P-05-214

Forsmark site investigation

Borehole KFM07A

Thermal conductivity and thermal diffusivity determined using the TPS method

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November 2005

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Keywords: Thermal properties, Rock mechanics, Thermal conductivity, Thermal diffusivity, Heat capacity, Transient Plane Source Method, AP PF 400-05-024.

Abstract

Thermal properties of nine specimens from borehole KFM07A, Forsmark, Sweden, were measured at ambient temperature (20°C). The samples were collected from two levels in the borehole: 300–380 m respectively 670–680 m (borehole length). The rock types of the samples are medium-grained granite, pegmatite and amphibolite. The determination of the thermal properties is based on a direct measurement method, the so called "Transient Plane Source Method" (TPS), Gustafsson, 1991 /2/.

Thermal conductivity and thermal diffusivity at 20°C were in the range of 2.41–3.83 W/(m, K) respectively 0.94–1.78 mm^2/s. The heat capacity, which was calculated from the thermal conductivity and diffusivity, ranged between 1.73 and 2.64 $MJ/(m^3, K)$.

Sammanfattning

Termiska egenskaper hos nio provkroppar från borrhål KFM07A, Forsmark, bestämdes vid rumstemperatur (20 °C) med den s k TPS metoden (”Transient Plane Source”), Gustafsson 1991 /2/. Proverna hade tagits från två nivåer i borrhålet: 300–380 m respektive 670–680 m borrhålslängd. Proven bestod av bergarterna medelkornig granit, pegmatit och amfibolit.

Den termiska konduktiviteten och den termiska diffusiviteten hos provkropparna vid 20 °C uppgick till 2,41–3,83 W/(m, K) respektive 0,94–1,78 mm^2/s. Utgående från dessa parametrar kunde värmekapaciteten beräknas och befanns ligga i intervallet 1,73–2,64 $MJ/(m^3, K)$.

Contents

1 Introduction

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

This report presents investigations of thermal properties of rock samples from borehole KFM07A at Forsmark. 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 density, as well as the porosity of the samples, were determined within the scope of parallel activity /3/.

Borehole KFM07A, see Figure 1-1, is a telescopic drilled borehole inclined c 60º from the horizontal plane and with a total length of 1,001.55 m. The borehole section 0–100.40 m is percussion drilled, whereas the section 100.40–1,001.55 m is core drilled.

Rock samples were selected at Forsmark based on the preliminary core logging with the strategy to primarily investigate the properties of the dominant rock types. The specimens to be tested were cut from the rock samples in the shape of circular discs. The rock samples arrived at SP, department of Fire Technology, in April 2005. The thermal properties were determined on water saturated specimens. Testing was performed during June 2005.

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 as well as SP's (Swedish National Testing and Research Institure) Quality Plan (SP-QD 13.1).

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

Activity Plan	**Number**	**Version**
KFM07A. Bergmekaniska och termiska laboratoriebestämningar	AP PF 400-05-024	1.0
Method Description	**Number**	**Version**
Determination of density and porosity of intact rock	SKB MD 191.001	1.0
Quality Plan		
SP-QD 13.1		

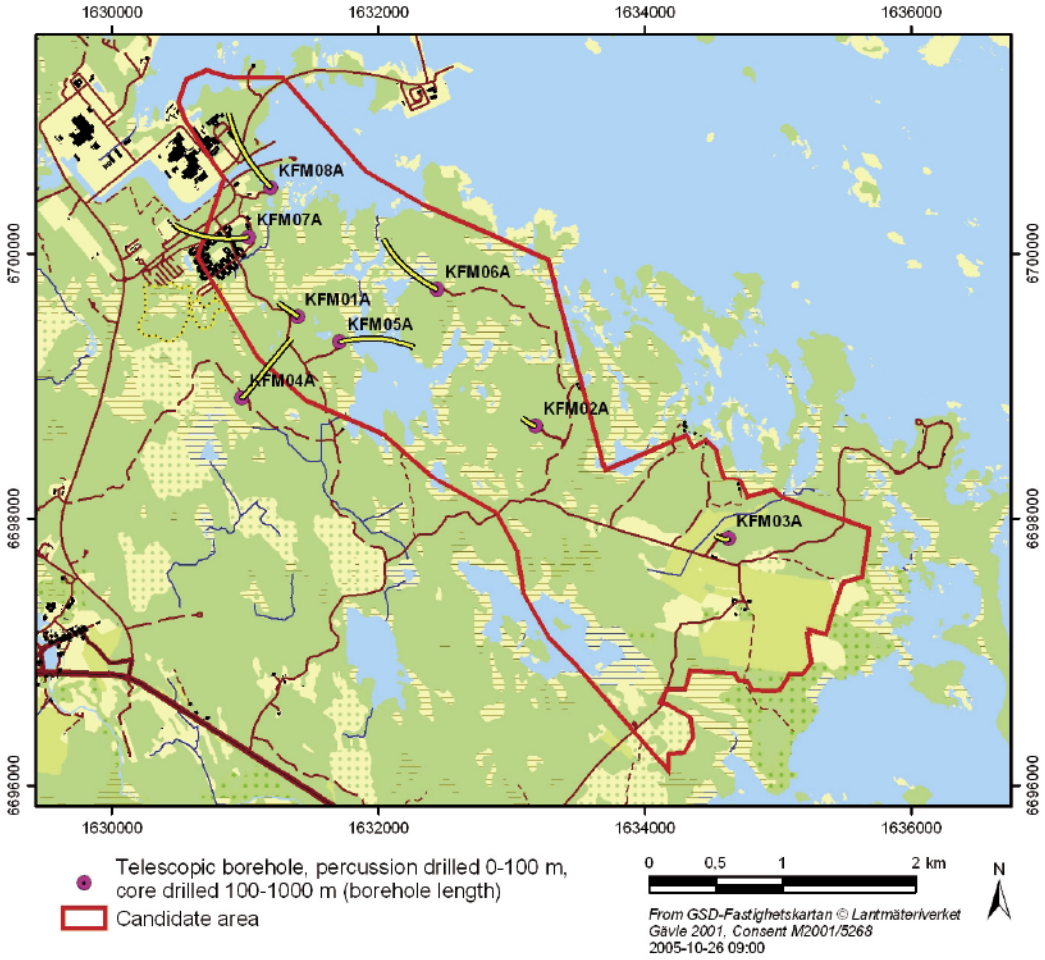

Figure 1-1. *Location of all telescopic boreholes drilled up to mid-August 2005 within or close to the Forsmark candidate area. The projection of each borehole on the horizontal plane at top of casing is also shown in the figure.*

2 Objective

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 Forsmark.

3 Equipment

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 /4/.
- 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.

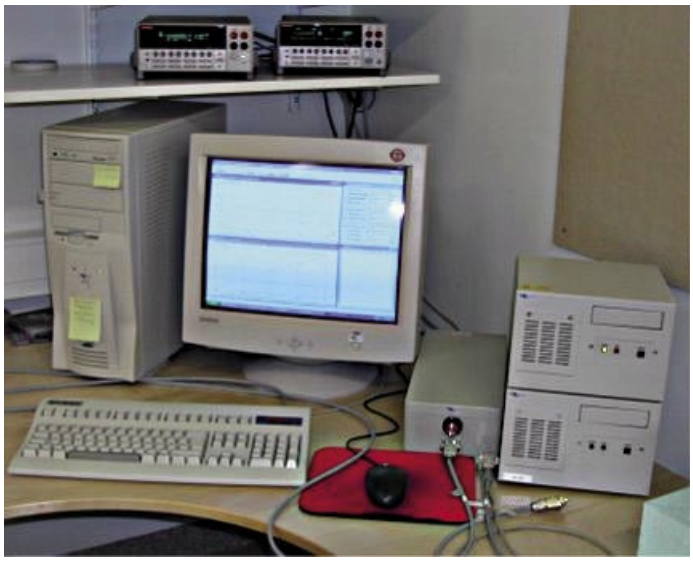

Figure 3-1. *TPS-apparatus with source meter, multi-meter, bridge, and computer.*

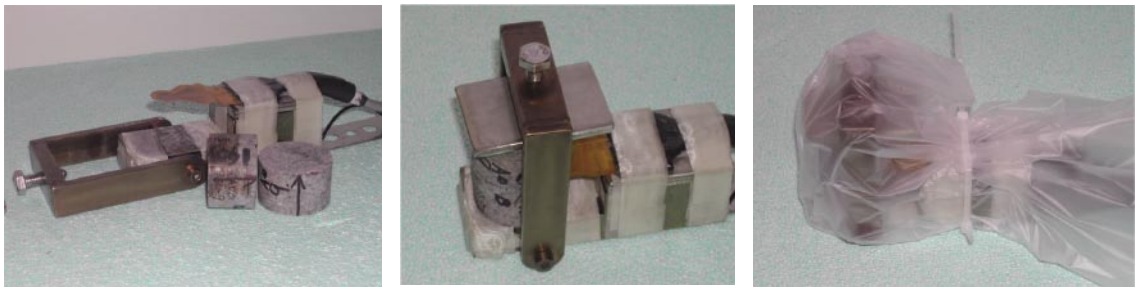

Figure 3-2. *Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).*

4 Execution

Determination of the thermal properties conductivity and diffusivity at ambient temperature (20°C) by applying the TPS-method was made in compliance with SKB's method description SKB MD 191.001, and Hot Disc Instruction Manual /4/ at SP, department of Fire Technology, see SP-QD 13.1. The density determination of the samples is described in /2/.

4.1 Description of the samples

Nine pairs of cores (designated A and B) were randomly sampled from two levels of the drill core of borehole KFM07A. The sampling levels were 300–380 m respectively 670–680 m borehole length. The eighteen 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 types and sampling levels of the specimens are presented in Table 4-1. Detailed geological description of the entire core of KFM07A is given in SKB's database SICADA (Boremap data).

Table 4-1. Identification marks, rock type and sampling level (borehole length) of the specimens from KFM07A for determination of thermal properties (rock-type classification according to Boremap). Each identification mark represents two specimens, designated A and B, respectively.

Identification	Rock type	Sampling level (Sec low)
KFM07A-90V-01	Medium-grained granite	300.18
KFM07A-90V-02	Medium-grained granite	319.86
KFM07A-90V-03	Medium-grained granite	340.64
KFM07A-90V-04	Medium-grained granite	358.85
KFM07A-90V-05	Medium-grained granite	379.92
KFM07A-90V-06	Pegmatite	678.55
KFM07A-90V-07	Pegmatite	678.61
KFM07A-90V-08	Amphibolite	674.05
KFM07A-90V-09	Amphibolite	674.11

4.2 Test Procedure

The present activity was performed parallel to another activity /2/, conducted by the department of Building Technology at SP, and by which the wet and dry density as well as the porosity of the specimens were determined.

The following logistic sequence was applied for the two 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.
4. Specimens were sent from SP Building Technology and Mechanics to SP Fire Technology.
5. Thermal properties were determined by SP Fire Technology.
6. Specimens were sent from SP Fire Technology to SP Building Technology and Mechanics.
7. Dry density of the specimens was determined at SP Building Technology and Mechanics.

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, and from these parameters the volumetric heat capacity can be determined, provided the density is known.

The specimens 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.

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 SKB catalogue at the SP network. Further calculations of mean values and standard deviations were performed in the same catalogue.

Determinations of the thermal properties as well as density and porosity measurements were performed during May–June 2005.

The dry weight was measured after the specimens had been dried to constant mass according to ISMR /5/ at 105°C. The drying procedure took seven days.

4.3 Nonconformities

There were no deviations to the plan.

5 Results

Data from 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 Sections 5.1 and 5.2. Values of each separate measurement of thermal properties as described in Section 4.2 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 range between 0.4 and 1.

5.1 Test results of individual specimens

5.1.1 Specimens KFM07A-90V-01

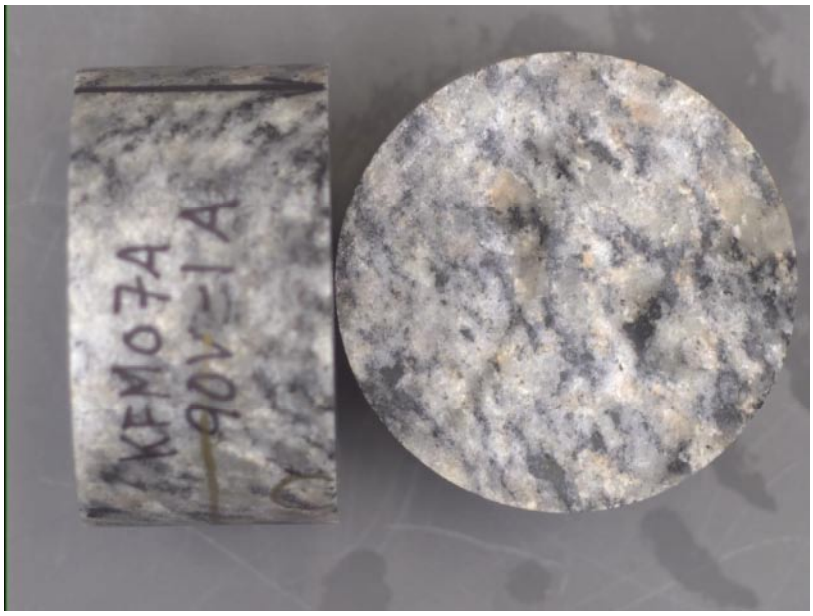

Figure 5-1. *Specimens KFM07A-90V-01 A and B.*

Table 5-1. Porosity, wet and dry density of specimens KFM07A-90V-01 A and B, average values.

Sample	Density, wet (kg/m^3)	Density, dry (kg/m^3)	Porosity (%)
KFM07A-90V-01 Sec low: 300.18	2,640	2,640	0.4

Table 5-2. Thermal properties of specimens KFM07A-90V-01 at ambient temperature.

KFM07A-90V-01 Sec low: 300.18	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
	20°C		
Mean value	3.58	1.72	2.07
Standard deviation	0.008	0.034	0.043

5.1.2 Specimens KFM07A-90V-02

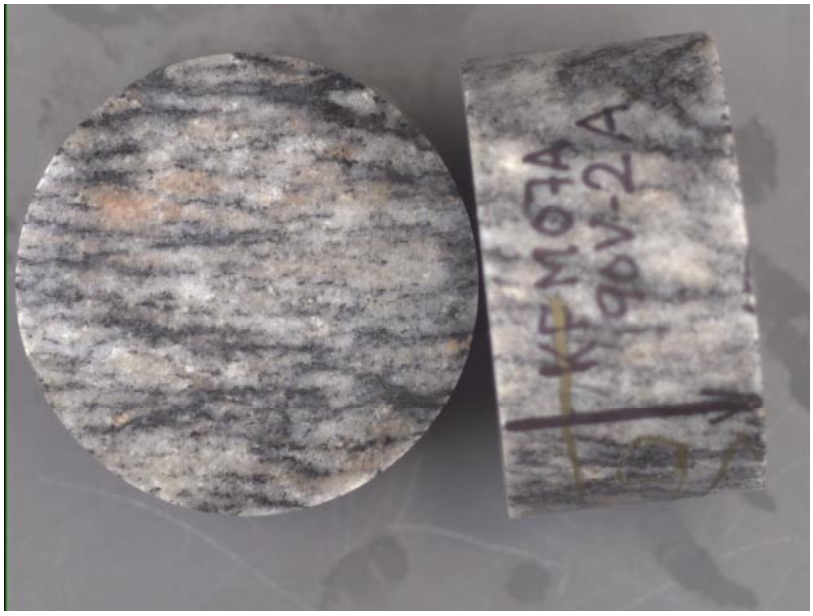

Figure 5-2. *Specimens KFM07A-90V-02.*

Table 5-3. Porosity, wet and dry density of specimens KFM07A-90V-02 A and B, average values.

Sample	Density, wet (kg/m^3)	Density, dry (kg/m^3)	Porosity (%)
KFM07A-90V-02 Sec low: 319.86	2,650	2,650	0.4

Table 5-4. Thermal properties of specimens KFM07A-90V-02 at ambient temperature.

KFM07A-90V-02 Sec low: 319.86	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
	20°C		
Mean value	3.69	1.60	2.30
Standard deviation	0.001	0.007	0.010

5.1.3 Specimens KFM07A-90V-03

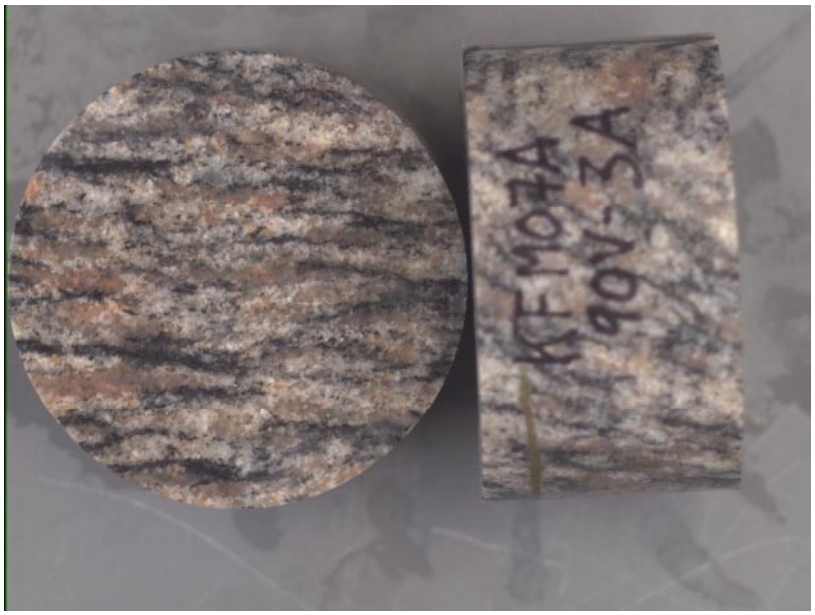

Figure 5-3. *Specimens KFM07A-90V-03.*

Table 5-5. Porosity, wet and dry density of specimens KFM07A-90V-03 A and B, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
KFM07A-90V-03 Sec low: 340.64	2,650	2,650	0.4

Table 5-6. Thermal properties of specimens KFM07A-90V-03 at ambient temperature.

KFM07A-90V-03 Sec low: 340.64	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.83	1.68	2.28
Standard deviation	0.007	0.011	0.019

5.1.4 Specimens KFM07A-90V-04

Figure 5-4. *Specimens KFM07A-90V-04.*

Table 5-7. Porosity, wet and dry density of specimens KFM07A-90V-04 A and B, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
KFM07A-90V-04 Sec low: 358.85	2,660	2,660	0.3

Table 5-8. Thermal properties of specimens KFM07A-90V-04 at ambient temperature.

KFM07A-90V-04 Sec low: 358.85	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.53	1.70	2.07
Standard deviation	0.008	0.015	0.022

5.1.5 Specimens KFM07A-90V-05

Figure 5-5. *Specimens KFM07A-90V-05.*

Table 5-9. Porosity, wet and dry density of specimens KFM07A-90V-05 A and B, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
KFM07A-90V-05 Sec low: 379.92	2,650	2,650	0.3

Table 5-10. Thermal properties of specimens KFM07A-90V-05 at ambient temperature.

KFM07A-90V-05 Sec low: 379.92	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.69	1.70	2.17
Standard deviation	0.007	0.015	0.017

5.1.6 Specimens KFM07A-90V-06

Figure 5-6. *Specimens KFM07A-90V-06.*

Table 5-11. Porosity, wet and dry density of specimens KFM07A-90V-06 A and B, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
KFM07A-90V-06 Sec low: 678.55	2,610	2,610	0.4

Table 5-12. Thermal properties of specimens KFM07A-90V-06 at ambient temperature.

KFM07A-90V-06 Sec low: 678.55	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.28	1.58	2.07
Standard deviation	0.005	0.007	0.009

5.1.7 Specimens KFM07A-90V-07

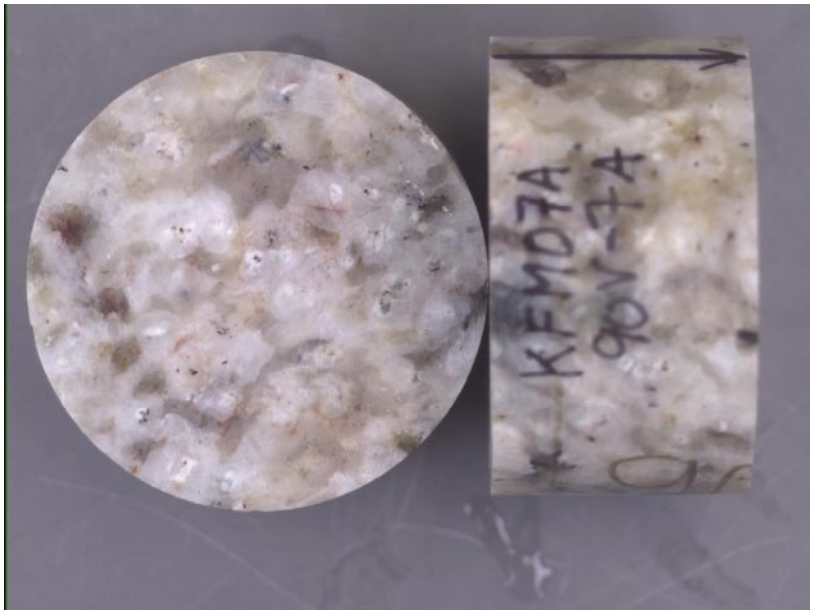

Figure 5-7. *Specimens KFM07A-90V-07.*

Table 5-13. Porosity, wet and dry density of specimens KFM07A-90V-07 A and B, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
KFM07A-90V-07 Sec low: 678.61	2,630	2,630	0.3

Table 5-14. Thermal properties of sample KFM07A-90V-07 at ambient temperature.

KFM07A-90V-07 Sec low: 678.61	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.07	1.78	1.73
Standard deviation	0.006	0.009	0.012

5.1.8 Specimens KFM07A-90V-08

Figure 5-8. *Specimens KFM07A-90V-08.*

Table 5-15. Porosity, wet and dry density of specimens KFM07A-90V-08 A and B, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
KFM07A-90V-08 Sec low: 674.05	3,030	3,030	0.2

Table 5-16. Thermal properties of sample KFM07A-90V-08 at ambient temperature.

KFM07A-90V-08 Sec low: 674.05	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	2.48	0.94	2.64
Standard deviation	0.004	0.003	0.013

5.1.9 Specimens KFM07A-90V-09

Figure 5-9. *Specimens KFM07A-90V-09.*

Table 5-17. Porosity, wet and dry density of specimens KFM07A-90V-09 A and B, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
KFM07A-90V-09 Sec low: 674.11	3,030	3,030	0.3

Table 5-18. Thermal properties of sample KFM07A-90V-09 at ambient temperature.

KFM07A-90V-09 Sec low: 674.11	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	2.41	0.97	2.48
Standard deviation	0.002	0.004	0.012

5.2 Results for the entire test series

Table 5-19 displays the mean value of five repeated measurements of the thermal properties. Standard deviation is shown in Table 5-20.

The thermal conductivity and thermal diffusivity of the specimens representing different depths at 20°C were in the range of 2.41-3.83 W/(m, K) respectively 0.94-1.78 mm^2/s. From these results the heat capacity was calculated and appeared to range between 1.73 and 2.64 MJ//(m^3, K). A graphical representation of the heat conductivity and heat capacity versus borehole length is given in Figure 5-10.

Table 5-19. Mean value of thermal properties of samples at 20°C.

Sample identification	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
KFM07A-90V-01	3.58	1.72	2.07
KFM07A-90V-02	3.69	1.60	2.30
KFM07A-90V-03	3.83	1.68	2.28
KFM07A-90V-04	3.53	1.70	2.07
KFM07A-90V-05	3.69	1.70	2.17
KFM07A-90V-06	3.28	1.58	2.07
KFM07A-90V-07	3.07	1.78	1.73
KFM07A-90V-08	2.48	0.94	2.64
KFM07A-90V-09	2.41	0.97	2.48

Table 5-20. Standard deviation of the values presented in Table 5-19 at 20°C.

Sample identification	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
KFM07A-90V-01	0.008	0.034	0.043
KFM07A-90V-02	0.001	0.007	0.010
KFM07A-90V-03	0.007	0.011	0.019
KFM07A-90V-04	0.008	0.015	0.022
KFM07A-90V-05	0.007	0.015	0.017
KFM07A-90V-06	0.005	0.007	0.009
KFM07A-90V-07	0.006	0.009	0.012
KFM07A-90V-08	0.004	0.003	0.013
KFM07A-90V-09	0.002	0.004	0.012

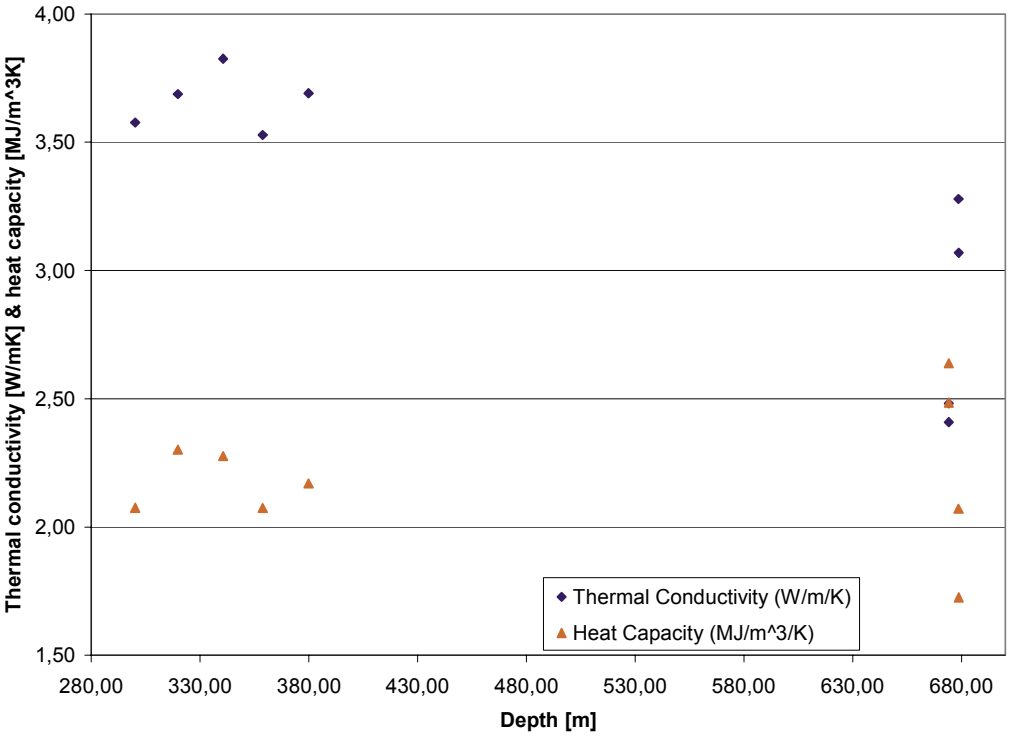

Figure 5-10. *Thermal conductivity and heat capacity versus borehole length at 20°C.*

6 References

/1/ **SKB, 2001.** Site investigations. Investigation methods and general executions programme. SKB TR-01-29, 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/ **Savukoski M, 2005.** Forsmark site investigation. Borehole KFM07A. Determination of porosity by water saturation and density by buoyancy technique. SKB P-05-215. Svensk Kärnbränslehantering AB.

/4/ Instruction Manual Hot Disc Thermal Constants Analyser Windows 95 Version 5.0, 2001.

/5/ **ISRM, 1979.** 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:	13.44 W/(m. K)	± 0.06%
Thermal Diffusivity:	3.510 mm^2/s	± 0.35%
Heat Capacity:	3.837 $MJ/(m^3. K)$	± 0.36%

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

Borås 25/04 2005

Patrik Nilsson

Appendix B

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

Measurement number	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
KFM07A-90V-01			
1	3.58	1.71	2.09
2	3.59	1.71	2.09
3	3.57	1.78	2.00
4	3.58	1.70	2.11
5	3.57	1.71	2.08
KFM07a 90V-02			
1	3.69	1.61	2.28
2	3.69	1.60	2.31
3	3.69	1.60	2.30
4	3.69	1.60	2.30
5	3.69	1.60	2.31
KFM07a 90V-03			
1	3.82	1.69	2.26
2	3.82	1.69	2.27
3	3.83	1.68	2.28
4	3.84	1.66	2.31
5	3.82	1.68	2.27
KFM07a 90V-04			
1	3.52	1.71	2.06
2	3.54	1.68	2.11
3	3.53	1.71	2.06
4	3.53	1.71	2.06
5	3.53	1.69	2.09
KFM07a 90V-05			
1	3.69	1.71	2.15
2	3.70	1.72	2.16
3	3.69	1.70	2.18
4	3.68	1.70	2.17
5	3.69	1.68	2.20
KFM07a 90V-06			
1	3.27	1.58	2.07
2	3.28	1.59	2.07
3	3.28	1.59	2.06
4	3.28	1.58	2.08
5	3.28	1.57	2.09
KFM07a 90V-07			
1	3.06	1.78	1.72
2	3.07	1.79	1.72
3	3.07	1.78	1.72
4	3.07	1.78	1.72
5	3.08	1.76	1.75

Measurement number	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
KFM07a 90V-08			
1	2.48	0.94	2.65
2	2.48	0.94	2.65
3	2.48	0.94	2.63
4	2.48	0.95	2.62
5	2.49	0.94	2.65
KFM07a 90V-09			
1	2.41	0.97	2.47
2	2.41	0.96	2.50
3	2.41	0.97	2.49
4	2.41	0.97	2.48
5	2.41	0.97	2.48

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
KFM07A-90V-01			
1	20	0.83	87–200
2	20	0.83	87–200
3	20	0.87	87–200
4	20	0.82	88–199
5	20	0.83	88–200
KFM07A 90V-02			
1	20	0.78	45–198
2	20	0.77	45–198
3	20	0.77	47–198
4	20	0.77	45–198
5	20	0.77	45–198
KFM07A 90V-03			
1	20	0.82	34–199
2	20	0.81	34–199
3	20	0.81	36–199
4	20	0.80	34–199
5	20	0.81	34–199
KFM07A 90V-04			
1	20	0.83	70–199
2	20	0.78	70–190
3	20	0.83	70–199
4	20	0.83	71–199
5	20	0.82	70–199
KFM07A 90V-05			
1	20	0.80	46–193
2	20	0.80	53–193
3	20	0.76	46–185
4	20	0.74	56–179
5	20	0.77	59–188
KFM07A 90V-06			
1	20	0.76	63–198
2	20	0.74	72–192
3	20	0.74	68–191
4	20	0.76	63–198
5	20	0.74	63–195
KFM07A 90V-07			
1	20	0.82	37–191
2	20	0.83	97–191
3	20	0.83	37–191
4	20	0.83	37–191
5	20	0.82	37–191

Measurement number	Total time(s)	Total/Char. Time	Points
KFM07A 90V-08			
1	20	0.46	39–200
2	20	0.45	39–200
3	20	0.46	41–199
4	20	0.46	39–200
5	20	0.46	39–200
KFM07A 90V-09			
1	20	0.47	38–200
2	20	0.47	38–200
3	20	0.47	38–200
4	20	0.47	38–200
5	20	0.47	38–200