

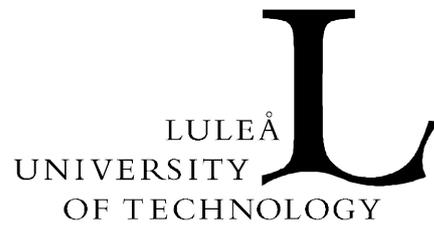
# LICENTIATE THESIS

## Thermal Response Test - In Situ Measurements of Thermal Properties in Hard Rock

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**Licentiate thesis**

Institutionen för Samhällsbyggnadsteknik  
Avdelningen för Vattenteknik



**Thermal Response Test - In-Situ Measurements of  
Thermal Properties in Hard Rock**

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## SUMMARY

Knowledge of ground thermal properties is most important for the proper design of large Borehole Thermal Energy Storage (BTES) systems. Thermal energy is stored in the rock volume and the boreholes are the heat exchangers of the system. The thermal properties of the rock and borehole collector are technical key parameters in designing BTES systems and greatly affect the number of boreholes required for the system. In-situ measured thermal properties improve the optimisation of BTES systems.

This thesis treats a new mobile thermal response test equipment (TED), developed at Luleå University of Technology, Sweden, during 1995-98. TED is set up on a small trailer, and contains a circulation pump, a heater, temperature sensors and a data-logger for recording the temperature data. A constant heat power is injected into the borehole through the pipe system of TED and the resulting temperature change in the borehole is recorded. The recorded temperature data are analysed with a line-source model, (Eskilson 1987), which gives the effective in-situ values of rock thermal conductivity and borehole thermal resistance. The thermal response measurement procedure is analogous to hydraulic single-well injection test. Thermal response tests take into account the interaction of the bedrock with the duct piping and filling, the borehole installation geometry and groundwater. TED has been tried out on groundwater-filled ducts in crystalline rock, fitted with single or double U-tube collectors. It has been used on several commercial BTES systems for the direct cooling of telephone switching stations, and on test-holes in a well-documented closed-down heat store at Luleå.

The measurements performed have been analysed with regard to test accuracy and reproducibility, collector types, external effects and geographical variations. The tests on the boreholes in Luleå show that the variation in estimated thermal conductivity is acceptable ( $\pm 3\%$ ). The thermal resistance varies in the order of  $\pm 0.01$  ( $\text{KmW}^{-1}$ ), which will improve with a better analysis method. Most of the variation is explained by the influence of temperature changes in the ambient air combined with insufficient insulation of the measurement equipment. The measurements confirm the importance of rigorous insulation of the response tester (Austin, 1997). Two collector types (single and double U-tubes) were compared regarding thermal resistance. The results confirm laboratory tests by Kjellsson and Hellström (1997) showing a significantly lower thermal resistance in double U-tube collectors. The field test estimation of  $\lambda = 3.6$   $\text{W/m,K}$  is higher than the laboratory estimation of  $\lambda = 3.4$   $\text{W/m,K}$ , from 1983. The difference may be explained by the laboratory tests being performed on a hydraulically sealed borehole, which is not the case in the field tests, where groundwater flow-through causes convection in the borehole, that improves the heat transfer. The local groundwater flow and injected power rate are two important factors that may influence the borehole thermal resistance.

Thermal response tests on groundwater-filled boreholes in Swedish hard rock show significant geographical variation in thermal conductivity. This demonstrates the importance of good in-situ estimation of the thermal properties of the rock for the design and optimisation of large BTES systems. TED measurements has the potential of becoming an important standard tool for the design and optimisation, quality control and development of new materials and techniques for BTES.

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Signhild Gehlin  
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### SUMMARY

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- II Hellström G, Gehlin S (1997). Direct Cooling of Telephone Switching Stations Using A Borehole Heat Exchanger. *Proc. Megastock'97, Sapporo*. Japan. June 18-21 1997, p. 235-240.
- III Gehlin S, Nordell B (1998). Thermal Response Tests of Boreholes - Results from In Situ Measurements *Underground Thermal Storage and Utilization*. Vol. I, 1998.
- IV Gehlin S (1998). Thermal Response Tests of Single and Double U-tube Ground Collectors in Luleå. *Underground Thermal Storage and Utilization*. (Submitted 1998).

#### APPENDICES:

- A. Measurement Data from Response Tests in Luleå
  - B. Measurement Data from Response Tests on Commercial BTES
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## 1. OUTLINE OF THESIS

This licentiate thesis is the half fulfilment of a doctoral work. It summarises the results from the development and evaluation of a new mobile equipment for in-situ determination of the thermal conductivity and thermal resistance of borehole systems. The aim of the work was to:

- ◇ Describe and give recommendations for the design of mobile equipment for thermal response tests
- ◇ Evaluate the accuracy and reliability of the measurements
- ◇ Discuss and picture different applications of thermal response test

In depth analysis of the theoretical models used for the modelling of thermal behaviour of boreholes or BTES systems, is not comprised within this study.

The thesis consists of a short summary, two appendices and the following four papers:

- I Gehlin S, Nordell B (1997). Thermal Response Test - A Mobile Equipment for Determining Thermal Resistance of Boreholes. *Proc. Megastock'97, Sapporo*. Japan. June 18-21 1997., p. 103-108.
- II Hellström G, Gehlin S (1997). Direct Cooling of Telephone Switching Stations Using A Borehole Heat Exchanger. *Proc. Megastock'97, Sapporo*. Japan. June 18-21 1997, p. 235-240.
- III Gehlin S, Nordell B (1998). Thermal Response Tests of Boreholes - Results from In-situ Measurements. *Underground Thermal Storage and Utilization*. Vol. I, 1998. [www.geo-journal.stockton.edu/directory.html](http://www.geo-journal.stockton.edu/directory.html).
- IV Gehlin S (1998). Thermal Response Tests of Single and Double U-tube Ground Collectors in Luleå. *Underground Thermal Storage and Utilization*. [www.geo-journal.stockton.edu/directory.html](http://www.geo-journal.stockton.edu/directory.html). (Submitted 1998.).

The first paper describes the principles of thermal response test and the test equipment. The second paper describes the direct cooling systems for telephone switching stations used by Telia AB, on which the first thermal response test were performed. The third paper reports on tests performed at ten of Telia AB's direct cooling systems for telephone switching stations in Sweden. Paper four deals with the results from a series of response tests performed at a well documented BTES system in Luleå, where single U-tube collectors and double U-tube collectors were evaluated.

Appendices A and B contain graphs of all the measurements in Luleå and on commercial BTES in Sweden, respectively.

## 2. INTRODUCTION

Underground Thermal Energy Storage (UTES) was introduced at the end of the 1970's, with the aim of storing heat for winter use. Since then UTES has become more and more established in the field of thermal energy. UTES comprises seasonal storage of thermal energy in the underground, but also large systems for heat and cold extraction. UTES is divided into the subgroups;

1. Aquifer Thermal Energy Storage (ATES) which uses the groundwater-filled porous medium of the aquifer as a storage volume;
2. Borehole Thermal Energy Storage (BTES) where thermal energy is stored in the bedrock between the boreholes in the ground and is heat exchanged by the boreholes;
3. Rock Cavern Thermal Energy Storage (CTES) where thermal energy is stored in water which is kept in a rock cavern.

This thesis treats BTES systems and the measuring of thermal properties needed for their design. BTES systems consist of a few up to some hundred boreholes drilled in rock to a depth of 100-200 m.

In 1997 the Swedish Geological Research (SGU) registered 7030 new boreholes drilled in Sweden and 3706 of these were specified for energy applications. The actual number of energy wells is expected to be even larger, since there is also a considerable number of unspecified and unrecorded wells drilled every year (SGU 1998).



Figure 1. Construction of the 120 boreholes heat store in Luleå, 1983. The upper part of the boreholes are seen as rings on the ground surface. Photo: R. Lindfors.

Traditionally there have been several ways to obtain the design value of the ground thermal properties. The simplest method is to use the average value for Swedish bedrock. A slightly better estimation is the regional average, taken from a geological map. However, the thermal conductivity, which is a critical parameter for the sizing of the duct system, may vary  $\pm 20\%$  from the average value for a certain type of rock. As an example, the standard Swedish granite has a thermal conductivity in the range  $3.55 \pm 0.65$  W/m,K (Sundberg, 1988). Determining the local thermal properties is therefore a feasible move to obtain more elaborate optimisation of BTES systems. The next step to improve the accuracy of the estimated design value is to select and examine a rock sample from the location. Even better is a core drilling sample and an investigation of the mineral composition of the local bedrock. Another method to obtain an in-situ estimation of the thermal conductivity of the bedrock is to perform a *thermal response test*.

The idea of measuring the thermal response of BTES boreholes in-situ was first presented by Mogensen (1983) at a conference in Stockholm, in June 1983. Mogensen suggested a simple arrangement with a circulation pump, a chiller with constant power rate, and continuous logging of the inlet and outlet temperatures of the duct. The thermal response data (i.e. temperature development in the borehole at a certain energy injection/extraction) allow estimation of the effective thermal conductivity of the ground and the thermal resistance of the collector. The effective thermal conductivity includes the heat transfer effects of convective flow in the borehole and of local groundwater flow. Mogensen's concept was used on several sites for thermal response tests of full-scale BTES during their first days of operation e.g. Mogensen (1985), Eskilson (1987) and Hellström (1994). Full-scale response tests give a good estimation of the local thermal properties of the bedrock. However, since the BTES system is already constructed, there is little gain from finding the thermal properties being better or worse than the design values. Therefore mobile measurement equipment which may perform a thermal response test on one test-hole is a feasible tool to obtain reliable data for the final BTES design.

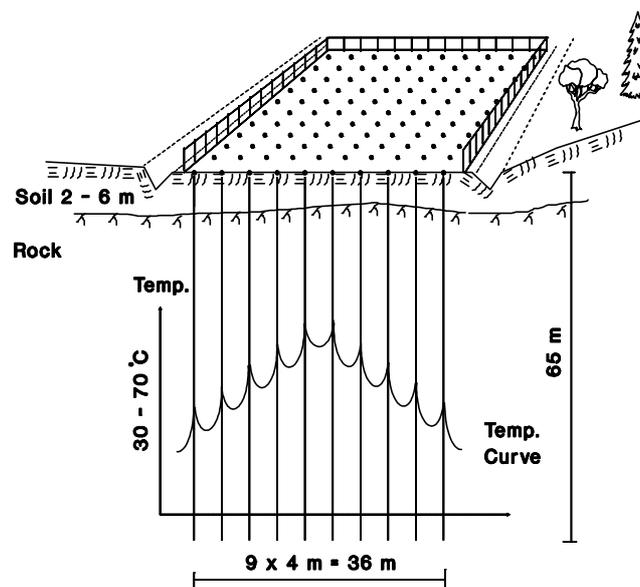


Figure 2. Geometry of a borehole heat store at Luleå, Sweden (From Nordell 1987).

The first mobile thermal response test equipments were developed in 1995-96; TED at Luleå University of Technology, Sweden, (Eklöf & Gehlin, 1996) and another at Oklahoma State University, USA (Austin, 1998). Both equipments use constant heating power injection. TED has been used only on groundwater filled ducts in bedrock, while the American equipment has been used only on grouted ducts. During 1998 the development of thermal response testers accelerated. Groenholland, Amsterdam, is experimenting with a container for measuring thermal properties of BTES and Ground Coupled Heat Pumps (GCHP), using a chiller instead of a heater. It will be used to test single boreholes and groups of boreholes (Witte, 1998). Another model is at present under early development at the University of Massachusetts (DiPippo, 1998). Several other countries have also shown interest in a response test equipment. Environment Canada, Dartmouth, and NGU (Norwegian Geological Investigation) have decided to invest in a refined model of TED.

The Swedish thermal response tester TED, which is dealt with in this thesis, was initiated in a student's project in 1995 by Eklöf et al. (1995) and constructed in late 1995. TED was delivered in early 1996 and was tested and evaluated in a Master thesis by Eklöf and Gehlin later that year. The work continued as a PhD study, and this licentiate thesis reports the first 2 years of experience with TED.

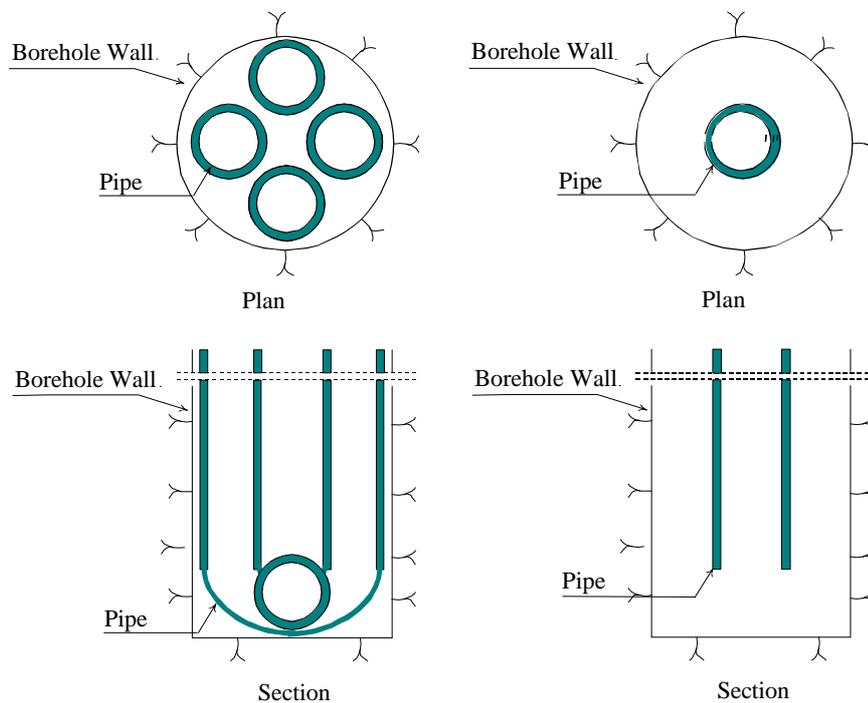


Figure 3. Closed system with two U-loops (left) and open collector (right).

### 3. THERMAL RESPONSE TEST (*Papers I and IV*)

This section gives a short introduction to the theory of borehole systems, the response tester TED, the measurement procedure and analysis of data.

#### 3.1 Borehole systems

A borehole heat storage is a system where heat is stored in the bedrock and the borehole system is used for heat exchange between a heat carrier fluid - which is circulated through the boreholes - and the storage volume (rock). The heat transport in the ground is mainly by heat conduction. Thus there are two basic constituents of a BTES system; geological medium that provides the storage capacity, and the ground heat exchanger, the *collector*. The collector may be of an open or a closed design. In an *open* system a single plastic tube, through which the fluid is transported to the bottom of the borehole, is inserted into the borehole. The region between the plastic tube and the borehole wall constitutes the borehole upward flow. The fluid is in direct contact with the surrounding rock, which provides for good heat transfer between the heat carrier fluid and the rock. However, the geohydrological and geochemical conditions are often unfavourable for an open system. The most common alternative is to provide a *closed* system by inserting one or more U-shaped loops of plastic tubing into the borehole. The base of the loops reaches the bottom of the borehole. The heat transfer from the heat carrier fluid to the surrounding rock takes place via the plastic material and the groundwater or material that fills the borehole. The heat transfer is consequently not as good as for the open system.

#### 3.2 Thermal response

The thermal response of a BTES borehole is pictured by the temperature change in the boreholes when heat is injected or extracted. The transfer of heat to/from the boreholes causes a change in temperature in the surrounding ground. The mathematics are described by Hellström (1994), Mogensen (1983) and Eskilson (1987) as below. The temperature field as a function of time and radius around a borehole, described as a line heat source with constant heat injection is well known:

$$\Delta T(r_b, t) = \frac{q}{4\pi l} \int_{r/2\sqrt{at}}^{\infty} \frac{e^{-b^2}}{b} db \quad (1)$$

where

- $\Delta T(r_b, t)$  = temperature increase
- $q$  = heat injection rate per unit borehole length
- $\lambda$  = thermal conductivity
- $H$  = effective borehole depth
- $t$  = time after application of heat injection
- $a$  = thermal diffusivity ( $\lambda/c$  where  $c$  is the thermal capacity)
- $r$  = radius from the borehole

For the response test, Eq.1. can be approximated by the following expression for the temperature of the borehole wall:

$$\Delta T(r_b, t) = \frac{q}{4\pi l} \left( \ln \frac{4at}{r_b^2} - \gamma \right) \quad \text{provided that } t > \frac{4r_b^2}{a} \quad (2)$$

where  $r_b$  is the borehole radius and  $\gamma$  is Euler's number (0.5772...).

The above derivation assumes

- ⇒ Constant temperature along the borehole which is not the case in practice. The axial temperature gradient is however in practice almost always small compared to the radial gradient, thus the effect on the validity of the equations will be insignificant.
- ⇒ Infinite length of the borehole. In practice the borehole length is very much larger than the borehole radius, so for short periods of time (as in the case of a response test) the end effects can be ignored (Ingersoll et al. 1951).

An important factor for the design of borehole systems is the *thermal resistance* between the heat carrier fluid in the borehole flow channels and the borehole wall. The fluid-to-borehole wall thermal resistance dictates the temperature difference between the fluid temperature in the collector ( $T_f$ ) and the temperature at the borehole wall ( $T_b$ ) for a certain heat flux  $q$  (W/m):

$$T_f - T_b = R_b \cdot q \quad (3)$$

This so-called borehole thermal resistance depends on the arrangement of the flow channels and the thermal properties of the materials involved, and causes temperature losses in the material which affect the heat transfer negatively.

The expression for the temperature field with the additional temperature drop by the thermal resistance is:

$$\Delta T_{fluid} = q \left[ R_b + \frac{1}{4pl} \left( \ln \frac{4at}{r_b^2} - g \right) \right] \quad (4)$$

where

$\Delta T_{fluid}$  = difference from initial fluid temperature

$R_b$  = thermal resistance (fluid-to-borehole wall)

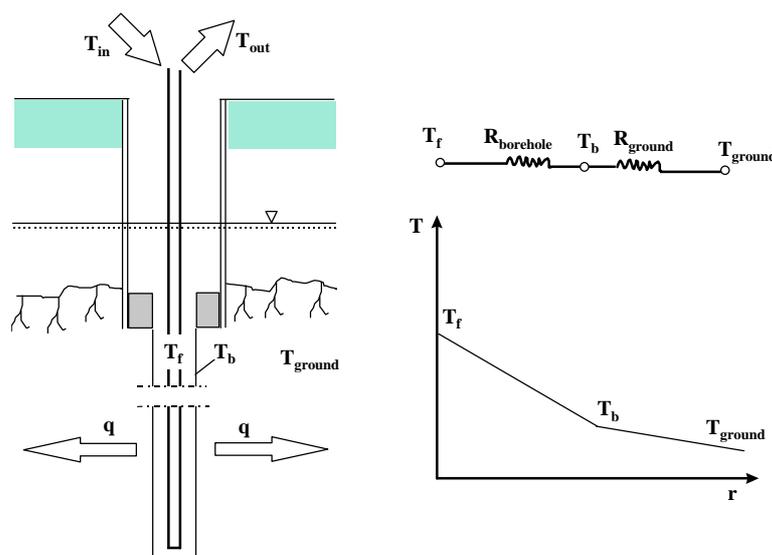


Figure 4. The thermal resistance causes a temperature loss in the materials of the borehole (collector pipes, borehole filling) and in the ground itself. The larger resistance, the larger temperature loss.

Typical heat transfer rates of 25-100 W/m result in a temperature difference within the borehole of about 2-10°C. The borehole thermal resistance should be kept as small as possible. Filling materials (e.g. bentonite, concrete etc.) in grouted boreholes have usually better heat transfer capacities than pure water, however in water-filled boreholes, the heat transfer induces natural convection in the borehole water. This phenomenon, which is more pronounced at high temperature and large heat transfer rates, leads to a reduction of the thermal resistance (Kjellsson and Hellström, 1997). The thermal resistance of a borehole collector is calculated from the results from a thermal response test.

### 3.3 Hydraulic well test analogy

There is a clear analogy between energy wells and hydraulic wells. In the hydraulic well, the aquifer and well correspond to the bedrock and borehole collector respectively. Consequently, the rate of pumping is analogous to the heat extraction. The water-level change at the distance  $r$  from the pumping well is a function of the pumping rate, properties of the aquifer, and time. Similarly the temperature change at some distance  $r$  from the energy well is a function of the extracted heat, thermal properties of the bedrock, and time. The hydrologic analogy to Eq.1. was given by Theis in 1935 (Domenico and Schwartz, 1998) and is of the form

$$h_0 - h = s = \frac{q}{4pT} \int_{r^2 S/4Tt}^{\infty} \frac{e^{-z}}{z} dz \quad (5)$$

where  $h_0$  is the original head at any distance  $r$  from a fully penetrating well at time  $t$  equals zero,  $h$  is the head at some later time  $t$ ,  $s$  is the difference between  $h_0$  and  $h$  and is called the draw-down,  $q$  is a steady pumping rate,  $T$  is the transmissivity,  $S$  is the storage coefficient. Eq.5. is referred to as the *non-equilibrium equation*. The hydrologic analogy with the thermal response test is the non-stationary single-well water-injection test in which the change of water-level in the well is related to the hydraulic properties of the aquifer according to Eq.6:

$$s = \frac{q}{4pT} \left( \ln \frac{4Tt}{r_w^2 S} - \mathbf{g} \right) \quad (6)$$

where  $s$  is the change in water-level, corresponding to the temperature change  $DT$  in the energy-well, the hydraulic transmissivity  $T$  corresponds to the thermal conductivity  $I$ , and the aquifer storage coefficient  $S$  is analogous to the thermal capacity of the rock in Eq. 2.

### 3.4 TED

The mobile thermal response test equipment, TED, was constructed at Luleå University of Technology in 1995-96. The equipment is set up on a small trailer and consists of a 1 kW pump circulating the heat carrier through the borehole collector and through a cross-flow heater with adjustable and stable heating power in the range 3-12 kW. Fluid temperature is measured at the inlet and outlet of the borehole with thermistors, with an accuracy of  $\pm 0.2^\circ\text{C}$ . The temperatures are recorded at a set time interval by a data-logger. The equipment is powered by 16 A electricity. In 1998 TED was slightly altered from its original construction (compare Figure 6 on the following page, and Figure 5 in Paper I) in order to obtain self-airing and automatic pressure control. The thermal insulation of TED has gradually been improved in order to minimise energy losses and influence of temperature changes in the ambient air.



Figure 5. The thermal response test equipment - TED, 1998. Photo: Peter Olsson.

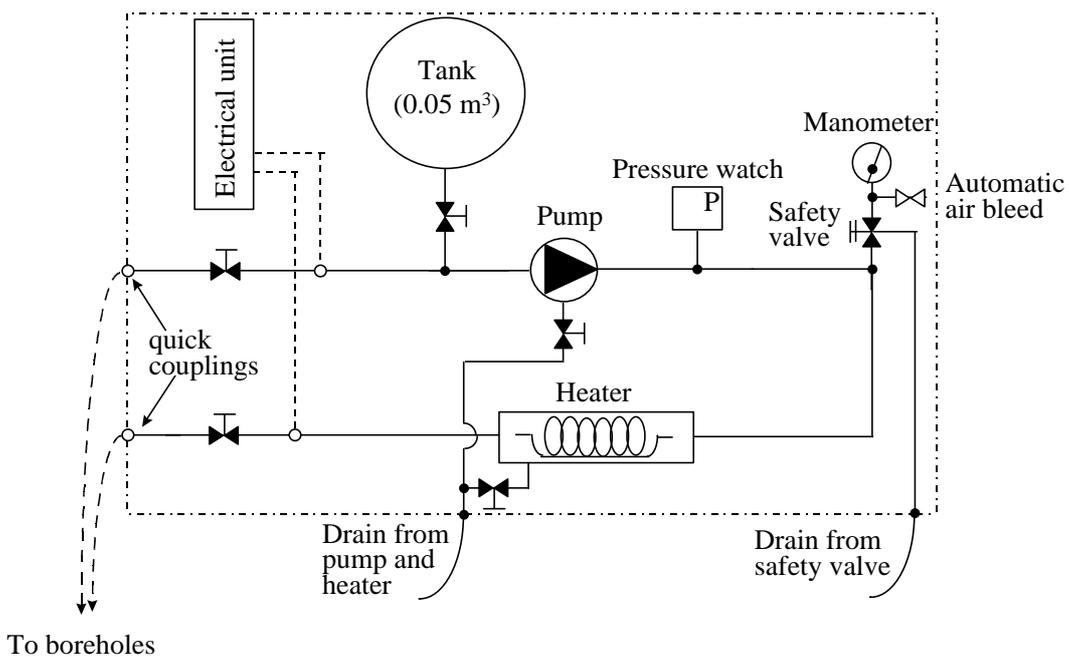


Figure 6. Schematic of the thermal response test equipment - TED, 1998.

### *3.5 Measurement procedure*

The borehole collector pipes are connected to the equipment with quick couplings at the back of the trailer and the heat carrier fluid is pumped through the system in a closed loop. The fluid passes through the heater, and the inlet and outlet fluid temperatures are recorded every second minute by a data-logger. Also the power supply is recorded during the measurements in order to determine the actual power injection. The power supply has showed to be stable during the measurements. The test is fully automatic including the recording of measured data, and takes about three days to execute. The groundwater level is determined manually with a separate fluid alarm during the measurements.

To determine the undisturbed ground temperature, the heat carrier is initially circulated through the system without heating during a 20-30 minutes. The mean fluid temperature along the piping will then show, and this temperature corresponds to the temperature of the undisturbed ground. After this procedure, the heater is switched on and the measurement is proceeding for 60-72 hours.

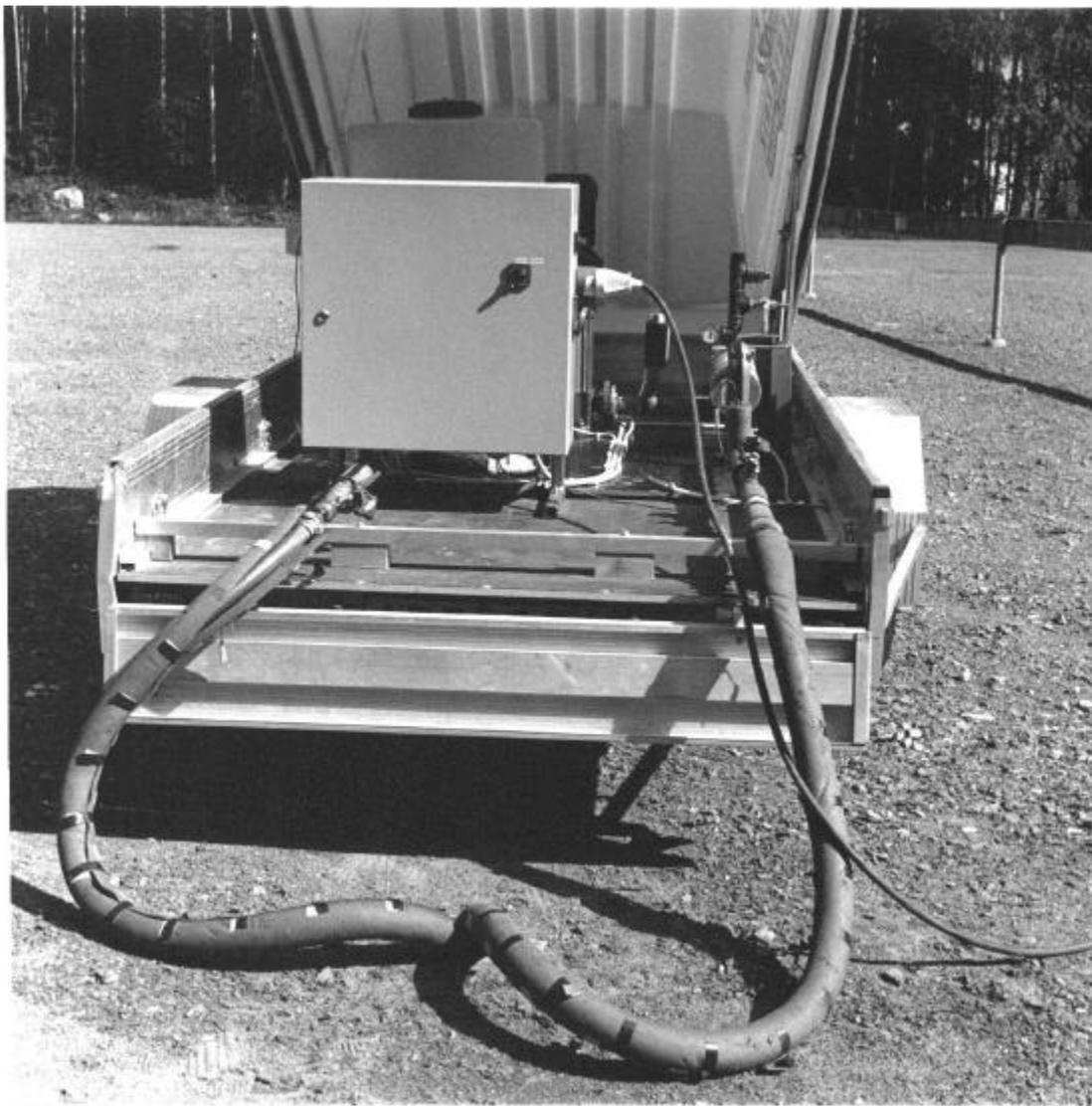


Figure 7. TED - measurements at the heat store in Luleå. Photo: Peter Olsson.

### 3.6 Data analysis

The analysis of the response test data is based on a description of the heat as being injected from a line source (Mogensen 1983, Eskilson 1987, Hellström 1991). When heat is injected into a borehole a transient process starts that is approximated by:

$$T_f = \frac{Q}{4\pi l H} \ln(t) + \left[ \frac{Q}{H} \left( \frac{1}{4\pi l} \left( \ln\left(\frac{4a}{r_b^2}\right) - g \right) - R_b \right) + T_{sur} \right] \quad \text{for } t \geq \frac{5r_b^2}{a} \quad (7)$$

$$T_f = \text{heat carrier mean fluid temperature} = \frac{T_{in} + T_{out}}{2} \quad [^{\circ}\text{C}]$$

$Q$  = injected heat power [W]

$\lambda$  = thermal conductivity [W/m,K]

$H$  = effective borehole depth [m]

$t$  = time from start [s]

$a$  = thermal diffusivity ( $\lambda/c$  where  $c$  is the thermal capacity) [ $\text{m}^2/\text{s}$ ]

$r_b$  = borehole radius [m]

$g$  = Euler's constant (0.5772)

$R_b$  = thermal resistance [K/(W/m)]

$T_{sur}$  = undisturbed initial temperature of the ground [ $^{\circ}\text{C}$ ]

The equation can also be simplified to a linear relation between  $T_f$  and  $\ln(t)$ :

$$T_f = k \ln(t) + m \quad (8)$$

where  $k$  and  $m$  are constants.  $k$  is proportional to the thermal conductivity according to Eq. 10, and

$$m = \frac{Q}{H} \left( \frac{1}{4\pi l} \left( \ln\left(\frac{4a}{r_b^2}\right) - g \right) - R_b \right) + T_{sur} \quad (9)$$

The thermal conductivity is estimated by plotting the mean fluid temperature versus the dimensionless time parameter  $t = \ln(t)$ , and  $l$  is calculated from the inclination of the graph as:

$$l = \frac{Q}{4\pi k H} \quad (10)$$

The effective thermal conductivity is used in Eq (7), to calculate the thermal resistance between the heat carrier fluid and the borehole wall,  $R_b$  (K/(W/m)).

A reliable method has proved to be matching the plot of the experimental mean fluid temperature ( $T_f$ ) with curves for different thermal resistances according to Eq (7). Once the thermal conductivity is graphically estimated according to the inclination of the curve, the thermal resistance comes out of the temperature level of the fluid (see Figure 8 and Figure 9).

This graphical method allows an accuracy of  $\lambda \pm 0.05$  W/m,K and  $R_b \pm 0.005$  K/(W/m). Critical parameters for the analysis are the power rate, groundwater level and undisturbed ground temperature. It is therefore important that these parameters are correctly estimated on site.

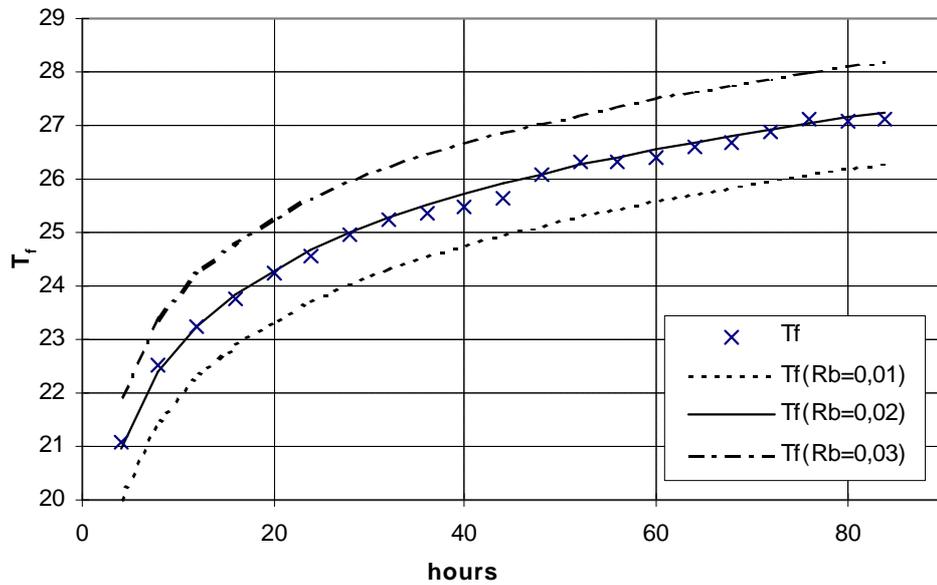


Figure 8. Mean fluid temperature from response test on double U-tube collector at Luleå, fitted to Eq(7) with  $\lambda = 3.7$  W/m,K and  $R_b = 0.02$  K/(W/m).

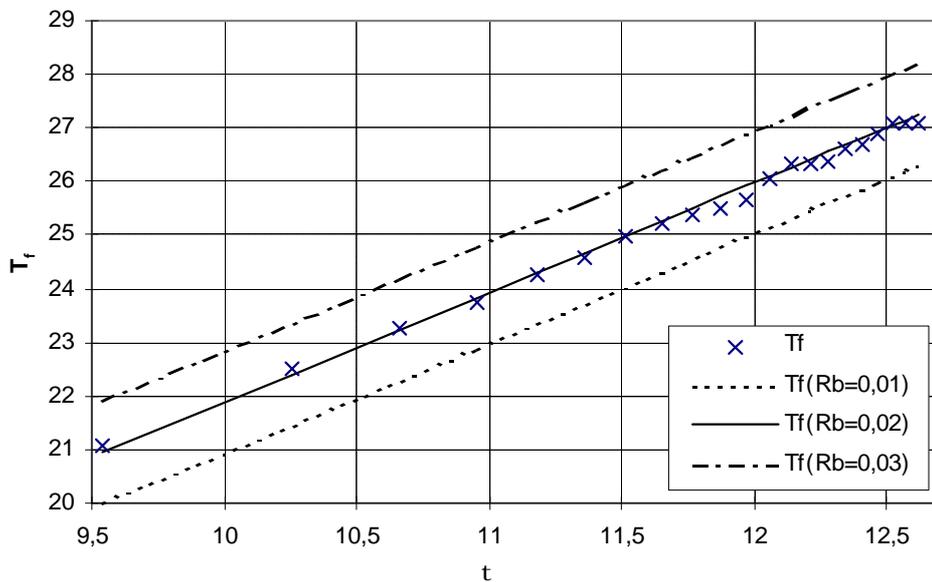


Figure 9. Mean fluid temperature from response test on double U-tube collector at Luleå, versus  $\tau$ .  $\lambda = 3.7$  W/m,K and  $R_b = 0.02$  K/(W/m).

#### **4. DESCRIPTION OF MEASUREMENT SITES** (*Papers II, III and IV*)

This section gives a brief description of the locations where TED-measurements have been performed. More detailed information is available in papers II, III and IV.

##### *4.1 Luleå Heat Store*

The aim of the measurements performed at the heat store in Luleå, presented in Paper IV, was to picture the reliability of the measurements, and to investigate the external influence from groundwater and the ambient air. The measurements were also used to compare the performance of single and double U-tube fitting.

The experimental heat store in Luleå (Nordell, 1986, 1987, 1989, 1990, 1994) is located close to Luleå University of Technology. It was taken into operation in July 1983, and was shut down in 1990 due to changes in the ownership. The depth of the soil cover varies between 2 m and 6 m in the area and the bedrock consists of streaked medium-grained granite and gneiss-granite. The undisturbed ground temperature was determined to +3.5°C. During the first 15 days of operation of the store in 1983, a thermal response test was performed for the entire store (i.e. 120 boreholes). The response test was not used to estimate the thermal conductivity of the ground but only the thermal resistance of the open borehole system used. An estimated thermal conductivity of the rock from laboratory test of representative rock samples from a drill core, was used in the analysis (Hellström, 1989, Nordell 1991). The mean value of four rock samples was 3.4 W/m,K but could not be adjusted with respect to the total mineral composition of the rock.

Table 1. Technical Data of the Luleå Heat Store

Storage Volume	120 000 m <sup>3</sup>
Soil Cover	2-6 m
Type of Rock	Medium Grained Gneiss
Estimated Thermal Conductivity	3.4 W/m,K
Estimated Thermal Capacity	2.216 MJ/m <sup>3</sup> ,K
Storage Land Area (36x44 m)	1584 m <sup>2</sup>
Number of boreholes	120
Borehole Depth	65 m
Borehole Diameter	0.152 m
Borehole Spacing	4 m
Undisturbed Rock Temperature 1983	3.5°C
Temperature in heat store 1990	70°C

In 1996, seven of the peripheral boreholes (see Figure 10) were re-opened, and three of them were fitted with new collector piping. Borehole 5A was fitted with PEM 32 mm single U-tubes, and boreholes 3A and 2A were both fitted with PEM 32 mm double U-tubes. The heat carrier in all collectors was Svedol (30% ethanol), and the boreholes were groundwater-filled. Temperature measurements in the recovered boreholes revealed that the temperature after 6 years had decreased from 70°C to 13-15°C in the peripheral boreholes (Magnusson and Rosén, 1996). This correlates well with simulations of the temperature decrease in the store over time, which was performed in a master thesis by Gidmark & Nilsson (1997).

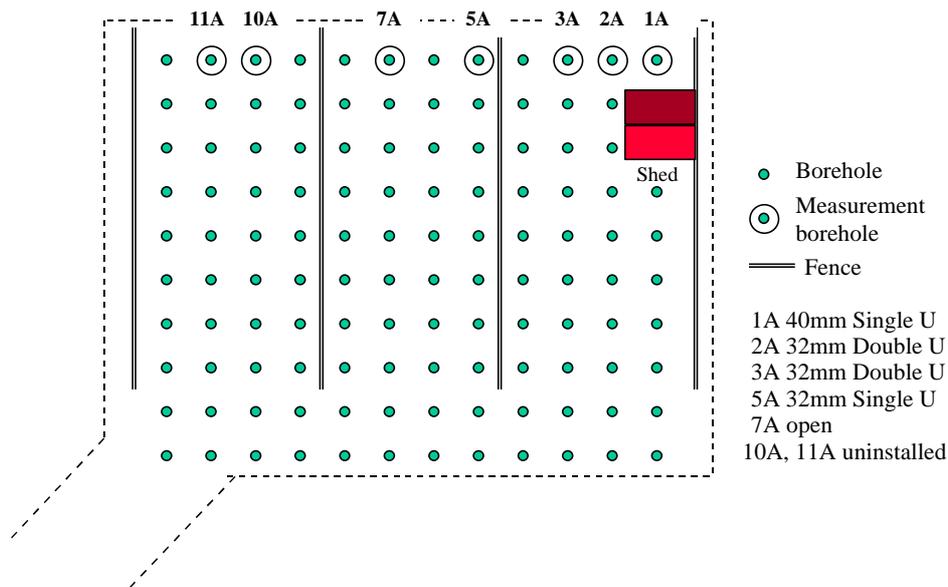


Figure 10. The experimental boreholes at Luleå heat store. Measurements have been done on boreholes 2A, 3A and 5A.

#### 4.2 Telephone switching stations

The very first TED-measurements in 1996 were performed at two different sites for direct cooling of telephone switching stations in Stockholm (Eklöf & Gehlin, 1996). The cooling systems had been in operation for 2 years and proved to be significantly more efficient than expected. The response tests showed a higher thermal conductivity and lower thermal resistance than the standard values used for pre-simulations. Since then TED has been used for measurements at a number of commercial direct cooling systems in Sweden (see Figure 12).

The design of a system with a borehole heat exchanger for direct cooling is shown in Figure 11. The heat generated in the electronic equipment causes warm air to rise to the ceiling of the telephone station. The warm air is cooled by an air-to-water heat exchanger mounted in the ceiling, and the heat carrier fluid transports the excess heat to the borehole heat exchanger. The groundwater-filled boreholes, which have a diameter of 0.115-0.130 m, are usually about 150 meters deep. They are fitted with single U-tubes of polyethylene tubing for circulation of the heat carrier fluid. The heat carrier fluid used in these systems is normally water or water mixed with an anti-freezer.

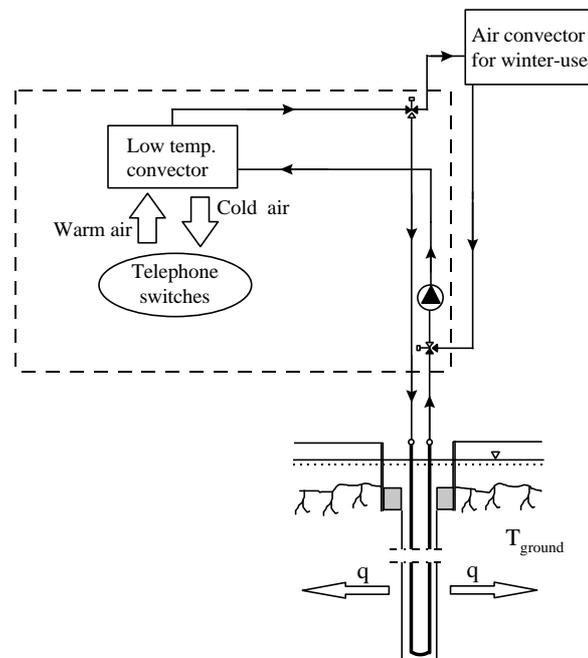


Figure 11. System design of a borehole heat exchanger for direct cooling.

The number of boreholes used in realised projects varies from 4 to 60 depending on the required cooling capacity. The cooling requirement is relatively constant throughout the year. The borehole heat exchanger may be designed to meet the cooling load during either the whole year or only the warm season, in which case the outside air is used for ventilation during the colder season. The current design criterion for the cooling system is to keep the maximum air temperature in the station below 25°C for ten years. For typical Swedish conditions, (bedrock - granite - with a thermal conductivity of 3.5 W/m,K and an undisturbed ground temperature of about 8°C), it is possible to maintain a continuous heat rejection rate of about 25 W per meter of borehole provided that the spacing between adjacent boreholes is sufficiently large.

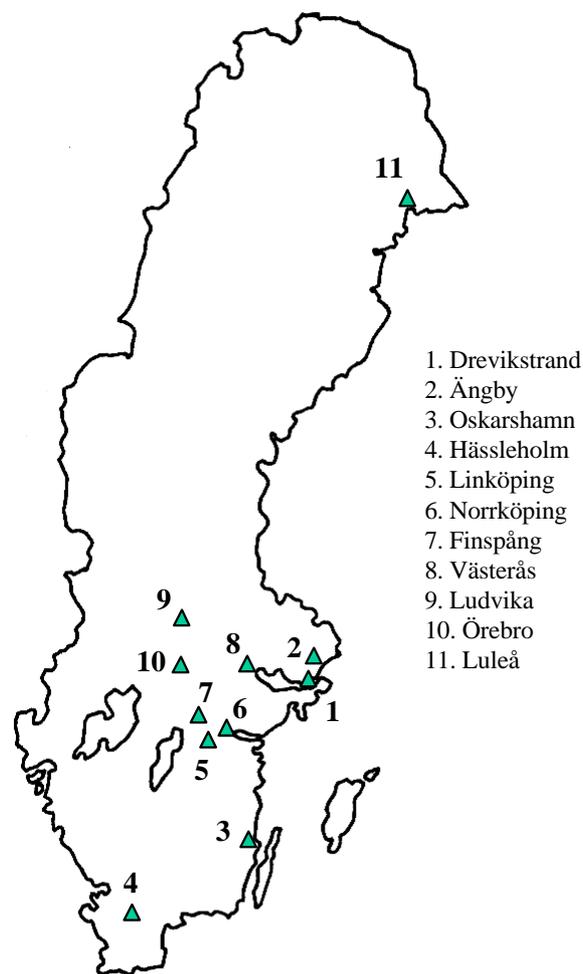


Figure 12. Map over Sweden with test sites marked out

## 5. RESULTS AND DISCUSSION

The main results of performed measurements are presented and discussed with regard to:

- ◇ Test accuracy and reproducibility
- ◇ Collector types
- ◇ External effects
- ◇ Geographical variation

Discussed data origin from 14 tests (6 tests on single U-tube collectors and 8 tests on double U-tube collectors) at the test site in Luleå, and 10 tests performed on single U-tube collectors in different geographical locations in Sweden. Plots of all tests are found in Appendices A and B.

### *5.1 Accuracy and reproducibility*

Table 2 shows means and range for the experimentally estimated thermal conductivity and thermal resistance in boreholes 2A, 3A and 5A at the test site in Luleå. Further details on each measurement, are given in paper IV. The variation of the measured thermal conductivity is in the range of  $\pm 3\%$ , which is a reasonable accuracy for this type of field measurement. The thermal resistance varies less than  $\pm 10\%$ , which will improve with a better curve-fitting analysis tool. These small variations imply that TED is a reliable tool for in-situ measurement of thermal properties of energy wells.

Table 2. Mean values and ranges of results from response tests

Installation Type	$\lambda$ [W/m,K]	$R_b$ [K/(W/m)]
Single U-pipe (5A)	3.62 [3.55-3.7]	0.056 [0.05-0.06]
Double U-pipe (3A and 2A)	3.62 [3.55-3.7]	0.025 [0.02-0.03]

The thermal resistance in the boreholes is lower than expected from laboratory experiments. This means that there are factors in field that decrease the resistance and that do not exist in laboratory environment. The explanation could not be found in pure natural convection due to temperature gradients within the borehole, as this would occur in the same way in laboratory tests. Also the thermal conductivity is higher than the laboratory estimated mean value from the four drill core samples ( $\lambda = 3.6$  W/m,K and  $\lambda = 3.4$  W/m,K, respectively). According to Ericsson (1985) in-situ determined thermal conductivity is generally slightly higher than corresponding laboratory estimations, due to the laboratory measurements not taking into account water-filled cracks and fissures in the rock.

The duration of the measurements was 68-117 hours. The line-source model is not valid for an initial period of about 12-20 hours, normally, because of influence from the thermal capacity of the collector and borehole filling. To obtain a reliable series of data, the measurements must proceed for at least 60 hours but 72 hours is

recommended. American experience with in-situ measurements, using a numerical model for the analysis, recommends ignoring the initial 12 hours, and proceed with the measurements for no less than 50 hours (Austin 1998).

Critical parameters for the analysis of the data are groundwater level, the actual power injection rate and the undisturbed ground temperature. It is essential that these parameters are appropriately determined during the TED-measurements.

### *5.2 Collector types and thermal resistance*

The field tests in Luleå confirm laboratory estimations of thermal resistance by Kjellsson and Hellström (1997) showing significantly lower values for collectors with double U-tubing than with single U-tubing. The laboratory estimations of the thermal resistance for single and double U-tubing were 0.10 K/(W/m) and 0.056 K/(W/m) respectively at a heat load of 50 W per meter borehole. This resistance is higher than those obtained from the field measurements with TED. The heat load in the field measurements were however about twice as high (84-113 W per meter borehole) as in the laboratory tests. The thermal resistance is dependent on the power load, thus a lower thermal resistance is expected at the higher heat load. A recommendation is therefore to run the response test with a power load similar to the expected operational load to obtain accurate estimation of the thermal resistance.



Figure 13. A single U-tube collector and a double U-tube collector at the test site in Luleå with quick couplings for connection to TED. Photo: Peter Olsson.

### 5.3 External effects

External effects such as large temperature changes in the ambient air, and increased groundwater flow, strongly disturbed the measurements. To reduce errors in the temperature data, caused by heat losses to the surroundings, it is important to thermally insulate the equipment and connection-pipes. Logging the ambient air temperature enables corrections for energy losses to the surroundings.

Groundwater flow through fractured rock influences the heat transfer in boreholes. Extreme examples of this phenomenon are the two occasions where drilling was carried out in the vicinity of the measurement hole (Ludvika and Örebro measurements, Table 3). This demonstrated the very strong influence of an artificially enlarged groundwater flow, which significantly improved the effective thermal conductivity and heat transfer in the borehole. Natural increases in groundwater flow e.g. during snow melting, also disturb the measurements. Rain - although heavy - has however not proved to affect the measurements.

### 5.4 Geographical variation

The field tests in different parts of Sweden show a large range of values in thermal conductivity. Also the hydrological conditions vary considerably between sites. These local variations justify thermal response tests as a method to estimate local parameters for accurate dimensioning of BTES systems.

The geographical differences in ground temperature underlines the importance of determining the ground temperature well at each particular site. It is a very sensitive parameter in the analysis. The used method to determine the mean ground temperature along the borehole in the TED measurements is to initially circulate the fluid through the collector without any power injection, for a period of time which corresponds to at least one residence time of the fluid in the collector pipes. This gives a reasonable estimation of the undisturbed ground temperature.

Table 3. Results from measurements in Sweden 1996-1998

Site	Active borehole depth (m)	Undisturbed ground temp (°C)	Maximum measured temp (°C)	Heat Load (kW)	Measured Thermal Conductivity (W/m,K)	Measured Thermal Resistance (K/(W/m))
Drevikstrand	160	9.2	20.8	11	5**	0.08
Ängby	132	9	22,9	11	5.5**	0.08
Oskarshamn	161	10.5	18	6.4	3.6	0.06
Hässleholm	126	8.7	23.4	11	3.8	0.06
Linköping	115	8.1	25.7	11	3.4	0.04
Norrköping	157	8.5	21.3	11	3.5	0.05
Finspång	96	9.5	18.6	4.9	3.6	0.06
Västerås	154	8	19	9.9	3.9	0.07
Ludvika	117	11*	16.3*	6.4	11*	0.05*
Örebro	197	9.5*	16.2*	6.4	6*	0.12*

\*) On-going drilling in an adjacent borehole disturbed the measurements.

\*\*) 20 m thermally un-insulated horizontal piping 0.7 m below ground surface to connect boreholes to machine-room.

## 6. THERMAL SIPHON EFFECT

In-situ performed measurements of thermal conductivity in rock generally give a slightly higher value than laboratory measurements. Ericsson (1985) explains this effect by natural cracks and fissures in the rock being more or less closed depending on the pressure from the rock itself. These cracks and fissures are often filled with groundwater, which will drain in laboratory. The air has a considerably lower heat transfer capacity than water, thus thermal conductivity will be higher when measured in-situ.

The groundwater movement in a borehole is difficult to survey as it depends on the extent of possible flow paths between interconnecting natural fractures and the borehole. The hydrostatic equilibrium is changed due to the heat transfer to the borehole water, and a thermal siphon type of circulation through the borehole is induced. This siphon effect does not show in laboratory measurements on rock samples. In a dissipative system, small-scale and large-scale natural convection and regional flow may contribute to improve the thermal performance, whereas in a storage type of system they may improve the heat transfer from the borehole to the store but also increase the thermal energy losses (Hellström, 1998).

### 6.1 Theory

In general the temperature in a borehole is raised 10-20°C during a response test. This temperature increase results in a water volume expansion of about 0.25% (Franks 1972). In a hydraulically perfectly sealed borehole of 150 m this corresponds to a raised water level of about 0.4 m. However, normal boreholes are far from perfectly sealed, but will be more or less fractured, especially in the upper part of the borehole. In this region the hydraulic pressure will cause the heated (lighter) water to drain through fractures. Then, the surrounding hydraulic pressure will be higher at the lower parts of the borehole. Thus, a thermally driven convective groundwater flow is induced where fractures corresponding with thermally undisturbed groundwater will flow into the borehole to re-establish the hydraulic equilibrium. This convective flow will continue as long as there is a density difference between the borehole water and the undisturbed groundwater (Figure 14). The thermal siphon flow is thus driven by the injected heating power rate only, and may contribute significantly to an improved heat transfer in the borehole system.

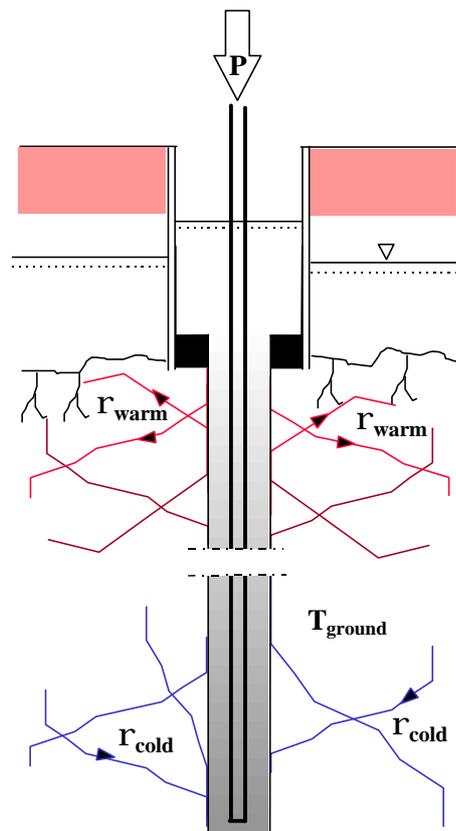


Figure 14. Thermal siphon effect in boreholes

### 6.2 Laboratory model of thermal siphon

A small-scale laboratory model of the thermal siphon was constructed at Luleå University of Technology in 1998 (Figure 15). The model consisted of two 500 mm high and 70 mm diameter transparent plastic cylinders interconnected at the bottom of the cylinders with a short 7 mm diameter pipe. The upper part of the cylinders was both brimmed at the same level. The cylinder simulating the borehole was heated with an immersion heater with power levels at 15 W, 95 W, 190 W, 280 W and 300 W. The outflow was measured on an electronic balance. The other cylinder, simulating the undisturbed groundwater, was kept at a constant temperature and water level throughout the measurements. The measurements show a linear relation between injected power rate and water outflow (Figure 16).

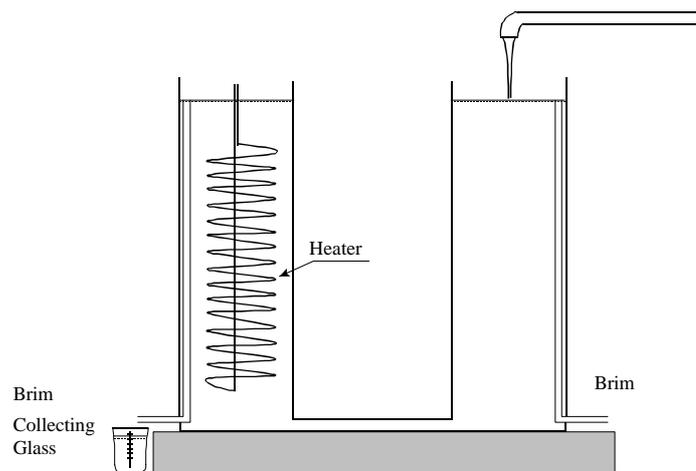


Figure 15. Laboratory model of thermal siphon

A closer investigation of this theory will be done during 1999, and if confirmed, this siphon effect should be considered when constructing small BTES and cooling systems. The siphon effect does not occur in grouted boreholes.

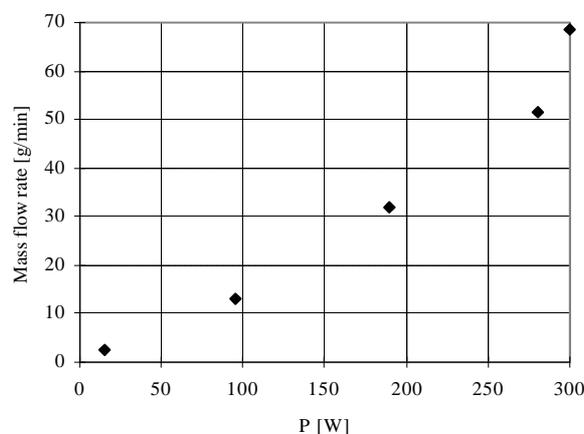


Figure 16. Results from preliminary model measurements of thermal siphon. The outflow from the borehole shows a nearly linear relation vs. injected power rate at steady-state conditions.

## **7. CONCLUSIONS AND RECOMMENDATIONS**

This thesis focused on three main issues; the measurement equipment, the reliability of the measurements, and the potential applications of thermal response tests.

### *7.1 Thermal response test equipment - TED*

Mobile equipment for performing thermal response test in-situ should consider the following items:

- ◇ Equipment: The equipment should include
  - ⇒ Stable power supply at pre-set power rates.
  - ⇒ Circulation pump for at stable flow rate of about  $0.5-1.0 \cdot 10^{-3} \text{ m}^3/\text{s}$  through the collector pipes. The pump must be easily water-filled and drained without corroding.
  - ⇒ A flow through water heater with at least 3 kW power rate. Non-corroding.
  - ⇒ Water supply tank (approx.  $50 \cdot 10^{-3} \text{ m}^3$ ) to fill the measurement equipment and connection pipes (the collector pipes are normally filled with heat carrier fluid before fitted into the borehole).
- ◇ Instrumentation:
  - ⇒ Temperature measurements of inlet and outlet temperatures of the boreholes and of ambient air temperature.
  - ⇒ Flow rate meter.
  - ⇒ Power input to the heater and circulation pump.
  - ⇒ Data-logger
  - ⇒ Security arrangements to prevent overheating, over-pressure etc.
- ◇ Design:
  - ⇒ Rigorous insulation of connection pipes, couplings, pipes on trailer and the trailer itself inside the cover to minimise heat losses and influence from ambient air temperature.
  - ⇒ The equipment could be arranged with a very compact design, but it is important to consider that the valves and switches etc. must be comfortable to reach.
  - ⇒ To obtain reliable flow measurements, the flow meter must be placed where the velocity profile in the pipe is fully developed.
  - ⇒ A small covered (and insulated) trailer is recommended for the set-up of the equipment.

### *7.2 Accuracy and Reliability of thermal response test*

The results of performed thermal response tests justify the use of TED-measurements for in-situ determination of thermal conductivity and thermal resistance of BTES boreholes. The following items must however be considered in the interpretation of the measurement results:

- ◇ Test procedure:
  - ⇒ The equipment should be connected as close to the borehole as possible to minimise heat and friction losses, and facilitate the measurements.
  - ⇒ Thermal insulation of all exposed piping and couplings.
  - ⇒ Use a power injection rate of the same order as for planned operation.

- ◇ Data:
  - ⇒ Determine the undisturbed ground temperature by circulating the heat carrier without heat injection for 20-30 minutes. Data recordings with 1-2 minutes interval.
  - ⇒ Carefully measure the groundwater level in the borehole.
- ◇ Data analysis:
  - ⇒ Ignore the initial 12-20 hours of measurements since they are not valid for the model used.
  - ⇒ The line-source model is simple to use and seems to work well for boreholes in crystalline rock.
  - ⇒ Other models may be useful for grouted boreholes and boreholes in sedimentary ground.
  - ⇒ Suitable software should be developed to optimise and simplify the analysis with different models.

### *7.3 Potential of TED*

Thermal response measurement with mobile equipment has many potential applications:

- ◇ Geothermal mapping
- ◇ Testing of new collector materials and designs
- ◇ Quality control and certification of BTES
- ◇ In-situ pre-investigation of thermal properties for large BTES systems
- ◇ The results from response test may be used for improving existing modelling and design tools for BTES systems.

### *7.4 Further work*

Research on response tests at the Luleå heat store will continue with measurements on grouted boreholes, open systems with and without forced convection, frozen systems and multiple borehole response tests. Thermal siphon effect will be further investigated as well as groundwater flow and natural convection. The work is planned to result in a doctoral thesis.

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## **PAPER I**

### **Thermal Response Test A Mobile Equipment for Determining Thermal Resistance of Boreholes.**

THERMAL RESPONSE TEST  
- MOBILE EQUIPMENT FOR DETERMINING THE THERMAL RESISTANCE OF  
BOREHOLES

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ABSTRACT

This study treats the advantage of in situ measurements of the heat transfer capacity of a borehole, using mobile equipment, to determine the thermal properties of the entire borehole system. The results from the response test include not only the thermal properties of the ground and the borehole, but also conditions that are difficult to estimate, e.g. natural convection in the boreholes, asymmetry in the construction, etc. By testing one borehole and evaluating its capacity in situ, the design of the borehole system can be optimised regarding the total geological, hydrogeological and technical conditions at the location. The equipment is technically very simple. Basically it consists of a pump, a heater and temperature sensors for measuring the inlet and outlet temperatures of the borehole. In order to make the equipment easily transportable it is set up on a small trailer. Since the response test takes about one week to execute, the test is fully automatic including the recording of measured data. The results are then easily evaluated from the data. The measurement equipment has been tested at a number of boreholes of various kinds. These studies show that the method can be used to accurately evaluate the total capacity and efficiency of the borehole system. On account of its simple construction and easy operation, the mobile equipment for the thermal response test is a valuable tool for improving the economical potential of underground heat systems.

1. INTRODUCTION

The main part of the construction cost of a borehole UTES system is the drilling cost. More elaborate optimisation of the systems would reduce the number of boreholes required, which would consequently reduce the drilling cost and make these systems more economically competitive.

The efficiency of a borehole system, i.e. its heat transfer capacity, is crucially dependent on the thermal resistance between the heat carrier and the surrounding rock. A lower thermal resistance means that a smaller temperature difference is required between the bedrock and the heat carrier, for a given heat power. This thermal resistance is seen as a temperature drop between 1/ the heat carrier fluid and the borehole wall, and 2/ the borehole wall and the surrounding rock. These temperature losses depend on the thermal properties of the pipe materials and borehole filling,

shank spacing, flow conditions, etc. (in the borehole) and on the thermal conductivity of the bedrock, fractures, ground water flow, etc. (outside the borehole).

One way of optimising a borehole system is to measure the thermal response of the borehole installation. The effective thermal conductivity of the ground and thermal resistance of the borehole are then determined from these measurements. These two parameters are of fundamental interest for the efficiency of an energy well and can be determined in situ by the thermal response test.



Fig.1: Mobile Equipment for thermal response test (TED) at Luleå University of Technology, Sweden. Photo: Signhild Gehlin.

## 2. IN SITU MEASUREMENTS

The advantage of in-situ measurements of the thermal properties of the borehole is that conditions that are difficult to foresee in theoretical calculations will be taken into account. The theory, i.e. mathematical computer simulation models, all assume ideal conditions. That means that in the computer models, the borehole is straight and has a constant radius, there are no fractures in the bedrock, and the installation is perfect with constant shank spacing, ideal materials, and no convection in the borehole filling. In practice, the thermal properties may vary, the groundwater level and groundwater flow rate vary, fractures occur and the bedrock is not homogeneous. The actual installation is asymmetric, the borehole is not drilled without deviation, the shank spacing varies due to twisted pipes and the distance between the pipes and the borehole wall varies. Natural convection is most likely to occur in boreholes without filling material due to the temperature difference between the fluid in the pipes and the borehole wall (Hellström 1994).

By performing thermal response tests on one borehole, the effective thermal conductivity of the bedrock and thermal resistance of the borehole are determined. Thermal response tests have been carried out and reported by Hellström (1994), Eskilson (1987), Claesson et al. (1985), but so far only performed at full-scale plants. There is a considerable advantage if the response test is run before the plant is fully constructed. The effective thermal conductivity is generally higher than the thermal conductivity of the bedrock. The thermal resistance of the borehole is sometimes lower because of convection in the borehole, which improves the heat transfer. These values are likely to be significant for the rest of the site, and can be used in the computer simulations to size the complete borehole system.

The economical value of the thermal response test is a result of improved design, i.e. the number of boreholes required are calculated with a greater accuracy, which usually means that the required number of boreholes is reduced. If in-situ measurements of this kind become a standard tool for dimensioning of UTES systems, the computer simulations will be more reliable, and the design of the plant will be improved resulting in reduced construction costs.

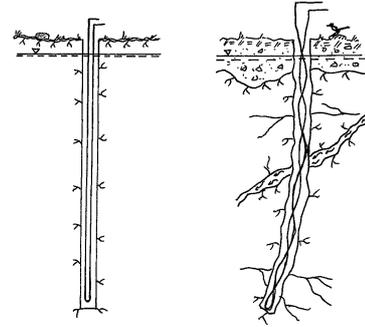


Fig. 1: The ideal borehole and the actual borehole.

## 2. THERMAL RESPONSE TEST

### 2.1 Physical Background

The thermal resistance  $R_b$  (K/(W/m)) between the heat carrier fluid and the borehole wall is defined as  $T_f - T_b = R_b \cdot q$ , where  $T_f$  and  $T_b$  are the temperatures of the fluid and the borehole wall respectively, and  $q$  (W/m) is the heat flux. The total resistance depends on several factors in and around the borehole. The material properties of the pipes, the heat carrier fluid, borehole filling and bedrock influence the thermal resistance, and also geometrical conditions such as the pipe and borehole diameter, shank spacing, pipe location in the borehole, site conditions such as groundwater flow, cracks and fissures, and the occurrence of natural convection (Hellström 1994).

When heat is injected into a borehole a transient process starts, described by:

$$T_f = \frac{Q}{4\pi l H} \ln(t) + \left[ \frac{Q}{H} \left( \frac{1}{4\pi l} \left( \ln\left(\frac{4a}{r_0^2}\right) - \gamma \right) - R_b \right) + T_{sur} \right] \quad \text{For } t \geq \frac{5r_0^2}{a} \quad (1)$$

where  $T_f$  is the mean temperature of the heat carrier fluid,  $Q$  is the injected heat power,  $\lambda$  is the thermal conductivity,  $H$  is the borehole depth,  $t$  is time,  $a$  is the thermal diffusivity ( $\lambda/c$  where  $c$  is the thermal capacity),  $r_b$  is the borehole radius,  $\gamma$  is Euler's constant (0.5772),  $R_b$  is the thermal resistance and  $T_{sur}$  is the undisturbed temperature of the ground. Eq. (1), which is derived from Hellström (1991), has a maximum error of 2%.

Eq.(1) can also be simplified to a linear relation between  $T_f$  and  $\ln(t)$ :

$$T_f = k \ln(t) + m \quad (2)$$

where  $k$  and  $m$  are constants. When plotting the mean fluid temperature versus the logarithmic time, the effective thermal conductivity is calculated from the inclination of the graph. The

effective thermal conductivity is then used to calculate the thermal resistance of the borehole. The method is also described by Mogensen (1983) and Eskilson (1987).

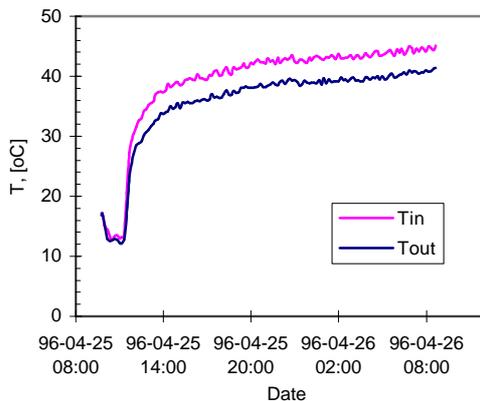


Fig. 2: Inlet and outlet temperatures from a borehole during a response test.

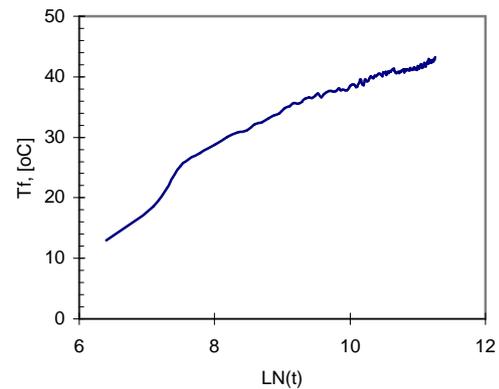


Fig. 3: Mean fluid temperature plotted versus logarithmic time.

### 2.3 Technical Description

The basic equipment required for the thermal response test comprises a pump, heater, temperature sensors for measuring inlet and outlet temperatures and a data logger to collect the data. The prototype equipment used a 1.5 kW pump and thermally insulated copper pipes with a diameter of 25 mm. The heater can be run on two power levels: 4.5 kW and 9 kW. This gives for a 150 m borehole a temperature increase of 5°C and 10°C respectively during a normal 4-5 day response test with a flow rate in the pipes of about 1 l/s. To make the equipment mobile it was set up on a car trailer which measured 1.70x2.70 m. The total cost for the equipment was USD 10,000.

The borehole pipes are connected to the pipe ends on the trailer. The pipes are filled with heat carrier fluid, which is pumped through the system. The fluid passes through the heater and is heated at constant power. The temperature sensors measure the fluid temperatures at the inlet and outlet pipes and the temperatures are recorded by the logger. The date, time and the two temperatures are logged at a selected time interval. The equipment is powered by electricity. A more detailed description is found in Eklöf and Gehlin (1996).

## 3. EXPERIENCE

The mobile equipment for the thermal response test was developed at the Division of Water Resources Engineering, Luleå University of Technology, Sweden. The equipment has been tested at a number of borehole cooling systems for telephone switching stations in Sweden. The measurements show that the method can be used to determine the effective thermal conductivity and thermal resistance of a borehole, and that the number of boreholes required for a borehole system can be reduced (generally by 10-30 %) when using the effective thermal properties for dimensioning the systems.

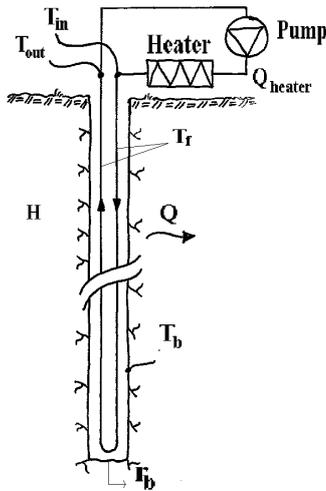


Fig. 4: Outline of the response test measurements.

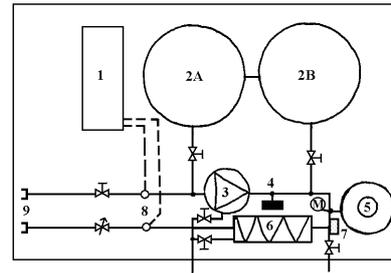


Fig. 5: View of the response test equipment. (1) electrical unit, (2A,B) plastic tanks, (3) pump, (4) pressure watch, (5) expansion tank, (6) heater, (7) switch for heater power, (8) temperature sensors, (9) quick couplings.

#### 4. FUTURE WORK

The Swedish telecommunications company, Telia, plans to expand the application of borehole cooling of telephone switching stations and has shown a great interest in the mobile response test equipment. With their help, a rough geothermal survey may also be performed for Sweden, i.e. a map of the effective thermal properties of the Swedish bedrock. The Swedish Heat Pump Consortium, SVEP, is supporting the research, based on their interest in using the thermal response test for resolving juridical controversies concerning heat extraction boreholes that do not keep the promised capacity, etc. and to avoid future controversies.

The development of the measurement method and equipment continues. There are 120 well-documented boreholes from a previous research project in Luleå (Nordell 1994) available for further research. These holes will be used for studying different types of borehole installations, the materials of the pipes and fillings, installation techniques, heat carrier fluids, natural convection, forced convection, the effects of cracks, groundwater flow, soil layers, etc. The method will also be used for studying parameters in soil, clay and complex rock species.

#### 5. CONCLUSIONS

In computer-based simulation models for the dimensioning of borehole UTES systems the actual ground conditions are approximated by assuming ideal and constant conditions in and around the borehole. In practice neither the installation nor the ground are perfect, and the actual thermal properties vary. The thermal response test is used to investigate the effective thermal properties of a borehole installation in situ. These effective properties can then be used to improve the accuracy of the computer simulations.

The response test equipment has a very simple construction and is easily operated. Mobile equipment for thermal response tests is a valuable tool for more elaborate optimisation when dimensioning a borehole UTES system.

## ACKNOWLEDGEMENTS

The financial support by the Swedish Council for Building Research (BFR) and the Swedish Heat Pump Consortium (SVEP) is gratefully acknowledged.

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## **PAPER II**

### **Direct Cooling of Telephone Switching Stations Using a Borehole Heat Exchanger.**

DIRECT COOLING OF TELEPHONE SWITCHING STATIONS  
USING A BOREHOLE HEAT EXCHANGER

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ABSTRACT

The Swedish telecommunication company Telia has during last two years tested and developed a method to cool telephone switching (AXE) stations by rejecting the excess heat via boreholes to the relatively cold bedrock. The heat from the electronic equipment inside the telestation is cooled by the air-to-water heat exchanger mounted in the ceiling. The heated water then flows to the borehole heat exchanger, which consists of groundwater-filled boreholes fitted with a single U-shaped loop of plastic tubing, where the heat is transferred to the surrounding bedrock. Several telestations have already been equipped with this type of direct cooling system. The number of boreholes used varies from 4 to 20 depending on the required cooling capacity. Thermal response tests lasting a few days have been performed at several installations in order to determine important design parameters such as the effective thermal conductivity of the bedrock and the thermal resistance between the heat carrier fluid in the U-pipes and the borehole wall. Long-term measurements of the heat balance and relevant temperatures have been made in some installations. The measurements show good agreement with results obtained by simulation models. The benefits of recharging, or storing, cold in the ground during the winter will be investigated. The paper summarizes recent field experiences and design studies.

1. INTRODUCTION

Borehole heat exchangers for direct cooling are used instead of, or as a complement to, conventional chillers. The capital investment for the borehole heat exchanger is on the same order as for a conventional cooling system, and the largest part of the investment is the drilling costs. Primary energy is only required for the circulation of the heat carrier fluid between the borehole and an indoor heat exchanger. This makes the operation very reliable and cheap. The maintenance cost of the system is also very low. Another important advantage of the borehole heat exchanger is the small space requirement. The borehole heat exchanger, located

completely below the ground, is as good as invisible. It is also possible to build on top of the borehole area.

The borehole heat exchanger cooling systems can be designed for *dissipation*, or rejection, of heat and/or cold to the ground. This is how the ground is used in common ground-coupled heat pump systems. In multiple borehole installations with an unbalanced heat budget it may be necessary to recharge the ground to maintain the efficiency. Multiple borehole heat exchangers are also designed for *storage* of heat or cold, or for both purposes, in which case the alternating heating and cooling of the ground becomes mutually beneficial. If natural cold is available during parts of the year, the store can be charged with cold.

## 2. SYSTEM DESCRIPTION

The design of a system with a borehole heat exchanger for direct cooling is shown in Fig. 1. The heat generated in the electronic equipment causes warm air to rise to the ceiling of the telestation. The warm air is cooled by an air-to-water heat exchanger mounted in the ceiling, and the heat carrier fluid transports the excess heat to the borehole heat exchanger. The water-filled boreholes, which have a diameter of 0.115-0.130 m, are usually about 150 meters deep. They are fitted with a single U-shaped loop of polyethylene tubing for circulation of the heat carrier fluid.

The number of boreholes used in realized projects varies from 4 to 20 depending on the required cooling capacity. The cooling requirement is relatively constant throughout the year. The borehole heat exchanger may be designed to meet the cooling load during either the whole year or only the warm season, in which case the outside air is used for ventilation during the colder periods. The current design criterion for the cooling system is to keep the maximum temperature in the station below 25°C for ten years. For typical Swedish conditions, bedrock (granite) with a thermal conductivity of 3.5 W/mK and an undisturbed ground temperature of about 8°C, it is possible to maintain a continuous heat rejection rate of about 25 W per meter of borehole provided that the spacing between adjacent boreholes is sufficiently large.

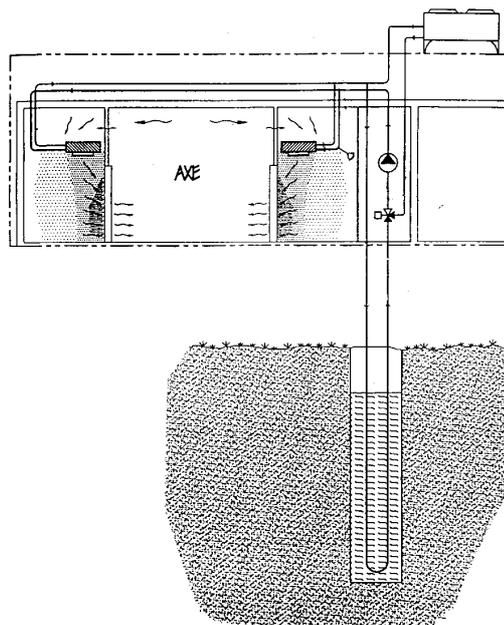


Fig. 1: Design of the system with a borehole heat exchanger for direct cooling.

### 3. THERMAL BEHAVIOR

The transfer of heat from the boreholes causes a change of temperature in the surrounding ground. This transient thermal response depends primarily on the thermal properties of the ground, the undisturbed ground temperature, the diameter and length of the borehole, the spacing between adjacent boreholes, and the specific heat transfer rate (W per meter borehole). The details of short-term variations in the heat transfer rate will only be noticeable in the vicinity of each borehole, whereas the long-term heat balance slowly will affect the temperature in a much larger ground region.

In *dissipative* systems where the rejection of heat (or cold) is the main purpose, the long-term thermal influence may significantly reduce the heat transfer capacity of closely spaced boreholes compared to widely spaced boreholes (Eskilson, 1987). In real applications, the borehole spacing is subject to both economical and physical constraints, so there is typically substantial thermal influence to be accounted for. The systems may be recharged with cold during the winter to balance the heat injection during the summer, so that the effects of the long-term temperature increase can be reduced or avoided. The presence of groundwater flow may enhance the dissipation of heat.

In *storage* systems, the intention is often to preserve the quality (temperature level or entropy) of the stored heat or cold. Thermal influence between adjacent boreholes is then desired, so that the difference between the heat carrier fluid temperature and the average store temperature can be kept as small as possible. Energy losses, dissipation, to the ground surrounding the storage region is here undesired. Ground water flow may decrease the efficiency of the store.

A common problem for both dissipative and storage systems is the thermal resistance between the heat carrier fluid in the borehole flow channels and the borehole wall. This so-called borehole thermal resistance depends on the arrangement of the flow channels and the thermal properties of the materials involved. Typical heat transfer rates of 25-100 W/m result in a temperature difference within the borehole of about 2-10°C. It is important to keep the borehole thermal resistance small. In water-filled boreholes, the heat transfer induces natural convection in the borehole water. This phenomenon, which is more pronounced at high temperature and large heat transfer rates, leads to a reduction of the borehole thermal resistance (Kjellsson and Hellström, 1997).

### 4. THERMAL RESPONSE TEST

The dimensioning of the cooling system is done using computer-based simulation programs. However, the quality of the results from the simulation depends on the quality of the input data. The thermal conductivity and the borehole thermal resistance are usually estimated according to the knowledge of the geology at the site. The uncertainty about the actual properties of the boreholes and occurrence of natural convection may cause over-dimensioning of the cooling systems, which then become unnecessarily expensive. Therefore a mobile equipment for the thermal response tests, used for in-situ measurements of the actual thermal conductivity and thermal resistance, has been developed. This creates new possibilities to make more elaborate dimensioning of the cooling systems (Gehlin and Nordell, 1997).

## 5. DESIGN METHODS

Several design tools have been developed that are capable of simulating the thermal response in both dissipative and storage systems using borehole heat exchangers. The Superposition Borehole Model (SBM) is a detailed model that allows for arbitrary-placed, vertical or graded, boreholes (Eskilson and Claesson, 1988). This finite-difference model has been validated against of several field experiments with both vertical and graded boreholes. The SBM model has been used to calculate dimensionless thermal response functions for a large number borehole configurations. These precalculated functions, which are stored in a database, provides for fast estimates of the thermal performance by the Earth Energy Designer (EED), which has a user-friendly interface and databases for thermal properties of ground, pipes, heat carrier fluid, etc (Hellström et al, 1997). The borehole thermal resistance can be calculated with an accurate analytical model. The Duct Ground Heat Storage Model (DST) is a fast simulation model for multiple borehole configurations with uniform borehole spacings. It has been used extensively as a stand-alone model, but has also been implemented as a module for ground heat storage in the well-known TRNSYS model, which is a modular program where the heat balance of different system designs can be studied (Pahud and Hellström, 1997).

## 6. CASE STUDY

The borehole heat exchanger at the telephone switching station at Drevikstrand, south of Stockholm, has been in operation since February 1995. The cooling system consists of four boreholes with a 130 mm diameter and 160 m depth, placed in a line with about 5 m spacing. See Fig. 2. The water-filled boreholes are fitted with a single U-pipe containing a glycol-water mixture. The boreholes are graded in order to increase the spacing and to improve the efficiency. They are connected to the AXE-station with horizontal pipes at a depth of about one meter. The horizontal pipes may increase or decrease the cooling capacity of the system, depending on the relation between the seasonal temperature variations of the cooling circuit and the ground surface. The undisturbed ground temperature at the location is 9°C. The design criteria for the cooling system is to allow a maximum temperature of 22°C at the inlet and 19°C at the outlet from the borehole. The four boreholes have a capacity for constant cooling of about 20 kW (i.e. ca 30 W/m).

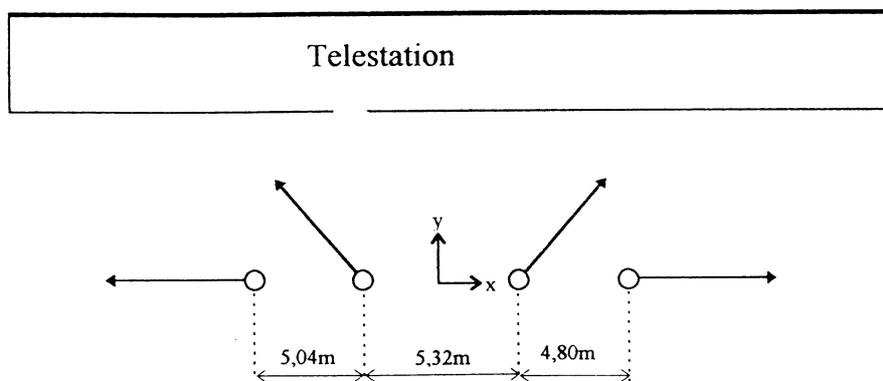


Fig. 2: Plan of the borehole heat exchanger at Drevikstrand, Sweden.

Figure 3 shows the measured and the simulated values of the inlet and outlet fluid temperature of the borehole heat exchanger at Drevikstrand from February to September during 1995. Three of the boreholes were used to reject 18-kW during the initial two weeks of the test period. From February 14th to May 12th about 16 kW were rejected through two of the boreholes. The heat rejection rate was then increased to about 25-kW, with all four boreholes used until the end of June, and three boreholes used from July to September. The fluid flow rate varied from 0.0014 m<sup>3</sup>/s (2 boreholes) to 0.0024 m<sup>3</sup>/s (4 boreholes).

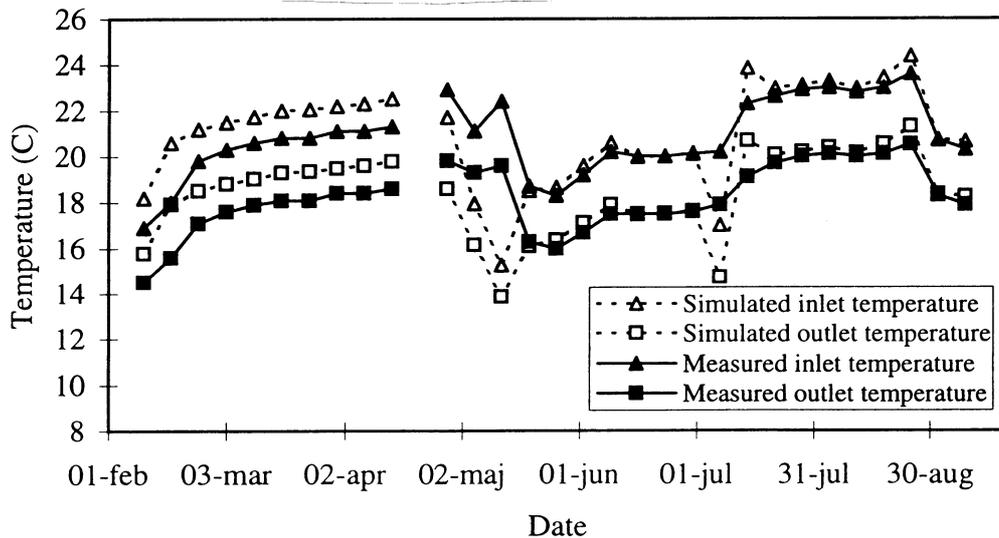


Fig. 3: Inlet and outlet fluid temperature of the borehole heat exchanger at Drevikstrand during eight months in 1995.

## 7. FUTURE DEVELOPMENT

The recent interest in direct cooling systems provides for new possibilities of further developing the borehole heat exchanger technique. New materials and designs will be developed to minimize the borehole thermal resistance and to increase the thermal efficiency of the cooling system. The capital investments can be decreased by developing new and more efficient equipment and methods for drilling.

A wide market potential for this type of cooling system can be seen. The borehole heat exchanger is suitable for many different applications, in small as well as large scale: comfort cooling of buildings and offices, industrial cooling, cold storage, etc.

## ACKNOWLEDGEMENT

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**PAPER III**

**Thermal Response Tests of Boreholes  
Results from In Situ Measurements.**

## THERMAL RESPONSE TESTS OF BOREHOLES - RESULTS FROM IN SITU MEASUREMENTS

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### ABSTRACT

During the last year thermal response tests of boreholes in rock were carried out with a mobile test equipment (TED) in several duct stores for heating and/or cooling. Most of the tests were made for the Swedish telephone company TELIA that is constructing a great number of direct cooling systems for their telephone switching stations. The size of these duct systems in the different plants tested, varies from 4 to 60 boreholes, drilled in hard rock - mostly granite and gneiss. This paper summarises results and experience from the measurements.

### 1. INTRODUCTION

The main part of the construction cost of a borehole heating/cooling system is the drilling cost and the pipe system. More elaborate optimisation of the systems would reduce the number of required boreholes, which would consequently reduce the cost and make the systems more economically competitive.

The heat transfer capacity of a borehole system is crucially dependent on the thermal resistance between the heat carrier and the surrounding rock. A lower thermal resistance means that a smaller temperature difference is required between the bedrock and the heat carrier, for a given heat power. This thermal resistance is seen as a temperature drop between 1/ the heat carrier fluid and the borehole wall, and 2/ the borehole wall and the surrounding rock. These temperature losses are dependent on the thermal properties of the pipe materials and borehole filling, shank spacing, flow conditions, etc. (in the borehole) and on the thermal conductivity of the bedrock, fractures, ground water flow, etc. (outside the borehole).

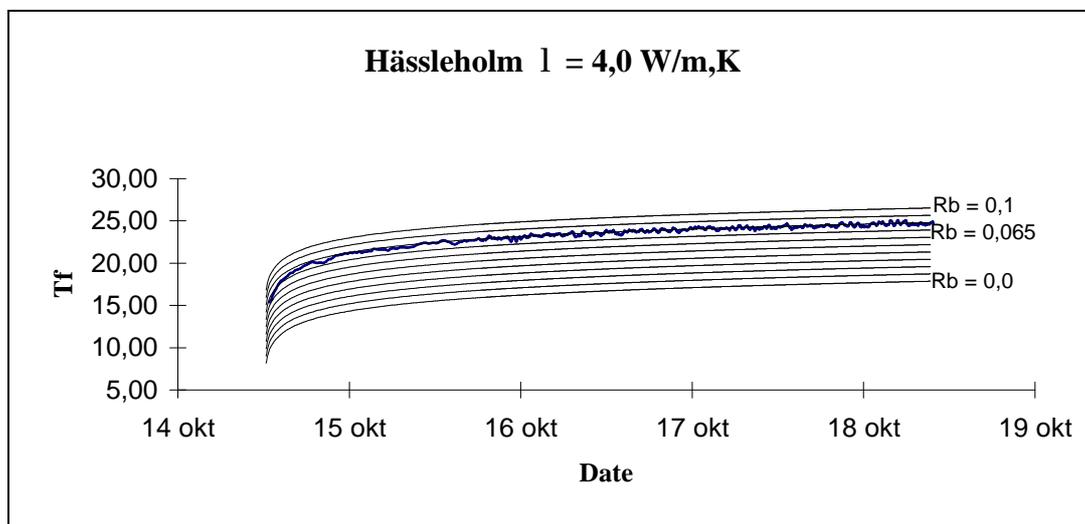
The thermal response test - TED measurements - means in situ measurements of the heat transfer capacity of boreholes for energy injection or extraction. The evaluated results include thermal properties of the ground and the borehole, but also the effect of factors that are difficult to estimate, e.g. natural convection in the boreholes, asymmetry in the construction, etc. By testing one borehole and evaluating its capacity in situ, the design of the borehole system can be

optimised regarding the total geological, hydro-geological and technical conditions at the location. Consequently, there are two reasons for performing such measurements:

1. To obtain reliable heat transfer data for dimensioning
2. To study new ground heat exchangers

### 1.1 Measurement Equipment

A mobile thermal response test equipment, TED, was constructed at Luleå University of Technology in 1995. The equipment consists of a pump, a heater and temperature sensors for measuring the inlet and outlet temperatures of the borehole. It is set up on a small trailer and easily transportable. The test is fully automatic including the recording of measured data and takes 4-5 days to execute. The results are easily evaluated from the data. Plotting the mean fluid temperature versus time as in Fig 1 the thermal conductivity is proportional to the inclination of the graph. The temperature level of the graph is proportional to the thermal resistance of the borehole.



**Fig 1** Example of measured mean fluid temperature in borehole compared to calculated mean temperatures for thermal conductivity of 4 W/m,K at different thermal resistance.

The borehole pipes are connected to the pipe ends on the trailer. The pipes are filled with heat carrier fluid, which is pumped through the system. As the fluid passes through the heater it is heated at constant power. Temperature sensors measure the fluid temperatures at the inlet and outlet pipes and the temperatures are recorded along with date and time by the logger at a selected time interval, usually 2 minutes. The equipment is powered by electricity and the prototype uses two power levels for the heater. Including the contribution from the circulation pump, the two power levels are 6.4 kW and 11 kW. For an average 150 m borehole, the heater causes a temperature rise in the borehole of 10°C and 15°C respectively during a normal 4-5 day response test with a flow rate in the pipes of about 1 l/s. The total cost for the equipment was USD 10,000 (Gehlin & Nordell, 1997). A more detailed description of the measurement equipment and of the analysis procedure is given in Eklöf and Gehlin (1996).

Date, time and inlet- and outlet temperatures are the minimum logged data requirements for the evaluation of a response test. It is however recommended to record ambient temperature,

hydraulic pressure in the pipes, flow rate and power demand to obtain a more complete set of data to check the measurements. These measurements will be included in the new version of the prototype.

## 2. PERFORMED TED MEASUREMENTS

### 2.1 TELIAs direct cooling system

The main part of the TED measurements have been performed at duct systems for direct cooling of telephone switching stations. The Swedish telephone company TELIA is gradually replacing their cooling machines (CFC) with the more environmentally friendly direct duct cooling systems in hard rock. The total energy savings from the use of this system is estimated to 40% and the savings in electrical energy is 80% (Hellström & Gehlin, 1997).

The telephone switches operate at their optimum at a temperature of around 25°C but generate a constant heat power which must be removed. Therefore TELIA has developed a new low temperature heat exchanger which is well suited for connecting to duct systems as a cold source.

The heat from the telephone switches raise to the ceiling by natural convection forces and are fanned through the low temperature heat exchanger. There the warm air meets the cold fluid from the boreholes, and the cooled air is then let out at the floor level. The cold fluid from the boreholes is circulated with a circulation pump through U-shaped loops of plastic piping in the groundwater filled boreholes (ducts). The fluid transfers the heat to the surrounding hard rock, which has a natural undisturbed temperature of about 8°C in Sweden. The duct systems are sized so that the maximum outlet temperature from the boreholes will not exceed 19°C.

Several of the direct cooling duct systems are constructed for continuous operation and can therefore use water as heat carrier. In systems combined with direct air cooling in winter time so that the ducts only will operate seasonally, some frost preventive additive must be used (e.g. glycol, ethanol etc.).

The duct systems are all constructed with single U-pipe installations, but lately an increased interest for double U-pipes has shown from TELIA. Double U-pipes result in lower thermal resistance and lower hydraulic loss and thus lower energy losses. Recently performed field experiments have shown that the thermal resistance for double U-pipe systems is 3-4 times lower than for single U-pipe systems, which corresponds to experience from laboratory experiments at Lund University of Technology (Hellström 1998). An overview of the size of the measured cooling systems is shown in ? .

Table 1 Description of direct cooling duct systems for TELIA

Location	Number of boreholes	Active Mean Depth (m)	Maximum Cooling Load (kW)	Annual Cooling Load (MWh)
Drevikstrand	4	155	20	173
Ängby	6	154	27	237
Oskarshamn	4	161	30	259
Hässleholm	19	150	105	185
Linköping	7	157	45	80
Norrköping	20	157	108	192
Ludvika	5	149	35	49
Örebro	60	199	200	173

## 2.2 Results from measurements

The cooling systems where measurements have been performed are located in south Sweden. The ground is typically granitic with a high groundwater level. At the locations the groundwater level varied between 1-18 m below ground surface, with a typical level of 3-4 m. The undisturbed ground temperature is typically about 9°C but vary slightly due to latitude etc. ? summarises the physical data for the systems. The measured boreholes have depths between 115-161 m, except for the site in Örebro (197 m), where a new type of water driven down-the-hole well drilling equipment has been tested, allowing the boreholes to be drilled much deeper than today's standard (Nordell et al, 1998). The borehole diameter varies between 115-160 mm.

The basic results from the measurements are over-viewed in ? . A remarkably high undisturbed ground temperature is observed in Oskarshamn and Ludvika. In Oskarshamn the elevated ground temperature is likely due to the duct system being located on a hill in the centre of the town, and surrounded by heat sources such as large houses and streets with considerable traffic.

For the case of Ludvika, the measurement was disturbed partly due to measurements being done too short time after the drilling of the hole, and also by on-going drilling in an adjacent hole. The results from the Ludvika measurement could not be used for dimensioning, but however, the results are interesting not only to show the influence of the heat from the drilling, but even more to confirm the importance of convection in the boreholes. As two strongly permeable layers were reported from the drilling, and drilling was performed in a nearby borehole during the measurements, there is reason to suspect a highly elevated forced groundwater flow through the measured borehole. This is observed as an extremely high effective thermal conductivity, giving the impression that the rock is highly conductive. It is however the groundwater flow that transports much of the heat and causes this effect.

Table 2 Physical data for measurements

Site	Rock	Fluid	Groundwater (m)	Active borehole depth (m)	Borehole diameter (mm)
Drevikstrand	granite	Etylenglycol	3	160	140
Ängby	granite	Etylenglycol	7	132	115
Oskarshamn	granite	Ethanol	4	161	135
Hässleholm	granite	Water	18	126	160
Linköping	granite	Water	5	115	160
Norrköping	granite	Water	3	157	115
Ludvika	granite	Water	3	117	140
Örebro	granite	Water	1	197	115

From the other locations the thermal conductivity typically varies between 3.2-4.2 W/m,K. This should be compared with the typical values for Swedish granite, which is in the interval 3-4.5 W/m,K (Sundberg, 1988). The high values for Drevikstrand and Ängby are notable, and will be analysed further.

Thermal resistance varies between 0.04-0.10 K/(W/m). Standard value for dimensioning of duct systems has so far been 0.10 K/(W/m), but the TED measurements indicate a slightly lower resistance to be expected. The reason is probably natural convection in the boreholes, which increases the heat transfer.

Table 3 Results from measurements (*corrections have been done compared to original manuscript.*)

Site	Active borehole depth (m)	Undisturbed ground temp (°C)	Maximum measured temp (°C)	Heating Load (kW)	Measured $\lambda$ (W/m,K)	Measured Thermal Resistance (K/(W/m))
Drevikstrand	160	9.2	21	11	5	0.08
Ängby	132	9	23	11	5.5	0.08
Oskarshamn	161	10.5	18	6.4	3.6	0.06
Hässleholm	126	8.7	23.4	11	3.8	0.06
Linköping	115	8.1	24.7	11	3.4	0.04
Norrköping	157	8.5	21.3	11	3.5	0.05
Ludvika	117	11*)	16.3*)	6.4	11*)	0.05*)
Örebro	197	9.5*)	16.2*)	6.4	6*)	0.12*)

\*) The measurements were disturbed by on-going drilling in an adjacent borehole

### 3. DISCUSSION

#### 3.1 Measurements

The field measurements indicate that the thermal resistance in the boreholes is lower than expected from laboratory experiments. This means that in field there are factors that decrease the resistance and that do not exist in laboratory environment. The explanation could not be found in pure natural convection due to temperature gradients within the borehole, as this would occur in the same way in laboratory.

A possible explanation could be the volume expansion of the heated water in the borehole. In general the temperature in a borehole is raised 10-15°C during a response test. With a volume expansion for water of 0.25% (Franks, 1972), this would give an elevation of the water level in a 150 m borehole of about 0.4 m. This elevated groundwater level would cause a convective movement in the ground, as the water is tapped off in fractures at the top of the borehole at the same time as cold water is pressed into the boreholes from fractures deeper down. This large scale natural convection would not show in laboratories or in a theoretical perfectly sealed borehole. Such perfectly sealed boreholes are, however, not very likely to be found in nature. A closer investigation of this theory will be done during 1998.

The Ludvika measurement tells that groundwater flow through fractured rock does influence the heat transfer in boreholes. The elevated convection in the borehole due to the drilling in an adjacent borehole shows that groundwater flow can improve the effective thermal conductivity and heat transfer in the borehole.

Experience from the measurements tells that a correct estimation of the undisturbed ground temperature at a location is important, since this parameter greatly affects the calculations. The influence on the ground temperature from permanent buildings and roads as heat sources may be of interest to investigate further.

It is important that the test equipment is well insulated to prevent the influence from changes in ambient temperature, which could give a wrong impression of the amount of heat transferred to the ground.

#### 3.2 Planned measurements

During 1997 a series of measurements have been performed at the borehole heat store in Luleå (Nordell, 1991). More measurements will be executed during 1998 and the experiment schedule is shown in ? . Measurements and analysis are under procedure at the time for this paper being written, and will be thoroughly reported in a licentiate thesis later in 1998.

The main objectives of the experiments are to further investigate and analyse the effects of natural and forced convection in the boreholes, and tests will be done with external circulation pumps descended into boreholes. Different fillings and installation performances (e.g. single U, double U, coaxial, open) will be compared on a technical as well as economical basis, and also experiments with freezing in boreholes are planned.

The results from the measurements will in a later stage be used to study the transient period during the first hours of measurements. This will give valuable information about the thermal behaviour of the volume within the borehole wall and can be of use for the design of systems with intermittent operation.

Table 4 Experimental schedule for measurements in Luleå

Installation Type	Arrangement	Comments
Single U-pipe	Simple	Performed
	External Convection	Performed
	Filled	Planned
	Frozen	Planned
Double U-pipe	Simple	Performed
	External Convection	Planned
	Filled	Planned
Open	Simple	Planned
	External Convection	Planned
Coaxial	Simple	Planned

## ACKNOWLEDGMENTS

The authors acknowledge SVEP, LTU and the Swedish Council for Building Research for their financial support of this work.

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## **PAPER IV**

### **Thermal Response Tests of Single and Double U-tube Ground Collectors in Luleå.**

## THERMAL RESPONSE TESTS OF SINGLE AND DOUBLE U-TUBE GROUND COLLECTORS IN LULEÅ

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### ABSTRACT

A series of thermal response tests with a mobile test equipment (TED) were carried out on groundwater-filled boreholes in hard rock during 1996-98 in a shut down heat store at Luleå, Sweden. Measurements were performed on one borehole with a single U-tube collector and two boreholes with double U-tube collectors. The results were compared with laboratory tests of the rock thermal conductivity and borehole thermal resistance. The field measured thermal conductivity is slightly higher and the borehole thermal resistance is lower than predicted from laboratory tests. The TED-estimation of thermal conductivity and thermal resistance takes into account the heat transfer induced natural convection in the borehole and by groundwater flow in cracks and fissures, which helps to improve the heat transfer of the borehole system. These effects are not measured in laboratory tests.

### 1. INTRODUCTION

TED measurements - thermal response tests - mean in situ measurements of the heat transfer capacity of boreholes for thermal energy injection or extraction. By analysing measured data the thermal properties of the ground and the borehole are obtained. The heat transfer capacity of a borehole system depends on the effective thermal conductivity of the ground including groundwater and natural convection, and on the thermal resistance between the heat carrier and the surrounding rock. A lower thermal resistance means that a smaller temperature difference is required between the bedrock and the heat carrier, for a given heat power.

The borehole thermal resistance depends on the thermal properties of the pipe materials and borehole filling, shank spacing, flow conditions, etc. (in the borehole) and on the thermal conductivity of the bedrock, fractures, ground water flow, etc. (outside the borehole). This in-situ

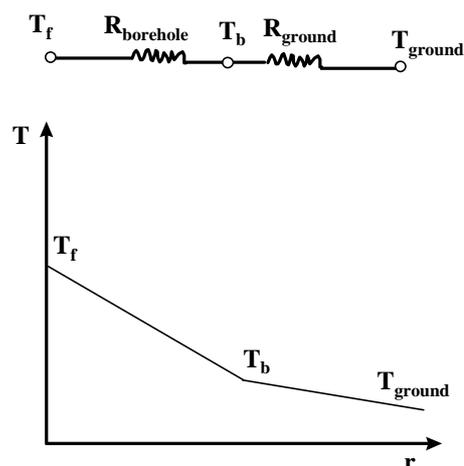


Figure 1. The thermal resistance causes a temperature difference between the heat carrier fluid in the pipes and the borehole wall and between the temperature at the borehole wall and the ground.

measurement of the thermal conductivity and thermal resistance gives reliable dimensioning data for the design of borehole systems. In this paper a series of response test measurements on single and double U-tube collectors, in a well-documented heat store at Luleå are compared with the design data from the store.

## 2. DESCRIPTION OF THE TEST SITE

The heat store used for the measurements is located close to Luleå University of Technology and was taken into operation in July 1983. It was the very first large-scale storage system of this type (Nordell, 1986, 1987, 1989, 1990, 1994). The store was shut down in 1990. The heat store consists of a volume of rock amounting to about 120 000 m<sup>3</sup> beneath the 2-6 m overburden of mineral soil. Vertical boreholes were drilled to a depth of 65 m in a rectangular pattern 12x10 holes with a spacing of 4 m. During 1983-90 the store was heated during the summer to a temperature of 65-70°C by injection of industrial waste heat. During the discharge season the minimum temperature in the store was about 30°C. The initial temperature of the rock was 3.5°C.

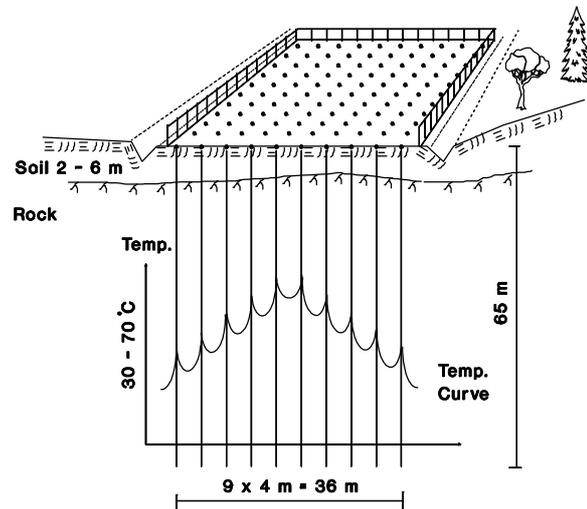


Figure 2. Geometry of heat storage at Luleå University. (From Nordell 1987).

The bedrock was investigated with core-mapping and consists of streaked medium-grained granite and gneiss-granite. The thermal conductivity and heat capacity of the bedrock were obtained from laboratory measurements on five core samples taken from one borehole. The rock characteristics varied considerably along the drill core (Table 1). Unfortunately the core samples were not identified to the type of rock associated with each sample. Sample 3 was taken from a thin streak of pegmatite, which was found in a proportion of only 1.5 % in the core. Mean values calculated with and without sample 3 are shown in table 5.

Table 1. Technical Data of the Luleå Heat Store

Storage Volume	120 000 m <sup>3</sup>
Soil Cover	2-6 m
Type of Rock	Medium Grained Gneiss
Estimated Thermal Conductivity	3.428 W/m,K
Estimated Thermal Capacity	2.166 MJ/m <sup>3</sup> ,K
Storage Land Area (36x44 m)	1584 m <sup>2</sup>
Number of boreholes	120
Borehole Depth	65 m
Borehole Diameter	0.152 m
Borehole Spacing	4 m
Type of Circulation System	Open
Charging Temperature	70-82°C
Extracting Temperature	65-30°C
Undisturbed Rock Temperature 1983	3.5°C

Table 2. Thermal characteristics of the bedrock.(From Nordell, 1987)

Sample no.	Thermal Capacity [MJ/m <sup>3</sup> ,K]	Thermal Conductivity [W/m,K]
1	2.365	3.529
2	2.300	3.288
3*	1.968*	4.439*
4	2.097	3.184
5	2.100	3.698
Mean Value	2.166	3.628
<i>Mean Value except *</i>	2.216	3.425

\* Pegmatite streak, non representative for the rock as a whole

Water loss measurements were performed to estimate the hydraulic permeability of the rock. It was concluded that apart from the uppermost 10 m of rock, the bedrock is highly impervious, but in parts of the store the bedrock is considerably fractured.

Based on temperature measurements of the first 15 days of operation of the store in 1983, a thermal response evaluation was performed for the entire store (i.e. 120 boreholes) to determine the borehole thermal resistance. The thermal response analysis was performed with the assumption that the thermal conductivity of the store was 3.42 as estimated in the laboratory tests of drill core samples (Hellström, 1991a). The collector type used was open with a siphon system between the boreholes. The expected thermal resistance was 0.01 K/(W/m) but the actual thermal resistance of 0.10 K/(W/m) was explained by the pipes not being well centred in the boreholes.

In 1996, seven of the peripheral holes (see Figure 2) were re-opened, and three of them were fitted with new collector piping. Borehole 5A was fitted with PEM 32 mm single U-tube, and boreholes 3A and 2A were fitted with PEM 32 mm double U-tubes. All collectors were filled with Svedol (30% ethanol). Temperature measurements in the recovered boreholes revealed that the temperature after 6 years had decreased from 70°C to 13-15°C in the peripheral boreholes (Magnusson and Rosén, 1996). This correlates well with simulations of the temperature decrease in the store over time, which was performed in a master thesis by Gidmark and Nilsson (1997).

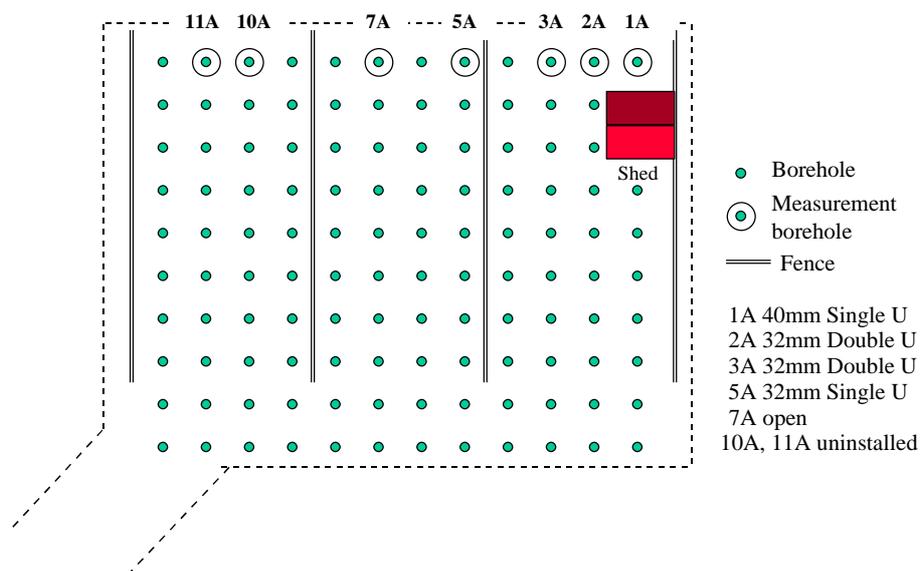


Figure 3. The experimental boreholes at the Luleå Heat Store

### 3. THERMAL RESPONSE TEST

#### 3.1 Measurement Equipment

The mobile thermal response test equipment, TED, was constructed at Luleå University of Technology in 1995-96 (Eklöf and Gehlin, 1996; Gehlin and Nordell, 1997). The equipment is set up on a small covered trailer and consists of a 1 kW pump circulating the heat carrier through the borehole collector and through a cross-flow heater with adjustable heating power in the range 3-12 kW. Fluid temperatures are measured at the inlet and outlet of the borehole by thermistors with an accuracy of  $\pm 0.2^\circ\text{C}$ . The temperatures are recorded at a set time interval by a data-logger. The equipment is powered by 16 A electricity.

#### 3.2 Measurement Procedure

The pipe endings of the borehole collector are connected to the equipment with quick couplings at the rear end of the trailer and the heat carrier fluid is pumped through the system. The fluid passes through the heater and the inlet and outlet temperatures are recorded every second minute by a data-logger. The test, which is fully automatic including the recording of measured data, takes about three days to execute.

To determine the undisturbed ground temperature, the heat carrier is initially circulated through the system without heat injection during 20-30 minutes. The mean fluid temperature along the piping will then be recorded, and this temperature in the borehole corresponds to the temperature of the undisturbed ground. Then, the heater is switched on and the measurement is proceeding for 60-72 hours. The groundwater level is determined manually with a separate fluid alarm during the measurements. Also the power supply is measured during the measurements to record the actual power injection. The power supply has proved to be relatively stable during the measurements.



Figure 4. Thermal response test at Luleå heat store. Photo: Peter Olsson.

### 3.3 Data Analysis

The analysis is based on a line source model (Mogensen 1983, Eskilson 1987, Hellström 1991). When heat is injected into a borehole a transient process starts that is approximated by:

$$T_f = \frac{Q}{4plH} \ln(t) + \left[ \frac{Q}{H} \left( \frac{1}{4pl} \left( \ln\left(\frac{4a}{r_b^2}\right) - g \right) - R_b \right) + T_{sur} \right] \quad \text{for } t \geq \frac{5r_b^2}{a} \quad (1)$$

$$T_f = \text{heat carrier mean fluid temperature} = \frac{T_{in} + T_{out}}{2} \quad [^\circ\text{C}]$$

Q = injected heat power [W]

$\lambda$  = thermal conductivity [W/m,K]

H = effective borehole depth [m]

t = time from start [s]

a = thermal diffusivity ( $\lambda/c$  where c is the thermal capacity) [ $\text{m}^2/\text{s}$ ]

$r_b$  = borehole radius [m]

$\gamma$  = Euler's constant (0.5772)

$R_b$  = thermal resistance [K/(W/m)]

$T_{sur}$  = undisturbed temperature of the ground [ $^\circ\text{C}$ ]

The thermal conductivity is estimated by plotting the mean fluid temperature versus time and match the plot of the experimental mean fluid temperature ( $T_f$ ) with curves for different thermal resistances according to Eq (2). The thermal conductivity decides the inclination of the curve while the thermal resistance is decided from the temperature level of the fluid.

This graphical method allows an accuracy of  $\lambda \pm 0.05$  W/m,K and  $R_b \pm 0.005$  K/(W/m). Critical parameters for the analysis are the power rate, groundwater level and undisturbed ground temperature, which must therefore be properly estimated on site.

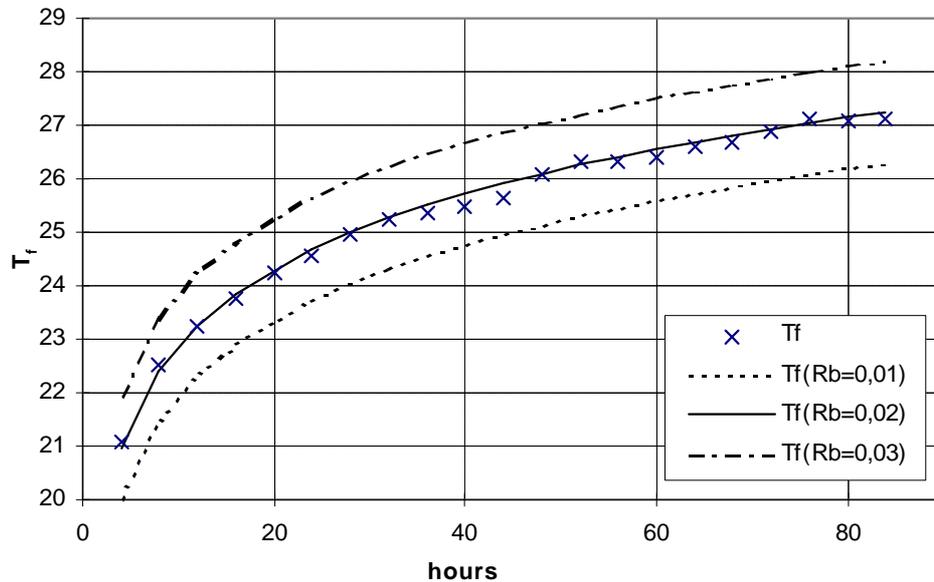


Figure 5. Mean fluid temperature from response test on double U-tube collector fitted to Eq(2) with  $\lambda = 3.7$  W/m,K and  $R_b = 0.02$  K/(W/m).

## 4 THERMAL PERFORMANCE OF THE BOREHOLES

From October 1996 to June 1998, 14 successful response tests were executed at the heat store at Luleå University of Technology. Of these measurements, 6 tests were run on borehole 5A fitted with a single U-tube (Table 3), while 5 and 3 tests were run on borehole 3A and 2A respectively, both fitted with the same type of double U-tubes (Table 4). The ground temperature in the old store is about 13-15 °C 8 years after the shut-down of the store. The temperature in borehole 5A is some degree higher than 3A and 2A, since the latter are more peripheral. When several consecutive response tests were run, the ground did not fully recover between the measurements, and the ground temperature was therefore slightly increased. Normal ground temperature in Luleå is 3.5°C. Average for Sweden is about 8°C.

The groundwater level in the boreholes varied from 1.8-3.7 m below ground surface over the year, normally 3.3 m. However, during the days of heavy snow melting in April 1998 (marked with \* in Table 3 and 4), pulses of groundwater appeared punctually between 11 am -1 pm, pressing up warmer water from the warm inner parts of the heat store. The groundwater level in the boreholes then raised to ground surface. This phenomenon severely disturbed the measurements, which can be seen in Table 3 and Table 4 as a lower thermal conductivity due to the extra heat coming from the heat store, and a significantly lower thermal resistance, likely to be due to the large groundwater flow through the ground.

Table 3. Response tests on single U-tube collector (5A) at Luleå heat store.

Date	Measured time[h]	Groundwater level [m]	q [W/m]	Ground temp [°C]	$\lambda$ [W/m,K]	$R_b$ [K/(W/m)]
961005	91	3.5	98	14.9	3.55	0.06
971017	81	3.1	97	14.5	3.7	0.05
971029	116	3.3	97	14.7	3.65	0.06
980406	91	3.5	98	14.6	3.6	0.05
980420*	93	3.3-0.00*	97	16*	2.8*	0.01*
980611	68	2.2	113	14	3.6	0.06

\* The measurement was disturbed by groundwater flow due to snow melting

Table 4. Response tests on double U-tube collectors (3A and 2A) at Luleå heat store

Bore-hole	Date	Measured time[h]	Groundwater level [m]	q [W/m]	Ground temp [°C]	$\lambda$ [W/m,K]	$R_b$ [K/(W/m)]
3A	971024	97	2	95	14	3.7	0.02
3A	971104	101	3.3	97	13.8	3.65	0.03
3A	971124	117	3.7	98	13.8	3.65	0.02
3A	971216	86	3.5	98	14.5	3.7	0.02
3A	980330	95	2.3	96	13.1	3.6	0.03
2A	980402*	70	3.3-0.00*	97	15*	3.6*	0.02*
2A	980423	68	3	97	13.8	3.6	0.03
2A	980615	93	1.8	84	14	3.55	0.03

\* The measurement was disturbed by groundwater flow due to snow melting

#### 4.1 Thermal conductivity

Table 3 and Table 4 show that the variation in the results from the in-situ measurements of the thermal conductivity at the site is small. Measured thermal conductivity is  $3.62 \pm 2\%$  W/m. The suggested thermal conductivity from the geological investigations (Table 1), is 3.428 W/m.K. The difference between the geological value and the response test value may be explained by the fact that the geological samples were not weighted considering the mean constitution of the bedrock. In situ performed measurements of thermal conductivity in rock are reported to give a slightly higher thermal conductivity than laboratory measurements. Ericsson (1985) explains this effect by natural cracks and fissures in the rock being more or less closed depending on the pressure from the rock itself. These cracks and fissures are also often filled with groundwater, which will drain in laboratory. The air has a considerably lower heat transfer capacity than water, thus thermal conductivity will be higher when measured in situ.

#### 4.2 Thermal Resistance

The thermal resistance varies little between the measurements. The mean values for the single U-pipe and the double U-pipes are shown in Table 5. The mean value for the single U-tube collector,  $R_b = 0.056$  K/(W/m), is lower than the standard value for single U-tubes,  $R_b = 0.08$  K/(W/m), which is used in most calculations. Laboratory results from Lund University of Technology suggest 0.07 K/(W/m) for the same type of piping at a temperature of around 30°C, and a heat load of 100W/m (Kjellsson & Hellström, 1997). The lower value from the field tests is probably due to thermal convection in the groundwater filled borehole. The mean value of the thermal resistance of double U-tube collector was  $R_b = 0.025$  K/(W/m). Standard values for double U-tube collectors is 0.06 K/(W/m). At this time the results from laboratory measurements on double U-tubes at Lund University are not available. Natural convection in the borehole water is not likely to occur to the same extent in boreholes with double U-tubing, since the thermal contact with the borehole wall is very good and the amount of surrounding groundwater is small. As can be seen from the results of the response tests, the thermal resistance of the double U-tube is about 50% lower than that for the single U-tube.

Injected power per meter borehole varied from 95-113 W/m, but no obvious relation between the heat load per meter and the thermal resistance can be observed for such a small difference in heat load. The load during the measurements was however about twice as high as normal operational load for heat store applications. Since the natural convection in the borehole water increases with increasing heat load, the measured thermal resistance in the response tests is slightly lower than expected during normal operational conditions of a UTES system. Table 5 shows the mean values of all the response tests on the boreholes at Luleå heat store. The values from the measurements affected by the enlarged groundwater flow from snow melting are not counted in the means.

Table 5. Mean values of results from response tests

Installation Type	$\lambda$ [W/m,K]	$R_b$ [K/(W/m)]
Single U-pipe (5A)	3.62	0.056
Double U-pipe	3.62	0.025
3A	3.66	0.024
2A	3.58	0.027

## 5. CONCLUSIONS

The response tests show reasonable results for thermal conductivity and for thermal resistance. The difference between the TED-measurements and laboratory estimations can be explained partly by the laboratory set-up is a hydraulically completely sealed borehole, which is not the case in field, thus the effects of groundwater and natural convection are not measured in laboratory tests. The groundwater movement in a borehole is difficult to survey as it depends on the extent of possible flow paths between interconnecting natural fractures and the borehole. The hydrostatic equilibrium is changed due to the heat transfer to the borehole water, and a thermal siphon type of circulation through the borehole is induced. This siphon effect does not show in laboratory measurements. In a dissipative system, small-scale and large-scale natural convection and regional flow may contribute to improve the thermal performance, whereas in a storage type of system they may improve the heat transfer from the borehole to the store but also increase the thermal energy losses (Hellström, 1998).

Critical parameters for the analysis of the data are the groundwater level, actual power injection rate and undisturbed ground temperature. It is essential that these parameters are appropriately determined during the TED-measurements. The measurements are sensitive to weather conditions such as snow melting with large groundwater flow, cold winter days and large amplitudes in day and night temperatures. It is therefore necessary to thermally insulate the equipment and pipes well to prevent uncontrolled energy losses to the surroundings. If possible measurements during weather conditions that may cause anomalies in groundwater flow should be avoided. It has not been observed that normal rain -although heavy- affected the measurements.

The graphical analysis method with curve fitting is more reliable than the linearization method, and gives an accuracy of  $\lambda \pm 0.05$  W/m,K and  $R_p \pm 0.005$  K/(W/m). The development of a better computerised curve fitting method would be convenient for the future development of TED-measurements. The response test at the Luleå heat store will continue with measurements on grouted boreholes, open systems with and without forced convection, frozen systems and groups of boreholes. The thermal siphon effect will be further investigated.

## ACKNOWLEDGMENTS

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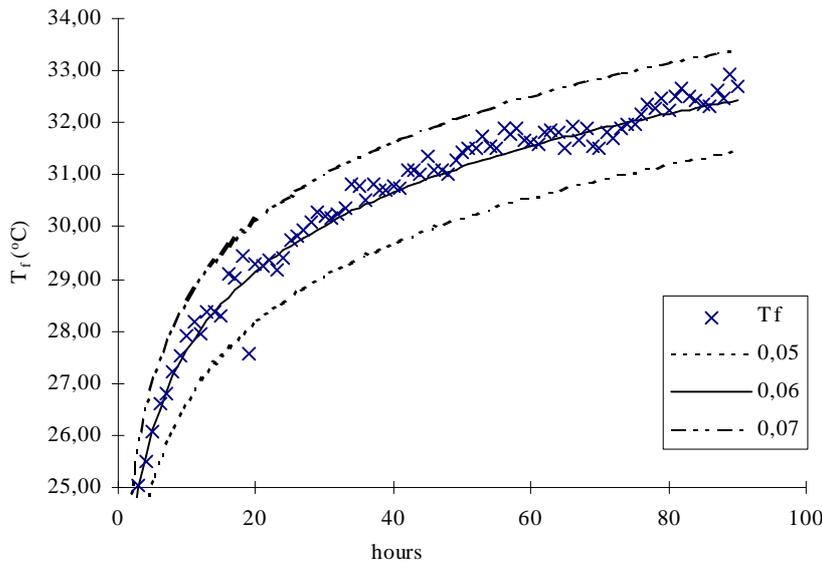
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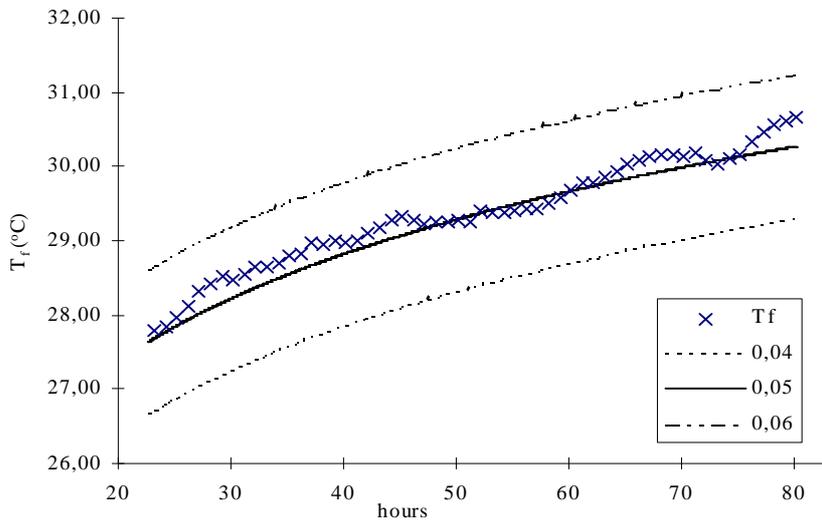
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# **APPENDIX A**

## **Measurement Data from Response Test in Luleå**

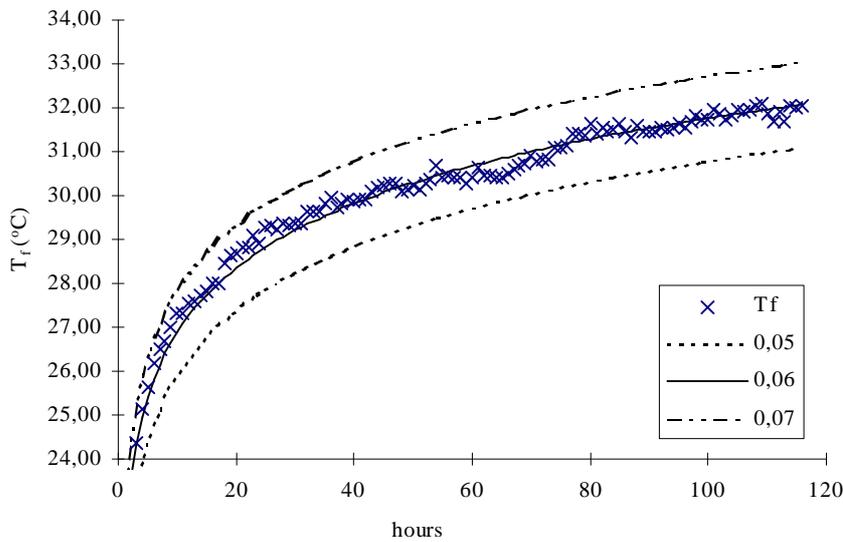


Borehole 5A  
 Single U-tube  
 Date: 961002-961005  
 Active Depth = 61.5 m  
 Diameter = 154 mm  
 $q = 98 \text{ W/m}$   
 $T_o = 14.9^\circ\text{C}$   
 $\lambda = 3.55 \text{ W/m,K}$   
 $R_b = 0.06 \text{ K/(W/m)}$

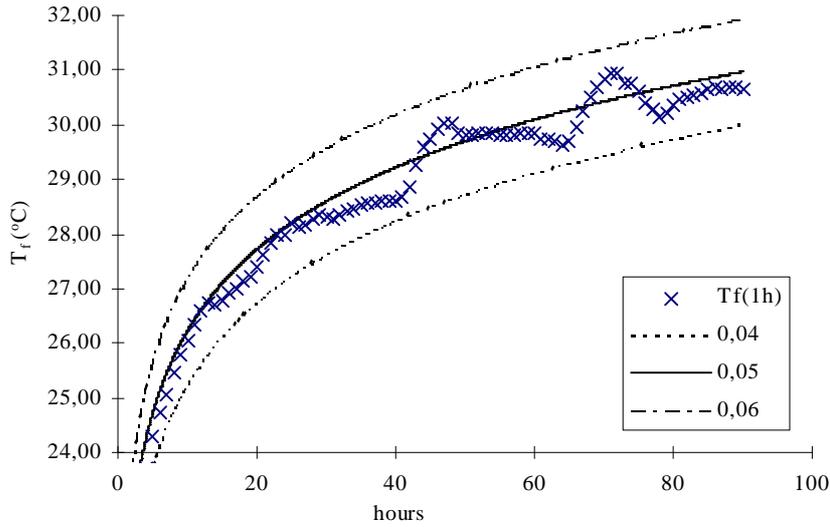


Borehole 5A  
 Single U-tube  
 Date: 971015-971017  
 Active Depth = 61.9 m  
 Diameter = 154 mm  
 $q = 97 \text{ W/m}$   
 $T_o = 14.5^\circ\text{C}$   
 $\lambda = 3.7 \text{ W/m,K}$   
 $R_b = 0.05 \text{ K/(W/m)}$

Data from the first 24 hours are lost.

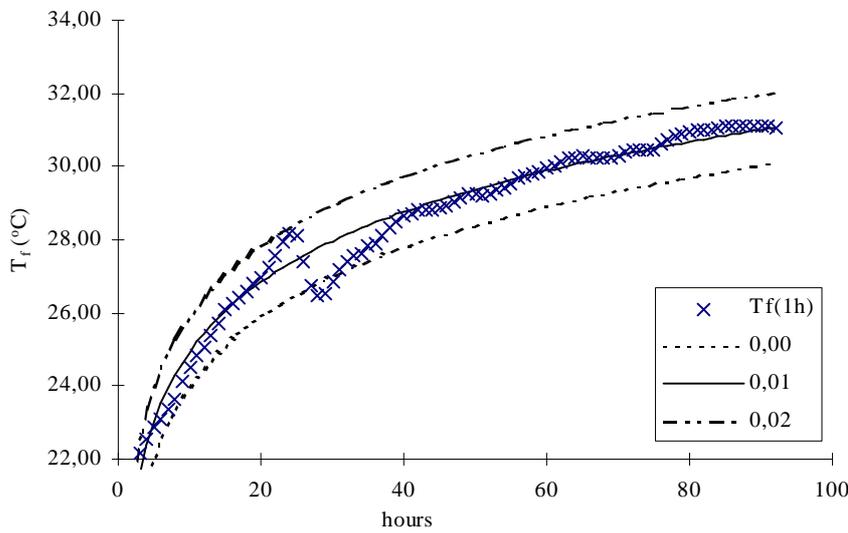


Borehole 5A  
 Single U-tube  
 Date: 971024-971029  
 Active Depth = 61.7 m  
 Diameter = 154 mm  
 $q = 97 \text{ W/m}$   
 $T_o = 14.7^\circ\text{C}$   
 $\lambda = 3.65 \text{ W/m,K}$   
 $R_b = 0.06 \text{ K/(W/m)}$



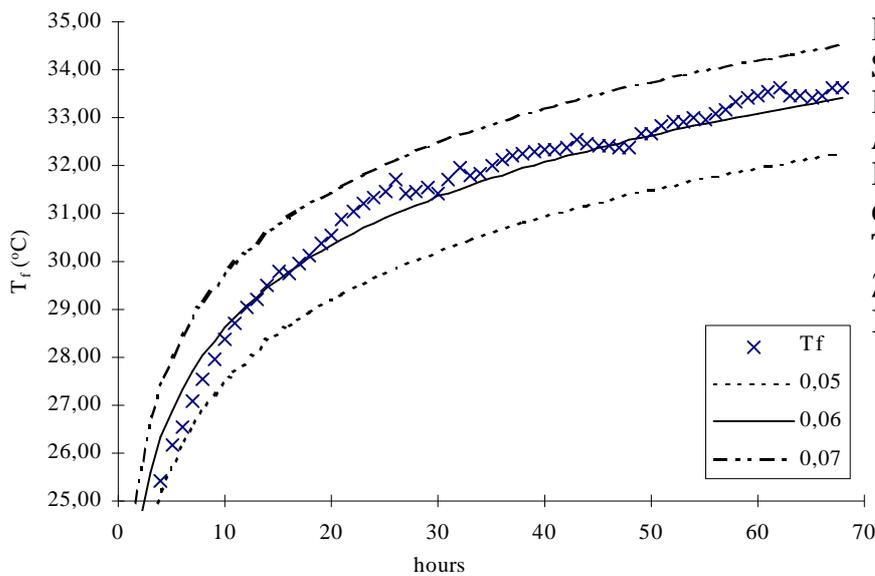
Borehole 5A  
 Single U-tube  
 Date: 980402-980406  
 Active Depth = 61.5 m  
 Diameter = 154 mm  
 $q = 98 \text{ W/m}$   
 $T_o = 14.6^\circ\text{C}$   
 $\lambda = 3.6 \text{ W/m,K}$   
 $R_b = 0.05 \text{ K/(W/m)}$

Heavy snow melting.  
 Warm water is pressed up from the warmer inner part of the store by colder melt-water from up hill.

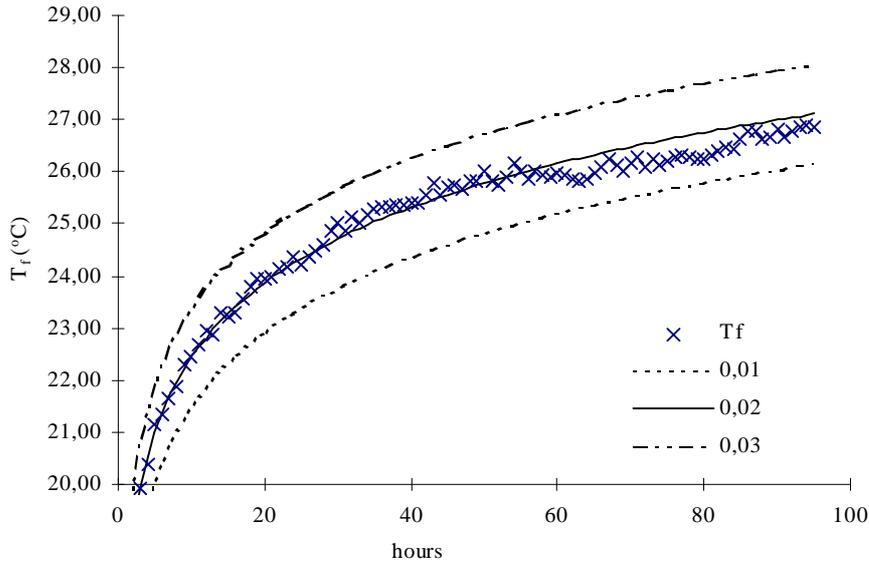


Borehole 5A  
 Single U-tube  
 Date: 980426-980420  
 Active Depth = 61.7 m  
 Diameter = 154 mm  
 $q = 97 \text{ W/m}$   
 $T_o = 16^\circ\text{C}$   
 $\lambda = 2.8 \text{ W/m,K}$   
 $R_b = 0.01 \text{ K/(W/m)}$

Heavy snow melting.  
 Warm water is pressed up from the warmer inner part of the store by colder melt-water from up hill during first 30 hours.

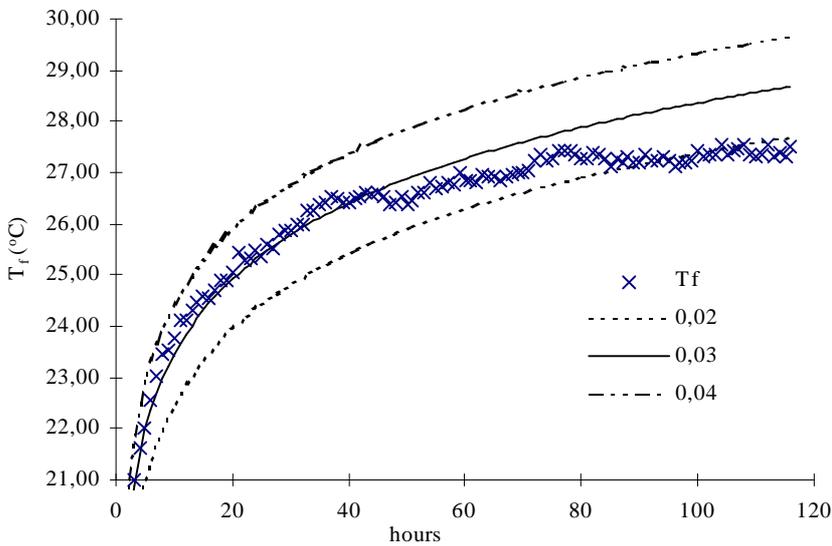


Borehole 5A  
 Single U-tube  
 Date: 980608-980611  
 Active Depth = 62.8 m  
 Diameter = 154 mm  
 $q = 113 \text{ W/m}$   
 $T_o = 14^\circ\text{C}$   
 $\lambda = 3.6 \text{ W/m,K}$   
 $R_b = 0.06 \text{ K/(W/m)}$



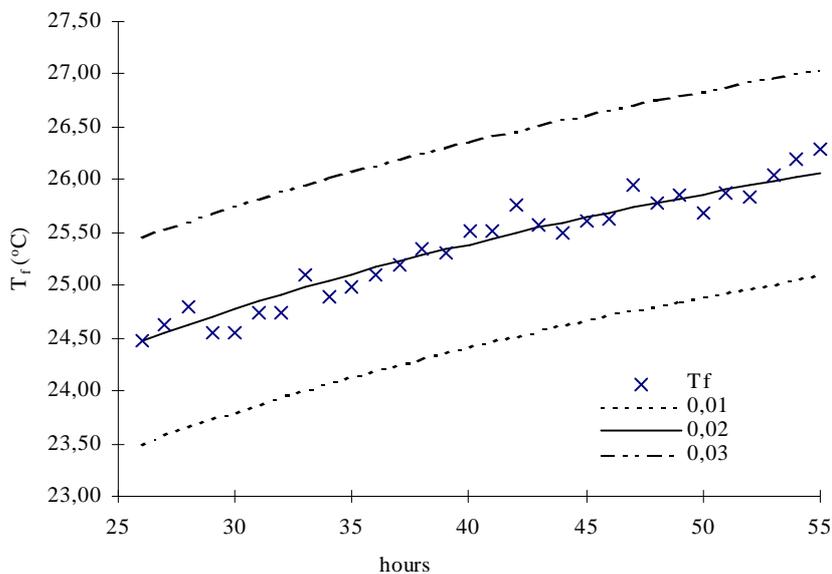
Borehole 3A  
 Double U-tube  
 Date: 971020-971024  
 Active Depth = 63 m  
 Diameter = 154 mm  
 $q = 95 \text{ W/m}$   
 $T_o = 14^\circ\text{C}$   
 $\lambda = 3.7 \text{ W/m,K}$   
 $R_b = 0.02 \text{ K/(W/m)}$

Measurement disturbed  
 by cold-front at 55 hours



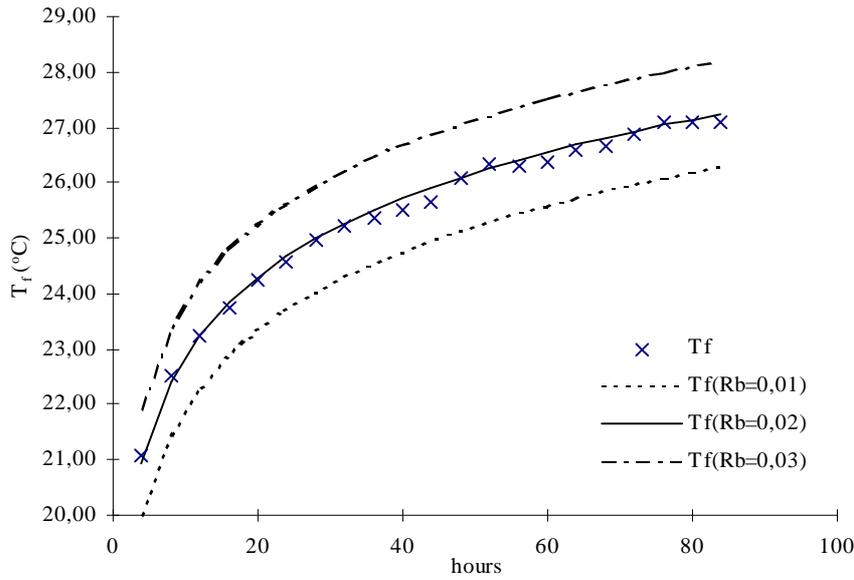
Borehole 3A  
 Double U-tube  
 Date: 971030-971104  
 Active Depth = 61.3 m  
 Diameter = 154 mm  
 $q = 98 \text{ W/m}$   
 $T_o = 13.8^\circ\text{C}$   
 $\lambda = 3.65 \text{ W/m,K}$   
 $R_b = 0.03 \text{ K/(W/m)}$

Disturbed by cold-front  
 after 40 hours.

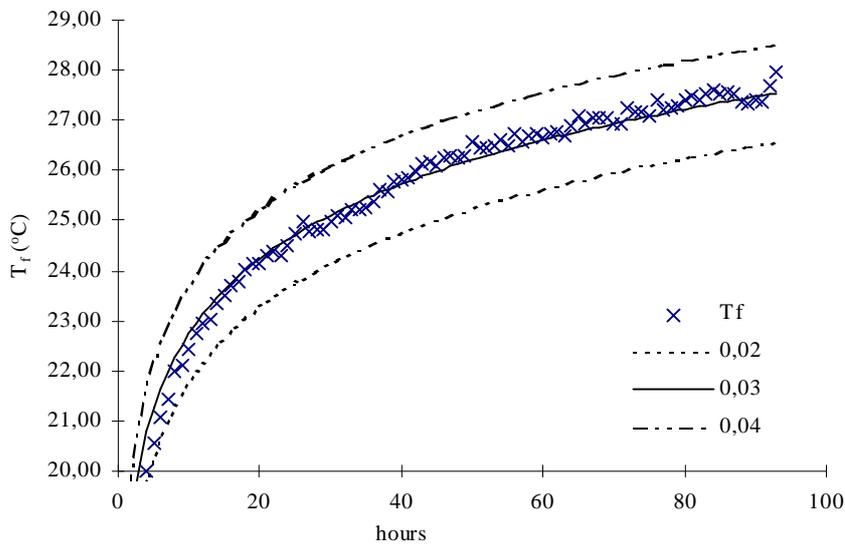


Borehole 3A  
 Double U-tube  
 Date: 971121-971124  
 Active Depth = 61.5 m  
 Diameter = 154 mm  
 $q = 98 \text{ W/m}$   
 $T_o = 13.8^\circ\text{C}$   
 $\lambda = 3.65 \text{ W/m,K}$   
 $R_b = 0.02 \text{ K/(W/m)}$

Data from first 24 hours  
 are lost.

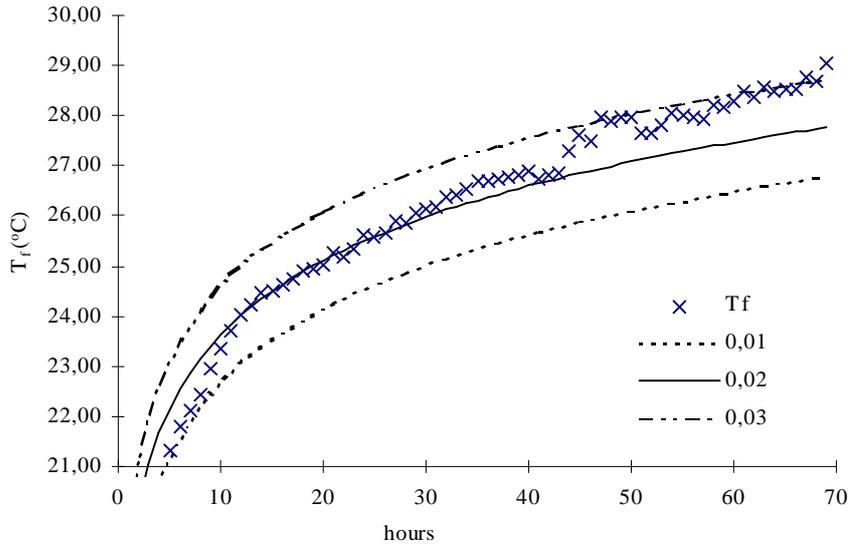


Borehole 3A  
 Double U-tube  
 Date: 971212-971216  
 Active Depth = 62.7 m  
 Diameter = 154 mm  
 $q = 96 \text{ W/m}$   
 $T_o = 14.5^\circ\text{C}$   
 $\lambda = 3.7 \text{ W/m,K}$   
 $R_b = 0.02 \text{ K/(W/m)}$



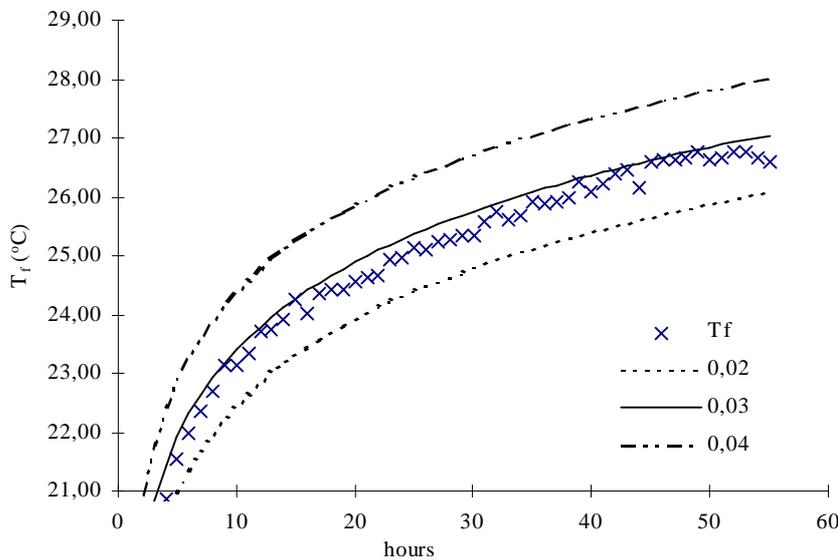
Borehole 3A  
 Double U-tube  
 Date: 980326-980330  
 Active Depth = 61.7 m  
 Diameter = 154 mm  
 $q = 97 \text{ W/m}$   
 $T_o = 13.1^\circ\text{C}$   
 $\lambda = 3.6 \text{ W/m,K}$   
 $R_b = 0.03 \text{ K/(W/m)}$

Snow melting

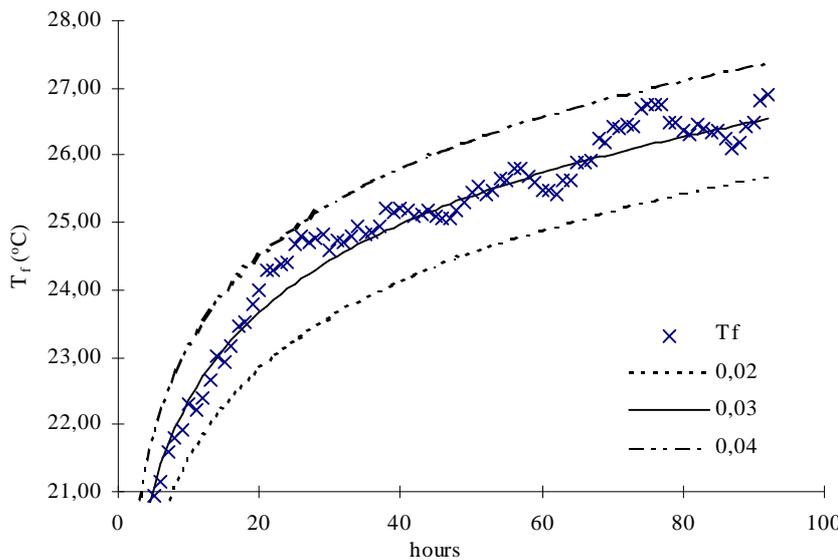


Borehole 2A  
 Double U-tube  
 Date: 980330-980402  
 Active Depth = 62 m  
 Diameter = 154 mm  
 $q = 97 \text{ W/m}$   
 $T_o = 15^\circ\text{C}$   
 $\lambda = 3.6 \text{ W/m,K}$   
 $R_b = 0.02 \text{ K/(W/m)}$

Cold days after snow melting.



Borehole 2A  
 Double U-tube  
 Date: 980420-980423  
 Active Depth = 62 m  
 Diameter = 154 mm  
 $q = 97 \text{ W/m}$   
 $T_o = 13.8^\circ\text{C}$   
 $\lambda = 3.6 \text{ W/m,K}$   
 $R_b = 0.03 \text{ K/(W/m)}$

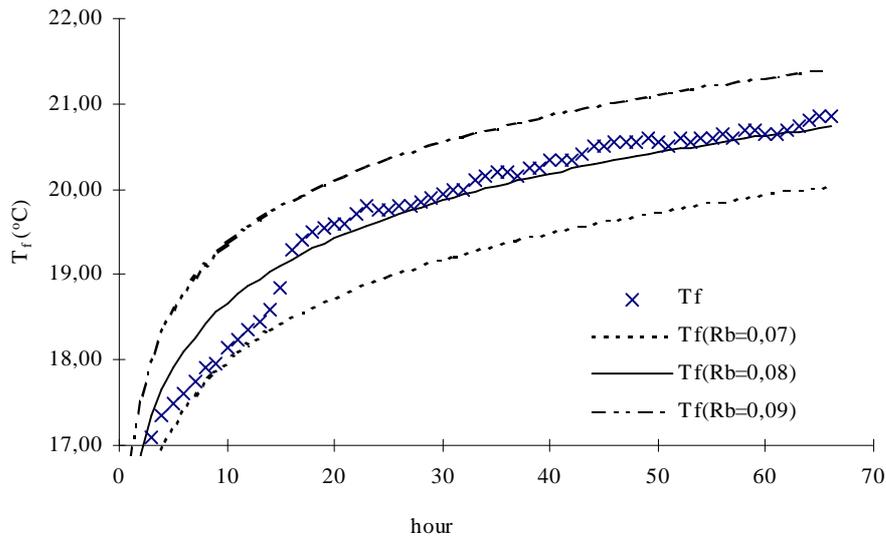


Borehole 2A  
 Double U-tube  
 Date: 980611-980615  
 Active Depth = 63.3 m  
 Diameter = 154 mm  
 $q = 84 \text{ W/m}$   
 $T_o = 14^\circ\text{C}$   
 $\lambda = 3.55 \text{ W/m,K}$   
 $R_b = 0.03 \text{ K/(W/m)}$

Unsufficient insulation on joints

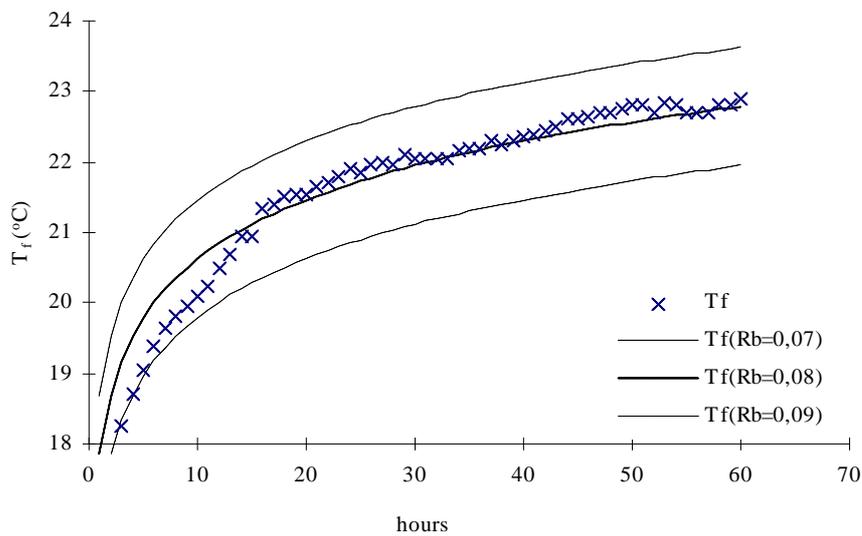
## **APPENDIX B**

### **Measurement Data from Response Tests on Commercial BTES**



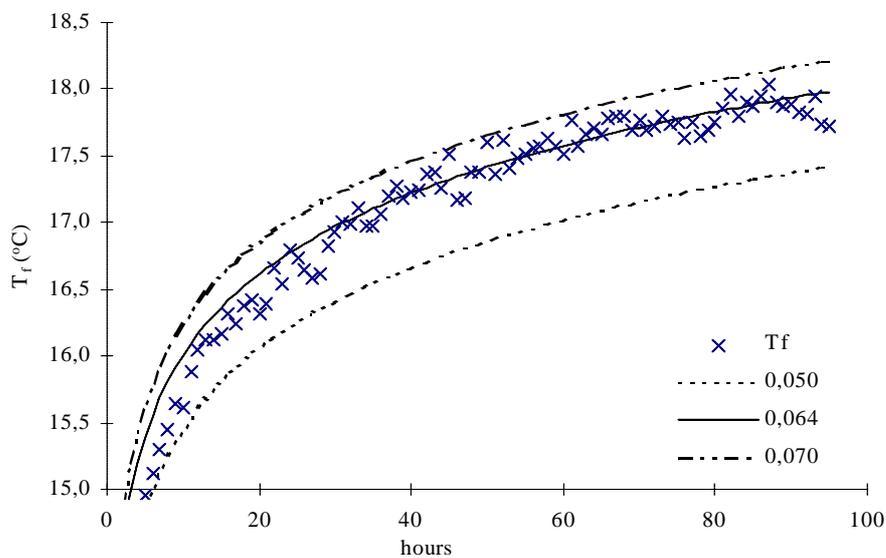
DREVIKSTRAND  
 Single U-tube  
 Date: 960515-960517  
 Active Depth = 160 m  
 Diameter = 140 mm  
 $q = 69 \text{ W/m}$   
 $T_o = 9.2^\circ\text{C}$   
 $\lambda = 5.0 \text{ W/m,K}$   
 $R_b = 0.08 \text{ K/(W/m)}$

Large groundwater flow.  
 15 m connection pipes  
 between boreholes and  
 machine-room contributes.



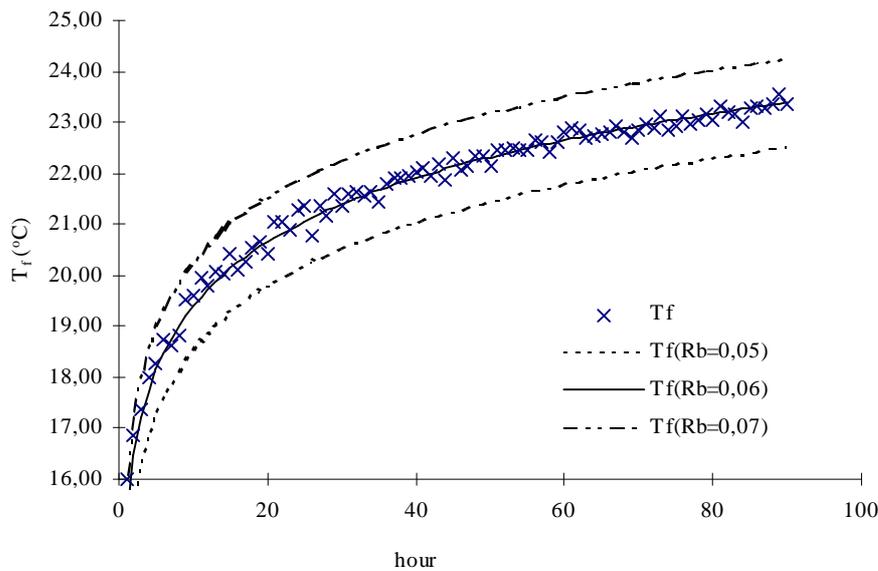
ÄNGBY  
 Single U-tube  
 Date: 960521-960523  
 Active Depth = 132 m  
 Diameter = 115 mm  
 $q = 83 \text{ W/m}$   
 $T_o = 9.0^\circ\text{C}$   
 $\lambda = 5.5 \text{ W/m,K}$   
 $R_b = 0.08 \text{ K/(W/m)}$

Large groundwater flow.  
 30 m connection pipes  
 between boreholes and  
 machine-room contributes.



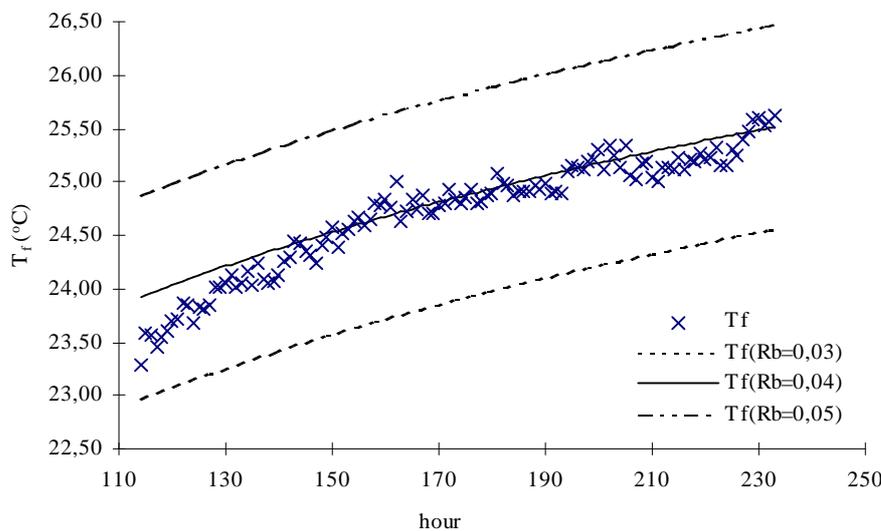
OSKARSHAMN  
 Single U-tube  
 Date: 960705-960709  
 Active Depth = 161 m  
 Diameter = 135 mm  
 $q = 40 \text{ W/m}$   
 $T_o = 10.5^\circ\text{C}$   
 $\lambda = 3.6 \text{ W/m,K}$   
 $R_b = 0.06 \text{ K/(W/m)}$

Borehole in the town centre



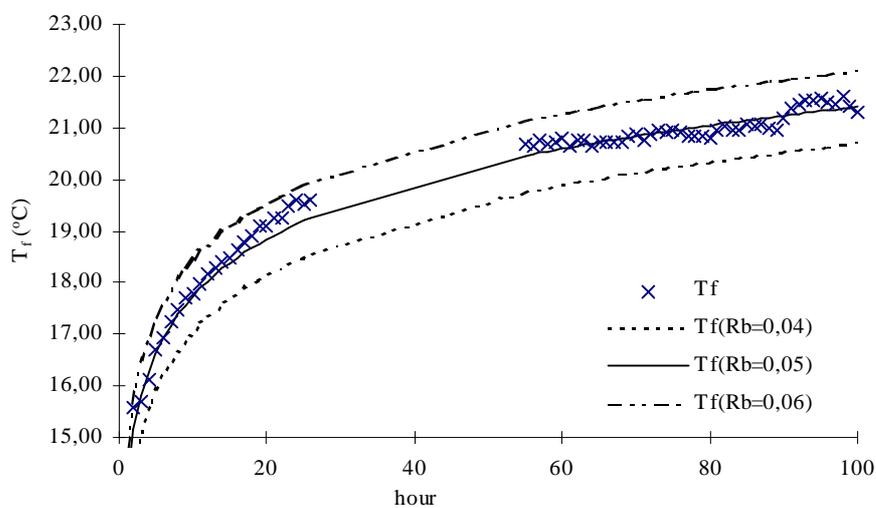
**HÄSLEHOLM**  
 Single U-tube  
 Date: 971014-971018  
 Active Depth = 127 m  
 Diameter = 164 mm  
 $q = 87 \text{ W/m}$   
 $T_o = 8.7^\circ\text{C}$   
 $\lambda = 3.8 \text{ W/m,K}$   
 $R_b = 0.06 \text{ K/(W/m)}$

Values corrected for 18 m un-insulated pipes in warm, convective air (ca 30°C).



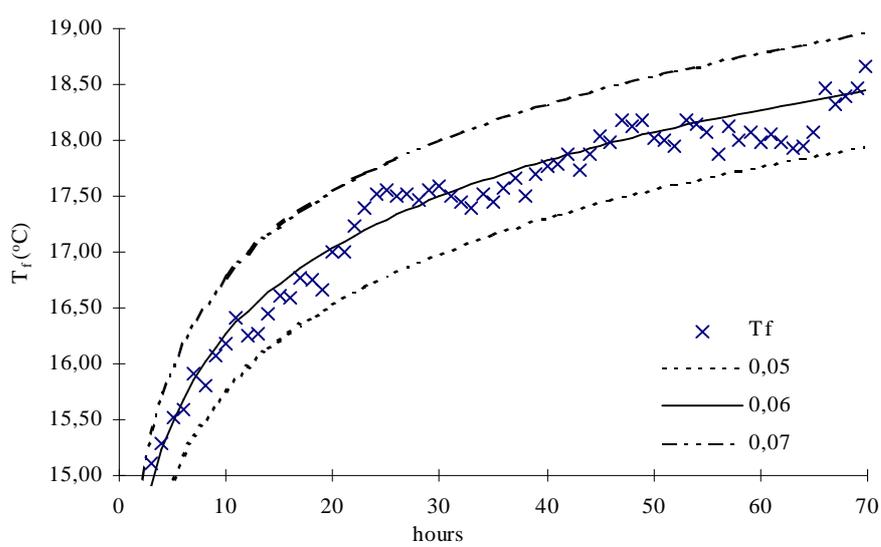
**LINKÖPING**  
 Single U-tube  
 Date: 970205-970214  
 Active Depth = 115 m  
 Diameter = 164 mm  
 $q = 96 \text{ W/m}$   
 $T_o = 8.1^\circ\text{C}$   
 $\lambda = 3.4 \text{ W/m,K}$   
 $R_b = 0.04 \text{ K/(W/m)}$

Fractured rock with high groundwater flow. First 110 hours data lost. Measurement performed by drilling company.

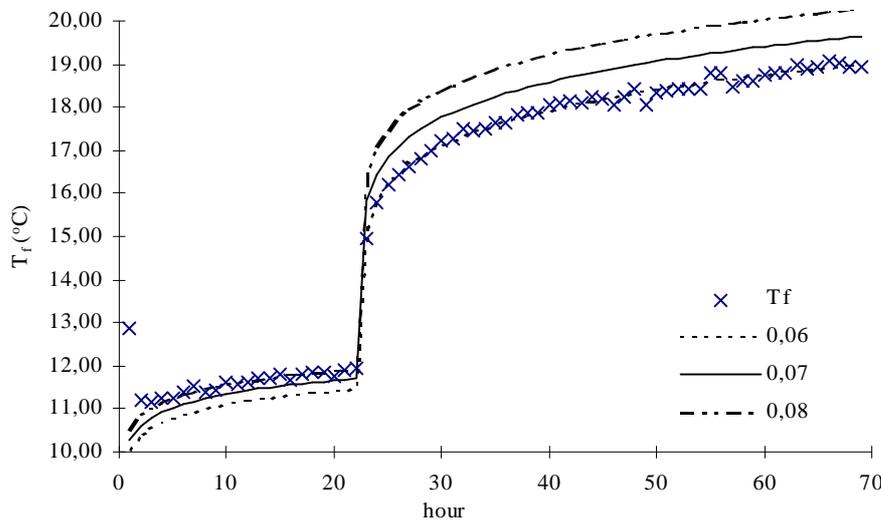


**NORRKÖPING**  
 Single U-tube  
 Date: 970223-970227  
 Active Depth = 157 m  
 Diameter = 115 mm  
 $q = 70 \text{ W/m}$   
 $T_o = 8.4^\circ\text{C}$   
 $\lambda = 3.5 \text{ W/m,K}$   
 $R_b = 0.05 \text{ K/(W/m)}$

High groundwater flow. 24 hours data lost. Measurement performed by drilling company.

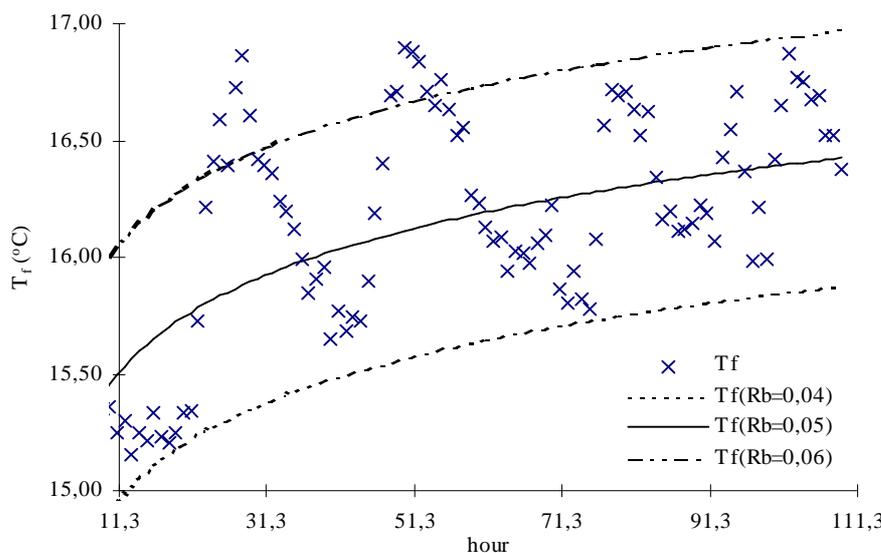


**FINSPÅNG**  
 Single U-tube  
 Date: 980803-980806  
 Active Depth = 96.3 m  
 Diameter = 140 mm  
 $q = 51 \text{ W/m}$   
 $T_o = 9.5^\circ\text{C}$   
 $\lambda = 3.6 \text{ W/m,K}$   
 $R_b = 0.06 \text{ K/(W/m)}$



**VÄSTERÅS**  
 Single U-tube  
 Date: 980304-980307  
 Active Depth = 154 m  
 Diameter = 115 mm  
 $q = 21 \text{ W/m}$  and  $64 \text{ W/m}$   
 $T_o = 8^\circ\text{C}$   
 $\lambda = 3.9 \text{ W/m,K}$   
 $R_b = 0.06-0.08 \text{ K/(W/m)}$

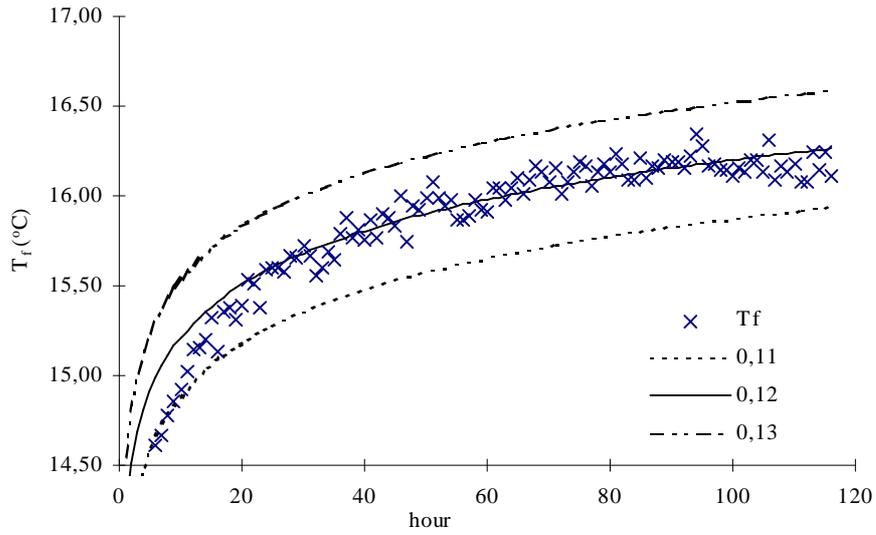
Two power steps. TED indoors during measurements.



**LUDVIKA**  
 Single U-tube  
 Date: 970619-9706.23  
 Active Depth = 117 m  
 Diameter = 140 mm  
 $q = 55 \text{ W/m}$   
 $T_o = 11^\circ\text{C}$   
 $\lambda = 11 \text{ W/m,K}$   
 $R_b = 0.05 \text{ K/(W/m)}$

Measurement performed by drilling company. High ground water flow due to adjacent drilling. Borehole warmed by drilling.

Insufficient insulation. Results not characteristic for the rock.



## ÖREBRO

Single U-tube

Date: 970813-970817

Active Depth = 197 m

Diameter = 115 mm

 $q = 32 \text{ W/m}$  $T_o = 9.5^\circ\text{C}$  $\lambda = 6 \text{ W/m,K}$  $R_b = 0.12 \text{ K/(W/m)}$ 

Measurement performed

by drilling company.

Measurement disturbed

by adjacent drilling.

Borehole warmed by

drilling. Results not

characteristic for the

rock.

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Sammanfattning, högst 150 ord/Abstract, max 150 words

In-situ determination of thermal properties in bedrock is important for the sizing of larger BTES systems. In-situ values of thermal conductivity may reduce required borehole length up to 30%. This thesis treats a new mobile thermal response test equipment (TED), developed in Luleå, Sweden, 1995-98. TED is set up on a small trailer, and is tried out on groundwater filled boreholes, fitted with single and double U-loop piping. It has been used at several commercial borehole direct cooling systems for telephone switching stations in Sweden, and on test-holes in a well documented closed down heat store in Luleå. The response tests show good accuracy and reliability of the measured thermal conductivity and thermal resistance provided good insulation of the equipment. The tests take into account the interaction of the bedrock with the duct piping and filling, the borehole geometry and groundwater and is a valuable tool for pre-investigations for BTES.

Nyckelord, högst 8/Keywords, max 8

TED, thermal response, thermal conductivity, thermal resistance, UTES, borehole

Underskrift av granskare/handledare / Signature of examiner/supervisor  
/ Bo Nordell