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The Energy Research Program
of the Danish Ministry of Energy

Risø-M-2852

Report No. 1-5

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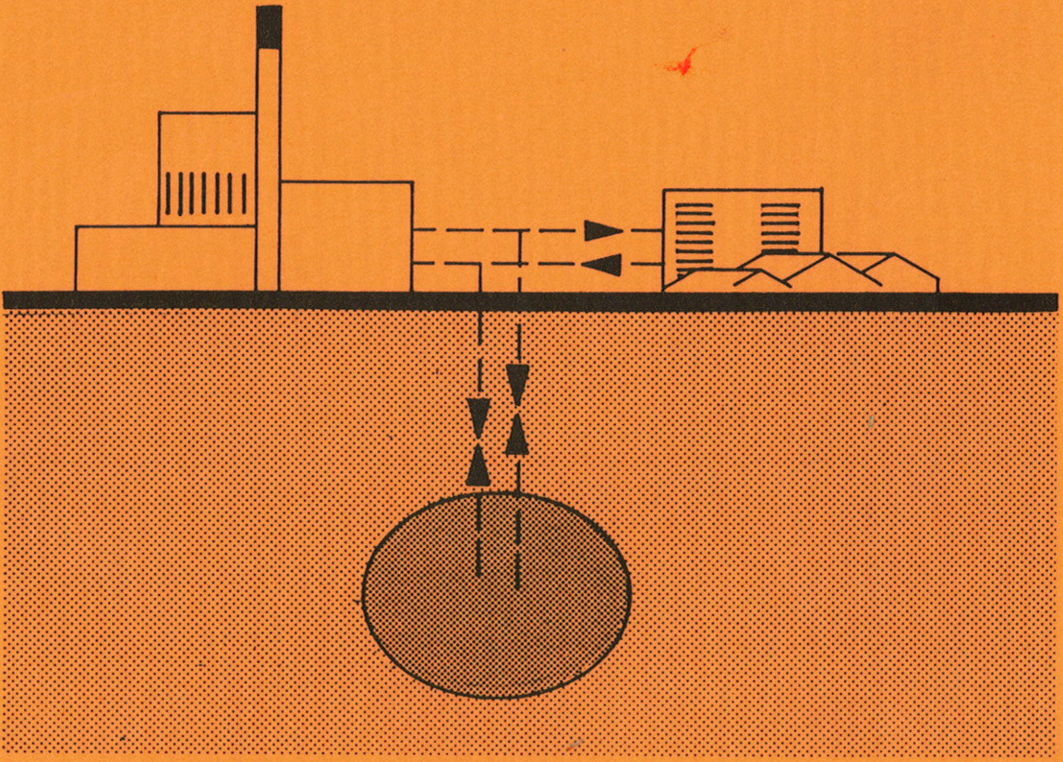
Lotte Schleisner Ibsen, Bjørn Qvale and Lyt Brejl



The Laboratory for Energetics, DTH
The Geological Survey of Denmark
Risø National Laboratory
N & R Consult A/S
Nordforbrænding I/S

June 1990

Aquifer Thermal Energy Storage

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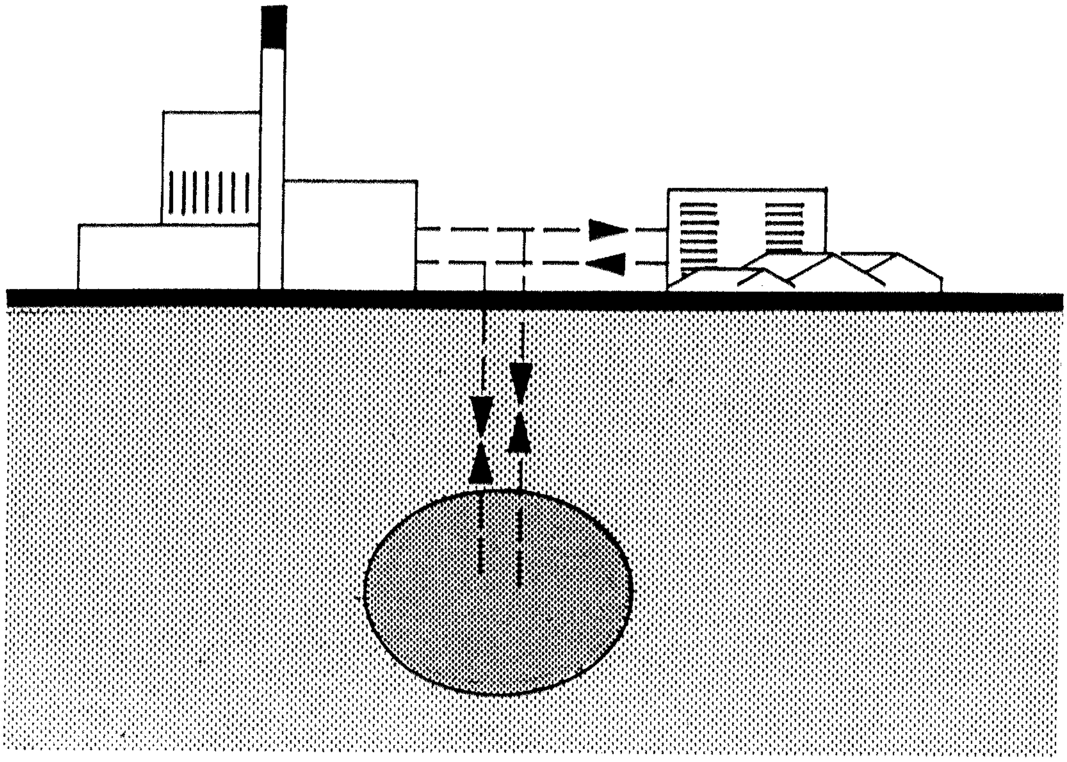

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## ABSTRACT

A part of the Danish aquifer thermal-energy storage project consisted in construction and operation of a demonstration plant. The demonstration plant was established in Hørsholm north of Copenhagen in 1982. During the years of 1982-1987, altogether six charging processes have been carried out. Due to various difficulties for some years, the discharge (recovery) part of the storage cycle had to be omitted. In 1988 the demonstration plant was closed down.

The project has been a collaboration between Risø National Laboratory, the Laboratory for Energetics at the Technical University of Denmark and the Geological Survey of Denmark. In 1986 N&R Consult A/S and the owner of the incineration plant Nordforbrænding I/S joined the project. At the same time the storage plant was taken over by Nordforbrænding I/S.

The project has been financed by the Danish Ministry of Energy's energy research programs EM-2, EFP-80, EFP-81, EFP-82 (EM-J.No. 22633), EFP-84 (EM-J.No. 2263-411) and EFP-85 (EM-J.No. 1443/85-9). During 1986-1988 the project was partly financed by "new technologies" under the Danish Ministry of Energy.

The present report describes the experiences gained and results of the six storage-recovery cycles which have been carried out during the project.

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## THE DANISH AQUIFER THERMAL ENERGY STORAGE PROJECT.
## DEMONSTRATION PLANT - OPERATIONAL EXPERIENCES AND RESULTS.

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TABLE OF CONTENT - PART 1

TABLE OF CONTENT - PART 2

The Energy Research Program
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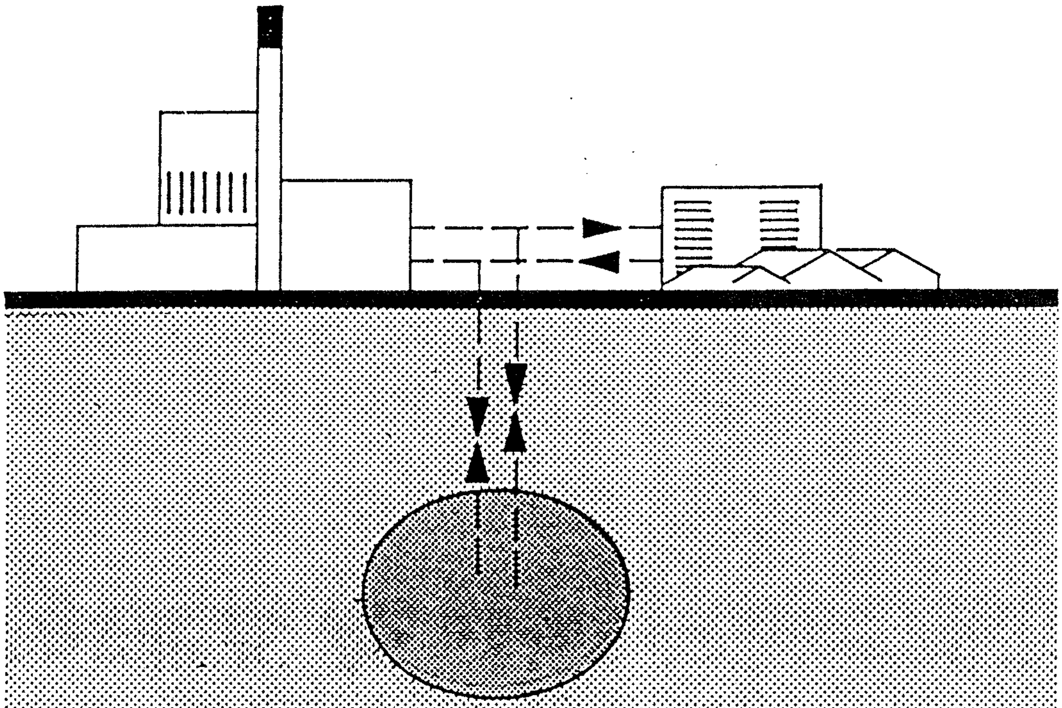
Risø-M-2852

# The Danish Aquifer Thermal Energy Storage Project



## Part 1

# 1. INTRODUCTION

In Denmark a large amount of the heat demand is covered by district heating. In many occasions there may be a need for large thermal energy stores in connection to the district heating systems. By utilization of these stores, the load of the district heating plants will be equalized, and it will be possible to utilize the surplus heat, which has been produced at times with low heat demand. The stores may be short term stores or seasonal stores, lowtemperature- or hightemperature stores.

In the beginning of the seventies, the idea of utilizing natural aquifers as heat stores was started, and since the seventies, there have been made theoretical studies in many countries concerning the possibility for storing heat in aquifers in practice. Mathematical models for simulation of the utilization of these stores have been developed, and there have been made several experiments in practice.

Not only in Denmark, but in many western countries, aquifers are considered as the cheapest way for storing large amounts of seasonal heat.

Denmark is nearly everywhere covered by Glacial deposits with porous water bearing layers, called aquifers. Therefore a cheap way of storing heat may be utilization of these aquifers as stores.

There are two kinds of reservoirs, a closed reservoir and an open reservoir. The closed reservoir consists of a porous water-bearing layer, which upwards and downwards is defined by watertight layers of clay. The groundwater is in this way under pressure.

In the open reservoir, the upper layer of clay is missing, and the groundwater surface is directly exposed to atmospheric pressure through the upper porous layers. Water is able to seep down to the groundwater.

The closed reservoir is fitted for storing at both low and high temperatures. The open reservoir is only fitted for storing at low temperatures and may be used in connection with a heat pump.

In 1977 the Danish energy project was started as a part of the programme for energy research of the Danish Ministry of Energy. The purpose of the Danish energy project, was to investigate the feasibility of thermal energy storage in aquifers at high temperatures.

The first part of the project, was theoretical studies during which a mathematical model was developed. Next part of the project consisted of construction and operation of a demonstration plant for heat storage.

In order to find a suitable site of the demonstration plant hydrogeological mapping was carried out in areas around heat sources, where storage of hot water was a possibility.

The preliminary identification of possible aquifers for heat storage was mainly done by the use of the Geological Base Data Maps, which exist for all parts of Denmark. From these maps it was possible to evaluate some of the most important criteria for aquifer heat storage. Beside the sites chosen in the first place, two at Randers and one at Hørsholm, sites at Aarhus, Aalborg and Herning, which were potential for aquifer heat storage, were identified.

The sites at Randers and Hørsholm were chosen near heating plants with surplus of heat and with extensive aquifers under confined conditions. The first site at Randers was abandoned due to insufficient thickness and strength of the confining bed. A second site at Randers was given up because of too high permeability and the investigations were hereafter concentrated around Hørsholm, which was found suitable for the demonstration plant. Here the geological tests proved that conditions were acceptable, and an incineration plant with combined district heating network situated nearby, could be both a supplier and consumer of heat.

# 2. UNDERGROUND HEAT STORAGE

## 2.1 Different concepts of storage

Underground heat stores can be divided into high-temperature and low-temperature stores. The kind of store depends on, whether the heat recovered is used directly in a district heating system (high-temperature storage), or whether a heat pump is neccesary to increase the temperature level to make it suitable for heating consumption in a district heating system, (low-temperature storage). The temperature levels for these two kind of stores is not clearly defined as the temperature of storage may vary considerably during the year.

In the present chapter, for the purpose of discussion, the stores are assumed to lie in one of the two following temperature ranges:

low-temperature storage: 8°C - 60°C
high-temperature storage: 60°C - 150°C

This division is shown in figure 2.1.

The utilization as a function of energy source, type of reservoir, energy use and temperature is shown in figure 2.1.

The lower temperature limit of the low-temperature store is determined by the average groundwater temperature.

If the temperature in the store is lower than the groundwater temperature, the heat from the surrounding groundwater is used as an energy source, and the plant is not described as a heat store. The choice of the upper temperature limit of 60°C is more arbitrary. But only in special low-temperature systems is heat at this temperature level useful. Low-temperature surplus heat from industrial plants is often available in the temperature range of 20°C-60°C.

The lower temperature limit to qualify as a high-temperature store is determined by the lowest temperature that may be considered useful in a district heating system. The upper limit of 150°C is the highest temperature acceptable in a closed (artesian) groundwater store above the limestone layer compatible with the geology in Denmark. In order to store heat at

**Figure 2.1. Draft for storage**

| | High-temperature store (60°C-150°C) | Low-temperature store (8°C-60°C) |
|---|---|---|
| Energy source | Surplus heat:<br>District heating plant<br>Industrial processes | Natural heat:<br>Solar heat<br>Surface water<br>Groundwater |
| | Alternative fuels:<br>Coal<br>Combustible waste<br>Surplus straw and -tree | Other low-temperature heat sources:<br>Industrial waste heat<br>Waste water |
| Type of reservoir | Type of store:<br>Artesian store | Open store<br>Artesian store |
| | Drilling configurations:<br>Double-well system<br>Multi-well system | Single-well system<br>Double-well system<br>Multi-well system |
| Energy use | Technology:<br>Heat exchanger | Heat exchanger<br>Heat pump |
| | Use:<br>District heat<br>Warm water<br>Cooling for buildings<br>Low-temperature process heat | District heat<br>Warm water |

this temperature level a closed store is required into which it is possible to inject water at a pressure of at least 4.5 bar. Storage is theoretically possible at higher temperatures, but the pressure will be correspondingly high causing structural problems. For instance, at 180°C the pore pressure in the store must be 10 bar or more. A pressure of this size cannot be expected to occur under natural conditions in upper, artesian stores in Denmark. In depths beyond 100 m the pressure will normally be about 10 bar in artesian stores. Roughly speaking, the absolutely pressure level increases 1 bar for each 8-10 m of depth, and the natural groundwater temperature increases by about 3°C per 100 m. The technical and economical problems concerning heat storage in deep stores include among others the spontaneous formation of steam during pumping, large amounts of salt dissolved in the groundwater and high drilling costs increasing with depth.

A closed (artesian) store, limited on the top by a low-permeable layer of, for instance, clay or marl, is required for high-temperature storage. For a low-temperature store the upper, low-permeable layer is not required. Therefore, both artesian and non-artesian aquifers may be used.

A single-well system may be sufficient for low-temperature storage of smaller amounts of heat, for instance for storage of natural heat, where the temperature difference between the groundwater temperature and the average operational temperature in the store is small. The characteristic feature of a single-well system is the two screens that are located at two different levels in the well. This feature leads to the requirement of greater aquifer height than in the case of multi-well configurations. Groundwater is usually injected through one screen, while the other screen is used for pumping.

Double-well systems or multi-well systems are often chosen for storing greater amounts of heat at higher temperatures. If the capacity of a double-well system is too small relative to the thermal power required by the store, it is possible to expand the double-well system to four, six or more wells. The configuration of a multi-well system also includes the possibility of a different number of pumping and injection wells. An example of this is the aquifer thermal-energy storage plant in Hørsholm. Here, groundwater is pumped from four peripheral wells and injected in one central well during charging and the reverse during recovery.

## 2.2 Potential heat sources

Heat storage in groundwater may be useful in almost every energy system in which the rate of production and consumption of heat do not coincide. In the following some examples are mentioned.

Natural heat. Heat from naturally occurring heat sources such as sun heated air, river water and sea water, might be stored in the summer, when the temperature of the source is high. In the winter, the heat may be recovered by use of a heat pump and used for district heating, for instance.

Solar heat, absorbed in glass-covered enclosures or in simple absorber constructions, may be stored from summer to winter. The store may also be used as a diurnal store where the solar heat stored from daytime is used at night.

District heat from district systems is often coupled to the generation of electrical power (cogeneration systems with extraction turbines or back-pressure turbines). By use of heat storage the generation of heat can be decoupled from the generation of electric power, thus permitting production at economically advantageous times and recovered after demand.

Industriel surplus heat. Heat stores may be of great importance for the utilization of industriel surplus heat: In 1980 31% of the gross energy consumption in Denmark were used in industriel processes. Some of the industriel surplus heat can be used for district heating, but only a small part is utilized today.

Most of the waste heat is available at low temperatures, about 40-60°C, and in most cases a heat pump will be required.

Certain specifications concerning the actuel amounts of heat (amounts of surplus heat, heat demand for the factory in question and heat demand in the neighbouring district heating system) and its distribution through the year has to be satisfied

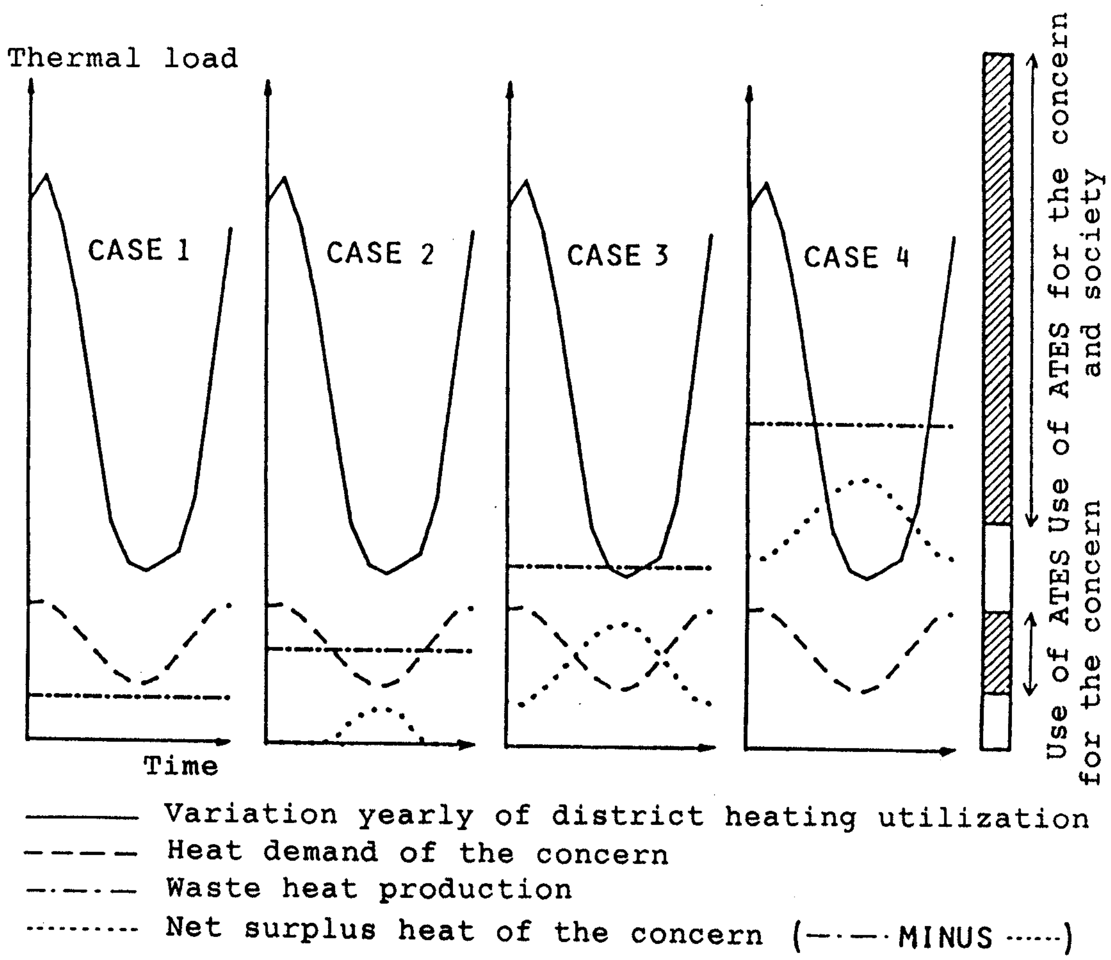


Figure 2.2. Different relations between utilization and production of heat. Possible utilizations of stores are indicated in the hatched fields in the column to the right.

for utilization of a seasonal store. This is shown in the subsequent 4 cases concerning waste heat, where the temperature of the waste heat is the same as the temperature of the heat demand (taken from Reference 3).

Case 1

The production of waste heat is always smaller than the heat demand of the factory. Utilization of a store is impossible.

Case 2

The production of waste heat is greater than the heat demand of the factory in summer. By utilization of a store connected to the factory it is possible to store surplus heat for heating the factory in winter. Another possibility is to sell the surplus heat to a district heating system with a greater demand of heat. In this way heat storage is out of the question.

Case 3

The production of waste heat is greater than the heat demand of the factory throughout the year. The surplus heat, never exceeding the demand of heat in the district heating system is sold to the district heating system. There is no need for heat storage.

Case 4

The surplus heat from the factory exceeds the demand of heat in the district heating system during the summer. The difference between these may be stored.

The hatched fields in the column to the right shows the two intervals for the size of the waste heat production, where heat storage is of interest.

If the production of waste heat is available at a temperature too low for direct utilization in the district heating system the situation is slightly more complex, as the amount of heat available is increased in accordance with the electrical or mechanical energy used by the heat pump for raising the temperature. However, the reasoning is, in principle, the same.

An investigation has been carried out (ref. 3) showing how these limitations influence the possibilities for utilization of industriel surplus heat in Denmark. Specifying a maximum acceptable distance of 2 km from the industry to the district heating system, it was found that only 6 out of 21 plants producing waste heat (above 60°C) satisfied all the requirements. 16 out of 67 plants satisfied the requirements below 60°C. For the whole group of 88 plants considered in the investigation, 5 plants were situated too far from the district heating system, 3 plants had too small a demand of district heating, and in 58 plants the demand of heating was too high to require heat storage (case 3).

## 2.3 Primary functions

The integration of groundwater heat stores into an energy system might in principle take place on the production side, in the distribution network or on the consumption side. The choice of most suitable interconnection is based on an evaluation of the local hydrogeological conditions and the chosen store configuration conditions and the primary functions of heat storage in the given system.

These primary functions may be:

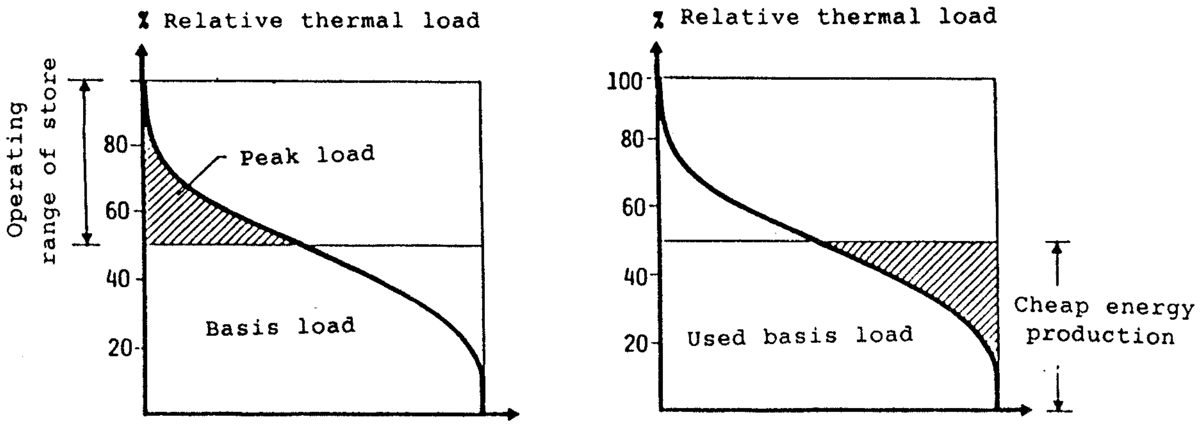
* load compensation
* energy utilization
* capacity utilization

The consideration of the establishment of a groundwater heat store might be based on priority of these functions. Typical the decision to make a groundwater heat store will be based on its expected contribution to the above mentioned functions.

The three primary functions are illustrated schematically in figure 2.3 for a standard duration curve illustrating the distribution of heat production during the year.

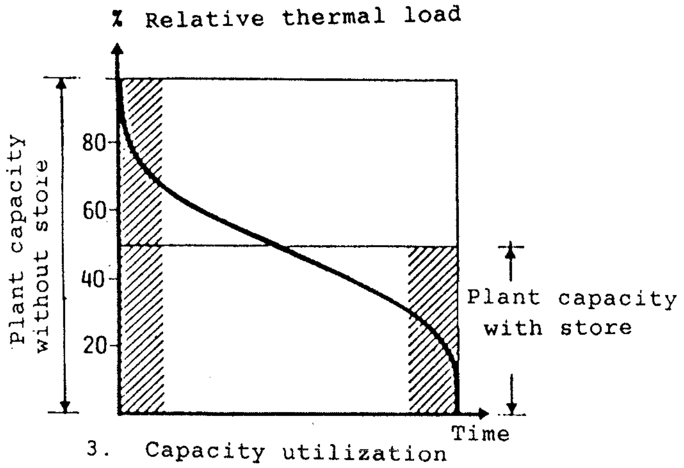
In the first example in the figure the range of store operation is hatched. The operation of the store will be seasonal storage alone or in combination with a short-time store. The second example illustrates the function of the store as a contributor to better utilization of a cheap heat source, for instance waste heat. In the third example, it is possible to decrease the generating capacity of the plant by establishing a store close to the consumers. However, in this case, reserve generating capacity is required.

When the primary function of the store is load compensation (1) and capacity utilization (3) the store should be situated close to the consumers. When the primary function is improvement of energy utilization (2) the store should be placed close to the heat source.



1. Load compensation

2. Energy utilization



3. Capacity utilization

Figure 2.3. Primary functions of heat store

The establishment of a heat store will also affect the distribution in an additional way. The existence of the store will contribute to the reliability of the heat supply system, but as the amount of energy is limited, it can only serve as a back-up for short periods of time.

# 3. DEMONSTRATION PLANT IN HØRSHOLM

## 3.1 Description of the demonstration plant

This chapter is a short presentation of the demonstration plant in Hørsholm. A detailed description of the plant has been given in (1).

The Danish aquifer thermal-energy storage project started in 1977 as a part of the research program of the Ministry of Energy. The object was to investigate the feasibility and economics of aquifer storage, theoretically and experimentally.

Based on several geological investigations, in 1982 a demonstration plant was constructed at Hørsholm, 30 kilometers north of Copenhagen. The store is connected to an incinerator plant (Nordforbrænding) with its associated district heating network. The heat is primarily produced by refuse burning, but during the winter the plant has to generate supplemental heat with oil fired boilers. During the summer, there is a surplus production of heat due to refuse burning. This surplus heat is removed in a cooling tower, but by introducing a store into the system, it is possible to store the surplus heat from summer to winter.

The storage plant is based on the existence of a natural aquifer, confined vertically by water-tight layers of clay. The hot storage volume consists of a cylinder between these layers. The concept of the pilot plant in Hørsholm is shown in figure 3.1.

A number of wells are drilled into the aquifer. One or more wells are located at the center of the store, surrounded by a number of wells at the periphery of the store.

During the first storage cycle, cold groundwater is pumped from the peripheral wells and heated in heat exchangers. The heated water is reinjected into the aquifer through the central well, and a hot volume, with a nearly vertical temperature front, will propagate until it reaches the peripheral wells. At this point the store is fully charged.

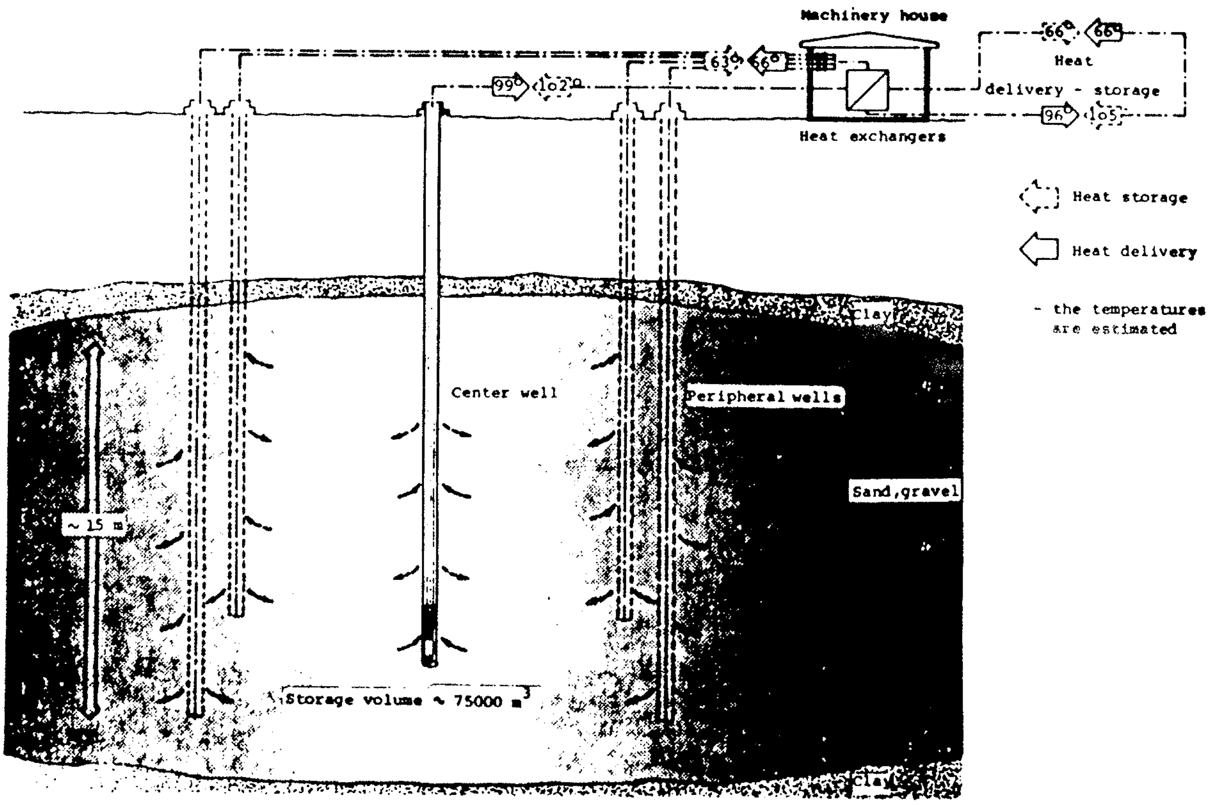


Figure 3.1. The storage concept

During heat recovery the flow direction is reversed, and the cooled water is reinjected through the peripheral wells. The temperature of the cooled water is determined by the return temperature of the receiver system and is a reflection of the amount of energy, which can not be recovered. It may be considered as an initial investment, since the starting point of the next storage cycle is at a temperature only slightly lower than the temperature of the cooled water.

The heat is stored in the water-filled space in the aquifer and in the aquifer materiel. The aquifer materiel is sand with a porosity of about 30% and a permeability of about 10 Darcy. Due to the porosity of 30%, the heat capacity of the aquifer is smaller than the heat capacity of water. The heat capacity of the aquifer is 2,7 MJ/$m^3$.

The permeability of the aquifer is a crucial parameter. If it is too low, the capacity of the wells may be too small. If it is too high, the tendency of tilting of the temperature front, caused by buoyancy of the hot water, may be too high.

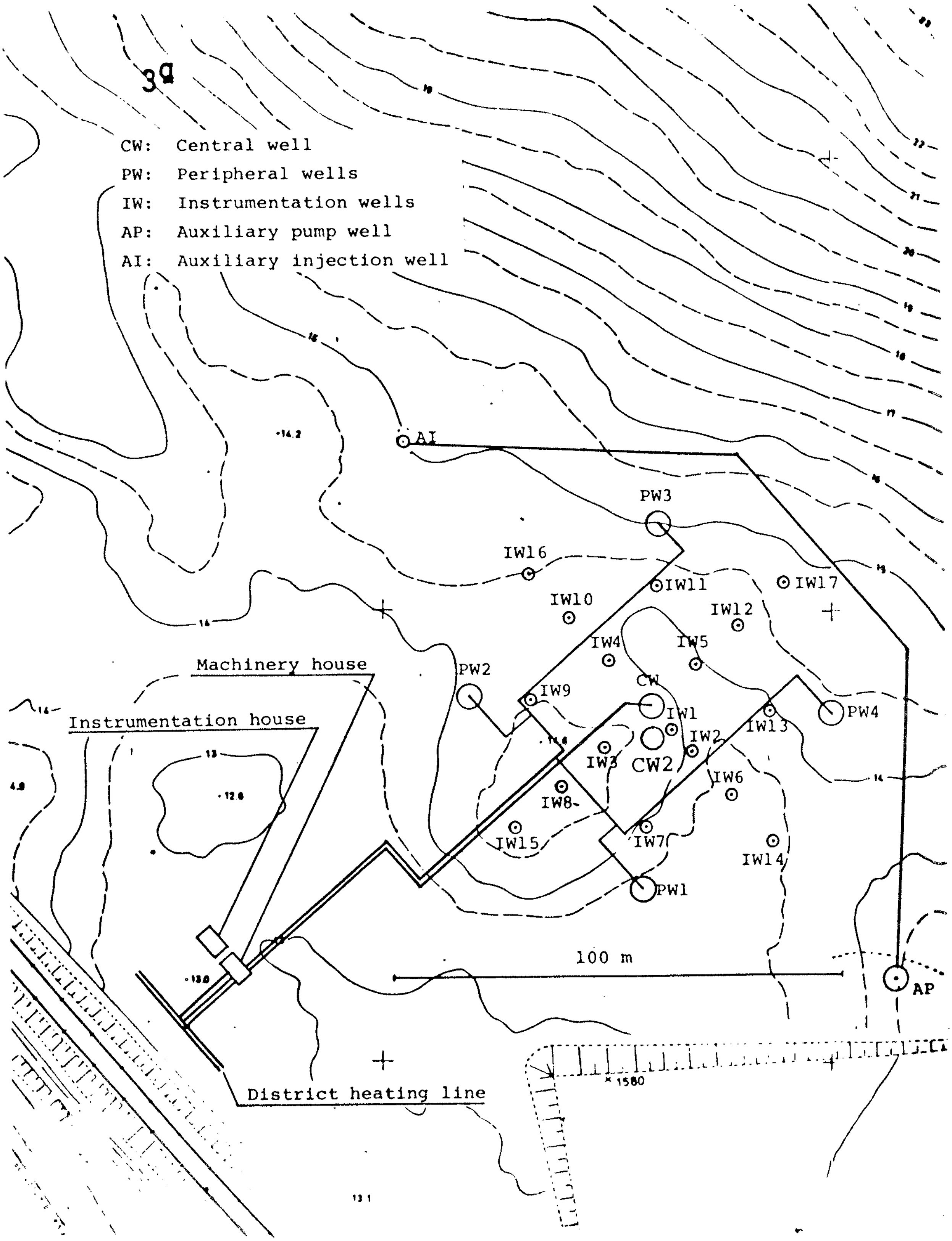


Figure 3.2. Ground plan of the storage plant

A ground plan of the plant is shown in figure 3.2. A central well is surrounded by four peripheral wells situated on a circle with a diameter of 80 m. The wells, that are buried, are connected to the heat exchanger station, located in the machinery house by insulated pipes. The machinery house also contains such additional mechanical equipment as booster pumps and water treatment plant. 17 instrumentation wells for temperature measurements are drilled into the storage aquifer.

Due to several leaks through the upper layer of clay close to the central well, a new central well was established during the winter 1984/85. The new central well (CW2) is placed 6 meters South East of the old central well (CW1).

If the natural, regional flow of the groundwater is too strong, it has to be prevented by means of relief wells. In order to do this, a well on each side of the store in the flow direction is drilled. Groundwater, pumped from the well in the upstream direction, bypasses the store area through a pipeline and is reinjected in the well on the other side of the store.

The two relief wells are also indicated on the plan.

The thickness of the aquifer is about 15 m, and the depth to the top of the aquifer is about 10 m.

The volume of the storage reservoir is about 75,000 $m^3$. With a scheduled storage temperature of $100^oC$ and return temperature from the district heating system of 65 - $70^oC$ the stored amount of energy is about 1,740 MWh.

## 3.2 Design of the demonstration plant

The flow diagram, figure 3.3, shows the connection of the wells to the heat exchangers and other mechanical equipment in the machinery house.

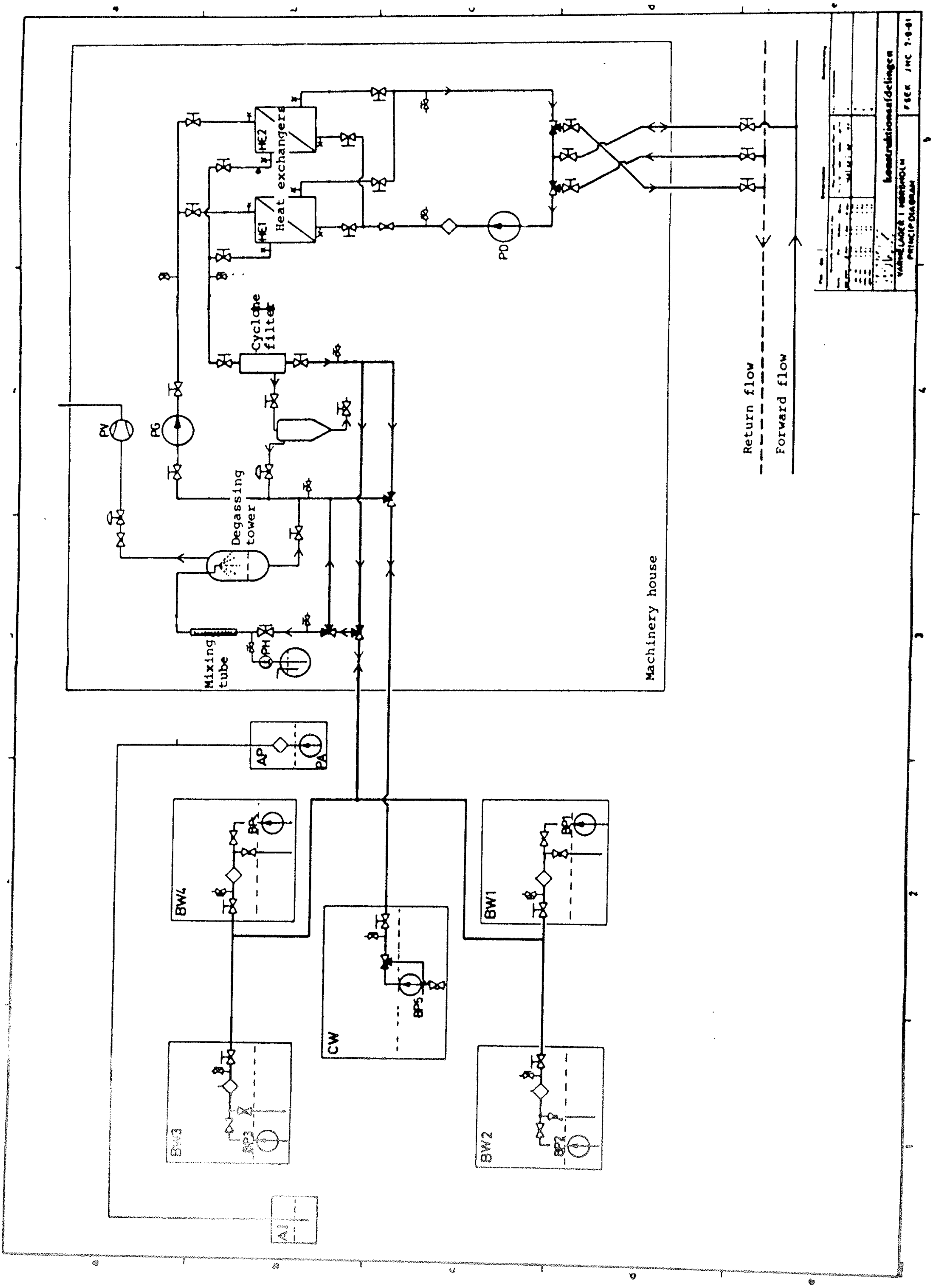


Figure 3.3. Flow diagram of the plant

The old central well is a 14" well equipped with a 10" screen. The well is screened over the entire aquifer height, except for a length of 1 meter dividing the screen into two parts. Between these two parts a hydraulically controlled valve is inserted, making it possible to close off the lower part of the screen.

The new central well CW2, is a 28" well equipped with a 20" screen. The well is screened over 9 m in the lower part of the aquifer, as it is only intended for use during injection. The old central well is still used for production. CW2 is equipped with 4 sounding tubes situated at different levels in the upper layer of clay.

The dimensions of the peripheral wells are 10" and they are equipped with 6" screens, which are placed in the lower third of the aquifer height.

The well screens are made from acid-proof stainless steel, which makes it possible to dissolve any depositions in the wells by chemical treatment. The perforation around the well casings of the upper layer of clay, is sealed by water resistant cementing.

The pump wells are all equipped with variable-flow borehole pumps, dimensioned for a total flow through the system of 80 $m^3/h$.

It is necessary to obtain as small a logarithmic mean temperature difference between the two media as possible (a value of $3^oC$) in order to utilize the relatively small temperature difference between the outlet- and return temperature of the district heating system. Because of the large heat transmission area of plate exchangers this type has been chosen.

During heating of the groundwater, precipitation of calcium carbonate must be avoided. This is done by addition of a small amount of hydrocloric acid before heating. During the chemical process which follows, cloride ions replace the bicarbonate ions, which are dissolved and removed in the form of $CO_2$-gas in a degasser. The amount of hydrocloric acid added, will only result in a small increase in the natural concentration of cloride ions in the aquifer.

Downstream of the heat exchanger, the groundwater passes a filter, which removes particles before the water is reinjected. In this way clogging of the wells should be prevented.

## 3.3 Instrumentation

The instrumentation consists of temperature and level measurements in the aquifer.

The temperatures in the aquifer are measured by integrated circuits which deliver 1 ampere per degree K. The temperature sensors are mounted dry inside copper tubes in the instrumentation wells and are separated by distances of approximately 2 m. Around every temperature sensor is a foam spacer to prevent natural convection around the temperature sensor. The heat is transferred from the aquifer to the temperature sensors mainly by radiation. If one of the temperature sensors fails it is possible to replace it.

In 4 of the instrumentation wells (IW1, IW2, IW6, IW14) and in all of the pump wells, the water level is measured.

Flow, pressure, and temperature are measured at various places in the pipe system, and from these measurements other parameters such as for instance the heat output are calculated.

In the piping system, a pressure switch is placed for measurement of the injection pressure. This pressure switch is activated when the high injection pressure exceeds a specified value, causing the plant to close down.

At the pump wells, temperature, level and flow are measured. At the heat exchangers, the flow, temperature and pressure are measured. On the groundwater side the acidity is also measured. The data is recorded at specified time intervals during operation.

## 3.4 Control and regulating system

It is important that the shape of the storage volume can be controlled, so that an optimum geometry is achieved. In the horizontal plane this is done by independent control of the flows to and from each of the peripheral wells. In the vertical plane, the tendency to tilting can to some extent be neutralized by placing the well screens between proper levels of depth in the aquifer. In addition, the temperature front can be influenced by controlling the flow through the well screen of the central well, by means of a remotely-activated valve, which can close off or open sections of the well.

The data acquisition and regulating system is designed for unmanned operation. The heat store is controlled from a remote host computer. At the heat store, the data acquisition and regulating system is managed by a local mini computer, which is connected to the host computer via a data transmission line. The regulators from the pumps and the valves are implemented as software on the local computer.

When the heat store is operated, the valve-pattern and the regulator setpoints are transmitted from the host computer to the local computer. The collected data are transmitted to the host computer, where data that is of importance for the operation of the heat store are evaluated.

## 3.5 Dimensioning conditions

The heat source, i.e. the incinerator plant Nordforbrænding, is not able to store large amounts of combustible refuse, and the incineration rate is therefore kept at an approximately constant level throughout the year. In this way, there is a surplus production of heat during the summer at about 8,300 MWh. The delivery temperature of the system is 105°C, and the return temperature is 63°C.

The surplus heat produced during the 4 summer months is removed in a cooling tower, and thus wasted. The amount of heat delivered to the cooling tower during the warmest months is about 6 MW.

The incinerator plant is not dimensioned to cover the peaks of the heat demand. For this reason the plant has to supplement the heat generation with heat from oil fired boilers during the winter. Some years ago, no refuse was burned in the weekends and also this demand was covered by oil-produced heat. This has been changed and presently refuse is being burned in weekends, too.

The geology of the area in Hørsholm which was selected for heat storage sets limits both on the size and on the capacity of the store. As already mentioned, the store is confined upwards by a layer of clay at a depth of 10 m and downwards by a layer of clay at a depth of 25 m. The extension of the upper layer of clay in the horizontal direction has set a natural limit for the diameter of the store of 80 m.

The volume of the store is 75,000 $m^3$. With a heat capacity at 2.7 $MJ/m^3$ $^oC$ and a storage temperature at $100^oC$ about 5,120 MWh can be stored above the natural groundwater temperature of $8^oC$.

The plant is dimensioned for full charging during the first storage cycle.

## 3.6 Operational conditions

Heat storage during summer. During storage cold or warm water is pumped from the peripheral wells, heated in the heat exchangers placed in the machinery house, and then injected in the central well. The nominal flow rate is 60 $m^3/h$. At a delivery temperature from the district heating system of $105^oC$ and a return temperature of $66^oC$, corresponding to heating of the groundwater from $63^oC$ to $102^oC$, the stored energy rate will be about 2.7 MW. A temperature difference of $3^oC$ in the heat exchangers have been accounted for in these numbers.

The flow conditions during storage are shown in figure 3.4.

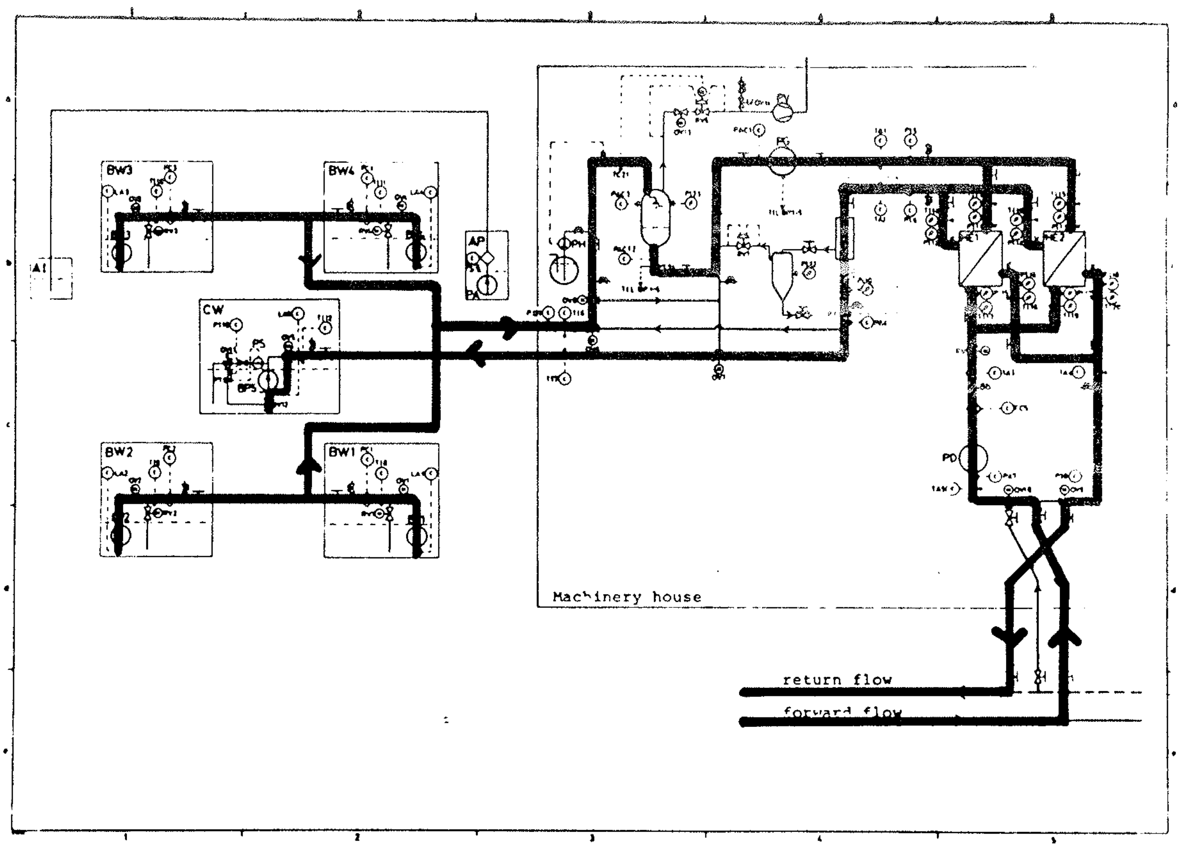


Figure 3.4 Flow conditions during storage

Heat delivery. During delivery, hot water is pumped from the central well to the heat exchangers where some of the thermal-energy of the store water is given off to the district heating system by heat exchange. The cooled (warm) store water is re-injected in the peripheral wells.

During recovery, only heat in the temperature range of 65-100°C is utilized. That is, about one third of the total amount of energy stored can be utilized in the district heating system.

The amount of energy delivered from the store is delivered to the return pipe in the district heating system. In this way heat delivery is possible, as long as the temperature of the store water is higher than the temperature of the district-heating water in the return pipe. The nominal flow rate of store water during delivery is 60 $m^3/h$. At a forward temperature of store water of 99°C and a return temperature of 69°C the nominal thermal output from the store is about 2.1 MW.

The flow conditions during delivery is shown on figure 3.5.

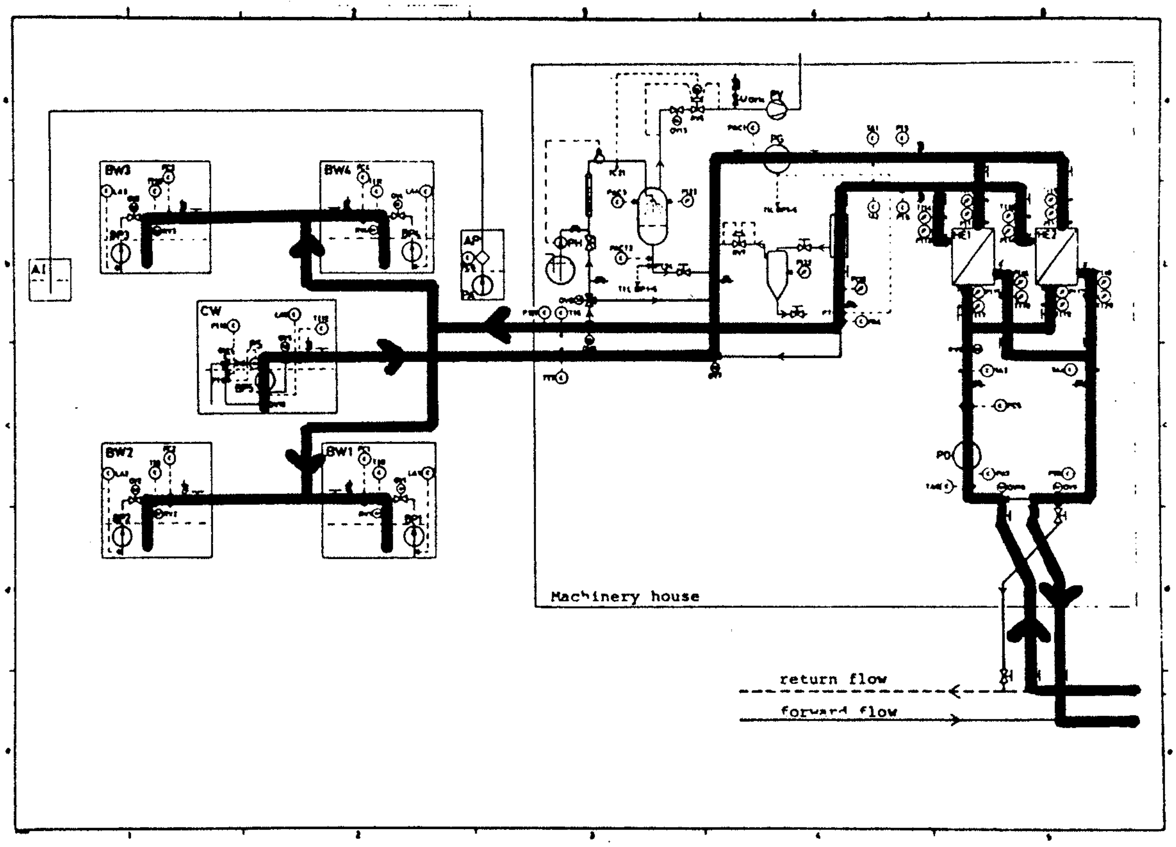


Figure 3.5 Flow conditions during delivery

During delivery of heat, in summer weekends, the flow rate had to be increased from 60 $m^3/h$ to 80 $m^3/h$ in order to deliver the maximal thermal output at 2.8 MW. The heat was intended for the delivery pipe in the district heating system.

During delivery of heat, the regulating valves are controlled by the computer, whereby the flow to the four peripheral wells is distributed evenly.

# 4. SYSTEM ANALYSES

In this chapter the system considerations of the establishment and operation of an aquifer store are explained, including the practical design of the store and the connection to the associated energy system. Furthermore, the geohydrological and thermal parameters, which have to be known in order to estimate the use of the store, are presented. In connection with this, an overview of relevant models for dimensioning and operation of an aquifer heat store are presented.

## 4.1 System configuration

Choice of system configuration and dimensioning of the wells are based on the assumed thermal output and capacity of the store, on temperature conditions of the heat source and consumer, the hydrogeological conditions, where the storage plant is placed, and the chosen store configuration.

The thermal conditions of the store are estimated from the projected connection with the associated energy system. The required period of storage, the required maximum output and the required storage capacity are estimated from the projected function of the store in the energy system.

Dimensioning parameters. The main factors that determine the dimensions of the store are estimated from the primary functions of the store (chapter 2.1). These dimensions are dimensions such as the maximum thermal output stored or recovered from the store, the amount of heat stored and the amount of heat recovered from the store.

If the primary function is load compensation, the maximum thermal output from the store is determined by the size of the peak heat rate which is required by the heat store. The size of the store is determined by the heat required during the peak-load period (the hatched area in figure 2.3). There are no general guidelines for choice of operating range for a store, but figure 4.1 indicates the connection between the dimensioning output of the store and the size in a typical district heating

| Share of store in peak load in the district heating system | Share of store in heat production yearly in the district heating system | Specific Size of store |
|---|---|---|
| 5% | 0% | - |
| 10% | 0% | - |
| 15% | 0% | - |
| 20% | 1% | 0,02 |
| 30% | 3% | 0,06 |
| 40% | 8% | 0,16 |
| 50% | 15% | 0,30 |
| 60% | 26% | 0,52 |
| 70% | 40% | 0,80 |
| 76% | 50% | 1,00 |

Figure 4.1 Connection between specific size of store and the share of the store in peak load in the district heating system. The specific size of store is chosen to 1.0 at a covering at 50% of the yearly heat production in the district heating system.

system. The table indicates the necessary size of store as a function of the desired size of the maximum heat load in the district heating system that is served by the heat store.

The first column in figure 4.1 shows the share of the maximum heat load in the district heating system (Operating range of the store in figure 2.3.a). The second column is the associated heat production (peak load in figure 2.3.a), which is negligible for the peak load production, but increasing as the share is increased. The third column is the specific size of store. A specific size of store at 1.0 is chosen to cover 50% of the heat production yearly corresponding to a construction of 76% of the peak load output in the district heating network. The connection between first and second column is shown in the load duration curve from ref. 7, section 19.

From figure 4.1 it appears that a relatively small store covering a small amount of heat annually may be obtained by designing the store for covering 20 to 40% of the peak load of the district heating network.

The dimensioning conditions are changed if the primary function is improved utilization of cheap energy in periods of low load (figure 2.3.b). In this case the highest rate of generation of cheap energy, or the maximum heat output delivered to the store, is the dimensioning factor. The size of the store is determined by the amount of heat available as surplus above the cheap-energy base load.

If the primary use is improved utilization of the installed capacity , the store is dimensioned, so that the store and the existing installed capacity together, is able to cover the largest demand of heat.

Furthermore, if the store is intended for reserve supply, the maximum thermal output will be determined by the desired reserve heat rate. The size of the store will have to satisfy the heat demand during the longest expected period of failure of the heat generating plants (which may be very long).

In practice, a store is established to fulfil two or more of the functions mentioned. The dimensioning is made from an evaluation of the separate criteria and on evaluation of the integrated system.

### Thermal output

The heat rate is calculated by the expression

$$\dot{Q} = \dot{m} \cdot \Delta T \cdot c_p$$

where

$\dot{Q}$ = heat rate (kW)

$\dot{m}$ = mass flow of groundwater (kg/s)

$\Delta T$ = temperature difference between hot and cold reservoir (in the production well and the injection well) ($^{o}C$)

$c_p$ = specific heat of water ($kJ/kg\ ^{o}C$) (4.19 $kJ/kg\ ^{o}C$ in the interval 0-150$^{o}C$). The deviation from this value is not more than 3% in the specified interval.

In hydrology, volume flow is used instead of mass flow, as it is easier to measure. The formula is then written as,

$$\dot{Q} = \dot{V} \cdot (\rho \cdot c)_w \cdot \Delta T$$

where

$\dot{V}$ = volume flow of groundwater ($m^3/s$)

$(\rho \cdot c)_w$ = specific heat of water ($kJ/m^3 \cdot {}^{o}C$)

Figure 4.2 shows the relationship between the dimensioning parameters.

From the heat rate and the temperatures it is possible to determine the flow of water - given in the right part of the nomogram. The heat rate or the temperature difference can be determined similarly from the other parameters.

The left part of the nomogram is used for transformation of water flow from kg/s to litre/s and vice versa.

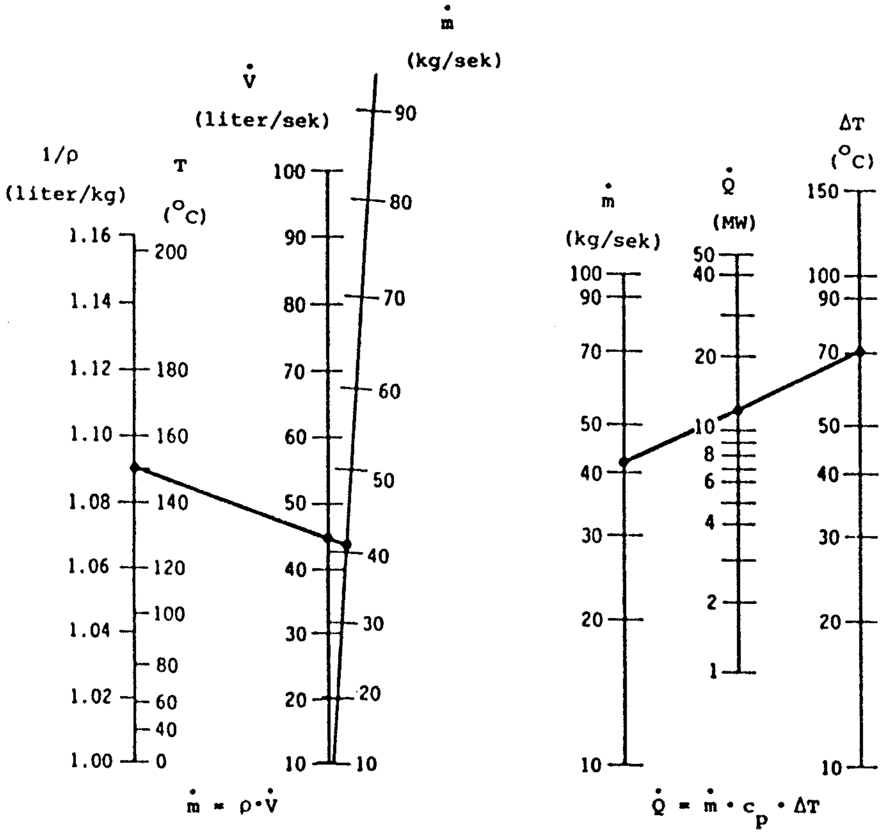


Figure 4.2 Nomogram of the relationship between water flow, temperature and heat rate (from ref. 1)

Numerical example:

The following data are specified: water flow (45 litres/s), injection temperature (150 $^{o}$C) and temperature difference (70 $^{o}$C). The heat rate is calculated to about 12 MW.

The same data used in the analytical expression give ( specific density of the water is 1.09 l/kg at 150 $^{o}$C),

$$\dot{Q} = \frac{45\ l/s}{1.09\ l/kg} \cdot 70\ ^{o}C \cdot 4.19\ kJ/kg\ ^{o}C = 12.1\ MW$$

### Thermal capacity

The amount of heat Q (kJ) injected in the store is determined by,

$$Q = \dot{Q} \cdot t$$

where

$t$ = the time (s) elapsed during which heat $\dot{Q}$(kJ/s) has been added to the store.

As the heat rate usually varies during the storage cycle, the stored amount of heat must be calculated in reasonably short intervals of time, in which the thermal output might be considered as constant.

### Numerical example:

For three months, 100 kJ/s is charged into a store and for two months 50 kJ/s.

The total amount of heat stored is,

$$\begin{aligned} Q = \; & 100 \text{ kJ/s} \cdot 3 \cdot 30 \cdot 24 \cdot 3600 \text{ s} + \\ & 50 \text{ kJ/s} \cdot 2 \cdot 30 \cdot 24 \cdot 3600 \text{ s} = \\ & 778 \text{ GJ} + 259 \text{ GJ} = 1040 \text{ GJ} \end{aligned}$$

Likewise, it is possible to determine the amount of heat recovered from the store by measuring water flow, temperatures and time.

Due to loss of heat from the store, the amount of heat recovered will be smaller than the amount of heat added. A description of the determination of the losses during storage is made in section 4.4 and 4.7.

### Temperature conditions:

The temperature level of storage is among other things limited by the temperature level required for recovery of heat and of the losses during storage.

If a heat pump is connected to the recovery system, the temperature of storage can be chosen independently of the temperature level of the district heating system.

The temperature difference between the cooled and the hot reservoir has to be as large as possible for a high temperature energy store, thereby increasing the effective energy content of the store. This is one way of lowering the costs for the establishment of a store.

## Water flow:

From the specified (required) volume flow the flow of groundwater is determined. This flow is important for design of well systems, pipes, pumps, valves etc., and therefore for the costs of establishing the storage plant.

## Storage period:

The storage period is primarily determined by the variations of the load on the consumption side and on the production side.

The period of storage influences the design of the store directly: a long storage period gives a large store, a short storage period gives a small store.

Often there will be periods in which there is no injection or recovery of heat from the store, so-called dwell periods. This might be the situation in the spring and in the autumn for a seasonal store, where a surplus production of heat in the summer months is stored for recovery in the winter.

These dwell periods also have an important influence on the location and design of the wells in the store, as they influence the heat loss, extent and control of the thermally affected area, the natural groundwater flow etc.

### Well systems:

The well configurations may be classified as:

- single-well systems
- double-well systems
- multi-well systems

### Single-well system:

The store consists of only one well used for as well injection as for production.

The well is screened over two sections, and injection is made in the one section while pumping is carried out in the other one.

There is only very limited experience with this concept, and it is probably of little interest for high temperature storage.

### Double-well system:

During the charging period, cold water is pumped from well A (figure 4.3), heated in a heat exchanger and injected in well B. During recovery, hot water is pumped from well B, cooled by heat exchange with the district heating water and injected as cooled water in well A.

A double-well system is also called a dipole system.

Due to imperfect heat transfer, the water injected in well A during recovery will have a slightly higher temperature than the return temperature in the district heating system. In the next storage period this cooled, but warm water is pumped from well A.

When making up the energy accounts, the initial investment of heating the store from groundwater temperature to the warm-water temperature must be included.

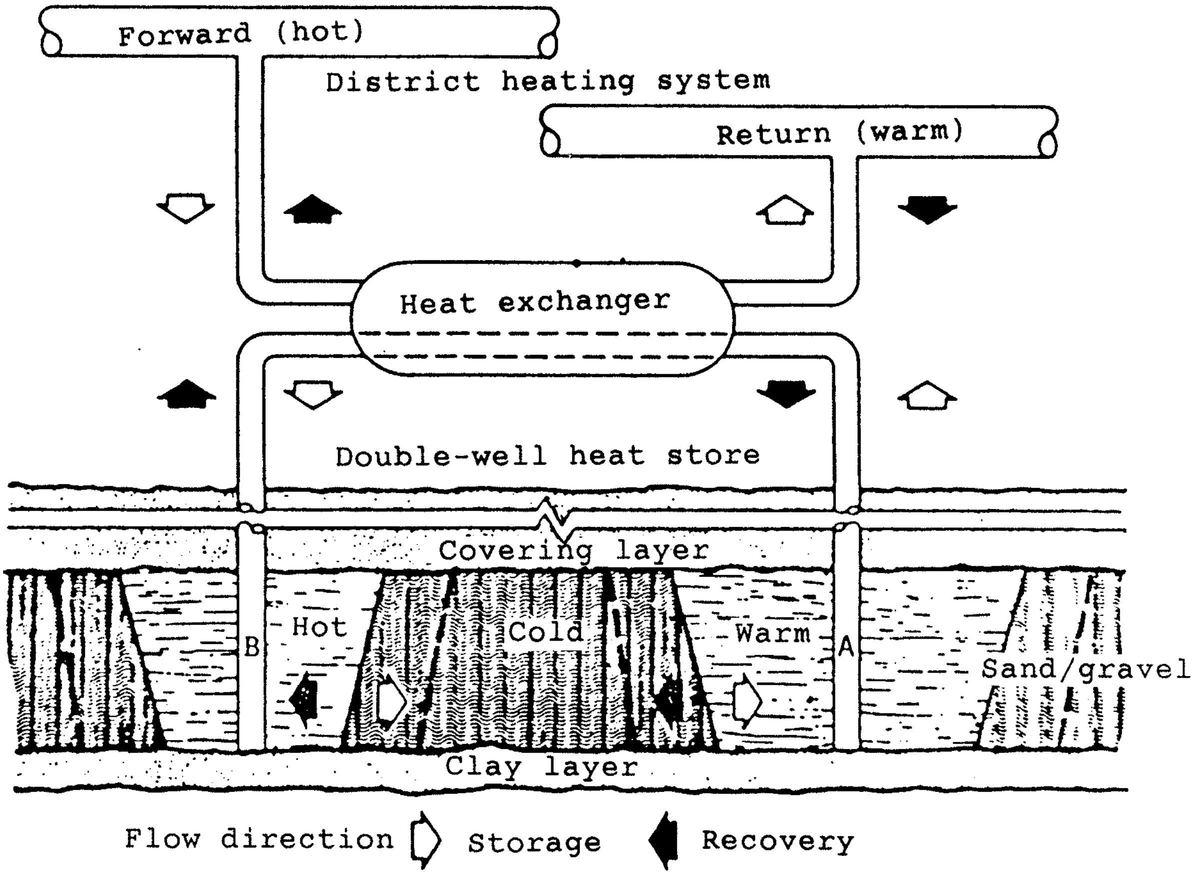


Figure 4.3 Schematic outline of a double-well system (from ref. 1)

In the subsequent cycles, loading and recovery from the store take place between temperature levels corresponding to production temperature of the heat and return temperature of the district heating system.

The capacity of a double-well system is limited by the maximum water flow, which can be produced from or injected into one well in the aquifer.

The capacity will not increase significantly with greater dimensions of wells. Therefore, establishment of a multi-well system may be necessary.

Multi-well system:

Several double-well systems may for instance be placed in parallel, figure 4.4.

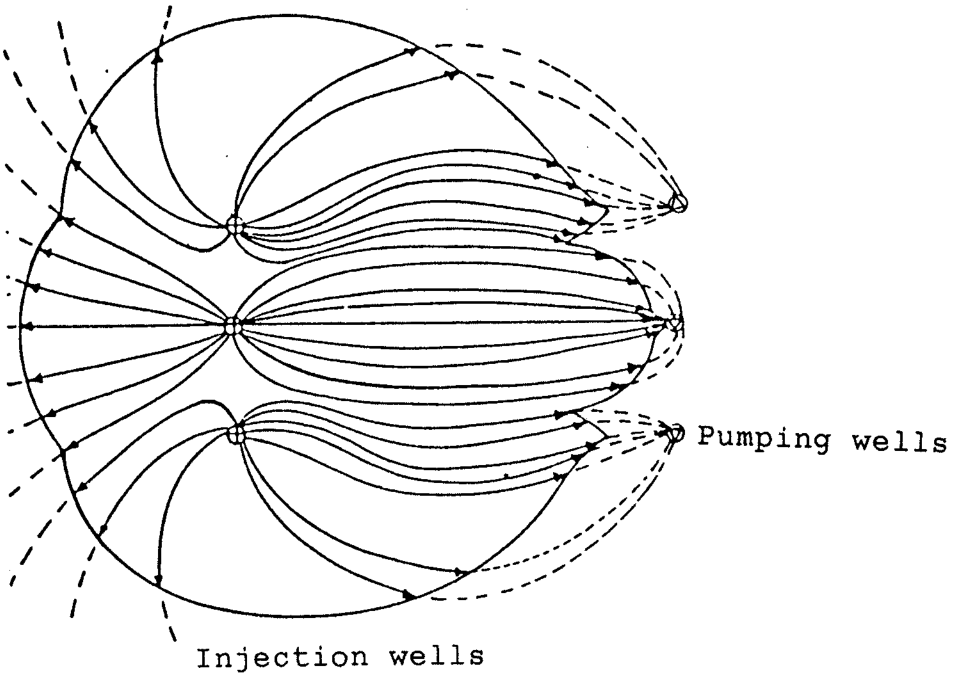


Figure 4.4 Three parallel double-well systems with ground water streamlines and delimitation of the theoretically largest extent of the thermally affected region (just before break-through). From ref. 2.

The heat loss becomes smaller if the separate dipole systems are placed close to each other. In general it may be stated that the heat capacity increases with well distance.

A multi-well system may be constructed with different numbers of production wells and injection wells. The local hydrogeological conditions may make this desirable. The plant in Hørsholm is an example of this.

Distance between the wells:

The distance between injection - and production wells is chosen large enough to avoid thermal break-through, e.g. that the thermal front around the injection well(s) after a period of pumping reaches the pumping well(s), whereby the temperature of the recovered water rises. Ref. 1 recommends - as a rule of thumb - a distance between the wells three times as big as the largest thermal radius expected during operation of the store. The thermal radius is the radial extension of the temperature front from the injection well.

Section 4.2 describes a method for calculating the thermal influence radius from specifications of injected water flow, injection period, the thickness of the aquifer and the heat capacity conditions.

## 4.2 Influence radius models

In this chapter, mathematical models, describing the extension of the thermal and hydraulic front around an injection well, are described.

Thermodynamic and fluid dynamic considerations are central points in designing the wells of an aquifer store. The thermodynamic calculations are based on a knowledge of the geometry of the reservoir, structure and hydraulic qualities (type of reservoir, depth, permeability, porosity, water capacity, injection capacity, extent).

The number of wells and the well configuration (one, two or several wells) is dictated by the wells pumping- and injection capacities. Practical experience with groundwater injection, have shown, that the injection- and production capacity of a well is rarely the same. Normally, a well is able to give more water than it can receive. An increase in injection temperature increases the injection capacity of the well, because the viscosity of water decreases with increasing temperature. Due to this, every well in an aquifer energy store has to be dimensioned primarily after the injection conditions.

Both flow conditions and reservoir parameters enter into the dimensioning of the well. The distance between the wells is based on the required amounts of energy and water. The distance between production- and injection wells, has to be large enough to avoid break-through.

<u>Simple influence radius models (single well).</u> The single-well influence radius model described below is useful for the first estimates. The model indicates the extent of the thermally affected area combined with the temperature distribution around a single well. The results have to be treated with some caution due to the idealizations of the model.

Groundwater is injected at a constant flow rate into a well, screened in the entire height of an artesian reservoir with homogeneous depth between horisontal impermeable clay layers. The thermal influence radius $r_{th}$ as a function of the injection period is determined as:

$$r_{th}(t) = \frac{(\rho \cdot c)_w}{(\rho \cdot c)_a} \cdot \frac{V \cdot t}{\pi \cdot H_a}$$

$r_{th}$ = thermal influence radius to the time t (m from the injection well)

$\frac{(\rho \cdot c)_w}{(\rho \cdot c)_a}$ = the ratio of the specific heat capacities of the groundwater to the aquifer

$\dot{V}$ = injected volume flow ($m^3/s$)

$t$ = injection period (s)

$H_a$ = height of the aquifer (m)

The heat capacity of the aquifer $(\rho \cdot c)_a$ is determined as

$$(\rho \cdot c)_a = (1 - \Phi_{tot}) \cdot (\rho \cdot c)_r + \Phi_{tot} \cdot (\rho \cdot c)_w$$

$(\rho \cdot c)_r$ = the heat capacity of the gravel/sand matrix of the aquifer

$\Phi_{tot}$ = the porosity of the reservoir, that is the pore volume per volume unit

The hydraulic radius is an expression of the radial extent of the injected water (the thermal radius is an expression of the propagation of the temperature front). The hydraulic radius is determined as:

$$r_{hy}(t) = \sqrt{\frac{\vec{V} \cdot t}{\Pi \cdot \Phi_{tot} \cdot H_a}}$$

In this way it is possible to estimate the thermal radius and the hydraulic radius when the specific hydrogeological aquifer parameters and injection flow and period are known.

In order to simplify the calculation procedure these relationships have been converted to the nomograms of figure 4.5 for determination of the thermal radius and the hydraulic radius.

Example: The injection flow is 4000 $m^3$ per 24 hours for 30 days. The height of the aquifer is 40 m. The nomogram gives a thermal radius of nearly 40 m and a hydraulic radius (distance between well and hydraulic front) of a little more than 60 m. Such a large flow normally requires several wells.

The same conditions are calculated from formula

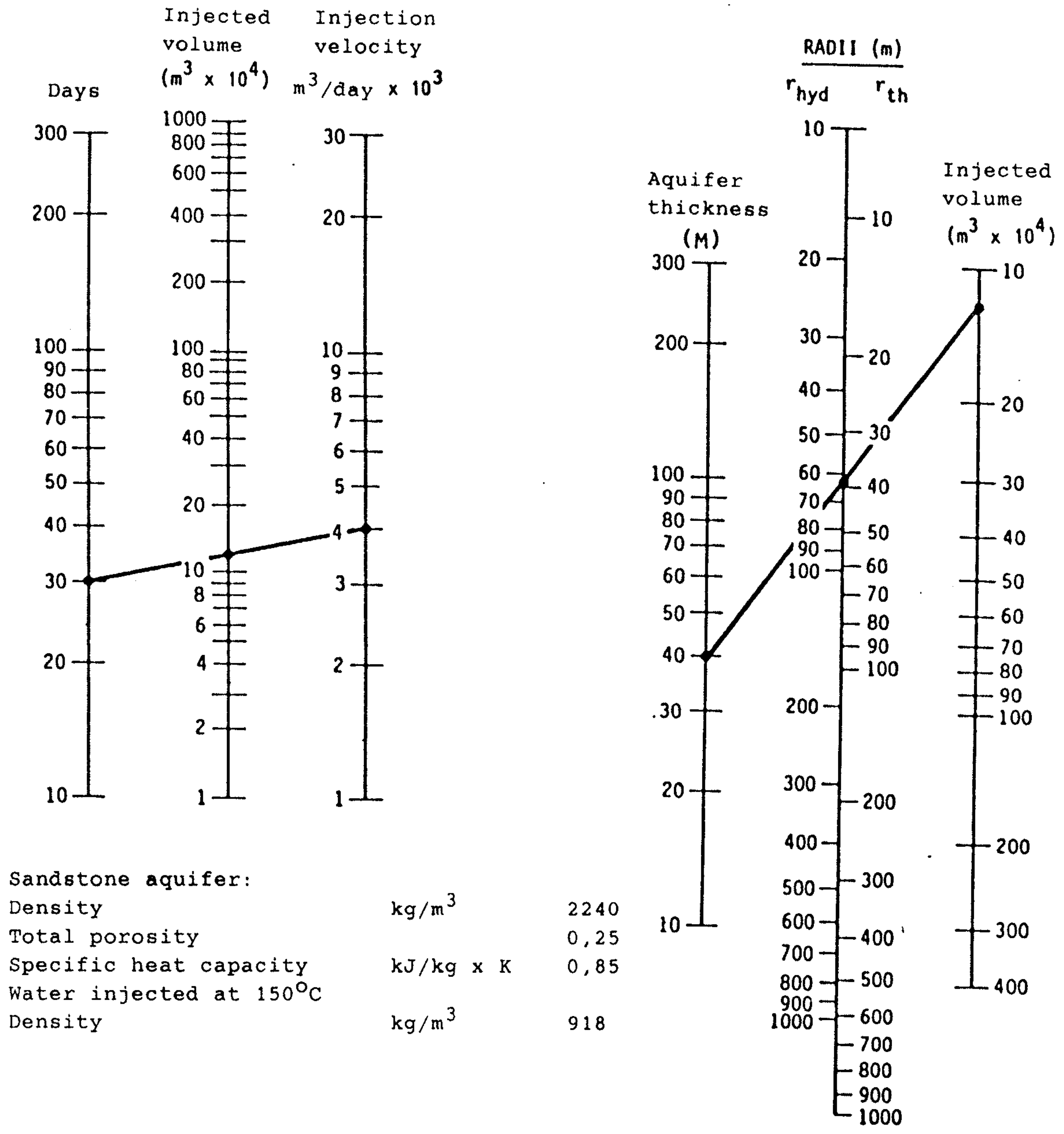
$$\frac{(\rho \cdot c)_w}{(\rho \cdot c)_a} = \frac{4190 \text{ kJ}/(\text{m}^3 \cdot {}^{\circ}\text{C})}{0.75 \cdot 2240 \text{ kg/m}^3 \cdot 0.85 \text{ kJ/kg}^{\circ}\text{C} + 0.25 \cdot 4190 \text{ kJ/m}^3 \cdot {}^{\circ}\text{C}} = 1.693$$

$$r_{th}(t) = \sqrt{1.693 \cdot \frac{4000 \text{ m}^3/\text{day} \cdot 30 \text{ days}}{\Pi \cdot 40 \text{ m}}} = 40.2 \text{ m}$$

$$r_{hy}(t) = \sqrt{\frac{4000 \text{ m}^3/\text{day} \cdot 30 \text{ days}}{\Pi \cdot 0.25 \cdot 40 \text{ m}}} = 61.8 \text{ m}$$

The velocity, whereby the thermal front is extended from the injection well is determined by

$$u_{th} = \frac{(\rho \cdot c)_w}{(\rho \cdot c)_a} \cdot u_D$$



| | | |
|---|---|---|
| Sandstone aquifer: | | |
| Density | kg/$m^3$ | 2240 |
| Total porosity | | 0,25 |
| Specific heat capacity | kJ/kg x K | 0,85 |
| Water injected at 150°C | | |
| Density | kg/$m^3$ | 918 |

Figure 4.5. Nomogram for determination of thermal and hydraulic radius (ref. 1)

The natural ground water temperature is $T_0$ and the natural ground water velocity is ignored.

$u_D$ = the radiel velocity of the ground water (Darcy-velocity) determined by

$$u_D = K \cdot \frac{dh}{dr}$$

K = the hydraulic conductivity of the aquifer (m/s)

dh/dr = the hydraulic gradient in radiel direction from the well.

The propagation velocity of the thermal front compared with the natural groundwater velocity gives an indication of the physical properties of the aquifer.

The propagation of the thermal front is not only affected by the convective heat transport, but also by heat propagation by conduction, diffusion and dispersion. Normally the front will not stay vertical, but it will tilt due to the difference in density between the injected, hot water and the cold pore water in the aquifer. This is described in chapter 4.5.

Double-well systems

The above described calculation of thermal influence radius is only useful for a double-well store if the distance between the injection well and the pumping well is large, i.e. the thermally affected area is limited to a distance corresponding to 0.3 times of the time required for thermal break through of the well pair. The time of thermal break-through is determined as:

$$t_{bt} = \frac{\Pi}{3} \cdot \frac{(\varrho \cdot c)_a}{(\varrho \cdot c)_w} \cdot \frac{H_a}{\bar{V}} \cdot D^2$$

where D is the distance between the wells.

The conditions of this formula are the same as of the influence radius model for single wells.

The minimum demand on the distance, D, is that the thermal break-through time is shorter than the injection period or the delivery period.

The effects of diffusion, dispersion and tilting are not reflected in the above expression.

It is possible to establish a relation between the injection time and the storage time and the time of break-through. From this relationships the minimum distance between the wells, D, can be determined. In ref. 1 it is suggested as a rule that the time of break-through is set to 3 times the period of injection.

## 4.3 Simplified flow model for a five-well system

A simplified flow model, describing flow in a horizontal plan, has been developed for the investigation of the propagation of the isotherms in a five-well plant such as the plant in Hørsholm. The model is based on the analytically described potential field for the five-well system. Hereby, it has been possible to estimate the propagation of the thermal front, that separates the cold and the heated zone in the store. Heat convection is ignored in the model, i.e. hot and cold water is considered to be two non-miscible fluids.

In a high-temperature energy store such as the Hørsholm store it is important that the surface area of the heated zone is as small as possible in order to keep the heat losses small. Therefore, it is of great importance to be able to estimate the extension of the thermal front. The calculated isotherms show a nice nearly cylindrical pattern (figure 4.6). This observation is useful in the development of larger and more detailed mathematical models, as symmetry around the central well reduces the complexity of mathematical simulation models significantly.

Figure 4.6 is an example of the preliminary studies of the Hørsholm ATES based on the following data:

$\dot{V} = 25\ m^3/h = 6.94 \cdot 10^{-3}\ m^3/s$
$H_a = 15\ m$

Heat capacity data are:

groundwater : $(\rho \cdot c)_w = 4.18\ MJ/m^3 \cdot {}^oC$
aquifer : $(\rho \cdot c)_a = 2.74\ MJ/m^3 \cdot {}^oC$
reservoir matrix: $(\rho \cdot c)_r = 2.12\ MJ/m^3 \cdot {}^oC$

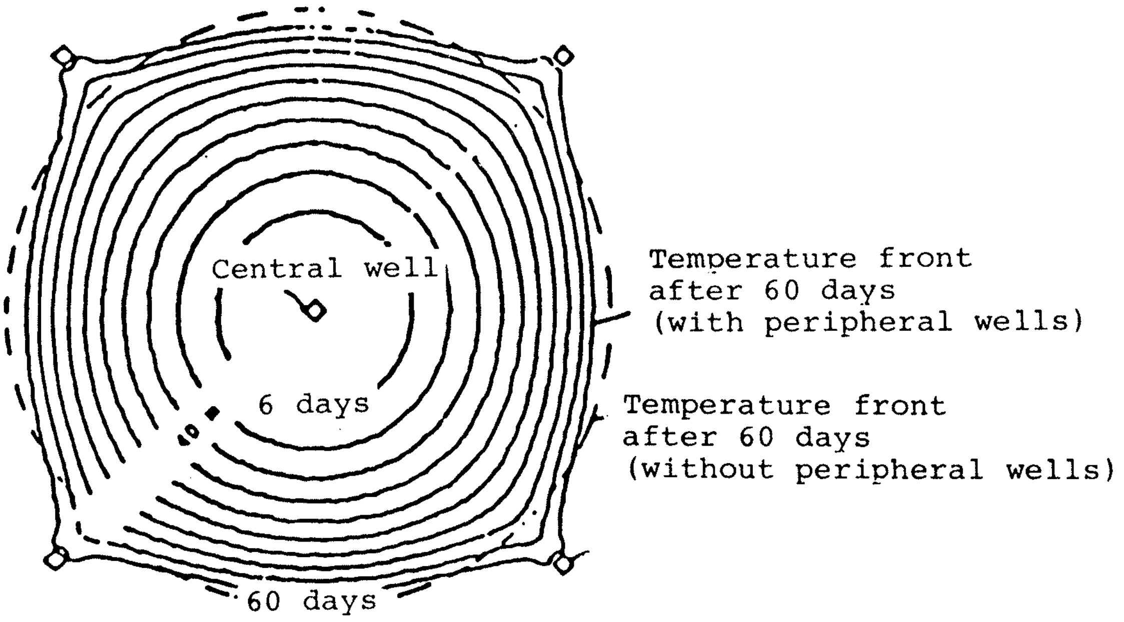


Figure 4.6 The thermal front after 6, 12, 18 ... and 60 days of injection

## 4.4 Determination of storage efficiency for single wells

Heat losses calculated from this model are based on an artesian aquifer. Injection and production of heated water takes place in the same well. The flow in the aquifer is assumed to be unaffected by differences in viscosity and density of hot and cold water.

The model is based on a numerical solution of the one-dimensional energy transportation equation, describing energy transportation in radial direction (i.e. horizontal flow) combined with an approximate method for determination of heat losses to the formation above and below the store.

The model has been used for determination of the relationships between different storage parameters and storage efficiency.

The efficiency of the store is defined as the ratio of stored energy to recovered energy, when the amounts of energy are considered relative to the natural groundwater temperature.

Figure 4.7 shows the relationship between storage efficiency and the two key numbers, the Fourier number $N_{Fo}$ and the Peclet number $N_{Pe}$. These two numbers are defined as:

$$N_{Fo} = \frac{\alpha \cdot t}{H_a^2} \quad \text{and}$$

$$N_{Pe} = \frac{(\rho \cdot c)_w \cdot \frac{V}{H_a}}{\lambda_a}$$

where

$$\alpha = \frac{\lambda}{(\rho \cdot c)_a}$$

In the expression above $\lambda$ and $\lambda_a$ is the heat conduction in the covering layer and in the aquifer respectively. $H_a$ is the height of the store, assumed constant. t is the injection time and production time, assumed to have same length in the calculations.

$\bar{V}$ is the injection rate and production rate, assumed equal. The production is assumed to start immediately after the end of injection. $(\rho \cdot c)$ is the product of density and heat capacity for groundwater (indices w) and aquifer (indices a).

The model has been used for a general study of the parameters upon which the storage efficiency depends. Due to the approximations and assumptions introduced the results of such a parametric study can only be considered as qualitative guides, but are useful for a first estimate of the most important parameters. In this way, the model has been used for the first selection of aquifers suitable for thermal-energy storage. The model is described in ref. 14.

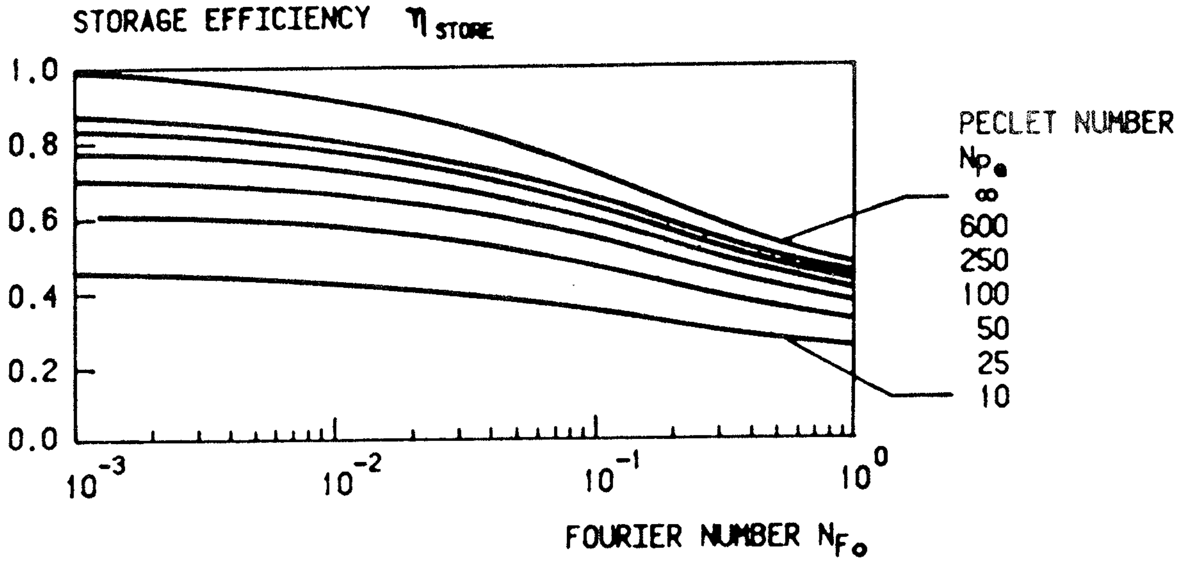


Figure 4.7 Storage efficiency for the first storage cycle as a function of Fourier number and Peclet number.

Storage efficiency in Hørsholm

Beyond the formerly mentioned parameters, the heat conduction in the covering layer and in the aquifer are needed for the calculation of the storage efficiency. The heat conduction in the covering layer is assumed to be 3 W/m °C, and the heat conduction in the aquifer is assumed to be 2-3 times larger than this. This is due to dispersion during the propagation of the heat front. Its value is set at 9 W/m °C.

$$\alpha = \frac{\lambda}{(\rho \cdot c)_a} = \frac{3}{2.74 \cdot 10^6} = 1.09 \cdot 10^{-6} \text{ m}^2/\text{s}$$

$$N_{Fo} = \frac{\alpha \cdot t}{H_a^2} = \frac{1.09 \cdot 10^{-6} \cdot (2 \cdot 30 \cdot 24 \cdot 3600)}{15^2} = 2.5 \cdot 10^{-2}$$

$$N_{Pe} = \frac{(\rho \cdot c)_w \cdot \frac{\dot{V}}{H_a}}{\lambda_a} = \frac{4.18 \cdot 10^6 \cdot \frac{7.14 \cdot 10^{-3}}{15}}{9} = 221$$

The storage efficiency is read in figure 4.7:

$\eta \simeq 72\%$.

For the operation of the plant in Hørsholm as originally planned, where the store was filled in stages, interrupted by short periods of recovery, an increase of tilting of the heat front is expected.

This must be considered when the efficiency is estimated using this simple model. By using a higher value of heat conductivity, the curves may be interpreted as describing the results including tilting of the heat front. An increase of the heat conductivity will result in a decrease of the Peclet number. The resulting storage efficiency, read of figure 4.7, decreases.

But, the final evaluation of the storage efficiency and of the system performance have to be determined by use of more detailed models.

## 4.5 Tilting problems

The difference in density between water at groundwater temperature and at injection temperature leads to an unstable equilibrium in the aquifer. This instability results in tilting of the temperature front, which separates the cold and the heated part of the aquifer. The tilting is undesirable making it more difficult to recover the heat stored. At worst the warm water will rise to the upper covering layer, so that the average temperature in the store of facing the screen is much lower than the injection temperature or simply corresponds to the original groundwater temperature. Even though the heat is present in the aquifer it may not be recoverable by the user.

The difference in density in the reservoir results in internal differences in pressure, which are able to drive the water in the store, even if no net outside pressure is imposed for production or injection. This is called free convection.
For normal water supply plants it is advantageous to use a reservoir with a high permeability, giving a high capacity for a small driving pressure difference. In heat storage there may be a danger that the differences in pressure caused by the differences in temperatures in the reservoir give rise to a strong free convection, when the permeability is high. Therefore, the most interesting reservoirs from a water-supply view point often have to be rejected, and the attention is centered on reservoirs with lower low-permeability.

In order to evaluate the importance of free convection, the dimensionless key number $N_L$, called the Lapwood-number is calculated. This is defined as:

$$N_L = \frac{\Delta\rho \cdot g \cdot H_a \cdot k}{\alpha \cdot \tilde{\mu}}$$

$\Delta\rho$ = difference in density of water at original groundwater temperature and at injection temperature

$g$ = acceleration due to gravity

$H_a$ = height of reservoir

$k$ = permeability

$\tilde{\mu}$ = average value of the viscosities at the two temperatures mentioned

$\alpha$ = is defined in section 4.4.

During stagnation (the dwell periods) when there is no imposed flow field, a condition of no free convection is that $N_L < 4\,\Pi^2$ (ref. 15).

The problem with free convection is reduced during the injection or production phases. This means, that a situation with a Lapwood number higher than $4\,\Pi^2$ does not neccesarily cause tilting problems during these operating situations, even if free convection takes place during stagnation (dwell periods). A detailed investigation of the propagation and tilting of the heat front can be carried out by means of a numerical model such as the one mentioned in chapter 4.6.

Another problem caused by high-permeable reservoirs might be, that injection of hot water is only possible through parts of the screen as differences in densities result in "negative" injection pressure at the bottom of the screen. The following relation must be satisfied in order to ensure outflow over the entire height of the screen (ref. 14).

$$N_L < \frac{\ln\left(\frac{r_{rew}}{r_{cw}}\right)}{\Pi} \cdot \tilde{\mu} \cdot N_{Pe}$$

$N_{Pe}$ = Peclet number is defined in section 4.4.

$r_{cw}$ = radius of the central well

$r_{rew}$ = outer extent of the store. For the above-mentioned five-well system $r_{rew}$ is equal to the distance to the 4 peripheral wells.

$\tilde{\mu}$ = relative viscosity, defined as the ratio between the actual value for the injected water and the average value of the viscosity at the two temperature levels, T0 at start and T1 at injection.

This can be written as:

$$\mu = \frac{\mu_{T1}}{1/2 \cdot (\mu_{T0} + \mu_{T1})}$$

With knowledge of reservoir - and temperature conditions it is possible to determine the critical flow rate at which an acceptable charging process is achieved.

## 4.6 Two-dimensional aquifer model

For the use of a more detailed analysis of the operation of the store and an analysis of testing data, an actual storage simulation model has been developed. The model D2AQ is based on a numerical solution (based on the Finite Element method in space and the Finite Difference Method in time) of the equations, describing flow and energy equilibrium in the porous structure.

The model is constructed as a two-dimensional model, able to calculate flow fields (expressed by the pressure) and the temperature propagation in a cut, either vertically or horizontally in the store. In the vertical case it is possible to get a three-dimensional description by assuming symmetry around an injection/production well. This is an obvious assumption for a single-well system and applies approximately for a five-well system as illustrated in figure 4.6.

It is of great importance to be able to evaluate the influence of the buoyancy of the heated water on the propagation of the thermal front. The model pays respect to the influence of temperature on density and viscosity of water. This model may be used for studies of the suitability of a given reservoir to function in a specified operational situation. Problems with strong buoyancy effects can sometimes be solved by modifying the screen intervals in the wells. For the plant in Hørsholm investigations proved the advantage of establishing a variable screen section in the central well. Here it is possible to close a part of the screen. Simultaneously it was demonstrated (by use of the mathematical models) that the peripheral wells should only be screened in the lower third of the reservoir.

The results from this simulation model are presented in terms of pressures and temperatures in chosen points. The possibility of evaluation of pressures and temperatures at arbitrary points in the reservoir by interpolation exists. In this way, it is possible to plot flow fields (velocities) and isotherms for use in a visual evaluation of the operational situation. Furthermore, the model can indicate the pumping temperature by production from the reservoir, and in this way it is possible to keep an account of the amounts of energy stored and recovered. These amounts are used directly into the assessment of the storage efficiency, which can be calculated from a detailed simulation with relevant hydrogeological and thermodynamic parameters including specified operational parameters, including variations in flow rates and injection temperatures.

In general, it must be said that simulation models such as the one mentioned here, make it possible to describe the hydrogeological and thermodynamic conditions in much greater detail than normal. The interpretation of the results of simulations of real tests has revealed, that the thermal propagation differed from the picture a more simple description of the parameters would give.

It has to be kept in mind that the determination of storage efficiency mentioned in chapter 4.1 is only valid for a single-well configuration. For instance, a double-well system will exhibit a greater loss of heat, since the extension of the thermally affected area around the injection well is not circular.

## Simulation of Hørsholm ATES using a two-dimensional aquifer model

In this section the results from runs with the simulation model D2AQ are represented by plots of the propagation of isotherms.

In figure 4.8 a typical example of tilting is shown, illustrated by isotherms in a reservoir with injection of hot water in the left side and production of cold water in the right side of the reservoir. The values of the isotherms correspond to 91°C, 73°C, 55°C, 37°C and 19°C from left to right.

The plot to the right clearly shows the superposed flow caused by buoyancy just in the thermal front, where hot water is displacing cold water in the reservoir.

By simulation it is possible to study what happens if a part of the screen in the peripheral wells is closed. This will immediately correct tilting temperature front.

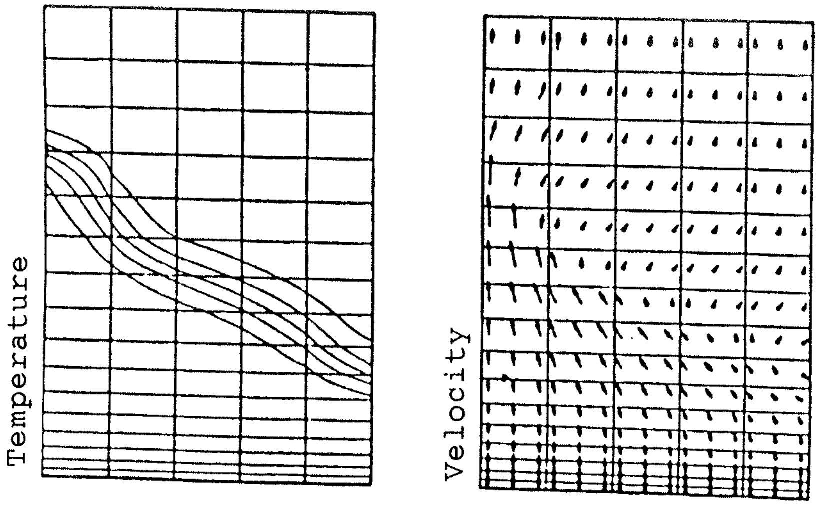


Figure 4.8 Isothermal plot and plot of velocity with tilting of thermal front.

In figure 4.9, showing isothermal plots, the difference in the propagation of the thermal front of a fully screened peripheral well and a partly screened peripheral well are shown. In the store in Hørsholm the peripheral wells are only screened in 5 metres at the bottom of the aquifer. Simulations like the ones shown clearly demonstrated that the break-through was delayed significantly causing a better loading of the storage volume.

## 4.7 System efficiency

The storage efficiency defined in section 4.4 expresses the heat losses of a single-well configuration, relative to the energy content of the store above the natural ground water temperature, and without regard to the temperature fall due to the heat exchange between the district heating water and the ground water.

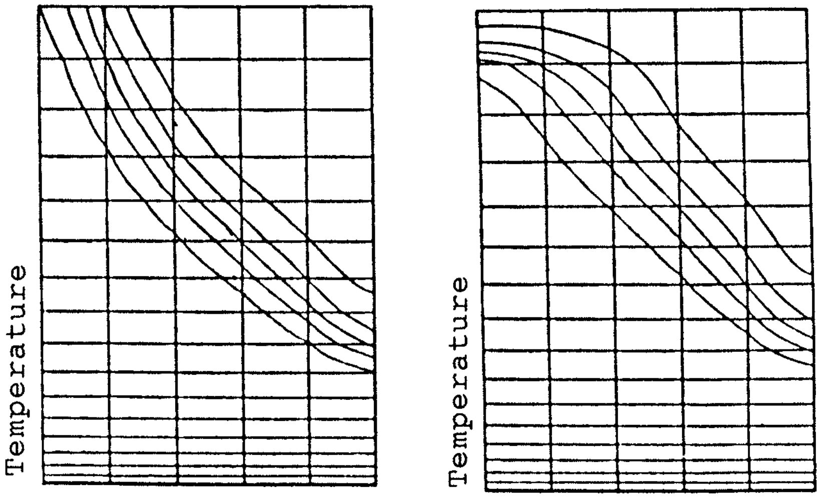


Figure 4.9 Isothermal plots for fully-screened (at left) and partly screened (at right) peripheral wells.

This storage efficiency does not permit a direct evaluation of the amount of heat recoverable in a district heating system. The reasons for this are:

- The storage efficiency is an expression of the relationship between recovered and injected amount of heat, both amounts relative to the natural ground water temperature. But it is not possible to recover heat at a temperature lower than the return temperature of the district heating system. The district heating temperature is, therefore, more suitable as a reference level for recovered and injected energy (in systems containing a heat pump, the heat may be recovered at temperatures lower than the return temperature).

- During injection and recovery the temperature is reduced by some degrees. They are "lost" due to heat exchange between the district heating water and the ground water. The heat is, therefore, injected at a temperature of for example 3°C below the forward temperature and recovered at a temperature of for example 3°C above the return temperature.

In ref. 3 a system efficiency is defined, which considers the above-mentioned circumstances and, therefore, more truly expresses the real recovery of stored heat of the system.

In ref. 3 methods for determination of the storage efficiency separately and of the system efficiency of the store in connection with the energy system are described.

In figure 4.10 the relationships between system efficiency and storage efficiency are shown. The figure illustrates the dependence of the efficiency on the temperature parameters $\sigma$ and in the district heating system. The parameter $\sigma$ is defined as the ratio between the decrease in temperature across the heat exchanger and the difference in temperature in the district heating delivery pipe and in the groundwater. The parameter $\epsilon$ is defined as the ratio between the differences of the return water and the groundwater temperatures and of the delivery water and groundwater temperatures.

$$\sigma = \frac{\Delta T_{vv}}{T_f - T_g}$$

$$\epsilon = \frac{T_r - T_g}{T_f - T_g}$$

where

$\Delta T_{vv}$ = difference in temperature across heat exchanger
$T_r$ = return temperature
$T_f$ = forward temperature
$T_g$ = groundwater temperature

The curves are not valid during the first storage cycle, due to the circumstances that have been outlined in section 4.

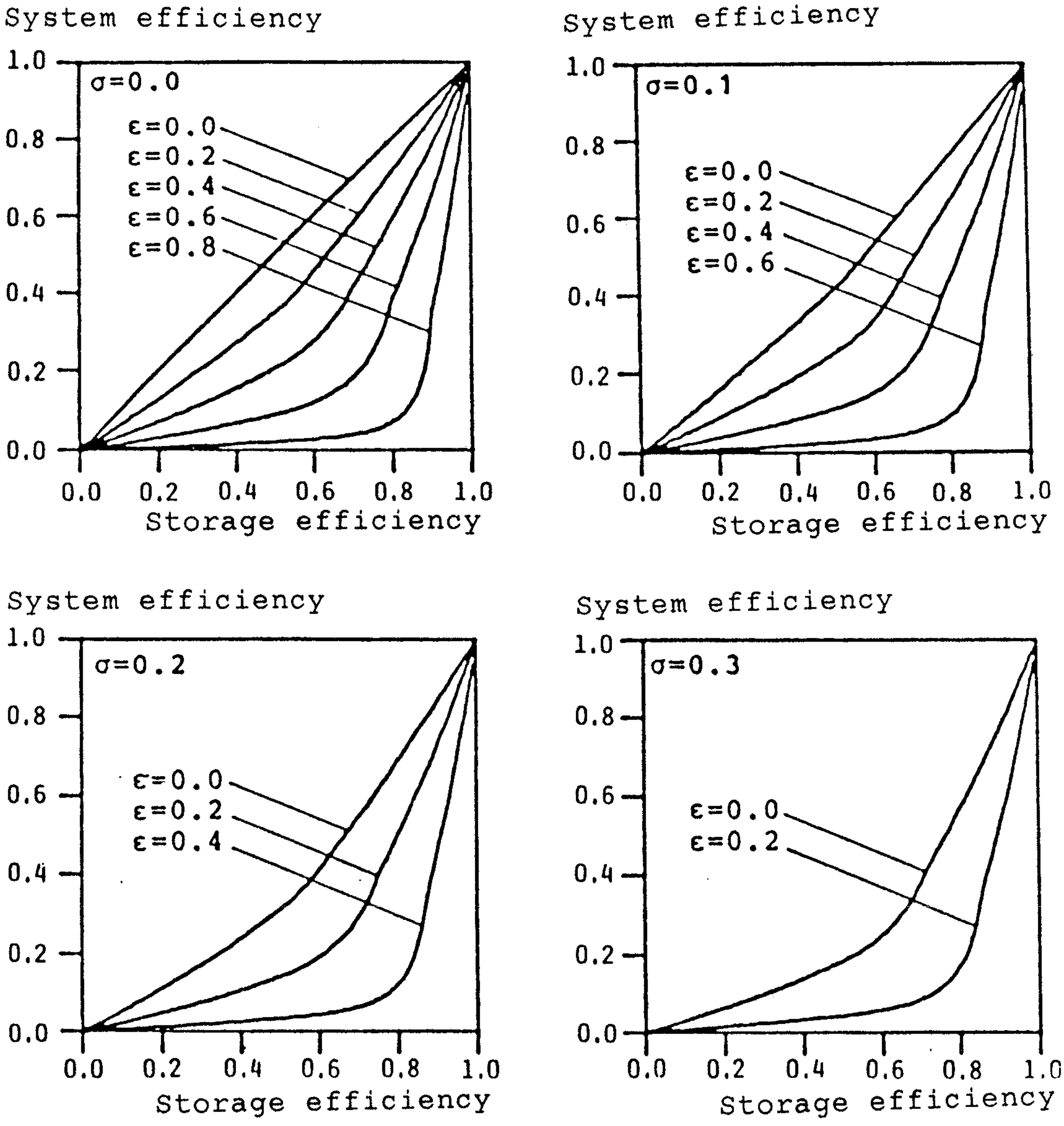


Figure 4.10 Connection between system efficiency and storage efficiency as a function of the temperature parameters σ for district heating heat exchanger and ε for the return temperature of the district heating system (from ref. 3).

A typical Danish district heating system has a forward temperature at 80°C and a return temperature at 56°C. The ground water temperature is 8°C.

This gives:

$$\epsilon = \frac{56 - 8}{80 - 8} = 0.667$$

The heat exchanger is a large exchanger with a temperature difference of 3°C.

$$\sigma = \frac{3}{80 - 8} = 0.042$$

The heat is assumed to be stored in a relatively good heat store with a storage efficiency at 0.84. The system efficiency is (extrapolation in figure 4.10 or by use of formula in ref. 3):

$$n_{sys} = 0.12$$

This surprisingly low system efficiency for a typical Danish district heating system connected to a groundwater heat store expresses the two conditions mentioned above that contribute to a reduction of the heat recovered. It will often be necessary to start development work - dedicated at improving the system efficiency in order to get a good economy in a high-temperature thermal-energy store. This work may be directed towards:

- decreasing the district heating return temperature

- increasing the storage temperature - the storage efficiency will be lower, but the overall effect on the system efficiency will be positive.

The conclusion is that there is a great difference between storage efficiency and system efficiency (the potential for the system to recover the heat stored). Therefore, it is necessary to make detailed system analyses before a decision is made to connect a seasonal thermal-energy store to a district heating network and it may be necessary to make modifications of the district heating system.

The above-mentioned considerations are limited to high temperature stores without heat pump. By connection of a heat pump to the system, the amount of heat recovered may be increased significantly. However, the relationships that have been presented here are not directly applicable for such a situation.

# 5. PAPER PRESENTED AT ENERSTOCK 85

## RECENT PROGRESS ON THE DANISH AQUIFER ENERGY STORAGE PROJECT

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### ABSTRACT

A demonstration storage plant was completed in Hørsholm north of Copenhagen during the summer 1982. The heat store is connected to an incineration plant, which charges the store with surplus heat in the summer, and receives heat from the store for distribution to its associated district heating system in the autumn. The plant is based on the existence of a meltwater aquifer, confined vertically by impervious layers of clay. The storage volume is located between these layers.

The hot water on the delivery side of the heating system is recharged into or discharged from one central well, while the cooler water from the return side is being pumped simultaneously from 4 peripheral wells, or alternatively injected in the same.

Three minor charging cycles have been carried out (1982, 1983 and 1984). During the second cycle, a leak in the confining layer was discovered. The possible explanation and the partially successful repairs that have been carried out are described.

The existence of the leak did not prevent the store from being operated in the reverse mode the summer 1984. Consequently, about 2050 MWh energy has been introduced into the peripheral wells during the summer. The operation is resumed during this spring (1985), but with injection in a new central well.

The experience and observations, during the charging and ensuing dwell periods are reported.

### 1. INTRODUCTION

The Danish aquifer thermal-energy storage project started in 1977 as a part of the research program of the Ministry of Energy. The project is a collaboration between the Laboratory for Energetics (Technical University of Denmark), the Geological Survey of Denmark and Risø National Laboratory. The object is to investigate the feasibility and economics of aquifer storage, theoretically and experimentally. The activities have been centered around the design, construction, and operation of a demonstration plant at Hørsholm.

The present paper gives a short description of the concept and the concrete design with the pertinent statistics, accompanied by the experiences gained during the design, construction and operating phases. The organisation of these sections follows closely the paper presented at the conference "Subsurface Heat Storage" (1) in Stockholm in 1983. The central topic of the present paper is the report of operational experience, technical problems and their solutions and finally the thermodynamic data acquired. Readers that are interested in more complete descriptions of the design, construction, mathematical models, systems studies etc. are referred to an earlier review article (2).

### 2. CONCEPT, DESIGN AND DIMENSIONS OF THE STORAGE PLANT

#### Lay out and main dimensions

The drawing, Figure 1, shows the concept. One well is located at the center of the store, surrounded by four wells at the periphery of the store, 40 meters from the center.

During charge, cold ground water is pumped from the peripheral wells and heated in heat exchangers situated in the machinery house shown on the ground plan in Figure 2. The heated water is returned to the aquifer through the central well. The wells are connected to the heat exchangers by buried preinsulated pipes. The reinjected water will form an expanding warm volume with a nearly vertical temperature front, that will propagate until it reaches the peripheral wells. At this point the store is fully charged.

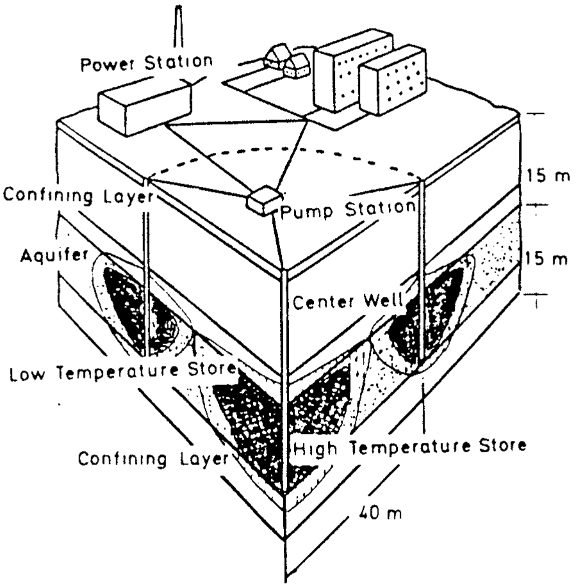

Figure 1: Configurations of the Danish aquifer store

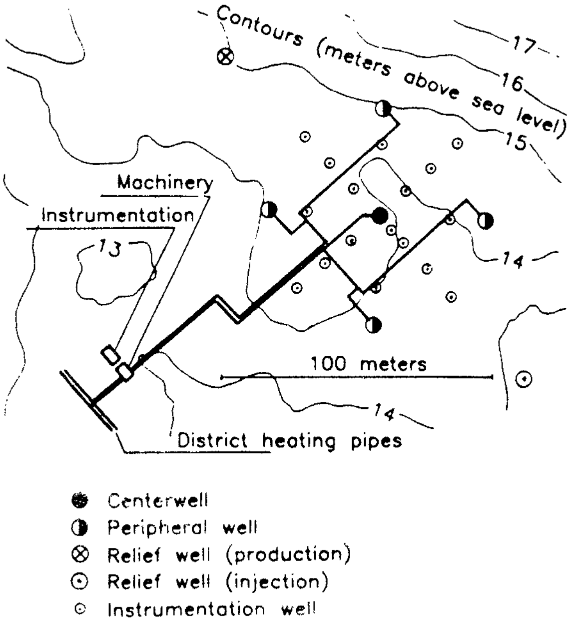

Figure 2: Ground plan of the storage plant

During heat recovery, the flow direction is reversed, and the cooled water is injected through the peripheral wells.

17 instrumentation wells are drilled into the storage aquifer for monitoring of temperature and heat. Two relief wells which have the function of stopping the natural ground water flow through the storage reservoir, are also indicated at the plan. Until present, the natural hydraulic potential gradient of 3 $^{o}/oo$ has not required the use of this relief system.

The volume of the storage reservoir is about 75000 $m^3$. With a storage temperature of 100°C and a return temperature from the district heating system of 65 - 70°C, the stored amount of energy is about 1500 Gcal.

The central well is a 14 inch. well completed with a 10 inch. screen and 10 inch. casing, that has been cemented. The well is fully penetrating, except for a length of 1 m dividing the screen into two sections. Between these two sections, a hydraulically controlled valve, is inserted, which makes it possible to close the lower part of the screen.

The dimensions of the peripheral wells are 10 inch. and they are completed with 6 inch. screens and cemented casing to the surface. The screens are placed in the lower third of the aquifer.

The well screens are made from acid-proof stainless steel, which makes it possible to give the wells chemical treatment. It has been necessary to give the central well acid treatment 3 times, once during the first cycle and twice during the second.

The pump wells are all equipped with variable flow deep-well pumps, dimensioned for a total flow through the system of 80 $m^3/h$.

Plate heat exchangers with a logarithme mean temperature of 3°C are used because of the large heat transmission area of this type. Another reason for this choice is the potential scaling problem. Plate heat exchangers may easily be washed by acid. This has only been done twice and was not strictly necessary. Some minor leaks have occured in the gaskets of the heat exchangers, but these have not presented serious problems.

During the heating of the ground water

(hardness as calciumcarbonate of approx. 290 pp m, which is relatively high) precipitation of the calciumcarbonate could occur. This is prevented by the addition of a small amount of hydrochloric acid before heating. During the chemical process which follows, chloride ions replace the bicarbonate ions, which are dissolved and removed in the form of $CO_2$-gas in a degasser. This method has the additional advantage, that it preserves the ion strength during heating. The amount of hydrochloric acid added, will only result in a small increase in the natural concentration of chloride ions in the aquifer. After some run-in problems connected with measurement accuracy and control, this water treatment has functioned satisfactory and is now operating automatically.

After the heat exchangers, the ground water passes a cyclone filter, which removes suspended material before the water is reinjected. In this way clogging of the wells has been successfully avoided.

## Instrumentation

The instrumentation consists of temperature and level monitoring equipments in the aquifer. At the pump wells, temperature, water level and flow are measured. In the heat exchange parts of the system, flow, temperature and pressure are measured. On the groundwater side the pH also is measured.

The temperatures in the aquifer are measured by integrated circuits. The temperature sensors are mounted dry inside copper tubes in the 17 instrumentation wells and are separated vertically by a distance of approx. 2 m. Around each temperature sensor there is a foam spacer in order to prevent convection around the temperature sensor. The heat is transferred from the aquifer to the temperature sensors mainly by radiation. If one of the temperature sensors fails, it is possible to replace it. After 3 years, 79 out of the 115 temperature-sensors originally mounted are still functioning.

The water levels in the pumping wells are measured by pressure transducers. These have frequently given problems and after the charging period of 1984, four out of five were defect and had to be replaced. It is not yet clear whether the problems are caused by poor craftsmanship, design errors, poor choice of material or whether they simply will not be able to function with the high temperatures prevailing in the aquifer store or with the vibrations present in the pumping wells.

## Data acquisition and control system

This system has functioned satisfactorily and most of the heat acquired during 1984 has been stored during unmanned operation.

## Geological integrity

During the second small charging process a leak appeared. An analysis of the circumstances gave the conclusion that the confining layer, possibly because of a special geological configuration had been overloaded and had broken. The break acted like a one-way valve, opening up during injection and closing during production. The leak appeared on the ground surface at a distance of approx. 20 meters from the central well, but it was concluded that the leak passage originated at, or very close to, the central well. Consequently concrete was injected in the upper part of the aquifer through the central well. This repair appeared to be successful and the water injection was continued until the end of the season 1983, which due to the delay caused by the repairs, was a very short period.

In the spring of 1984, the injection was resumed. A short period thereafter the leak reappeared. In order to utilize the waste heat during the summer, the store was operated in reverse, and a significant amount of energy was injected through the four peripheral wells. The winter 1984/1985 was then used to prepare for and carry out the design and construction of a second central well located six meters away from the first one. The dimension of this well is 28 inch. and it is completed with a 20 inch. screen. The length of the screen is 9 meters and it is placed in the lower two thirds of the aquifer. The casing is 20 inch. and surrounded by alternating sections of expanding bentonite and cement to the surface.

During the establishment of this well special care has been taken to avoid caving below the covering layer by using the so-called reverse circulation rotary method. Also the screen has been lowered a significant distance below the covering layer. This well will be used for injection only, while the old central well will be used for production. 4 observation tubes with screens are installed in the interval between the top of the 20 inch. screen and the confining layer.

The construction of the second central well appears to have been completed successfully. The warm water injected in the four peripheral wells during the summer of 1984 has now been pumped into this central well, and the injection of the waste heat from the garbage incineration of the summer 1985 has started during the month of May.

## 3. THE FIRST STORAGE CYCLE (1982)

The conditions during injection were as follows:

Injection temperature (average): 36°C
Injection pressure: <1 bar above hydrostatic pressure
Injection flow: 20-30 $m^3$/h
Accum. injection time: 150 hours (12 days)

The permeability is highest in the lower part of the aquifer, and the valve in the central well was closed during injection, in order to restrict the flow to this section. When the injection was complete, there was a dwell period of three weeks, and then a discontinuous heat withdrawal was started. In the beginning of this phase, the recovery temperature was 34°C, which is 2°C below the injection temperature.

The withdrawal was stopped when the reservoir temperatures in the observation well 7 meters from the central well had decreased to approximately the original values. The withdrawal temperature was, at that point in time, 17°C and the total recovered heat energy was about 55% of the recharged energy.

## 4. THE SECOND STORAGE CYCLE (1983)

The conditions during the injection temperatures were as follows:

1st period, 12 hrs: 30°C
2nd period, 12 hrs: 60°C
3rd period, 240 hrs. accum.: 100°C
Inj. pressure: < 0.9 bar above normal ground water level
Injection flow: 20-45 $m^3$/h
Injected heat: 2340 GJ

The leak appeared after a few hours of operation. The leak was then repaired during the summer, and the injection resumed late summer. There was therefore only waste heat enough to fill up about 10% of the store.

After a dwell period of three weeks, the heat recovery was started. In the beginning the recovery temperature was 80°C. The recovery stopped after ten days. At that time the recovery temperature was 70°C (the forward temperature of the district heating system had an average value of 65°C). The total amount of energy recovered from the store was 8 MWh.

## 5. THE THIRD STORAGE CYCLE (1984)

The conditions during injection were as follows:

Injection temperature: 100°C
Inj. pressure: < 0.9 bar above normal ground water level
Injection flow: 25-45 $m^3$/h
Injected heat: 7390 GJ

Due to the reappearance of the leak during spring the store was operated in reverse mode, so that warm water was injected in the four peripheral wells. The warm water has been stored around the peripheral wells during the winter.

## 6. RESULTS

The volume of the 1982 injection was quite limited and only a modest amount of data was recorded. Some of these have been reported elsewhere (1, 2).

The 1983 injection was carried out at normal operating temperatures, and the total amount of energy was increased significantly above the 1982 level. However, the total injected volume was not much larger. The most remarkable result of the 1983 cycle was the return of 8 MWh of the energy stored to the district heating system.

The warm water of the 1984 cycle was injected in the peripheral wells. This means that the warm water is moving inward towards the central well, where a number of temperature transducers are located, and outward from the peripheral wells where there are none.

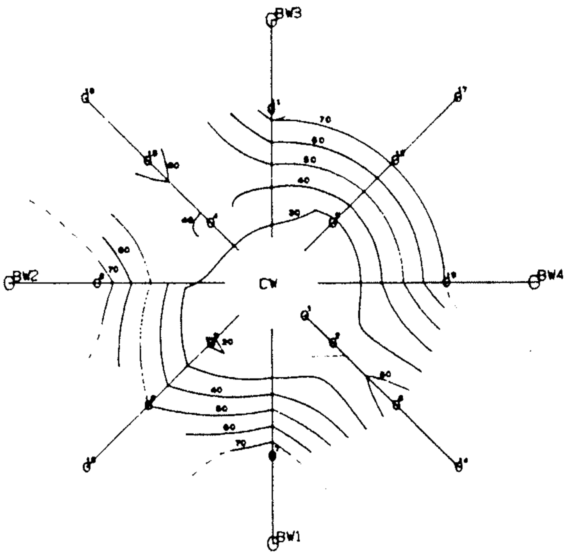

Figure 3:
Depth: 7,5 m below top of the aquifer
Date: 84.09.26
Isotherms: 70, 60, 50, 40, 30, 20
Solid lines represent interpolation between measurements.
Broken lines represent conjecture.

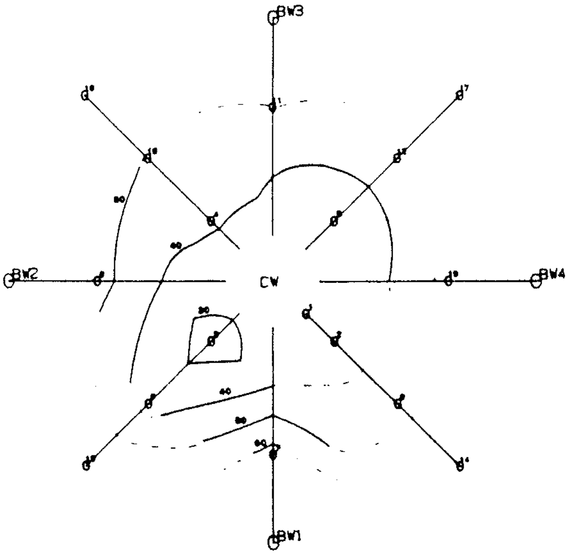

Figure 4:
Depth: 7,5 m below top of the aquifer
Date: 84.12.18
Isotherms: 60, 50, 40, 30
Solid lines represent interpolation between measurements.
Broken lines represent conjecture.

Typical isotherms are shown in Figure 3 which was recorded immediately after the end of the injection and Figure 4, which was recorded after about 3 months storage. A significant amount of dissipation is observed.

## 7. SUMMARY AND CONCLUSIONS

The purpose of establishing a demonstration plant was to identify potential problems, find solutions to these and to gain operational experience.

The demonstration plant has met these objectives, and although the operational experience has been quite limited, no problems have been identified so far, that should prohibit the use of aquifer thermal energy stores in Denmark.

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2. Qvale, B., Hagelskjær, J., Andersen, L.J., Leth, J.A., and Boldt, J.; 1984; "Aquifer Thermal Energy Storage. Technology, Systems. Economics"; Refrigerating and Air-Conditioning Engineers; Paper KC-84-03.

# 6. PAPER PRESENTED AT JIGASTOCK 88

## The Danish Aquifer Energy Storage Project
## - Operational Experience.

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Technical University of Denmark

**Lotte Schleisner Ibsen** Risø National Laboratory, Denmark

**Lars Jørgen Andersen** Geological Survey of Denmark

ABSTRACT

As a part of the Danish Aquifer Thermal Energy Storage Project a demonstration storage plant has been established at Hørsholm north of Copenhagen in 1982.

The store is connected to an incineration plant with its associated district heating network.

In the subsequent years altogether six charging processes have been carried out. Due to various difficulties in some years, the discharge (recovery) part of the storage cycle had to be omitted.

During the summer and fall of 1987, for the first time a full storage cycle has been completed, during which 5365 GJ have been injected. 522 GJ have been returned to the high-temperature district heating system. The results are described together with the experiences gained from this complete cycle and from several previous, partial cycles.

## 1. INTRODUCTION

The Danish aquifer thermal-energy storage project started in 1977 as a part of the research program of the Ministry of Energy. The project is a collaboration between the Laboratory of Energetics (Technical University of Denmark), the Geological Survey of Denmark and Risø National Laboratory. The objective is to investigate the feasibility and economics of aquifer storage, theoretically and experimentally. The activities have been centered around the design, construction, and operation of a demonstration plant at Hørsholm.

The present paper gives a short description of the concept and the concrete design with the pertinent statistics, accompanied by the experiences gained during the design, construction and operating phases. The organisation of these sections follows closely the paper presented at the conference ENERSTOCK 85 in Toronto in 1985 (3). The central topics of the present papers are the operational experience, technical problems and their solutions and the thermodynamic data acquired. Readers that are interested in more complete descriptions of the design, construction, mathematical models, systems studies etc. are referred to an earlier rewiew article (2).

## 2. CONCEPT, DESIGN AND DIMENSIONS OF THE STORAGE PLANT

### Lay out and main dimensions

The drawing, Figure 1, shows the concept. One well is located at the center of the store, surrounded by four wells at the periphery of the store, 40 meters from the center. During charge, cold ground water is pumped from the peripheral wells and heated in heat exchangers situated in the machinery house shown on the ground plan in Figure 2. The heated water is returned to the aquifer through the

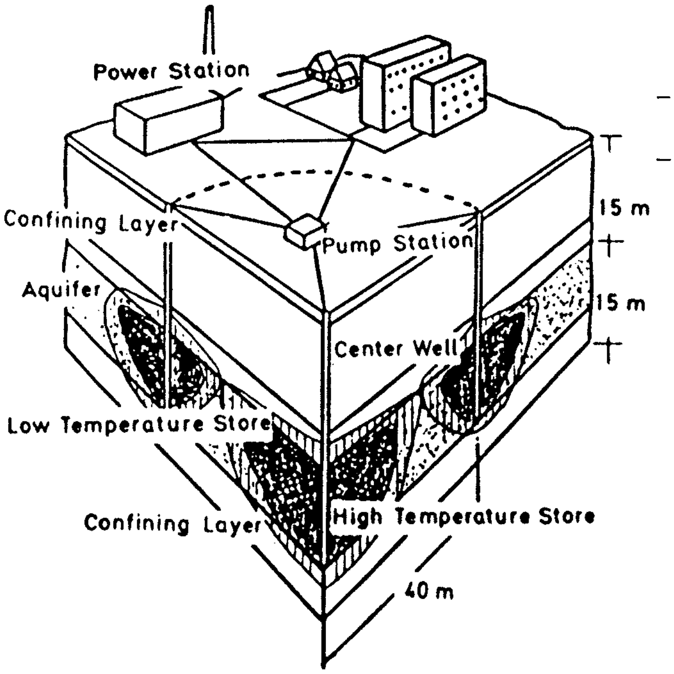

**Figure 1:** Configurations of the Danish aquifer store

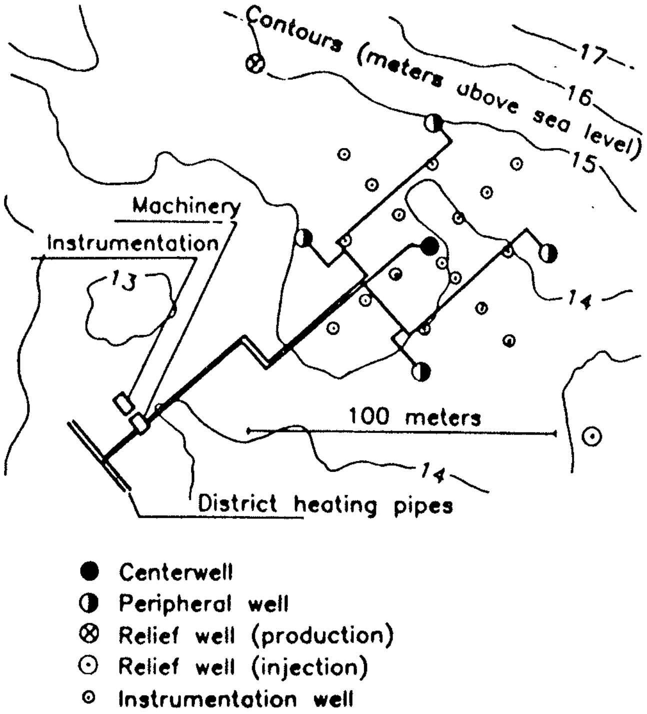

**Figure 2:** Ground plan of the storage plant

central well. The wells are connected to the heat exchangers by buried preinsulated pipes. The reinjected water will form an expanding warm volume with a nearly vertical temperature front, that will propagate until it reaches the peripheral wells. At this point the store is fully charged.

During heat recovery, the flow direction is reversed, and the cooled water is injected through the peripheral wells. The volume of the storage reservoir is about 75000 $m^3$. With a storage temperature of 100°C and a return temperature from the district heating system of 65 - 75°C, the stored amount of energy is about 6400 GJ.

Precipitation of the calciumcarbonate is prevented by the addition of a small amount of hydrochloric acid before heating. During the chemical process which follows, chloride ions replace the bicarbonate ions, which are dissolved and removed in the form of $CO_2$-gas in a degasser. This method has the additional advantage, that it preserves the ion strength during heating. The amount of hydrochloric acid added, will only result in a small increase in the natural concentration of chloride ions in the aquifer. This water treatment is now operating satisfactorily.

After the heat exchangers, the ground water passes a filter, which removes suspended material before the water is reinjected thus preventing clogging during charging. However, it has not been possible to prevent the precipitation of iron during the discharge process.

## Instrumentation

The instrumentation consists of temperature and level monitoring equipment in the aquifer. At the pump wells, temperature, water level, and flow are measured. In the heat exchange parts of the system, flow, temperature, and pressure are measured. On the groundwater side the pH also is measured.

If the temperature sensors fail, it is possible to replace them. After 3 years, 79 out of the 115 temperature-sensors originally mounted were still functioning. The sensors that failed have recently been replaced and presently 100 are functional. The pressure transducers that were installed originally have failed and been replaced by a simple hydrostatic balancing system using pressurized nitrogen.

## 3. THE FIRST, SECOND AND THIRD STORAGE CYCLE (1982, 1983 AND 1984)

The specifications of the conditions under which these tests were carried out have been reported elsewhere (3) and will not be repeated here.

However, a short description of the results will be given:

The volume injected in 1982 was quite limited and only a modest amount of data was recorded. Some of this has been reported formerly (1, 2).

The 1983 injection was carried out at normal operating temperatures, and the total amount of energy was increased significantly above the 1982 level. However, the total injected volume was not much larger. The most remarkable result of the 1983 cycle was the return of 29 GJ of the energy stored to the district heating system.

The warm water of the 1984 cycle was injected in the peripheral wells due to a failure of the central well.

Subsequently a new central well was established and the following cycles were carried out with injection of hot water in the central well.

## 4. THE FOURTH CYCLE (1985)

Injection temperature 100°C
Injection pressure < 0.5 bar above normal groundwater level
Injection flow: 20-60 $m^3/h$
Injected heat 7596 GJ

The amount of heat injected was still below the value expected for normal operation. The amount of heat returned to the district heating system was quite small (43 GJ). The amount was limited due to problems in the temperature controls elsewhere in the district heating system. Calculations based on the amount of water returned and the measured temperatures, give an equivalent amount of heat returned of 310 GJ, which is acceptable.

## 5. THE FIFTH CYCLE (1986)

Injection temperature 95°C - 100°C
Injection pressure < 0.6 bar above normal groundwater level
Injection flow 12-30 $m^3/h$
Injected heat 3193 GJ

In 1986 the operation of the store was taken over by the user, the incineration plant Nordforbrænding I/S. In order to make the store better suited for commercial operation, some technical remodelling was carried out, delaying or interrupting the operation at various times. This was also the reason for not attempting to return heat to the district heating system at the end of the season. The injection of heat was also discontinued in periods due to renovation of the incineration plant itself. Finally, there was the usual number of smaller technical mishaps. But, all-in-all the operation is regarded as successful.

Typical isotherms from cycle number 5, that were recorded towards the end of the injection period, are shown in Figure 3.

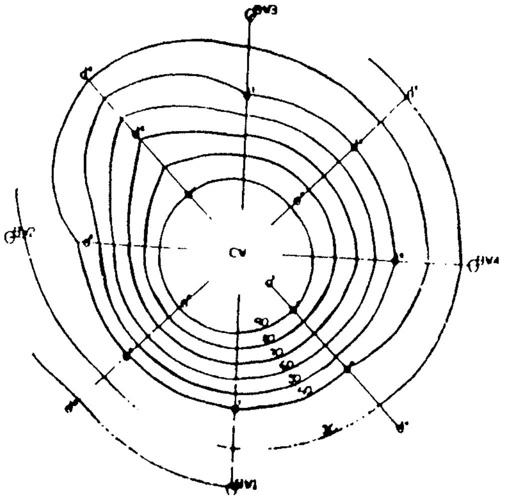

Figure 3: Isotherms from cycle number 5.

Depth: 3 m below top of the aquifer.
Date 86.10.10.
Isotherms: 90, 80, 70, 60, 50, 40, 30, 20
Solid lines represent interpolation between measurements.

## 6. THE SIXTH CYCLE (1987)

Injection temperature 82°C (night) - 94°C (day)
Injection pressure < 0.4 bar above groundwater level
Injection flow 15-40 $m^3/h$
Injected heat 5365 GJ

The injection started in late May and was terminated in late September. The store and its surroundings are now beginning to approach steady-state temperatures. Hence the heat losses are now smaller than previous years. An amount of 432 GJ of heat was returned to the district heating system before it was closed down due to scaling and clogging. Subsequently the precipitates have been analyzed and found to derive from the iron content of the groundwater. As the store was designed to be air tight this problem was not expected. Further operation will not be possible before this problem is solved.

The heat exchangers were given acid treatment in an attempt to alleviate the problem and this gave temporary improvements.

## 7. SUMMARY AND CONCLUSIONS

The purpose of establishing a demonstration plant was to identify potential problems, find solutions to these, and to gain operational experience. The project in Hørsholm was, from the beginning quite ambitious. The aim was to develop a pilot plant to function in an existing high-temperature district heating system, as well as producing research results. Therefore, the resulting design was complex with a high degree of automation and monitoring and with a large number of running temperature, flow, pressure and acidity measurements. Problems arising from these aspects of the plant, that are incidental to the actual aquifer storage process have been dominating for a number of years. It is only during the last two years that the practical difficulties concerned with the unmanned operation have been reduced to a point where the physical properties of the actual storage process have come into focus.

Important results are that:

- heat may be delivered from and returned to a high-temperature district heating system.
- the store will function well in unmanned operation.
- the treatment chosen to prevent calcium scaling can be made to work.
- the mathematical models of groundwater flow are sufficient for the study of such stores. The experimental results are in fair agreement with the theoretical predictions.
- iron precipitation has occurred in spite of intensive efforts to make the plant air tight. This problem has to be solved before the operation is continued.

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2. Qvale, B.; Hagelskjær, J.; Andersen, L.J.; Leth, J.A.; Boldt, J.; Kansas City; 1984; "Aquifer Thermal Energy Storage. Technology, Systems, Economics"; Refrigerating and Air-Conditioning Engineers; Paper KC-84-03.

3. Ibsen, L. Schleisner et al.; Toronto; 1985; "Recent progress on the Danish Aquifer Energy Storage Project". ENERSTOCK 85.

# 7. OPERATIONAL PROBLEMS

The operation of the plant has during the years been influenced by operational problems that have caused frequent close-downs of the plant. Many of the problems have been trivial and of a mechanical or electrical nature, such as for instance valves opening instead of closing, or pressure transducers giving incorrect reading of the water level in the wells.

But non-trivial problems that have been a direct consequence of the high temperatures of the storage have also occurred. These problems are discussed in the present chapter.

## 7.1 Corrosion

The water quality of groundwater will determine if the water is corrosive. The following parameters indicate corrosive waters.

- pH < 7
- dissolved oxygen > 2 mg/l
- hydrogen sulphide > 1 mg/l
- total dissolved solids > 1000 mg/l
- carbon dioxide > 50 mg/l
- chlorides > 500 mg/l

More than one corrosive parameter will intensify the corrosive attack.

There are five basic types of corrosion,

- general
- galvanic
- pitting
- intergranular
- stress corrosion

General corrosion, as its name indicates, occurs over the entire surface exposed to the groundwater.

Galvanic corrosion occurs at the junction of dissimilar metals and therefore it can be avoided by good design and choice of materials or by cathodic protection.

Pitting is a localised corrosion.

Intergranular corrosion occurs at grain boundaries i.e. at surface fissures or cracks.

Stress corrosion cracking can occur if a metal is under tensile stress. Stressed parts are more likely to corrode than unstressed parts.

High temperatures and high velocities increase corrosion rates.

In an ATES plant, corrosion can be expected as general (thinning) corrosion over all the installations including the well screens, heat exchangers and pipes. Pitting will occur in the parts of the plant with high velocities or exposed points such as at the injection well.

Aeration of the groundwater as well as water treatments involving acidification or addition of carbon dioxide will aggravate corrosion. The presence of small particles in the water will cause erosion of the installations and encourage corrosion processes. It will be expected that the heat exchangers will be especially sensitive to corrosion.

## Corrosion experiences

The operation of the storage cycles 1984 and especially 1985 was dominated by corrosion problems. In 1985, 5 out of 9 major close-downs were caused by corrosion either in pipes in the machinery house or in pumping motors.

The pipes which corroded were pipes placed immediately after injection of hydrochloric acid. Also pipes placed immediately after the heat exchangers corroded. The corrosion mostly appeared in the welds. The material of the piping in the machinery house is steel ST37.

The wall thickness of the pipes at different locations in the machinery house and in the pumping wells was measured. The measurements are listed below. The bracketed values are the original wall thickness. The points measured are marked at figure 7.1.

BW 1: Wall thickness in average 3.68 mm (3.65 mm) (measuring error)
BW 2: Wall thickness in average 3.47 mm (3.65 mm)
BW 3: Wall thickness in average 3.45 mm (3.65 mm)
BW 4: Wall thickness in average 3.39 mm (3.65 mm)
CW 1: Wall thickness in average 4.29 mm (4.85 mm)

In 1988, when the plant was closed down, the wall thickness of the pipe buried in the ground leading to CW 1 was 4.0 mm. This was the original thickness of the pipe at that location.

| Location machinery house Point No. | Measured average wall thickness |
|---|---|
| 1 | 3.03 mm (4.50 mm) |
| 2 | 3.02 mm (4.50 mm) |
| 3 | 3.39 mm (4.50 mm) |
| 4 | 3.44 mm (4.50 mm) |
| 5 | 4.08 mm (4.50 mm) |
| 6 | 1.94 mm (4.50 mm) |
| 7 | 3.36 mm (4.85 mm) |
| 8 | 4.00 mm (4.85 mm) |
| 9 | 3.18 mm (4.50 mm) |
| 10 | 2.20 mm (4.50 mm) |
| 11 | 2.51 mm (4.50 mm) |
| 12 | 3.14 mm (4.50 mm) |
| 13 | 3.33 mm (4.50 mm) |
| 14 | 4.36 mm (4.85 mm) |
| 15 | 2.67 mm (4.50 mm) |
| 16 | 2.90 mm (4.50 mm) |

In 1985, the Danish Welding Institute (DWI) was contacted. Two pipes placed near the cyclone separator just after the heat exchangers were inspected by the DWI. The pipes are marked A and B in figure 7.1. The following was stated by the DWI:

The water quality of the groundwater in the aquifer thermal-energy store in Hørsholm seems not to be corrosive. A water sample from the aquifer indicates this from the size of the following critical parameters. The critical value is indicated in brackets:-

| | | | |
|---|---|---|---|
| pH | 6.9 -7.2 | | ( < 7) |
| dissolved oxygen | 0 -0.8 | mg/l | ( > 2 mg/l) |
| hydrogen sulphide | 0.01-0.02 | mg/l | ( > 1 mg/l) |
| total dissolved solids | 497 -718 | mg/l | ( >1000 mg/l) |
| carbon dioxide | 0 | mg/l | ( > 50 mg/l) |
| chlorides | 79 -102 | mg/l | ( > 500 mg/l) |

The parameters of total dissolved solids and carbon dioxide are measured during stand still (9 March 1987). The rest of the parameters are measured during charging (3 September 1987).

The acidity expressed by the parameter pH is the only one that is at the critical level of corrosive water. The pH value of the groundwater outside the aquifer is 7.3. Due to addition of hydrochloric acid during storage, the value of pH decreases in the aquifer. The measured pH values in the central well (injection of hot water with HCl added) are lower than in the peripheral wells.

There are two reasons for corrosion of the piping system:

1. The presence of oxygen in the water.

   Several leaks in the system during operation have allowed oxygen to enter into the water on the groundwater side. The presence of oxygen in the water accelerates the corrosion in the pipes. It is, therefore, necessary to check frequently for presence of oxygen in the water.

   Nevertheless, the appearance of oxygen in the plant quickly manifests itself by an increase of the injection pressure.

   In August 1985 the oxygen content was measured at 3 different places in the plant.

Peripheral well : 0.25 mg $O_2$/l
Machinery house after water treatment: 4 mg $O_2$/l
Central well : 2 mg $O_2$/l

The amount of 0.25 mg $O_2$/l seems to be characteristic for the oxygen content in the groundwater in Hørsholm. The reason for the very high content of oxygen measured in the machinery house is the appearance of a leak in the vacuum system preventing $CO_2$ from being removed (part II chapter 2.4). When the water flows from the machinery house to the central well some of the oxygen disappears through air-escape valves.

2. An overdose of hydrochloric acid.

   During test runs of the water treatment plant, the dosage of HCl has varied considerably. An accidental value of pH below 5 may have caused the visible corrosion in the pipes. pH has never been allowed to sink below 6.7. Under these conditions the presence of the HCl should not affect the corrosion in the pipes.

The reason for the corrosion of the pump motor placed in the cellar is the presence of hydrochloric acid in the cellar. A number of times, leaks in the water treatment system have resulted in the presence of acid in the cellar. Although the motor has not been exposed directly to acid, it has been corroded. Even vapours of acid is enough for corrosion of the motor.

## Choice of material

The material of the piping system was considered during construction of the plant especially with respect to the presence of hydrochloric acid in the system.

Cost considerations lead to the selection of ordinary steel St 37 for the pipes, while elements especially exposed to acid were reconsidered.

The mixing tube, in which hydrochloric acid is mixed, and the screens and casings in the wells are made of acid proof stainless steel, AISI 316 (0.05% C, 17.5% Cr, 11% Ni, 2.6% Mo).

The plates in the heat exchangers are made of an alloy especially resistant to chloride, Avesta 254 SMO (0.02% C, 20% Cr, 18% Ni, 6.1% Mo, 0.7% Cu, 0.2% N). Neither the mixing tube nor the plates in the heat exchangers have been corroded. It is not known whether the screens have been corroded.

## 7.2 Clogging

Changes in water chemistry can lead to precipitation or dissolution of chemical components in the aquifer that could possibly lead to clogging or instability of the aquifer.

The many studies of water chemistry as related to aquifer thermal energy storage have indicated the following problems:

- precipitation of calcium carbonate and co-precipitation of other compounds such as magnesium carbonate, calcium sulphate, barium sulphate and aluminium hydroxide,
- dissolution of silica at elevated temperatures, followed by precipitation at lowered temperatures,
- oxidation and precipitation of iron and manganese compounds,
- precipitation of organics.

In Hørsholm the precipitation of calcium carbonate is prevented by addition of hydrochloric acid to the groundwater before the groundwater is heated. The following chemical reaction will take place:

$$HCO_3^- + HCl \rightarrow CO_2 + H_2O + Cl^-$$

After the addition of acid, the water is degassed in a degassing column, whereby $CO_2$ is removed.

The $HCO_3^-$ ions have been replaced by $CL^-$ ions, and insoluble chemical products are not formed. Clogging caused by calcium carbonate after heating of the groundwater is prevented by this water treatment.

Most countries have restrictions with respect to injection of chemically polluted or chemically treated water to the groundwater. The Hørsholm project has received the permission to add an amount of hydrochloric acid to the groundwater corresponding to the acidity of the amount of $CO_2$ removed. The net result of the addition of acid is a rise of the chloride concentration. It has been calculated that the chloride concentration in Hørsholm will rise from 30 mg/l to 180 mg/l. The limiting concentration of chloride in drinking water is 300 mg/l, and there are no environmental problems. Water samples taken after 5 years of operation show a maximum content of chloride of 150 mg/l in the central well during storage.

## Clogging experiences

By water treatment ahead of the heating, clogging due to calcium carbonate during charging, has been prevented. Nevertheless, the central well has been treated by acid because of clogging four times during the five years of operation.

The acid used is called Herli Rapid and consists of:

- formic acid
- phosphoric acid
- hydrochloric acid
- isopropyl alcohol

Herli Rapid is especially made for treatment of groundwater wells.

In 1983, no scaling of the heat exchangers was experienced, but during the first three weeks of injection, the central well was gradually clogged.

The reason for this clogging was either $CaCO_3$ deposits due to inadequate adjustment of the water treatment system, or small mineral particles.

In 1985 the newly established central well, CW 2, clogged during storage. The reason for this clogging was the presence of oxygen in the system. The appearance of oxygen was quickly discovered by the injection pressure increase.

When adding hydrochloric acid to the groundwater, the $CO_2$ generated should be removed by vacuum in a degassing column. $CO_2$ and oxygen which enters the system would be removed completely by the low pressure of between -0.9 bar and -0.98 bar.

However, a leak in a tube to the vacuum pump resulted in a lesser vacuum preventing the complete removal of $CO_2$ and oxygen. Thus $CO_2$ and oxygen had been injected in the central well, causing clogging of the well.

In 1986 the central well, CW 2, clogged once more because of the appearance of oxygen in the system. This time it was difficult to localize the oxygen intake. Air may enter between the peripheral wells and the degassing column if there is a leak since the system here is under low pressure. In the degassing column, oxygen and $CO_2$ are completely removed under vacuum. In the pipe from the degasser to the central well the system is under pressure 1 bar - 0.5 bar above the atmosphere, and seepage of oxygen into the pipe should be impossible. Nevertheless, the oxygen leak was found to be located in the cyclone separator, after the degassing column immediately downstream of the heat exchangers.

The pressure conditions in the cyclone separator are rather complex, figure 7.3.

The cyclone separation is obtained by a combination of two hydrodynamic principles: the centrifugal separation of particles in a primary outer whirl and the separation in a secondary inner whirl at the slotted pipe because of inertia.

In the cyclone separator itself there is no possibility of low pressure and a leak in the cyclone separator will only cause flow of water out of the cyclone just like the rest of the system that is under pressure above the atmosphere.

On the other hand low pressure is possible in the inlet of the cyclone separator. The groundwater enters the cyclone through small gaps, figure 7.3. By use of the Bernoulli equation and the Continuity equation it may be shown that the pressure at this place is below atmosphere and a leak here may cause air to enter the system.

It should be mentioned at this point, that there still is a possibility of oxygen entering the system by diffusion through the pipe walls, driven by the partial pressure in the outside air.

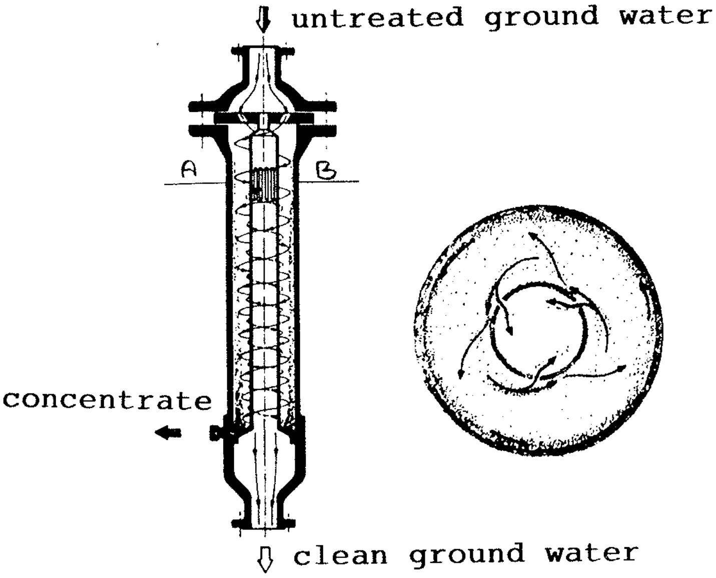


Figure 7.3 Cyclone separator

The central well clogged in 1987, too. This time the clogging was caused by precipitation of $CaCO_3$. The reason for this precipitation was that the plant had been in operation without addition of hydrochloric acid for four days. During these days, the amount of chalk that was precipitated was large enough to clog the injection well. There was no precipitation of $CaCO_3$ in the heat exchangers. The precipitation of $CaCO_3$ was expected during heating, when there was no addition of hydrochloric acid, but it was expected that the precipitate would be retained by the filters, for such a limited period of time.

## 7.3 Bacteriology

Microorganisms are present throughout the environment even in deep aquifers. However, there is a great difference in the number of microorganisms which are in an active growth fase, the growth rate, the conditions required for growth, and the consequences of growth e.g. the formation of slimes or precipitate.

Growth of microorganisms can occur under both anaerobic (without the presence of oxygen) or aerobic (presence of oxygen) conditions. Some microorganisms are dependent on redox reactions for energy. Many microorganisms function as catalysts increasing the rate of chemical reactions. For this reason many scaling and corrosion processes have a microbiological component.

In the years of 1987 and 1988, bacteriological samples were taken in the pumping wells in the aquifer in Hørsholm. The bacteriological samples were taken with a clorine-desinfected tube. The analyses of the samples are presented in the table next page.

The symbols and the location of the wells are shown on figure 3.2.

The auxiliary well AP 1 is placed in upstream direction. Therefore the groundwater here should be unaffected by the temperature in the aquifer. The water quality in AP 1 should be representative of the groundwater in the whole area in Hørsholm.

The most remarkable parameters of the bacteriological tests are the total colony count at 21°C and at 37°C. The values of these two parameters are very high in the peripheral wells, while the amount in the central well corresponds to the amount in the original groundwater. The temperature in the central well is high, 49°C - 52°C, and apparently the bacteria can not survive at these high temperatures. On the other hand the conditions for growth are favourable in the peripheral wells where the temperatures lie between 24°C and 44°C.

| 9 March 1987<br>Stagnation | AP 1 | BW 1 | BW 2 | BW 3 | BW 4 | CW 1 |
|---|---|---|---|---|---|---|
| Temperature | 8°C | 26°C | 30°C | 33°C | 35°C | 49°C |
| Total colony count at 21°C | 2/ml | 1600/ml | 470/ml | 68/ml | 25/ml | 1/ml |
| Fluorescents of this | 0/ml | 0/ml | 0/ml | 0/ml | 0/ml | |
| Coliforms | < 1/100 ml | < 1/100 ml | < 1/100 ml | < 1/100 ml | < 1/100 ml | < 1/100 ml |
| Faecal coliforms | | | | | | |
| Total colony count at 37°C | < 1/ml | 3900/ml | 590/ml | 670/ml | 39/ml | < 1/ml |
| 29 February, 1988<br>Stagnation | Method for analysis | BW 1 | BW 2 | BW 3 | BW 4 | CW 1 |
| Temperature | | 24°C | 38,5°C | 44°C | 31°C | 52°C |
| Total colony count at 21°C | DS 2252 | 230/ml | 1200/ml | 310/ml | 200/ml | 5/ml |
| Fluorescents of this | DS 2252 | < 1/ml | 1/ml | < 1/ml | < 1/ml | < 1/ml |
| Coliforms | DS 2255 | < 1/100 ml | < 1/100 ml | < 1/100 ml | < 1/100 ml | < 1/100 ml |
| Faecal coliforms | DS 2255 | < 1/100 ml | < 1/100 ml | < 1/100 ml | < 1/100 ml | < 1/100 ml |
| Total colony count at 37°C | DS 2254 | 670/ml | 13000/ml | 1500/ml | 680/ml | 25/ml |

Under normal circumstances the total colony count at 21°C is higher than the total colony count at 37°C. The reason for this is that the bacteria normally live in the groundwater at the temperature level 8°C. By heating to 21°C some of the bacteria die and by further heating up to 37°C more of the bacteria die. Such are normally the conditions in traditional drinking water reservoirs.

The conditions in the aquifer thermal-energy store are somewhat different. The temperature level in the store has risen to about 30°C during the years that injection has been carried out. Because of this, new bacteria which are able to live at temperatures about 30°C have found a home. Due to the existence of these bacteria the total colony count in the store at 37°C is higher than the total colony count at 21°C.

## 7.4 Precipitation

Groundwater in the aquifer is usually in equilibrium with geological materials at the temperature and pressure at that point in the aquifer. Extraction of water from its natural environment can cause changes in temperature and pressure, escape of gases (carbon dioxide, hydrogen sulphide, methane), addition of gases (oxygen), etc.

These events will alter the conditions for equilibrium, and this change can lead to the precipitation and dissolution of chemical components. The changes in equilibrium are often complex. Many chemical reactions are dependent on pH, redox, temperature and the presence of other chemicals and the number of potentially active reactions is high.

The rate of a given chemical reaction is also influenced by the presence of other chemicals and the establishment of a new equilibrium condition can often be slow.

The implication of slow reactions is that chemical precipitates can be a problem both in the installations on the surface of an aquifer thermal-energy storage plant, and in the boreholes in the filter packs in the well screens, and in the porous structure of the aquifer itself.

## Precipitation experiences

In 1986 the injection pressure was at maximum during the entire summer. The reason for this high pressure is thought to be a large amount of black deposit in the piping. By closer inspection it appeared that the deposit precipitated in the piping from the peripheral wells to the machinery house. In the piping from the machinery house to the central well there was no precipitation, but the deposit already precipitated was carried by the water to the central well, making injection impossible. After some days the precipitation died out.

The reason for the precipitation in the piping from the peripheral wells to the machinery house is thought to be air that entered the system in the peripheral wells. During the summer of 1986 new air-escape valves were mounted in the peripheral wells. During injection these air-escape valves did not function satisfactorily. The valves allowed air into the piping during close-down due to pressure difference. When these valves allow air into the pipes, the oxygen may combine with the steel pipes and form a precipitate of Fe. The chemical composition of the precipitate was:

| | |
|---|---|
| 42% | Fe |
| 0.57% | Mn |
| 8-9% | Insoluble |
| 0% | Sulphides |

The precipitate was removed from the center well by a suction pump.

In 1987 there were no precipitation problems during charging. Immediately after the end of charging, the plant was prepared for recovery, but after 14 days of recovery the heat exchangers clogged. Cleaning with $HNO_3$ and NaOH made recovery possible for another month. At this time both the heat exchangers and the peripheral wells clogged.

One of the heat exchangers was disassembled. The plates were covered with a black coat with a thickness of 2 mm at the groundwater side, while the district heating side was entirely clean (part II, chapter 3.6).

Samples of the coating were subjected to dissolution experiments with HCl, $HNO_3$, NaOH and $HNO_3 + H_2O_2$, of which HCl showed to be the most efficient. Heating with HCl did not evolve any $H_2S$-odour; the absence of metastable iron sulfides (FeS) as mackinawite, greigite and others is thus strongly indicated. The presence of pyrite is indicated by the black colour of the coating.

In an attempt to clean the heat exchangers after the end of recovery, Herli-Rapid (mixture of HCl, $H_3PO_4$, formic acid and isopropyl alcohol) was used. The 300 l Herli-Rapid contained a total of 10.5 kg $PO_4^{3-}$ and during cleaning, the system was open to the atmosphere allowing oxygen to be dissolved in the circulating cleaning water. No $H_2S$-odour was noticed during cleaning with Herli-Rapid.

Samples of the black coating was stored in plastic bags at 5°C for later investigations.

In 1989 (after 1½ years of storage), the black coating was subjected to comprehensive analyses involving:

- x-ray diffraction (XRD)
- scanning electron microscope (SEM)
- energy dispersive analysis of x-ray (EDX), and
- wavelength dispersive analysis of x-ray (WDX)

The x-ray diffractogramme (fig. 7.4) is dominated by the diffraction lines of pyrite ($FeS_2$) and gypsum ($CaSO_4 \cdot 2H_2O$), and also the presence of goethite (FeOOH), is evident. A broad diffraction peak at an angle corresponding to a d-spacing of 2.5 Å shows the presence of the poorly crystalized iron-oxyhydroxide, ferrihydrite. The presence of FeS, Si and $CaHPO_4$ can not be excluded, but other results makes their presence unlikely (see text above and below).

The coating is somewhat magnetic, which is partly due to the ferrihydrite but also the presence of an iron-spinel (magnetite or maghemite) is evident. A rough estimate of the quantitative importance of the three iron-minerals is ferrihydrite ∿ 75%, goethite ∿20% and iron-spinel ∿5%.

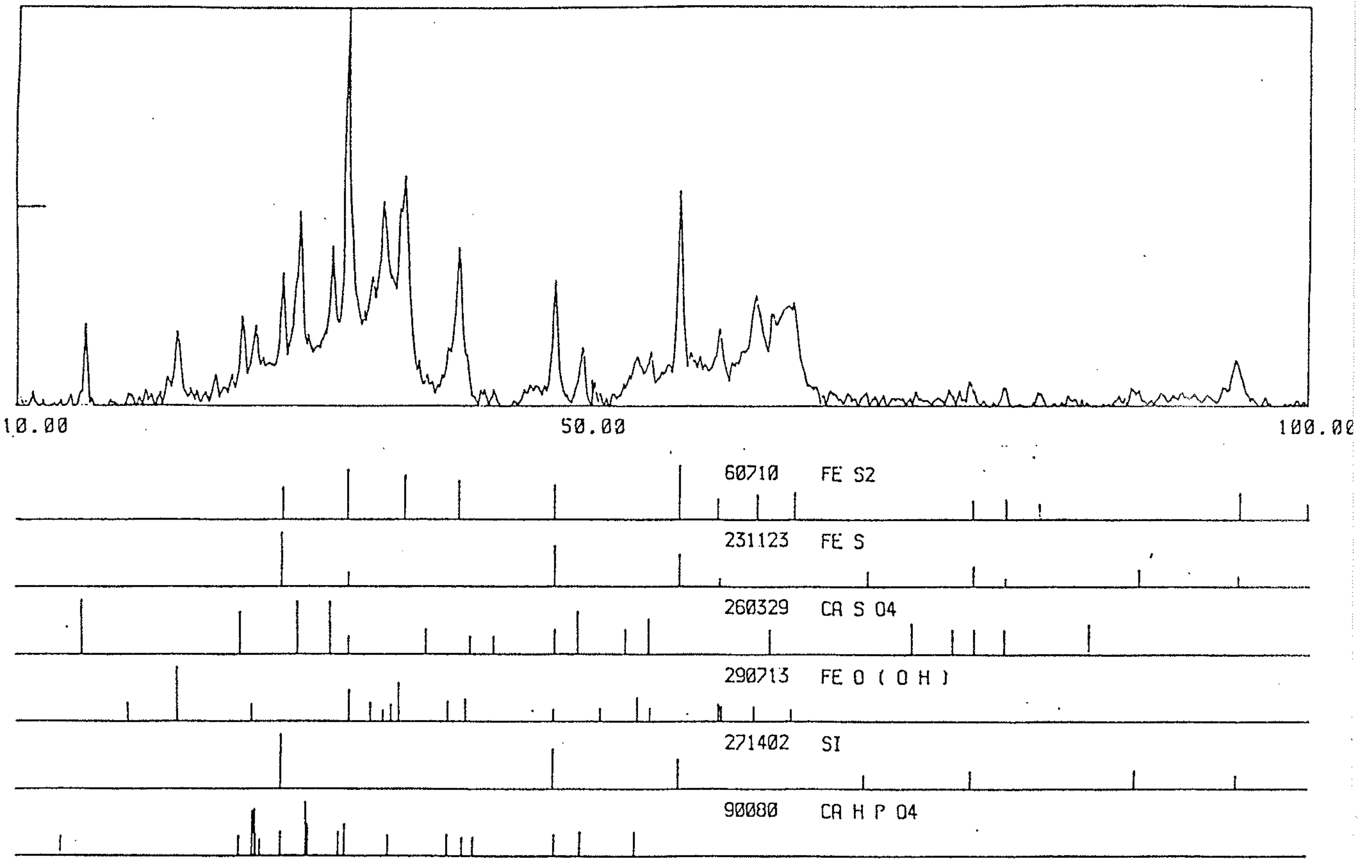


Fig. 7.4. X-ray diffractogramme of the black precipitate, with diffraction lines of Pyrite, FeS, Gypsum, Goethite, Silica and $CaHPO_4$ shown below.

<u>SEM investigations combined with EDX-analyses</u> identified six morphologically and chemically different constituents of the black coating. EDX allows quantification of elements from element no. 11 (sodium) and identification of elements from element no. 6 (carbon).

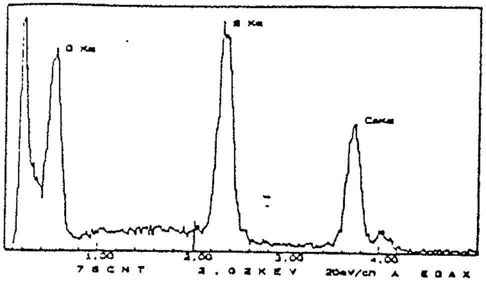
In plate 1 photo-micrographs and EDX analyses of the six components, described as follows, are given:

- Gypsum is present as regular, monocline crystals with a size of 5-30 µm.

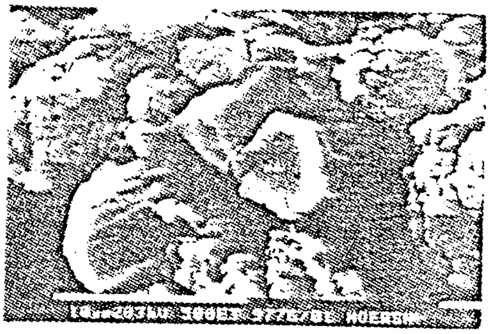
- Pyrite occurs as single spheres (~5 µm) or aggregates of spheres, i.e. the commonly reported framboidal pyrite texture.

## PLATE 1 See text for explanation

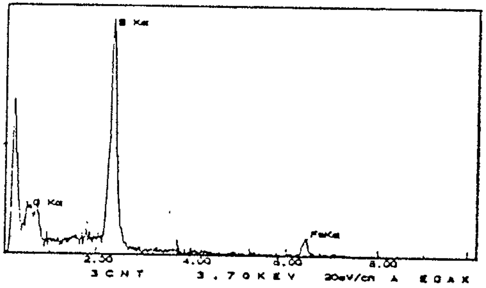
Gypsum $CaSO_4 \cdot 2H_2O$



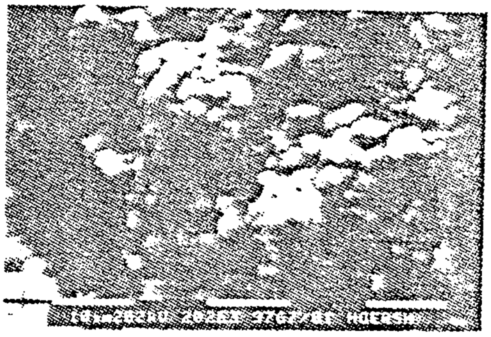
| | WT.% | AT.% | % S.E. |
|---|---|---|---|
| S K | 43.47 | 49.21 | 0.52 |
| CAK | 54.93 | 49.75 | 0.52 |
| FEK | 1.59 | 1.04 | 8.03 |



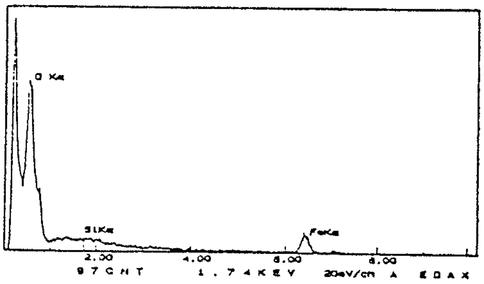
Pyrite $FeS_2$



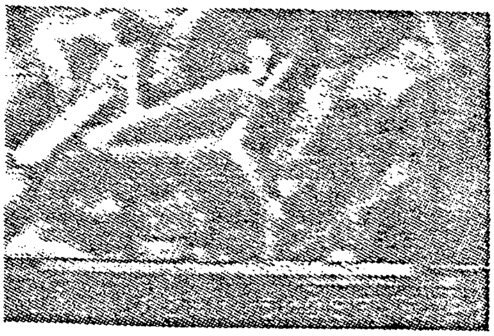
| | WT.% | AT.% | % S.E. |
|---|---|---|---|
| SIK | 1.50 | 2.12 | 3.84 |
| P K | 2.12 | 2.72 | 2.63 |
| S K | 50.44 | 62.38 | 0.36 |
| CLK | 0.37 | 0.42 | 14.94 |
| CAK | 0.23 | 0.23 | 18.59 |
| FEK | 44.85 | 31.84 | 0.58 |
| CUK | 0.47 | 0.29 | 22.03 |



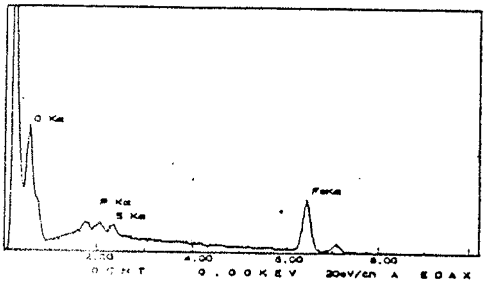
Fe-oxide "house of cards"



| | WT.% | AT.% | % S.E. |
|---|---|---|---|
| SIK | 0.51 | 1.00 | 7.97 |
| P K | 0.49 | 0.87 | 7.25 |
| S K | 0.55 | 0.94 | 6.00 |
| CLK | 0.11 | 0.18 | 27.44 |
| CAK | 0.64 | 0.88 | 5.24 |
| FEK | 97.70 | 96.14 | 0.35 |

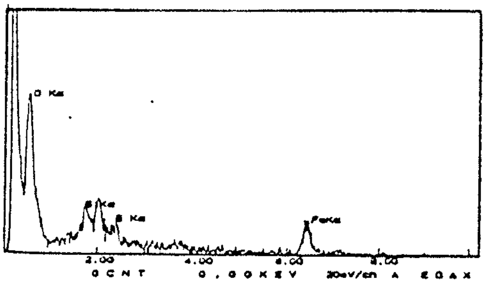


Fe-oxide plates



| | WT.% | AT.% | % S.E. |
|---|---|---|---|
| SIK | 1.82 | 3.42 | 2.87 |
| P K | 2.56 | 4.38 | 1.95 |
| S K | 2.05 | 3.39 | 2.10 |
| CLK | 0.16 | 0.24 | 21.41 |
| CAK | 0.57 | 0.75 | 5.81 |
| FEK | 92.29 | 87.37 | 0.30 |
| CUK | 0.54 | 0.45 | 16.57 |

Fe-oxid flaky texture



| | WT.% | AT.% | % S.E. |
|---|---|---|---|
| SIK | 7.68 | 12.77 | 1.47 |
| P K | 7.49 | 11.30 | 1.37 |
| S K | 7.63 | 11.11 | 1.27 |
| CAK | 1.09 | 1.27 | 5.31 |
| FEK | 74.70 | 62.50 | 0.46 |
| CUK | 1.42 | 1.04 | 9.04 |

- Silicon-oxide is present as large (~200 µm) well-rounded (detrital sand) grains. On one occasion, Si-oxide was also observed as 20 µm angular crystals.

Iron oxide occurs in 3 different morphologies also showing differences in chemical composition, i.e. the amount of impurities (Si, P and S).

- The very rare and most clean form of iron-oxide is the house of cards texture (~5 µm crystals) with Si, P and S contents below the detection limit.

- Irregular plates (~200 µm), with Si, P and S contents of around 3 molar percent each, are common.

It is thus tempting to interprete the three morphologies of iron as respectively iron-spinel, goethite and ferrihydrite.

WDX-analyses was carried out over two different areas of the precipiate, in order to assess the bulk element composition. The WDX-technique quantifies elements from element no. 5 (boron), i.e. H is the only important element not quantified.

The bulk composition is given in table 7.1 (molar percent), and the elements are distributed between the identified minerals as follows:

- All Ca is present as gypsum, $CaSO_4 \cdot 2H_2O$
- The remaining S is present as pyrite
- All Si is present as $SiO_2$
- All P is present as phosphate, $PO_4^{3-}$

The only phosphate-mineral indicated is $CaHPO_4$ (XRD-analysis). However, this can not be the major $PO_4$-component since the bulk $Ca^{2+}/PO_4^{3-}$-ratio is only 0.1-0.6 and Ca is known to be present as gypsum in large amounts (SEM, EDX, XRD). As the presence of $FePO_4$ can not be detected, it is most likely that $PO_4^{3-}$ is adsorbed to the iron oxides. P/Fe-ratios of 0.1 are frequently reported from iron oxide sludge of water works, but it is also possible that leaching with Herli-Rapid has introduced $PO_4^{3-}$ into the precipitate.

The rest ratio of O to Fe (table 7.1) is 2 meaning that "low ratio minerals" as $Fe_3O_4$ and $Fe_2O_3$ are uncommon. The ratio thus supports the XRD-results as to the relative importance of the various iron-minerals. The stoichiometry of ferrihydrite is rather variable, but the frequently applied formula: $Fe_5HO_8 \cdot 4H_2O$ agrees well with our data.

The interpretation of the various components of the precipitate is not straight foreward, since not only the ATES-operation, but also the later effects of Herli-Rapid leaching and storage have to be taken into consideration. Existing analyses of water samples taken before and after the heat exchanger gives no clue to the origin of the precipitate.

The presence of both FeOOH (in the following used to describe all iron-oxides), and $FeS_2$, as major constituents of the precipiate, is somewhat contradictory since the former indicates oxic conditions, whereas the later indicates anoxic conditions. Formation of FeOOH by oxidation of $FeS_2$ during storage and perhaps during leaching could be an explanation. Due to the low pH of the Herli-Rapid solution, it is, however, unlikely that major FeOOH precipitation has occurred during leaching. Oxidation of FeS, during storage should have left S in the precipitate as $SO_4$. The total amount of S is, however, much too low to account for all the iron (S/Fe = 0.1-0.2) meaning that $FeS_2$ as well as FeOOH must have precipitated during ATES-operation.

| | WDX-Bulk Composition | | All Ca as $CaSO_4 \cdot 2H_2O$ | | Rest S as $FeS_2$ | | All Si as $SiO_2$ | | All P as $PO_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1. | 2. | 1. | 2. | 1. | 2. | 1. | 2. | 1. | 2. |
| Ca | 0.3 | 1.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S | 2.3 | 3.7 | 2.0 | 2.6 | 0 | 0 | 0 | 0 | 0 | 0 |
| Si | 5.1 | 7.1 | 5.1 | 7.1 | 5.1 | 7.1 | 0 | 0 | 0 | 0 |
| P | 2.6 | 1.7 | 2.6 | 1.7 | 2.6 | 1.7 | 2.6 | 1.7 | 0 | 0 |
| Fe | 21.4 | 22.0 | 21.4 | 22.0 | 20.4 | 20.7 | 20.4 | 20.7 | 20.4 | 20.7 |
| O | 68.3 | 64.4 | 66.5 | 57.8 | 65.5 | 57.8 | 55.3 | 43.6 | 44.9 | 36.8 |
| O/Fe-ratio | | | | | | | | | 2.2 | 1.8 |

Table 7.1. Break down of bulk composition between the basic constituents in two samples of black coating from Hørsholm, see text for explanation. All concentrations are given as molar percent.

In fact, it is thermodynamically possible that oxygen entering the ATES-system will oxidize native iron of the pipes rather than sulfide and iron (II) in solution. This means that FeOOH may precipitate as a consequence of oxygen occasionally entering the system even though the water in general is anoxic due to equilibrium with $FeS_2$ in the aquifer.

FeOOH accumulates/precipitates preferentially in the heat exchanger due to locally reduced flow velocity and temperature decrease.

The precipitate has been weighed and the density was found to 1 $cm^3$ = 1.1 g. With a surface area in each of the 2 heat exchangers at 87.5 $m^2$ and a cover thickness of 2 mm over the entire surface area the total amount of precipitate is 385 kg. The porosity is unknown. Nevertheless, the porosity has been set to 90%, giving a total amount of solid precipitate at approximately 40 kg.

The total amount of precipitate ( 40 kg) contains about 24 kg iron as iron oxides; precipitation of the amount of iron takes 4-10 kg oxygen (14 $m^3$ - 32 $m^3$ air) depending on the iron-source (dissolved and/or native). Since atmosphere air contains about 78% v/v nitrogen and 21% v/v oxygen, the equivalent mass of nitrogen present in the water will be about 15-37 kg. The total recovered volume of water (about 15,000 $m^3$) at a temperature of $85^{\circ}C$ is assumed to be able to dissolve at least 30 kg oxygen and 60 kg nitrogen and, therefore, the formation of free gases is not expected (the solubility of oxygen and nitrogen in water in equilibrium with atmospheric air at a temperature of $85^{\circ}C$ is about 2 and 4 mg/l respectively). At lower temperatures, the solubility increases. Even if gas bubbles are present in the system, they will only cause problems if their size and number are excessive in comparison with the volume of water.

These calculations demonstrate that precipitation of the iron oxides can be caused by the diffusion of about 1,000 $cm^3$ air per $m^3$ water or an average oxygen concentration of 0.2-0.6 mg oxygen/l if the iron oxide originates from native iron. These quantities will not be detected by measurement of pressure losses due to gas bubble formation. If the iron oxide on the contrary originates from dissolved iron the precipitation will be caused by a diffusion of about 2,100 $cm^3$ air per $m^3$ water or an average oxygen concentration of 0.5-1.2 mg oxygen/l.

The above mentioned considerations are based on a porosity at 90%. If the porosity is only 80% the required amount of dissolved nitrogen will produce gas bubbles.

Precipitation of pyrite in the heat exchangers during recovery is expected theoretically due to the temperature decrease. The solubility of pyrite is during ordinary groundwater conditions (8°C) very low. During storage the groundwater around the central well is heated until 95°C. At this temperature the solubility of pyrite increases, meaning that the heated groundwater is able to dissolve a large amount of pyrite. During recovery the heated groundwater is cooled until 60°C in the heat exchangers and pyrite precipitates due to a decrease in solubility.

The presence of quartz grains is attributed on the basis of morphological criteria, to suspended transport of aquifer material. The much more rare $SiO_2$ crystals are most likely a consequence of coprecipitation with FeOOH. Also adsorption of Si, most likely as $H_2SiO_4^{--}$, on the surface of FeOOH is strongly indicated by the EDX-analyses (plate 1).

The occurence of gypsum in the heat exchangers after recovery is very strange since:

A) At the temperatures of recovery 80-60°C (table 2) anhydrite, not gypsum is the stable phase for $CaSO_4$.

B) The solubility of both gypsum and anhydrite increases as the temperature is lowered from 80-60°C.

C) The highest saturation-index ever recorded for gypsum or anhydrite during the lifetime of the Hørsholm-plant is -1 (i.e. one tenth of saturation concentration).

The formation of gypsum must thus have taken place after operation of the ATES. During Herli-Rapid leaching oxidation of pyrite according to eq. 2 could produce $SO_4^{2-}$. Substitution of $Ca^{2+}$ with $2H^+$ on the cation exchange complex of FeOOH according to eq. 3 could liberate $Ca^{++}$ and gypsum could form according to eq. 4.

$4FeS_2 + 15O_2 + 10H_2O \rightarrow 8SO_4^{2-} + 4FeOOH + 16H^+$ (2)

$2H^+ + Ca\text{-}R(FeOOH) \rightarrow Ca^{2+} + H_2\text{-}R(FeOOH)$ (3)

$Ca^{2+} + SO_4^{2-} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O$ (4)

From a mass-balance point of view, the above explanation is also possible since pyrite is known to be present in sufficient amounts and a cation exchange capacity of 100 meqv. per 100 g, or even more is to be expected for freshly precipitated FeOOH.

The most likely scenario for the formation of the black precitate is summarized as follows:

During recovery

- $O_2$ enters the system, oxidizes the iron (II) in solution and FeOOH precipitates.

- $FeS_2$ forms in the heat exchangers as a consequence of temperature decrease.

- Suspended quartz grains settle in the heat exchanger and some $SiO_2$ coprecipitates with FeOOH.

During Herli-Rapid leaching

- $SO_4^{2-}$ is liberated from $FeS_2$ due to oxidation, $Ca^{++}$ is liberated from the cation exchange complex of FeOOH (substituted by $H^+$), and gypsum is precipitated.

- $PO_4$ enters most adsorption sites on the FeOOH.

During storage of the precipitate

- Some additional oxidation of $FeS_2$ and recrystallation of FeOOH (colour changes from black to dark brown) takes place.

The major reason for clogging of the heat exchangers during recovery seems to be pyrite precipitation. Another important reason for clogging is oxygen entering the system. However, the pyrite precipitation may be the fundamental reason for clogging as clogging only takes place during recovery.

The precipitation of pyrite upon cooling is very interesting, since this has not been reported before. The reason for this may be that the aquifer in Hørsholm has a very high content of iron compared with other aquifers. If clogging in the heat exchangers caused by pyrite precipitation turns out to be a general problem for ATES-operation, some kind of Fe-treatment connected to the recovery phase of ATES will be necessary.

## 8. GROUNDWATER ANALYSIS PROGRAM

In 1986 the Department of the Environment presented additional requirements in connection with future addition of hydrochloric acid to the groundwater before reinjection in the aquifer.

One groundwater analysis each three months in 1987 was required. The sample should be analysed for $Ca^{++}$, $HCO_3^-$, $Cl^-$, pH and temperature.

Furthermore, a groundwater analysis was required once per year in 1987 and 1988 according to an expanded control in the announcement No. 6 of 4 January 1980 from the Department of the Environment.

Analyses from all the pumping wells were required. The results of the analyses are presented and discussed in the following pages.

Date: 9 March 1987

| | | AP 1 | BW 1 | BW 2 | BW 3 | BW 4 | CW 1 |
|---|---|---|---|---|---|---|---|
| Smell | | $H_2S$ | $H_2S$ | | $H_2S$ | $H_2S$ | sharp |
| Conductivity | (mS/m) | 70.2 | 92.4 | 75.9 | 95.7 | 91.3 | 91.3 |
| pH | | 7.2 | 7.2 | 7.2 | 6.8 | 7.1 | 6.2 |
| $KMnO_4$ | (mg/l) | 11.0 | 23.0 | 19.0 | 24.0 | 18.0 | 22.0 |
| $NH_4^+$ | (mg/l) | 0.27 | 0.61 | 0.75 | 1.1 | 0.58 | 0.65 |
| $Na^+$ | (mg/l) | 19.0 | 22.0 | 23.0 | 25.0 | 22.0 | 25.0 |
| $K^+$ | (mg/l) | 2.2 | 1.6 | 2.3 | 3.6 | 1.5 | 2.5 |
| $Ca^{++}$ | (mg/l) | 132.0 | 155.0 | 153.0 | 161.0 | 157.0 | 156.0 |
| $Mg^{++}$ | (mg/l) | 10.0 | 15.0 | 14.0 | 12.0 | 13.0 | 12.0 |
| Fe | (mg/l) | 3.7 | 11.0 | 8.2 | 9.6 | 8.0 | 4.0 |
| Mn | (mg/l) | 0.57 | 1.6 | 1.4 | 1.1 | 1.1 | 1.3 |
| Total hardness | (°dH) | 20.8 | 25.0 | 24.6 | 25.3 | 25.0 | 24.5 |
| Temperature | (°C) | 8.0 | 26.0 | 30.0 | 33.0 | 35.0 | 49.0 |
| Pt | (mg/l) | 52.0 | 58.0 | 100.0 | 83.0 | 75.0 | 110.0 |
| Turbidity | (FTU) | 1.9 | 40.0 | 39.0 | 43.0 | 31.0 | 33.0 |
| $NO_2^-$ | (mg/l) | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.01 |
| $NO_3^-$ | (mg/l) | 0.5 | 0.6 | 0.7 | 0.7 | 0.6 | 0.9 |
| P | (mg/l) | 0.10 | 0.38 | 0.30 | 0.21 | 0.39 | 0.22 |
| $F^-$ | (mg/l) | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 |
| $Cl^-$ | (mg/l) | 70.0 | 91.0 | 75.0 | 94.0 | 90.0 | 90.0 |
| $HCO_3^-$ | (mg/l) | 334.0 | 324.0 | 323.0 | 326.0 | 327.0 | 334.0 |
| $SO_4^{--}$ | (mg/l) | 90.0 | 120.0 | 110.0 | 110.0 | 120.0 | 89.0 |
| Total solids | (mg/l) | 497.0 | 674.0 | 670.0 | 718.0 | 661.0 | 675.0 |
| $CO_2$ | (mg/l) | 0 | 0 | 0 | 0 | 0 | 0 |
| O | (mg/l) | 0 | 0 | 0 | 0 | 0 | 0 |
| $H_2S$ | (mg/l) | 0.03 | 0.03 | 0.07 | 0.07 | 0.05 | <0.01 |
| $CH_4$ | (mg/l) | 0.03 | 0.14 | 0.10 | 0.07 | 0.16 | 0.09 |

Date: 6 May 1987

| | | BW 1 | BW 2 | BW 3 | BW 4 | CW 1 | Method of analysis |
|---|---|---|---|---|---|---|---|
| $Ca^{++}$ | (mg/l) | 151.0 | 118.0 | 163.0 | 139.0 | 140.0 | DS 248 |
| $HCO_3^-$ | (mg/l) | 313.0 | 231.0 | 321.0 | 340.0 | 337.0 | DS 253 |
| $Cl^-$ | (mg/l) | 49.0 | 70.0 | 115.0 | 49.0 | 61.0 | DS 249 |
| pH | | 7.6 | 7.4 | 7.2 | 7.5 | 7.7 | DS 287 |
| Si | (mg/l) | 7.4 | 3.2 | 17.0 | 9.3 | 9.1 | SE |

Date: 29 July 1987

| | | BW 4 | BW 2 | BW 4 | CW 1 | Method of analysis |
|---|---|---|---|---|---|---|
| $Ca^{++}$ | (mg/l) | 136.0 | 181.0 | 145.0 | 150.0 | DS 248 |
| $HCO_3^-$ | (mg/l) | 311.0 | 320.0 | 325.0 | 188.0 | DS 253 |
| $Cl^-$ | (mg/l) | 38.0 | 68.0 | 79.0 | 128.0 | DS 249 |
| pH | | 7.7 | 7.3 | 7.3 | 7.2 | DS 287 |
| Si | (mg/l) | 9.6 | 17.0 | 16.0 | 14.0 | SE |
| Temperature | ($^{o}$C) | 14.5 | 27.0 | 24.5 | 91.0 | |

Date: 3 September 1987

| | BW 1 | BW 2 | BW 4 | Machinery house | CW 1 | Method of Analysis |
|---|---|---|---|---|---|---|
| Conductivity (mS/m) | 87.5 | 94.7 | 83.9 | 66.2 | 88.0 | DS 288 |
| pH | 7.1 | 6.9 | 7.0 | 7.1 | 7.2 | DS 287 |
| $NH_4^+$ (mg/l) | | 1.0 | | 0.86 | 0.79 | DS 224,Mod |
| $Na^+$ (mg/l) | | 25.0 | | 24.0 | 23.0 | FF |
| $K^+$ (mg/l) | | 5.2 | | 4.5 | 3.9 | FF |
| $Ca^{++}$ (mg/l) | 161 | 176.0 | 149.0 | 168.0 | 167.0 | DS 248 |
| $Mg^{++}$ (mg/l) | | 6.0 | | 7.0 | 4.0 | DS 250 |
| Fe (mg/l) | | 2.3 | | 3.7 | 1.9 | DS 219 |
| Mn (mg/l) | | 1.1 | | 0.92 | 0.83 | DS 220 |
| Temperature (°C) | 21.5 | 39.0 | 31.0 | 30.0 | >65.0 | |
| $NO_3^-$ (mg/l) | | 0.8 | | 0.8 | 0.8 | SM 418 A |
| P | | 0.16 | | 0.16 | 0.13 | DS 292 |
| $F^-$ (mg/l) | | 0.4 | | 0.3 | 0.3 | DS 218 MOD |
| $Cl^-$ (mg/l) | | 110.0 | 102.0 | 98.0 | 91.0 | DS 249 |
| $HCO_3$ (mg/l) | 310.0 | 276.0 | 294.0 | 292.0 | 298.0 | DS 253 |
| $SO_4^{--}$ (mg/l) | | 118.0 | | 100.0 | 96.0 | SM 496 |
| Total solids (mg/l) | | - | | | | |
| O (mg/l) | | 0 | | 0.5 | 0.8 | DS 277 |
| $H_2S$ (mg/l) | | <0.01 | | - | 0.02 | DS 278 |
| Si (mg/l) | 15.0 | 28.0 | 17.0 | 22.0 | 20.0 | SE |

The sample from the machinery house was taken after water treatment, but before heat exchanging.

Date: 1. December 1987.

| | BW 1 | BW 2 | BW 4 | CW 1 | Method of analysis |
|---|---|---|---|---|---|
| Temperature (°C) | 40.0 | 46.5 | 42.5 | 56.0 | |
| $Ca^{++}$ (mg/l) | 146.0 | 149.0 | 152.0 | 155.0 | DS 248 |
| $HCO_3^-$ (mg/l) | 283.0 | 283.0 | 303.0 | 320.0 | DS 253 |
| $Cl^-$ (mg/l) | 94.0 | 98.0 | 96.0 | 92.0 | DS 249 |
| pH | 7.3 | 7.3 | 7.2 | 7.3 | DS 287 |
| Si (mg/l) | 20.0 | 18.0 | 18.0 | 21.0 | SE |
| Fe (mg/l) | 19.0 | 18.0 | 7.2 | 4.0 | DS 219 |
| Mn (mg/l) | 1.4 | 1.4 | 1.1 | 0.88 | DS 220 |

Date: 29. February 1988.

| | | BW 1 | BW 2 | BW 3 | BW 4 | CW 1 | Method of analysis |
|---|---|---|---|---|---|---|---|
| Smell | | $H_2S$ | $H_2S$ | $H_2S$ | $H_2S$ | $H_2S$ | |
| Conductivity | (mS/m) | 79.8 | 93.5 | 82.0 | 72.6 | 75.4 | DS 288 |
| pH | | 7.2 | 7.2 | 7.0 | 7.2 | 7.0 | DS 287 |
| $KMnO_4$ | (mg/l) | 12.0 | 20.0 | 20.0 | 14.0 | 21.0 | DS 275,MOD |
| $NH_4^+$ | (mg/l) | 0.65 | 0.64 | 0.61 | 0.87 | 0.53 | DS 224,MOD |
| $Na^+$ | (mg/l) | 19.0 | 22.0 | 22.0 | 20.0 | 20.0 | FF |
| $K^+$ | (mg/l) | 4.5 | 2.3 | 2.6 | 1.8 | 3.4 | FF |
| $Ca^{++}$ | (mg/l) | 142.0 | 158.0 | 139.0 | 127.0 | 138.0 | DS 248 |
| $Mg^{++}$ | (mg/l) | 10.0 | 15.0 | 10.0 | 9.0 | 9.0 | DS 250 |
| Fe | (mg/l) | 5.3 | 5.1 | 6.0 | 5.3 | 3.7 | DS 219 |
| Mn | (mg/l) | 1.3 | 1.3 | 1.2 | 1.2 | 0.68 | DS 220 |
| Total hardness | (°dH) | 22.1 | 25.5 | 21.9 | 19.9 | 21.3 | DS 250 |
| Temperature | (°C) | 24.0 | 38.5 | 44.0 | 31.0 | 52.0 | |
| Pt | (mg/l) | - | - | - | - | - | DS 289B |
| Turbidity | (FTU) | - | - | - | - | - | DS 290 |
| $NO_2^-$ | (mg/l) | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | DS 222 |
| $NO_3^-$ | (mg/l) | 0.6 | 0.7 | <0.5 | 0.5 | <0.5 | SM 418A |
| P | (mg/l) | 0.24 | 0.24 | 0.31 | 0.37 | 0.16 | DS 292 |
| $F^-$ | (mg/l) | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | DS 218,MOD |
| $Cl^-$ | (mg/l) | 46.0 | 85.0 | 75.0 | 39.0 | 46.0 | DS 249 |
| $HCO_3^-$ | (mg/l) | 291.0 | 306.0 | 303.0 | 306.0 | 378.0 | DS 253 |
| $SO_4^{--}$ | (mg/l) | 122.0 | 114.0 | 76.0 | 76.0 | 43.0 | SM 496 |
| Total solids | (mg/l) | 541. | 680.0 | 577.0 | 494.0 | 527.0 | DS 204 |
| $CO_2$ | (mg/l) | 0 | 0 | 0 | 0 | 0 | DS 236 |
| $O_2$ | (mg/l) | 0 | 0.8 | 1.1 | 0.2 | 0.8 | DS 277 |
| $H_2S$ | (mg/l) | 0.02 | 0.02 | 0.01 | 0.02 | <0.01 | DS 278 |
| $CH_4$ | (mg/l) | <0.02 | 0.05 | 0.19 | 0.03 | 0.1 | GC |
| Si | (mg/l) | 10.3 | 16.7 | 16.9 | 11.2 | 17.5 | SE |

The groundwater analyses from December 1987, show a very large content of iron in the water. At that time recovery had taken place and the cooled water had been injected into the peripheral wells. The iron content in the central well (heated water) is 4.0 mg/l, while the iron content in the peripheral wells (recovered water) is 19 mg/l in BW 1, 18 mg/l in BW 2 and 7.2 mg/l in BW 4.

The solubility of iron is often represented as a function of pH and the electrode potential. Oxidation of ferrous iron (Fe II) to ferric iron (Fe III) results in the precipitation of ferric oxide at normal pH values.

Below about 200 mVolt, ferric ion (Fe III) are reduced to ferrous ions (Fe II). At this redox potential, dissolved oxygen is essentially absent. For manganese the redox potential must be below 300 mV for the conversion of Mn IV to Mn II.

The redox potential has been measured in the pumping wells 29th February 1988. The store at that time had been in stagnation since the middle of November. The redox potential measured for the pumping wells was as follows:

| | |
|---|---|
| BW 1 | 85 mVolt |
| BW 2 | 57 mVolt |
| BW 3 | 46 mVolt |
| BW 4 | 54 mVolt |
| CW 1 | 9 mVolt |

The measurements point to the fact that there is no oxygen present in the aquifer.

An explanation for the elevated iron concentrations has been given as pyrite oxidation according to:

$$2\ FeS_2 + 7\ O_2 + 2\ H_2O \rightarrow 4\ SO_4^{--} + 2\ Fe^{++} + 4\ H^+$$

Evidence for this explanation are shown in figure 8.1, where iron, sulfate and pH values from an upstream well are compared with values from wells in the store.

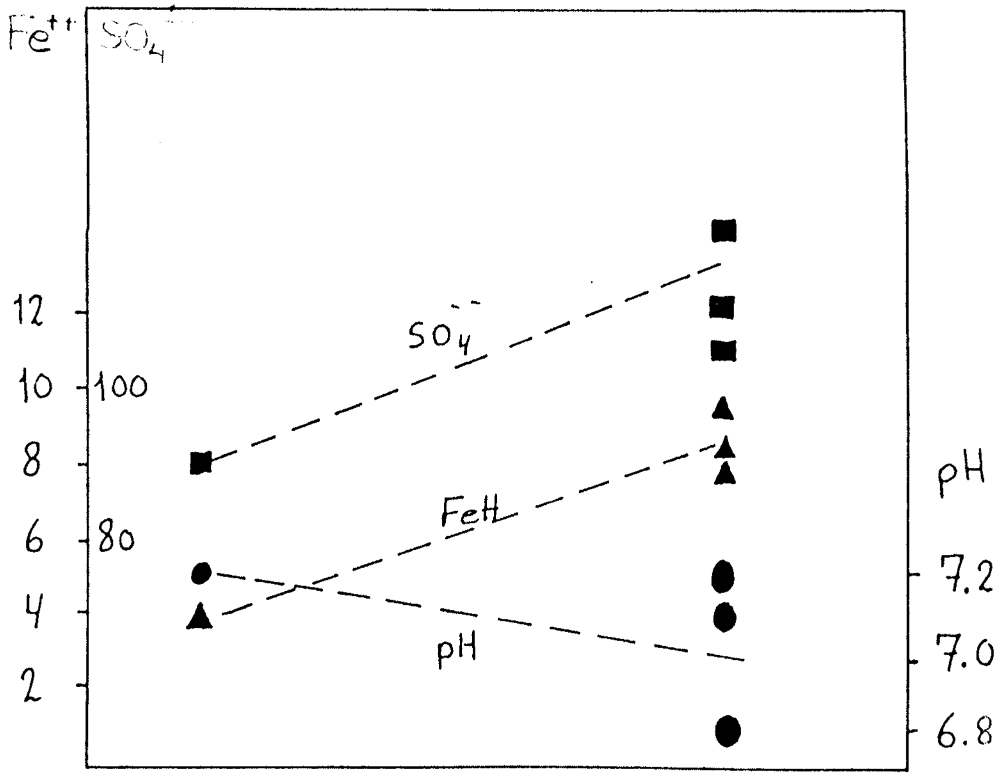


Figure 8.1. $SO_4$, $Fe^{++}$ and pH upstream (left side) and in the store (right side).

The iron increase is $\simeq$ 0.07 - 0.13 mMole and the corresponding sulfate increase is 0.21 - 0.31 mMole which equals a $SO_4$/Fe-ratio of 2.4 - 3.0. The theoretical ratio according to the equation is 2.0, which, when considering possible iron-oxide precipitation and ion exchange, is in good agreement with observations. The pH change is too small, probably due to $CaCO_3$-dissolution buffering the acid production.

The equation requires the appearance of 7 $O_2$ for the precipitation of 2 $Fe^{++}$. This means that for an iron content of 19 mg/l in the wells, there has to be 38.1 mg/l $O_2$ in the well. The solubility for $O_2$ is about 10 mg/l, whereby an amount of 38.1 mg/l $O_2$ pumped into the reservoir does not seem possible.

The high content of iron has been measured 14 days after end of recovery. Recovery ended as the heat exchangers as well as the screens in the peripheral wells clogged (part II chapter 3.7). The high content of iron that occurred in the peripheral wells therefore only seems to be connected with the precipitation in the heat exchangers during recovery.

## 9. SIMULATION OF OPERATIONAL CYCLES

(This chapter is an exempt of reference 3).

Heat and mass transport through porous media may be described mathematically by a set of partial differential equations. These are the mass conservation equation, the energy equation and the Darcy equations. To obtain a closed form solution of the mathematical problem defined by these equations is often not possible. In most cases a numerical technique has to be used in order to obtain a solution. The model D2AQ described in chapter 4.6 is based on the use of the Finite Element Method as the numerical technique to solve the problem. Using the Finite Element Method the partial differential equations are reduced to a set of ordinary differential equations in time representing the change in pressures and temperatures at selected points (nodes) in the aquifer. Between these nodal values the solution is obtained by means of interpolation using quadratic interpolation functions. The resulting set of ordinary differential equations in time, are integrated using a backward Finite Difference scheme.

The solution obtained from the model is in the form of pressure and temperature distributions in the aquifer at successive time intervals.

In this and other experiments buoyancy and viscosity effects have proven to be critical with respect to the maintenance of a stable displacement process.

The developed model includes these effects and has during the design phase been used to study the impact of different well patterns and positions of well screens on the stability of the displacement of cold groundwater by injected warm water.

### 9.1 Test run

After the completion of the pilot plant in Hørsholm the first test run was started in late 1982 and completed in January 1983. The objective of this first test run was to get enough data for a verification of the simulation model and to test and calibrate the instrumentation of the store. Only a minor portion of the total storage capacity was used in this test and injection temperatures were moderate (35 °C). However, the test run gave enough data for the calibration of instruments and verification of models.

In the aquifer, horizontal permeability varies from 27 Darcy at the bottom 5 metres through 10 Darcy in the middle to very low-permeable structures near the top of the reservoir. The ratio of vertical to horizontal permeability is assumed to be 0.1 throughout the reservoir, and porosity takes the value 0.3 in all layers.

Due to the necessity of manual control and other practical difficulties, the test run suffered from strong variations in injection rate and temperature (2.2 - 8.7 kg/s and 24 -54°C). The duration of the experiment combined with the limited injection temperature resulted in the storage of about 64 MWh, which is just a small fraction of the storage capacity. Hence only the probes of the first instrumentation well (r = 7m) were affected.

The temperature obtained in the instrumentation well indicated a relatively low-permeable layer near the middle of the aquifer and a significant transmissivity at the top of the aquifer. The permeability distribution deduced from observations gave rise to the isotherms shown in figure 9.1 at the end of the injection phase.

All stops during the 240 hour injection period have been neglected in the simulation, so that the simulated injection phase lasts only 150 hours. Accordingly the total of 52 hours of production time during the two month recovery period are concentrated in the end of the period. This simulation procedure ensures a good approximation of the heat loss to the surroundings during the storage cycle.

Figure 9.2 gives the observed and simulated production temperatures. The observed values have been plotted at the end of the production cycle from 2130 h, though they started at 880 h. This gives rise to the temperature deviations seen at 2130 - 2150 h. The production is divided into two parts referring to a full screen production for 15 hours and production from the upper part of the storage for 37 hours. In this way the quick

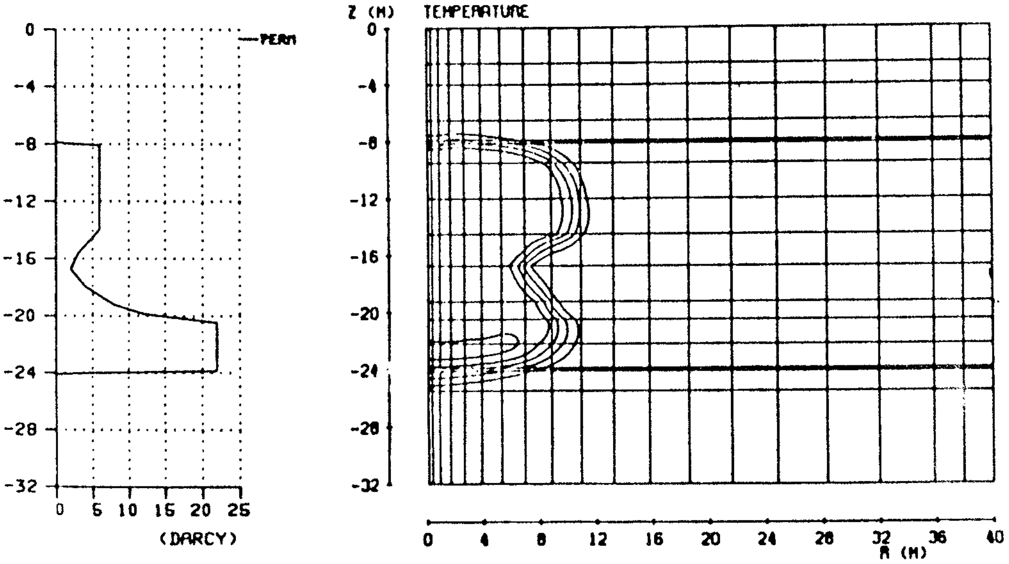


Figure 9.1. Horizontal permeability and temperatures in the reservoir at the end of injection. Isotherms are 35, 30, 25, 20 and 15°C.

breakthrough of cold water in the high-permeable zone in the bottom is prevented. At the end of the production phase, where the correspondance between real and simulated time is better, a very good agreement is found. The model performance is also illustrated by the calculated 55% energy recovery compared to 56% observed. A total of 90% of the volume was recovered.

## 9.2 Simulation of the first storage cycle.

A four week period of continuous injection of 100°C water at a rate of 7 kg/s has been simulated. Production is initiated immediately after the injection and is terminated, when the production temperature has fallen to 75°C. This criteria is given by the temperature levels of the associated district heating network. At a rate of 12 kg/s the production period lasts for 11 days and corresponds to a recovery of 65% of the injected water volume.

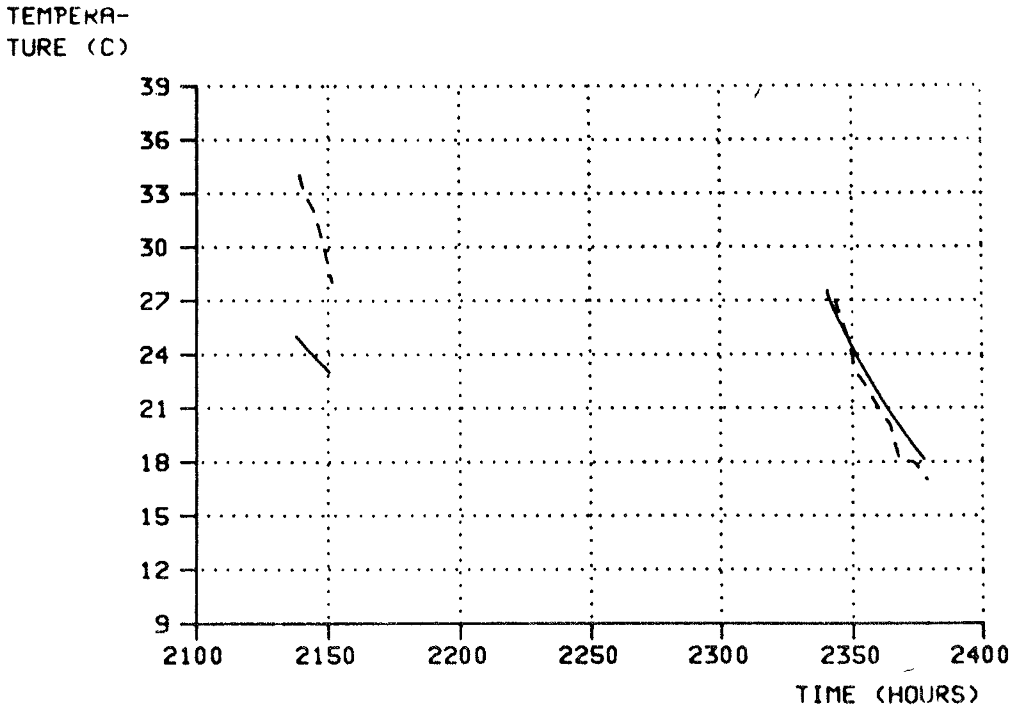


Figure 9.2. Simulated (full line) and observed (dashed) production temperatures.

The energy recovery in this simulation is 60%, which is a very promising result for a first storage cycle and concerning the very high temperature in the district heating network.

## 9.3 Conclusion.

The simulation model has proven to be a very effective tool for prediction and interpretation of aquifer storage experiments. The propagation of the heated zone is seen to be strongly dependent on the stratification within the reservoir. The permeabilities found by flowlogs were modified in order to obtain a satisfactory agreement between simulated and observed temperature fields. In this way the model supplemented and improved the understanding of the hydrological and thermal properities of the aquifer.

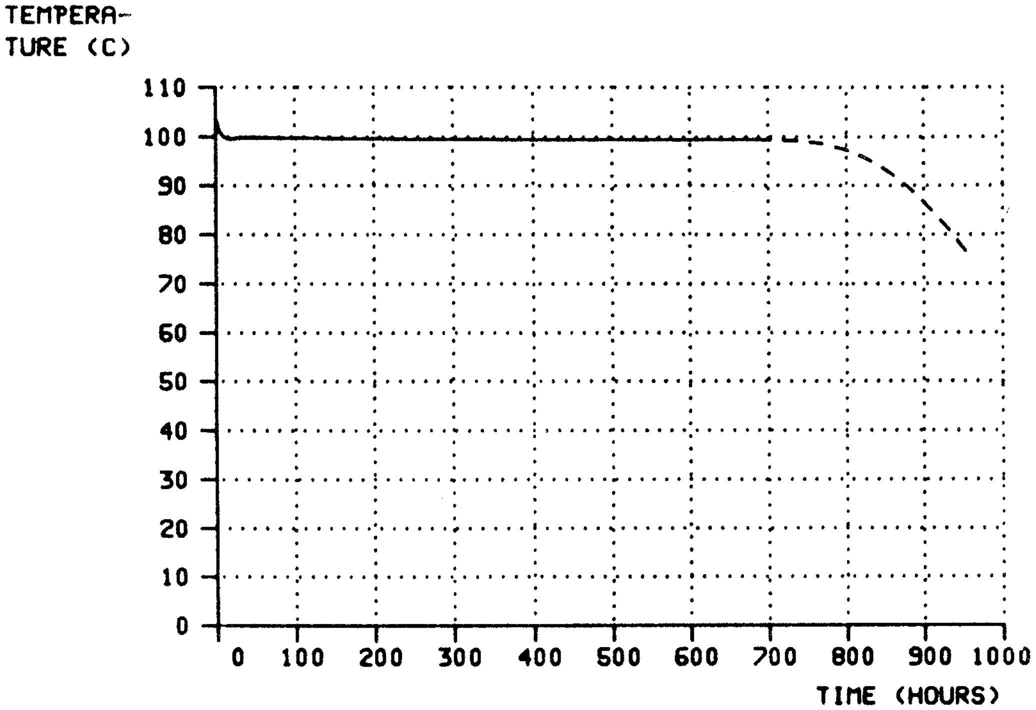


Figure 9.3. Injection (full line) and production (dashed) temperatures. Simulation of hypothetic cycle.

# 10. ECONOMICS

The following section presents an assessment of the economics of a commerciel ATES plant corresponding to the demonstration plant in Hørsholm.

The estimation is based on the concept configuration, geological conditions, dimensions, characteristics of the system connected to the store, and the function of the store.

Main data:

| | | |
|---|---|---|
| Maximum amount of energy for recovery | : | 1740 MWh |
| Maximum storage/recovery heat rate | : | 1.5 MW |
| Efficiency (estimated) | : | 80 % |

The store is connected to an incineration plant. During the summer, free surplus heat from the incineration plant is charged into the store. At Hørsholm the heat is returned to the district heating system both on summer weekends and during the autumn. However, in the economical evaluation only the autumn recovery is considered. Thus only seasonal storage aspects are considered.

Costs for construction of the plant are calculated from the real expenses of the plant in Hørsholm, but only expenses for instrumentation and dataprocessing that are needed in a commercial plant are included. Depreciation of costs for research is not included.

Costs in the start-up phase for heating of the aquifer from groundwater temperature to the lower working temperature and costs to meet heat losses are put to zero, as the heat source is free surplus heat.

The surface of the earth above the store may be used for other purposes, such as parking, roads, sport fields, grazing area for cattle or parks. Therefore the cost of the land has been set at zero.

## 10.1 Construction costs.

The costs for construction of a plant depend mostly on the required peak load output. This output determines flow rate and therefore the required number of wells, dimensions of the pumps, pipe dimensions etc..

The required flow rate may be reduced and with it the costs for construction decrease, if the difference in temperature between the hot and the warm reservoir increases. An increase of this temperature difference furthermore contributes to a better profitability by increasing the system efficiency (section 4.7).

An itemized listing of construction costs in Hørsholm are given below.

| | |
|---|---|
| Central well: | |
| One well with screen, pumping station, valves, pump, motors, ventilation and erection | 298,000 DKr. |
| Peripheral wells: | |
| 4 wells with screens, pumping stations, valves, pumps, motor, ventilation and erection | 805,000 DKr. |
| Auxiliary wells: | |
| 2 wells, the one with screen, pumping station, pump and regulation | 140,000 DKr. |
| Instrumentation wells: | |
| 8 wells with temperature-measurement instrumentation and pumping stations | 459,000 DKr. |
| Connecting pipes: | 385,000 DKr. |

Equipment in machinery house:

| | |
|---|---|
| 2 booster pumps with motors and regulations | 111,000 DKr. |
| 2 heat exchangers | 383,000 DKr. |
| Filtering system | 62,000 DKr. |
| Water treatment plant | 200,000 DKr. |
| Valves, expansion joints, coarse filters | 70,000 DKr. |
| Piping and insulation | 281,000 DKr. |
| Ventilation | 12,000 DKr. |
| Total | 1,119,000 DKr. |

Machinery house:

| | |
|---|---|
| Steel work, wood work, foundation, painting | 158,000 DKr. |

Instrumentation:

| | |
|---|---|
| Water level meters, pressure transducers, pressure switches, flowmeters, temperature-transmitters, manometers and thermometers | 195,000 DKr. |

Cable laying:

| | |
|---|---|
| Cables for signals and for power | 226,000 DKr. |

Electrical work:

| | |
|---|---|
| Electrical erection, control panel, computer, transmission line | 675,000 DKr. |
| Construction in total | 4,460,000 DKr. |

The prices are 1982 level inclusive taxes.

Converted into 1989 level construction costs in total, inclusive taxes, are 6,330,000 DKr.

(Rise in construction cost index from 1982 to 1989 is, according to the Statistical Bureau of Denmark, 1.42).

## 10.2 Operating costs.

Based on the experiences in Hørsholm ATES it seems probable that during operation of an ATES plant over extended periods of time, unforeseen operational problems, will occur. Examples are operations such as acid treatment of the wells, return flushing and cleaning etc.. Therefore an amount of money should be earmarked for extraordinary costs of operation and maintenance.

### Costs for operation of a store (Hørsholm)

| | |
|---|---|
| Consumption of electricity (for pumps): | |
| Loading and unloading the store,<br>40 KWh/MWh, totally 70 MWh of 775 DKr. | 54,250 DKr. |
| Data transmission: | 5,000 DKr. |
| Hydrocloric acid: | |
| Consumption is 480 ml 30% $HCl/m^3$ $H_2O$<br>in total | 40,000 DKr. |
| Maintenance: | |
| 60 hours (technician) | 8,700 DKr. |
| Supervision: | |
| 30 hours (technician) | 4,350 DKr. |
| Operating cost in total | 112,300 DKr. |

Operating costs per MWh recovered = 64 DKr./MWh

## 10.3 Pay back time

| | |
|---|---|
| Actuel price of fuel oil, incl. taxes | 3700 DKr./$m^3$ |
| Efficiency of oil burner | 0.88 |
| Lower thermal value | 40,614 KJ/Kg |

|  |  |
|---|---|
| Density | 965 Kg/m$^3$ |
| Net content of energy | 9.58 MWh/m$^3$ |
| Oil savings per MWh | 386 DKr./MWh |

|  |  |
|---|---|
| Construction costs | 6,330,000 DKr. |
| Oil savings per MWh | 386 DKr./MWh |
| Operating costs perMWh | 64 DKr./MWh |
| Net savings | 322 DKr./MWh |
| Net savings per year (1740 MWh) | 560,280 DKr. |
| Simple pay back time | 11 years |

The aquifer thermal-energy storage plant in Hørsholm is a pilot plant, which is not dimensioned optimally from an economical view point. The above mentioned pay-back time is therefore not as good as would be expected for a commercial plant with the same function. This is mainly due to the following factors:

The price for an ATES plant depends mainly on the maximum storage/recovery heat rate (peak-load output). The dimensions of the components such as wells, pumps, pipes, heat exchangers etc., are determined by the heat rate.

The size of the store at a given location is determined by the positioning of the wells relative to each other, and will not have much influence on the price. The maximum energy transfer, on the contrary, is determining the annual income. The pay back time of the store therefore depends on the relative importance of the size of the store and of the peak-load output. As an example, this means that economics are improved, for a given peak-load output, if the store size is increased. However, this may not be possible with the available existing geologically conditions, surplus heat, and the need for energy stored.

For the plant in Hørsholm, a doubling of the diameter, increasing the size of the store by form, would reduce the pay-back time to below 3 years.

## 10.4 Price estimates

A correlation for the total costs of high temperature energy stores is proposed in ref. 3 based on the investment costs, and the operational costs. The proposal is based upon the construction costs of Hørsholm aquifer thermal-energy store without extra measuring equipment and upon the operating costs of the Hørsholm plant.

The construction costs of Hørsholm ATES are calculated to 6,330,000 Kr. in 1989 prices. For the size of other plants, it is assumed that the price of heat exchangers etc. is proportional to the thermal output Q (MJ/s), and that the price of the rest of the store is proportional to the diameter of the store. This corresponds to a price proportional to the square root of the storage volume V ($m^3$) for a constant thickness of the aquifer. Hence the influence of the temperature on the price of the components has been neglected. As storage at high temperatures may require more expensive materiels this is a gross simplification.

The total investments in a high temperature aquifer energy store can be expressed as:

$$I = 0.42 \cdot Q + 0.0207 \cdot \sqrt{V}$$

The prices are converted from 1980 level to 1989 level by a 1,82 factor.

The corresponding cost of the plant in Hørsholm in 1989 prices is:

$$I = 0.42 \cdot 1.5 + 0.0207 \cdot \sqrt{75.000} = 6.3 \text{ mill DKr.}$$

The operating costs for Hørsholm ATES are about 150,000 Kr. including maintenance. These costs are not proportional to the size of the store. Here it is assumed that the operating costs in million DKr. per year can be expressed by:

$$W = 0.373 \cdot 10^{-3} \cdot Q_{max}^{0.8}$$

where $Q_{max}$ is the maximum possible heat content of the store in MWh. In the store in Hørsholm $Q_{max}$ = 1,740 MWh.

For the aquifer thermal energy store in Hørsholm, the operating costs in 1989 prices are calculated as:

$$W = 0.373 \cdot 10^{-3} \cdot 1740^{0.8} = 0.15 \text{ mill DKr.}$$

It should be pointed out that this price is for a commercial plant without the large amount of measuring equipment (e.g. 17 instrumentation wells) installed in Hørsholm.

An annual cycle with a four-month charging filling and a four-month discharging period of the store as shown in figure 10.1 is assumed. The thermal output (MJ/s) and maximum heat content (MWh) are then related by:

$$Q = \frac{\pi}{2 \cdot 2880} \cdot Q_{max}$$

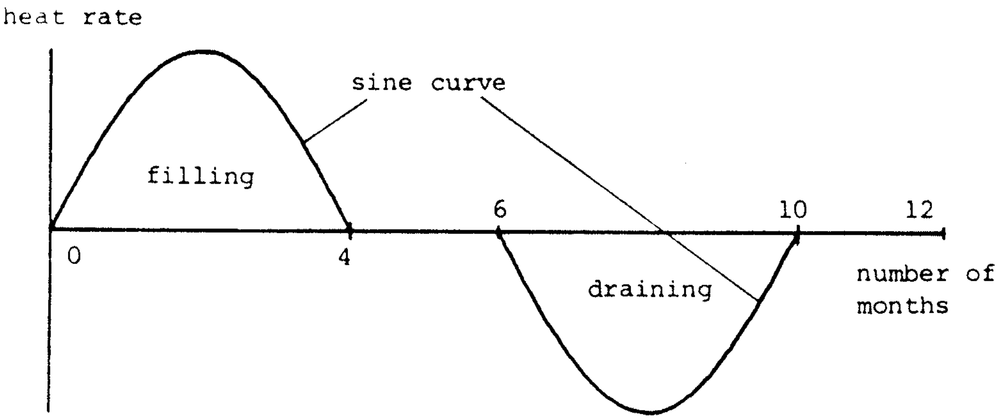


Figure 10.1 Assumed storage cycle for an ideal store (system efficiency of store equals one).

An economic lifetime of a store is assumed to be N years, and the effective rate of interest (corrected for inflation) is 100 r per cent per year. Thereby, the total annual storage expenses, E, (operating costs plus depreciation of investments costs) can be expressed as:

$$E = W + \frac{I - r}{(1 - (1+r)^{-N})}$$

If N = 20 years and r = 0.05, the expression gives for the plant in Hørsholm:

$$E = 0.15 + \frac{6.3 - 0.05}{(1 - 1.05^{-20})} = 0.65 \text{ mill. Dkr.}$$

These four formula expressions reflects the total specific costs, C, for establishment and operation of a store.

The specific storage costs are defined as:

$$C = \frac{E}{Q_{max}}$$

With E = 650,000 DKr. and $Q_{max}$ = 1,740 MWh the specific storage costs are 370 DKr/MWh.

In figure 10.2 curves for the specific storage costs are recorded, as a function of the size of the store and the temperature difference between hot and warm storage volumes. The figure applies to an ideal heat store, where the heat is delivered to the store at no cost.

The figure is to be considered as a first estimate only of the expected price level.

The key figures for a high-temperature store such as the one in Hørsholm are:

| | | | |
|---|---|---|---|
| $Q_{max}$ | , | maximum heat content at 40°C temperature difference | 1,740 MWh |
| I | , | investment in 1989 level | 6,330,000 DKr. |
| W | , | operating costs in 1989 level | 150,000 DKr. |
| E | , | total specific costs | 650,000 DKr. |

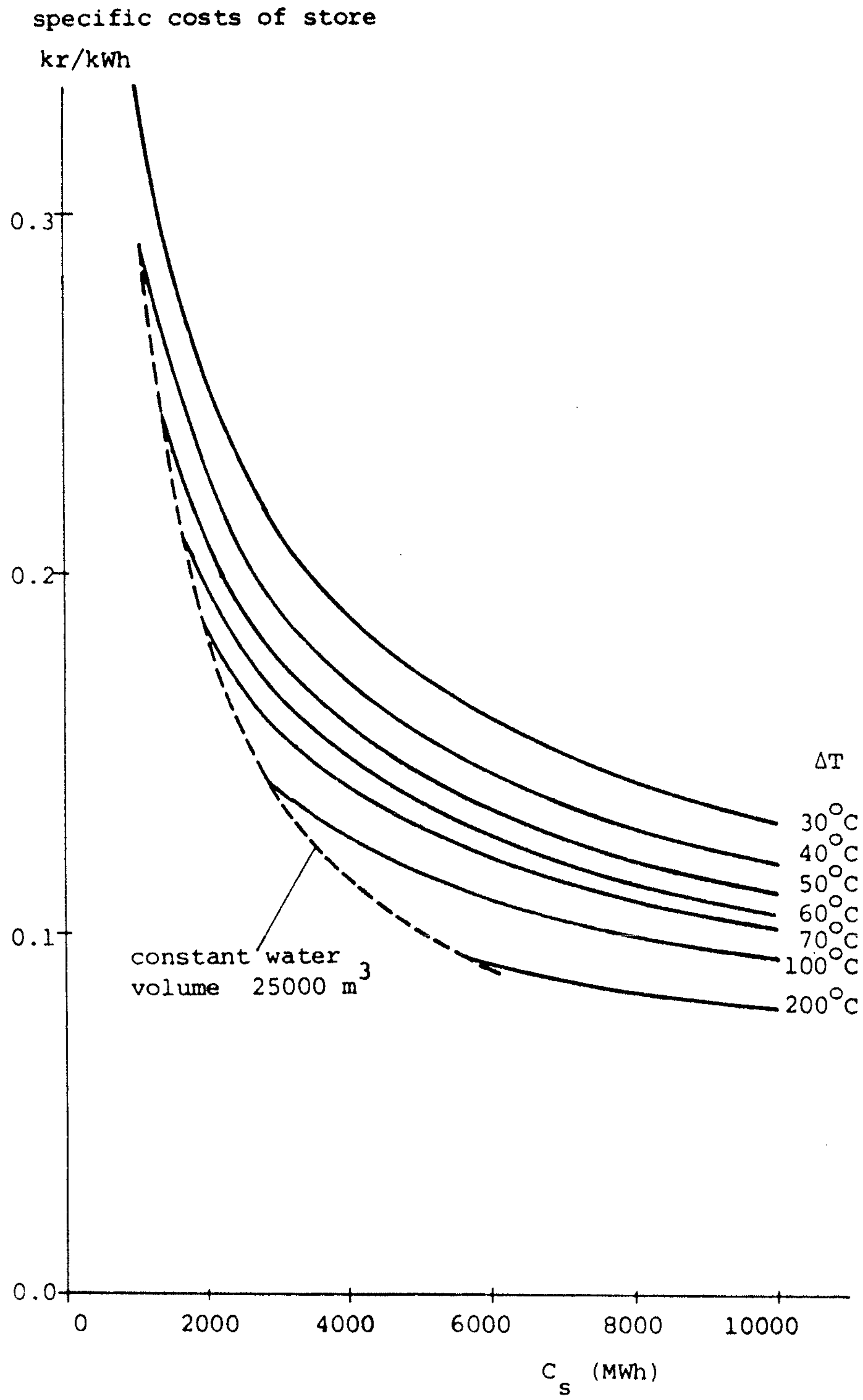


Figure 10.2 Total specific costs to charge and discharge one kWh of heat into and out of an ideal confined aquifer store. Δ T is the temperature difference between the hot well and the warm well. The curves are estimated based on the costs of Hørsholm ATES.

# 11. CONCLUSION

The experiences that have been compiled have confirmed that the project has been quite ambitious from the start. The design has been complex with a high degree of automation and monitoring and with a large number of running measurements of temperature, flow, pressure and acidity. Problems arising from these secondary aspects of the plant dominated the operation for a number of years.

It has also been a major problem that a research project namely the store has been connected to an existing high-temperature district heating system. The consequence of this has been that storage has only been possible when surplus heat has been available. Renovation and failures in the district heating system have caused interruption of the operation of the storage plant.

Important results from the operation of the store are that:

- heat may be delivered from and returned to a high-temperature district heating system.

- the store functions well in unmanned operation.

- the treatment chosen to prevent calcium scaling has been made to function.

- the mathematical models of groundwater flow are sufficient for the study of such stores. The experimental results are in fair agreement with the theoretical predictions.

- iron precipitation has occurred in spite of intensive efforts to make the plant airtight. This problem has not been solved.

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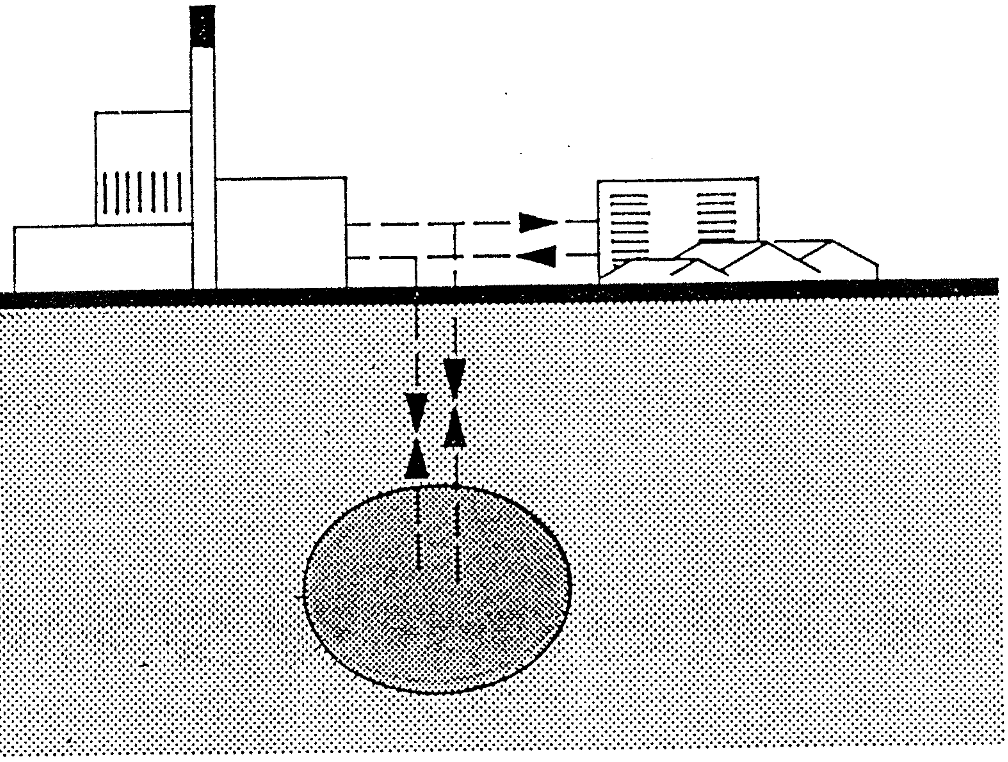
Aquifer Thermal Energy Storage

The Energy Research Program
of the Danish Ministry of Energy

Risø-M-2852

# The Danish Aquifer Thermal Energy Storage Project



## Part 2

# 1. OPERATIONAL CYCLES

During the lifetime of the project a total of six cycles of storage and recovery have been carried out more or less successfully. In spite of several mishaps, a storage cycle has been carried out each year during the years 1982 - 1987. Recovery has only been carried out successfully twice.

The 5 operational cycles are described in this chapter.

## 1.1 The first cycle, 1982

The construction of the plant was not completed until the end of the summer of 1982 and there was only a limited time left for storage of waste heat. Therefore, the amount of heat injected during the initial experiment was small. The period left for storage was 3 weeks and the injection temperature did not attain the nominal value.

As permeability is highest in the lower part of the aquifer the valve in the central well was closed during injection, in order to restrict the flow to this section.

When injection was complete there was a waiting period of three weeks, and then heat withdrawal was started, discontinuously.

The withdrawal was stopped when the reservoir temperatures in the observation well IW1 had decreased to approximately the original values.

## 1.2 The second cycle, 1983

The first full-scale storage cycle of the plant was planned to be carried out during the summer of 1983.

The injection started in mid June. Shortly after the start a spring of water was discovered from several points on the ground around the instrumentation well IW12. Evidently, there was a leak through the upper confining clay layer close to the instrumentation well.

Injection stopped and an investigation was undertaken, in order to locate the leak. During this, several test wells were drilled into the upper reservoir, in which the water level could be logged during test injections. The explanation was arrived that is was a crevice through the clay which was issuing from the central injection well. A flowlog in the central well during injection indicated that 65% of the volume flow originated from the top of the reservoir.

The reason for the leak through the upper layer of clay seemed to be a too high injection pressure combined with an existing weakness in the layer of clay. The geological investigation showed that a thin sandy layer was present in the clay. Material from this layer could have been washed away from the top of the storage reservoir during the initial tests, and a weakness of the clay could then have been exposed that would cede when subjected to the full injection pressure.

The rupture was repaired by injection of concrete through the upper part of the screen in the central well. Before injection of concrete - an annular blocking was cast below the leak in order to prevent intrusion of concrete into the reservoir. The injection of concrete was controlled by packers placed in the screen.

The rupture occured at a very inconvenient time. The geological investigations and repairs lasted most of the summer.

In the late summer the injection of heat was resumed, but due to the late time of the season, there was only enough waste heat to charge about 10% of the store. Injection stopped in October when there was no more surplus heat available.

After a dwell period of 3 weeks, recovery was started. Due to the modest amount of heat injected into the aquifer energy recovery was only possible for ten days. Recovery stopped when the temperature of the ground water was very close to the temperature of the district heating system.

## 1.3 The third cycle, 1984

During winter, the water treatment system was improved, and in spring cold water was injected into the central well in order to test the water treatment system. During this test cycle in April, a new leak appeared about 20 metres away from the central well. It seemed as if the old leak had reopened.

By several tests it was determined that the leak turned out to be active only during injection into the central well, not during production.

To avoid any more leaks it was decided to establish a new and larger central well for injection. In this way the injection pressure could be kept at a low level. Establishment of a new central well was delayed until February 1985 in order to make use of the surplus heat produced at the incinerator plant during the summer months.

The system was reversed so that water was pumped from the central well, heated in heat exchangers, and the hot water was injected in the peripheral wells. In this way, the plant was operated during the whole summer, storing heat through the 4 peripheral wells.

Storage started late May. For the first 3 weeks of storage, storage was only possible during the day, as the computer controlling system did not work and personnel had to supervise the plant .From the middle of June, the plant worked automatically and storage took place both day and night.

During operation, a number of operational problems appeared such as valves opening at wrong points, corrosion of thermal pockets and valves sticking.

Storage through the peripheral wells was discontinued at the beginning of October. Recovery did not take place that year, since the leak made injection in the central well impossible.

The log book for the 1984 storage cycle is shown below.

| Date | Event |
|---|---|
| 04.12 | Start of injection of cold water in order to test the acid treatment plant. |
| 04.16 | Leak reopened. Injection stopped. |
| 04.17 -<br>05.21 | The plant is made ready for storage in the peripheral wells. |
| 05.22 | Start of storage in the peripheral wells.<br>Ground water flow is 40 $m^3$/h. |
| 05.22 -<br>06.18 | Storage in peripheral wells during day. The plant is closed down at night as the automatically operation is not working. |
| 06.19 | Storage at nights, too. The automatic control is now working. |
| 07.12 | Close down required by the incinerator plant. |
| 07.17 | Injection started again in agreement with the incinerator plant. |
| 07.18 | Close down due to failure in the computer controlling system. |
| 07.23 | Start of injection very difficult due to closed regulating valves in the wells. |
| 08.14 | Close down due to defective motor at the borehole pump in the central well. |
| 08.21 | Start of injection. |
| 09.03 -<br>09.07 | Amount of surplus heat unstable and not large enough for storage. Close down. |
| 09.08 | Injection started again in agreement with the incinerator plant. |

10.04 Close down due to leak in pipe system.

10.10 No more surplus heat. End of charging.

## 1.4 The fourth cycle, 1985

Due to the appearance of a leak close to the central well two years in succession a new center well was drilled during the winter of 1985. The new well was drilled 6 metres southwest of the old well. In order to reduce the injection pressure the diameter of the new well was increased to 28 inches. The diameter of the old well was 14 inches. The well was screened from 14.73 to 23.73 metres below ground level. In order to permit observation of injection pressures, four filters were placed at different depths between 7.5 and 14.5 metres in the gravel outside the screen. The new well was used for heat injection only, while the old well was used for production.

Heat storage started in May, but several new problems were encountered during the 1985 storage season. In the machinery building the weldings in many of the steel pipes corroded. Also, the HCl system leaked, causing HCl to be sprayed onto pipes and pumps, leading to corrosion of the pumps. The reason for this leak, was a one-way valve specially constructed for the acid treatment system (vacuum) which did not open. Still the acid pump pumped acid towards the closed valve until packings leaked and HCl was sprayed all over the installations and components in the machinery house. This resulted in corroded motors, pipes and meters (pressure, pH, temperature).

A leak occurred in the vacuum system used for $CO_2$ removal, preventing the $CO_2$ from being removed. This allowed the entrance of air, whereby iron precipitated in the new central well, clogging this thus causing the injection pressure to increase. Acid treatment of the central well was therefore required. There were also problems at the incineration plant, and these resulted in several periods without surplus heat.

The charging was discontinued in September due to problems with the boilers at the incineration plant.

The log book for the 1985 cycle is shown below.

| Date | Event |
|---|---|
| 05.29 | Start of charging. Ground water flow is 30 m$^3$/h. |
| 06.03 | Storage interrupted due to leak in 2 pipes in machinery house. Pipes renewed and storage continued. Flow is 35 m$^3$/h. |
| 06.05 | No surplus heat. Close down. |
| 06.07 | Storage started in agreement with the incinerator plant. Ground water flow is 40 m$^3$/h. |
| 06.17 | Break down. Leak in the acid system. |
| 06.18 | No surplus heat. |
| 07.09 | Storage started after repairs due to the leak in the acid system. Flow is 30 m$^3$/h. |
| 07.22 | Flow decreased to 25 m$^3$/h because of shortage of surplus heat. |
| 07.26 | Storage discontinued by order from the incinerator plant. |
| 08.06 | Storage started again in agreement with the incinerator plant. Flow is 60 m$^3$/h. |
| 08.07 | Flow decreased to 50 m$^3$/h. |
| 08.08 | Flow decreased to 40 m$^3$/h due to high injection pressure. |
| 08.09 | Flow decreased to 25 m$^3$/h. |
| 08.10 | Storage discontinued because of failure in the computer controlling system. |
| 08.12 | Storage continued. Flow is 30 m$^3$/h. |

08.13 Flow decreased to 25 $m^3/h$ due to high injection pressure.

08.16 Close down after order from the incinerator plant.

08.20 Storage started in agreement with the incinerator plant. Flow is 25 $m^3/h$.

08.22 No surplus heat. Storage discontinued.

09.01 Acid treatment of the new central well CW2.

09.04 Storage started.

09.15 Problems with boilers in the incinerator plant. End of storage.

Heat delivery was started immediately after shut down. At this time the return temperature of the district heating system was 80°C, while the temperature delivered from the store was about 84°C. About two months of injection passed by before it was discovered that the reason for this high return temperature seemed to be an insufficient cooling of district heating water in a school connected to the district heating system just upstream of the heat store.

In the middle of November the return temperature in the system was lowered but at this time most of the heat stored had risen to the top of the store due to buoyancy flow and the amount of energy recovered was very small.

## 1.5 The fifth cycle, 1986.

The grant from the energy research program was terminated in 1985. Other possibilities for grants were therefore investigated and with support from the program for "new technologies" under the Ministry of Energy it became possible to continue the project for 2 more years. Under the new grant, the ownership of the aquifer thermal energy storage plant was transferred to "Nordforbrænding" I/S as owner of the incinerator plant which supplies the district heating system.

The final confirmation of the grant was delayed and arrived in May 1986. The project was therefore inactive until May. In connection with the transfer of the incinerator plant some repairs and redesigns were to be carried out. These repairs and redesigns etc. were not started until May and not finished until July.

For these reasons, the fifth period of injection started only in July 1986. New elements introduced to the system caused troubles during operation and the injection cycle was unstable. A by-pass valve introduced as a pressure protection device caused problems by opening and closing at wrong pressures. The one-way valve that was designed especially for the acid system, had been replaced by an ordinary one-way valve, which did not function under vacuum, and air-venting valves mounted in the pumping wells allowed air to enter into the system during close down. The most important problem during the 1986 cycle was a leak in the system in the cyclone separator allowing air enter into the system. This caused clogging in the central well. After replacing the cyclone separator with an ordinary bag filter and after acid treatment of the central well, the plant operated satisfactorily until the supply of surplus heat stopped and the plant closed down for storage.

The log book for the 1986 storage cycle is shown below.

| Date | Event |
|---|---|
| 07.02 | Start of charging. |
| 07.04 | Vacuum pump defective. Booster pump at groundwater side not operational.<br>Injection interrupted. |
| 07.09 | Booster pump repaired. Acid valve defective. |
| 07.10 | Acid valve replaced. Start of storage. |
| 07.17 | No surplus heat. Injection discontinued. |
| 07.29 | Surplus heat again. Injection flow is 25 $m^3$/h. |

| | |
|---|---|
| 07.30 | Injection flow increased to 30 $m^3/h$ in agreement with the production of heat from the incinerator plant. |
| 07.31 | Injection flow decreased to 26 $m^3/h$ due to high injection pressure measured in CW. |
| 08.15 | Close down due to too high injection pressure. The high injection pressure is caused by a ferrous precipitation in the central well. |
| 08.16 - 08.21 | Pruning of the CW 2. |
| 08.21 | Injection started at 15 $m^3/h$. |
| 08.21 | High injection pressure due to air intake in the system. |
| 09.17 | Close down required by the incinerator plant. |
| 09.17 | Acid treatment of the central well. |
| 09.23 | Injection started in agreement with the incinerator plant. |
| 09.29 | Close down required by the incinerator plant. |
| 10.02 | Injection started in agreement with the incinerator plant. |
| 10.03 | Close down due to fire at the incinerator plant. No surplus heat. |
| 10.04 - 10.05 | Surplus heat at night. The plant is in operation only at nights. |
| 10.07 | Injection started both day and night in agreement with the incinerator plant. |
| 10.27 | End of injection. |

Immediately after end of injection, the system was prepared for recovery. It was discovered that the three-way-valves were leaking, and had to be repaired. After the completion of the repair and until Christmas, the temperature of the return pipe in the district heating system was too high (above 74°C) to make recovery possible.

At the time when the return temperature was lowered to about 65°C, most of the heat had risen to the top of the reservoir and was impossible to retrieve.

Therefore no recovery occurred.

## 1.6 The sixth cycle, 1987

The sixth period of injection started in May 1987. The injection lasted four days. Early in the morning of 25 May the system closed down due to an alarm installed in the control system. The alarm caused power cut in the operating system.

The reason for close-down was as follows:

During the weekend a valve in the hydrocloric-acid (HCl) system leaked. The acid system is placed above the cellar that was established for the degassing column. The cellar also contains the booster pump at the ground water side. HCl had been leaking into the cellar for the entire weekend.

An alarm placed 2 cm above the cellar floor was actuated when the liquid level rose above the alarm. The alarm caused power cut in the operating system for as long as the liquid level was above the alarm.

Due to the many operationel problems during the earlier years of the project it was questioned whether another injection cycle would be economically feasible.

Late June, the decision was made to go ahead with the injection starting 6 July until 15 August. Recovery would take place immediately thereafter.

On 7 July 1987 the second period of injection started. Storage proceeded without any major problems and it was decided to continue storage as long as possible.

Late September, the injection cycle discontinued due to clogging of the central well CW2. The injection flow was then decreasing from day to day.

The log book for the 1987 storage cycle is shown below.

| Date | Event |
|---|---|
| 05.21 | First start of charging. |
| 05.25 | HCL in the cellar due to a leak in valve in acid system. Injection stopped. |
| 06.02 | Injection interrupted until further decisions. |
| 06.29 | Decision has been made that injection will continue from 6 July until 15 August. |
| 07.07 | Second start of injection. Ground water flow is 30 $m^3$/h. |
| 07.09 | Injection interrupted due to leak in booster-pump. |
| 07.17 | Injection started with an injection flow at 20 $m^3$/h. |
| 07.20 | Injection flow increased to 30 $m^3$/h. |
| 07.21 | Injection flow increased to 40 $m^3$/h. |
| 07.23 | Precipitation of FeO in filters due to a leak allowing air to enter into the system. |
| 07.27 | No surplus heat. Injection discontinued. |
| 07.28 | Surplus heat again. Injection flow is 35 $m^3$/h. The temperature in the district heating system is only $80^{\circ}$C. |

| | |
|---|---|
| 08.07 | Injection flow decreased to 25 m$^3$/h to accomodate the production of heat from the incinerator plant. The temperature in the district heating system rose to 90$^{\circ}$C. |
| 08.18 | Injection flow increased to 30 m$^3$/h in agreement with the production of heat from the incinerator plant. The temperature in the district heating system rose to 92$^{\circ}$C. |
| 08.28 | Close down due to too high injection pressure. |
| 08.31 | High injection pressure was caused by air in the central well, CW2. Injection was restarted with an injection flow of 30 m$^3$/h. |
| 09.06 | Close down required by the incinerator plant. |
| 09.08 | Injection started at 28 m$^3$/h in agreement with the incinerator plant. |
| 09.09 | Injection flow arose to 30 m$^3$/h in agreement with the incinerator plant. |
| 09.12 | Close down due to lack of surplus heat. |
| 09.13 | Injection started again with an injection flow of 30 m$^3$/h in agreement with the incinerator plant. |
| 09.20 | CW2 was clogging. The injection flow decreased to 15 m$^3$/h. |
| 09.21 | End of injection. |

Immediately after close down and end of injection the plant was prepared for start of recovery.

Recovery started 24 September. The recovery temperature from the store was 90$^{\circ}$C, and the temperature of the water in the district heating system was 66$^{\circ}$C. Recovery went on without major problems for two weeks, but the heat transfered in the heat exchangers decreased gradually. 8 October the plant was closed down for cleaning of the heat exchangers. At this time there was a temperature difference between the two sides of the heat exchangers of 8°C (the heat exchangers are dimensioned for a difference of 3°C).

One of the heat exchangers was cleaned with $HNO_3$ for three hours. The precipitation was black and oily. Due to the appearance of the precipitation (not chalk) cleaning continued with NaOH for another 2 days. The cleaning process was succesful.

13 October recovery was started once more. The recovery temperature from the store was at this time 81°C. The temperature difference across the heat exchanger was 4°C.

From 26 October the recovery was interrupted during night time. The reason was that the temperature of the return water in the district heating system was 65-70°C. The recovery temperature from the store was 71°C.

Recovery continued until 16 November. During this last recovery period the recovery temperature was typically around 67-70°C. At this time heat exchangers as well as screens in the peripheral wells clogged and recovery was discontinued.

The recovery cycle 1987 is listed below.

| Date | Event |
|---|---|
| 09.24 | Start of recovery. Ground water flow 33 m$^3$/h. Recovery temperature from the store 90°C. The return temperature in the district heating system 66°C. Energy rate recovered 0,55 MW. |
| 09.25 | Flow decreased to 22m$^3$/h. Energy rate recovered 0,4 MW. |
| 09.30 | Close down required by the incinerator plant. |
| 10.01 | Injection started again in agreement with the incinerator plant. |
| 10.07 | Increase in temperature between the two sides of the heat exchangers at 8°C. Heat exchangers are clog- |

ging.
Recovery temperature from the store 84°C.

10.08-12 Cleaning of heat exchanger with $HNO_3$ and NaOH.

10.13 Start of recovery with a ground water flow at 20 $m^3/h$. Decrease in temperature across heat exchanger at 4°C.
Recovery temperature from the store 81°C.

10.26 Recovery temperature from the store 71°C.
Recovery during night time is stopped, as the return temperature in the district heating system is 65-70°C.

11.05 Close down due to too high injection pressure.

11.10 Dirt in regulating valves has caused high pressure.
Start of recovery with a ground water flow at $15m^3/h$. Recovery temperature from the store is 66°C. The pressure drop in the peripheral wells increase. Heat exchangers are about to clog.

11.16 End of recovery.

## 2. OPERATIONAL EXPERIENCES

The problems that have appeared, have made it impossible to carry out a complete storage/recovery cycle. Most of the problems have been of a technical nature.

In the subsequent sections the most important of the problems that have caused operational stops of the plant are presented. The reasons or explanations for the mishaps are also presented. Many of the mishaps have occurred repeatedly, but have only been mentioned once in the subsequent list.

### 2.1 Operational experiences, 1982

The construction of the plant was completed at the end of the summer of 1982, and there was only a short time left for operation. The plant was operated manually during the 3 weeks of injection and the subsequent period of withdrawal, and the operation of the plant was carried out without any technical problems.

### 2.2 Operational experiences, 1983

The predominant problem during the summer of 1983, was the appearance of a leak through the upper layer of clay. The leak made injection in the central well impossible.

The origin of the leak seamed to be a weakness in the upper layer of clay combined with a too high injection pressure.

The plant was closed down during the summer months, where investigations of the leak were carried out.

During the first three weeks of injection in september, the central well was gradually clogged. When the injection flow had decreased too much, the well was regenerated to its original performance by acid treatment.

## 2.3 Operational experiences, 1984

In 1984 the leak problem appeared once more, and the plant was operated by injection in the peripheral wells during the entire summer.

The operational mishaps which have occurred during storage in the peripheral wells in 1984, and the reasons or explanations for them, are listed below.

### Charging

| Date | Event |
|---|---|
| 05.24 | Break down of vacuum pump:<br>When the water level in the degassing column rises, an automatically controlled valve should close off the pipe to the vacuum pump. The control of this valve has functioned incorrectly.<br><br>The vacuum pump is dismounted and replaced.<br><br>The plant is closed down for 5 days. |
| 06.03 | Pressure transducers placed in the central well and the peripheral wells are out of function:<br>The pressure transducers do not tolerate high temperatures and vibrations from the pumps.<br><br>The plant is operated without measuring the water level in the wells. |
| 06.21 | Data transmission not working:<br>Failure in the permanent modem.<br><br>Data transmission is operated through the usual telephone line instead of the permanent modem line.<br><br>The plant is not closed down. |

08.06 Corrosion of thermal pockets:
Addition of hydrocloric acid in the first years of the project has not been controlled sufficiently close, and sometimes too much acid has been added.

Thermal pockets are replaced.

The plant is closed down for a few hours.

08.13 High injection pressure in several of the peripheral wells:
The regulating valves are unable to open completely.

The regulating valves are replaced whereby the flow rate is doubled.

The plant is closed down for half a day to permit replacement of the valve. The plant had been operated at a low flow rate for 14 days due to the malfunction of the regulating valves.

08.14 Borehole pump in the central well not operational:
Control of the borehole pump defective.

The control is replaced by the control of the booster pump in the district heating system.

The plant is closed down for one day.

08.16 Vacuum pump out of function:
A cover plate of the vacuum pump has fallen off due to vibrations, causing oil spray in the machinery house.

The vacuum pump is dismounted, repaired and mounted once more.

The plant is closed down for 2 days.

| | |
|---|---|
| Sept. | Heat exchanger leaks:<br>Double seals in the heat exchanger is broken.<br>The heat exchanger system is dismounted and seals are repaired.<br>The plant is closed down for 2 days. |
| 10.05 | Leak in pipe in machinery house:<br>The pipe is corroded due to overdosage of acid during the first years of the project.<br>The pipe is dismounted and replaced.<br>The plant is closed down for 5 days, while another pipe is fitted and mounted. |

## 2.4 Operational experiences, 1985

In the winter/spring of 1985, a new and larger central well was established and heat was in 1985 injected in this new well. Due to this, the injection pressure was low this year compared with the flow rate.

Nevertheless, the operation of the plant in 1985 was dominated by many operational problems. These problems and the reasons or explanations for them are listed below.

### Charging

| Date | Event |
|---|---|
| 05.31 | High injection pressure:<br>Three-way valve in central well is positioned incorrectly.<br>Air-escape valve out of function.<br>The three-way valve is replaced and the air-escape valve is cleaned. |

The plant is closed down for 1 day.

06.03 Leaks in pipes in machinery house:
2 pipes in the machinery house placed after the heat exchangers have corroded.

The pipes are welded.

The plant is closed down for half a day.

06.06 Leak in pipe in machinery house:
Another pipe is corroded.

The pipe is welded.

The plant is closed down for 1 day.

06.14 Leaks in 2 pipes in machinery house:
2 more pipes in the machinery house, placed after the heat exchangers, are corroded.

The pipes are welded.

The plant is closed down for half a day.

06.17 The plant has closed down due to an alarm: "Water in cellar in machinery house":
A submerged pump placed in the cellar for the purpose of sucking water in the cellar has not functioned. The water contains hydrochloric acid, that has ruined the submerged pump, the groundwater booster pump and the electrical installations located in the cellar.

The reason for the presence of acid in the cellar, appears to be a mal-function of an especially constructed one-way valve placed in the acid system.

The acid pump has pumped hydrocloric acid continously against the closed one-way valve, causing the acid to seep into the cellar beneath the acid treatment system.

The acid in the cellar is removed, and the cellar is cleaned and heated.

The electrical installations are replaced.

The booster pump is repaired by the manufacturer. The inside of the pump is corroded.

The plant is closed down for 21 days.

07.13 Hydrochloric acid evrywhere in the machinery house:
The acid treatment system has leaked, but the acid pump has continued to pump acid into the machinery house and into the cellar.

The ground water booster pump is once more out of function due to the acid spray.

The acid is removed from the cellar and the cellar is cleaned and heated.

The booster pump is repaired at Risø.

The plant is operating continously without booster pump.

07.31 Ground water booster pump not operational:
The commutator in the pump is corroded due to acid vapours in the cellar.

The pump is repaired by the manufacturer.

During these events, the plant was closed down anyhow because of shortage of surplus heat.

08.28 Air in the system. The content of oxygen in the water is measured in the machinery house to be twice as high as in the wells:
A leak is found in the tube to the vacuum pump and the pump is not able to remove the $CO_2$ from the degasser.

The tube is replaced.

The plant is still in operation, but for 3 weeks the flow rate has been low due to high injection pressure caused by air in the system.

09.02 Too high injection pressure:
The central well has clogged due to air in the system.

The central well is treated by a special acid for well cleaning.

The plant is closed down for 3 days.

## 2.5 Operational experiences, 1986.

New mechanical and electrical components were introduced to the plant during the spring of 1986 and this caused many problems.

The operational mishaps which have occurred in 1986 and the reasons or explanations for them, are listed below.

### Charging

| Date | Event |
|---|---|
| 07.04 | Ground water booster pump not operational:<br>Due to acid vapours in the cellar during previous years, the motor to the booster pump has corroded.<br>The motor has been separated and cleaned.<br>The plant is closed down for 4 days. |
| 07.09 | Hydrochloric acid is sucked into the system:<br>An especially constructed one-way valve (vacuum conditions) in the HCl acid pipe has been replaced by an ordinary one-way valve.<br>The plant is closed down half a day. |

| | |
|---|---|
| July | Too high water level in the degassing coloumn:<br>The absolute pressure conditions have not been considered when specifying the by-pass valve. |
| 07.24 | Non vacuum:<br>Leakage at vacuum tube.<br>Vacuum tube is replaced. |
| July | Oxygen registered in the system:<br>Air escape valves mounted in the pumping wells suck air into the system during close down.<br>Non-return valves are mounted in the air escape valves to avoid air sucktion. |
| 08.01-<br>08.15 | High injection pressure:<br>Precipitation in the central well.<br>The central well is pruned.<br>The plant is closed down for 4 days. |
| 08.21 | High injection pressure:<br>The central well has clogged due to air entering the system. Air leakage is located in the cyclone separator.<br>Cyclone separator is replaced by pipes. The central well is treated by acid (Herli Rapid). |

## 2.6 Operational experiences, 1987

The operational mishaps which have occurred in 1987 and the reasons or explanations for them, are listed at the following pages.

## Charging

| Date | Event |
|---|---|
| 05.25 | Leak in valve in acid system:<br>A screw-on connection made of plastic has broken. Plastic is the only materiel resistant to HCl, but it is not as strong as steel.<br>Screw-on connection has been replaced by one made of steel until the one of plastic has been repaired. |
| 05.25 | Break down of ground water booster pump:<br>Due to the above mentioned leak in the acid system, HCl has trickled down into the cellar where the booster pump is placed. Acid vapors have affected the booster pump motor.<br>The motor has been replaced by the motor from the pump placed in the center well.<br>The plant is closed down until 07.07. |
| 07.09 | Break down of ground water booster pump:<br>A bearing in the booster pump is broken, which has caused internal damage to the pump.<br>The pump has been separated and the internal parts have been renewed.<br>The plant is closed down for 7 days until the pump is mounted. |
| 07.09 | Break down of vacuum pump:<br>A motorized valve is placed in the pipe connecting the degassing column and the vacuum pump which is controlled by the water level in the degassing column. The valve opens if the water level is below 1,5 m.<br>Due to an indication error in water level, the valve has been open when the water level rose and water has entered the vacuum pump. |

Bearings in the pump are broken and the shaft has been damaged.

Bearings have been renewed and the shaft has been repaired.

The plant is in operation without vacuum pump for 3 days.

07.16 Break down of motor of the ground water booster pump;
It seems that the motor has seized during the break down of the pump.

The motor is replaced by a similar motor from a pump at the district heating side of the system.

The plant is closed down for 2 days.

08.03 Clogged filters:
Due to a leak in the system allowing air to enter, the filters are clogged by FeO.
Filters are cleaned.
The leak in the acid system allowing air to enter is repaired.

The plant is closed down due to too high pressure for 2 days.

08.28 Air-escape valve in CW 2 out of function:
As the air-escape valve in the injection well CW 2 has been out of function, an air cushion has been built up in the well, causing too high injection pressure.
Air-escape valve is cleaned.

The plant is closed down for the weekend due to the high injection pressure.

09.02 The HCl supply was exhausted.
The operation of the plant was continued after consulting chemists. Precipitation of chalk due to

absence of HCl.
It was expected that precipitated calcium would be retained by the filter for a limited period of time.

The plant is in operation without HCl for 4 days.

Recovery

| Date | Event |
|---|---|
| 10.08 | Too high temperature drop across heat exchangers:<br>Precipitation in heat exchangers. Heat exchangers are cleaned with $HNO_3$ and NaOH.<br>The plant is closed down for 5 days during cleaning of heat exchangers. |
| 10.15 | Decrease of 3°C in water temperature between entrance into the machinery house and the heat exchanger.<br>The ground water booster pump has been insulated. The booster pump is cooled by a fan, whereby cooled air from a tube connected to the fan, unfortunately, also cools the pipes in the cellar. The tube from the fan cooling the booster pump has been removed to reduce heat losses.<br>The plant is still in operation. |
| 11.08 | Too high back pressure in the peripheral wells:<br>Dirt in the regulating valves placed in the peripheral wells has caused high pressure in the system. The valves have been cleaned.<br>The plant is closed down due to high pressure for 2 days. |
| 11.10 | High pressure drop across heat exchangers: Heat exchangers clogged again.<br>The plant is still in operation, but the injection flow decreases gradually. |

# 3. OPERATIONAL RESULTS

The operational results of the five cycles are divided up into technical data and qualitative description of every cycle. The technical data gives the operational conditions listed during storage and if possible recovery, while the qualitative description is a publication of the results gained during the respective cycles.

## 3.1 Operational results, 1982

### 3.1.1 Technical data

The operational conditions of the injection period in 1982 were as follows:

Charging

| | |
|---|---|
| Accumulated injection period | 150 hours |
| Injection temperature (average) | 36°C |
| Injection pressure | 10 m above normal ground water level |
| Injection flow | 20-30 $m^3/h$ |
| Thermal power | 0,6 -0,9 MW |
| Total amount of energy injected | 65 MWh |

Recovery

| | |
|---|---|
| Charging period | 3 weeks |
| Recovery temperature, start | 34°C |
| Recovery temperature, stop | 17°C |
| Recovery percent | 55% |

### 3.1.2 Qualitative description

The course of the experiment is presented in figure 1. The two lower curves show the accumulated heat in the store, and the injection temperature as a function of time.

The seven upper curves show the reservoir temperature at different depths of the observation well IW1, located at a distance of 7m from the central well. Because of the limited scale of the experiment, an increase in temperature was not detected in the wells further away from the central well.

Since temperature measurements are only available for one single instrumentation well, it is not possible to conclude anything about the propagation in the horizontal plane.

In the vertical plane, the temperature development shows the fastest increase in the lower part of the aquifer. The reason for this, is a higher permeability here, than in the upper part. In the middle of the aquifer, the temperature rise is much slower than in the upper and lower parts, probably due to a very low local permeability.

Because of the small amount of energy stored, the recovery factor of this cycle is not representative of the full scale store.

The practical experience gained from the experiment is limited because of the low injection temperature. There is no basis for evaluations concerning the water chemical problems. However, additional results have been obtained. The various functions of the plant were tested and some technical problems were detected. Another result of the experiment is, that a set of data has been provided for testing and trimming of the mathematical model.

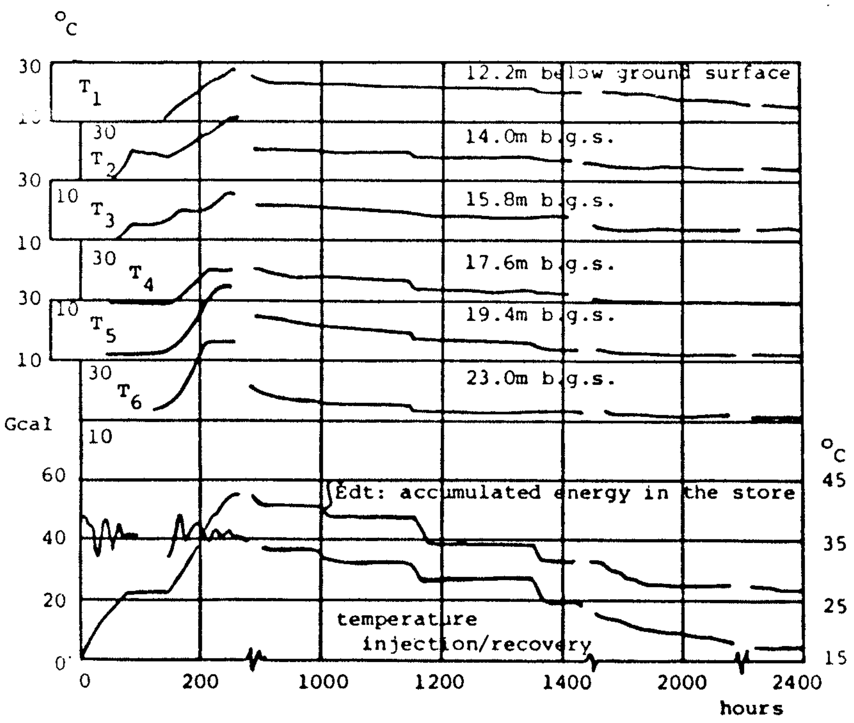


Figure 1. Temperatures in IW 1 as a function of time.

## 3.2 Operational results, 1983

### 3.2.1 Technical data

The operational conditions of storage and recovery in 1983 are listed below:

#### Charging

| | |
|---|---|
| Injection start | 6th September |
| Injection stop | 7th October |
| Injection period, accumulated | 264 hrs |
| Injection temperature | |
| 1st period, 12 hrs. | 30°C |
| 2nd period, 12 hrs. | 60°C |
| 3rd period, about 240 hrs accumulated | 100°C |

| | |
|---|---|
| Injection pressure | 9 m above normal ground water level |
| Injection flow | 20-45 $m^3/h$ |
| Thermal power | 1-4 MW |
| Total injected volume | About 6150 $m^3$ |
| Total amount of energy injected | 650 MWh |

Recovery

| | |
|---|---|
| Recovery start | 1st November |
| Recovery stop | 11th November |
| Recovery temperature, start | $80^\circ C$ |
| Recovery temperature, stop | $70^\circ C$ |
| Forward temperature, district heating system | $65^\circ C$ (average) |
| Thermal power | 0.25-0.35 MW |
| Flow, ground water | About 35 $m^3/h$ |
| Recovery time, accumulated | 25 hrs |
| Total recovery volume | 875 $m^3$ |
| Total amount of energy recovered | 8 MWh |
| Recovery percent | 1,2% |

### 3.2.2 Qualitative description

During the very short injection period the first experiences with the water treatment system were gained. In order to find the optimum adjustment of the system, water samples were taken under different conditions and analyzed.

No scaling of the heat exchanger was experienced, but during the first three weeks of injection, the central well was gradually clogged either because of $CaCO_3$ deposits due to inadequate adjustment of the water treatment system, or because of small mineral particles.

Figure 2 shows the temperature at different depths of the instrumentation well IW 2 placed 13 m from the central well. The curves are taken on 16th September after 10 days of charging.

Figure 3 shows the temperature in difference depths in IW 2 at the end of storage. Obviously the temperature level has risen during storage. Especially the temperature at the bottom of the aquifer has become higher, because of the high permeability at the bottom of the aquifer.

In figure 4 the isotherms are shown in both horizontal and vertical plots. The energy injected has been transported downstream. This stresses the importance of the auxiliary system whereby the natural ground water flow is bypassing the store. The isotherms are taken on 20 December 1983 one and one half months after the end of recovery.

The very low efficiency recorded is due to the fact, that only a very small part of the store was filled and that it was the first injection with nominal injection temperature. The temperature difference between the hot volume and surroundings therefore was very high. Therefore, the bouyancy has had a strong influence on the thermal front, causing cold water to break through to the central well in the lower part of the aquifer. But, when this has been said, it also has to be emphasized, that for the first time an amount of heat has been delivered from the store to the district heating system.

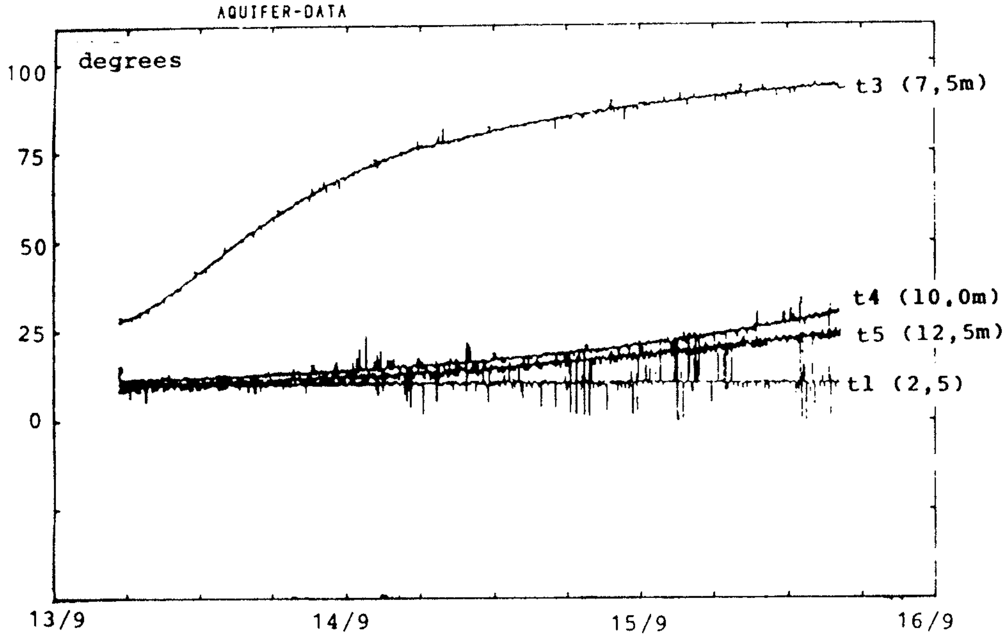


Figure 2. Temperatures in IW 2 after 10 days of storage.

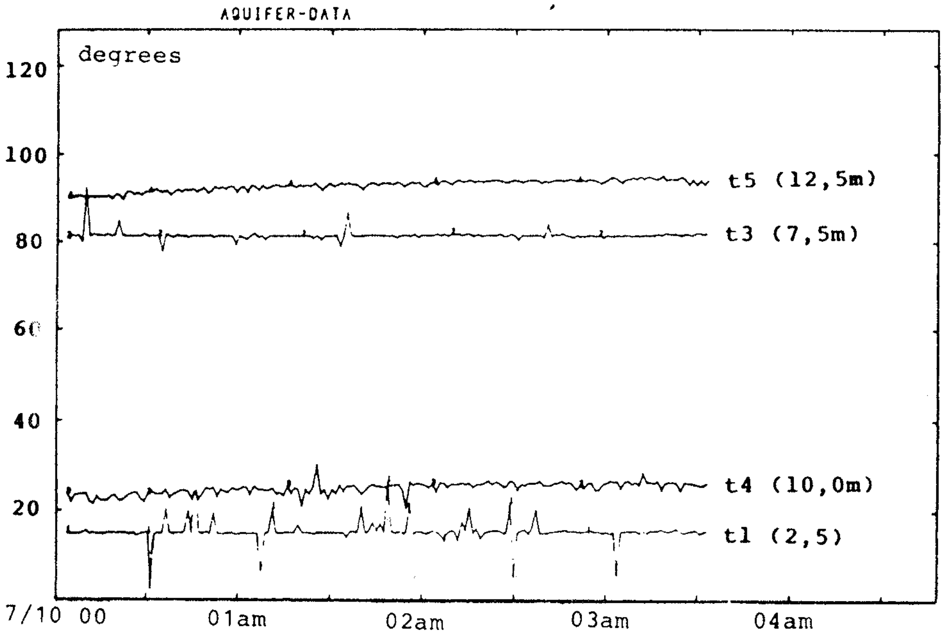


Figure 3. Temperatures in IW 2 at end of storage.

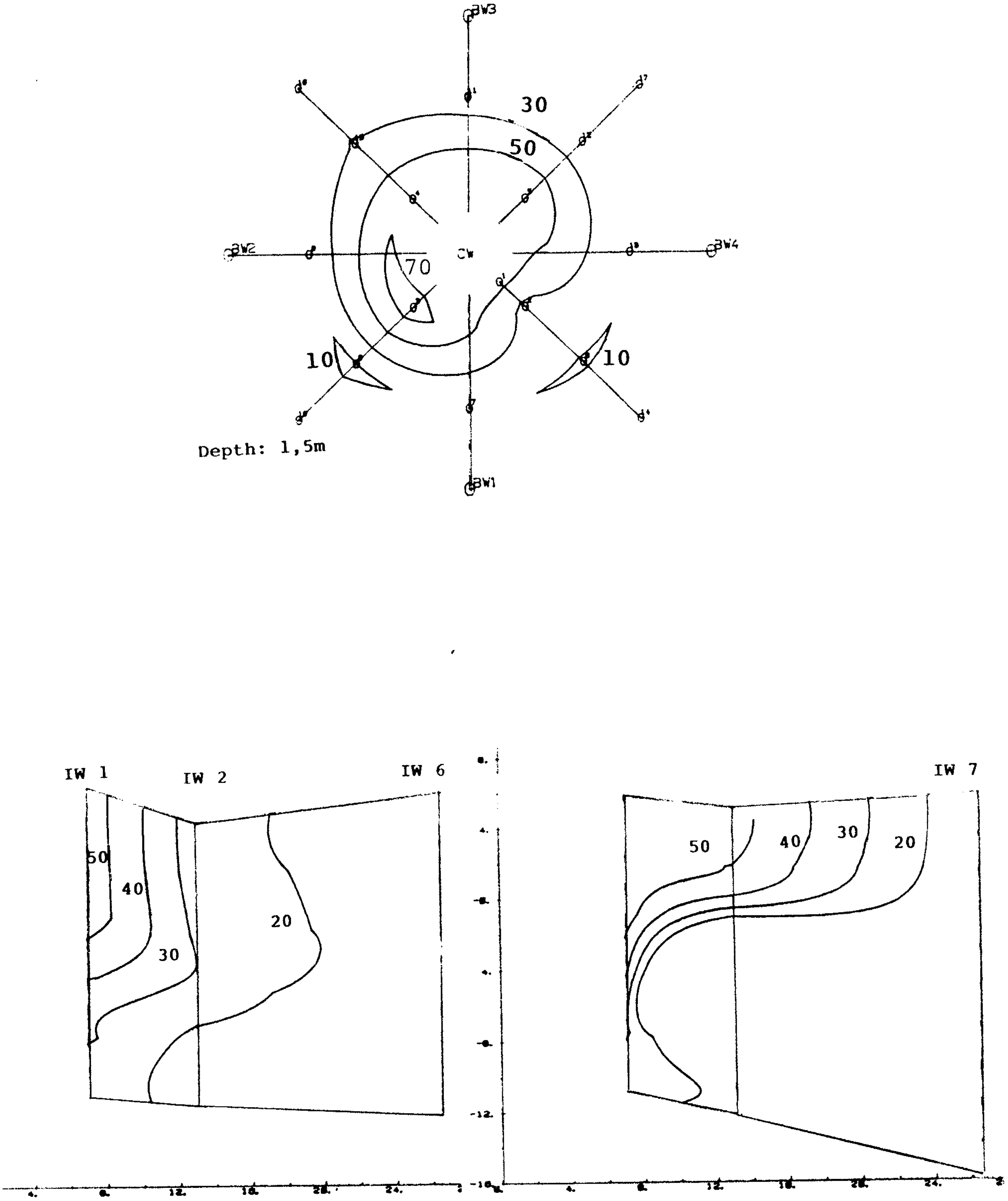
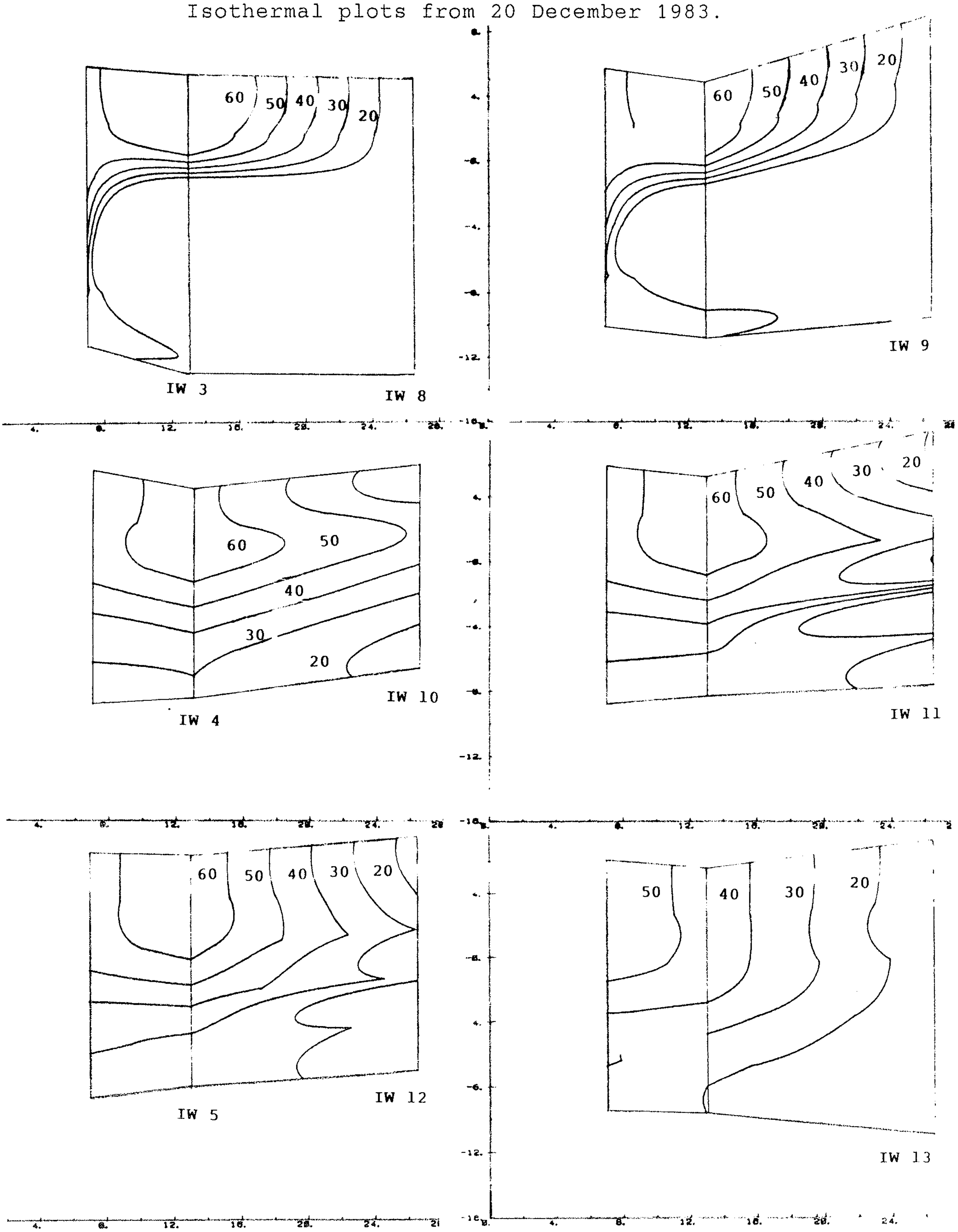


Figure 4. Horizontal and vertical cuts through the aquifer. Isothermal plots from 20 December 1983.

Figure 4. Continued:
Horizontal and vertical cuts through the aquifer.
Isothermal plots from 20 December 1983.



## 3.3 Operational results, 1984.

### 3.3.1 Technical data

The operational conditions of charging, which took place in the peripheral wells this year, are listed below:

Charging

| | |
|---|---|
| Injection start | 22th May |
| Injection stop | 5th October |
| Injection period, accumulated | 2300 hrs |
| Injection temperature | 100°C |
| Injection pressure | 9 m above normal ground water level |
| Injection flow | 25-45 $m^3/h$ |
| Thermal power | 1-3 MW |
| Total injected volume | About 60.000 $m^3$ |
| Total amount of energy injected | 2053 MWh |

### 3.3.2 Qualitative description

Due to the appearance of a leak close to the central well charging took place in the peripheral wells. The flow direction, therefore, has been reversed relative to the normal design during this charging period.

The charging in the peripheral wells was an emergency measure, to circumvent the problems created by the leak around the central well.

Recovery was not considered, as the only way to deliver heat, was to pump the hot water stored around the peripheral wells to the heat exchangers and inject the cooled water in the central well which would not be possible due to the leak.

However, experience with the operation of the plant was gained, and important elements were made working.

During the entire period of injection, the water treatment system worked satisfactorily. After the end of storage, one of the heat exchangers was inspected, and only a very thin film of $CaCo_3$ was visible.

The injection pressure has been steady during charging as there has been no clogging of the wells.

This year, the automatic computer controlled system has been put into operation, and during the last months of injection, the whole plant has been operated automatically. The computer caused occasional problems.

The purpose this year of injecting hot water in the peripheral wells, was to make use of the amount of surplus heat by increasing the temperature of the groundwater in the aquifer.

Figure 5 shows the temperature at different depths in the instrumentation well IW 8, placed 26.5 m from the central well. As the hot water has been stored in the peripheral wells, it is more interesting that IW 8 is placed between the peripheral wells BW 1 and BW 2, 28 m from each. The figure shows the rise in temperature during the complete period of storage. Again the temperature is highest at the bottom of the aquifer due to the high permeability.

Figure 6 shows vertical cuts through the aquifer along various radii. The mathematical model is made for storage in the central well with radially symmetrical propagation towards the peripheral wells. Since the charging was carried out in the peripheral wells, the model gives uncorrect facts of the isotherms in horizontal cuts. Because of this, only vertical cuts are illustrated. The isotherms are from 15 October, 10 days after end of storage.

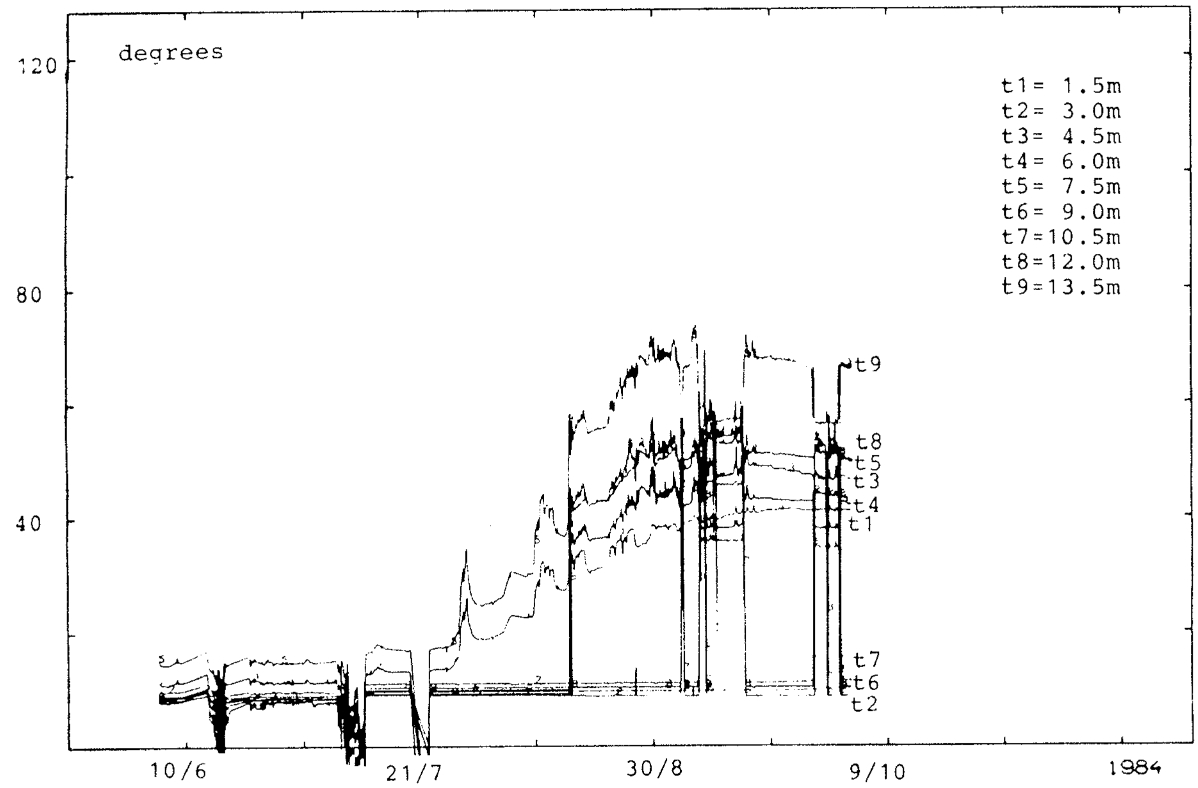


Figure 5. Temperatures in IW 8 during storage.

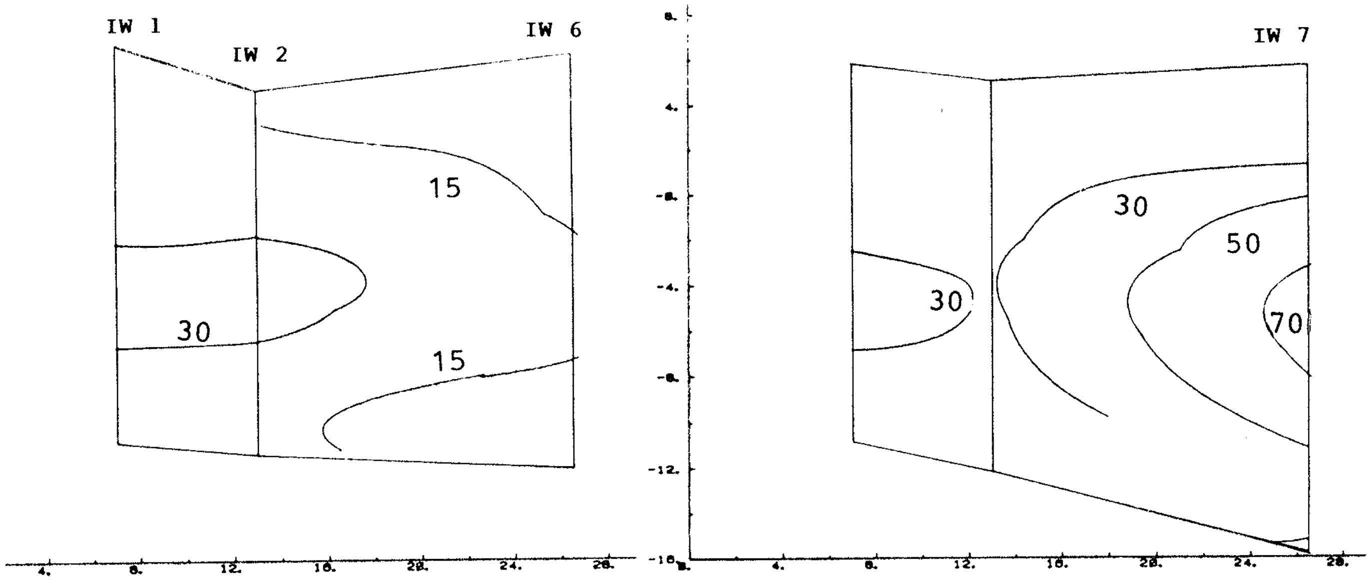
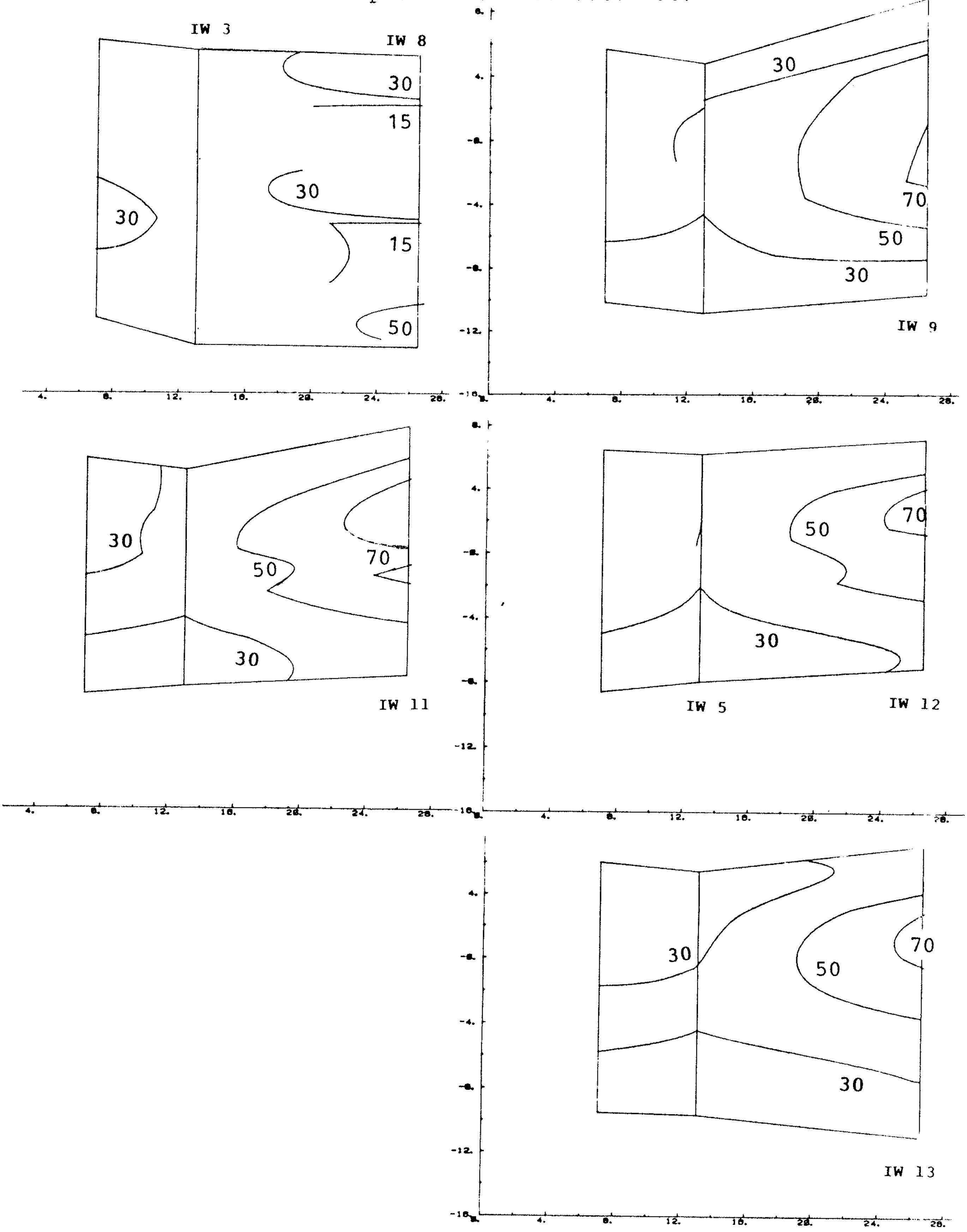


Figure 6. Vertical cuts through the aquifer.
Isothermal plots from 15. Oct. -84.

Figure 6. Continued
Vertical cuts through the aquifer.
Isothermal plots from 15. Oct. -84.



## 3.4 Operational results, 1985

### 3.4.1 Technical data

The operational conditions during charging and recovery in 1985 were as follows:

#### Charging

| | |
|---|---|
| Injection start | 29 May |
| Injection stop | 15 September |
| Injection period, accumulated | 530 hrs |
| Injection temperature | 95-100°C |
| Injection pressure | 5 m above normal ground water level |
| Injection flow | 20-60 $m^3$/h |
| Thermal power | 1-3 MW |
| Total injected volume | About 15.000 $m^3$ |
| Total amount of energy injected | 2110 MWh |

#### Recovery

| | |
|---|---|
| Recovery start | 24 October |
| Recovery stop | 5 December |
| Recovery temperature, start | 84°C |
| Recovery temperature, stop | 63°C |
| Forward temperature, district heating system | 80-62°C |
| Thermal power | 0,07-0,7 MW |
| Flow, groundwater | 15-30 $m^3$/h |
| Recovery time, accumulated | 208 hrs |
| Total recovered volume | About 3120 $m^3$ |
| Total amount of energy recovered | 12 MWh |
| Recovery percent | 0,6% |

### 3.4.2 Qualitative description

In order to solve the leak problem which occurred in 1983 and 1984 it was decided to establish a new central well for injection. This new well was established in the winter of 1985. It is located six metres away from the old central well. For the purpose of getting a smaller injection pressure it is necessary to get a greater area of the screen. Therefore, the diameter of the new central well is increased to 28 inches with a screen at 20 inches. The diameter of the old central well is 12 inches with a screen at 10 inches.

This year, the charging was started in May and because of some boiler problems at the incineration plant it was discontinued already in September. The injection pressure was very low (below 0.5 bar above normal ground water level) throughout the entire period.

The flow rate was between 20 and 60 $m^3/h$. The low flow rate was required in order to reduce some leak problems in the water treatment system.

In order to avoid clogging in the heat exchangers and the screens, hydrochloric acid was added by a dosage pump. Hereby, $CO_2$ was formed and removed in a degassing column. This year, there has been a leak in the vacuum system, preventing the removal of carbondioxide. Due to this, iron has precipitated in the new central well and the injection pressure increased.

Therefore, it has been necessary to give the new central well acid treatment, whereafter the system has functioned well.

This year the water treatment system caused an additional problem.

In the hydrochloric acid dirt clogged an injection nozzle. This did not prevent the dosage pump from adding hydrochloric acid. Leaks appeared in the O-rings and hydrochloric acid was pumped all over the machinery house.

Taught by bitter experience a filter has now been placed at the absorption side to remove dirt. Furthermore, a new injection nozzle with bigger gaps has been installed and a counter pressure valve has been placed between the pressure side and the vacuum side in order to by-pass the acid treatment unit in case of recurring clogging.

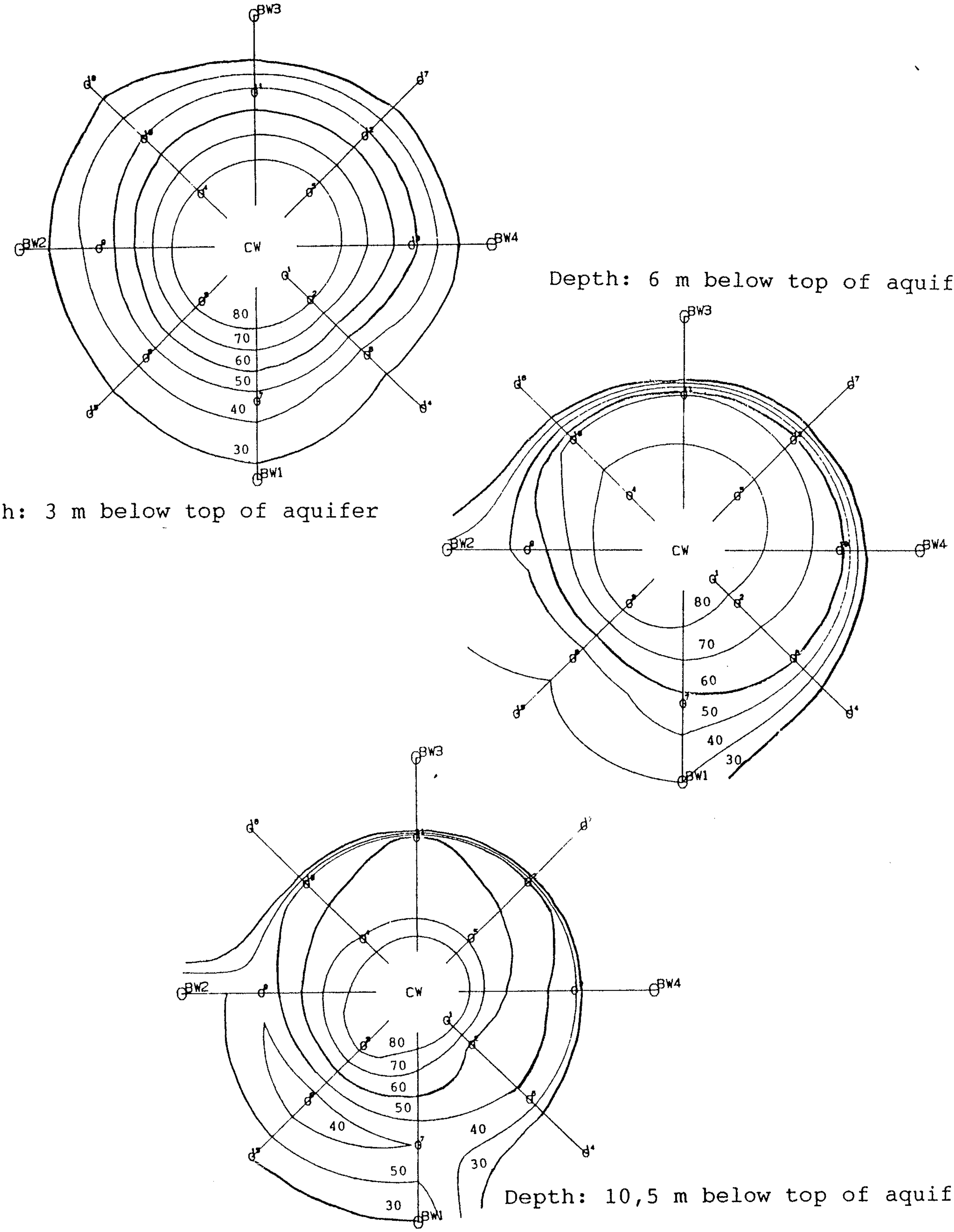
Charging ended late September and the plant was made ready for recovery immediately after. Nevertheless, recovery was not possible until the beginning of November, since the forward temperature in the district heating system was as high as 80°C. The temperature of the ground water in the central well was 84°C.

It took 2 months with day-to-day contact with the incineration plant until an explanation for the high district heating temperature was found. The explanation was that the control system of a school connected to the district heating system mal-functioned and caused the high temperature.

In the beginning of November the return temperature was lowered, but by this time most of the stored heat had risen to the top of the store due to buoyancy flow. Therefore, it was only possible to deliver 12 MWh to the district heating system.

Figure 7 shows the isotherms in three horizontal cuts: a) 3 m below top of the aquifer, b) 6 m below top of the aquifer and c) 10.5 metres below top of the aquifer. The bottom of the aquifer is at 15 metres. The isothermal plots are from 14 November at the time when recovery was possible. It is seen that most of the heat has risen to the upper part of the aquifer. At the depth of 10.5 metres the 70°C isotherm has a radius of 13 metres while the same isotherm (70°C) at a depth of 6 metres has a radius of about 22 metres.

Figure 8 shows the isotherms in a horizontal plot at a depth of 12.75 metres. The isotherms are from 6 September, 9 days before end of charging. At this time the 70°C isotherm has a radius of about 20 metres. Comparison with figure 7 shows that about 2/3 of the heat has risen to the upper part of the aquifer.



Depth: 3 m below top of aquifer

Depth: 6 m below top of aquifer

Depth: 10,5 m below top of aquifer

Figure 7. Horizontal cuts through the aquifer. Isothermal plots from 14 November.

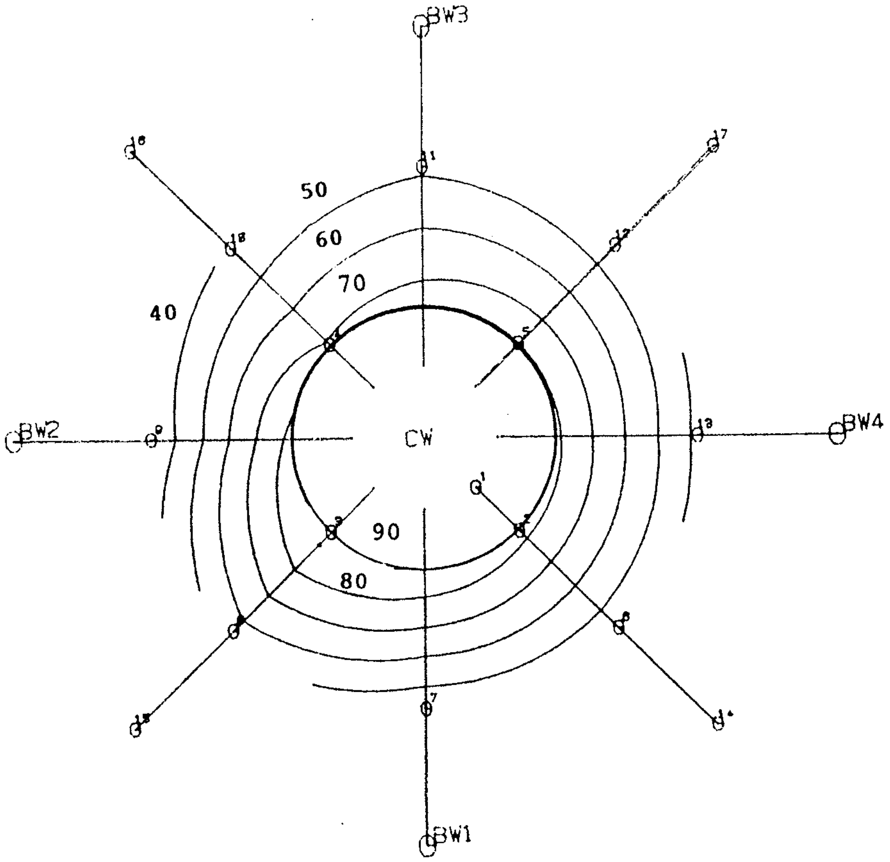


Figure 8. Horizontal cut in a depth of 12.75 metres below top of the aquifer. Isothermal plot from 6 September.

## 3.5 Operational results 1986.

### 3.5.1 Technical data.

The operational conditions during storage in 1986 are listed below:

Charging

| | |
|---|---|
| Injection start | 2nd July |
| Injection stop | 27th October |
| Injection period, accumulated | 1200 hrs |
| Injection temperature | 94°C - 100°C |
| Injection pressure | 6 metres above normal ground water level |

| | |
|---|---|
| Injection flow | 12 - 30 $m^3/h$ |
| Thermal power | 0.7 - 2 MW |
| Total injected volume | About 24,000 $m^3$ |
| Total amount of energy injected | 1003 MWh |

### 3.5.2 Qualitative description.

In 1986 important reconstructions were planned before the injection was to start. These reconstructions were not completed until May 1986, because of delays in the financing.

Unfortunately, some of these reconstructions caused more harm than good.

The main problem in the system had been the injection pressure. To avoid too high injection pressure, three pressure safety devices in the system seemed necessary.

One pressure safety device placed in the machinery house already existed. This pressure controller was activated at a pressure at this point at 0.6 bar, (the highest advisable injection pressure).

The second pressure transducer was placed in the central well. A copper pipe through which nitrogen was injected, has been installed below water level. A pressure transducer that had been placed in the well, the pressure needed for the nitrogen to displace the water, was registered. The pressure transducer was connected to the computer, which shut off the injection at a pressure above 0.6 bar.

The last pressure safety device installed was a bypass valve across the booster-pump. This valve was to open at a pressure at 1.3 bar and was to be completely open at 1.7 bar. The booster pump was placed before the heat exchangers, which caused a decrease in the pressure of about 1 bar. The bypass valve required much time for trimming before it fulfilled its function.

Two changes were made to the acid dosage system. The acid dosage pump was placed outside the machinery house.

Also, the control of the acid dosage system was designed, so that the hydrocloric acid addition was proportional to the actual groundwater flow, and then checked by a pH-measurement. In former years, the HCl was controlled by the pH, but the pH electrode was drifting during a season.

Before the season started, several air escape valves were installed in the piping system. These valves have been two-way valves that by faulty functioning were sucking air into the piping system during close down. The valves were replaced by one-way valves.

The injection pressure was at maximum throughout the summer, but the injection flow was less than 30 $m^3$/h. The reason for this high pressure seemed to be a large amount of black deposit in the piping. This was thought to be corrosion in the piping from the peripheral wells to the machinery house.

After some days the deposit disappeared. The cause of this deposit was never found, but it might have been the air-escape valves installed in the peripheral wells, sucking air into the pipes. The incoming oxygen could combine with the steel pipes and form a precipitate of Fe. The chemical composition of the precipitate was

| | |
|---|---|
| 42 % | Fe |
| 0,57% | Mn |
| 8-9 % | Insoluble |
| 0 % | Sulphides |

The precipitate was removed from the central well by a suction pump.

Several oxygen measurements were made in the system. These measurements showed a content of 0.5 mg oxygen/l in the peripheral wells and 3 mg oxygen/l in the machinery house upstream of the heat exchangers. These measurements helped to locate an intake of oxygen through the cyclone separator.

Therefore, the cyclone was replaced by ordinary bag filters. After this replacement no oxygen was measured in the pipes in the machinery house.

The central well has been cleaned with Herli Rapid consisting of

- formic acid
- phosphoric acid
- hydrocloric acid
- isopropyl alcohol

Herli Rapid is especially made for ground water wells.

Before cleaning, the injection flow was 12 $m^3/h$ at an injection pressure of 0.6 bar. After cleaning the injection flow rose to 40 $m^3/h$.

Isotherms immediately after end of storage are shown in Figure 9.

In preparation for recovery, each three-way valve was redesigned. The inset in the valve was removed as it did not fulfill its function and a plate was inserted between the pipe and the valve to close off one direction.

The disadvantage of this system was the impossibility of automatic direction changes. But the system now proved to be tight.

At the time in which the plant was ready for recovery, the return temperature of the district heating system was too high, and due to the technical remodelling necessary to lower the return temperature, recovery was first possible in late January 1987.

At this time, the hot water had risen to the upper third of the aquifer and was impossible to recover, since the upper third of the screen in the pumping central well had been closed off by concrete.

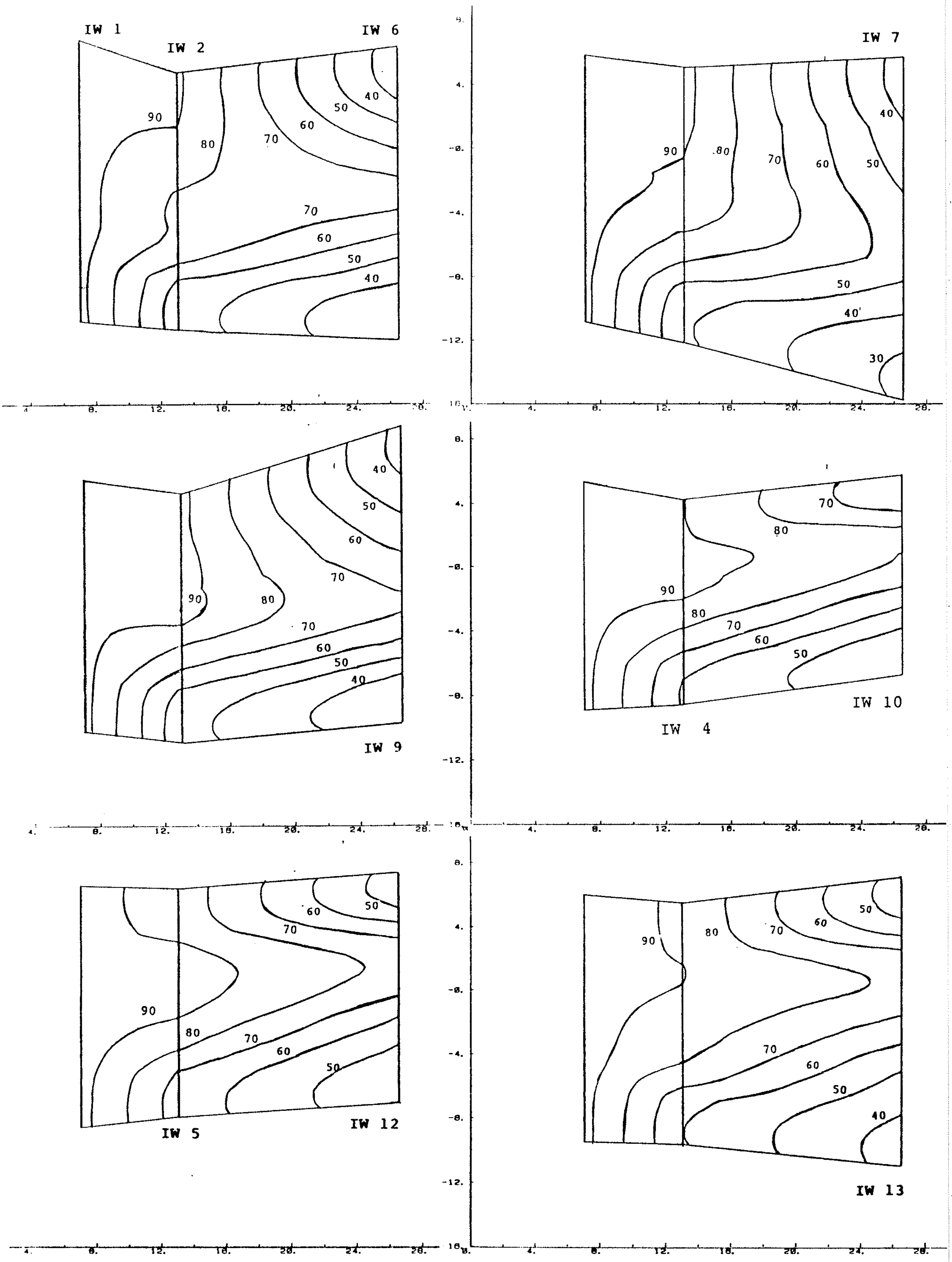
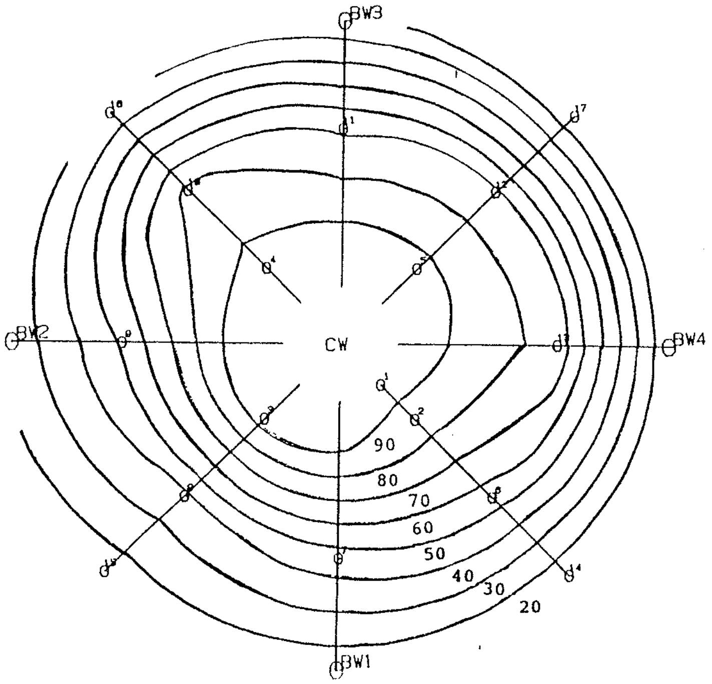
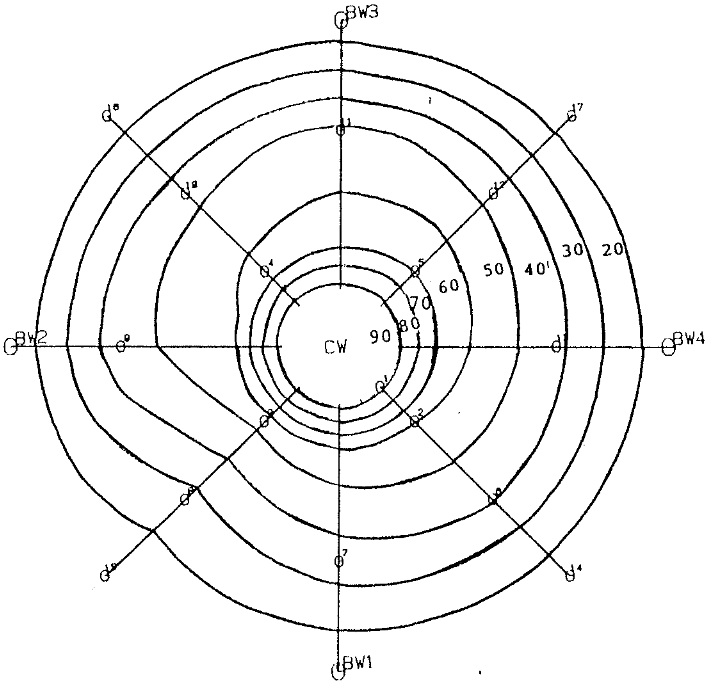


Figure 9. Vertical and horizontal cuts through the aquifer. Isothermal plots from 5 November 1986.

Figure 9. Continued:
Vertical and horizontal cuts through the aquifer.
Isothermal plots from 5 November 1986.



Depth: 4,5 m below top of aquifer



Depth: 12 m below top of aquifer

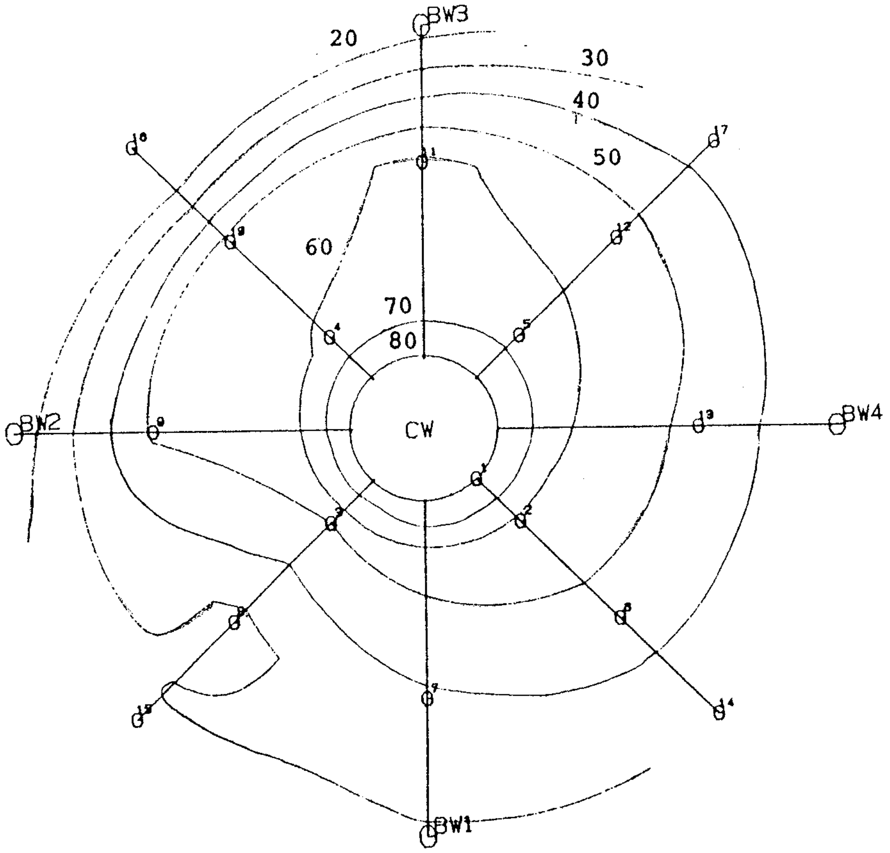
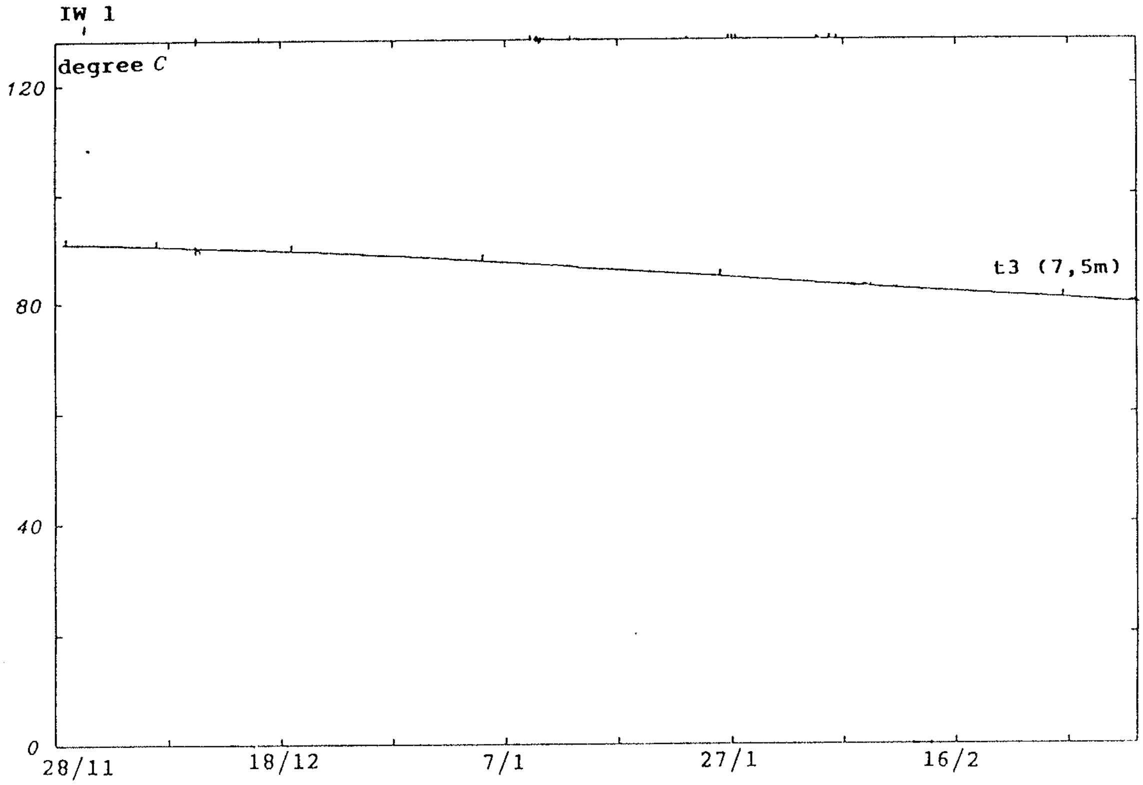


Figure 10. Horizontal cut at a level of 9 metres below the top of the aquifer.
Horizontal plot from 18 February 1987.

Isotherms 3 1/2 month after end of storage are shown in Figure 10. Comparison of these isotherms with isotherms immediately after end of charging (Figure 9) at the same level shows a movement of about 25 m of the isotherms towards centre during rest.

Figure 11 shows the course of temperatures at different levels during the rest period from 24 November 1986 to 28 February 1987. Four profiles are shown: a) 7 metres from the central well, b) 13 metres from the central well, c) 26.5 metres from the central well and d) 40 metres from the central well. The four sets of temperature measurements were taken in the instrumentation wells IW1, IW2, IW6 and IW14 at the same radius in south-east direction (upstream).



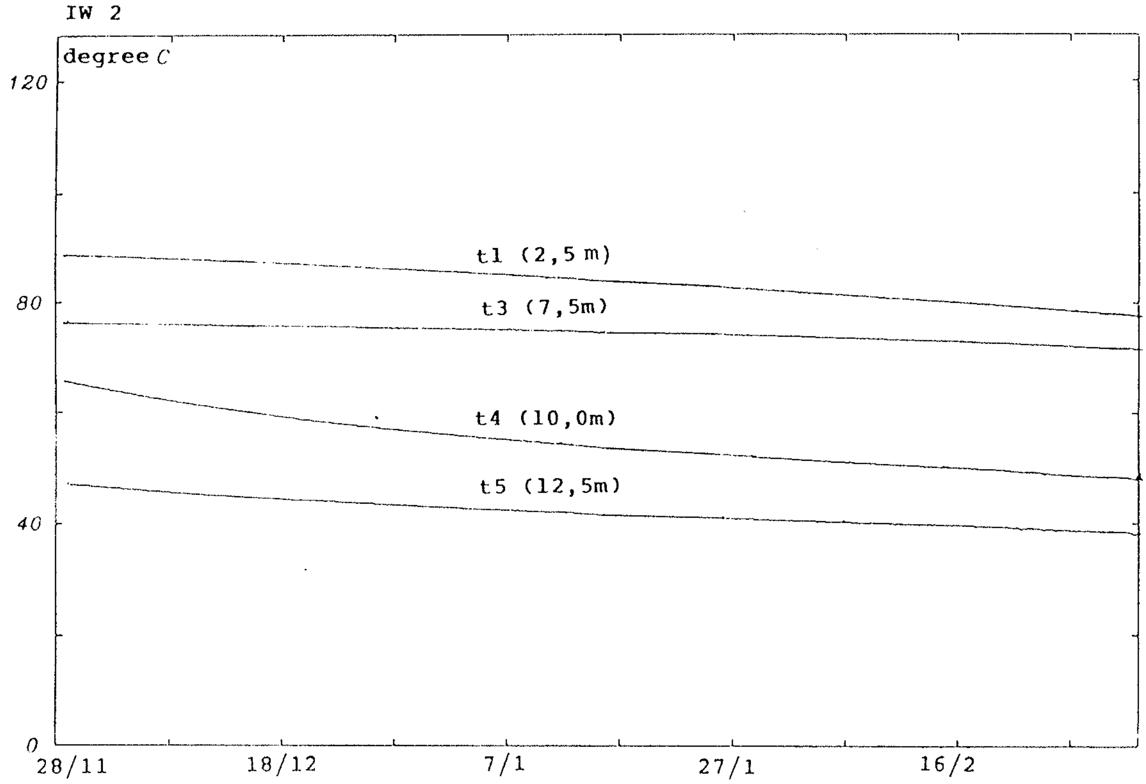
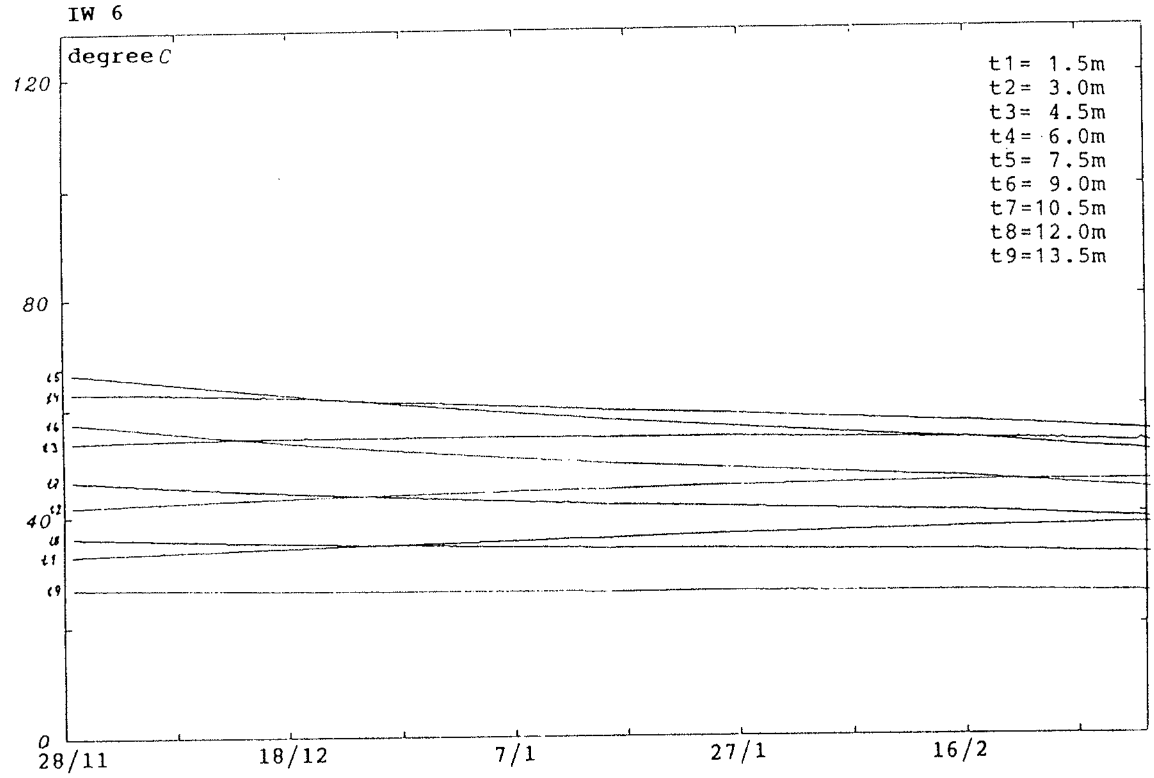
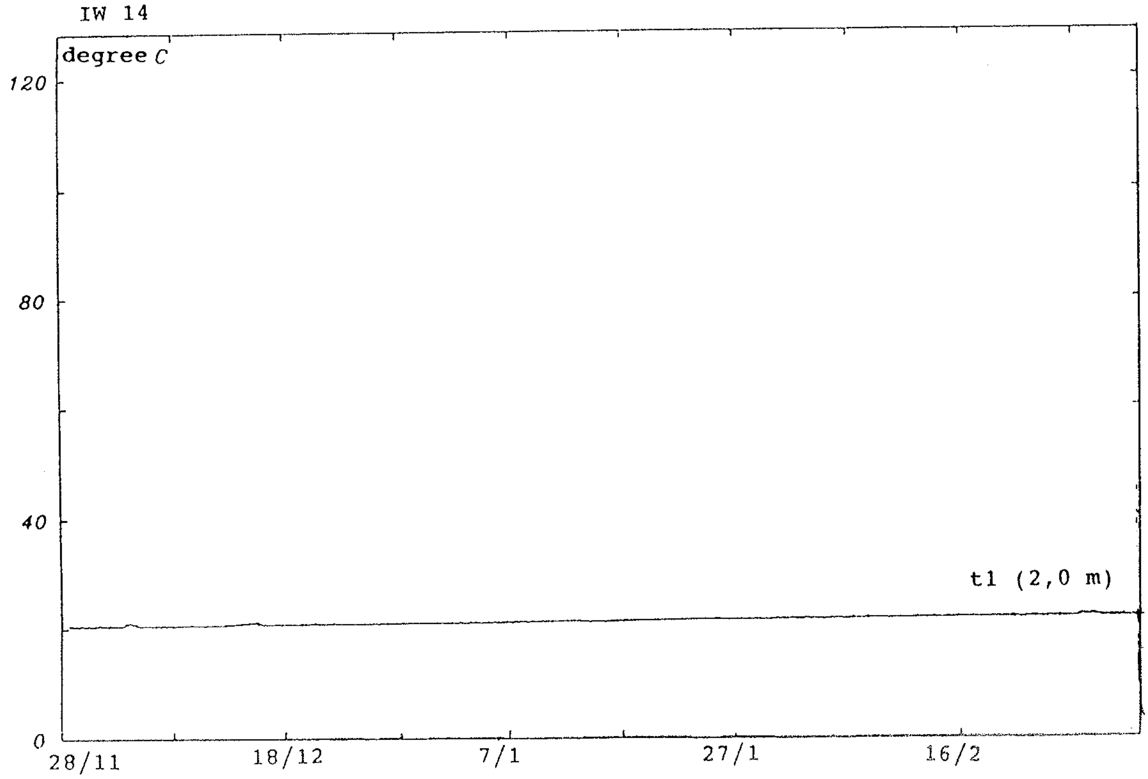


Figure 11. Temperatures in IW1, IW2, IW6 and IW14 during rest (28 November 1986 - 28 February 1987)

Figure 11. Continued
Temperatures in IW1, IW2, IW6 and IW14 during rest (28 November 1986 - 28 February 1987)





The figures show a minimum temperature in the aquifer of 30°C. In the nearest instrumentation wells IW1 (6 metres) and IW2 (13 metres) the temperatures decrease with time. In the instrumentation well IW6 located 26.5 metres from the central well, the temperature in the upper part (0 - 4.5 m) increases (drift from centre), while the temperatures in the middle and lower parts decrease with time due to buoyancy. The temperature at the periphery (IW14) is not changing.

## 3.6 Operational results, 1987

### 3.6.1 Technical data

The operational conditions during charging and recovery in 1987 are listed below:

#### Charging

Injection start: First time 21 May. Second time 7 July
Injection stop : 21 September
Injection temperature at day: 92°C-96°C
at night: 84°C
Injection pressure: 2-5 m above normal ground water level
Injection flow: 25-30 $m^3/h$
Thermal power: 1-1.5 MW
Total amount of energy injected: 1490 MWh

#### Recovery

Recovery start: 24 September
Recovery stop: 16 November
Recovery temperature, start: 90°C
Recovery temperature, stop: 66°C

| | |
|---|---|
| Forward temperature,<br>district heating system at day: | 60°C-66°C |
| at night: | 66°C-70°C |
| Thermal power: | 0.3-0.5 MW |
| Flow, ground water: | 15-20 m$^3$/h |
| Total amount of energy recovered: | 159 MWh |
| Recovery percent: | 11% |

### 3.6.2 Qualitative description.

3 days after start of charging the acid system leaked and the ground water booster pump broke down. The repair of the pump was quite expensive. As the allowable expenses were very limited, the discussion arose whether it was realistic to continue operation or whether the plant should be closed down. It was not possible to raise more money for the operation. It was concluded that operation might continue from 7 July until 15 August barring major mishaps.

After the second start of the injection, the system functioned without any significant operationel problems and it was decided to continue injection as long as possible.

In the middle of September the back pressure in the injection well CW 2 gradually increased and as the amount of surplus heat from the incinerator plant was small, it was decided to stop the injection.

The reason for the growing resistance in the central well is though to be that the plant had been in operation without addition of HCl for a few days. It has apparently not been possible to trap all of the precipitation of chalk in the bag filters, and the central well has been approaching clogging.

During injection, the control system has proved to be a success and the plant has been working in an automatic unattended mode both day and night.

The limits on the size of the ground water flow have this year been caused by limits on the amounts of surplus heat available from the incinerator plant. Due to a very bad summer, radiators have been heated, causing less surplus heat for storage. Without restriction of surplus heat a ground water flow at 50 $m^3/h$ could reasonably have been expected without operational problems.

The injection temperature has been relatively low. This is caused by the incinerator plant that has lowered the temperature in the district heating system to 95°C during the day and 84°C during the night.

The injected amount of energy through the earlier years has resulted in constantly rising ground water temperatures in the peripheral wells. In July the ground water temperature in the periphery was 18°C but rose constantly to 37°C during storage.

The thermal power during injection has decreased continuously due to the increase in this ground water temperature. On the other hand, a smaller amount of the energy injected is then used for heating up the store and the surroundings of the store.

Curves of the temperature in the store as a function of time are shown in Figure 12.

Figure 12 shows the course of temperature in different levels in the aquifer during rest (spring 87), charging and recovery. The temperature measurements are from 3 different wells: a) IW2 13 metres from the central well, b) IW11 26.5 metres from the central well and c) IW15 40 metres from the central well. Figure a) clearly shows a decrease in temperature during rest, a great increase during charging and a great decrease during recovery. The lower level is more easily influenced by temperature than the lower level. Figure b) shows an increase during stagnation in the upper level (t1, t2) and a decrease in the lower level. The rise in temperature during charging is largest in middle level (t3 - t8). During recovery the temperature in upper level (t1 - t3) still rises, while the temperature in lower level (t8, t9) is steady. In middle level the temperature decreases during recovery. Figure c) shows a minor increase in temperature during the whole period.

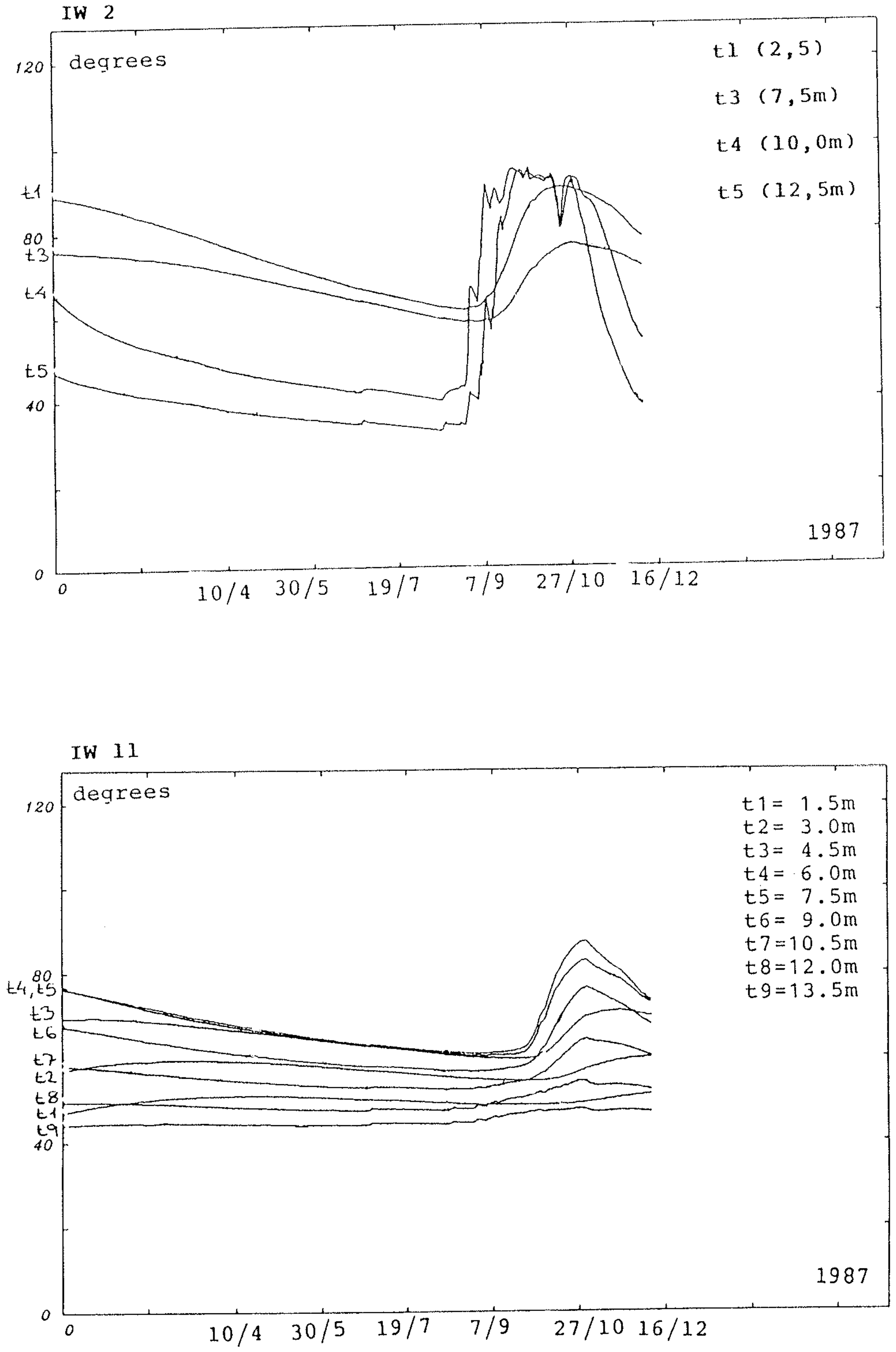
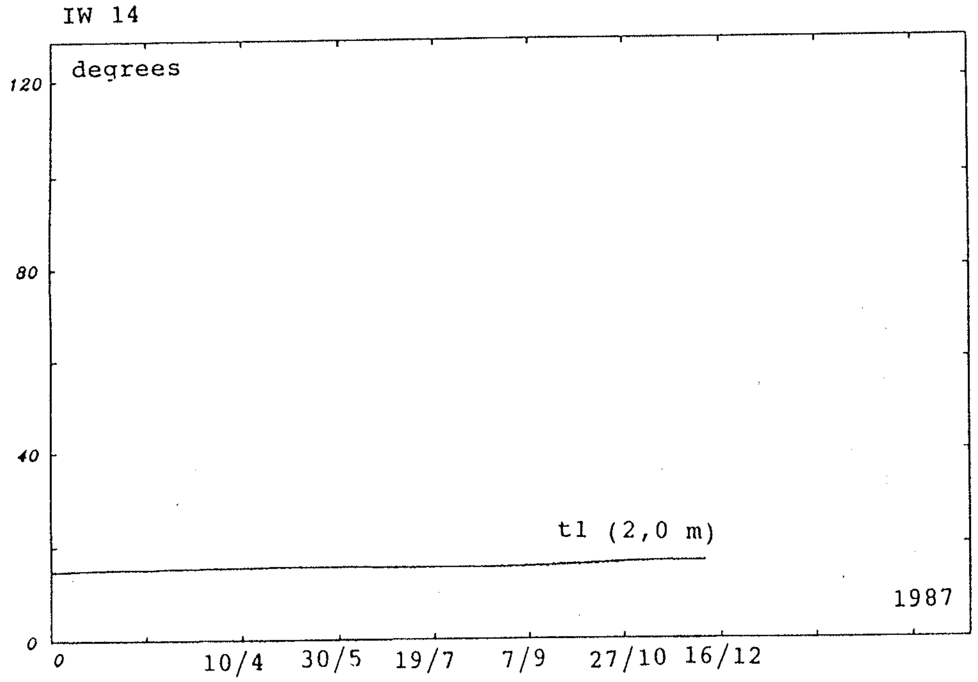


Figure 12. Temperatures in IW2, IW11 and IW15 during stagnation, charging and recovery.

Figure 12. Continued
Temperatures in IW2, IW11 and IW15 during stagnation, charging and recovery.



Immediately after the end of injection, the plant was prepared for recovery. After 3 days, the flow direction was reversed by removing plates inserted ahead of the valves (these plates have been inserted as the inside parts of the valves causing troubles have been removed). Simultaneously, the function of the pumps was checked, and the filters were cleaned.

When recovery started, the pumping temperature from the store was 90°C, while the temperature of the return line of the district heating system was 66°C.

After 14 days of recovery, the heat exchangers were clogged. Cleaning with $HNO_3$ and NaOH permitted continuation of the recovery for another month. At this time both the heat exchangers and the peripheral wells were clogged.

The heat exchangers were disassembled. The plates were covered with a black coat with a thickness of 2 mm at the ground water side, while the district heating side was entirely clean.

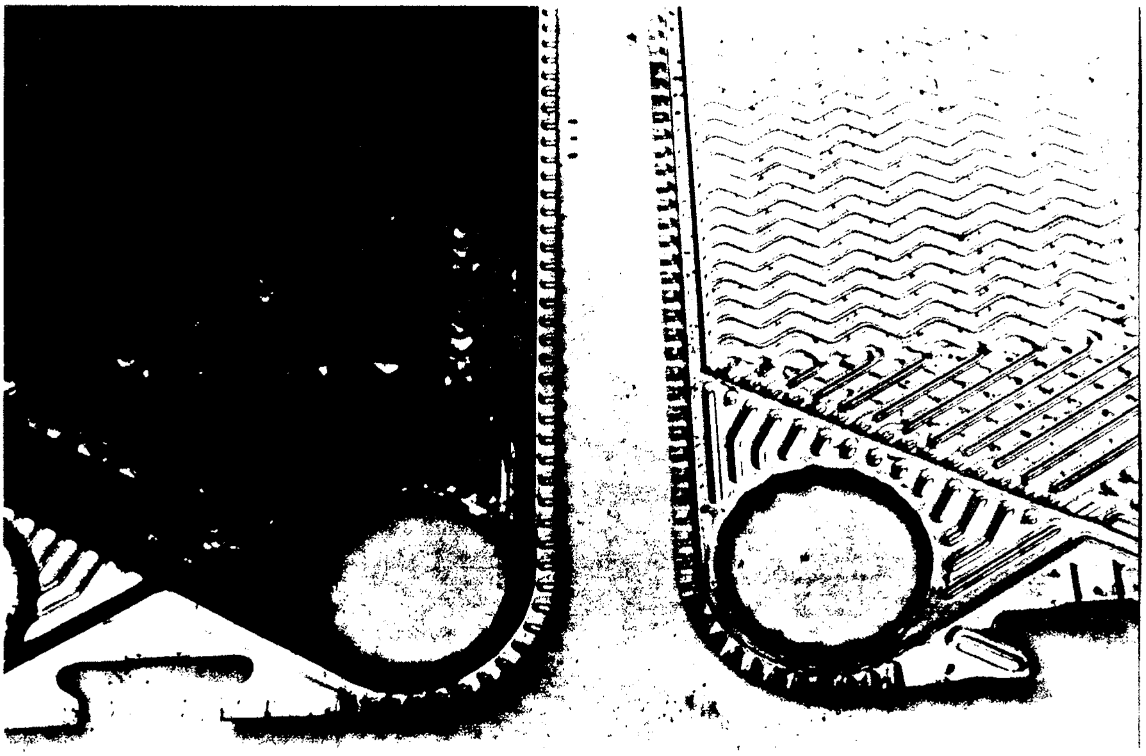


Figure 13. Plates from heat exchanger. To the left, plate from ground water side, to the right, plate from district heating side.

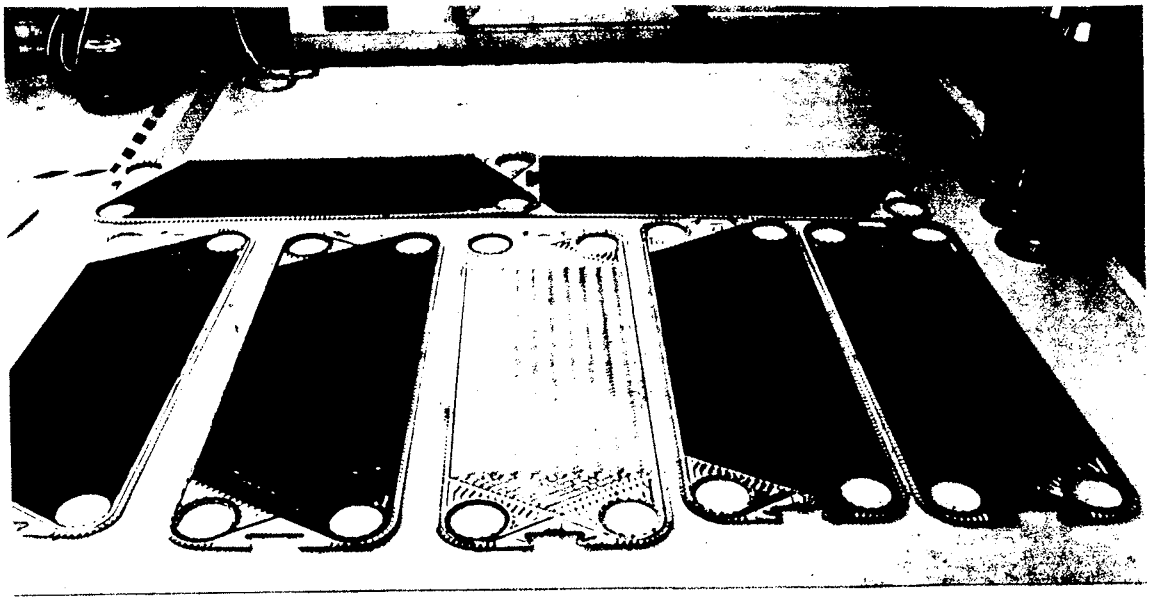


Figure 14. Plates from heat exchanger. One plate from district heating side surrounded by 6 plates from ground water side.

Four methods for removing the coat were tested:

- the first sample was treated by $HNO_3$
- the second sample was treated by $HNO_3$ and $H_2O_2$
- the third sample was treated by HCL, and
- the fourth samples was treated by NaOH.

The samples were heated for 2 hours, followed by filtration, washing and drying. The removal by HCL was the most effective.

By glowing this sample, the sample was reduced by 19%, corresponding to the content of organic material. By applying hydrofluorid-acid, the sample was reduced by 35%, corresponding to the content of silicic acid. Iron constituted the last 46%.

To estimate the origin of the coat, the water in the central well was studied. The water was muddy, but the muddiness vanished by filtration. The precipitate contained 38% of iron and 8.6% of carbon. The cover at the heat exchangers consisted of 49% of iron and 2.58% of carbon. Calculations show a precipitation of more than 1 g per $m^3$ water. With a ground water flow at 30 $m^3$/h the coat will grow at a rate of 820 g per day.

During recovery, the pumping temperature from the store decreased from 90°C to 66°C. The temperature in the district heating system varied between 62°C and 70°C. At night the temperature was 66-70°C.

During operation, an unfavourable design feature was uncovered. The temperature in the district heating system rose when the flow from the district heating system to the heat exchangers was increased. The reason for this is that when flow in the pump at the district heating side is increased, it sucks more. Hereby, some of the water already heated is sucked back into the heat exchanger and once more mixed with the colder water entering the system. Therefore, recovery was only possible at a low flow rate.

Figure 15 shows the amount of energy recovered as a function of time in the period 24 November 1987 until 10 January 1988.

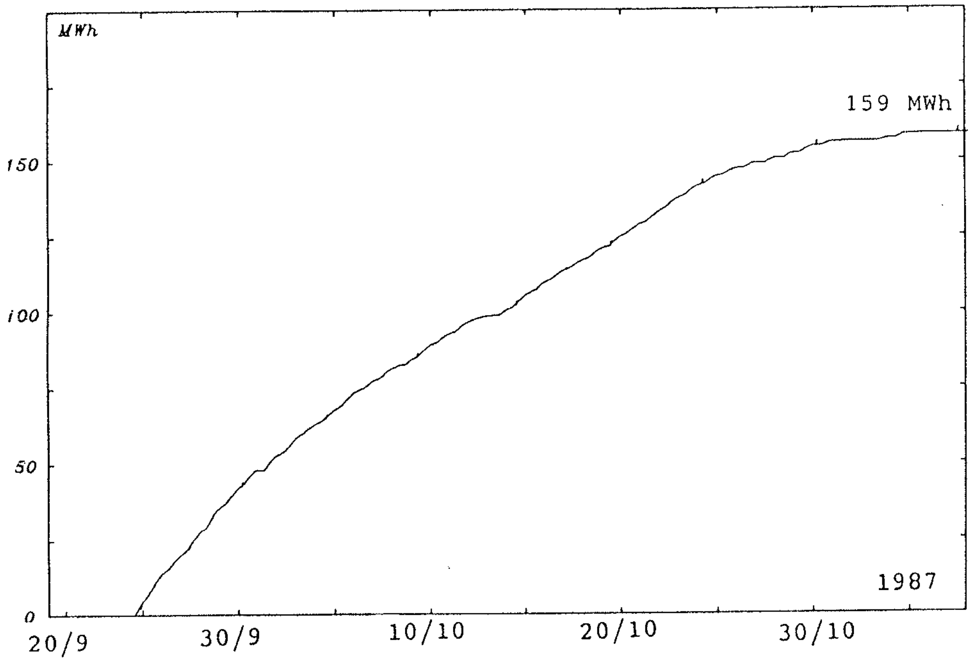


Figure 15. Energy recovered as a function of time

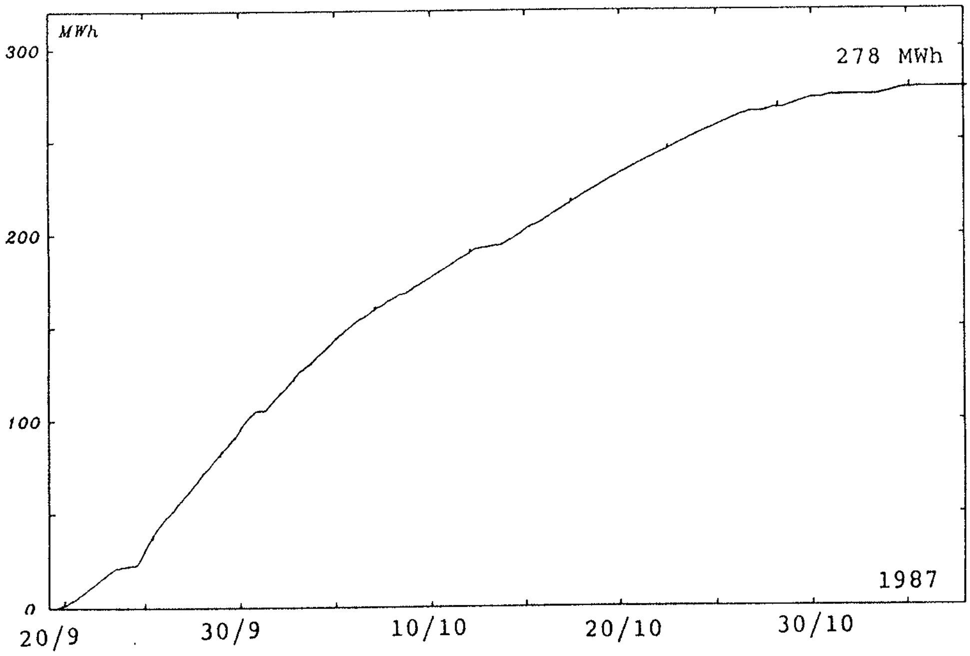


Figure 16. Energy recovered with a steady temperature of 60°C in the district heating system.

Figure 16 shows the amount of energy recovered as a function of time (24 November 1987 - 10 January 1988) if the temperature in the district heating system was steady at 60°C. The recovery percent would increase to 19% (278 MWh contra 159 MWh).

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The Danish Aquifer Thermal-Energy Storage Project. Demonstration Plant. Operational Experiences and Results.

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**Abstract (Max. 2000 char.)**

A part of the Danish aquifer thermal-energy storage project consisted in construction and operation of a demonstration plant. The demonstration plant was established in Hørsholm north of Copenhagen in 1982. During the years of 1982-1987, altogether six charging processes have been carried out. Due to various difficulties for some years, the discharge (recovery) part of the storage cycle had to be omitted. In 1988 the demonstration plant was closed down.

The project has been a collaboration between Risø National Laboratory, the Laboratory for Energetics at the Technical University of Denmark and the Geological Survey of Denmark. In 1986 N&R Consult A/S and the owner of the incineration plant Nordforbrænding I/S joined the project. At the same time the storage plant was taken over by Nordforbrænding I/S.

The project has been financed by the Danish Ministry of Energy's energy research programs EM-2, EFP-80, EFP-81, EFP-82 (EM-J.No. 22633), EFP-84 (EM-J.No. 2263-411) and EFP-85 (EM-J.No. 1443/85-9). During 1986-1988 the project was partly financed by "new technologies" under the Danish Ministry of Energy.

The present report describes the experiences gained and results of the six storage-recovery cycles which have been carried out during the project.

**Descriptors** – EDB
AQUIFERS; COMPUTER CONTROL SYSTEMS; DEMONSTRATION PLANTS; DENMARK; DESIGN; DISTRICT HEATING; GEOLOGICAL STRUCTURES; SEASONAL THERMAL ENERGY STORAGE; SITE CHARACTERIZATION; SPECIFICATIONS; THERMAL ENERGY STORAGE EQUIPMENT; UNDERGROUND STORAGE

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