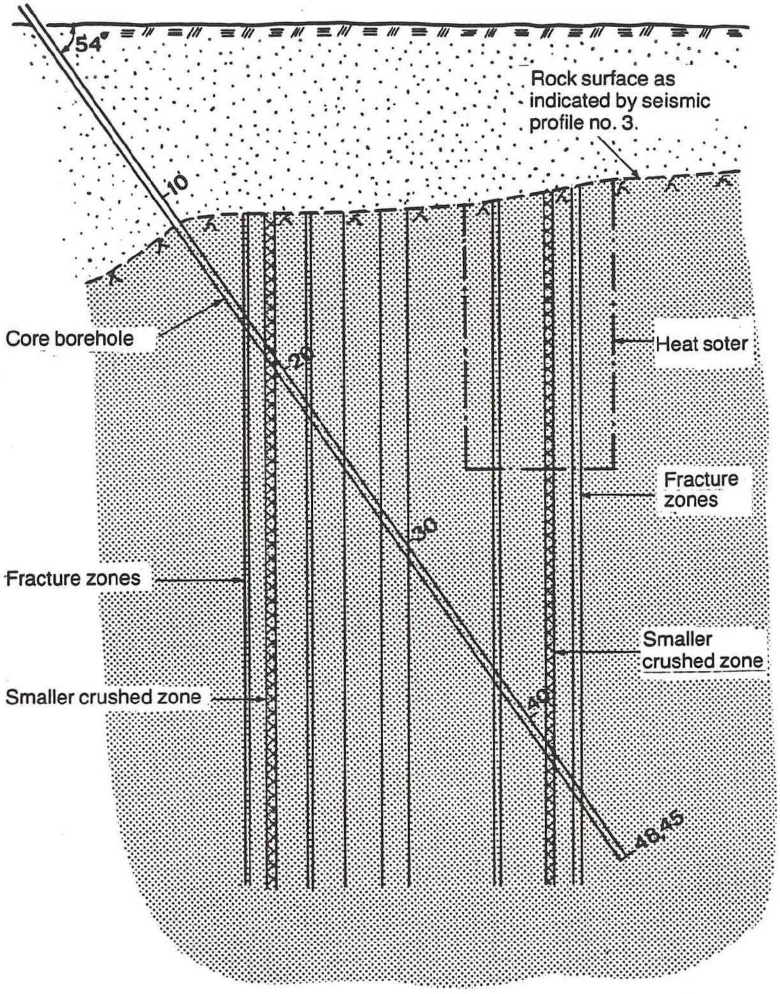



Figure 4.4 Vertical section through the core borehole.

## 4.6 Permeability measurement

The permeability of the rock was determined by Marton, M. and Andersson, A., 1981 (11), by hydraulic test pressurization, using cold water, before the charging and discharging trials began.

Pressure testing was carried out by applying a constant pressure to water in the centre hole of the store and measuring the changes in groundwater level in the peripheral holes. Testing was performed as a single packer test over the whole of the borehole length. Using conventional methods of calculation, a permeability of the order of $2 \times 10^{-7}$ m/s (or, more exactly, $2 \times 10^{-7}$ $m^3/m^2$, s) was indicated.

It should be pointed out that, as pressure testing was applied over the whole length of the hole in one step, the as-measured permeability could theoretically be due to a single crack. However, the measured value is in good agreement with several other measurements made at various sites in Sweden and at minimum depths below the surface of the rock (3).

The permeability of the crack system for a hot store can differ considerably from the value found by test pressurization. The viscosity of hot water is lower than that of cold water, which could result in a higher flow rate if all other parameters remained unchanged. However, heating the store also affects the crack system, probably in such a way as to reduce the size of the cracks, which would then tend to reduce the permeability. It is therefore of interest to investigate the effect that the completed series of heating/cooling trials has had on the crack system, and to investigate permeability behaviour in a heated store.

## 4.7 Physical data for the rock and soil cover

The initial investigation quantified a number of physical parameters and data, as shown below.

ROCK

| | |
|---|---|
| Type of rock : | Folded medium-grained gneiss |
| Thermal capacity: | 2.03 $MJ/m^3$, K |
| Thermal conductivity: | 3.7 W/m, K |
| Density: | 2742 $kg/m^3$ |
| Hydraulic conductivity: | $2 \times 10^{-7}$ m/s |
| Initial temperature: | 3.5 °C |

SOIL

| | |
|---|---|
| Type of soil: | Sulphide soil |
| Thickness of cover: | 6.0 m |
| Groundwater level: | 0.7 m below ground surface |
| Thermal capacity: | 3.49 $MJ/m^3$, K |
| Thermal conductivity: | 0.75 W/m, K |
| Bulk density: | 1540 $kg/m^3$ |
| Hydraulic conductivity | $10^{-9}$ - $10^{-11}$ m/s (estimated value) |

## 4.8 Groundwater chemistry

### 4.8.1 General

Groundwater chemistry is of interest in connection with a borehole heat store, particularly for one having an open circulation system, partly with respect to its corrosivity, and partly due to the risk of deposits in pipes and equipment.

The chemical equilibrium which normally exists between the rock and the groundwater is altered when the temperature is increased. The rock layer nearest to the water phase is affected chemically through leaching of ions from the rock to the water, changing the chemical composition of the circulating water. The solubility of the majority of materials encountered in rocks, apart from carbonate compounds, increases with increasing pressure and temperature.

It is not generally possible simply to combine leach-out data for pure mineral substances to obtain the relevant data for any particular type of natural rock in which these substances are incorporated. This is because the minerals in a rock interact in such a complex manner that it is necessary to establish empirical ion leach-out data for the particular type of rock in which a heat store might be built.

Laboratory and field trials have been carried out by Claesson, T. and Ronge, B., 1982 (12), with the aim of investigating conditions associated with the trials store in Luleå more closely. The following material is a brief summary of the results from this work.

### 4.8.2 Laboratory experiments

Autoclaves were used to determine the solubility of rock materials in the laboratory. Samples of rock taken from cores from the Luleå store were sawn into 60 mm long cylinders in order to produce definable reaction surfaces, and allowed to react with water at different temperatures in the autoclaves.

In order to simulate the cyclical heating and cooling behaviour of the Luleå store as far as possible, the program as shown in Table 4.1 was followed for the laboratory investigations. All experiments were carried out at temperatures of 50 °C, 75 °C, 100 °C, 125 °C and 150 °C. The water was analysed for Al, Ca, Fe, Mn, Mg, Na and Si. Figure 4.5 can serve as an example of the results, and shows the silicon content at different temperatures throughout the sequence of storage cycles.

| Cycles* | U | A | U | A | U | A | U | A | U | A | | Time, days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | X | X | Analysis | | | | | | | | | 24 |
| 2 | X | X | X | X | Analysis | | | | | | | 48 |
| 3 | X | X | X | X | X | X | Analysis | | | | | 72 |
| 4 | X | X | X | X | X | X | X | X | Analysis | | | 96 |
| 5 | X | X | X | X | X | X | X | X | X | X | Analysis | 120 |

* U = heating, followed by resting for 14 days.
A = cooling, followed by resting for 10 days.

Table 4.1 Analysis programs for the five annual cycles of the Luleå store.

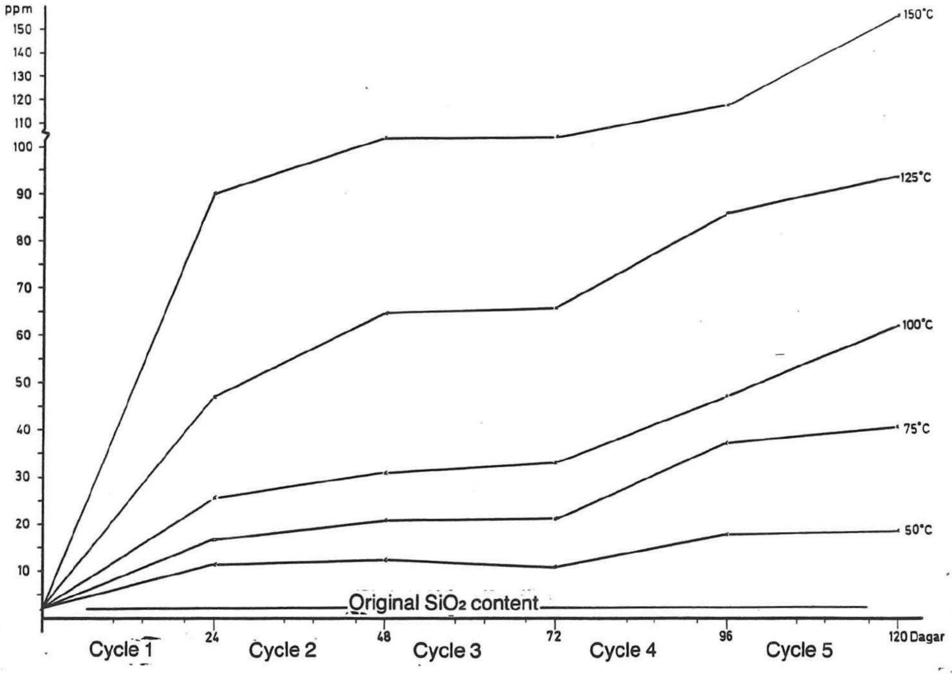



Figure 4.5 Silicon dissolved in water (as $SiO_2$) as a function of temperature during each of the cycles.

### 4.8.3 Field trials

Four water samples were taken for analysis during each complete cycle of the store. The samples were taken from the water after each period of charging, resting, abstraction and charging respectively. They were analysed at the University of Luleå for pH, conductivity, oxygen content, bicarbonate, phosphate and nitrate levels, while cation measurement and analysis of chloride, sulphate and TOC levels were carried out at Chalmers University of Technology.

Based on the results of the analyses, the following observations can be made:

- pH values rose from 7.0 to 7.8.
- conductivity increased from 400 to 550 µs/cm.
- there was a surprisingly large increase in phosphate content, from <0.1 to 0.5 - 1.0 mg/l.
- there was considerable variation in iron content during the trials, but with stabilization towards the end of the trials period. Considerable red discoloration of the circulating water was observed during the first three cycles.

Agreement between the laboratory results and field results concerning cation leach-out can be regarded as good. The 50 $^{o}C$ laboratory level corresponds to the cation levels found for the field trials, which means that the laboratory experiments ought to provide a good picture of what can be expected with an increase in water temperature.

The groundwater encountered around the Luleå store has high $SO_4$, Cl, $PO_4$ and Na levels, and would have to be considered as corrosive at higher temperature levels. However, provided temperatures did not exceed 100 $^{o}C$, and that water chemistry remained as described above, SIS 2333 stainless steel should be suitable for pipework. Polyethylene, too, is a perfectly acceptable piping material as far as water chemistry is concerned.

## 4.9 Ecology

Heat storage in borehole heat stores would probably have only a limited effect on immediately adjacent ground surface areas and upper soil layers. Visible biological effects resulting from heat storage would probably be of strictly local character and restricted in extent. The most serious effect that can be foreseen would probably be a progressive killing-off of certain vegetation. It might be possible in some cases to utilize the positive effects (e.g. an increased heat flow towards the ground surface in the vicinity of the store) for horticultural purposes (e.g. greenhouses etc.).

The ecological effects should be monitored and analysed in connection with any planned full-scale trials. Partly to obtain certain initial data in anticipation of such work, temperature measurements have been made in both the soil cover above the store and in similar unaffected reference points.

# 5. RESULTS OF THE TRIALS

## 5.1 The trials and comparative calculations

The trials started on 3rd July 1981 and continued until 31st October 1981. During this period, five annual cycles were simulated, each as follows:

| | | |
|---|---|---|
| Charging: | 10 days | (= 5 months in full-scale store) |
| Rest: | 4 days | (= 2 months " " ) |
| Abstraction | 6 days | (= 3 months " " ) |
| Rest: | 4 days | (= 2 months " " ) |
| Total | 24 days | (= 12 months in full-scale store) |

The relative and absolute lengths of these periods have been determined with respect to future solar energy heating requirements. Some notes on time and size scaling can be found in Section 3.2.

The storage cycles were run continuously without interruption. The storage temperature, i.e. the temperature of the incoming water during charging, varied somewhat during the trials, due to varying loading on the hot water boiler plant from which the heat was being supplied. Apart from these slight variations, storage temperature rose as the temperature of return water leaving the store increased, although the temperature difference between the water entering the store and that leaving the store was maintained relatively constant at 8-10 K. With a total flow rate through the store of about 1 l/s, as was used here, this temperature difference represents a total charging power of about 33-42 kW. However, temperature difference and power were considerably higher at the start of each cycle.

During discharge simulation, heat was removed through a heat exchanger connected to a fire hydrant. It was found that the capacity of this heat exchanger was insufficient, and so it was not possible to achieve the desired abstraction powers.

About 250 000 readings of flow and temperature measurements were recorded during the 120 days of the trial.

Comparison between as-measured and theoretical values was made using a three-dimensional rotational-symmetric mathematical model, developed by the Department of Mathematical Physics at the University of Lund by Claesson, J. and Eskilson, P., 1982 (13). The input data for the mathematical model are inlet temperature and flow of the circulating water, and the output represents the entire temperature field in and around the store at any time.

The following pages present and describe some of the results obtained that are regarded as being of particular interest in illustrating the behaviour of the store.

## 5.2 Temperature measurements

Temperatures measured in the bedrock, both inside the periphery of the store and outside it, show generally good agreement with theoretical results predicted by the above-mentioned three-dimensional mathematical model (13).

This good agreement can be seen, for example, in Figure 5.1, in which the as-measured temperatures in the circulating water and in the rock are indicated by unbroken lines, with the corresponding theoretical values indicated by points, crosses etc. Some of the differences may be due to differences in thermal conductivity in different parts of the rock body, but most of them are probably due to water flowing through the crack system in the rock and conducting away heat. As the mathematical model considers only thermal transport due to conductivity mechanisms, heat will travel more rapidly through a real store than indicated by the model.

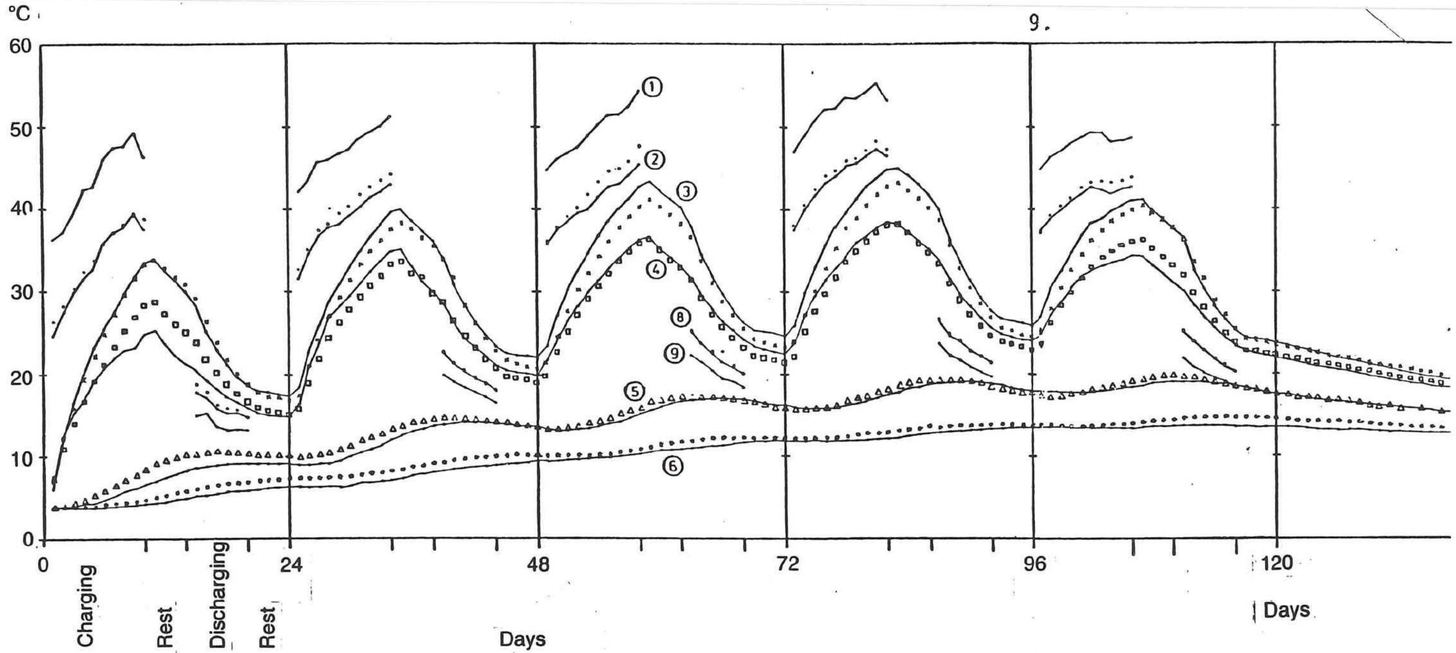
The importance of the crack system on heat transport through the store was indicated during the first cycle, when the temperature rose more rapidly in some of the peripheral holes than at the centre of the store. This effect diminished during subsequent cycles, which can be accounted for by closure of the cracks due to expansion of the rock.

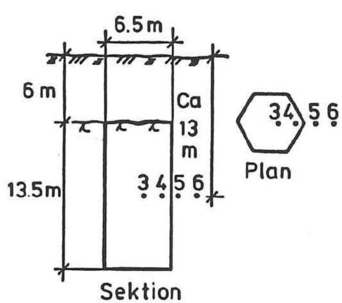
Figure 5.1 also illustrates the exponential trend of various temperatures towards equilibrium conditions. Energy supply was interrupted during the fifth cycle, but if it had not been interrupted, the shape of the temperature curves during this cycle would have been almost identical with the corresponding curves from the fourth cycle.

Figure 5.2 shows as-measured and theoretical radial temperature profiles through the store at a depth of 13 m, i.e. 7 m beneath the rock/soil interface, illustrated here by conditions at the start of charging for the third cycle. Figure 5.3 illustrates the same measurements at the end of this charging stage ten days later.

Figures 5.4 and 5.5 illustrate corresponding radial profiles after discharge, at the beginning of the third cycle, at the beginning of abstraction and six days later respectively.

Figures 5.6, 5.7 and 5.8 illustrate as-measured temperatures in and around the store by means of isotherms at the end of charging (day 58), at the start of discharging (day 63) and at the end of the rest period (day 72) respectively.




(1) Supply temperature, circulating water, charging mode.
(2) Leaving temperature, circulating water, charging mode.
(3) Temperature measurement point, 0.65 m from centre: see figure.
(4) Temperature measurement point, 1.95 m from centre: see figure.
(5) Temperature measurement point, 3.90 m from centre: see figure.
(6) Temperature measurement point, 5.20 m from centre: see figure.
(7) Temperature measurement point, reference hole, 14 m deep, approx. 200 m from store.
(8) Leaving temperature, circulating water, discharging mode.
(9) Supply temperature, circulating water, discharging mode.

Figure 5.1 As-measured temperatures (continuous lines) and corresponding theoretical temperatures (point plots).

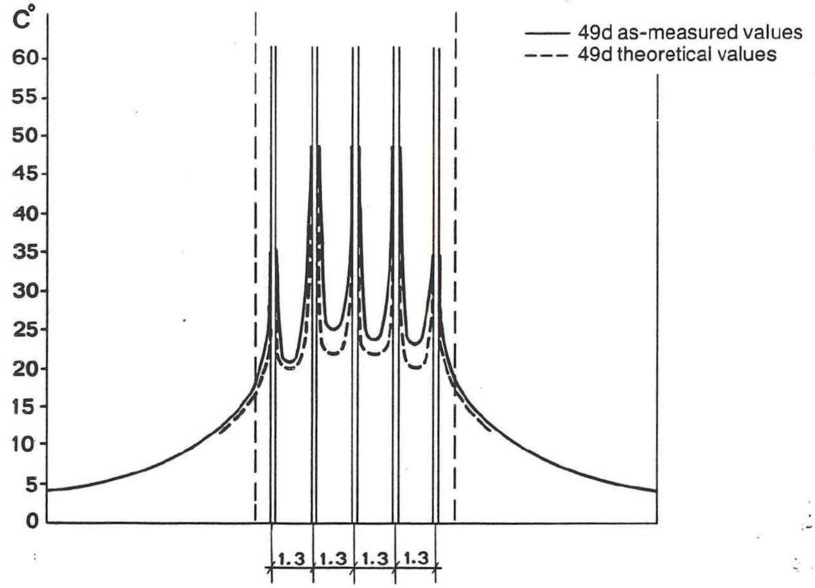



Figure 5.2 As-measured and theoretical temperatures at the start of the charging phase of the third cycle (day 49). Depth: 7 m below the rock/soil interface.

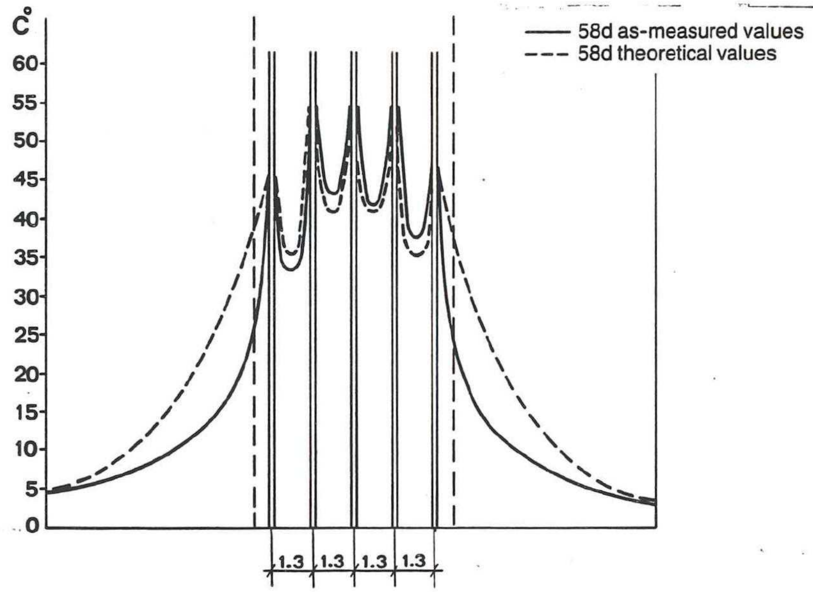



Figure 5.3 As-measured and theoretical temperatures on conclusion of the charging phase of the third cycle (day 58). Depth: 7 m beneath the rock/soil interface.

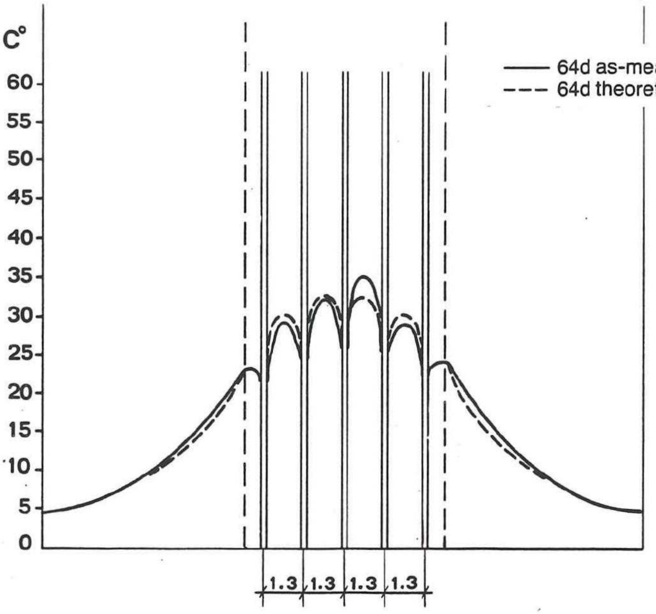



Figure 5.4 As-measured and theoretical temperatures at the start of the discharge phase of the third cycle (day 64). Depth: 7 m below the rock/soil interface.

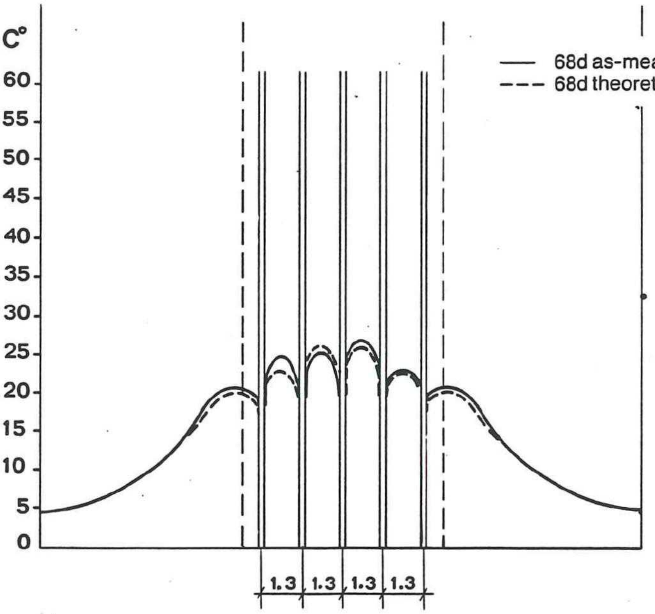



Figure 5.5 As-measured and theoretical temperatures on conclusion of the discharge phase of the third cycle (day 68). Depth: 7 m beneath the rock/soil interface.

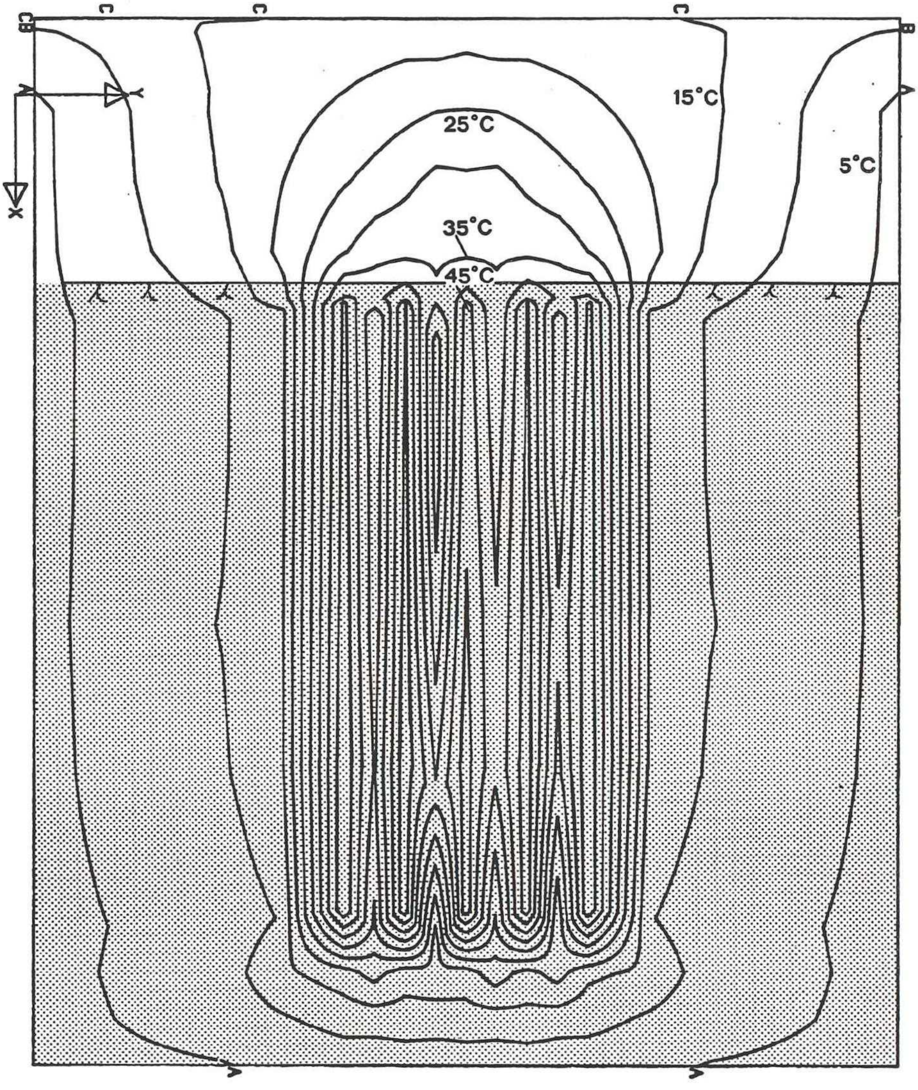



Figure 5.6 As-measured temperatures, using 5 K isotherms, on conclusion of the charging phase of the third cycle (day 58).

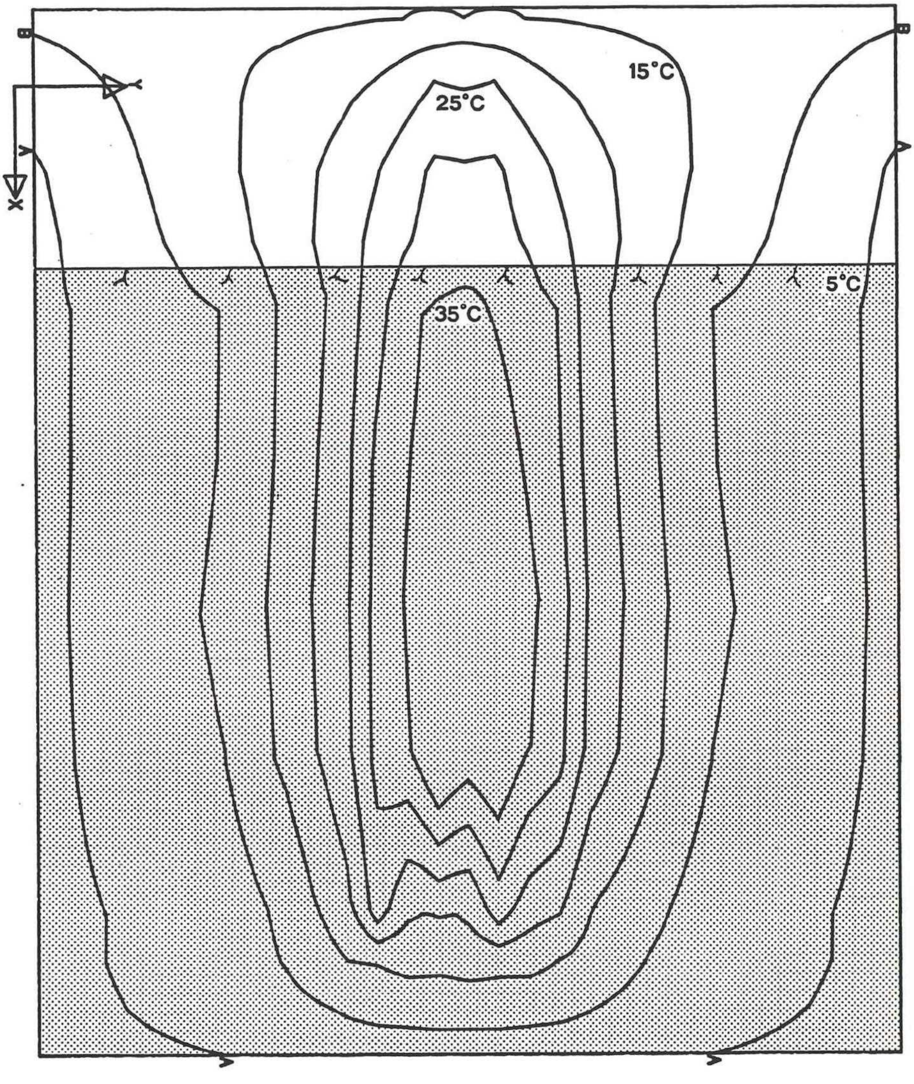



Figure 5.7 As-measured temperatures, using 5 K isotherms, on conclusion of the discharge phase of the third cycle (day 63).

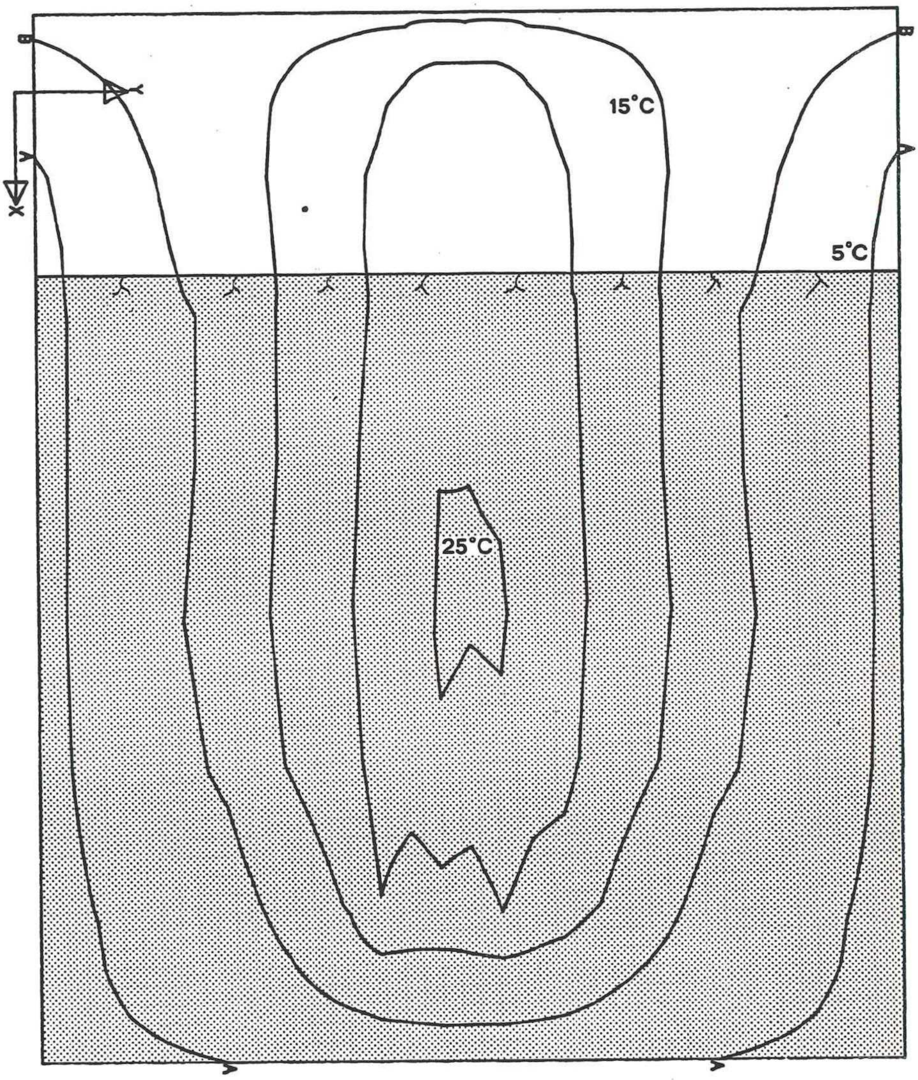



Figure 5.8 As-measured temperatures, using 5 K isotherms, on conclusion of the cold rest period of the third cycle (day 72).

Figures 5.9 and 5.10 illustrate respectively the temperature drop in the water during charging and the temperature rise in the water during heat abstraction as it passes through the boreholes. The positions of boreholes 1 and 5 are shown in Figure 3.5.

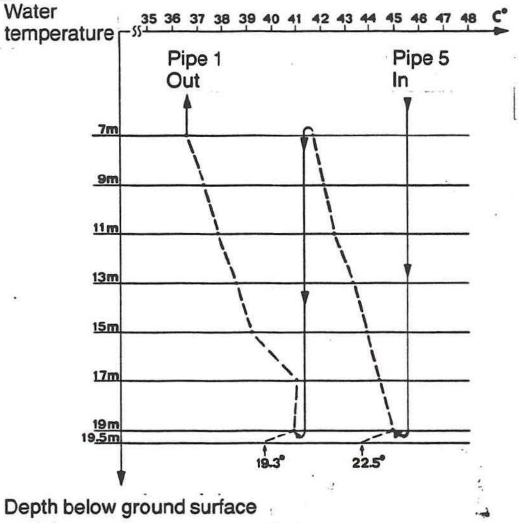



Figure 5.9 Temperature drop of the circulating water in passing through boreholes Nos. 5 and 1. Data shown is from the charging phase during the second cycle (day 27).

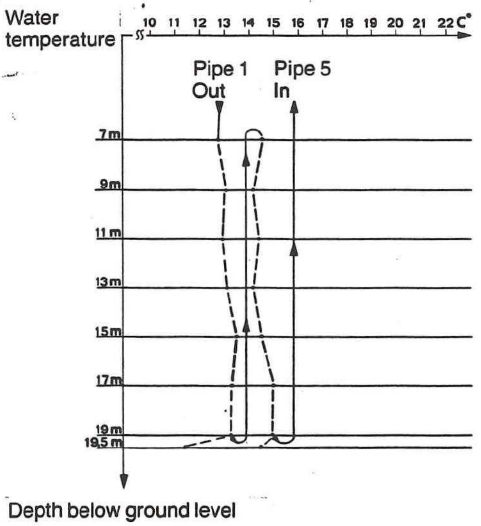



Figure 5.10 Temperature rise of the circulating water in passing through boreholes Nos. 1 and 5. Data shown is from the discharge phase in the first storage cycle (day 6).

Figure 5.11 illustrates borehole water temperatures during the resting phase, and is taken from the first rest period in the third storage cycle.

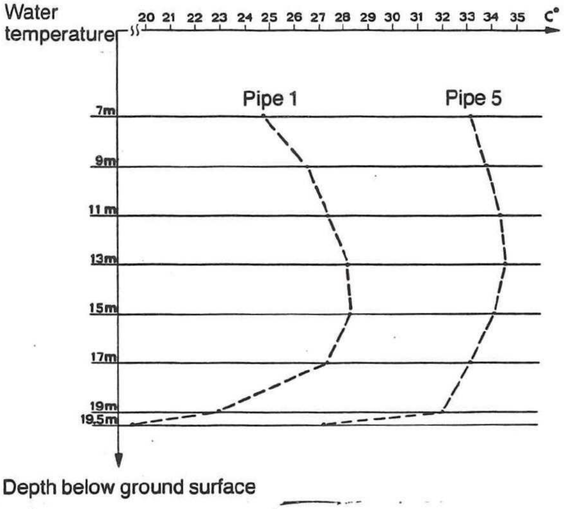



Figure 5.11 Water temperatures in boreholes Nos. 1 and 5 during the first rest period in the third storage cycle (day 62).

## 5.3 Charging and abstraction powers

Specific charging and abstraction powers per meter of borehole length are primarily a function of the thermal conductivity of the rock and of the temperature difference between the circulating water and the surrounding rock. There is no difference in principle between the charging and abstraction processes, which means that the charging and abstraction powers are the same for the same temperature differences between the circulating water and the rock.

Figure 5.12 shows the as-measured charging and abstraction powers. The low abstraction powers are due to the fact that the cooler used during the trials was not capable of cooling the circulating water by more than about 2-3 K.

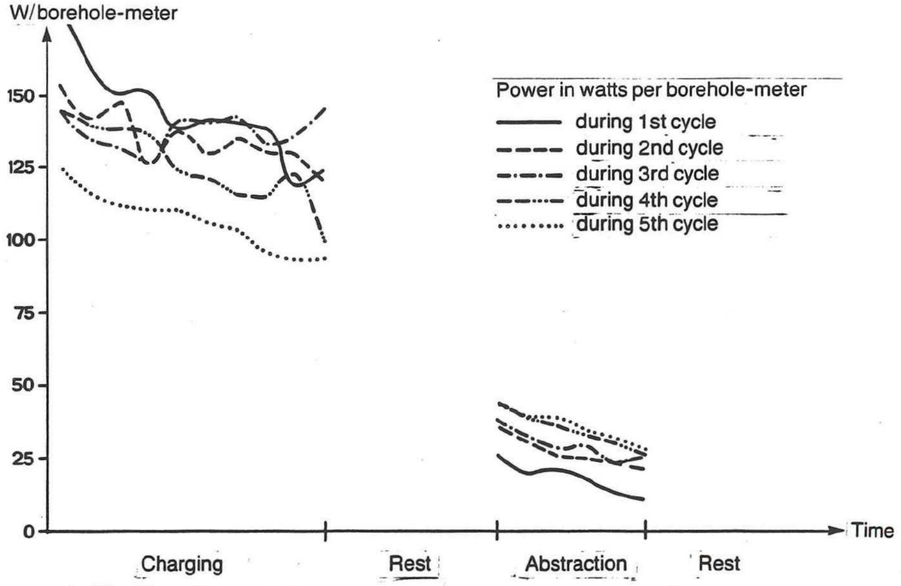



Figure 5.12 Charging and abstraction powers of the store per borehole-meter. Powers shown are mean 24-hour values for all boreholes.

## 5.4 Charged and recovered energy

In total, 37 MWh were loaded into the store during the five cycles. Energy input was greatest during the first cycle, at 8.0 MWh, falling to 7.3 MWh during the fourth cycle. Problems with the hot water supply resulted in only 6.2 MWH being loaded into the store during the fifth cycle.

The total amount of energy recovered amounted to 4.2 MWh. During the fourth cycle, with relatively stationary conditions, 1.2 MWh of energy were abstracted, as against an energy input of 7.3 MWh, representing an energy efficiency during this cycle of about 16%. The corresponding value for the fifth cycle was 18%.

The low efficiencies are due primarily to the very small volume of the store, involving disproportionately large heat losses in relation to the energy content of the store. The under-dimensioned cooling facilities have also contributed to the low efficiency by limiting the amount of temperature reduction possible during the discharge period, and the relatively short discharge period has also contributed to the low efficiency.

## 5.5 Operational problems and other observations

During the charging period in the first cycle, problems were encountered with air locks due to leaking connections. This was put right during the following rest period, and the equipment thereafter operated essentially without trouble.

Some of the circulating water overflowed from some of the boreholes at the centre of the store during the first charging period. The high water level in these holes was due partly to the abovementioned venting problems, and partly to the difference in density between the heated water and the surrounding cold groundwater. Calculations indicate that the difference in density is equivalent to a water column of 0.2 m.

The circulating water was coloured light red during the three first storage cycles. The reason for this discoloration has not been definitely established, but both organic materials and iron compounds could be responsible. The colour disappeared completely at the start of the fourth cycle.

Energy supply was interrupted during the fifth cycle due to service and maintenance work in the hot water boiler plant, as described in Section 5.2.

It has hardly been possible to investigate the ecological effects in such a brief and physically limited trial as this. However, a 6-7 m high ash tree is growing only 2 m away from the store, and no visible effects have been observed in the form of, for example, delayed shedding of its leaves.

Measurements of snow cover along a profile through the centre of the store have been made on two occasions. As can be seen from Figure 5.13, heating has noticeably reduced the depth of snow cover in the vicinity of the store.

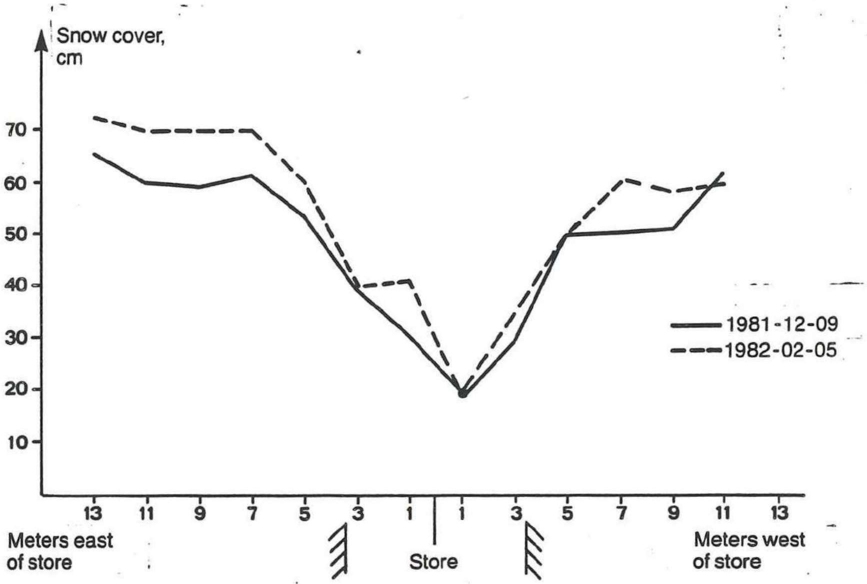



Figure 5.13 Snow cover profile through the centre of the store during the 1981/82 winter.

# 6 PRELIMINARY DESIGN OF AN EXPERIMENTAL AND DEMONSTRATION INSTALLATION

## 6.1 Background and summary

### 6.1.1 Background

SSAB in Luleå produces flammable gas which is supplied to the combined heat and power station owned by Luleå Kraft AB (LUKAB), and used as a fuel for simultaneous production of electricity and heat. Throughout the summer, there is surplus of heat from the power station if at least one furnace is in operation at the steel works. District heating in Luleå is supplied by the Luleå Energy Authority (LEAB).

The University of Luleå buildings are supplied with heat from the town district heating system. It is planned that the largest building (F Building) should be supplied with heat from a demonstration heat store, as this would mean that the size of the store would be suitable for testing and demonstrating full-scale technology at a reasonable cost. A suitable area of ground for building the store is available close to the building.

The heat requirement of the building is about 2.7 GWh/year.

### 6.1.2 Summary

The proposed heat store would consist of a circular cylindrical body of rock with a volume of about 100 000 $m^3$ and a diameter of 50 m. 144 150 mm vertical holes would be drilled in the rock, with an active length of 50 m. Heat would be supplied to, and abstracted from, the store by water circulating between the bore-holes and heat exchangers in an open system. Figure 6.1 shows the general layout. The store would be designed so that a radial temperature gradient would be established, with a mean change in the temperature of the bedrock of about 35 K during discharge.

Heat would be supplied by raising the temperature of the natural water in the store by means of heat from the district heating system. Maximum charging power would be 1.5 MW, and charging would need to continue for about six months each year.

Heat would be abstracted from the store by transferring heat from the water in the store to the secondary heating system of the building, as shown in Figure 6.4. If necessary, the temperature could be increased through use of a heat pump. Maximum output power would be 600 kW. The heat pump would have an output of 300-400 kW.

The secondary heating system in the building would not be affected by connection to the heat store. The existing heating substation would be available for immediate use to replace or complement heat supply from the store.

Calculations for a full-scale heat store with a capacity of about 20 GWh indicate that such a store would be economically viable at an annuity of 8%.

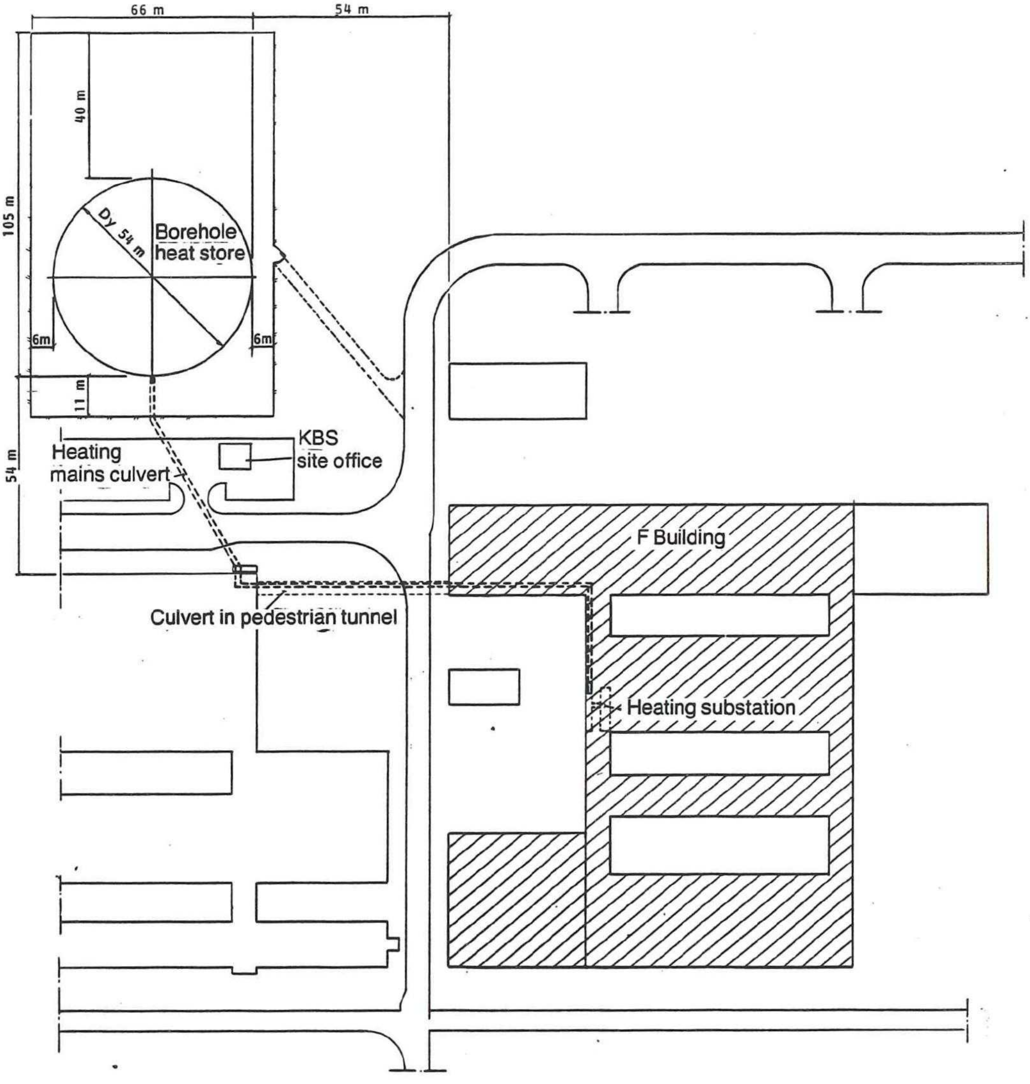



Figure 6.1 Plan of the store area.

Proposed basic data (approx.):

| | GWh/year |
|---|---|
| Charging energy | 2.8 |
| Losses, 40% | 1.2 |
| Energy recovered | 1.6 |
| Useful drive energy | 0.4 |
| Heat supplied | 2.0 |
| Building heat requirements | 2.7 |
| Degree of coverage | 74% |

## 6.2 Operating strategy

The store would be able to work with or without a temperature gradient between different sections of the overall borehole inventory. The temperature gradient could be radial, which could be produced by arranging the water flow through the boreholes to be in series in a radial direction, as shown in Figure 6.2. Alternatively, a vertical temperature gradient could be established if the water flow rate through the boreholes was kept low and if the thermal resistance of the walls of the supply pipe to the bottom of the holes was high, as shown in Figure 6.3. Heat transfer between the supply pipe and the water in the borehole reduces the gradient established.

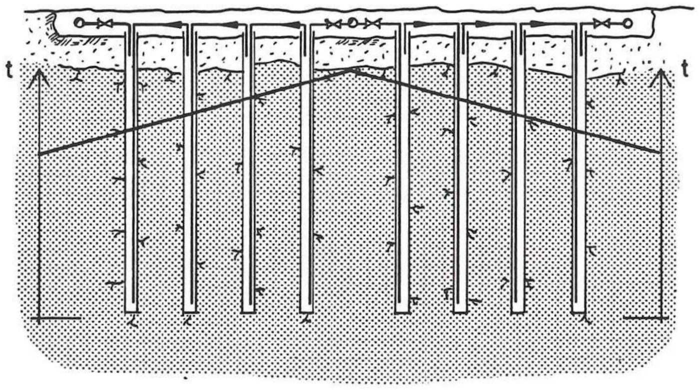



Figure 6.2 Radial temperature gradient.

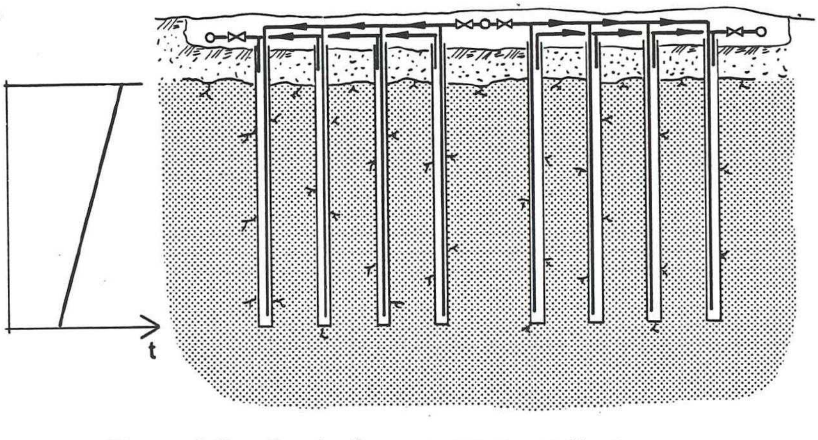



Figure 6.3 Vertical temperature gradient.

Briefly, the advantages of a temperature gradient are that high-temperature heat is retained in the store for a longer period during discharge, and that cooled return water to the store can abstract more heat. This reduces the need to employ a heat pump. Heat losses from the store are also reduced to about half their value (if there was no temperature gradient), as the temperature difference between the store and its surroundings is reduced.

Against this background, a store with a radial temperature gradient has been selected for this project.

The determining temperature level during storage is the supply temperature from the district heating system, which is normally 70 °C during the summer. The maximum rate of charge, 1.5 MW, can be achieved only during the start of the storage period, becoming subsequently restricted by the thermal resistance of the rock.

Water would be supplied to the centre of the store and pass through parallel paths of four boreholes connected in series out towards the periphery of the store, as shown in Figure 6.2. The centre of the store would thus be heated first, and the temperature at the periphery would always be lower than the mean temperature of the store. When heat is being abstracted, the water would flow in the opposite direction, i.e. from the periphery of the store towards the centre.

At the start of the heating season, it would be possible to supply the entire heating requirements of the building without recourse to the heat pump. As winter progressed, with an increasing heat demand and a requirement for higher temperatures, but with a falling temperature from the heat store, it would be necessary to start the heat pump. See Figure 6.4.

Heat pump output would be such that the entire power requirement of the building heating system could be met. When the heat pump and store could no longer supply sufficient power, the existing control valves in the district heating substation would be opened, and topping power would be supplied directly from the district heating system. No heat could be supplied by direct heat exchange: the entire building heat requirements must be supplied through the heat pump.

## 6.3 Rating

Considering the total heating energy requirement of the building, about 2.7 GWh, the expected heat losses and the amount of energy that can be supplied to the building at the power available from the store, the store would need to have a capacity of about 2.2 GWh. The thermal capacity of the rock is about 2 200 kJ/m$^3$,K. If the mean temperature change of the store is 35 K (between about 25 °C and about 60 °C), an active rock volume of about $10^5$ m$^3$ is needed. If the shape of this active volume is such that diameter and height are equal, a cylindrical body with a diameter and height of about 50 m is required. As described below, a borehole separation of 4 m is suitable. The total active borehole length is 7200 m, which means that with a maximum power abstraction of 75 W/m the total output power would be 500 kW.

The above data has been optimized through a number of runs of the computer model of the store. Figures 6.5 and 6.6 show the expected conditions during the first annual cycle. Equilibrium losses are estimated to amount to between 20% and 40%.

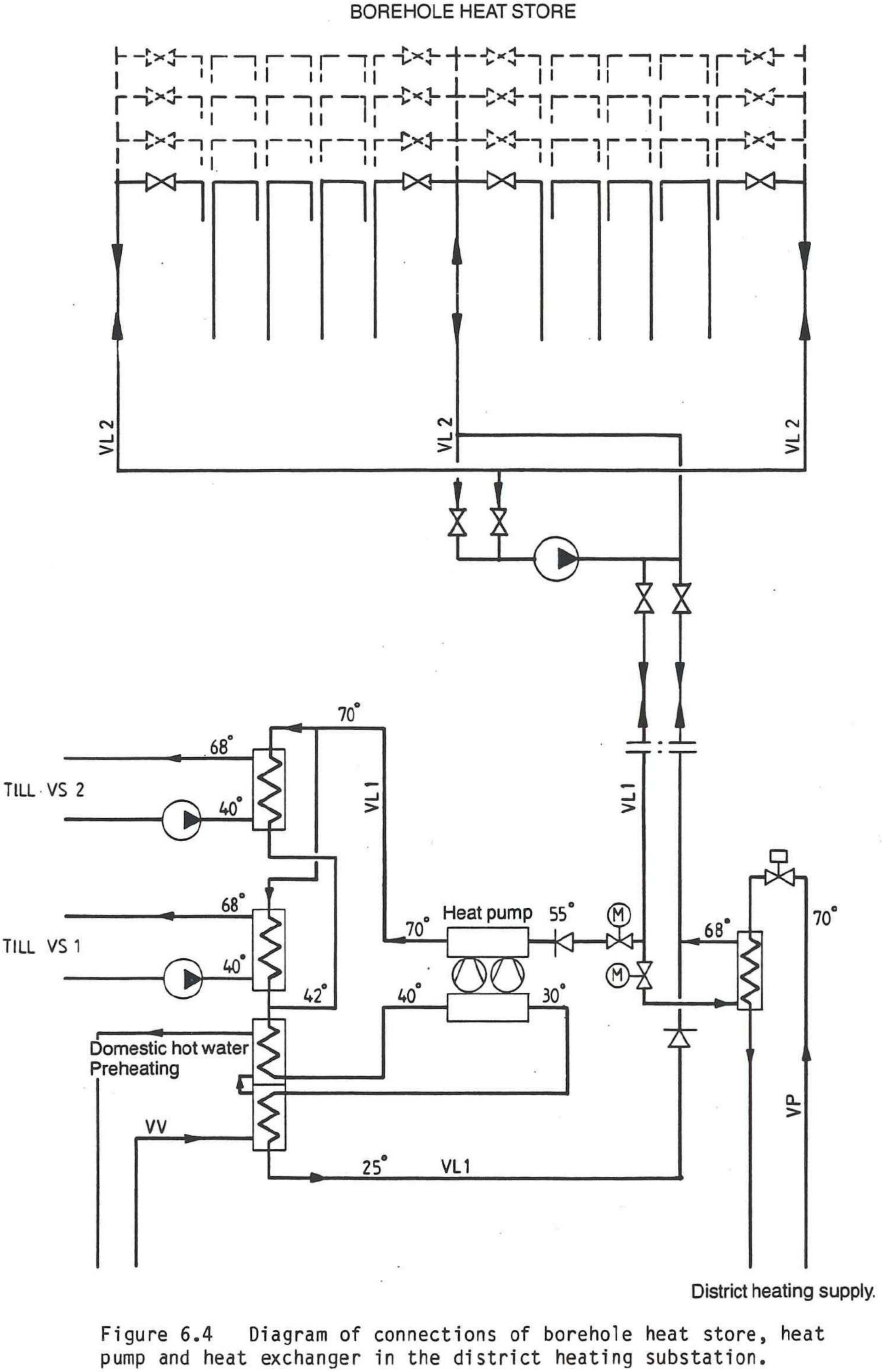



Figure 6.4 Diagram of connections of borehole heat store, heat pump and heat exchanger in the district heating substation.

Figure 6.6 shows the effect of borehole separation on losses. In order to reduce the cost of the store, borehole separation should be large. However, this results in a low temperature efficiency (i.e. heat would be recovered at a considerably lower temperature than the storage temperature). The computer model indicates that separations in excess of 4 m would be undesirable for the conditions concerned.

If the heat pump is to be able to supply the intended annual energy requirement, its capacity must be sufficient to enable the entire power requirement to be met, apart from periods with extremely low outdoor temperatures. Conditions during the latter half of the winter would determine the heat pump rating, as the store would then be supplying heat at a low temperature.

## 6.4 Equipment

The heat exchangers supplying heat to the building heating systems are rated so that they can transfer about 50% of full power, or 500-600 kW. The terminal temperature difference of the heat exchangers is low - a few degrees. This applies also for the heat exchanger used for supplying heat from the district heating system to the store. The heat exchangers and heat pump would be installed in the district heating substation. Domestic hot water would also be heated to the extent required, provided that there was space for the equipment.

In determining the requisite connection of the boreholes in the store, 36 radial paths connected in parallel and having four boreholes in each have been selected. This would give a temperature rise of about 6 K per hole and about 24 K across the whole store at maximum power of 600 kW.

Liquid transport involves lifting the water between each hole. A pump in each borehole would be unrealistic from a cost and reliability viewpoint. Instead, water transport can be arranged by actively maintaining a syphon between adjacent holes. A central pump would supply the necessary head to overcome flow resistance. Due to siphon effect and the necessary drive head, water levels would be different along the radii. Pipes would be dimensioned so that flow resistance is small. For successful operation, the groundwater surface must not be too low, and the maximum water temperature must be restricted.

Alternatively, liquid transport can be arranged by sealing the holes from the atmosphere and pressurizing them so that only one pump, or a few pumps, above ground level is/are required for operation, as shown in Figure 6.9. This method requires good tightness in the rock, particularly in the upper part of the store. The pipes between the boreholes can also be buried at a level below the lowest water level, although this would require a considerable amount of excavation work.

Figure 6.8 shows the relative water levels in the boreholes for flow through a store with uniform temperature. In reality, the levels in the boreholes would be higher, due to the fact that the heated water has a lower density than the groundwater in the rock. In this particular case, the level would vary from the original groundwater surface to a level almost 2 m higher. This means that the maximum original groundwater surface must be at least 2 m below ground level.

Final choice of the type of circulation system cannot be made until the geological and hydrological conditions are known.

The pumps and pipes for conveying water to and from the heat store and the heating substation in the building would be dimensioned for a temperature difference of 24 K and for absolute temperatures between +5 °C and 80 °C. Pipe sizes for water transport within the store, in 36 parallel circuits of four boreholes, would be about 50 mm if the pressure drop is to be limited to about 0.1 m WG/borehole. The circuit between the store and the heating substation would be designed for a storage power of 1.5 MW at 24 K temperature difference. This would require a flow of 15 l/s, giving a pressure drop of 24 mm/m with a pipe diameter of 100 mm, or a total of about $10^5$ Pa over a length of 220 m of pipe.

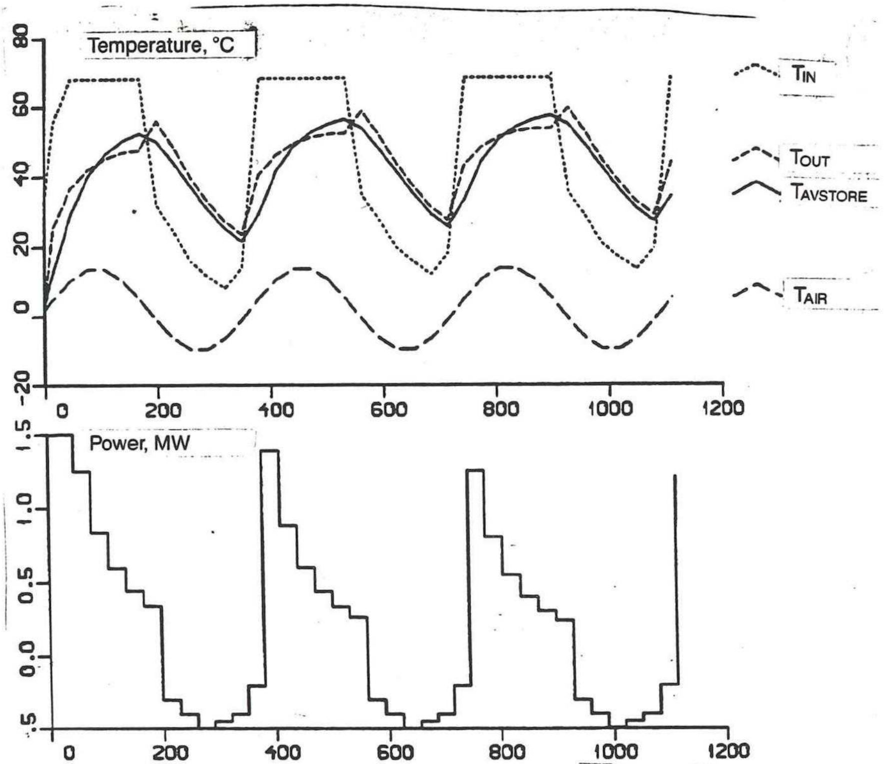



Figure 6.5 The average store temperature ($T_{AVSTORE}$, supply and return water temperature, air temperature and heating power as a function of time.
Parameters: H = 2R = 50 m:
Borehole separation = 4 m.

GLOBAL TEMPERATURE VERSUS RADIUS AND TIME

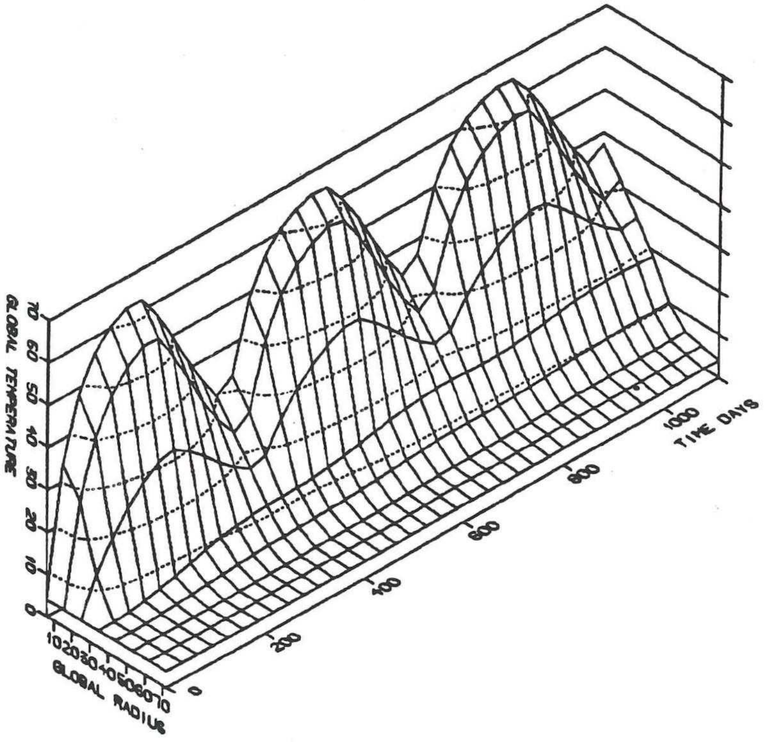



Figure 6.6 Temperature as a function of time and distance from the centre of the store. (Store radius = 25 m). Global temperature assumes that the local temperature variation around each borehole is evened out.

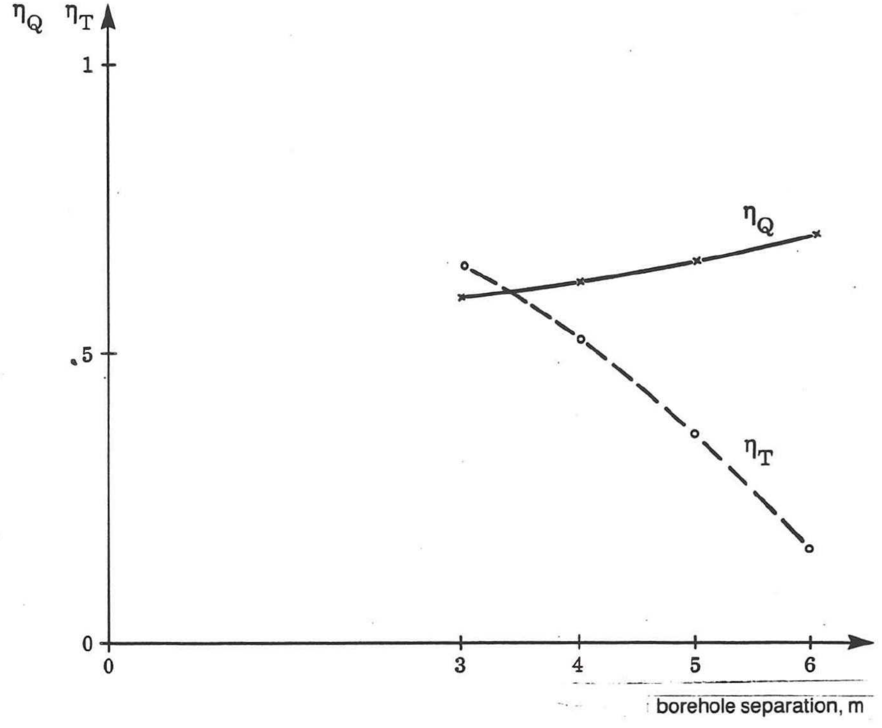



Figure 6.7 The effect of borehole separation on energy efficiency $\eta_Q$ and temperature efficiency, $\eta_T$. The curves apply for the third annual cycle: losses would be reduced when equilibrium conditions have been established.

The curves in Figure 6.7 are based on the following assumptions:

- Store size: H = 2R = 50.4 m: volume = $10^5$ $m^3$.
- The store is divided up into 4 series-connected radial zones.
- The storage cycle consists of 6 months' charging and 6 months' discharging at varying powers.
- Charging takes place with a falling power characteristic (from 1.5 MW to 0.5 MW), and with a maximum temperature limitation of 68 °C.
- There is no temperature limitation on energy abstraction.

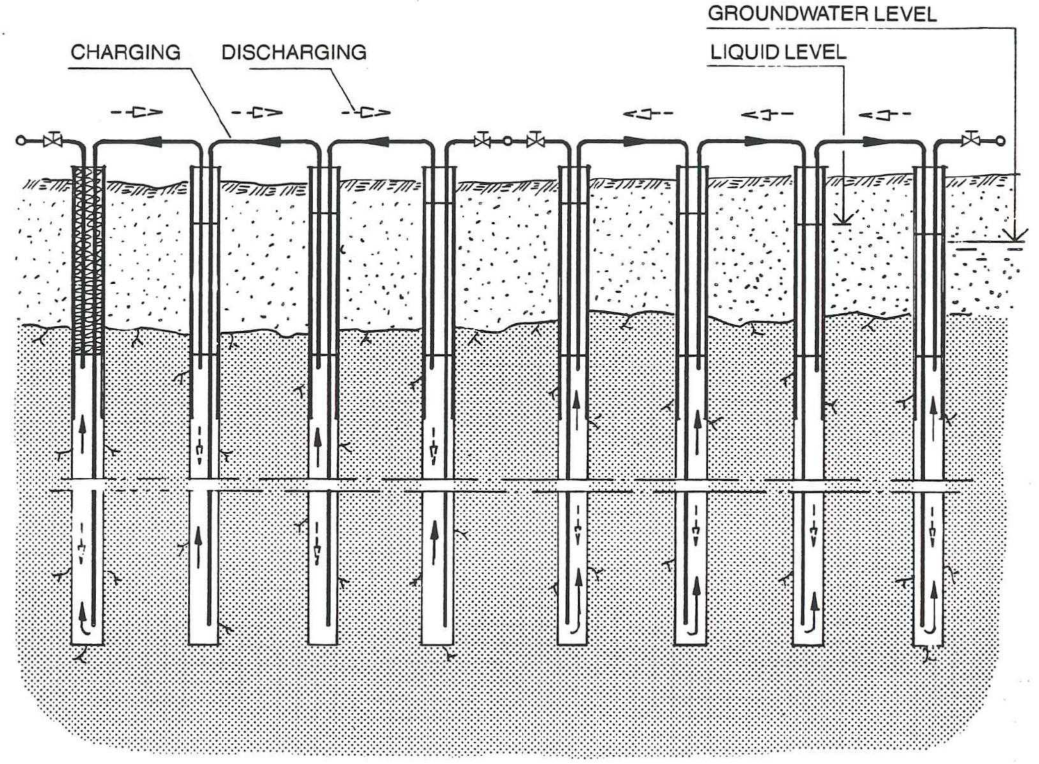



Figure 6.8 Siphon system for liquid transport through the store.

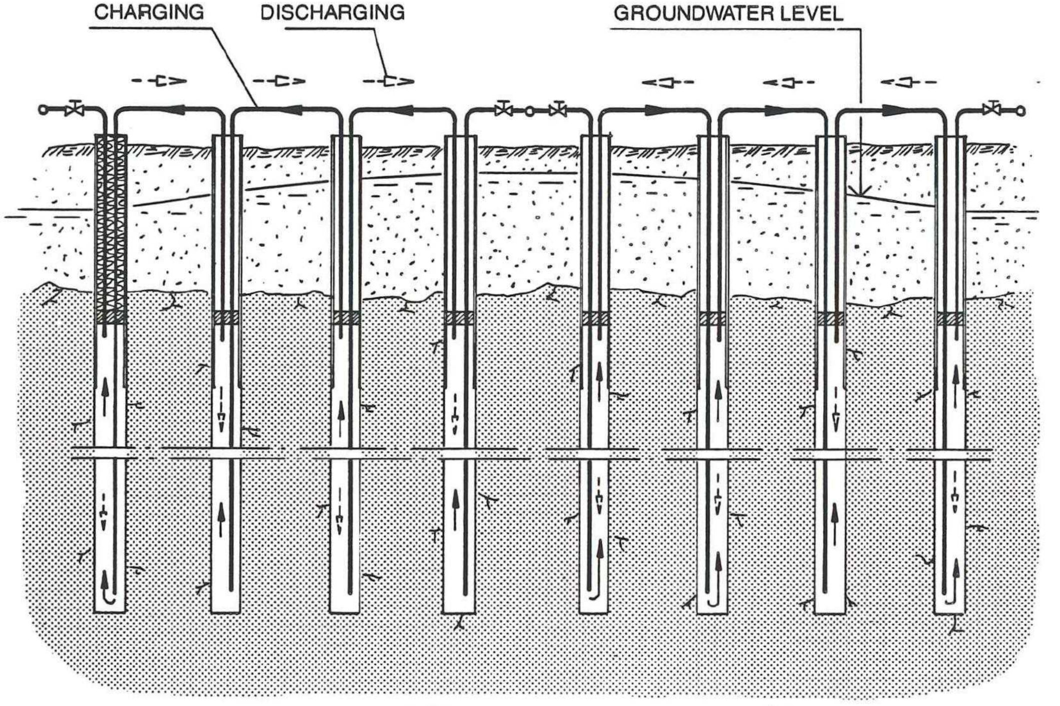



Figure 6.9 Pressurized system of liquid transport through the store.

Figures 6.10 - 6.11 show different layouts of hole patterns. The actual layouts, and connections between holes, would be determined at the detail design stage.

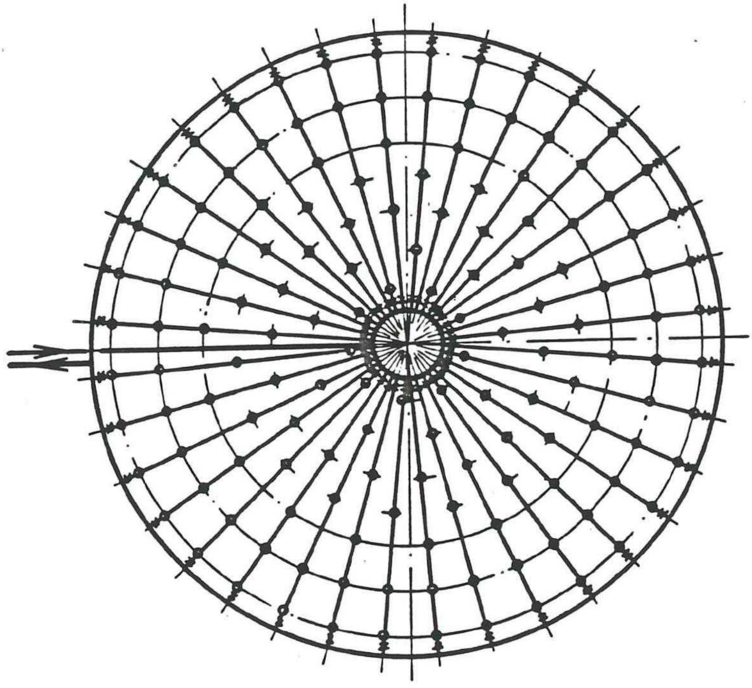


Figure 6.10 Strict radial layout.

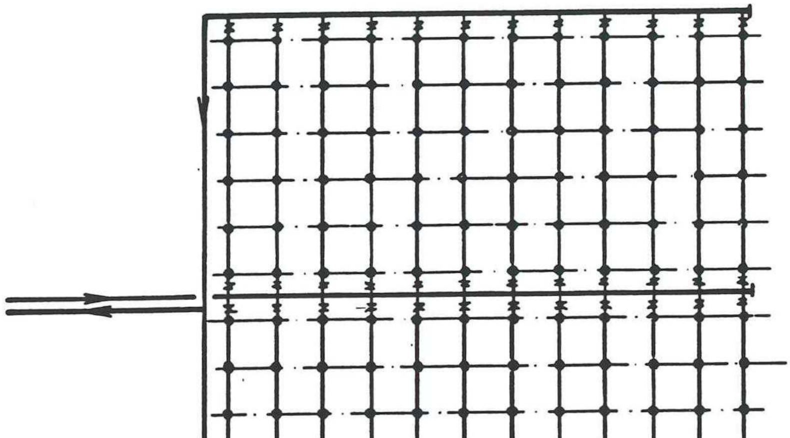


Figure 6.11 Block layout, easily expandable.

## 6.5 Costs

Materials and components have been specified first, after which costs have been calculated in conjunction with contractors.

| Ground and civil engineering | SEK x $10^3$ | |
|---|---|---|
| Geological site investigations | 260 | |
| Rock drilling (diameter 150 mm): | | |
| 144 holes, 50 m deep, 7200 m at SEK 110:- | 790 | |
| 144 holes, 5 m in overburden, with liner tube, SEK 2500/hole | 360 | |
| 10 boreholes for temperature measurement, 100 m | 140 | |
| Excavation and levelling | 95 | |
| Fence, 350 m at SEK 150:- | 50 | |
| Roads and vehicle stands | 20 | |
| Excavation for culvert, 50 m | 10 | |
| Reinstatement | 25 | |
| Pump pit | 45 | |
| Covering surface of store | 60 | |
| Work in pedestrian tunnel | 20 | 1875 |
| Contingency, 30% | | 520 |
| Design | | 360 |
| | | 2800 |

| | SEK x $10^3$ | |
|---|---|---|
| Mechanical equipment | Purchase cost | Installation cost |
| Heat pump, 300-400 kW heat power | 350 | 50 |
| Circulation pumps for piping system (see Figure 6.4): | | |
| VS 1 | 10 | 3 |
| VS 2 | 10 | 3 |
| VL 1 | 40 | 8 |
| VL 2 | 15 | 3 |
| Heat exchangers: | | |
| VP Dist. heating: tube type 70 $m^2$ | 80 | 15 |
| VS 1 Heating system: plate, 50 $m^2$ | 60 | 15 |
| VS 2 Heating system: plate, 50 $m^2$ | 60 | 15 |
| VV Dom. hot water: plate, 20 $m^2$ | 30 | 8 |
| Changes to existing systems | | 30 |
| Costs of pipes and components, excluding pumps, with erection, for the different systems: | | |
| VP, steel, 15 m of pipe | 10 | 15 |
| Heating systems VS 1 & VS 2, steel, | | 30 |
| 70 m | 30 | 2 |
| Cold water, KV, copper, 8 m of pipe | 2 | 4 |
| Warm water, VV, copper, 12 m of pipe | 4 | |
| Heat store, VL 1, Stainless steel | | 150 |
| 2343, 370 m of pipe | 180 | 150 |
| Heat store, VL 2, 9700 m of plastic | | 20 |
| pipe | 300 | 520 |
| Auxiliary systems | 20 | |
| | 1200 | 1720 |
| Total | | 520 |
| Contingency 30% | | 210 |
| Design | | 2500 |
| Total for mechanical equipment | | |

| Electrical equipment | SEK x $10^3$ |
|---|---|
| Power supply: | |
| Heat pump | 75 |
| Other equipment | 50 |
| System control equipment (regulators, valve actuators, sensors, installation): | |
| VP District heating | 20 |
| Secondary heating system VS. 1 | 20 |
| Secondary heating system VS. 2 | 20 |
| Heat store circuits | 30 |
| Interlocks | 30 |
| Start, stop and alarm equipment | 50 |
| Signal cable between the store and heat substation, 20-core, 200 m at SEK 10:- | 40 |
| | 335 |
| Contingency, 30% | 100 |
| Design | 45 |
| Total for electrical equipment: | 480 |

| Summary of costs | SEK x $10^3$ |
|---|---|
| Building and civil engineering | 2800 |
| Mechanical equipment | 2500 |
| Electrical equipment | 480 |
| Total: | 5800 |

It is also necessary to charge the store initially with energy to assist in achieving equilibrium conditions with constant annual losses. The necessary energy has been calculated as amounting to about 3 GWh, costing about SEK 30 000 at the prices indicated in Section 6.6.

## 6.6 Operating economics

The following basic costs have been assumed in calculating operational costs:

| | |
|---|---|
| Purchased heat | SEK 10/MWh |
| Heat supplied | SEK 220/MWh |
| Energy purchased | SEK 220/MWh |

| Annual operating costs | SEK x $10^3$/year |
|---|---|
| Purchased heat, 2.8 GWh | 28 |
| Purchased electricity, 450 MWh | 99 |
| Inspection and maintenance, 2% of 5.6 million | 112 |
| Total operating costs: | 239 |

Annual revenue and costs

| | |
|---|---|
| Energy supplied, 2GWh | 440 |
| Annual operating costs | 239 |
| Annual surplus | 201 |
| Annual capital costs at 8% annuity on SEK 5.6 million | 470 |
| Annual loss: | 260 |

This gives a heating cost of 35 öre/kWh with 8% annuity and with the above assumptions.

## 6.7 Economics of a full-scale borehole heat store

Scaling-up exponents have been estimated for different parts of an installation as follows, in order to illustrate the changing investment requirements with increasing installation size:

$$K = k \cdot a^b$$

where:
- K = cost of the larger unit.
- k = cost of the smaller unit.
- a = scaling-up factor.
- b = scaling-up exponent.

The table below and on the next page shows the necessary investments for a store ten times the size, calculated from the costs of the 2 GWh store. The scaling factor is 10: the table indicates the scaling-up exponent. The higher the exponent (e.g. as for drilling), the less the advantage of increasing size.

The necessary investment for the larger store is SEK 25 million. The corresponding scaling-up coefficient is 0.65. This figure is very common for installations such as process plants, but is unlikely to be valid for still larger stores. Further reductions in cost for larger stores should be achievable if allowance is made for the reduced heat losses.

| | 2 GWh | Scaling-up exponent | 20 GWh |
|---|---|---|---|
| Ground and civil engineering works: | | | |
| Drilling | 1.15 | 0.9 | 9.1 |
| Other | 1.65 | 0.3 | 3.3 |
| | 2.8 | | 12.4 |
| Mechanical equipment: | | | |
| Heat pump | 0.40 | 0.8 | 2.5 |
| Heat exchanger | 0.28 | 0.7 | 1.4 |
| Culvert and pumps | 0.32 | 0.6 | 1.3 |
| Pipes in the store | 0.45 | 0.9 | 3.6 |
| Other | 1.05 | 0.4 | 2.6 |
| | 2.5 | | 11.4 |
| Electrical equipment | 0.48 | 0.4 | 1.2 |
| Total investment, million SEK | 5.8 | (0.63) | 25.0 |
| Specific investment, kr/kWh | 2.9 | | 1.3 |

The annual costs of the larger store can be calculated from the information given in Section 6.6. Costs in the table below have been calculated on the assumption that specific operating costs remain unchanged. They indicate that the store would be profitable with low rate of return requirements.

Revenue and costs*:

| | | | |
|---|---|---|---|
| Energy supplied | 0.44 | 1 | 4.4 |
| Operating costs | -0.24 | 1 | -2.3 |
| Capital costs at 8% annuity | -0.47 | - | -2.0 |
| | -0.27 | | 0.1 |
| Cost of heat at 8% annuity and with the above costs (öre/kWh) | 35 | | 22 |

* For specific conditions, see Section 6.6.

The costs of the larger heat store would be further reduced if allowance was made for the reduced heat losses. A reduction in losses from 40% to 20% increases storage capacity to 27 GWh and reduces the cost of heat to 16 öre/kWh.

# 7 DEVELOPMENT IDEAS

## 7.1 Screening off groundwater flow

Groundwater flowing through a heat store can increase heat losses, as can groundwater flowing through the overburden above the store. Examples of conventional means of reducing or preventing groundwater flow are injection of the crack system in the rock, the drilling of wells for hydraulic control through pumping groundwater past the store, piling etc.

In some cases, a simpler and cheaper solution may be effected by making a circular underground drainage ditch round the store, as shown in Figure 7.1.

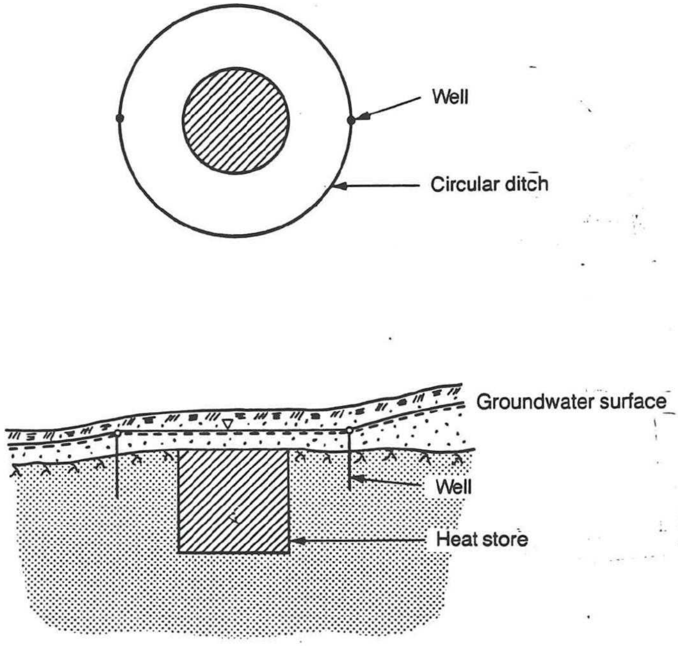



Figure 7.1 Plan and section of a heat store surrounded by a circular ditch.

The ditch can also be connected to drilled wells in order to exploit the gradient difference in the earth and rock. No pumps are required, but the system can maintain a horizontal groundwater table above the store. However, it is necessary that infiltration conditions are suitable.

## 7.2 Circulation system

The circulation system in the trials store has been based on siphonic action. Apart from a few leaks at the beginning of the trials, and which were easily put right, the method has worked without trouble.

However, application of the siphon system to a large heat store can be associated with certain difficulties, as the number of joints, connections etc. is very much greater, increasing the risk of air entering the system. The system cannot be used at all if the groundwater surface is a long way below the surface of the ground.

A circulation system, retaining the advantages of the siphonic system with self-regulating circulation, can be designed as shown in principle in Figure 7.2.

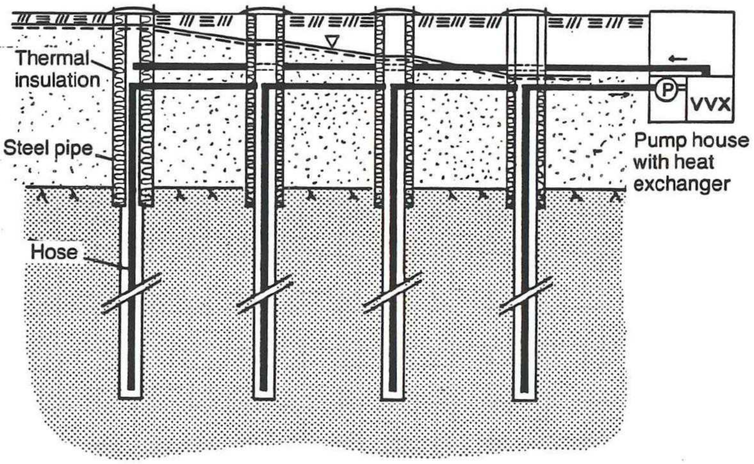



Figure 7.2 Open circulation system with deep groundwater level.

The water flow through the crack system in the rock, driven by the groundwater gradient, is in the same direction as circulation between the boreholes. Several boreholes can be connected in series. A disadvantage of this system is that, in certain cases, a considerable amount of excavation work is necessary, possibly down to below groundwater level.

This can be avoided if the circulation system is pressurized. Unlined boreholes can still be used, but a tightly-fitting packer must be used, ideally in the liner tube, and at a depth of a few meters below the top surface of the rock. The higher pressure of the water in the borehole, relative to the normal groundwater pressure, establishes a flow through the crack system in the rock away from the store, i.e. causing a loss of water. Mathematical models for the water and heat losses caused by the pressure in unlined boreholes are being developed. Preliminary results from such models indicate that the hydraulic conductivity of the bedrock should not exceed $10^{-6}$ $m^3/s,m^2$. Crystalline bedrocks in such models indicate that the hydraulic conductivity of the bedrock should not exceed $10^{-6}$ $m^3/s,m^2$. Crystalline bedrocks in Sweden generally comply with this condition: at least, if the store is constructed with its upper surface sufficiently deep below the rock/soil interface. However, crushed zones and significant cracks must unconditionally be avoided or be sealed.

Under favourable conditions, it is possible to avoid or reduce water losses from the pressurized system through recovering water from the peripheral holes by suction.

## 7.3 Hole positioning and piping layout

One of the advantages of the borehole heat store is that it can be expanded relatively easily if required. Symmetrical hole patterns facilitate any such expansion.

A hole pattern copying the seed pattern in a sunflower head is symmetrical, and also results in short piping lengths, as shown in Figures 7.3 - 7.5. Apart from the central section of the store, and assuming that supply and return connections are required to each borehole, piping length is minimized with this arrangement.

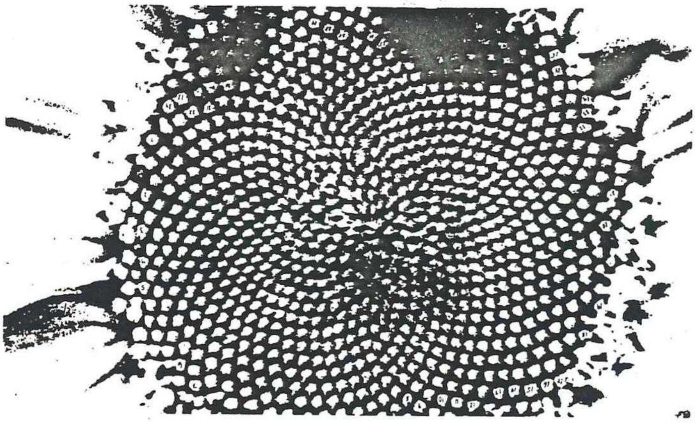


Figure 7.3 The seed pattern in a sunflower head.
Photo: Växternas värld, Lanzara, P., Nordstedt, 1979.

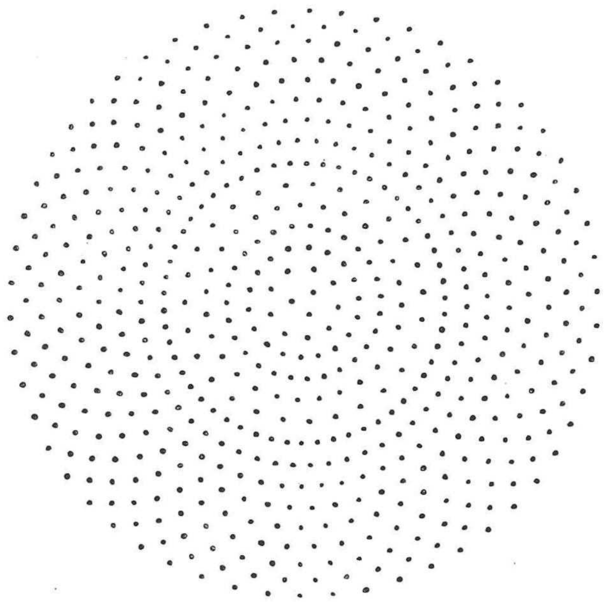


Figure 7.4 Borehole pattern for 596 boreholes, based on the sunflower seed pattern.

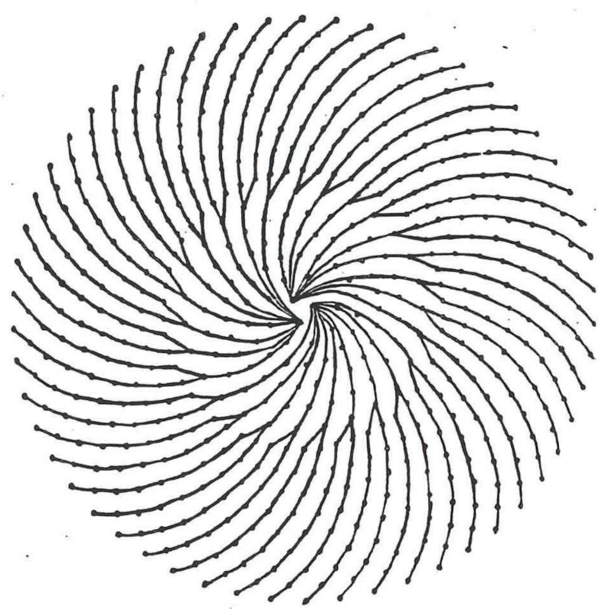


Figure 7.5 Piping connections for a store using the borehole pattern as shown in Figure 7.4. Several symmetrical circulation systems are possible with this arrangement.

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(S = Swedish, E = English.)