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# **Determination of thermal properties at Äspö HRL**

**Comparison and evaluation of methods and  
methodologies for borehole KA 2599 G01**

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August 2002

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

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# Foreword

This report presents various results from determinations of thermal properties of the rock mass surrounding borehole KA 2599 G01 at Äspö HRL. The possibility to predict the result of a large scale measurement with other methods has been investigated. The project was conducted by Geo Innova AB, on a commission by the Swedish Nuclear Fuel and Waste Management Co.

As a part of this work, samples of the rock were examined with respect to density and water absorption by the Swedish National Testing and Research Institute (SP). Geochemical and mineralogical composition of the rock were examined and evaluated by Terralogica AB. Laboratory measurements of thermal properties were performed by Hot Disk AB. In the field, a thermal response test was performed in a borehole by Luleå University of Technology.

# Abstract

Thermal properties of the rock mass surrounding borehole KA 2599 G01 at Äspö HRL have been investigated. A full-scale method, thermal response test, was performed and the result compared to what could be expected based on results from laboratory methods and assumptions regarding the rock type distribution.

The thermal conductivity obtained from the thermal response test in borehole KA 2599 G01 has been estimated to 3.55 W/m,K. The predicted thermal conductivity is in the interval 2.64–2.96 W/m,K, depending on different assumptions and methods. The thermal response test thus resulted in a 25% higher value compared to the prediction.

The most reliable result is the predicted thermal conductivity based on laboratory measurements and revised rock mapping. The resulting thermal properties, corrected for 14°C, for the borehole are 2.85 W/m,K (thermal conductivity) and 2.02 MJ/m<sup>3</sup>,K (volumetric heat capacity), based on 55% Äspö diorite, 25% Ävrö granite and 11% fine-grained granite. The influence of the temperature on the thermal conductivity is small for the measured rock types.

Reasons for the differences in the results can be related to different sources of errors in the methods or in the rock mapping. The thermal response test is, in this particular case, assumed to overestimate the thermal conductivity. The reasons for this may primarily be a combination of water movements in (parts of) the borehole due to high pressure gradients and thermal expansion of the water.

# Summary

The technique for long-term storage of used nuclear fuel is developed at the Äspö Hard Rock Laboratory. The deposit canisters generate heat due to nuclear fission. The temperature field in the repository depends on thermal properties of the rock and generated heat. The layout of the repository is dependent on the temperature field. The design criterion is the maximum temperature allowed on the surface of the canisters. A low thermal conductivity leads to a significantly larger distance between canisters than for a case with high thermal conductivity.

Some of the available methods to determine thermal properties of the rock mass have been studied. A large-scale method, thermal response test, has been tested in a borehole at the Äspö Hard Rock Laboratory. To make a prediction of the result of the response test other methods were used. The prediction was made using direct laboratory measurements, calculations based on the mineralogy of the rock and core logging.

The thermal conductivity obtained from the thermal response test in borehole KA 2599 G01 has been estimated to 3.55 W/m,K. The predicted thermal conductivity is in the interval 2.64–2.96 W/m,K, depending on different assumptions and methods. The full-scale thermal response test thus resulted in a 25% higher value compared to the prediction based on different assumptions about mapped rock types and methods for determining the thermal conductivity (calculations or laboratory measurements).

Reasons for obtained differences in the results can be related to different sources of errors in the methods or in the rock mapping. Thermal response tests measure an apparent thermal conductivity influenced by specific natural conditions in the field and the measurement itself. This influence can be small if the hydraulic conductivity of the rock mass is small. In the present case, large hydraulic pressure gradients exist in combination with a certain hydraulic conductivity, which increase the uncertainty of the measurements. Conditions influencing measurements of samples in the laboratory are more easily controlled and observed. However, the up scaling of the results from small samples to the whole drill core and the representativity of these samples can include uncertainties.

The thermal response test is, in this particular case, assumed to overestimate the thermal conductivity. The reasons for this is not clear but may primarily be a combination of water movements in (parts of) the borehole due to high pressure gradients and thermal expansion of the water. The small temperature rise makes the temperature measurements sensitive to different disturbances during the test.

The most reliable result is thus the predicted thermal conductivity based on laboratory measurements and revised rock mapping. The resulting thermal properties, corrected for 14°C, for the borehole are 2.85 W/m,K (thermal conductivity) and 2.02 MJ/m<sup>3</sup>,K (volumetric heat capacity), based on 55% Äspö diorite, 25% Ävrö granite and 11% fine-grained granite.

The influence of the temperature on the thermal conductivity is small for the measured rock types. The measured volumetric heat capacity in the laboratory increased with the temperature, in average 17% (15–22%) within the temperature interval 25–80°C.

Preliminary it is recommended to use the TPS method at SKB's site investigation program for determination of thermal properties of the rock mass. To eliminate possible systematic errors in the method it is recommended to perform comparisons with other laboratory methods. The thermal response test may be used for large-scale measurements of the rock mass if the uncertainties described above can be measured and held under control.

# Sammanfattning

Tekniken att under lång tid förvara använt kärnbränsle utvecklas vid Äspölaboratoriet. De kapslar som innesluter bränslet kommer att avge värme på grund av kärnklyvning. Temperaturfältet i och runt djupförvaret beror av bergmassans termiska egenskaper och den genererade värmens storlek. Utformningen av förvaret styrs av det förväntade temperaturfältet. Avgörande för dimensioneringen är den maximalt tillåtna temperaturen på kapslarnas yta. En låg värmeledningsförmåga medför betydligt större avstånd mellan kapslarna än för ett fall med hög värmeledningsförmåga.

En del av de metoder som är tillgängliga för bestämning av termiska egenskaper har studerats. En storskalig metod, utförd i ett borrhål, s k termiskt responstest har provats vid Äspölaboratoriet. Möjligheten att kunna använda resultaten från andra metoder till att förutse resultatet av responstestet undersöktes. Dessa metoder utgjordes av direkt mätning i laboratoriet, beräkningar baserade på bergprovers mineralinnehåll och kartering av borrhärnan.

Värmeledningsförmågan från termiskt responstest i borrhål KA 2599 G01 har uppskattats till 3,55 W/m,K. Den förväntade värmeledningsförmågan erhöles i intervallet 2,64–2,96 W/m,K., beroende på olika antaganden och metod. Fullskalemätning med termiskt responstest resulterade således i 25 % högre värde jämfört med vad som kan förväntas utifrån olika antaganden om karterade bergarter och metoder för bestämning av värmeledningsförmågan (beräkningar eller laboratoriemätningar).

Orsaker till erhållna skillnader i resultaten kan vara kopplade till felkällor i metoderna eller i bergartskarteringen. Termiskt responstest mäter en värmeledningsförmåga påverkad av specifika naturliga förhållanden i fält och mätningens utförande. Påverkan kan vara liten om bergmassans hydrauliska konduktivitet är liten. I det aktuella fallet förekommer stora hydrauliska tryckgradienter i kombination med en viss hydraulisk konduktivitet i berget, vilket ökar mätosäkerheten. Förhållanden som påverkar mätningar av prover i laboratoriet är lättare att kontrollera och observera. Emellertid, att skala upp resultat från små prover till hela borrhärnan och representerbarheten hos dessa prover kan ge upphov till osäkerheter.

För detta särskilda fall antas termiskt responstest överskatta värmeledningsförmågan. Orsakerna till detta är inte tydliga men de kan primärt bero på en kombination av vattenrörelser i (delar av) borrhålet på grund av höga tryckgradienter och termisk utvidgning av vattnet. Den låga temperaturgradienten gör temperaturmätningen känslig för olika störningar under försöket.

Det mest tillförlitliga resultatet är den förutsedda värmeledningsförmågan baserad på laboratoriemätning och reviderad bergartskartering. De resulterande termiska egenskaperna för borrhålet, korrigerade för 14 °C, uppgår till 2,85 W/m,K (värmeledningsförmåga) och 2,02 MJ/m<sup>3</sup>,K (värmekapacitet), med fördelningen 55 % Äspö diorit, 25 % Ävrö granit och 11 % finkornig granit.

Temperaturens påverkan på värmeledningsförmågan är liten för de uppmätta bergarterna. Den uppmätta värmekapaciteten i laboratoriet ökade med temperaturen, i medeltal 17 % (15–22 %) inom temperaturintervallet 25–80 °C.

För SKB:s plastundersökningsprogram rekommenderas preliminärt att använda TPS-metoden för bestämning av bergmassans termiska egenskaper. För att eliminera eventuella systematiska fel hos metoden rekommenderas att jämförelser görs mot andra laboratoriemetoder. Termiskt responstest kan användas för storskaliga mätningar om de beskrivna osäkerheterna ovan kan mättas och hållas under uppsikt.



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# 1 Introduction

## 1.1 Background

As part of the Swedish nuclear waste disposal program a series of site investigations are planned. For each of the studied sites design work will be carried out as a foundation for studies of constructability, environmental impact assessment and safety assessment. The technique for long-term storage of used nuclear fuel is developed at the Äspö Hard Rock Laboratory.

The deposit canisters generate heat due to nuclear fission. The temperature field in the repository depends on thermal properties of the rock and generated heat. The layout of the repository is dependent on the temperature field. The design criterion is specified as the maximum temperature allowed on the surface of the canisters. A low thermal conductivity leads to a significantly larger distance between canisters than in the case of a high thermal conductivity.

Some of the available methods to determine thermal properties of the rock mass have been studied. A method to determine the thermal properties on a large scale in a borehole, thermal response test, has been tested at the Äspö Hard Rock Laboratory. The borehole, KA 2599 G01, was specially drilled for in-situ measurement of rock stress /Janson and Stigsson, 2002/. The core has a total length of 128.3 m and is drilled vertically from the gallery in Äspö HRL at chainage 2599 m. Parallel to the response test other methods have been used to determine the thermal properties of the rock mass.

Geo Innova AB has been commissioned by the Swedish Nuclear Waste Management Co (SKB) to make a prediction of the result of the thermal response test using a range of different methods and to evaluate the results.

The prediction was made using direct laboratory measurement, calculations based on the mineralogy of the rock and core logging. The thermal response test was organised by Golder Associates AB. The test was performed and analysed by Luleå University of Technology. Measurements in the field were made by SKB's service personnel at Äspö HRL.

## 1.2 Objectives

The objective is:

- To investigate the possibility to predict the result of large scale measurement with other methods.
- To investigate the influence on the prediction, of the thermal response test, of the quality of the rock type mapping.
- To compare the thermal properties of different rock types according to different methods and earlier results.
- To evaluate the results of the different methods and methodologies and give a recommendation to SKB's site investigation programme.

## 2 Laboratory investigations

The investigations comprise:

- Laboratory measurements of thermal properties of rock samples.
- Detailed geological characterisation of samples of the drill core.
- Density and water absorption properties of rock samples.
- Calculations of thermal properties from mineralogical and chemical compositions.

A total of 11 samples were selected from the drill core (diameter about 60 mm). Each sample was split into 3 sub samples. The samples were selected with respect to a combination of evenly distributed samples and the ability of the samples to be representative for homogeneous parts of the dominating rock types. Two of the sub samples were used for thermal properties and density measurements. The other sample was used for chemical analyses and examinations of the mineralogical composition.

Hot Disk AB performed laboratory measurements of thermal conductivity and thermal diffusivity with the TPS method. All 11 samples were measured at room temperature (25°C) and 4 samples were measured at elevated temperatures, up to 80°C.

The Swedish National Testing and Research Institute (SP) performed laboratory measurements of density and water absorption (porosity). Mineralogical and geochemical evaluation of all samples were performed by Terralogica AB (SGAB Analytica performed the geochemical analysis).

**Table 2-1. Laboratory investigations of rock samples.**

| Sample no | Core section (KA 2599 G01)                     | Chemical and mineralogical | Thermal properties | Density and porosity |
|-----------|--|----------------------------|--------------------|----------------------|
| 1         | 5.90–5.94 + 6.0–6.04<br>5.94–6.0               | x                          | x                  | x                    |
| 2         | 14.63–14.67 + 14.58–14.63<br>14.67–14.73       | x                          | x                  | x                    |
| 3         | 25.32–25.36 + 25.42–25.46<br>25.36–25.42       | x                          | x                  | x                    |
| 4         | 44.28–44.32 + 44.32–44.36<br>44.36–44.42       | x                          | x                  | x                    |
| 5         | 50.10–50.14 + 50.20–50.24<br>50.14–50.20       | x                          | x                  | x                    |
| 6         | 61.89–61.93 + 61.99–62.03<br>61.93–61.99       | x                          | x                  | x                    |
| 7         | 70.60–70.64 + 70.64–70.68<br>70.68–70.74       | x                          | x                  | x                    |
| 8         | 85.10–85.50 + 85.50–85.56<br>85.56–85.62       | x                          | x                  | x                    |
| 9         | 101.85–101.89 + 101.95–101.99<br>101.89–101.95 | x                          | x                  | x                    |
| 10        | 120.05–120.09 + 120.15–120.19<br>120.09–120.15 | x                          | x                  | x                    |
| 11        | 126.35–126.39 + 126.45–126.49<br>126.39–126.45 | x                          | x                  | x                    |

## 3 Description of methods

### 3.1 Thermal response test

#### 3.1.1 Method

The thermal response test method has been described by /Gehlin, 1998/. The method is shortly as follows:

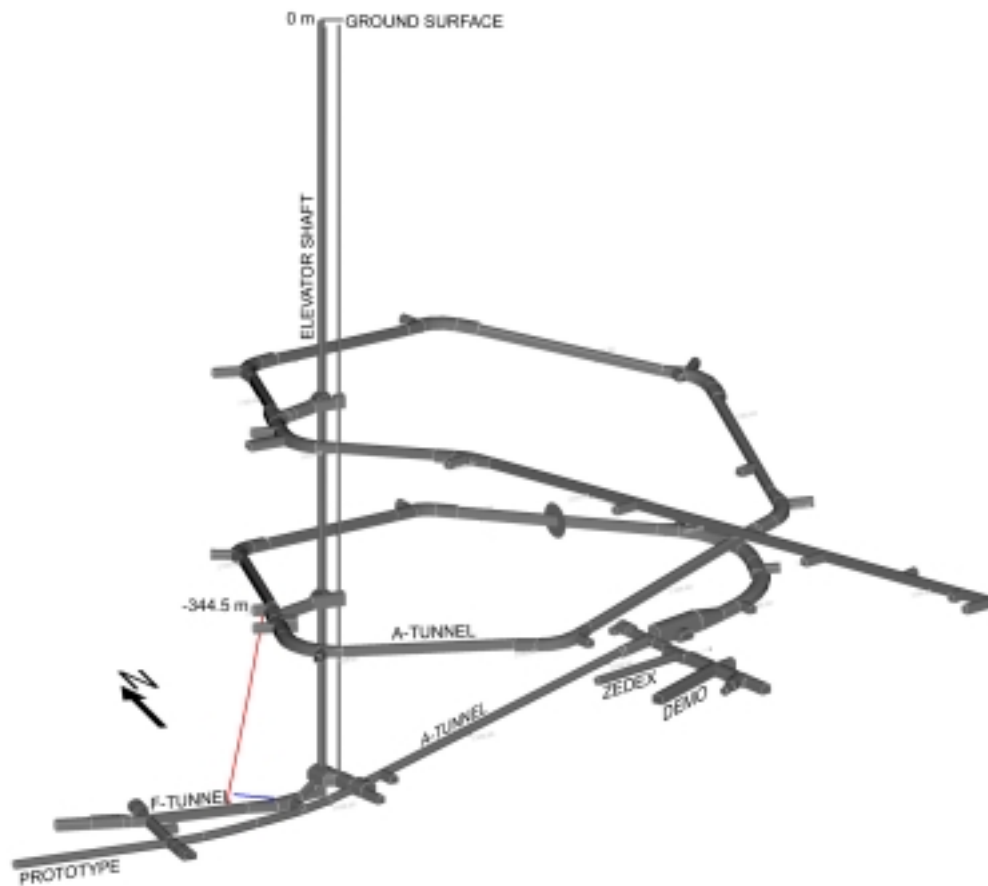
A U-pipe is placed in a borehole filled with groundwater. The pipe is filled with a fluid and connected to a heat generator. A constant heat supply of about 25–100 W/m is supplied to the borehole by circulating heated water in the U-pipe. The time dependent temperature rise of the fluid is measured during a minimum time of 60 hours. The evaluation is based on the assumption that the borehole acts like an infinite line heat source, which is acceptable after a certain time if the borehole is long enough. The measured thermal response is compared with a best fit for the thermal conductivity and the borehole thermal resistance. Primarily, an *apparent* thermal conductivity of the total rock mass surrounding the borehole is determined with this method. The analysis assumes heat conduction only but the measured actual heat transfer also includes convective heat transport. Thus the evaluated thermal conductivity includes effects of a possible ground water flow and effects of convection.

#### 3.1.2 Borehole

The borehole, KA 2599 G01, was specially drilled for in-situ measurement of rock stress (core drill Ø 96 mm), see /Janson and Stigsson, 2002/. The drilling was performed by Drillcone core AB with equipment from Hagby and started from the access ramp at the –344.5 m level, see Figure 3-1. An electric and hydraulic core drilling machine, Onram 2000 CCD, was used for the drilling. The borehole has a total length of 128.3 m and was drilled vertically from the gallery in Äspö HRL at chainage 2599 m (depth below sea level is 343 m). Due to the large depth, high water pressure (24 bar) was observed in the borehole and it was consequently sealed at the top to avoid leakage.

Sudden losses in pressure of the drilling water were observed during the drilling of the vertical hole. Normally, the drilling was stopped and a measurement of the inflow to the borehole was made. The total measured inflow to the vertical hole was 36 l/min of which 32 l/min came from depths between –371 m and –374 m. From level –409 m and deeper, there were no further observations of inflow to the hole.

A pressure build up test was performed in the vertical borehole. The pressure build up test resulted in a transmissivity of about  $2 \cdot 10^{-7} \text{ m}^2/\text{s}$ . The temperature in the borehole was measured at level –400 m, one month after the response test, during one week. The temperature was measured at 13.2°C (closed hole). This measurement was performed after the thermal response test had been evaluated.



*Figure 3-1. View of Äspö HRL from SSW. The borehole top is located at level –344.5 m.*

### 3.1.3 Test procedure

The thermal response test was performed in borehole KA 2599 G01 at Äspö HRL and has been reported in Appendix 4.

A special U-pipe made of aluminium was used due to the high external pressures. The undisturbed ground temperature was measured at 14.1°C, at the time for the measurements of rock stresses (open hole). Test data are given in Table 3-1.

**Table 3-1. Data for thermal response test in borehole KA 2599 G01 at Äspö HRL.**

| Item                           | Data  |
|--------------------------------|---|
| Measurement period             | 2001-09-05 – 2001-09-09                                       |
| Installation                   | Single U-pipe made of aluminium, $D_o = 33$ mm, $D_i = 20$ mm |
| Undisturbed ground temperature | 14.1°C  |
| Heat input                     | 6.25 kW (incl. pump power)                                    |
| Specific heat input            | 48 W/m  |
| Measurement time               | 89 hours  |

### **3.2 Laboratory analysis of density and porosity**

Selected rock samples were examined in the laboratory with respect to density and water absorption. Water absorption is a measure of the amount of water that can be accumulated in pores. The measured water absorption can be approximated with the porosity of the samples (pore volume in relation to total volume).

The density was determined according to standards, DIN 52102-RE VA. The water absorption was determined according to standards, DIN 52103-A. The precision has been increased compared to the standard in order to make it possible to detect differences between materials with very low water absorption properties.

The investigations were performed by the Swedish National Testing and Research Institute (SP).

### **3.3 Analysis of chemical and mineralogical composition**

To make an estimate of the distribution of rock types along the borehole, BIPS-images, chemical analysis, and microscopy were used resulting in a refined mapping.

The geochemical composition was determined using ICP analyses. Samples were also selected for mineralogical analyses using SEM and EDS techniques.

Inductively Coupled Plasma (ICP) is an analytical technique used for the detection of trace metals in environmental samples, such as rocks. The plasma is actually a gas in which atoms are present in an ionised state. ICP in conjunction with mass spectrometry utilises high temperature argon plasma to excite the atoms of the elements present in the introduced solution. By using ICP several elements can be determined simultaneously. Sample preparation includes crushing and grinding of the sample.

In scanning electron microscopy (SEM) an electron beam is scanned across a sample's surface. When the electrons strike the sample, a variety of signals are generated, and it is the detection of specific signals that produces an image of the sample's elemental composition. Interactions of the electron beam with atoms in the sample also result in the emission of X-rays. The emitted X-ray has an energy characteristic of the parent element. Detection and measurement of this energy using energy dispersive spectroscopy permits elemental analysis of the sample. Energy dispersive spectroscopy (EDS) can provide quantitative analysis of elemental composition with a sampling depth of 1–2 microns. The emitted X-rays can also be used to show the elemental distribution in the surface of a sample.

Investigations and evaluations of geochemical and mineralogical compositions were performed by Terralogica AB.



## **3.4 Laboratory measurements of thermal properties**

### **3.4.1 Method**

Measurements of thermal properties in the laboratory were performed using the TPS method /Gustafsson, 1991/. The TPS (transient plane source) method is used for measurements of thermal diffusivity and thermal conductivity of both fluids and solids, from cryogenic temperatures to about 250°C (if the sensor insulation is made of kapton). The thermal conductivity that can be measured ranges from 0.005 W/m°C to 500 W/m°C. This method has been used before by SKB /Sundberg and Gabrielsson, 1999/.

The method uses a sensor element with an engraved pattern of a thin double spiral. The spiral is made of Ni metal and has specific resistivity properties. The spiral is embedded between two layers of kapton, to give it mechanical strength and electrical insulation whereas measurements may be performed in electrically conductive materials. The total thickness of the sensor is 0.025 mm and for this specific application the diameter was 20 mm. The probing depth in a transient experiment should be of the same order as the diameter of the hot disk. To achieve this for different materials, sample-sizes and measurement-times, the sensor size can be varied.

Measurements are performed by placing the sensor between two samples of the same material. The surfaces of the samples have to be fairly smooth and reasonably flat in order to limit the contact resistance between the sensor and the sample surfaces. During the measurement, the sensor acts both as a heat generator of a heat pulse and as sensor for the temperature response. The temperature vs. time response is measured in 200 data points.

The evaluation uses the fact that the resistance for a thin Ni spiral at any time is a function of its initial resistance, the temperature increase and the temperature coefficient of the resistivity. A model of heat propagation through the sample, assuming a plane source (sensor) and an infinite sample in perfect contact with the sensor surfaces, is stored in the software. By fitting measured temperatures to this model, through a number of iterations, the thermal diffusivity and thermal conductivity are determined. From these, volumetric heat capacity is calculated.

The accuracy of the thermal conductivity measurements is better than 5% for the interval 0.01–400 W/m°C, and the repetitiveness is better than 2% according to the manufacturer.

### **3.4.2 Test procedure**

Rock samples from core drillings have a diameter of about 60 mm. The selected samples were cut in two halves, each with a thickness of about 40–45 mm. The two intersection surfaces were then carefully polished.

Initially, all samples were measured with respect to thermal diffusivity and thermal conductivity at room temperature (approximately 25°C). In order to water saturate the samples, all samples were placed under vacuum in water for 4–12 h, dried in air for >3 h and measured again. A selection of four samples was also measured at assumed dry conditions at elevated temperature (40, 60, 80°C) and finally at room temperature (sample no 3, 4, 8 and 9 in Table 2-1). The laboratory had never performed measurements on rock samples at elevated temperature why the measurements included elements of development.

For each sample and temperature, five measurements were performed with 30 minutes interval. Thermal properties are presented as a mean value of these measurements. For some samples, one or two measurements were excluded.

Measurements at elevated temperatures were performed by placing the sample in an oven. The sensor was not dismounted between the measurements. The total time in the oven was 15–20 h for each sample except for sample 4. The temperature tolerances in the oven for sample 4 were lower and therefore the time increased to about 36 h. This sample was also left in the oven at 80°C for an additional 24 h and then measured again.

The objective was to perform measurements at dry conditions at elevated temperatures but the results showed unstable water conditions for 40 and 60°C. These results were therefore excluded from the evaluation.

Measurements of thermal properties in the laboratory were performed by Hot Disk AB.

### **3.5 Computer calculations of thermal conductivity**

The thermal conductivity was calculated with the Condrock programme /Sundberg, 1991:2/. Condrock calculates the thermal conductivity of isotropic rock at normal temperature, about 10°C. The thermal conductivity of the rock is calculated using reference values of the thermal conductivity of different minerals together with the volume fractions as input. The numerical solution is based on the self-consistent approximation (SCA) that has previously proved to be in good agreement with measured values /Sundberg, 1988/.

The thermal conductivity of plagioclase, as well as olivine and pyroxene, depends on the chemical composition and may therefore vary within certain intervals.

## 4 Characterisation of rock types

### 4.1 Mapping of rock types

The drill core was originally mapped as “Äspö diorite”, “Fine-grained granite”, and “Meta-basite” (original mapping). However, during the course of the project a more detailed mapping was performed and it became clear that the term “Äspö diorite” involved a range of varieties including what has previously been mapped as “Ävrö granite” in the Äspö area and hybrid rocks (mingled types) between “Ävrö granite” and “Äspö diorite”. The core mapping revealed the following rock types (revised mapping);

- a) Äspö quartz-monzodiorite (Äspö QMD)
- b) Altered Äspö quartz-monzodiorite (Altered ÄQMD)
- c) Ävrö granite
- d) Altered Ävrö granite
- e) Fine-grained granite
- f) Meta-basite
- g) Mingled Ävrö granite/Äspö diorite

A closer description of the different rock types is given in Appendix 1. Table 4-1 shows sampled core intervals and rock types selected for chemical analyses and thin sections.

**Table 4-1. Samples from drillcore KA 2599 G01 selected for chemical analyses and thin sections.**

| Sampled core interval | Sample no | Rock type            |
|-----------------------|-----------|----------------------|
| 5.90–6.00             | 1         | Äspö diorite         |
| 14.63–14.73           | 2         | Äspö diorite         |
| 25.32–25.42           | 3         | Äspö diorite         |
| 44.36–44.42           | 4         | Ävrö granite         |
| 50.10–50.20           | 5         | Fine-grained granite |
| 61.89–61.99           | 6         | Fine-grained granite |
| 70.64–70.74           | 7         | Qz-rich Äspö diorite |
| 85.52–85.62           | 8         | Oz-rich Äspö diorite |
| 101.85–101.95         | 9         | Altered Äspö diorite |
| 120.05–120.15         | 10        | Ävrö granite         |
| 126.35–126.45         | 11        | Ävrö granite         |

## 4.2 Mineralogical composition

Mineral composition of the different rock types, based on mean values, is shown in Table 4-2. The mineral composition is based on microscopy and considerations have been taken regarding the chemical composition. The mineral composition varies between the examined rock types and small variations between samples of the same rock type are also common.

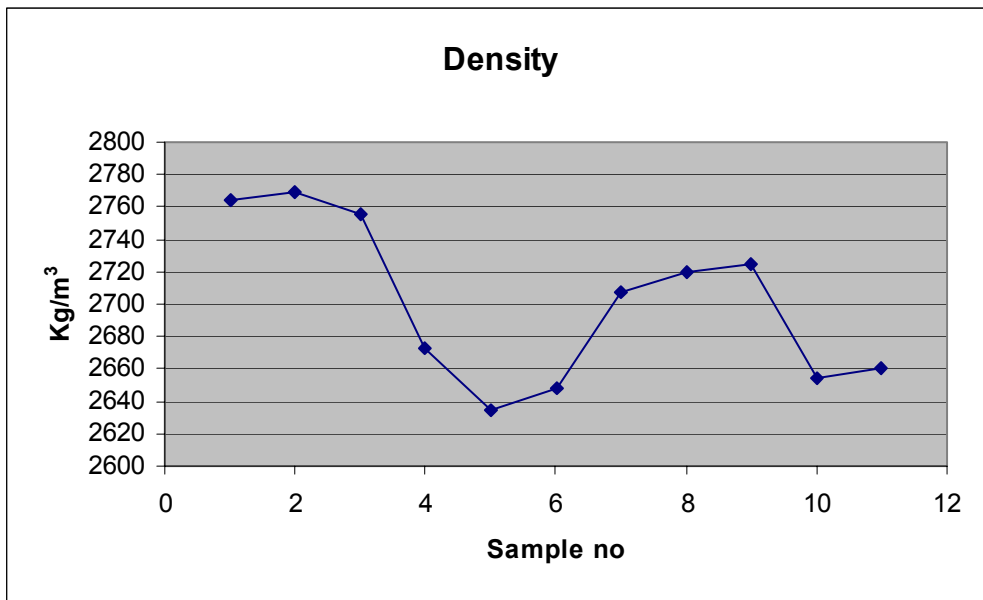
**Table 4-2. Estimated mineralogical composition of rock types (%).**

| Sample            | Äspö QMD           | Ävrö granite      | Fine-grained granite | Altered ÄQMD    |
|-------------------|--------------------|-------------------|----------------------|-----------------|
| Number of samples | 5                  | 3                 | 2                    | 1               |
| Quartz            | 12                 | 25                | 31                   | 15              |
| Plagioclase       | 40<br>(An* 25–30%) | 28<br>(An 20–30%) | 15<br>(An 20–25%)    | 25<br>(An 0–5%) |
| K-feldspar        | 20                 | 32                | 36                   | 23              |
| Biotite           | 18                 | 7                 | 3                    | 0.5             |
| Chlorite          | 0.3                | 1.0               | 0.5                  | 14              |
| Titanite          | 1.3                | 0.4               | 0.2                  | 1.3             |
| Amphibole         | 0.2                | –                 | –                    | –               |
| Epidote           | 4                  | 2.5               | 3                    | 10              |
| Sericite          | 4                  | 4                 | 10.5                 | 10              |
| Opaques           | 0.6                | 0.3               | 1.0                  | 0.4             |

\*) An = anorthite

## 4.3 Density and water absorption

Density of rock samples is shown in Figure 4-1. Type of rock of each sample is given in Table 4-1. The figure shows that samples with Äspö diorite have higher densities (1, 2, 3, 7, 8, 9) than Ävrö granite and fine-grained granite.



*Figure 4-1. Density of selected rock samples.*

The porosity of the rock was approximated with the ability to absorb water. Measured porosity of the samples varies from 0.22% to 0.4%, see Appendix 2. These values correspond to a porosity, which does not include isolated pores.

#### **4.4 Rock types in drill core**

The distribution of different rock types in drill core KA 2599 G01 has been estimated in Appendix 1. The mapping was performed by using the characteristics given in Table 4-2 and performing a re-visitation of the BIPS. The distribution is shown in Table 4-3. Äspö quartz-monzodiorite dominates before Ävrö granite and fine-grained granite. Compared to the rock type distribution in the prototype repository at Äspö HRL, the amount of Äspö diorite is smaller in the drill core. The Äspö diorite is also less altered in the drill core. According to the original mapping, the distribution was dominated by Äspö diorite (85%) followed by fine-grained granite (10%) and metabasite (5%), see Table 4-4.

**Table 4-3. Rock type distribution along drill core KA 2599 G01 according to revised mapping.**

| <b>Rock type</b>                      | <b>Percentage of core</b> | <b>Core section (m)</b>  |
|---------------------------------------|---------------------------|--|
| Äspö QMD                              | 54.6%                     | 4.0–28.0; 36.0–44.0; 68.9–75.1; 79.6–90.3; 96.6–101.6; 102.9–109.0; 109.6–115.1; 115.4–117.6 |
| Ävrö granite                          | 25.1%                     | 28.0–36.0; 44.0–45.9; 75.1–79.6; 90.3–96.6; 117.6–126.8; 127.1–128.3                         |
| Fine-grained granite                  | 11%                       | 45.9–51.4; 53.8–54.5; 56.0–58.9; 60.4–64.0; 109.0–109.6; 115.1–115.4                         |
| Meta-basite                           | 4.3%                      | 51.4–53.8; 54.5–56.0; 58.9–60.4  |
| Mingled Ävrö granite/<br>Äspö diorite | 3.7%                      | 64.0–68.9  |
| Altered ÄQMD                          | 1%                        | 101.6–102.9  |
| Altered Ävrö granite                  | 0.2%                      | 126.8–127.1  |

**Table 4-4. Rock type distribution along drill core KA 2599 G01 according to original mapping.**

| <b>Rock type</b>     | <b>Percentage of core</b> | <b>Core section (m)</b> |
|----------------------|---------------------------|-------------------------|
| Äspö diorite         | 85%                       | 4–46, 64–129            |
| Fine-grained granite | 10%                       | 46–51.5, 56–59, 60.5–64 |
| Meta-basite          | 5%                        | 51.5–56, 59–60.5        |

## 5 Result and prediction of thermal properties

### 5.1 Results from laboratory measurements

The results from measurements with the TPS method at room temperature are shown in Figure 5-1 (thermal conductivity) and Figure 5-2 (volumetric heat capacity). The samples were water saturated. A key to the sample numbers is found in Table 4-1 and Table 5-1. Complete results from the measurements of thermal properties are compiled in Appendix 3.

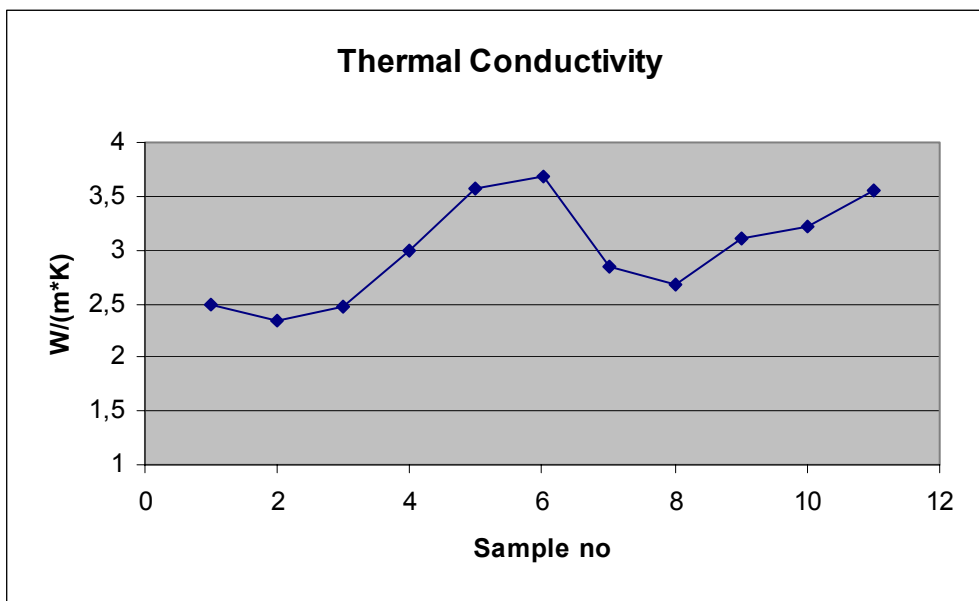


Figure 5-1. Measured thermal conductivity at room temperature.

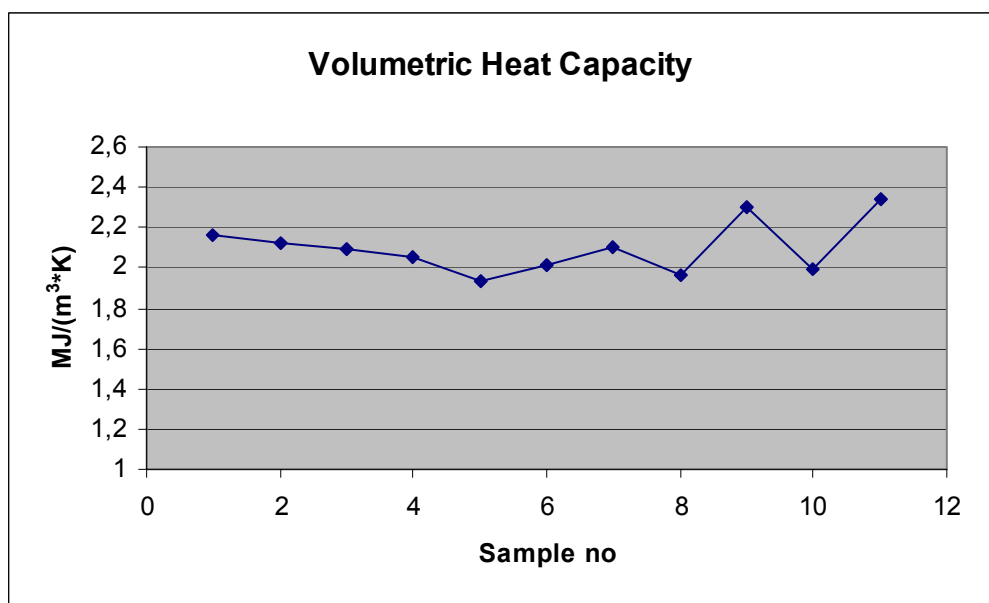


Figure 5-2. Measured heat capacity at room temperature.

Measured thermal conductivity at room temperature for different rock types are shown in Table 5-1.

**Table 5-1. Results from measurements on thermal conductivity at room temperature subdivided on rock type.**

| Sample no   | Äspö Diorite | Altered Äspö Diorite | Ävrö granite | Fine-grained granite |
|-------------|--------------|----------------------|--------------|----------------------|
| 1           | 2.49         |                      |              |                      |
| 2           | 2.34         |                      |              |                      |
| 3           | 2.47         |                      |              |                      |
| 4           |              |                      | 2.99         |                      |
| 5           |              |                      |              | 3.58                 |
| 6           |              |                      |              | 3.68                 |
| 7           | 2.84         |                      |              |                      |
| 8           | 2.69         |                      |              |                      |
| 9           |              | 3.11                 |              |                      |
| 10          |              |                      | 3.22         |                      |
| 11          |              |                      | 3.55         |                      |
| Geom. mean: | 2.56         | 3.11                 | 3.24         | 3.63                 |

Results from measurements with the TPS method at different temperatures are shown in Table 5-2 (thermal conductivity) and Table 5-3 (volumetric heat capacity). The samples were dry, which means that only the relative changes in the values are of interest and not the absolute values. The influence of the temperature is small for the thermal conductivity and rather high for the heat capacity. The other measurements at 40 and 60°C were neglected due to unstable water contents during the measurements.

**Table 5-2. Thermal conductivity (W/m,K) of dry samples at 25 and 80°C.**

| Temperature | Sample            |                   |                           |                        |
|-------------|-------------------|-------------------|---------------------------|------------------------|
|             | 3<br>Äspö Diorite | 4<br>Ävrö Granite | 8<br>Qz-rich Äspö Diorite | 9<br>Alt. Äspö Diorite |
| 80°C        | 2.395             | 2.805             | 2.606                     | 2.978                  |
| 25°C        | 2.419             | 2.83              | 2.584                     | 3.105                  |
| 25–80°C     | –0.99%            | –0.88%            | 0.85%                     | –4.09%                 |
| Per 100°C   | –1.80%            | –1.61%            | 1.55%                     | –7.44%                 |

**Table 5-3. Volumetric heat capacity (MJ/m<sup>3</sup>,K) of dry samples at 25 and 80°C.**

| Temperature | Sample            |                   |                           |                        |
|-------------|-------------------|-------------------|---------------------------|------------------------|
|             | 3<br>Äspö Diorite | 4<br>Ävrö Granite | 8<br>Qz-rich Äspö Diorite | 9<br>Alt. Äspö Diorite |
| 80°C        | 2.367             | 2.323             | 2.271                     | 2.619                  |
| 25°C        | 2.012             | 2.017             | 1.965                     | 2.148                  |
| 25–80°C     | 17.64%            | 15.17%            | 15.57%                    | 21.93%                 |
| Per 100°C   | 32.08%            | 27.58%            | 28.31%                    | 39.87%                 |



## 5.2 Results from calculations

Calculations of the thermal conductivity have been made with the Self Consistent Approximation /Sundberg, 1988/. The calculations are based on the mineral content for different rock types in Table 4-2 and available data on thermal properties for different minerals. The result from the calculations is summarised in Table 5-4. The densities of different rock types were calculated as mean values, from measurements on several samples, see also Figure 4-1 and Table 4-1.

**Table 5-4. Calculated thermal conductivity (W/m,K), volumetric heat capacity (MJ/m<sup>3</sup>,K) and measured density (kg/m<sup>3</sup>) for different rock types.**

|                      | Äspö Diorite | Altered Äspö Diorite | Ävrö granite | Fine-grained granite |
|----------------------|--------------|----------------------|--------------|----------------------|
| Thermal conductivity | 2.35         | 3.38                 | 3.01         | 3.45                 |
| Heat capacity        | 2.11         | 2.07                 | 2.01         | 1.99                 |
| Density              | 2745         | 2725                 | 2665         | 2640                 |

## 5.3 Prediction of thermal response test

The thermal conductivity for the entire borehole has been predicted by using different assumptions and methods.

1. The 11 laboratory *measurements* are representative for equal parts of the drill core (irrespective of actual rock type distribution).
2. The *measured* thermal properties of each rock type are representative for all parts of the drill core where the particular rock type has been mapped according to the original mapping.
3. The *measured* thermal properties of each rock type are representative for all parts of the drill core where the particular rock type has been mapped according to the revised mapping.
4. The *calculated* thermal properties of each rock type are representative for all parts of the drill core where the particular rock type has been mapped according to the revised mapping.

Parts of the drill core consist of rock types that have not been measured or calculated (meta-basites and mingled Äspö diorite/Ävrö granite). Thermal properties of meta-basites have been obtained from /Sundberg, 1991/ (calculated values). Thermal properties of mingled Äspö diorite/Ävrö granite have been approximated with mean values of the two rock types. The results are shown in Table 5-5 and Table 5-6. It is interesting to observe that quite different assumptions regarding representation of the measured values give rather small differences in thermal conductivity (assumptions 1–3). For the measured values assumption No. 3 is judged to be the most accurate and is therefore used in a comparison with the thermal response test. This value is also corrected for the temperature difference in the laboratory (25°C) compared to the field (14°C), based on results in Table 5-2 and Table 5-3.

**Table 5-5. Prediction of thermal response test (thermal conductivity for the entire rock mass in the borehole) with different assumptions and methods, see text. Values corrected for temperature a difference (25°C – 14°C) are in brackets.**

| Assumpt. method | Distribution of rock types / thermal conductivity (W/m,K) |                      |              |                      |         |             |
|-----------------|---|----------------------|--------------|----------------------|---------|-------------|
|                 | Äspö Diorite  | Altered Äspö Diorite | Ävrö Granite | Fine-grained granite | Mingled | Meta-basite |
| <b>1</b>        | Distribution irrelevant                                   |                      |              |                      |         |             |
|                 | <b>2.96</b>   |                      |              |                      |         |             |
| <b>2</b>        | 85%   | –                    | –            | 10%                  | –       | 5%          |
|                 | 2.83  | –                    | –            | 3.63                 | –       | 2.58        |
|                 | <b>2.89</b>   |                      |              |                      |         |             |
| <b>3</b>        | 54.5%   | 1%                   | 25%          | 11%                  | 3.7%    | 4.8%        |
|                 | 2.56  | 3.11                 | 3.24         | 3.63                 | 2.90    | 2.58        |
|                 | <b>2.84 (2.85)</b>  |                      |              |                      |         |             |
| <b>4</b>        | 54.5%   | 1%                   | 25%          | 11%                  | 3.7%    | 4.8%        |
|                 | 2.35  | 3.38                 | 3.01         | 3.45                 | 2.68    | 2.58        |
|                 | <b>2.64</b>   |                      |              |                      |         |             |

**Table 5-6. Prediction of volumetric heat capacity for the rock mass surrounding the borehole, with different assumptions and methods. Values corrected for temperature a difference (25°C – 14°C) are in brackets.**

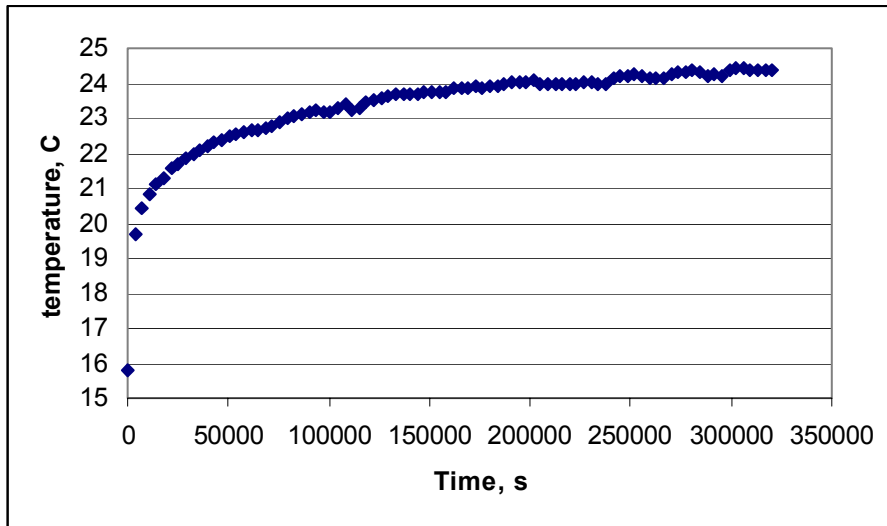
| Assumpt. method | Distribution of rock types / heat capacity (MJ/m <sup>3</sup> ,K) |                      |              |                      |         |             |
|-----------------|---|----------------------|--------------|----------------------|---------|-------------|
|                 | Äspö Diorite  | Altered Äspö Diorite | Ävrö Granite | Fine-grained granite | Mingled | Meta-basite |
| <b>1</b>        | Distribution irrelevant   |                      |              |                      |         |             |
|                 | <b>2.10</b>   |                      |              |                      |         |             |
| <b>2</b>        | 85%   | –                    | –            | 10%                  | –       | 5%          |
|                 | 2.13  | –                    | –            | 1.97                 | –       | 2.13        |
|                 | <b>2.11</b>   |                      |              |                      |         |             |
| <b>3</b>        | 54.5%   | 1%                   | 25%          | 11%                  | 3.7%    | 4.8%        |
|                 | 2.09  | 2.30                 | 2.13         | 1.97                 | 2.11    | 2.15        |
|                 | <b>2.09 (2.02)</b>  |                      |              |                      |         |             |
| <b>4</b>        | 54.5%   | 1%                   | 25%          | 11%                  | 3.7%    | 4.8%        |
|                 | 2.11  | 2.01                 | 1.99         | 2.07                 | 2.06    | 2.13        |
|                 | <b>2.08</b>   |                      |              |                      |         |             |

The thermal conductivity varies between 2.64 and 2.96 W/m,K depending on assumed rock type distribution and method. The corresponding heat capacity varies within a smaller interval (2.08–2.11 MJ/m<sup>3</sup>,K).

## 5.4 Thermal response test

The effective thermal conductivity from the thermal response test was evaluated at 3.55 W/m.K. Heat transfer was assumed mainly to take place through heat conduction and with negligible contribution from ground water movements. In Appendix 4, some possible sources of errors and uncertainties are presented.

Temperature versus time from the thermal response test is shown in Figure 5-3. The temperature is a measured average between in and out flow temperatures of the fluid.



*Figure 5-3. Time vs. temperature from thermal response test. Data from Appendix 4.*

## 6 Evaluation

### 6.1 Comparison between prediction and thermal response test

The thermal conductivity obtained from the thermal response test in borehole KA 2599 G01 has been estimated at 3.55 W/m,K (see Appendix 4). The predicted thermal conductivity is in the interval 2.64–2.96 W/m,K, depending on different assumptions and methods, see Table 5-5. In Table 6-1 a comparison is made between the thermal response test and the most reliable assumptions of rock type representation, for laboratory measurements and theoretical calculations. The correction for a temperature difference between laboratory and field determinations is very small and it is therefore ignored.

The thermal response test resulted in 25% higher values than laboratory measurements with a rock type distribution based on the revised core mapping.

**Table 6-1. Comparisons between results from thermal response test and predictions using laboratory measurements and calculations with an assumed rock type distribution.**

| Method/Assumption                                  | Thermal conductivity, W/m,K | Difference, % |
|--|-----------------------------|---------------|
| Laboratory measurements with revised core mapping  | 2.84                        | Base          |
| Theoretical calculations with revised core mapping | 2.64                        | -7            |
| Thermal response test                              | 3.55                        | +25           |

### 6.2 Comparison between laboratory measurements and calculated values

Table 6-2 shows results of thermal properties from laboratory measurements and theoretical calculations. The calculated thermal conductivity is about 5–8% lower than the measured value except for altered Äspö diorite where the calculated value is 9% higher. The calculated heat capacity is about 5–10% lower than the measured values for altered Äspö diorite and Ävrö granite and about equal to the measured values for Äspö diorite and fine-grained granite.

**Table 6-2. Comparison between laboratory measurements and calculated values for different rock types (SCA = self-consistent approximation).**

| Method                | Äspö Diorite |                      | Altered Äspö Diorite |                      | Ävrö granite |                      | Fine-grained granite |                      |
|-----------------------|--------------|----------------------|----------------------|----------------------|--------------|----------------------|----------------------|----------------------|
|                       | $\lambda$    | C                    | $\lambda$            | C                    | $\lambda$    | C                    | $\lambda$            | C                    |
|                       | W/m,K        | MJ/m <sup>3</sup> ,K | W/m,K                | MJ/m <sup>3</sup> ,K | W/m,K        | MJ/m <sup>3</sup> ,K | W/m,K                | MJ/m <sup>3</sup> ,K |
| Calculated (SCA)      | 2.35         | 2.11                 | 3.38                 | 2.07                 | 3.01         | 2.01                 | 3.45                 | 1.99                 |
| Measured (TPS method) | 2.56         | 2.09                 | 3.11                 | 2.30                 | 3.24         | 2.13                 | 3.63                 | 1.97                 |
| Diff, % (SCA-TPS)/TPS | -8.2%        | +1.0%                | +8.7%                | -10.0%               | -7.1%        | -5.6%                | -5.0%                | 1.0%                 |

### 6.3 Temperature dependence of thermal properties

Laboratory measurements of thermal conductivity show in general no obvious trends with respect to temperature for different rock types. This is in agreement with a previous study on the prototype repository /Sundberg and Gabrielsson, 1999/. The exception is altered Äspö diorite (sample 9), where there is a trend towards decreasing thermal conductivity values with the temperature (Table 5-2).

Studies of the temperature dependence of the thermal conductivity of common rocks presented in literature have shown a decrease in thermal conductivity with the temperature. The decrease may be in the order of 5–15% per 100°C /Sibbit et al, 1979/.

The measured volumetric heat capacity in the laboratory increased with the temperature, in average 17% (15–22%) within the temperature interval 25–80°C (Table 5-3). The result is in the same magnitude as a previous study on the prototype repository /Sundberg and Gabrielsson, 1999/.

An increase of the heat capacity with the temperature has also been reported in the literature. For example in a study by /Berman and Brown, 1985/ the heat capacity of common minerals increased by about 5% between 25 and 50°C and by about 10% between 100 and 200°C (quartz: 15%).

### 6.4 Comparison between measurements at dry and saturated conditions

Measurements at assumed dry and water-saturated conditions indicate a difference in thermal conductivity of 0–5% in spite of small differences in porosity, see Table 6-3. For 2 or 3 of the samples the difference is too large to be explained by pores shaped like spheres. Instead the porosity can be in the form of micro fissures, which can act like a barrier for the heat flow. For that type of porosity Hashin and Shtrikman's lower bound has been suggested to be relevant to estimate the difference in thermal conductivity between dry and water saturated conditions. Applying this to the data of Table 6-3 results in a difference of about 10%, which is too high a value. This indicates that the porosity appears both like spheres and micro fissures. The smallest difference (0%) is for alternated Äspö diorite.

**Table 6-3. Thermal conductivity ( $\lambda$ ) for rock samples under assumed dry and water saturated conditions.**

|                          | Sample            |                   |                           |                        |
|--------------------------|-------------------|-------------------|---------------------------|------------------------|
|                          | 3<br>Äspö Diorite | 4<br>Ävrö Granite | 8<br>Qz-rich Äspö Diorite | 9<br>Alt. Äspö Diorite |
| Porosity                 | 0.36%             | 0.34%             | 0.27%                     | 0.35%                  |
| $\lambda$ , Wet (W/m,K)  | 2.47              | 2.99              | 2.69                      | 3.11                   |
| $\lambda$ , Dry (W/m,K)  | 2.42              | 2.83              | 2.58                      | 3.11                   |
| Difference<br>(dry=base) | 2%                | 5%                | 4%                        | 0%                     |

**Table 6-4. Volumetric heat capacity (C) for rock samples under assumed dry and water saturated conditions.**

|                               | Sample            |                   |                           |                        |
|-------------------------------|-------------------|-------------------|---------------------------|------------------------|
|                               | 3<br>Äspö Diorite | 4<br>Ävrö Granite | 8<br>Qz-rich Äspö Diorite | 9<br>Alt. Äspö Diorite |
| Porosity                      | 0.36%             | 0.34%             | 0.27%                     | 0.35%                  |
| C, Wet (MJ/m <sup>3</sup> ,K) | 2.09              | 2.06              | 1.96                      | 2.30                   |
| C, Dry (MJ/m <sup>3</sup> ,K) | 2.01              | 2.02              | 1.97                      | 2.15                   |
| Difference<br>(dry=base)      | 4%                | 2%                | 0%                        | 7%                     |

The difference in volumetric heat capacity is about 0–7%, Table 6-4.

## 6.5 Comparisons with previous studies

Thermal properties of different rock types at Äspö have previously been calculated based on modal analyses of samples from the rock surface and from boreholes /Sundberg, 1991:1/, see Table 6-5. Furthermore, measurements and calculations for samples from the prototype repository have been made in another study /Sundberg and Gabrielsson, 1999/. For the calculations, estimated values of the thermal conductivity of plagioclase and pyroxene were used based on estimations of the chemical composition of these minerals.

The results from the present study and the two previous studies are presented in Table 6-6.

The difference in the results in calculated values for different investigations is probably due to real differences in mineral content and different assumptions with respect to the mineral composition. For example in /Sundberg and Gabrielsson, 1999/, it is shown that a chlorite content in the Äspö diorite significantly affects the thermal conductivity.

**Table 6-5. Mean values of thermal conductivity, from calculations based on estimations of mineral composition of different rock types at Äspö /Sundberg, 1991:1/.**

| Rock type                           | Thermal conductivity [W/m°C] | Heat capacity [J/kg°C] |
|-------------------------------------|------------------------------|------------------------|
| 1. Meta basite                      | 2.58                         | 775                    |
| 2. Dioritoids                       | 2.55                         | 770                    |
| 3. Quartz monzodiorite-granodiorite | 2.63                         | 760                    |
| 4. Granodiorite-granite             | 3.03                         | 755                    |
| 5. Granite                          | 3.48                         | 740                    |
| All samples                         | 2.96                         | 755                    |

**Table 6-6. Calculated and measured thermal conductivity (W/m,K) of different rock types from the Äspö area, from different studies.**

| Rock type            | /Sundberg, 1991/          | /Sundberg and Gabrielsson, 1999/ | Measured, TPS | Present study 2001 |               |
|----------------------|---------------------------|----------------------------------|---------------|--------------------|---------------|
|                      | Calculated, SCA           | Calculated, SCA                  |               | Calculated, SCA    | Measured, TPS |
| (Fresh) Äspö diorite | 2.63                      | 2.24                             | 2.41          | 2.35               | 2.56          |
| Altered Äspö diorite | group 3 <sup>1</sup>      | 3.20                             | 2.70          | 3.38               | 3.11          |
| Ävrö granite         |                           |                                  |               | 3.01               | 3.24          |
| Fine-grained granite | 3.48 group 5 <sup>1</sup> |                                  |               | 3.45               | 3.63          |
| Xenolith             | 2.58 group 1 <sup>1</sup> | 2.27                             |               |                    |               |

<sup>1</sup> Refers to Table 6-5.

Furthermore, the thermal conductivity in /Sundberg, 1991/ was calculated for a thermal conductivity of 1.8 W/m,K for the plagioclase, which corresponds to an anorthite content of 15%. In the present study and in /Sundberg and Gabrielsson, 1999/, the anorthite content in plagioclase is estimated at approx. 25% for the fresh Äspö diorite and the corresponding thermal conductivity becomes 1.6 W/m,K.

The difference in thermal conductivity for fresh Äspö diorite is small between the studies in 1999 and 2001 and may be connected to differences in the mineral composition.

Field values measured on Äspö diorite /Sundberg and Gabrielsson, 1999/ show somewhat higher values compared with laboratory measurements (2.83 W/m,K).

## **6.6 Possible reasons for differences in the results**

### **6.6.1 General**

Reasons for obtained differences in the results in Table 6-1 and Table 6-2 can be related to errors in the different methods or in the rock mapping. These potential sources of errors are:

1. Differences in properties of rock samples compared with the actual rock in the field.
2. Influence of conditions in the field.
3. Performance of the tests and applied test procedures.
4. Errors in the method and limitations of background theories.
5. Insufficient representativity and scale factors.

The possible reasons for the discrepancy are discussed under each method below.

### **6.6.2 Thermal response test**

The result of the thermal response test show an approximately 25% higher value of the thermal conductivity compared to laboratory tests on rock samples from the drill core. A number of reasons can influence the measurements in the field. They can be sorted in the following groups and will be discussed below:

- Convection in the borehole or in the rock mass.
- Errors in heat generation and temperature.
- Unstable temperature in the rock mass.
- Boundary effects.

The borehole has its top at level –343 m below sea level and it is 130 m deep. Some hydraulic investigations have been performed in the borehole but it has not been fully hydraulically characterised. The borehole has been tested by packer tests in different sections, in the lower part and for the whole borehole. The lower parts of the borehole have a low hydraulic conductivity. Observations during drilling and measurements of the total transmissivity for the borehole indicate a somewhat higher hydraulic conductivity in the upper parts.

The hydraulic situation is rather complicated and disturbed. Water is pumped from the whole tunnel system. These circumstances mean that there are large hydraulic gradients for water movements. The borehole is situated close to the tunnel system, see Figure 3-1. Water movements will most likely have an influence on the measurement. Water movements along (upper parts) of the borehole are possible and may have influenced the temperature and the generated heat to the rock. However, measurements that can indicate vertical water flow were not performed during the response test.

Water movements in the rock mass may also have some minor influence on the measurements.

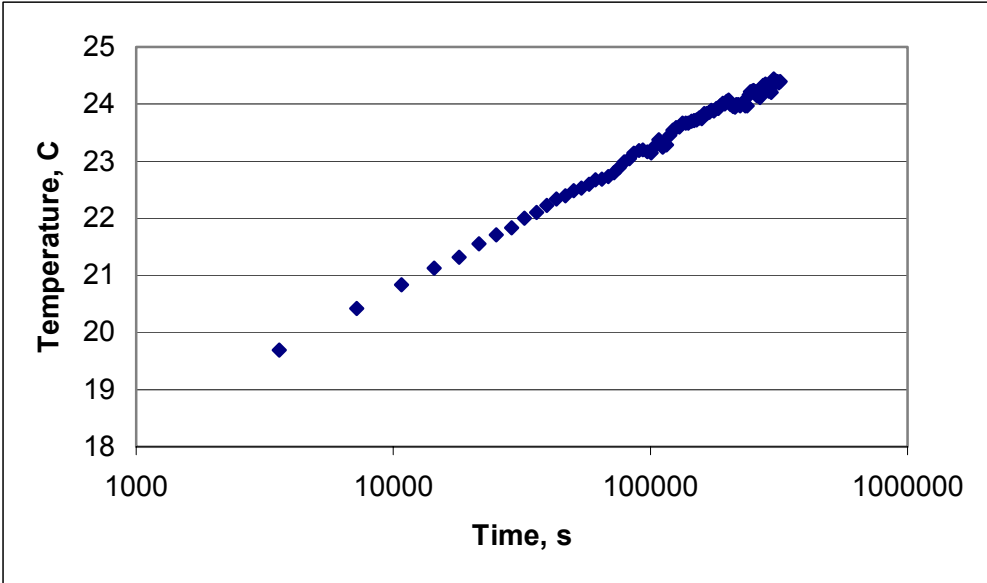


Movements due to expansion of the water with increasing temperature, during the test, may also occur. Water in the borehole can drain, possibly at the upper part of the borehole. Colder water from the surroundings can then sift through fissures at lower parts of the borehole. This phenomenon is referred to as thermal siphon effect /Gehlin, 1998/. The thermal effect on the measurements is similar to the above described flow due to hydraulic gradient.

The heat generated to the borehole consists of measured heat input from the generator plus electric energy transferred to heat in the circulation pump minus heat losses from the aggregate. If the generated heat is overestimated the evaluated thermal conductivity is also overestimated and vice versa. The heat input and the electric energy to the pump can be measured carefully. The heat losses from the aggregate have been estimated in Appendix 4 to be small, but these losses may be somewhat underestimated.

The temperature rise is calculated as a mean value of the inflow and outflow temperatures. If the relative temperature rise is small in the time interval used for evaluation, the temperature will be sensitive to different disturbances. The measured temperature rise is 0.01–0.05°C/h in the time interval 24–80 h, which means that quite small disturbances could cause significant errors. Such disturbance could be caused by small temperature changes in the rock mass due to temperature changes in the tunnel system or water movements. The temperature stability in the borehole at level –400 was measured a month after the response test and indicates that a temperature drift is less likely.

The temperature rise using a logarithmic time scale is shown in Figure 6-1. The curve indicates some kind of disturbance on the temperature rise. During pseudo steady state conditions (after about 100,000 s), the thermal conductivity normally can be evaluated from the slope of the asymptote. In this case quite different thermal conductivities can be evaluated depending on the selected part of the curve, which indicates disturbances on the measurements.



**Figure 6-1.** Thermal response test. Temperature vs. time (logarithmic time scale). Data from Appendix 4.

The measured temperature of the fluid is a mean value of the temperature of the fluid in the U-pipe along the borehole. This means that the temperature rise is lowered by the lower temperatures at the ends of the borehole, caused by 3-dimensional effects. Due to heat conduction this phenomenon should not have had a large influence on the temperature. However, this was not investigated, for example by separate temperature gauges at different depths.

### **6.6.3 Laboratory measurements**

It is not likely that there are errors in the theory, calculations or instrumentation for the TPS method. The theory has been published numerous times in scientific papers and is internationally accepted. The method was used in the Äspö prototype repository by /Sundberg and Gabrielsson, 1999/ and compared with a field method. The results differed by 10% (field values higher), which is lower than the difference in the present investigation. No obvious reason for the difference but it is possible that unobserved small water movements influenced the field measurements.

Influence from possible thermal short cuts and non-conductive heat transport is not likely and should have an opposite influence on the measurement results. In earlier investigation on the Äspö diorite /Sundberg and Gabrielsson, 1999/, some core samples contained large grains ( $\varnothing$  150 mm) embedded in a fine-grained mass. Laboratory measurements of thermal properties of these and other samples with a similar structure produced similar results. It may be assumed that the variations in grain size of the investigated samples did not influence the results. However, comparisons between different methods are rather rare why it is possible that some kind of systematic errors exist.

The porosity is small but has in some cases significant influence on the results, depending on if the porosity is saturated with water or air. Table 6-3 shows the thermal conductivity of 4 samples that were measured at assumed dry and saturated conditions. The differences are about 0–5% at about an average porosity of 0.3%. At porosities less than 1%, a difference of 25% in thermal conductivity has been reported. This shows the importance of the water saturation procedure of the samples before thermal measurements. It is known that core drilling can cause rock stress release and also damages to the core surface during the drilling. This may increase the porosity and thereby result in lower thermal conductivity values in the laboratory compared with the field. In this case, however, the porosity is low and porosity differences cannot explain the differences between the results of different methods.

No obvious foliation has been observed for the different samples and it is therefore assumed to have a minor influence on the results. The temperature influence on the estimated thermal conductivity is in general small why the difference in temperature in the field and in the laboratory has a very small influence on the results.

### **6.6.4 Theoretical calculations**

The estimated mineral content of different rock types has been calculated by using point counting in microscopy and chemical analyses. The Äspö diorite is rather coarse-grained which makes the point counting more difficult and it has to be corrected for the geochemical composition. The number of samples examined for each rock type is limited and varies between 1–5, and in addition, within each rock type there are

different varieties. For example, in earlier studies an altered variety of Äspö diorite has been distinguished with biotite replaced by chlorite, with a higher thermal conductivity as result. Transitional varieties between different rock types are also common.

For the evaluation of the thermal conductivity measurements, it is desirable to make comparisons with corresponding mineralogical composition of each sample. This is, however, not always possible due to factors such as the difficulty in point counting of coarse and inhomogeneous rock types. Instead, mineralogical compositions were given for the main rock types.

The above mentioned circumstances imply that there are uncertainties in the determined mineral content. However, a comparison between the results based on original and revised rock mapping shows that the difference in thermal conductivity is small.

It is also possible that there are errors in the reference values of the thermal conductivity for the different minerals, which were used in the calculations. This is discussed in /Sundberg, 1988/, and is supported by the fact that reference values from different sources sometimes show significant differences.

Different samples were used for different types of investigations. Differences between individual samples are thus a source to uncertainties when comparing and evaluating the results. From the above discussion, it is most likely that the mineral content of different samples used in the laboratory and in the calculations, and of the actual rock in the field, account for some of the discrepancies.

### **6.6.5 Methodology used for prediction**

Eleven samples from a 130 m long borehole have been used for both mineralogical determinations and measurements of thermal properties. The samples have been correlated to the drill core by a revised mapping and a predicted thermal conductivity for the whole drill core has been evaluated. This procedure is connected with a number of uncertainties, especially regarding the up scaling of the results from small samples to the whole drill core and the representativity of these samples.

However, the results for the different prediction methods are in a narrow interval, see Table 5-5. Furthermore, all of the samples have a thermal conductivity, which is significantly lower than that of the thermal response test.

It is also possible, but not likely, that the rock type in the drill core has large differences from the rock mass influenced by the thermal response test. If there is a larger body (than obtained from rock mapping) of, for example, fine-grained granite close to the borehole, the thermal response test would be influenced and generate a somewhat higher thermal conductivity value.

## 7 Conclusions and recommendations

A large difference in evaluated thermal conductivity exists between different methods, for the rock mass in borehole KA 2599 G01. The full-scale thermal response test resulted in a 25% higher value compared to the prediction, based on different assumptions about rock type distribution and methods to determine the thermal conductivity (calculations or laboratory measurements).

Thermal response tests measure an apparent thermal conductivity influenced by specific natural conditions in the field and the measurement itself. In the present case, large hydraulic pressure gradients exist in combination with a certain hydraulic conductivity, which increase the uncertainty of the measurements. For such cases the hydraulic situation should be thoroughly known. Conditions influencing measurements of samples in the laboratory are more easily controlled and observed. However, the up scaling of the results from small samples to the whole drill core and the representativity of these samples can include uncertainties.

The most reliable result, due to the discussion above, is the predicted thermal conductivity based on laboratory measurements and revised rock mapping. The resulting thermal properties, corrected to 14°C, for the borehole are 2.85 W/m,K (thermal conductivity) and 2.02 MJ/m<sup>3</sup>,K (volumetric heat capacity), based on 55% Äspö diorite, 25% Ävrö granite and 11% fine-grained granite.

The influence of the temperature on the thermal conductivity is small for the measured rock types. The measured volumetric heat capacity in the laboratory increased with the temperature, in average 17% (15–22%) within the temperature interval 25–80°C.

There is a clear relation between density and thermal conductivity for the investigated rock types. Higher thermal conductivity was measured in rock types with lower density and vice versa.

A comparison between thermal conductivity of the rock mass based on original and revised rock mapping shows that the difference is small (less than 2%). If the rock mass is assumed to consist of unknown rock types and each measurement represents equal parts of the borehole, the difference in thermal conductivity compared with revised mapping is about 4%. This shows that, for the current case, variations in the quality of the rock mapping only have a small influence on the thermal conductivity value.

The thermal response test is, in this particular case, assumed to overestimate the thermal conductivity. The reasons may primarily be a combination of water movements in (parts of) the borehole due to high pressure gradients and thermal expansion of the water. The small temperature rise makes the temperature measurements sensitive to different disturbances.

The thermal response test gives a large-scale value of the thermal conductivity. For some purposes (design of the repository etc) it is more interesting to know the distribution of conductivities for blocks in the scale of 1–10 m.

At SKB's site investigations, a program for determination of thermal properties of the rock mass is planned. Preliminary it is recommended to use the TPS method in these investigations. To eliminate possible systematic errors in this method it is recommended to perform comparisons with other laboratory methods. The thermal response test may be used for large-scale measurements of the rock mass if the uncertainties described above can be measured and held under control.

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### **Characterisation of rock types in core KA 2599G01 at the Äspö Hard Rock Laboratory**

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#### **Background**

Drill core KA 2599 G01 from the Äspö Hard Rock Laboratory (ÄHRL) was sampled in order to distinguish rock types present and their mineral content. The core has a total length of 128.3 m and is drilled vertically from the gallery in ÄHRL at chainage 2599 m. All together eleven samples were selected along the drill core to be representative for the dominating rock types (Table 1). These rock types were earlier mapped and distinguished as “Äspö diorite”, “Fine-grained granite”, and “Meta-basite”. However, during the sampling it was obvious that the term “Äspö diorite” involved a range of varieties including what has been mapped as “Ävrö granite” in the Äspö area and hybride rocks (mingled types) between “Ävrö granite” and “Äspö diorite”. For the purpose of making an estimate of the distribution of rock types along the bore hole, BIPS-images, chemical analysis, and microscopy were used resulting in a refined mapping as shown in Table 3 below.

In order to distinguish the rock types not only by their modal mineral contents but also by their chemistry, the same samples were selected for chemical analysis. This was done in order to check results from point-counting analyses since coarse-grained varieties may result in overestimates of the coarser minerals due to the small area considered in a thin-section. (The chemical analyses were carried out on samples of 6-cm long pieces of the core.) In addition multiple discs (A&B) were cut from the drill cores just close to the samples collected for chemical analyses in order to be used for determination of heat conductivity (the “divided-bar method”) and for density and connected porosity measurements.

#### **Results from chemical and mineralogical analyses**

The eleven samples were analysed on major and some trace elements by ICP-AES and SEM-EDS. In addition optically investigations were made using microscope with polarised light. The ICP-AES analyses were carried out at SGAB Analytica in Luleå and the SEM/EDS analyses were carried out at Earth Science Centre, Göteborg University, by Claes Ohlsson who also made the point counting. Results are shown in Appendix 1 and 2.

A comparison between point-counting analyses and chemical analyses shows that the point-counting partly yields figures that are not representative to the rocks involved mainly due to large grain sizes compared with the size of the thin sections. In order to overcome this problem an evaluation based on microscopy and chemical analyses were made (Table 2).

The samples used for divided-bar measurements were analysed concerning density and water absorption.

## Rock types distinguished

Figure 1 (below) shows a plot of SiO<sub>2</sub> versus major elements. There is a clear separation in SiO<sub>2</sub> contents among the samples selected. As shown below this separation also characterises the rock types. As expected Fe and Mg (and Ca) rich rocks also show low SiO<sub>2</sub> content while K rich rocks show relatively high SiO<sub>2</sub> contents.

A good correlation is shown when SiO<sub>2</sub> is plotted versus density as illustrated in Figure 2.

The drill core mapping revealed following rock types; a) Äspö quartz-monzodiorite, b) Altered Äspö quartz-monzodiorite, c) Ävrö granite, d) Altered Ävrö granite, e) Fine-grained granite, f) Meta-basite, g) Mingle Ävrö/Äspö.

**Table 1. Samples from drill core KA 2599 G01 selected for chemical analyses and thin sections.**

| Sampled core interval | Rock type            |
|-----------------------|----------------------|
| 5,9–6,0 A             | Äspö diorite         |
| 14,63–14,73 B         | Äspö diorite         |
| 25,32–25,42 C         | Äspö diorite         |
| 44,36–44,42 D         | Ävrö granite         |
| 50,10–50,20 E         | Fine-grained granite |
| 61,89–61,99 F         | Fine-grained granite |
| 70,64–70,74 G         | Qz-rich Äspö diorite |
| 85,52–85,62 H         | Oz-rich Äspö diorite |
| 101,85–101,95 I       | Altered Äspö diorite |
| 120,05–120,15 J       | Ävrö granite         |
| 126,35–126,45 K       | Ävrö granite         |

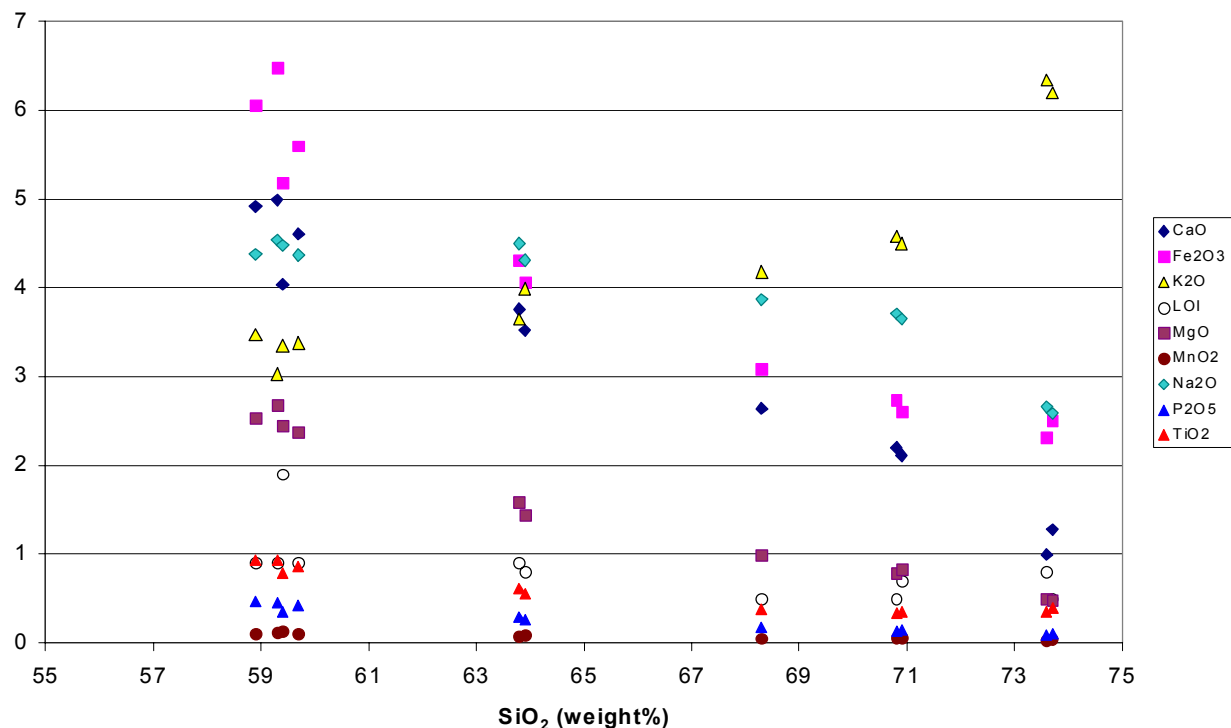
### *Äspö quartz-monzodiorite (ÄQMD):*

The ÄQMD samples are typically K-feldspar porphyric, reddish-grey to grey quartz-monzodiorites. They have low SiO<sub>2</sub> contents (~58–60%) while those samples showing a SiO<sub>2</sub> content of ~64% were distinguished as “quartz rich varieties of ÄQMD”. The ÄQMD samples also show a common density of >2.7 g/cm<sup>3</sup> and water absorption of 0.35 to 0.40 vol.-%, which is higher than other rock types analysed.

The K-feldspar content recorded in ÄQMD by point-counting is too high if comparison to the potassium content yielded by chemical analyses. This is explained by difficulties in point-counting rocks with porphyric texture (e.g. ÄQMD). Thus, the coarse-grained K-feldspar has been overestimated. An underestimation of plagioclase is also likely for these samples, since what has been calculated as sericite and K-feldspar should partly be referred to plagioclase.



Altered samples are similar in texture but more reddish in colour, and have a higher content of chlorite and sericite than the unaltered ÄQMD. However, their distribution is subordinate in the investigated drill-core as shown below.



**Figure 1.**  $SiO_2$  content versus major elements. The contents of  $Fe_2O_3$ ,  $CaO$ ,  $Na_2O$ ,  $MgO$ ,  $TiO_2$  and  $P_2O_5$  is highest in ÄQMD and decreases over the quartz rich ÄQMD and Ävrö granite to Fine-grained granite, which is lowest in these elements. The opposite is valid for  $K_2O$  and  $SiO_2$ .

#### Ävrö granite:

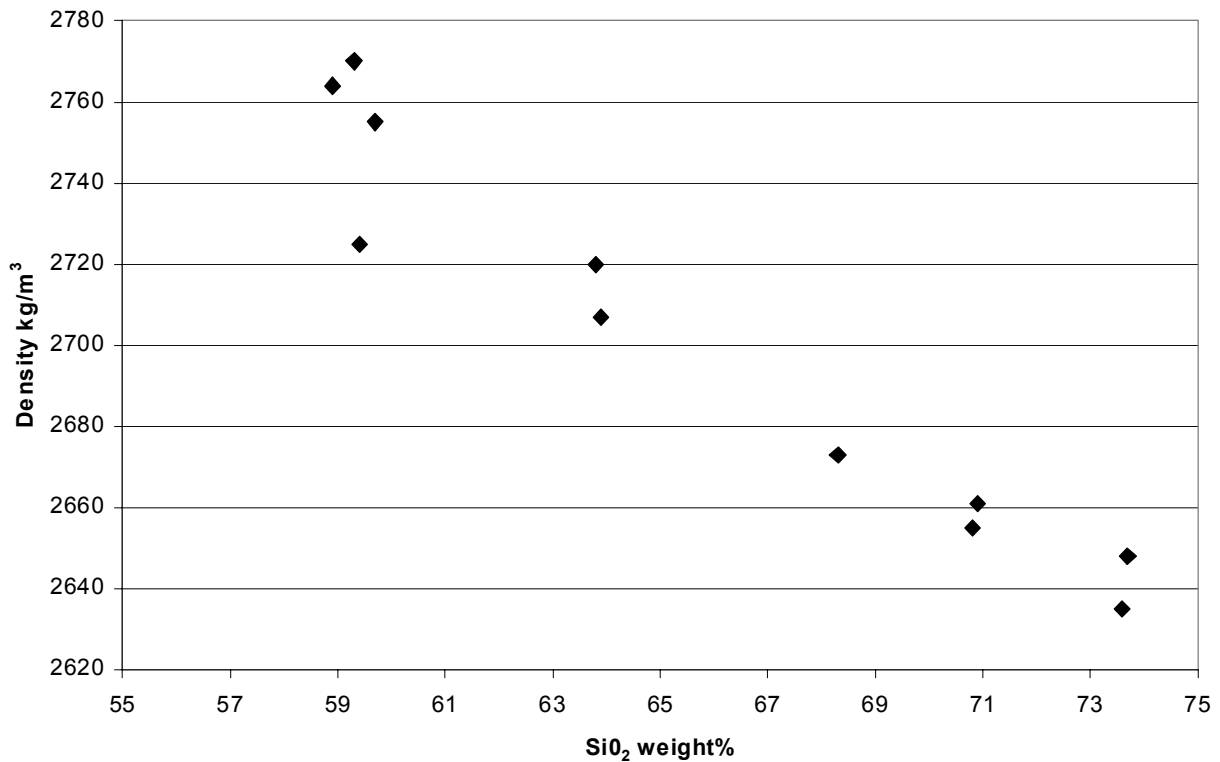
The samples distinguished as “Äspö granite” are typically granitic and aphyric. In Appendix 1, they are represented by three samples and are characterised by a  $SiO_2$  content of 68–71%, a density of 2.65–2.66 g/cm<sup>3</sup> and a relatively low water absorption of 0.28–0.22 vol.-%. Altered samples of this type are very uncommon in the drill-core.

#### Meta-basite:

This rock type is subordinate and has not been analysed.

#### Mingled Ävrö/Äspö:

This rock type has not been analysed. It is likely that the mineral content and chemistry is roughly a mean of what has been yielded for ÄQMD + Ävrö granite.



**Figure 2.** ÄQMD samples show the highest density of all samples and the lowest SiO<sub>2</sub>-content (~58–60%) while quartz-rich varieties of ÄQMD (~64% SiO<sub>2</sub>) show somewhat lower density. Ävrö granite is lighter and more SiO<sub>2</sub>-rich (~68–71%). The most silica-rich rock type is the Fine-grained granite, which has the highest SiO<sub>2</sub>-content (~71–74%) and the lowest density.

#### *Fine-grained granite:*

These samples are typically reddish and fine-grained. The fine-grained granite shows the highest quartz content of all samples analysed and a high content of K-feldspar. They show a SiO<sub>2</sub> content of ca. 71–74% and a density of ca. 2.63–2.65 g/cm<sup>3</sup>.

#### **Modal mineral content in rock types distinguished**

Estimated mineral contents for the different rock types have been calculated using microscopy and considerations taken concerning chemical composition (Table 2). However it must be noted that the mineral composition varies for the specific rock types distinguished and transitional varieties between the rock types are common.

**Table 2. Estimated mineralogical composition and plagioclase composition of rock types.**

| Sample            | Äspö QMD       | Ävrö granite   | Fine-grained granite | Altered ÄQMD |
|-------------------|----------------|----------------|----------------------|--------------|
| Number of samples | 5              | 3              | 2                    | 1            |
| Quartz            | 12             | 25             | 31                   | 15           |
| Plagioclase       | 40 (An 25–30%) | 28 (An 20–30%) | 15 (An 20–25%)       | 25 (An 0–5%) |
| K-feldspar        | 20             | 32             | 36                   | 23           |
| Biotite           | 18             | 7              | 3                    | 0.5          |
| Chlorite          | 0.3            | 1.0            | 0.5                  | 14           |
| Titanite          | 1.3            | 0.4            | 0.2                  | 1.3          |
| Amphibole         | 0.2            | –              | –                    | –            |
| Epidote           | 4              | 2.5            | 3                    | 10           |
| Sericite          | 4              | 4              | 10.5                 | 10           |
| Opagues           | 0.6            | 0.3            | 1.0                  | 0.4          |

### **Distribution of different rock types in drill core KA 2599 G01**

The distribution of the different rock types in drill core KA 2599 G01 has been estimated using the depicted characteristics (Table 3) and re-visitation of the BIPS. This means that the ÄQMD dominates (~54.6 vol.-%) followed by Ävrö granite (~25.1 vol.-%). There are also parts of the core showing mingling between these types (~3.7 vol.-%) The Fine-grained granite constitutes 11.0 vol.%, the Meta-basite ~4.3 vol.% and altered ÄQMD ~1 vol.%. A very small portion of altered Ävrö granite constitutes ~0.2 vol.%.

**Table 3. Rocktype distribution along the drill core KA 2599 G01.**

| <b>Rock type/<br/>Percentage of core<br/>(%)</b>      | <b>Core length (m)</b>   |
|---|--|
| Äspö QMD<br>(Incl. Quartz-rich<br>varieties)<br>54.6% | 4.0–28.0; 36.0–44.0; 68.9–75.1; 79.6–90.3; 96.6–101.6;<br>109.6–115.1; 115.4–117.6 |
| Ävrö granite<br>25.1%                                 | 28.0–36.0; 44.0–45.9; 75.1–79.6; 90.3–96.6; 117.6–126.8;<br>127.1–128.3            |
| Fine-grained granite<br>11%                           | 45.9–51.4; 53.8–54.5; 56.0–58.9; 60.4–64.0; 109.0–109.6;<br>115.1–115.4            |
| Meta-basite<br>4.3%                                   | 51.4–53.8; 54.5–56.0; 58.9–60.4  |
| Mingled Äspö/Ävrö<br>3.7%                             | 64.0–68.6  |
| Altered ÄQMD<br>1%                                    | 101.6–102.9  |
| Altered Ävrö granite<br>0.2%                          | 126.8–127.1  |

## Appendix 1: Chemical composition of rock samples (ICP- analyses)

| ELEMENT                          | Åspö diorite |             |             | Altered ÅQMD Qz-rich ÅQMD |             |             | Ävrö granite |               |               | Fine-grained granite |             |  |
|----------------------------------|--------------|-------------|-------------|---------------------------|-------------|-------------|--------------|---------------|---------------|----------------------|-------------|--|
|                                  | 5,9-6,0 A    | 14,63-14,73 | 25,32-25,42 | 101,85-101,95             | 70,64-70,74 | 85,52-85,62 | 44,36-44,42  | 120,05-120,15 | 126,35-126,45 | 50,10-50,20          | 61,89-61,99 |  |
| Al <sub>2</sub> O <sub>3</sub> % | 17,6         | 17,9        | 17,3        | 16,6                      | 16,9        | 17,1        | 15,3         | 14,8          | 14,5          | 13,3                 | 13,4        |  |
| CaO                              | 4,92         | 4,99        | 4,61        | 4,04                      | 3,52        | 3,76        | 2,64         | 2,2           | 2,11          | 0,994                | 1,28        |  |
| Fe <sub>2</sub> O <sub>3</sub>   | 6,06         | 6,48        | 5,6         | 5,19                      | 4,06        | 4,31        | 3,09         | 2,74          | 2,61          | 2,32                 | 2,51        |  |
| K <sub>2</sub> O                 | 3,47         | 3,03        | 3,38        | 3,35                      | 3,99        | 3,65        | 4,18         | 4,58          | 4,5           | 6,34                 | 6,2         |  |
| MgO                              | 2,53         | 2,68        | 2,38        | 2,44                      | 1,44        | 1,58        | 0,995        | 0,786         | 0,825         | 0,496                | 0,474       |  |
| MnO <sub>2</sub>                 | 0,106        | 0,109       | 0,103       | 0,131                     | 0,0884      | 0,0758      | 0,0479       | 0,0568        | 0,0587        | 0,0296               | 0,0467      |  |
| Na <sub>2</sub> O                | 4,38         | 4,54        | 4,37        | 4,48                      | 4,31        | 4,5         | 3,87         | 3,71          | 3,65          | 2,66                 | 2,59        |  |
| P <sub>2</sub> O <sub>5</sub>    | 0,468        | 0,455       | 0,423       | 0,349                     | 0,259       | 0,29        | 0,168        | 0,137         | 0,141         | 0,0878               | 0,0967      |  |
| SiO <sub>2</sub>                 | 58,9         | 59,3        | 59,7        | 59,4                      | 63,9        | 63,8        | 68,3         | 70,8          | 70,9          | 73,6                 | 73,7        |  |
| TiO <sub>2</sub>                 | 0,931        | 0,935       | 0,865       | 0,786                     | 0,553       | 0,611       | 0,386        | 0,338         | 0,356         | 0,35                 | 0,387       |  |
| LOI                              | 0,9          | 0,9         | 0,9         | 1,9                       | 0,8         | 0,9         | 0,5          | 0,5           | 0,7           | 0,8                  | 0,5         |  |
| Summa                            | 99,4         | 100,4       | 98,7        | 98,8                      | 99          | 99,7        | 99           | 100,1         | 99,7          | 100,2                | 100,7       |  |
| Ba ppm                           | 1770         | 1500        | 1640        | 1200                      | 1610        | 1470        | 1740         | 965           | 1240          | 893                  | 907         |  |
| Be                               | 2,08         | 2,05        | 1,99        | 1,87                      | 2,99        | 2,35        | 1,68         | 2,19          | 2,02          | 1,37                 | 1,61        |  |
| Co                               | 12,9         | 11,4        | 9,46        | 8,63                      | 8,41        | 12,4        | <6           | <5            | 7,66          | <6                   | <6          |  |
| Cr                               | 38,3         | 48,1        | 31,2        | 32                        | 32,4        | 29,6        | 21           | 12            | 13,6          | <10                  | <10         |  |
| Cu                               | 32,5         | 11,3        | 15,3        | <6                        | <5          | 14,1        | 6,08         | <5            | <6            | 12                   | <6          |  |
| La                               | 62,1         | 62,9        | 56,3        | 50,6                      | 43,2        | 52,8        | 28,1         | 46            | 59,2          | 116                  | 111         |  |
| Mo                               | <6           | <6          | <6          | <6                        | 6,57        | 5,88        | <6           | <5            | <6            | <6                   | <6          |  |
| Nb                               | 21,6         | 19          | 18,4        | 22,7                      | 25,6        | 20,9        | 9,02         | 11,2          | 14,8          | 16,8                 | 21          |  |
| Ni                               | 26,1         | 29,9        | 25,1        | 19,5                      | 15,9        | 18,4        | 14,2         | <10           | <10           | <10                  | <10         |  |
| Sc                               | 10,4         | 10,4        | 9,6         | 8,66                      | 8,38        | 7,33        | 1,15         | 2,96          | 3,91          | 4,12                 | 4,65        |  |
| Sn                               | <20          | <20         | <20         | <20                       | <20         | <20         | <20          | <20           | <20           | <20                  | <20         |  |
| Sr                               | 1410         | 1420        | 1370        | 1070                      | 970         | 1120        | 1080         | 651           | 704           | 223                  | 267         |  |
| V                                | 86,7         | 93,6        | 78,9        | 69,2                      | 42,8        | 56,1        | 35           | 25,5          | 25,3          | 13,9                 | 15,7        |  |
| W                                | <60          | <60         | <60         | <60                       | <50         | <50         | <60          | <50           | <60           | <60                  | <60         |  |
| Y                                | 26,8         | 25,4        | 25          | 29,6                      | 20,7        | 17,7        | 8,76         | 12,4          | 14,4          | 21,4                 | 33          |  |
| Zn                               | 98           | 100         | 93,3        | 91,6                      | 67,3        | 58,6        | 47,3         | 47,2          | 43,8          | 18,3                 | 36,5        |  |
| Zr                               | 271          | 261         | 261         | 303                       | 251         | 272         | 201          | 143           | 151           | 287                  | 316         |  |

Appendix 2: SEM/EDS analyses of Plagioclase, Epidote Chlorite and Biotite

| Sample A 5.9-6.0m |            |           |         |            |         |            |           |  |
|-------------------|------------|-----------|---------|------------|---------|------------|-----------|--|
| Sample sit        | A1         | A2        | A3      | A4         | A5      | A6         | A7        |  |
| Mineral           | Oligoclase | Andesine* | Biotite | Oligoclase | Epidote | Oligoclase | Andesine* |  |
| Na                | 5,09       | 5,18      | 0,11    | 6,15       | 0       | 5,31       | 5,29      |  |
| Mg                | 0,06       | 0         | 7,36    | 0          | 0       | 0          | 0         |  |
| Al                | 10,31      | 10,06     | 7,14    | 9,11       | 10,78   | 9,82       | 9,98      |  |
| Si                | 20,46      | 20,85     | 14,98   | 21,8       | 15,04   | 21,04      | 20,85     |  |
| K                 | 0,52       | 0,1       | 5,15    | 0,08       | 0       | 0,04       | 0,04      |  |
| Ca                | 1,94       | 2,19      | 0       | 1,26       | 9,81    | 2,2        | 2,22      |  |
| Ti                | 0          | 0         | 0,56    | 0          | 0       | 0          | 0         |  |
| Mn                | 0,1        | 0         | 0,12    | 0          | 0,05    | 0          | 0         |  |
| Fe                | 0,2        | 0,03      | 6,33    | 0          | 4,01    | 0          | 0         |  |
| O                 | 61,41      | 61,63     | 58,24   | 61,62      | 60,2    | 61,63      | 61,59     |  |
| An content        | 0,28       | 0,30      |         | 0,17       |         | 0,29       | 0,30      |  |

\*An30 is lower limit for Andesine

| Sample D 44.36-44.46m |         |            |            |         |
|-----------------------|---------|------------|------------|---------|
| Sample sit            | D1      | D2         | D3         | D6      |
| Mineral               | Andesin | Oligoclase | Oligoclase | Biotite |
| Na                    | 5,41    | 5,55       | 5,8        | 0       |
| Mg                    | 0       | 0          | 0          | 7,28    |
| Al                    | 9,59    | 9,61       | 9,22       | 7,51    |
| Si                    | 20,87   | 21,57      | 21,94      | 14,84   |
| K                     | 0,08    | 0,08       | 0          | 5,14    |
| Ca                    | 2,57    | 1,71       | 1,48       | 0       |
| Ti                    | 0       | 0          | 0          | 0,54    |
| Mn                    | 0       | 0          | 0          | 0,15    |
| Fe                    | 0,28    | 0,03       | 0          | 6,33    |
| O                     | 61,41   | 61,73      | 61,76      | 58,19   |
| An content            | 0,32    | 0,24       | 0,20       |         |

| Sample I 101.85-101.95 |        |          |             |
|------------------------|--------|----------|-------------|
| Sample sit             | I1     | I2       | I3          |
| Mineral                | Albite | Chlorite | Anortoclase |
| Na                     | 7,11   | 0,33     | 6,52        |
| Mg                     |        | 11,84    |             |
| Al                     | 7,82   | 8,99     | 7,75        |
| Si                     | 23,28  | 12,03    | 22,84       |
| K                      |        |          | 1,72        |
| Ca                     | 0,04   |          | 0,05        |
| Ti                     |        |          |             |
| Mn                     |        | 0,2      |             |
| Fe                     | 0,14   | 8,41     | 0,15        |
| O                      | 61,78  | 58,16    | 61,24       |
| An content             | 0,01   |          | 0,01        |

## Porosity and density of core samples



## RAPPORT

Geo Innova AB  
Jan Sundberg  
Teknikringen 1C  
583 30 Linköping

|   |              |                        |             |
|---|--------------|------------------------|-------------|
| Handledaren, ordet / Handled by, department | Datum / Date | Beteckning / Reference | Sida / Page |
| Lennart Hagnestål, Byggnadsteknik           | 2001-09-21   | F1116023               | 1 (3)       |
| Tel +46 (0)33 16 51 29                      |              |                        |             |

## Provning av natursten - borrhävar

## Uppdrag

Opertisk provning av natursten, 11 stycken prov om vardera två provkroppar. Beträffande providentifikation och egenskaper som provats, se under rubrikerna "Provfakta" och "Provningens omfattning".

## Provtagning och ankomstdatum

Proverna togs ut och skickades till SP genom uppdragsgivarens försorg. SP saknar kännedom om provtagningen. Proverna ankom till SP 2001-09-07. Proverna bestod av borrhävar av natursten.

## Provfakta

| Providentitet        | Delprovets märkning |                  | SP:s märkning |           |
|----------------------|---------------------|------------------|---------------|-----------|
|                      | Delprov 1           | Delprov 2        | Delprov 1     | Delprov 2 |
| KA 2599 G01, Prov 1  | 5,90-5,94 m         | 6,0-6,42 m       | 1A            | 1B        |
| KA 2599 G01, Prov 2  | 14,588-14,63 m      | 14,63-14,67 m    | 2A            | 2B        |
| KA 2599 G01, Prov 3  | 25,32-36 m          | 25,42-25,462 m   | 3A            | 3B        |
| KA 2599 G01, Prov 4  | 44,278-44,32 m      | 44,32-36 m       | 4A            | 4B        |
| KA 2599 G01, Prov 5  | 50,20-50,242 m      | 50,10-50,14 m    | 5A            | 5B        |
| KA 2599 G01, Prov 6  | 61,99-62,032 m      | 61,89-61,93 m    | 6A            | 6B        |
| KA 2599 G01, Prov 7  | 70,598-70,64 m      | 70,64-70,68 m    | 7A            | 7B        |
| KA 2599 G01, Prov 8  | 85,52-85,56 m       | 85,48-85,52 m    | 8A            | 8B        |
| KA 2599 G01, Prov 9  | 101,95-101,992 m    | 101,85-101,89 m  | 9A            | 9B        |
| KA 2599 G01, Prov 10 | 120,05-120,9 m      | 120,15-120,192 m | 10A           | 10B       |
| KA 2599 G01, Prov 11 | 126,45-126,492 m    | 126,35-126,39 m  | 11A           | 11B       |

## Provningens omfattning

| Egenskap         | Metod                  | Providentitet | Provningens datum          |
|------------------|------------------------|---------------|----------------------------|
| Densitet         | DIN 52102-RE, VA<br>1) | se ovan       | 2001-09-10 –<br>2001-09-21 |
| Vattenabsorption | DIN 52103-A<br>1)      | se ovan       | 2001-09-10 –<br>2001-09-21 |

1) Se under rubriken "Kommentar" nedan.

**Provningsresultat**
**Densitet och vattenabsorption, DIN 52102-RE-VA, DIN 52103-A**

| Provkroppens identitet |                      |                  | Provkroppens torra vikt (g) | Densitet (kg/m <sup>3</sup> ) | Vattenabsorption, ej kokning |          |
|------------------------|----------------------|------------------|-----------------------------|-------------------------------|------------------------------|----------|
|                        |                      |                  |                             |                               | (vikr%)                      | (volym%) |
| 1A                     | KA 2599 G01, Prov 1  | 5,90-5,94 m      | 344,04                      | 2761                          | 0,15                         | 0,40     |
| 1B                     | KA 2599 G01, Prov 1  | 6,0-6,42 m       | 346,39                      | 2768                          | 0,14                         | 0,40     |
| 2A                     | KA 2599 G01, Prov 2  | 14,588-14,63 m   | 351,37                      | 2771                          | 0,14                         | 0,38     |
| 2B                     | KA 2599 G01, Prov 2  | 14,63-14,67 m    | 353,06                      | 2768                          | 0,14                         | 0,38     |
| 3A                     | KA 2599 G01, Prov 3  | 25,32-36 m       | 349,15                      | 2757                          | 0,13                         | 0,37     |
| 3B                     | KA 2599 G01, Prov 3  | 25,42-25,462 m   | 347,19                      | 2753                          | 0,13                         | 0,35     |
| 4A                     | KA 2599 G01, Prov 4  | 44,278-44,32 m   | 369,95                      | 2673                          | 0,13                         | 0,35     |
| 4B                     | KA 2599 G01, Prov 4  | 44,32-36 m       | 369,26                      | 2673                          | 0,12                         | 0,33     |
| 5A                     | KA 2599 G01, Prov 5  | 50,20-50,242 m   | 357,98                      | 2635                          | 0,10                         | 0,27     |
| 5B                     | KA 2599 G01, Prov 5  | 50,10-50,14 m    | 357,17                      | 2636                          | 0,08                         | 0,22     |
| 6A                     | KA 2599 G01, Prov 6  | 61,99-62,032 m   | 361,80                      | 2648                          | 0,10                         | 0,26     |
| 6B                     | KA 2599 G01, Prov 6  | 61,89-61,93 m    | 363,96                      | 2648                          | 0,10                         | 0,26     |
| 7A                     | KA 2599 G01, Prov 7  | 70,598-70,64 m   | 373,95                      | 2706                          | 0,10                         | 0,28     |
| 7B                     | KA 2599 G01, Prov 7  | 70,64-70,68 m    | 381,18                      | 2709                          | 0,10                         | 0,28     |
| 8A                     | KA 2599 G01, Prov 8  | 85,52-85,56 m    | 366,20                      | 2723                          | 0,10                         | 0,26     |
| 8B                     | KA 2599 G01, Prov 8  | 85,48-85,52 m    | 341,02                      | 2717                          | 0,10                         | 0,28     |
| 9A                     | KA 2599 G01, Prov 9  | 101,95-101,992 m | 377,08                      | 2720                          | 0,14                         | 0,39     |
| 9B                     | KA 2599 G01, Prov 9  | 101,85-101,89 m  | 373,12                      | 2731                          | 0,11                         | 0,31     |
| 10 A                   | KA 2599 G01, Prov 10 | 120,05-120,9 m   | 333,36                      | 2651                          | 0,09                         | 0,25     |
| 10 B                   | KA 2599 G01, Prov 10 | 120,15-120,192 m | 325,79                      | 2658                          | 0,10                         | 0,28     |
| 11 A                   | KA 2599 G01, Prov 11 | 126,45-126,492 m | 333,48                      | 2662                          | 0,08                         | 0,22     |
| 11 B                   | KA 2599 G01, Prov 11 | 126,35-126,39 m  | 334,19                      | 2661                          | 0,09                         | 0,25     |



**Kommentar**

I metoderna för bestämning av densitet och vattenabsorption ska provet torkas respektive vattensmättas till konstant vikt. Konstant vikt vid torkning och vid vattenabsorption definieras i metoderna som en viktändring mindre än 0,1 % per 24 timmar. Vid denna provning har konstant vikt definierats som en viktförändring om 0,01 %, vilket motsvarar ca 0,04 g. Anledningen till detta är att öka precisionen så att skillnaden mellan material med mycket låg vattenabsorption kan detekteras.

Enligt metoden för bestämning av densiteten ska provningsresultatet avrundas till 10 kg/m<sup>3</sup>. I denna redovisning har resultaten avrundats till 1 kg/m<sup>3</sup>. Anledningen till detta är att tydliggöra små differenser i densitet mellan likvärdiga prov. Metodens ( DIN 52102-RE, VA ) mätosäkerhet är ej redovisad, angiven avrundning får gälla.

**Mätosäkerhet**

För information om mätosäkerheten kontakta teknisk handläggare.

SP Sveriges Provnings- och Forskningsinstitut  
Byggnadsmaterial



Björn Schouenborg  
Tekniskt ansvarig



Lennart Hagnestål  
Teknisk handläggare

## Thermal conductivity measurements with the TPS method



## Slutrapport Borrkärnor

Först mättes samtliga prover torra vid rumstemperatur. Varje mätning repeterades 5 ggr, och standardavvikelsen i % är given för samtliga resultat.

| Prov nr | kond.<br>W/mK | Std<br>% | Diff<br>mm <sup>2</sup> /s | std<br>% | Cp<br>MJ/m <sup>3</sup> K | std<br>% |
|---------|---------------|----------|----------------------------|----------|---------------------------|----------|
| 1       | 2.387         | 0.06     | 1.139                      | 1.0      | 2.096                     | 1        |
| 2       | 2.317         | 0.07     | 1.083                      | 0.43     | 2.141                     | 0.41     |
| 3       | 2.389         | 0.11     | 1.169                      | 0.34     | 2.043                     | 0.33     |
| 4       | 2.867         | 0.05     | 1.406                      | 0.14     | 2.040                     | 0.13     |
| 5       | 3.523         | 0.05     | 1.797                      | 0.38     | 1.961                     | 0.42     |
| 6       | 3.416         | 0.07     | 1.738                      | 0.31     | 1.966                     | 0.31     |
| 7       | 2.773         | 0.07     | 1.339                      | 0.58     | 2.071                     | 0.54     |
| 8       | 2.642         | 0.02     | 1.247                      | 0.27     | 2.119                     | 0.30     |
| 9       | 3.064         | 0.03     | 1.377                      | 0.17     | 2.226                     | 0.18     |
| 10      | 3.146         | 0.06     | 1.544                      | 0.44     | 2.037                     | 0.49     |
| 11      | 3.166         | 0.10     | 1.627                      | 0.35     | 1.946                     | 0.32     |

## Prover som kördes vid förhöjd temperatur

### Prov 3

Kördes i ugnen efter att ha legat i vacuum under vatten. Därefter fick proven yttorka (c:a 3 timmar). Det tog c:a 15 timmar att göra mätningar vid 25 C, 40 C, 60 C och 80 C. Vid varje temperatur gjordes 5 repetitioner med 30 min mellanrum. Resultat:

|          |       |      |       |      |       |  |
|----------|-------|------|-------|------|-------|--|
| 25 C     | 2.472 | 0.06 | 1.184 | 0.6  | 2.089 | 0.68 (4 av 5 resultat, första avviker) |
| 40 C     | 2.430 | 0.3  | 1.118 | 0.8  | 2.174 | 0.57 (4 av 5 resultat, första avviker) |
| 60 C     | 2.413 | 0.47 | 1.066 | 1.7  | 2.265 | 1.3                                    |
| 80 C     | 2.395 | 0.6  | 1.012 | 2.3  | 2.367 | 1.7 (4 av 5 resultat, första avviker)  |
| RT efter | 2.419 | 0.07 | 1.202 | 0.28 | 2.012 | 0.23                                   |

### Prov 4

Kördes i ugnen efter att ha legat i vacuum under vatten. Därefter fick proven yttorka (c:a 3 timmar). Vid denna körning hade temperatortoleransen ställts snålare (0.5 C), vilket medförde att uppehållstiderna vid de olika temperaturerna blev långa: 15 timmar vid 40 C, ytterligare 5 timmar vid 60 C och ytterligare 14 timmar vid 80 C. (Dessutom mättes provet vid 80C ytterligare en gång ett dygn senare, utan att tas ut ur ugnen). Vid varje temperatur gjordes 5 repetitioner med 30 min mellanrum. Resultat:

|                 |       |      |       |      |       |      |
|-----------------|-------|------|-------|------|-------|------|
| 25 C            | 2.986 | 0.11 | 1.453 | 0.22 | 2.055 | 0.13 |
| 40 C            | 2.902 | 0.26 | 1.374 | 0.9  | 2.112 | 0.67 |
| 60 C            | 2.840 | 0.34 | 1.278 | 1.24 | 2.226 | 0.78 |
| 80 C            | 2.805 | 0.44 | 1.225 | 1.23 | 2.291 | 0.82 |
| 80 C (+24 tim.) | 2.805 | 0.44 | 1.206 | 1.21 | 2.323 | 0.88 |
| RT efter        | 2.830 | 0.20 | 1.404 | 0.82 | 2.017 | 0.55 |

(3 första av 5 resultat har använts, för kort tid vid rumstemperatur för att nå jämvikt innan mätningen)

## Prov 8

Kördes i ugnen efter att ha legat i vacuum under vatten. Därefter fick proven yttorka (c:a 3 timmar). Totala tiden i ugnen var c:a 20 timmar, ungefär samma väntetid vid varje temperatur. Vid varje temperatur gjordes 5 repetitioner med 30 min mellanrum. Resultat:

|          |       |      |       |      |       |      |
|----------|-------|------|-------|------|-------|------|
| 25 C     | 2.685 | 0.06 | 1.369 | 0.41 | 1.961 | 0.37 |
| 40 C     | 2.647 | 0.24 | 1.294 | 0.53 | 2.045 | 0.32 |
| 60 C     | 2.636 | 0.36 | 1.228 | 0.85 | 2.147 | 0.49 |
| 80 C     | 2.606 | 0.6  | 1.148 | 1.87 | 2.271 | 1.28 |
| RT efter | 2.584 | 0.06 | 1.315 | 0.42 | 1.965 | 0.43 |

Även här var väntetiderna så långa (även vid rumstemperatur efter) att alla 5 värden kunde användas för samtliga mätningar.

## Prov 9

Kördes i ugnen efter att ha legat i vacuum under vatten. Därefter fick proven yttorka (c:a 3 timmar). Samma program och därför också samma ungefärliga tidsåtgång som för prov 8. Men trots detta så visade det sig att jämvikten ställer in sig långsammare hos prov 9. Första mätningarna avviker för mycket, kanske skulle i något fall även andra mätningarna uteslutas. Vid varje temperatur gjordes 5 repetitioner med 30 min mellanrum. Resultat:

|                     |       |      |       |      |       |  |
|---------------------|-------|------|-------|------|-------|--|
| 25 C                | 3.108 | 0.06 | 1.349 | 0.55 | 2.304 | 0.54                                   |
| 40 C                | 3.071 | 0.16 | 1.285 | 0.54 | 2.390 | 0.43 (4 av 5 resultat, första avviker) |
| 60 C                | 3.050 | 0.25 | 1.235 | 0.63 | 2.464 | 0.62 (4 av 5 resultat, första avviker) |
| 80 C                | 2.978 | 0.9  | 1.137 | 2.7  | 2.619 | 1.8 (4 av 5 resultat, första avviker)  |
| RT efter mätningar) | 3.105 | 1.46 | 1.446 | 3.94 | 2.148 | 2.4 (4                                 |

**Prover som kördes efter vatten-i-vacuum, utan att ha varit i ugnen.**

Slutligen mättes övriga prover efter att ha legat under vatten i vacuum under c:a 3-4 timmar, yttorkat 3-5 timmar:

|    |       |      |       |      |       |                 |
|----|-------|------|-------|------|-------|-----------------|
| 1  | 2.494 | 0.52 | 1.154 | 0.33 | 2.162 | 0.21            |
| 2  | 2.340 | 0.05 | 1.101 | 0.37 | 2.126 | 0.38            |
| -  |       |      |       |      |       |                 |
| -  |       |      |       |      |       |                 |
| 5  | 3.578 | 0.18 | 1.852 | 0.84 | 1.932 | 0.70            |
| 6  | 3.680 | 0.30 | 1.827 | 0.59 | 2.015 | 0.88            |
| 7  | 2.840 | 0.07 | 1.353 | 0.7  | 2.099 | 0.7             |
| -  |       |      |       |      |       |                 |
| -  |       |      |       |      |       |                 |
| 10 | 3.224 | 0.26 | 1.620 | 1.55 | 1.991 | 1.41            |
| 11 | 3.545 | 0.04 | 1.516 | 0.88 | 2.338 | 0.62            |
|    |       |      |       |      |       | (3 första av 5) |

Uppsala 010905

  
Lars Waldahl  
Hot Disk AB

**Thermal response test for determination of thermal conductivity in rock**

Denna skrift sammanfattar resultaten  
från en termisk responstest  
och är utförd på uppdrag av  
Thomas Jansson,  
Golder Associates AB

TERMISK RESPONSTEST FÖR BESTÄMNING AV  
VÄRMELEDNINGSFÖRMÅGA I BERG  
2001

Signhild Gehlin

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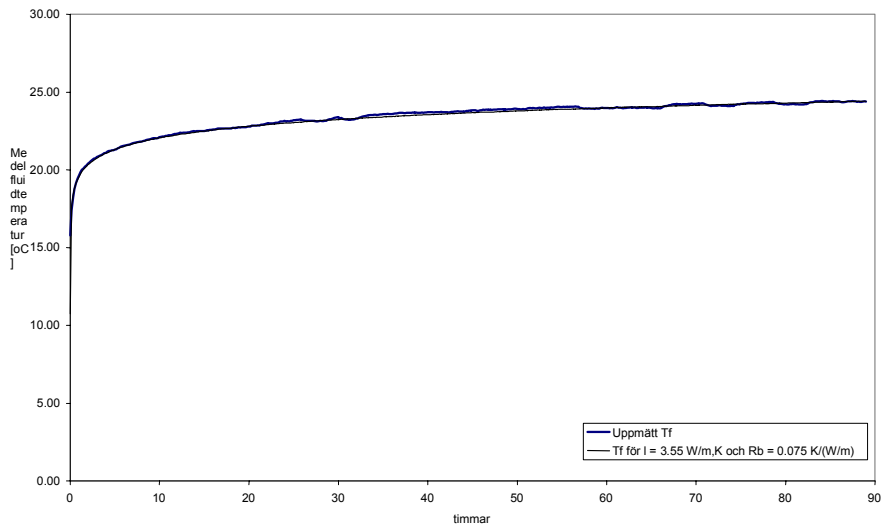
## ENGLISH SUMMARY

A thermal response test was conducted at Äspölaboratoriet, Oskarshamn, between 5–9 September 2001, on a test borehole fitted with a single aluminium U-pipe. The test borehole is drilled underground in granitic rock, approximately 240 m below sea level. The borehole is completely filled with saline groundwater and was sealed at the top. Heat carrier fluid in the aluminium piping was pure water. Undisturbed ground temperature at the time of the test was measured to 14.1°C.

The test equipment was placed next to the borehole and connected to the collector pipes. All piping was insulated before the test started.

| TECHNICAL DATA FOR TEST        |   |
|--------------------------------|---|
| Drilled depth                  | 130 m   |
| Groundwater level              | 0 m from the top of the borehole  |
| Effective borehole depth       | 130 m   |
| Borehole diameter              | d = 96 mm   |
| Heat carrier fluid             | Water   |
| Rock type                      | granitic  |
| Collector type                 | Single U-pip, aluminium<br>D <sub>o</sub> = 33 mm, D <sub>i</sub> = 20 mm |
| Undisturbed ground temperature | T <sub>om</sub> = 14.1°C  |
| Injected heat load             | 6.25 kW (incl. pumping power rate)  |

The thermal response test was conducted during 89 hours, and the effective ground thermal conductivity was estimated to 3.55 W/m,K.

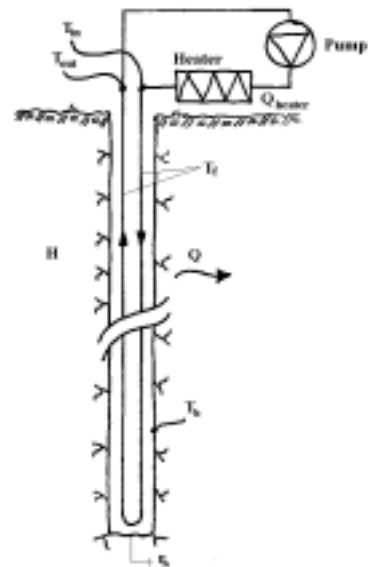


*Temperature response in borehole fitted to calculated thermal response for effective thermal response  $\lambda = 3.55 \text{ W/m,K}$  and borehole thermal resistance  $R_b=0.075 \text{ K/(W/m)}$ .*

### *Description Of Measurement Method And Equipment*

The principle for a thermal response test is a circulation pump, pumping the heat carrier through the closed loop system in the borehole heat exchanger. An inline electric heater injects constant heat, and the fluid temperature is recorded continuously at the inlet and outlet of the borehole during the test. The test proceeds for at least 60 hours.

The test equipment is mounted on a covered insulated trailer and all piping is well insulated. The equipment is run by electric power.



### *Data Analysis*

Measured inlet and outlet temperatures give the borehole temperature response. A line source model described by /Gehlin, 1998/ is used for the analysis of temperature data. Two-variable parameter estimation is used to match measured response data to the best estimate of effective ground thermal conductivity ( $\lambda$ ) and borehole thermal resistance ( $R_b$ ). The effective ground thermal conductivity is proportional to the gradient with which the mean fluid temperature in the borehole heat exchanger,  $T_f$ , changes over time (Eq. 1).



$$\lambda_{\text{eff}} = \frac{Q}{4\pi Hk} \quad (1)$$

$k$  denotes the inclination of the linearized curve,  $Q$  (W) is the injected heat load, and  $H$  is the effective borehole depth. The borehole thermal resistance,  $R_b$ , influences the temperature level of the curve. The theoretical temperature response is calculated with Eq. 2.

$$T_f(t) = \frac{Q}{4\pi\lambda H} \cdot \left( \ln\left(\frac{4at}{r^2}\right) - \gamma \right) + \frac{Q}{H} \cdot R_b + T_o \quad (2)$$

where  $\lambda$  is the effective thermal conductivity,  $a$  is effective diffusivity,  $r$  is borehole radius and  $T_o$  is the undisturbed ground temperature.

### *Comments on the response test at Äspö*

The response test at the Äspö test borehole gave an effective thermal conductivity of 3.55 W/m,K, which is close to average for Swedish bedrock.

Possible sources of error are the estimation of borehole depth, undisturbed ground temperature, and the estimation of injected heat load. An error in borehole depth estimation will not have a large impact on the conductivity estimation, however the heat injection and the undisturbed ground temperature are more sensitive parameters.

Uncertainty in the determination of injected heat load may be of three main kinds; 1) Measurement of injected heat 2) Estimation of heat load caused by the pump work 3) Heat loss to surroundings. Injected heat is estimated as the total electric power input to the measurement equipment, including pump work. It is assumed that all power used for pumping is transformed into friction heat in the collector. Heat losses to the surroundings are in the current case of little significance, since the ambient air temperature kept constant throughout the measurement, and the temperature was very close to the fluid temperature in the pipes.

Thermal response test may be a complement to other SKB measurements to determine thermal properties in rock. The test method was developed for ground heat exchangers, for which the total thermal function of the heat exchanger is of interest, including collector pipes and the influence of the borehole filling. The properties of the pipe system is not of interest for SKB, but only the ground properties. Thermal response test it at present not developed to identify and quantify partial contributions to the heat transfer, such as convective heat transport by groundwater movements.

Thermal response test may be conducted on deep boreholes provided that pipe dimensions and pumping capacity are properly chosen to overcome the pressure drop in the piping.

## SAMMANFATTNING

Responstestet i testborrhålet i Äspölaboratoriet utfördes under 89 timmar, dagarna 5–9 september 2001. Testborrhålet är borrarat i kristallin berggrund, och försett med det ett enkelt U-rör av aluminium. Borrhålet är borrarat vertikalt på nivån 240 m under havsytan. Det är fyllt med salt havsvatten och förseglat i toppen.

Vid mätningen kunde den termiska konduktiviteten i berget bestämmas till 3.55 W/m,K vilket är nära medelvärdet för svensk berggrund.

De viktigaste uppgifterna från responstestet i Äspö sammanfattas i tabellen nedan.

| <b>RESULTAT AV MÄTNINGAR,</b><br>Enkelt U-rör av aluminium |                   |
|--|-------------------|
| Aktivt Borrhålsdjup  | 130 m             |
| Borrhålsdiameter   | 96 mm             |
| Mäteffekt  | 48 W/m            |
| Ostörd marktemp  | 14.1°C            |
| <b>Termisk Konduktivitet</b>                               | <b>3.55 W/m,K</b> |

## BESKRIVNING AV MÄTOBJEKT

Under dagarna 5–9 september 2001 utfördes responstestmätning på ett provborrhål försett med ett enkelt U-rör av aluminium vid Äspölaboratoriet, Oskarshamn.

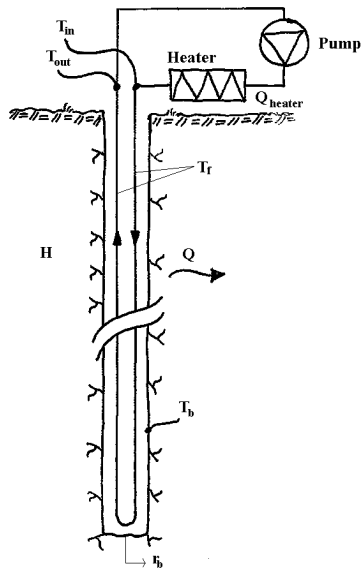
Testhålet är borrarat i granitiskt berg, under marknivå, ca 240 m under havsytan. Borrhålet är följaktligen fyllt från botten till topp med havsvatten, och måste förseglas tätt vid borrhålstoppen. Borrhålet var för testet försett med en testkollektor. För att klara de höga yttre trycken (ca 24 bar vid toppen och ca 37 bar vid botten) användes aluminiumrör med yttermättet 33 mm och tätade skarvar var tredje meter. I botten av borrhålet sammankopplades uppgående och nedgående rör via 2 st anslutningar i en rund metallburk med diameter 90 mm, höjd 70 mm och godstjocklek 5 mm. Värmebäraren i kollektorn var vanligt sötvatten.

Marktemperaturen i berget vid mättillfället uppmättes till ca 14.1°C, vilket stämmer överens med tidigare observationer av bergets temperatur på gällande nivåer.

Mätvagnen placerades direkt intill borrhålet, och kopplades till borrhålets U-rör via mjuka anslutningsslangar med snabbkopplingar. Samtliga rör isolerades med rörisolering inför mätningen.

| TEKNISKA DATA FÖR TEST                   |   |
|--|---|
| Provborrhål med enkelt U-rör i aluminium |   |
| Mätperiod                                | 2001.09.05–2001.09.09                         |
| Borrat djup                              | 130 m   |
| Grundvattennivå                          | 0 m under borrhålets topp*)                   |
| Effektivt borrhålsdjup                   | 130 m   |
| Borrhålsdiameter                         | d = 96 mm                                     |
| Fluid                                    | Vatten  |
| Berggrund                                | granitisk                                     |
| Installationstyp                         | Enkelt U-rör, aluminium                       |
|  | $D_y = 33 \text{ mm}$ , $D_i = 20 \text{ mm}$ |
| Ostörd marktemperatur                    | $T_{om} = 14.1^\circ\text{C}$                 |
| TESTDATA:                                |   |
| Testeffekt                               | 6.25 kW (inkl. pumpeffekt)                    |

\*) Borrhålets topp är beläget ca 240 m under havsnivån.



## MÄTMETOD OCH UTRUSTNING

Principen för en termisk responstest är enkel. En pump cirkulerar fluiden i det slutna rörsystemet i borrhålet. Effekttillförseln sker genom en värmare och temperaturen vid borrhålets in- och utlopp registreras kontinuerligt under hela mätningen. Värmen överförs från fluiden till borrhålsväggen genom ledning och konvektion i borrhålsfyllningen (grundvatten) och sedan vidare genom berggrunden genom ledning. (Se principfigur).

En termisk responstest tar minst 60 timmar att utföra för att få tillräckligt noggranna resultat.

Den utrustning som användes för testet vid Äspö består av en cirkulationspump, en 85 l fluidtank, en 2x4.5 kW elektrisk genomströmningvärmare med de möjliga effekttrogen 3 kW, 6 kW, 11 kW. Fyra stycken PT100 temperaturgivare mäter ingående och utgående temperatur, samt lufttemperaturen innanför och utanför mätvagnens kåpa.

Temperaturer och effekttillförsel registreras kontinuerligt med en datalogger.

Utrustningen är monterad på ett täckt bilsläp av längden 2.6 m och bredden 1.5 m. Vagnens plastkåpa är isolerad med 50 mm styrenplast. Rören inuti vagnen samt de yttre anslutningsslangarna är isolerade med 15 mm Armaflex isolering. Mätvagnen förses med ström genom ett 16 A trefas eluttag.

## MÄTNINGEN

Responstestet bestämmer in situ-värden för effektiv värmeledningsförmåga hos berget, och termiskt motstånd i borrhålskollektorn. Med effektiv värmeledningsförmåga menas bergets förmåga att föra bort en effektpuls, inkluderat effekten av eventuellt grundvattenflöde och konvektiva effekter.

Det termiska motståndet är ett mått på det temperaturfall mellan värmebärare och berggrund som orsakas av förluster i själva borrhålsinstallationen. Förlusterna påverkas bl a av rörmaterial, fyllnadsmaterial, avstånd mellan rör och mellan rör/borrhålsvägg,

strömningsförhållanden i och utanför rören etc. Ju mindre det termiska motståndet är, desto lägre temperaturskillnad behövs mellan berget och värmebäraren för att värmeväxla samma effekt. Termiskt motstånd är av underordnad betydelse för SKB:s studier.

Mätningarna på borrhålet vid Äspölaboratoriet utfördes under 89 timmar varvid värmebäraren läts cirkulera i u-röret under det att en konstant känd värmeeffekt (6.25 kW) tillfördes borrhålet via en genomströmningvärmare i mätvagnen. Fluidens till- och frånloppstemperaturer registrerades med tio minuters intervall och lagrades i en datalogger. Den tillförda värmande effekten, inklusive friktionsvärme från pumpen, registrerades kontinuerligt under mätningen. Även omgivande lufttemperatur samt temperatur inuti mätvagnen uppmättes och registrerades kontinuerligt. Pumpflödet var ca 0.4 l/s under mätningen.

## BERÄKNINGAR OCH MÄTRESULTAT

De uppmätta in- och utloppstemperaturerna visar temperaturutvecklingen i borrhålet. I den aktuella utvärderingen har en linjekällemodell, beskriven i /Gehlin, 1998/, använts för utvärderingen, och den uppmätta temperaturresponser jämförts med bästa passning för  $\lambda$  och  $R_b$ . Kollektorns effektiva värmeledningstal,  $\lambda_{eff}$ , är proportionellt mot den gradient med vilken fluidens medeltemperatur,  $T_f$ , ändras med tiden, enligt ekvation 1.

$$\lambda_{eff} = \frac{Q}{4\pi Hk} \quad (3)$$

där  $k$  betecknar den lineariserade kurvans lutning,  $Q$  (W) är den tillförda effekten, och  $H$  är det effektiva borrhåldjupet. Kollektorns termiska motstånd  $R_b$ , påverkar temperaturkurvans nivå.

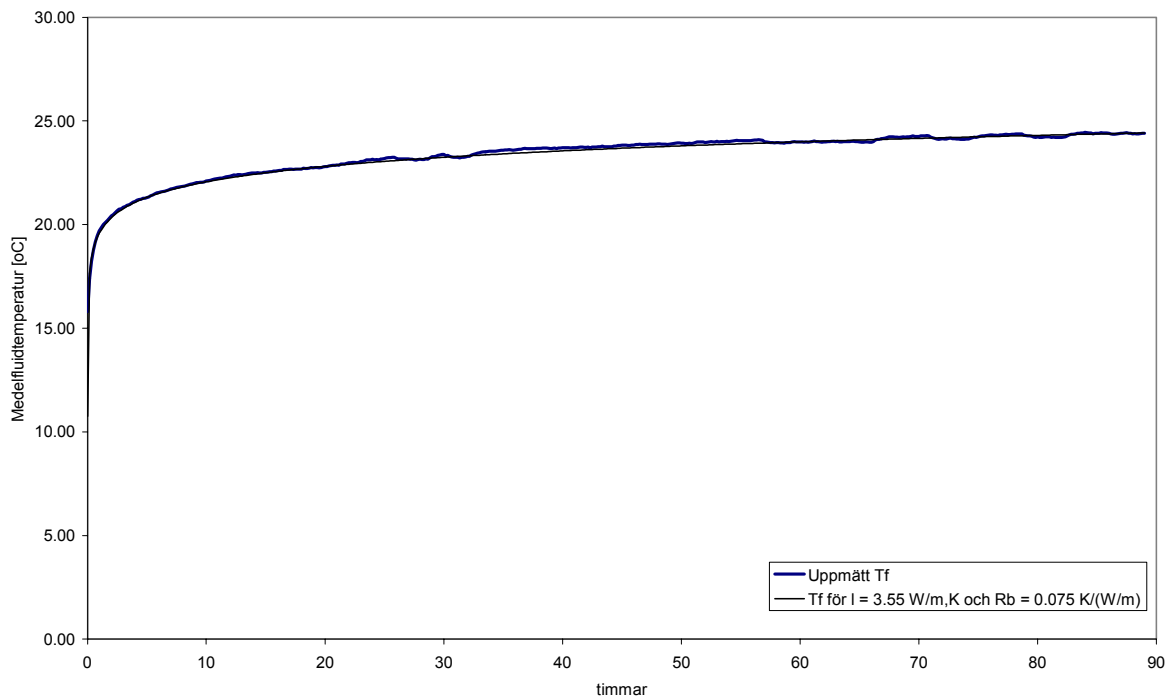
Den teoretiska temperaturresponser har beräknats enligt ekvation 2.

$$T_f(t) = \frac{Q}{4\pi\lambda H} \cdot \left( \ln\left(\frac{4at}{r^2}\right) - \gamma \right) + \frac{Q}{H} \cdot R_b + T_o \quad (4)$$

där  $Q$  (W) är den tillförda effekten, och  $H$  är det effektiva borrhåldjupet,  $\lambda$  är den effektiva värmeledningsförmågan,  $a$  är effektiv diffusivitet,  $r$  är borrhålsradien,  $R_b$  är aktuellt termiskt motstånd för kollektorn och  $T_o$  är bergets ostörda temperatur.

För testborrhålet erhöles bästa kurvanspassning för värdena enligt nedan:

|  |
|--|
| $\lambda_{eff} = 3.55 \text{ W/m, K}$<br>$R_b = 0.075 \text{ K/(W/m)}$ |
|--|



## DISKUSSION

Resultatet från responstestet på provborrhålet i Äspö ger att bergets effektiva värmeledningsförmåga är ca 3.55 W/m,K vilket är nära medelvärdet för svensk berggrund, och vanligt för granitiskt berg. Mätkurvan indikerar att det mesta av värmetransporten sker genom konduktion, och att bidraget från grundvattenrörelser är ringa.

Möjliga felkällor för mätningen består i huvudsak i bestämning av borrhålsdjup, ostörd marktemperatur, samt uppskattningen av till borrhålet tillförd värmeeffekt. Ett fel i borrhålsdjupet på 2 % motsvarar ca 4 % ändring av den effektiva värmeledningsförmågan. Ostörd temperatur i borrhålet har enligt uppgift från Thomas Jansson, Golder Associates AB, uppmätts vid ett flertal tillfällen, och befunnits vara konstant 14.1 °C. Ett fel på 0.5 °C i bestämningen av ostörd marktemperatur påverkar resultatet ca 12 %. Temperaturen är en känslig parameter.

Osäkerheter i bestämningen av effekttillförsel härrör från tre huvudsakliga källor. 1) Mätning av tillförd effekt 2) uppskattning av andel pumpeffekt som bidrar till uppvärmning 3) Förluster till omgivningen. Tillförd effekt bestäms som totala eleffekttillförseln till mätvagnen inklusive drift av pumpen, och beräknas genom bestämning av ingående ström och spänning. I bestämningen antas att all effekt som behövs för drift av cirkulationspumpen omvandlas till friktionsvärme i kollektorn. Pumpens effekt är ca 1.2 kW. Värmeförluster till omgivningen har i det aktuella fallet med en jämn omgivningstemperatur nära fluidtemperaturen, och isolerade slangar och vagnskåpa, uppskattats till totalt ca 10 W, vilket är ca 0.15 % av total tillförd effekt, och har ringa inverkan på resultatet. Effektbestämningens inverkan på testresultatet uppgår till ca 5 % av effektiv värmeledning på 2.5 % ändring av effekten.

Termisk responstest kan fungera som ett komplement till SKB:s övriga mätningar för att bestämma termiska egenskaper i berg. Termisk responstest är en testmetod som i huvudsak är utvecklad för energibrunnar. För energibrunnar är det intressant att göra en bestämning av totalfunktionen hos borrhålet, inklusive kollektorslangarnas och borrhålsfyllningens egen inverkan på den värmeöverförande effektiviteten. I SKB:s fall är egenskaperna hos slangsystemet i borrhålet inte av intresse, utan endast bergets egenskaper. Med termisk responstest är det i dagsläget inte möjligt att identifiera och kvantifiera delbidrag till värmeöverföringen, t ex värmetransport genom grundvattenrörelser.

För SKB:s del skulle det kunna vara av intresse att bestämma de termiska egenskaperna hos olika sektioner av borrhålsprofilen. Någon sådan mätning och utvärdering har hittills inte termisk responstest nyttjats för. Det finns dock en möjlighet att göra upprepade responstest i samma borrhål men med olika slanglängd nedförd i borrhålet. Förutsatt att borrhålet fått vila och komma i termisk jämvikt mellan varje delmätning, kan man därigenom identifiera skillnader mellan de termiska egenskaperna hos olika sektioner av borrhålet.

Termisk responstest går att utföra på djupa borrhål, förutsatt att slangdimensioner och pumpkapacitet är rätt avvägda för att klara av tryckfallet i slangarna.

Termisk responstest i horisontella hål är ur mätapparatus synpunkt möjligt, förutsatt att borrhålet är beläget nedanför mätvagnen, så att brine-nivån i mätvagnens vattentank är högsta punkt. I annat fall får man bekymmer med avluftning i den slutna slingan (med den utrustning som användes i aktuell test). En annan förutsättning är att det är god termisk kontakt mellan borrhålsslangar och borrhålsvägg, vilket betyder att borrhålet måste vara fyllt med något kontaktmaterial. Grundvattenfyllda borrhål kan inte användas för test på horisontella borrhål på grund av termisk skiktning i borrhålsvattnet. Däremot kan borrhålet fyllas med t ex bentonit sedan slangarna är insatta. Ett problem kan även vara att få slangarna att vara symmetriskt placerade i det horisontella borrhålet. Det finns centreringsclips att tillgå för att hålla kollektorslangarna på jämnt avstånd från varandra. Helst ska slangarna vara placerade på borrhålets diameterlinje och ligga an mot borrhålsväggen.

## REFERENSER

Gehlin S (1998). *Thermal Response Test – In-situ measurements of thermal properties in hard rock*. Licentiatavhandling 1998:37. Luleå tekniska Universitet.

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## Bilaga: Rådata

(här sammanställda i timvärden. Mätningen gjordes med 10 minuter intervall)

| Timmar | Tut   | Tin   | Tf    | Tluft |
|--------|-------|-------|-------|-------|
| 0      | 14.88 | 16.71 | 15.79 | 14.94 |
| 1      | 17.56 | 21.83 | 19.69 | 14.88 |
| 2      | 18.29 | 22.54 | 20.42 | 14.87 |
| 3      | 18.70 | 22.96 | 20.83 | 14.87 |
| 4      | 18.99 | 23.25 | 21.12 | 14.84 |
| 5      | 19.19 | 23.43 | 21.31 | 14.81 |
| 6      | 19.42 | 23.69 | 21.56 | 14.80 |
| 7      | 19.59 | 23.83 | 21.71 | 14.80 |
| 8      | 19.73 | 23.94 | 21.84 | 14.79 |
| 9      | 19.87 | 24.13 | 22.00 | 14.79 |
| 10     | 19.97 | 24.23 | 22.10 | 14.81 |
| 11     | 20.10 | 24.35 | 22.23 | 14.93 |
| 12     | 20.20 | 24.48 | 22.34 | 15.08 |
| 13     | 20.28 | 24.51 | 22.40 | 15.15 |
| 14     | 20.36 | 24.60 | 22.48 | 15.16 |
| 15     | 20.41 | 24.63 | 22.52 | 15.16 |
| 16     | 20.48 | 24.70 | 22.59 | 15.17 |
| 17     | 20.55 | 24.80 | 22.67 | 15.15 |
| 18     | 20.58 | 24.78 | 22.68 | 15.16 |
| 19     | 20.64 | 24.82 | 22.73 | 15.02 |
| 20     | 20.68 | 24.91 | 22.79 | 14.93 |
| 21     | 20.77 | 24.99 | 22.88 | 14.82 |
| 22     | 20.85 | 25.11 | 22.98 | 14.85 |
| 23     | 20.90 | 25.18 | 23.04 | 14.90 |
| 24     | 20.99 | 25.29 | 23.14 | 14.82 |
| 25     | 21.03 | 25.34 | 23.19 | 14.81 |
| 26     | 21.10 | 25.30 | 23.20 | 15.16 |
| 27     | 21.06 | 25.26 | 23.16 | 15.58 |
| 28     | 21.05 | 25.24 | 23.15 | 15.62 |
| 29     | 21.13 | 25.41 | 23.27 | 15.61 |
| 30     | 21.24 | 25.52 | 23.38 | 15.61 |
| 31     | 21.16 | 25.32 | 23.24 | 15.62 |
| 32     | 21.19 | 25.39 | 23.29 | 15.61 |
| 33     | 21.31 | 25.60 | 23.46 | 15.54 |
| 34     | 21.39 | 25.69 | 23.54 | 15.28 |
| 35     | 21.42 | 25.76 | 23.59 | 15.36 |
| 36     | 21.45 | 25.75 | 23.60 | 15.64 |
| 37     | 21.50 | 25.83 | 23.66 | 15.61 |
| 38     | 21.52 | 25.82 | 23.67 | 15.62 |
| 39     | 21.54 | 25.79 | 23.67 | 15.64 |
| 40     | 21.56 | 25.85 | 23.70 | 15.54 |
| 41     | 21.58 | 25.85 | 23.71 | 15.41 |
| 42     | 21.59 | 25.85 | 23.72 | 15.35 |
| 43     | 21.61 | 25.90 | 23.75 | 15.48 |
| 44     | 21.63 | 25.87 | 23.75 | 15.62 |
| 45     | 21.69 | 25.97 | 23.83 | 15.65 |

| Timmar | Tut   | Tin   | Tf    | Tluft |
|--------|-------|-------|-------|-------|
| 46     | 21.70 | 25.97 | 23.83 | 15.59 |
| 47     | 21.73 | 25.99 | 23.86 | 15.63 |
| 48     | 21.74 | 26.05 | 23.90 | 15.65 |
| 49     | 21.74 | 26.02 | 23.88 | 15.65 |
| 50     | 21.79 | 26.06 | 23.92 | 15.66 |
| 51     | 21.79 | 26.06 | 23.93 | 15.64 |
| 52     | 21.84 | 26.09 | 23.96 | 15.66 |
| 53     | 21.86 | 26.17 | 24.02 | 15.65 |
| 54     | 21.86 | 26.15 | 24.01 | 15.67 |
| 55     | 21.91 | 26.19 | 24.05 | 15.50 |
| 56     | 21.91 | 26.22 | 24.06 | 15.63 |
| 57     | 21.92 | 26.06 | 23.99 | 15.63 |
| 58     | 21.86 | 26.06 | 23.96 | 15.60 |
| 59     | 21.86 | 26.04 | 23.95 | 15.63 |
| 60     | 21.89 | 26.09 | 23.99 | 15.60 |
| 61     | 21.89 | 26.10 | 24.00 | 15.55 |
| 62     | 21.88 | 26.07 | 23.98 | 15.64 |
| 63     | 21.92 | 26.10 | 24.01 | 15.60 |
| 64     | 21.91 | 26.10 | 24.01 | 15.61 |
| 65     | 21.91 | 26.04 | 23.98 | 15.63 |
| 66     | 21.90 | 26.04 | 23.97 | 15.65 |
| 67     | 22.02 | 26.30 | 24.16 | 15.60 |
| 68     | 22.08 | 26.35 | 24.22 | 15.63 |
| 69     | 22.08 | 26.37 | 24.23 | 15.65 |
| 70     | 22.11 | 26.37 | 24.24 | 15.63 |
| 71     | 22.12 | 26.31 | 24.21 | 15.59 |
| 72     | 22.05 | 26.24 | 24.14 | 15.60 |
| 73     | 22.06 | 26.22 | 24.14 | 15.65 |
| 74     | 22.04 | 26.20 | 24.12 | 15.64 |
| 75     | 22.11 | 26.36 | 24.23 | 15.62 |
| 76     | 22.19 | 26.46 | 24.32 | 15.50 |
| 77     | 22.20 | 26.44 | 24.32 | 15.49 |
| 78     | 22.23 | 26.47 | 24.35 | 15.42 |
| 79     | 22.21 | 26.38 | 24.29 | 15.46 |
| 80     | 22.14 | 26.31 | 24.22 | 15.36 |
| 81     | 22.15 | 26.32 | 24.23 | 15.44 |
| 82     | 22.13 | 26.29 | 24.21 | 15.30 |
| 83     | 22.23 | 26.48 | 24.35 | 15.44 |
| 84     | 22.30 | 26.58 | 24.44 | 15.31 |
| 85     | 22.28 | 26.53 | 24.41 | 15.31 |
| 86     | 22.27 | 26.51 | 24.39 | 14.99 |
| 87     | 22.26 | 26.53 | 24.40 | 15.21 |
| 88     | 22.28 | 26.46 | 24.37 | 15.31 |
| 89     | 22.29 | 26.50 | 24.40 | 15.22 |