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Oskarshamn site investigation

Borehole KLX11A

Thermal properties of rocks using calorimeter and TPS method

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December 2006

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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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Abstract

Thermal properties on twelve specimens of drill hole KLX11A, Oskarshamn, Sweden, were measured at ambient temperature (20°C). The samples were taken from the rock type quartz monzodiorite (501036), at the borehole length 320–775 m. The determination of the thermal properties is based on a direct measurement method, the so called “Transient Plane Source Method” (TPS). The specific heat capacity of the samples was also measured by a calorimeter.

Thermal conductivity and thermal diffusivity at 20°C were in the range of 2.54–2.91 W/(m, K) respectively 1.14–1.34 mm²/s. The volumetric heat capacity, which was calculated from the thermal conductivity and diffusivity, ranged between 2.08 and 2.28 MJ/(m³, K).

The specific heat capacity that was measured by the calorimetric method was in the range of 0.78–0.84 [J/g, K].

Sammanfattning

Termiska egenskaper hos tolv provkroppar från borrhål KLX11A, Oskarshamn, bestämdes vid rumstemperatur (20 °C). Proverna hade tagits från bergarterna kvartsmonzodiorit (501036), vid borrhålslängderna 320–775 m. TPS metoden, ”Transient Plane Source”, användes för bestämning av de termiska egenskaperna. Specifika värmekapaciteten bestämdes även med en kalorimeter.

Den termiska konduktiviteten och den termiska diffusiviteten hos provkropparna vid 20 °C uppgick till 2,54–2,91 W/(m, K) respektive 1,14–1,34 mm²/s. Från värdena på dessa parametrar kunde den volymetriska värmekapaciteten beräknas och befanns ligga i intervallet 2,08 and 2,28 MJ/(m³, K).

Den specifika värmekapaciteten, bestämd med kalorimeter, uppgick till 0,78–0,84 [J/g, K].

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1 Introduction

SKB is planning to build a final repository for nuclear waste in bedrock, which demands knowledge about thermal properties of the rock. Oskarshamn, Sweden, is one of the areas selected for site investigations. The activity presented in this report is part of the site investigation program at Oskarshamn /1/.

Borehole KLX11A is a conventionally drilled cored borehole with a length of approximately 1,000 m. The borehole is inclined by 76° against horizontal plane and strikes 89° , see Figure 1-1. This report presents investigations of thermal properties of rock samples from borehole KLX11A at Oskarshamn. The thermal properties thermal conductivity and thermal diffusivity have been determined by using the Transient Plane Source Method (TPS), Gustafsson, 1991 /2/. The method determines thermal conductivity and diffusivity of a material. The volumetric heat capacity can be calculated if the density is known. The dry and wet densities, as well as porosity of the samples, were determined within the scope of a parallel activity /3/. In addition, the specific heat capacity of the samples was measured by a calorimetric method /4/.



Figure 1-1. Location of all telescopic and conventionally drilled boreholes completed up to November 2006.

Rock samples were selected at Oskarshamn based on the preliminary core logging with the strategy to investigate the properties of the dominant rock types. The rock type was quartz monzodiorite.

The specimens to be tested were cut from the rock samples in the shape of circular discs. The rock samples arrived at SP in May 2006. The thermal properties were determined on water-saturated specimens. Testing was performed during August 2006.

The controlling documents for the activity are listed in Table 1-1. Activity Plan and Method Descriptions are SKB's (The Swedish Nuclear Fuel and waste Management Company) internal controlling documents, whereas the Quality Plan (SP-QD 13.1) referred to in the table is an SP (Swedish National Testing and Research Institute) internal controlling document.

Table 1-1. Controlling documents for performance of the activity.

Activity plan	Number	Version
KLX11A. Bergmekaniska och termiska laboratoriebestämningar	AP PS 400-06-062	1.0
Method description	Number	Version
Determining thermal conductivity and thermal capacity by the TPS method	SKB MD 191.001	2.0
Quality plan		
SP-QD 13.1		

2 Objective and scope

The purpose of this activity is to determine the thermal properties of rock specimens. The obtained thermal properties will be used as input data for mechanical and thermal analysis in a site descriptive model that will be established for the candidate area selected for site investigation at Oskarshamn. The test programme included testing of twelve rock specimens.

3 Equipment

3.1 Transient Plane Source

Technical devices for determination of the thermal properties in question were:

- Kapton sensor 5501, with a radius of 6.403 mm, and a power output of 0.7 W. The sensor 5501 fulfils the recommended relation between sensor radius and sample geometry of the samples in /5/.
- TPS-apparatus, Source meter Keithley 2400, Multi-meter Keithley 2000 and bridge, see Figure 3-1.
- PC + Microsoft Office and Hot Disk version 5.4.
- Stainless Sample holder.

Function control of TPS instrumentation was performed according to BRk-QB-M26-02 (SP quality document), see Appendix A.

The experimental set-up is shown in Figure 3-2.

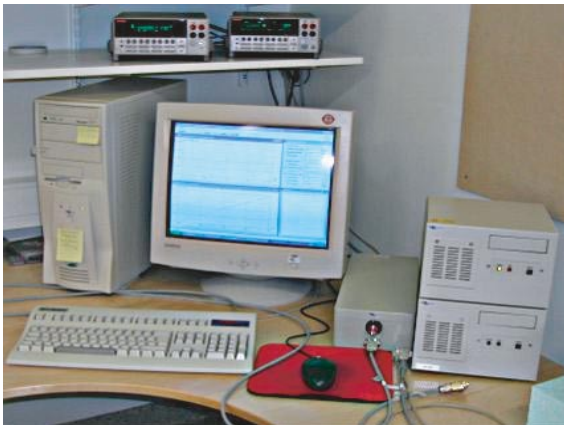


Figure 3-1. TPS-apparatus with source meter, multi-meter, bridge, and computer.



Figure 3-2. Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).

3.2 Calorimetric method

The measurement equipment used for the calorimetric determination of the specific heat capacity is shown in Figure 3-3 and consisted of:

- Calorimeter, made of Macrolon with low heat capacity and very low heat conductivity.
- Magnetic stirrer, IKA type BigSquid.
- Temperature logger, Keithley 2000 multimeter with scanner Keithley 7700 (temperature resolution 0.01 mK, accuracy 5 mK).
- Temperature controlled bath, Heto Thermostat 13 DT-1 (resolution 0.1°C).
- Three temperature sensors, Pt-100 Pentronic (2 for calorimeter, 1 for temperature controlled bath).
- Thermometer for Air, Pentronic CRL 206, s/n 270210 (resolution 0.01°C).
- Balance Mettler PM 2000 (resolution 0.01 g, accuracy 0.02 g).
- Air conditioning equipment, μ AC Carel, Essén Company.
- Laptop computer Toshiba programmed on Visual Basic 6 for the temperature monitoring of three channels per three seconds.
- Pure and de-aerated water, crushed ice for fast preparation of a “steady state” condition.
- Various accessories (stand, holder, clamps, hoses, dewar, syringe, timer, etc).

All measurement instruments are traceable via in-house calibration to national and international standards. The three temperature sensors connected to respective logger channel were calibrated immediately before the measurements. The balance was several times checked using relevant weight pieces.

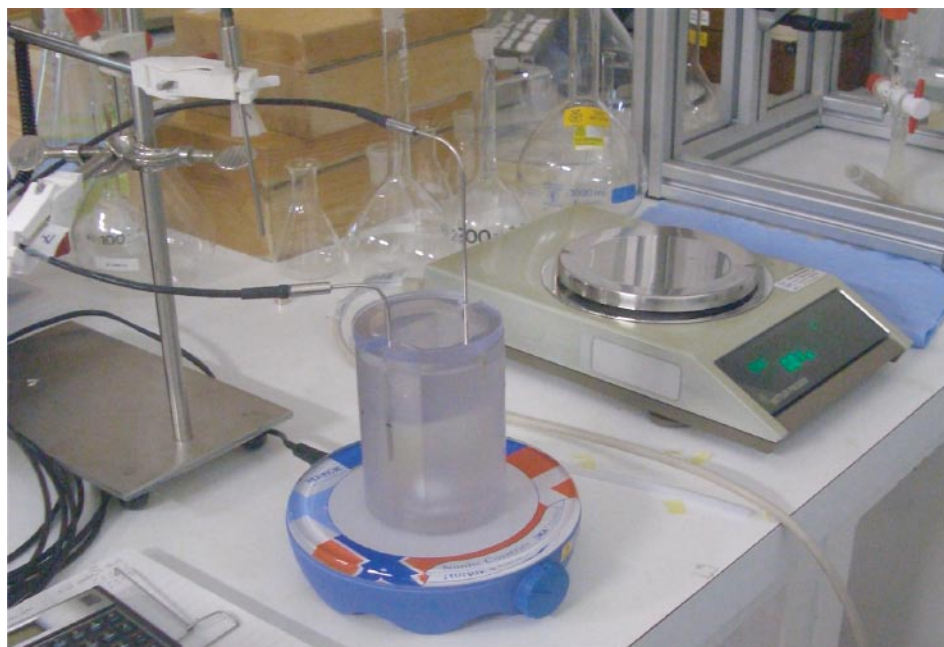


Figure 3-3. Calorimeter with two temperature sensors on magnetic stirrer.

4 Execution

Specific heat capacity was determined according to /4/ at SP Measurement Technology. The procedure of temperature measurement in conjunction with the determination of specific heat was modified in this project. The modification is explained in 4.3.

Determination of thermal properties conductivity and diffusivity was made in compliance with SKB's method description SKB MD 191.001 (SKB internal controlling document) and Hot Disc Instruction Manual /5/ at SP Fire Technology.

The density determinations, which were performed in a parallel activity at SP /3/, were carried out in accordance with SKB MD 160.002 (SKB internal controlling document) and ISRM /6/ at SP Building Technology and Mechanics.

Peter Lau at SP Measurement Technology conducted the specific heat capacity measurements, whereas Patrik Nilsson and Ingrid Wetterlund at SP Fire Technology conducted the thermal property measurements and preparation of the report.

4.1 Description of the samples

Twelve pairs of cores (designated A and B) were sampled from borehole KLX11A, Oskarshamn, Sweden. The cores were collected within the borehole length interval 320–775 m. The twenty-four specimens with a thickness of 25 mm each (see Figure 3-2) were cut from the rock samples at SP. The diameter of the specimens was about 50 mm. The identification marks, rock type and sampling levels of the specimens are presented in Table 4-1. Detailed geological description of the entire core of KLX11A is given in SKB's database SICADA (Boremap data).

Table 4-1. Rock type and identification marks (Rock-type classification according to Boremap). Sampling level refers to borehole length.

Identification	Rock type/occurrence	Sampling level (Sec low)
KLX11A-90V-01	Quartz monzodiorite (501036)	319.32
KLX11A-90V-02	Quartz monzodiorite (501036)	356.33
KLX11A-90V-03	Quartz monzodiorite (501036)	400.62
KLX11A-90V-04	Quartz monzodiorite (501036)	440.44
KLX11A-90V-05	Quartz monzodiorite (501036)	457.50
KLX11A-90V-06	Quartz monzodiorite (501036)	482.19
KLX11A-90V-07	Quartz monzodiorite (501036)	522.34
KLX11A-90V-08	Quartz monzodiorite (501036)	553.33
KLX11A-90V-09	Quartz monzodiorite (501036)	613.01
KLX11A-90V-10	Quartz monzodiorite (501036)	638.45
KLX11A-90V-11	Quartz monzodiorite (501036)	720.87
KLX11A-90V-12	Quartz monzodiorite (501036)	774.10

4.2 Test procedure

The present activity was performed parallel to other activities, conducted by SP Building Technology and Mechanics, by which the wet and dry density as well as the porosity of the specimens were determined /3/ and SP Measurement Technology, by which specific heat capacity was determined /4/.

The following logistic sequence was applied for the activities:

1. Specimens were cut and polished by SP Building Technology and Mechanics.
2. Specimens were photographed by SP Building Technology and Mechanics.
3. Specimens were water saturated and wet density was determined by SP Building Technology and Mechanics /3/.
4. Specimens were sent from SP Building Technology and Mechanics to SP Measurement Technology.
5. Specific heat was determined by SP Measurement Technology /4/.
6. Specimens were sent from SP Measurement Technology to SP Fire Technology.
7. Thermal properties were determined by SP Fire Technology.
8. Specimens were sent from SP Fire Technology to SP Building Technology and Mechanics.
9. Dry density of the specimens was determined at SP Building Technology and Mechanics.

The rock samples were water saturated and stored under this condition for 7 days. This yielded complete water saturation, whereupon the density and the thermal properties were determined. The specimens were photographed before testing.

Determinations of the thermal properties as well as density and porosity measurements were performed during August 2006.

The dry weight was measured after the specimens had been dried to constant mass according to ISMR /6/ at 105°C. The drying procedure took seven days.

4.2.1 Principle of the calorimetric method

The calorimetric technique involves heating the samples after mass determination to a well defined temperature. The samples are placed in a temperature controlled water bath long enough to stabilize.

The calorimeter is filled with prepared water (pure and de-aerated of 17°C) to a predefined level and stirred to produce nearly steady state conditions. Thereafter it is placed on the balance and excessive water is extracted with a syringe to reach a nominal mass, chosen with respect to the sample volume.

The so prepared calorimeter is stirred and the temperature logging program is started. After 90 to 150 seconds the sample is quickly moved (3 to 5 seconds) from the bath into the calorimeter. The temperature rise of water can be followed graphically during the equalization process, which typically takes 150 seconds and the experiment is terminated after another 300 to 600 seconds.

The calorimeter, water and sample are weighed again to determine the amount of water that unavoidably did follow with the sample into the calorimeter. This amount is typically 0.28 to 0.36% of the water contained in the calorimeter. If accidentally a water splash happens during the sample insertion, those droplets are absorbed with a small piece of prepared tissue that is weighed dry and wet. The corresponding mass is subtracted from the initial water mass. In extreme cases it has amounted to 0.03% of the total water mass.

All mass values for the determination of the specific heat were manually documented in a prepared form that was a printout of the corresponding Excel calculation sheet.

With the termination of the logging program each experiment was saved as raw data in an Excel file on the SP network. The main information was the bath temperature and two calorimeter temperatures as function of time.

4.2.2 Principle of Transient Plane Source

The principle of the TPS-method is to install a sensor consisting of a thin metal double spiral, embedded in an insulation material, between two rock samples. During the measurement the sensor works both as a heat emitter and a heat receptor. The input data and results of the direct measurement are registered and analysed by the same software and electronics that govern the measurement. The method gives information on the thermal conductivity and diffusivity of a material.

The thermal properties of the water-saturated specimens were measured in ambient air (20°C). In order to remain water saturation and obtain desired temperature, the specimens and the sensor were kept in a plastic bag during the measurements, see Figure 3-2.

Each pair of specimens (A and B) was measured five times. The time lag between two repeated measurements was at least 20 minutes. The result of each measurement was evaluated separately. The average value of these five measurements was calculated.

Measured raw data were saved as text files and analysed data as Excel files. These files were stored on the hard disc of the measurement computer and sent to the SKB catalogue at the SP network. Further calculations of mean values and standard deviations were performed in the same catalogue.

4.3 Nonconformities

Thermal conductivity and thermal diffusivity were measured and there were no deviations to the plan.

However, the measurement of specific heat according to the suggested procedure in /4/ was modified as follows:

- The sample temperature was measured inside a drilled hole in a dummy specimen that was positioned between specimens in the prepared bath.
- Despite a relative low temperature rise ($\approx 2^\circ\text{C}$) and low thermal conductivity and heat capacity of Macrolon, the calorimeter is not passive in the heat exchange process. Furthermore the stirrer, which is very important for supporting the temperature equalization, generates both thermal and mechanical energy that overlays the measured heat transfer process in the calorimeter. Therefore the time and the temperature dependent influences were studied in separate experiments simulating all conditions except the existence of the sample. From these a suitable correction technique was worked out and applied to each measurement record in order to compensate for the overlaid effects.

5 Results

The results of the activity are stored in SKB's database SICADA, where they are traceable by the Activity Plan number.

Mean values of measured data, five repeated measurements, are reported in 5.1 and in the SICADA database at SKB. Values of each separate measurement as described in section 5.1 are reported in Appendix B. Furthermore, the total measuring time, the ratio between total measuring time and characteristic time, and the number of analysed points are presented in Appendix C. In a correct measurement the ratio between the total measuring time and the characteristic time should be between 0.4 and 1.

5.1 Test results of individual specimens

Specimens KLX11A-90V-01A and B



Figure 5-1. Specimens KLX11A-90V-01A and B.

Table 5-1. Porosity, wet and dry density of specimens KLX11A-90V-01A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-01	2,770	2,770	0.3
Sec low: 319.32			

Table 5-2. Thermal properties of specimens KLX11A-90V-01A and B at ambient temperature, average values.

Sample KLX11A-90V-01 Sec low: 319.32	TPS method Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]	Calorimeter Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
Mean value	2.64	1.22	2.16	2.20	0.793
Standard deviation	0.003	0.007	0.015	–	–

Specimens KLX11A-90V-02A and B



Figure 5-2. Specimens KLX11A-90V-02A and B.

Table 5-3. Porosity, wet and dry density of specimens KLX11A-90V-02A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-02 Sec low: 356.33	2,740	2,740	0.4

Table 5-4. Thermal properties of specimens KLX11A-90V-02A and B at ambient temperature, average values.

Sample KLX11A-90V-02 Sec low: 356.33	TPS method Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]	Calorimeter Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
Mean value	2.79	1.34	2.08	2.20	0.802
Standard deviation	0.004	0.003	0.003	–	–

Specimens KLX11A-90V-03A and B



Figure 5-3. Specimens KLX11A-90V-03A and B.

Table 5-5. Porosity, wet and dry density of specimens KLX11A-90V-03A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-03	2,780	2,770	0.3
Sec low: 400.62			

Table 5-6. Thermal properties of specimens KLX11A-90V-03A and B at ambient temperature, average values.

Sample	TPS method Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]	Calorimeter Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
KLX11A-90V-03					
Sec low: 400.62					
Mean value	2.77	1.22	2.27	2.25	0.809
Standard deviation	0.002	0.004	0.007	–	–

Specimens KLX11A-90V-04A and B

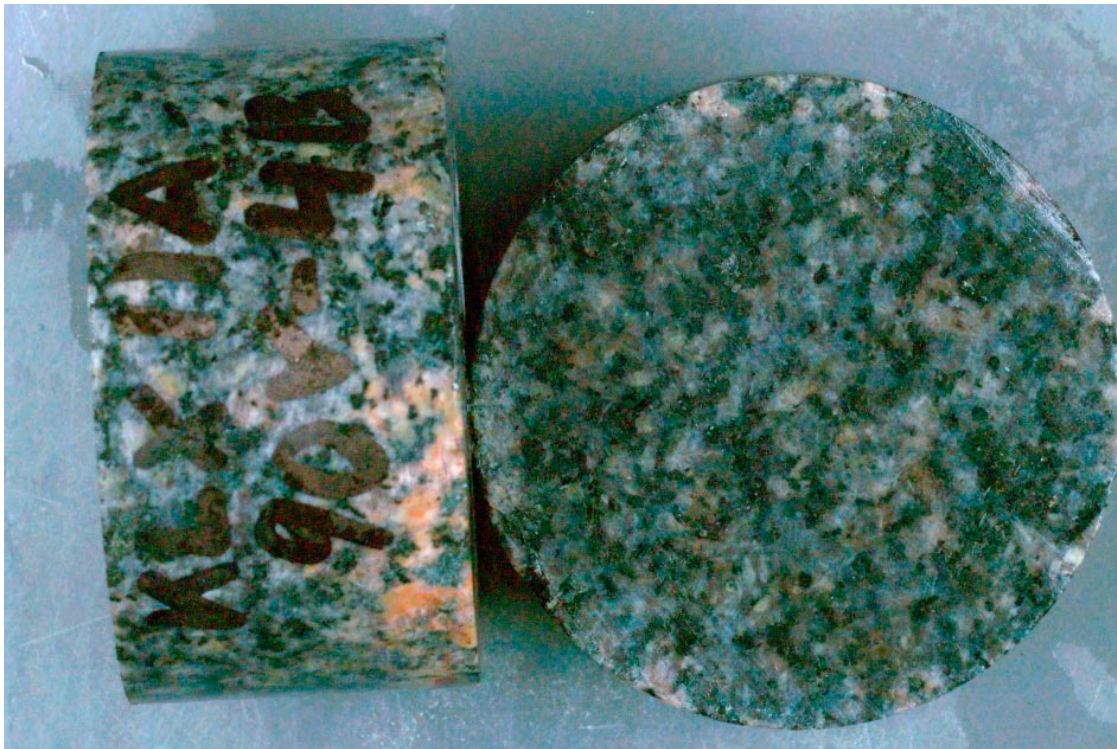


Figure 5-4. Specimens KLX11A-90V-04A and B.

Table 5-7. Porosity, wet and dry density of specimens KLX11A-90V-04A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-04	2,770	2,770	0.4
Sec low: 440.44			

Table 5-8. Thermal properties of specimens KLX11A-90V-04A and B at ambient temperature, average values.

Sample	TPS method			Calorimeter	
KLX11A-90V-04	Conductivity	Diffusivity	Volumetric heat capacity	Volumetric heat capacity	Specific heat capacity
Sec low: 440.44	[W/(m, K)]	[mm ² /s]	[MJ/(m ³ , K)]	[MJ/(m ³ , K)]	[J/(g, K)]
Mean value	2.68	1.19	2.25	2.34	0.844
Standard deviation	0.003	0.003	0.007	–	–

Specimens KLX11A-90V-05A and B



Figure 5-5. Specimens KLX11A-90V-05A and B.

Table 5-9. Porosity, wet and dry density of specimens KLX11A-90V-05A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-05	2,770	2,770	0.3
Sec low: 457.50			

Table 5-10. Thermal properties of specimens KLX11A-90V-05A and B at ambient temperature, average values.

Sample	TPS method			Calorimeter	
KLX11A-90V-05	Conductivity	Diffusivity	Volumetric heat	Volumetric heat	Specific heat
Sec low: 457.50	[W/(m, K)]	[mm ² /s]	capacity [MJ/(m ³ , K)]	capacity [MJ/(m ³ , K)]	capacity [J/(g, K)]
Mean value	2.58	1.17	2.20	2.26	0.814
Standard deviation	0.008	0.007	0.019	–	–

Specimens KLX11A-90V-06A and B



Figure 5-6. Specimens KLX11A-90V-06A and B.

Table 5-11. Porosity, wet and dry density of specimens KLX11A-90V-06A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-06 Sec low: 482.19	2,770	2,760	0.4

Table 5-12. Thermal properties of specimens KLX11A-90V-06A and B at ambient temperature, average values.

Sample KLX11A-90V-06 Sec low: 482.19	TPS method Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]	Calorimeter Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
Mean value	2.80	1.23	2.28	2.25	0.812
Standard deviation	0.002	0.002	0.005	–	–

Specimens KLX11A-90V-07A and B



Figure 5-7. Specimens KLX11A-90V-07A and B.

Table 5-13. Porosity, wet and dry density of specimens KLX11A-90V-07A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-07	2,790	2,780	0.3
Sec low: 522.34			

Table 5-14. Thermal properties of specimens KLX11A-90V-07A and B at ambient temperature, average values.

Sample	TPS method			Calorimeter	
KLX11A-90V-07	Conductivity	Diffusivity	Volumetric heat	Volumetric heat	Specific heat
Sec low: 522.34	[W/(m, K)]	[mm ² /s]	capacity [MJ/(m ³ , K)]	capacity [MJ/(m ³ , K)]	capacity [J/(g, K)]
Mean value	2.70	1.24	2.18	2.27	0.813
Standard deviation	0.002	0.001	0.001	–	–

Specimens KLX11A-90V-8A and B

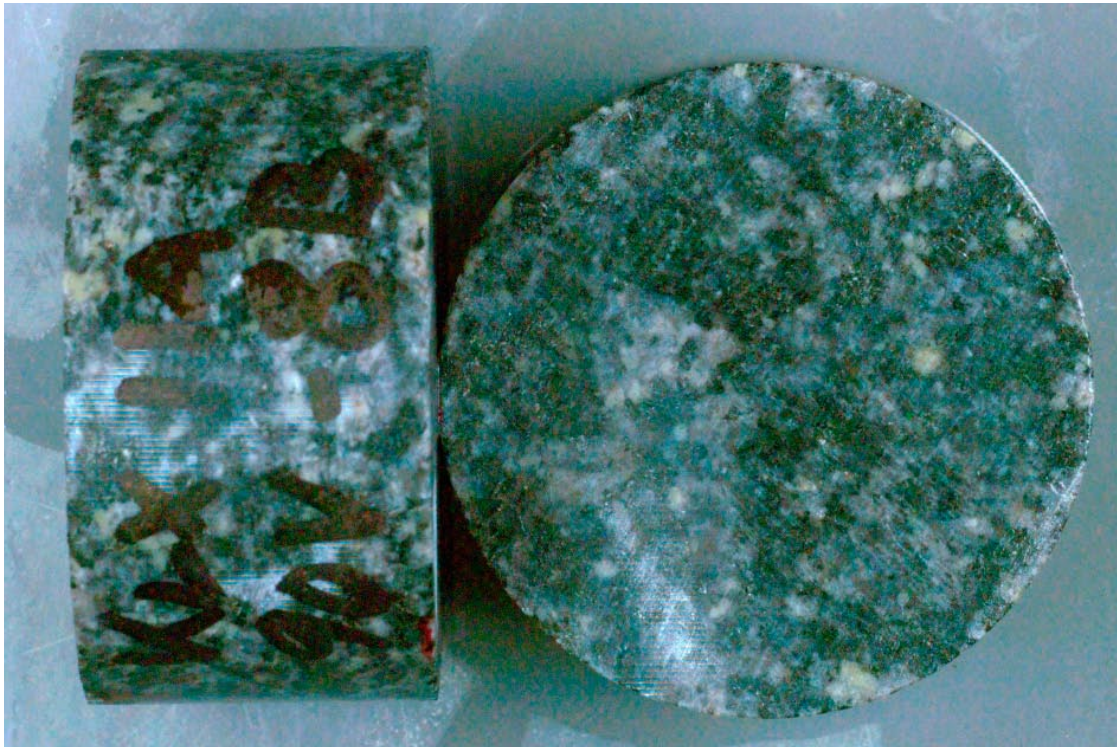


Figure 5-8. Specimens KLX11A-90V-08A and B.

Table 5-15. Porosity, wet and dry density of specimens KLX11A-90V-08A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-08 Sec low: 553.33	2,780	2,780	0.2

Table 5-16. Thermal properties of specimens KLX11A-90V-08A and B at ambient temperature, average values.

Sample KLX11A-90V-08 Sec low: 553.33	TPS method Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]	Calorimeter Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
Mean value	2.60	1.17	2.22	2.25	0.807
Standard deviation	0.002	0.005	0.010	–	–

Specimens KLX11A-90V-9A and B



Figure 5-9. Specimens KLX11A-90V-09A and B.

Table 5-17. Porosity, wet and dry density of specimens KLX11A-90V-09A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-09	2,770	2,770	0.3
Sec low: 613.01			

Table 5-18. Thermal properties of specimens KLX11A-90V-09A and B at ambient temperature, average values.

Sample	TPS method Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]	Calorimeter Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
KLX11A-90V-09					
Sec low: 613.01					
Mean value	2.91	1.34	2.17	2.23	0.805
Standard deviation	0.001	0.001	0.002	–	–

Specimens KLX11A-90V-10A and B



Figure 5-10. Specimens KLX11A-90V-10A and B.

Table 5-19. Porosity, wet and dry density of specimens KLX11A-90V-10A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-10 Sec low: 638.45	2,790	2,780	0.3

Table 5-20. Thermal properties of specimens KLX11A-90V-10A and B at ambient temperature, average values.

Sample KLX11A-90V-10 Sec low: 638.45	TPS method Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]	Calorimeter Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
Mean value	2.59	1.19	2.18	2.18	0.782
Standard deviation	0.004	0.005	0.011	–	–

Specimens KLX11A-90V-11A and B



Figure 5-11. Specimens KLX11A-90V-11A and B.

Table 5-21. Porosity, wet and dry density of specimens KLX11A-90V-11A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-11 Sec low: 720.87	2,790	2,780	0.4

Table 5-22. Thermal properties of specimens KLX11A-90V-11A and B at ambient temperature, average values.

Sample KLX11A-90V-11 Sec low: 720.87	TPS method Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]	Calorimeter Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
Mean value	2.56	1.14	2.24	2.19	0.785
Standard deviation	0.003	0.003	0.005	–	–

Specimens KLX11A-90V-12A and B



Figure 5-12. Specimens KLX11A-90V-12A and B.

Table 5-23. Porosity, wet and dry density of specimens KLX11A-90V-12A and B, average values.

Sample	Density, wet [kg/m ³]	Density, dry [kg/m ³]	Porosity [%]
KLX11A-90V-12	2,760	2,760	0.4
Sec low: 774.10			

Table 5-24. Thermal properties of specimens KLX11A-90V-12A and B at ambient temperature, average values.

Sample	TPS method			Calorimeter	
KLX11A-90V-12	Conductivity	Diffusivity	Volumetric heat capacity	Volumetric heat capacity	Specific heat capacity
Sec low: 774.10	[W/(m, K)]	[mm ² /s]	[MJ/(m ³ , K)]	[MJ/(m ³ , K)]	[J/(g, K)]
Mean value	2.54	1.17	2.17	2.17	0.787
Standard deviation	0.001	0.003	0.006	–	–

5.2 Results for the entire test series

Table 5-25 displays the mean value of five repeated measurements of the thermal properties. Standard deviation is shown in Table 5-26.

Table 5-27 displays the volumetric heat capacity as well as the specific heat capacity of the samples measured by the calorimetric method. The specific heat capacity ranged between 0.78 and 0.84 J/(g, K).

The thermal conductivity and thermal diffusivity of specimens measured by TPS representing different depths at 20°C were in the range 2.54–2.91 W/(m, K) respectively 1.14–1.34 mm²/s. From these results the heat capacity was calculated and appeared to range between 2.08 and 2.28 MJ/(m³, K). A graphical representation of the thermal conductivity and heat capacity versus borehole length is given in Figure 5-13.

Table 5-25. Mean value of thermal properties of samples at 20°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]
Rock type 501036			
KLX11A-90V-01	2.64	1.22	2.16
KLX11A-90V-02	2.79	1.34	2.08
KLX11A-90V-03	2.77	1.22	2.27
KLX11A-90V-04	2.68	1.19	2.25
KLX11A-90V-05	2.58	1.17	2.20
KLX11A-90V-06	2.80	1.23	2.28
KLX11A-90V-07	2.70	1.24	2.18
KLX11A-90V-08	2.60	1.17	2.22
KLX11A-90V-09	2.91	1.34	2.17
KLX11A-90V-10	2.59	1.19	2.18
KLX11A-90V-11	2.56	1.14	2.24
KLX11A-90V-12	2.54	1.17	2.17
Mean value	2.68	1.22	2.20

Table 5-26. Standard deviation of measured values at 20°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]
Rock type 501036			
KLX11A-90V-01	0.003	0.007	0.015
KLX11A-90V-02	0.004	0.003	0.003
KLX11A-90V-03	0.002	0.004	0.007
KLX11A-90V-04	0.003	0.003	0.007
KLX11A-90V-05	0.008	0.007	0.019
KLX11A-90V-06	0.002	0.002	0.005
KLX11A-90V-07	0.002	0.001	0.001
KLX11A-90V-08	0.002	0.005	0.010
KLX11A-90V-09	0.001	0.001	0.002
KLX11A-90V-10	0.004	0.005	0.011
KLX11A-90V-11	0.003	0.003	0.005
KLX11A-90V-12	0.001	0.003	0.006

Table 5-27. Specific heat capacity measured by calorimeter.

Sample identification	Volumetric heat capacity [MJ/(m ³ , K)]	Specific heat capacity [J/(g, K)]
Rock type 501036		
KLX11A-90V-01	2.20	0.793
KLX11A-90V-02	2.20	0.802
KLX11A-90V-03	2.25	0.809
KLX11A-90V-04	2.34	0.844
KLX11A-90V-05	2.26	0.814
KLX11A-90V-06	2.25	0.812
KLX11A-90V-07	2.27	0.813
KLX11A-90V-08	2.25	0.807
KLX11A-90V-09	2.23	0.805
KLX11A-90V-10	2.18	0.782
KLX11A-90V-11	2.19	0.785
KLX11A-90V-12	2.17	0.787
Mean value	2.23	0.805

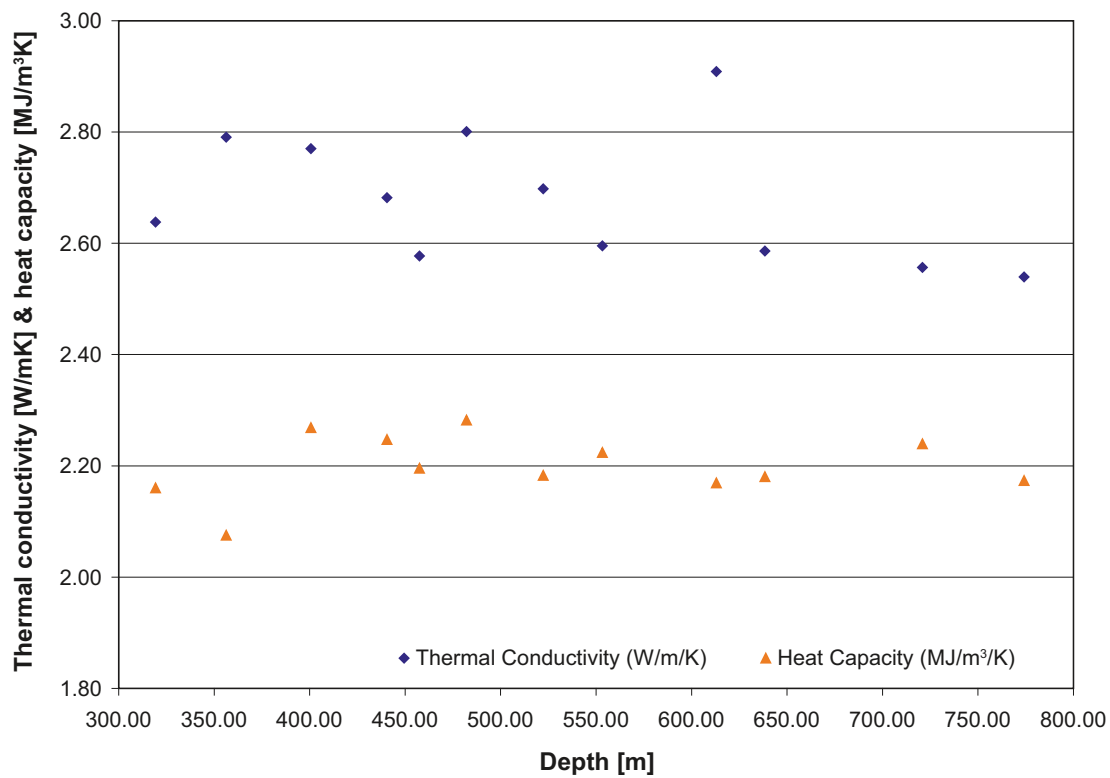


Figure 5-13. Thermal conductivity and heat capacity versus borehole length measured with the TPS method at 20°C.

6 References

- /1/ **SKB, 2001.** Site investigations. Investigation methods and general execution programme. SKB TR-01-10, Svensk Kärnbränslehantering AB.
- /2/ **Gustafsson S E, 1991.** Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials. Rev. Sci. Instrum. 62 (3), March 1991, American Institute of Physics.
- /3/ **Liedberg L, 2005.** Oskarshamn site investigation. Borehole KLX11A. Determination of porosity by water saturation and density by buoyancy technique. SKB P-06-268. Svensk Kärnbränslehantering AB.
- /4/ **Lau P, 2005.** Determination of specific heat capacity of rock samples, P502681-12, SP Swedish National Testing and Research Institute, Measurement Technology.
- /5/ Instruction Manual Hot Disc Thermal Constants Analyser Windows 95 Version 5.0, 2001.
- /6/ ISRM Commission on Testing Methods, ISRM, 1979.

Appendix A

Calibration protocol for Hot Disk Bridge System

Electronics:	Keithley 2400	Serial No. 0925167
	Keithley 2000	Serial No. 0921454
Hot Disk Bridge:		Serial No. 2003-0004
Computation device:		Serial No. 2003-0003, ver 1.5
Computer:	Hot Disk computer	Serial No. 2003-0003
Test sample:	SIS2343. mild steel	Serial No. 3.52
Sensor for testing:	C5501	

Test measurement: 10 repeated measurements on the test sample at room temperature.

Conditions: Power 1 W. Measurement time 10 s.

Results

Thermal conductivity:	13.48 W/(m, K)	± 0.06%
Thermal diffusivity:	3.530 mm ² /s	± 0.13%
Heat capacity:	3.810 MJ/(m ³ , K)	± 0.15%

This instrument has proved to behave according to specifications described in BRk-QB-M26-02.

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Table B-1. Thermal properties of samples at 20°C.

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]
KLX11A 90V-01			
1	2.64	1.23	2.14
2	2.64	1.22	2.16
3	2.64	1.21	2.18
4	2.63	1.22	2.15
5	2.64	1.21	2.17
KLX11A 90V-02			
1	2.80	1.34	2.08
2	2.79	1.35	2.07
3	2.79	1.35	2.07
4	2.79	1.34	2.07
5	2.79	1.34	2.08
KLX11A 90V-03			
1	2.77	1.22	2.27
2	2.77	1.22	2.27
3	2.77	1.21	2.28
4	2.77	1.22	2.26
5	2.77	1.22	2.26
KLX11A 90V-04			
1	2.68	1.19	2.25
2	2.68	1.19	2.26
3	2.68	1.20	2.24
4	2.68	1.20	2.24
5	2.69	1.19	2.25
KLX11A 90V-05			
1	2.59	1.18	2.20
2	2.58	1.17	2.21
3	2.58	1.17	2.20
4	2.58	1.17	2.20
5	2.56	1.19	2.16
KLX11A 90V-06			
1	2.80	1.23	2.28
2	2.80	1.22	2.29
3	2.80	1.23	2.28
4	2.80	1.23	2.28
5	2.80	1.23	2.28
KLX11A 90V-07			
1	2.70	1.24	2.18
2	2.70	1.24	2.18
3	2.70	1.24	2.18
4	2.70	1.24	2.18
5	2.70	1.24	2.18

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm ² /s]	Volumetric heat capacity [MJ/(m ³ , K)]
KLX11A 90V-08			
1	2.59	1.16	2.24
2	2.60	1.17	2.22
3	2.60	1.17	2.23
4	2.60	1.17	2.23
5	2.59	1.17	2.21
KLX11A 90V-09			
1	2.91	1.34	2.17
2	2.91	1.34	2.17
3	2.91	1.34	2.17
4	2.91	1.34	2.17
5	2.91	1.34	2.17
KLX11A 90V-10			
1	2.58	1.19	2.17
2	2.59	1.18	2.19
3	2.59	1.19	2.18
4	2.58	1.19	2.17
5	2.59	1.18	2.19
KLX11A 90V-11			
1	2.56	1.15	2.23
2	2.56	1.14	2.24
3	2.56	1.14	2.24
4	2.56	1.14	2.24
5	2.55	1.14	2.24
KLX11A 90V-12			
1	2.54	1.17	2.17
2	2.54	1.17	2.17
3	2.54	1.17	2.18
4	2.54	1.16	2.18
5	2.54	1.17	2.17

Appendix C

Table C-1. Total time of measurement, ratio of total time and characteristic time, and number of analysed points at 20°C.

Measurement number	Total time(s)	Total/Char. time	Points
KLX11A 90V-01			
1	20	0.60	52–200
2	20	0.59	52–200
3	20	0.59	52–200
4	20	0.59	52–200
5	20	0.59	53–200
KLX11A 90V-02			
1	20	0.64	39–195
2	20	0.64	39–195
3	20	0.64	39–195
4	20	0.64	39–195
5	20	0.63	39–195
KLX11A 90V-03			
1	20	0.59	62–200
2	20	0.59	62–200
3	20	0.59	62–200
4	20	0.59	62–200
5	20	0.59	62–200
KLX11A 90V-04			
1	20	0.58	76–200
2	20	0.58	76–200
3	20	0.58	76–200
4	20	0.58	76–200
5	20	0.58	76–200
KLX11A 90V-05			
1	20	0.57	68–200
2	20	0.57	68–200
3	20	0.57	68–200
4	20	0.57	68–200
5	20	0.58	70–200
KLX11A 90V-06			
1	20	0.60	39–200
2	20	0.59	39–200
3	20	0.60	45–200
4	20	0.60	39–200
5	20	0.60	39–200
KLX11A 90V-07			
1	20	0.60	39–200
2	20	0.60	39–200
3	20	0.60	39–200
4	20	0.60	39–200
5	20	0.60	39–200

Measurement number	Total time(s)	Total/Char. time	Points
KLX11A 90V-08			
1	20	0.56	46–200
2	20	0.57	46–200
3	20	0.57	46–200
4	20	0.57	46–200
5	20	0.57	46–200
KLX11A 90V-09			
1	20	0.65	35–200
2	20	0.65	35–200
3	20	0.65	35–200
4	20	0.65	35–200
5	20	0.65	35–200
KLX11A 90V-10			
1	20	0.58	84–200
2	20	0.57	84–200
3	20	0.58	84–200
4	20	0.58	84–200
5	20	0.57	84–200
KLX11A 90V-11			
1	20	0.56	15–200
2	20	0.55	19–200
3	20	0.55	19–200
4	20	0.55	19–200
5	20	0.55	19–200
KLX11A 90V-12			
1	20	0.57	58–200
2	20	0.57	58–199
3	20	0.57	58–200
4	20	0.57	58–200
5	20	0.57	58–200