P-05-123

Forsmark site investigation

Drill hole KFM06A

Thermal properties: heat conductivity and heat capacity determined using the TPS method

Bijan Adl-Zarrabi
SP Swedish National Testing and Research Institute

August 2005

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Keywords: Thermal properties, Rock mechanics, Thermal conductivity, Thermal diffusivity, Heat capacity, Transient Plane Source method, AP PF 400-04-121.

Abstract

Thermal properties on six rock core specimens from drill hole KFM06A, Forsmark, were measured at ambient temperature (20°C). The rock type of all samples is mapped as granite-aplitic (101058). The determination of the thermal properties are based on a direct measurement method, the so called "Transient Plane Source Method (TPS)", Gustafsson, 1991 /1/.

Thermal conductivity and thermal diffusivity of specimens at 825 m borehole length at 20°C were in the range of 3.70–4.06 W/(m, K) and 1.68–1.97 mm^2/s respectively.

Sammanfattning

Termiska egenskaper hos sex provkroppar från borrhål KFM06A, Forsmark, bestämdes vid rumstemperatur (20 °C). Bergarten är av typen granit-aplit (101058). TPS metoden, "Transient Plane Source", användes för bestämning av de termiska egenskaperna, Gustafsson 1991 /1/.

Den termiska konduktiviteten och den termiska diffusiviteten hos provkropparna vid 20 °C och vid 825 m borrhålslängd var 3,70–4,06 W/(m, K) respektive 1,68–1,97 mm^2/s.

Contents

1 Introduction

The objective of this investigation was to measure thermal properties of rock samples from borehole KFM06A at Forsmark, see Figure 1-1, at ambient temperature (20°C) by using the TPS-method /1/. The thermal properties were determined for water-saturated specimens. The specimens, in form of circular discs, were cut from drill cores. The samples were selected based on the preliminary core logging and with the strategy to primarily investigate the properties of the dominant rock types. The principle of the TPS method is to place a sensor between two rock samples. The sensor consists of a thin metal double spiral, embedded in an insulation material. 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 provides information on the heat conductivity and diffusivity of a material and from this the volumetric heat capacity can be determined, if the density is known.

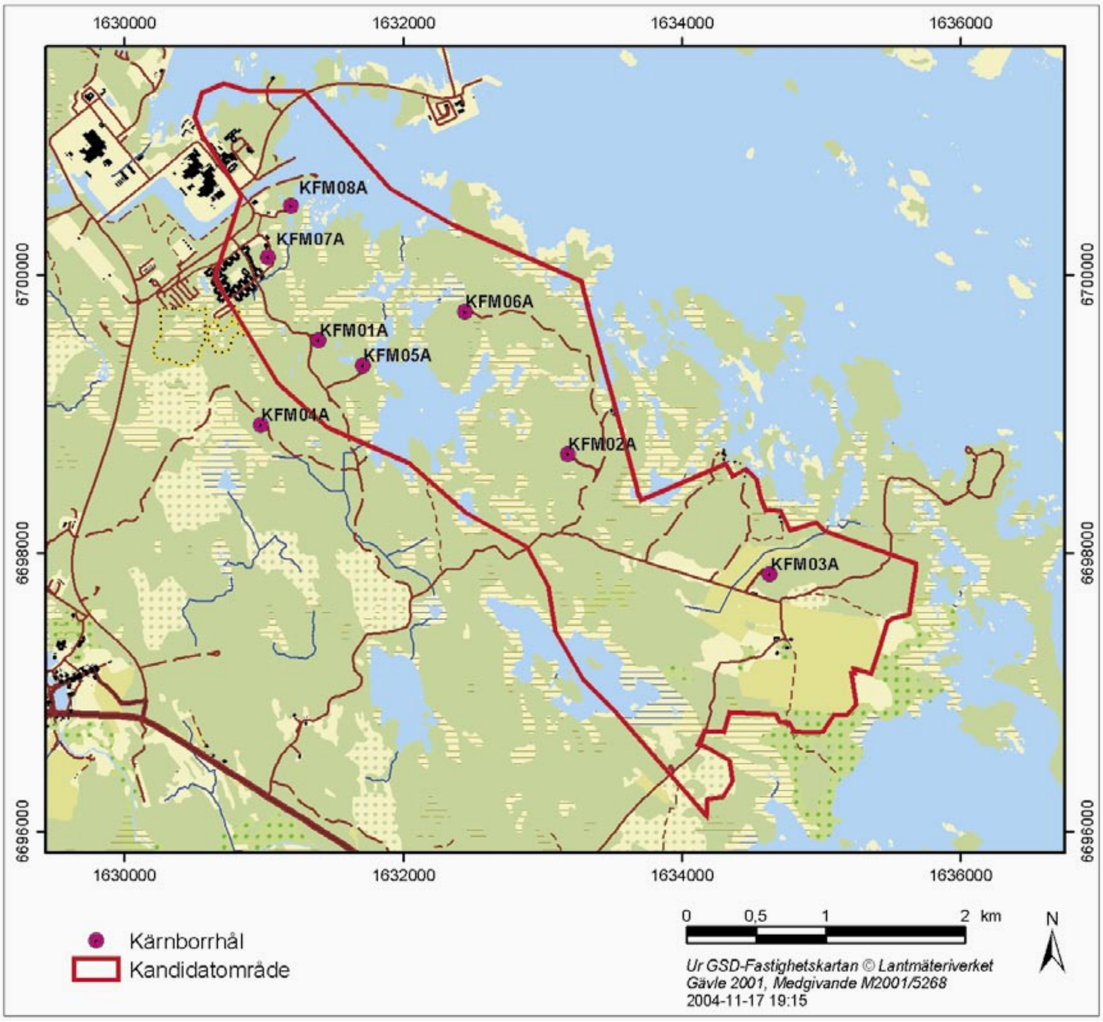

***Figure 1-1**. Location of borehole KFM06A at the Forsmark site investigation area.*

The test programme followed the activity plan AP PF 400–04-121 (SKB internal controlling document) and is controlled by SP-QD 13.1 (SP quality document).

The samples were water saturated and stored in this condition for seven days. This yields complete water saturation, whereupon the density and the thermal properties were determined. The specimens were photographed before testing.

The rock cores arrived at SP in January 2005. The testing was performed during March–April 2005.

Determination of thermal properties was made in accordance to SKB's method description SKB MD 191.001, (SKB internal controlling document) at SP Fire Technology. Density was determined in compliance with SKB MD 160.002, (SKB internal controlling document) at SP Building Technology and Mechanics.

2 Objective and scope

The purpose of the testing was to determine the thermal properties of rock specimens. The results shall be used for the site descriptive modelling of thermal properties, which will be established for the candidate area selected for site investigations at Forsmark.

The samples are collected from the telescopic borehole KFM06A in Forsmark, which is inclined c 60° from the horizontal plane and has a drilling length of c 1,000 m. Drill cores were produced within the interval c 100–1,000 m. The specimens were sampled at 825 m borehole length. The investigated rock type is mapped as granite-aplitic (101058).

3 Equipment

Technical devices for determination of thermal properties used were:

- Kapton sensor 5501, radius of the sensor was 6.403 mm, and output of power was 0.7 W. The sensor 5501 fulfils the recommended relation between the radius of sensor and geometry of the samples in /2/.
- 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.

Specimen mounting is shown in Figure 3-2.

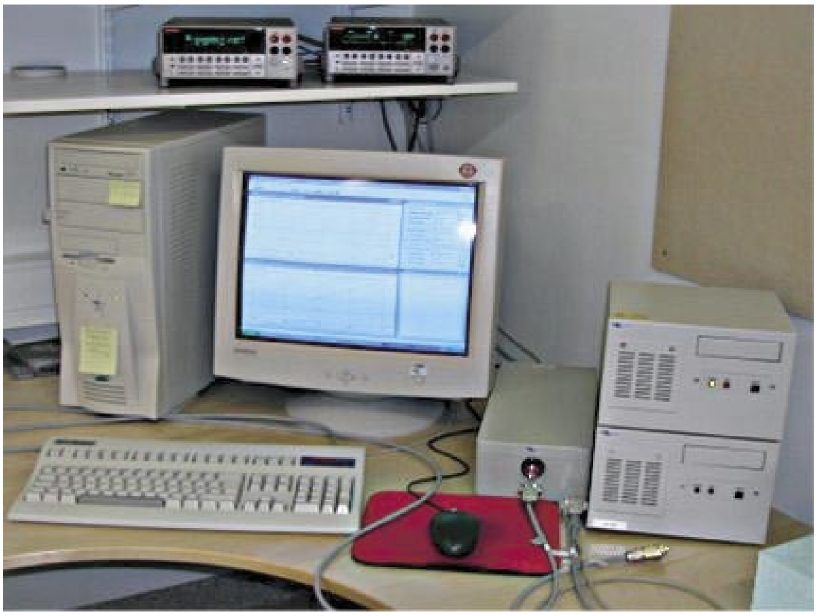

Figure 3-1. *TPS-apparatus with source meter, multi-meter, bridge, and computer.*

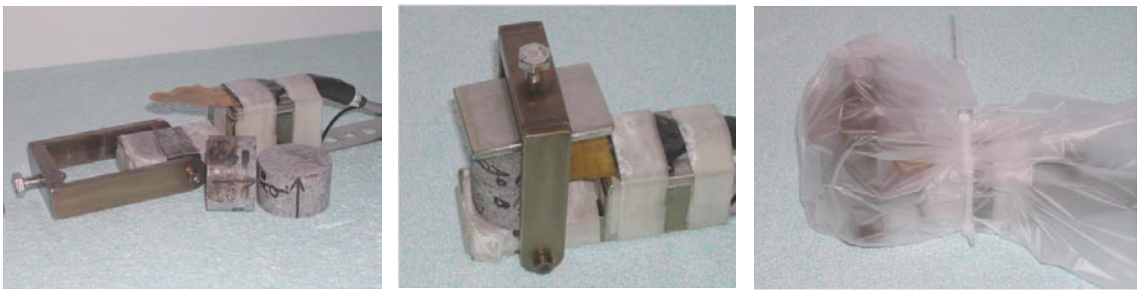

Figure 3-2. *Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).*

4 Execution

Determination of thermal properties was made in accordance to SKB's method description SKB MD 191.001, (SKB internal controlling document) and Hot Disc Instruction Manual /2/ at SP Fire Technology.

Density was determined in compliance with SKB MD 160.002, (SKB internal controlling document) and ISRM /3/.

4.1 Description of the samples

Six pairs of core samples were collected from one level of drill hole KFM06A, Forsmark, Sweden. The level ranged between 822 m and 830 m borehole length. Twelve specimens with a thickness of 25 mm each were selected from the samples at SP; see Figure 3-2. The diameter of the specimens was about 50 mm. The rock type, identification marks and depth of the specimens are presented in Table 4-1. Detailed geological description of the rock is given in SKB's BOREMAP of KFM06A and in the SICADA database at SKB.

Table 4-1. Rock type and identification marks (Rock-type classification according to the overview mapping).

Identification	Rock type	Sampling depth (borehole length) (Adj sec low)
KFM06A-90V-01	Granite-aplitic (101058)	822.81
KFM06A-90V-02	Granite-aplitic (101058)	822.87
KFM06A-90V-03	Granite-aplitic (101058)	822.96
KFM06A-90V-04	Granite-aplitic (101058)	828.89
KFM06A-90V-05	Granite-aplitic (101058)	828.96
KFM06A-90V-06	Granite-aplitic (101058)	829.02

4.2 Test procedure

4.2.1 Thermal properties

The following steps were performed:

1. Samples were cut and polished by SP Building Technology and Mechanics.
2. Samples were photographed by SP Building Technology and Mechanics.
3. Samples were water saturated and wet density was determined by SP Building Technology and Mechanics.
4. Samples were sent from SP Building Technology and Mechanics to SP Fire Technology.
5. Thermal properties were determined.

6. Samples were sent from SP Fire Technology to SP Building Technology and Mechanics.
7. Dry density of samples determined at SP Building Technology and Mechanics.

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

Each core pair 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.

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

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. These stored files were sent to SKB catalogue at SP network. Further calculations of mean values and standard deviations were performed in the same catalogue.

Thermal properties, density and porosity measurements were performed during March–April 2005.

Dry weight was measured after the specimens had been dried to constant mass according to ISMR /3/ at 105°C. The drying procedure took seven days.

4.3 Nonconformities

There were no deviations to plan.

5 Results

5.1 Thermal properties

Mean values of measured data, five repeated measurements, are reported in 5.1.1 and 5.1.2 and in the SICADA database at SKB where data are traceable by the activity plan number. Values of each separate measurement as described in 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 be between 0.4 and 1.

5.1.1 Test results, sample by sample

Sample KFM06A-90V-01

Figure 5-1. *Specimens KFM06A-90V-01.*

Table 5-1. Porosity, wet and dry density of specimens KFM06A-90V-01, average values.

Sample	Density, wet kg/m³	Density, dry kg/m³	Porosity %
KFM06A-90V-01	2,650	2,650	0.2
Adj sec low: 822.81			

Table 5-2. Thermal properties of sample KFM06A-90V-01 at ambient temperature.

KFM06A-90V-01 Adj sec low: 822.81	Conductivity W/(m, K)	Diffusivity mm²/s	Heat capacity MJ/(m³, K)
20°C			
Mean value	3.88	1.97	1.97
Standard deviation	0.008	0.034	0.034

Sample KFM06A-90V-02

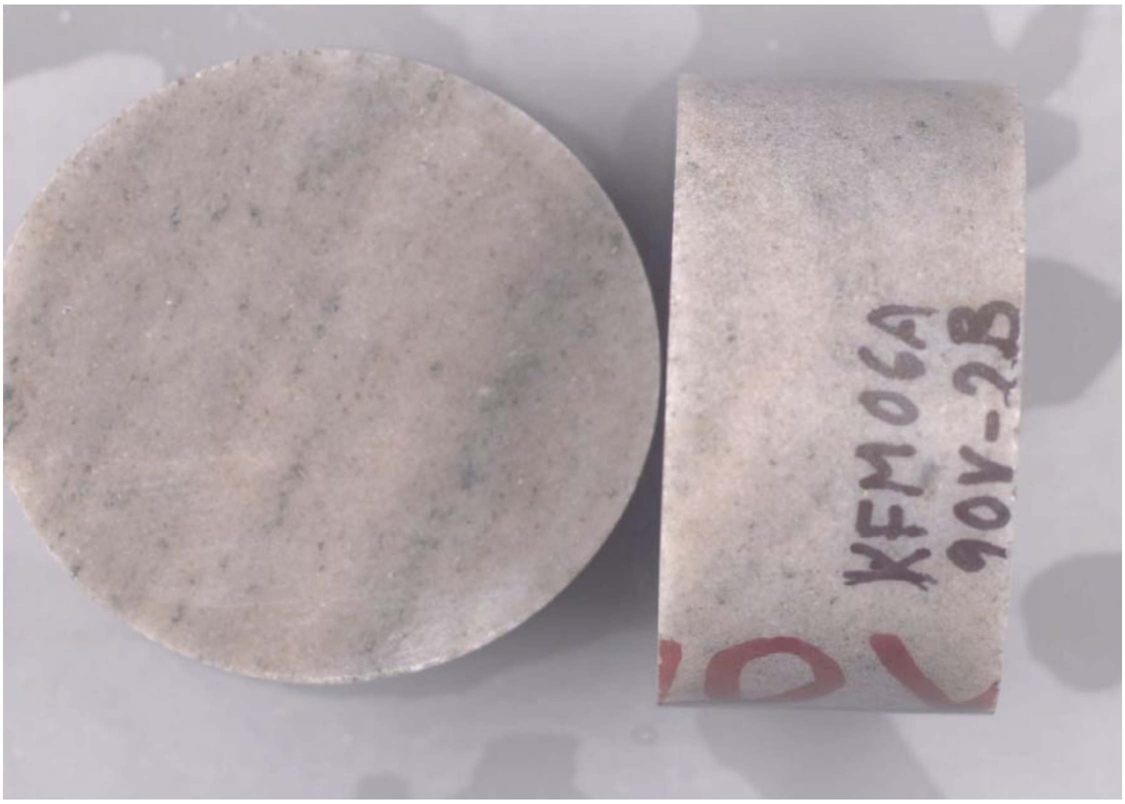

Figure 5-2. *Specimens KFM06A-90V-02.*

Table 5-3. Porosity, wet and dry density of specimens KFM06A-90V-02, average values.

Sample	Density, wet kg/m³	Density, dry kg/m³	Porosity %
KFM06A-90V-02	2,650	2,640	0.3
Adj sec low: 822.87			

Table 5-4. Thermal properties of sample KFM06A-90V-02 at ambient temperature.

KFM06A-90V-02 Adj sec low: 822.87	Conductivity W/(m, K)	Diffusivity mm²/s	Heat capacity MJ/(m³, K)
20°C			
Mean value	4.03	1.85	2.18
Standard deviation	0.009	0.035	0.045

Sample KFM06A-90V-03

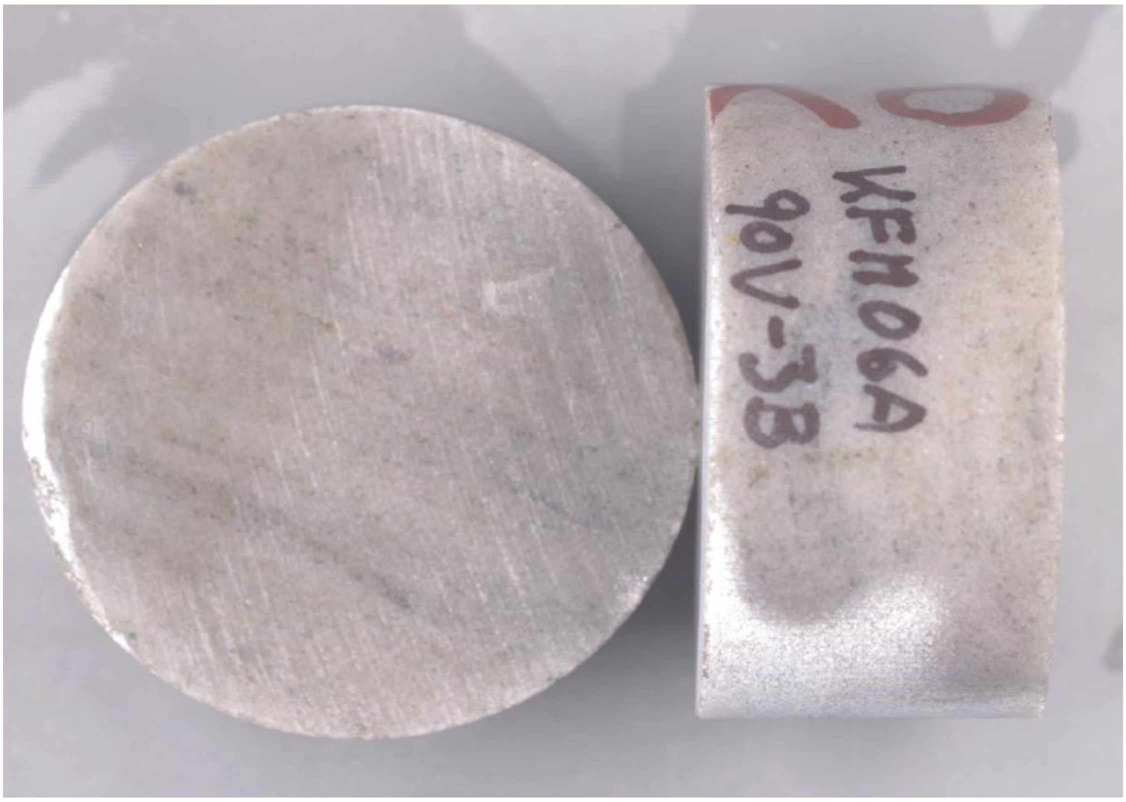

Figure 5-3. *Specimens KFM06A-90V-03.*

Table 5-5. Porosity, wet and dry density of specimens KFM06A-90V-03, average values.

Sample	Density, wet kg/m^3	Density, dry kg/m^3	Porosity %
KFM06A-90V-03	2,650	2,650	0.3
Adj sec low: 822.96			

Table 5-6. Thermal properties of sample KFM06A-90V-03 at ambient temperature.

KFM06A-90V-03 Adj sec low: 822.96	Conductivity W/(m, K)	Diffusivity mm^2/s	Heat capacity MJ/(m^3, K)
20°C			
Mean value	4.06	1.88	2.16
Standard deviation	0.003	0.005	0.006

Sample KFM06A-90V-04

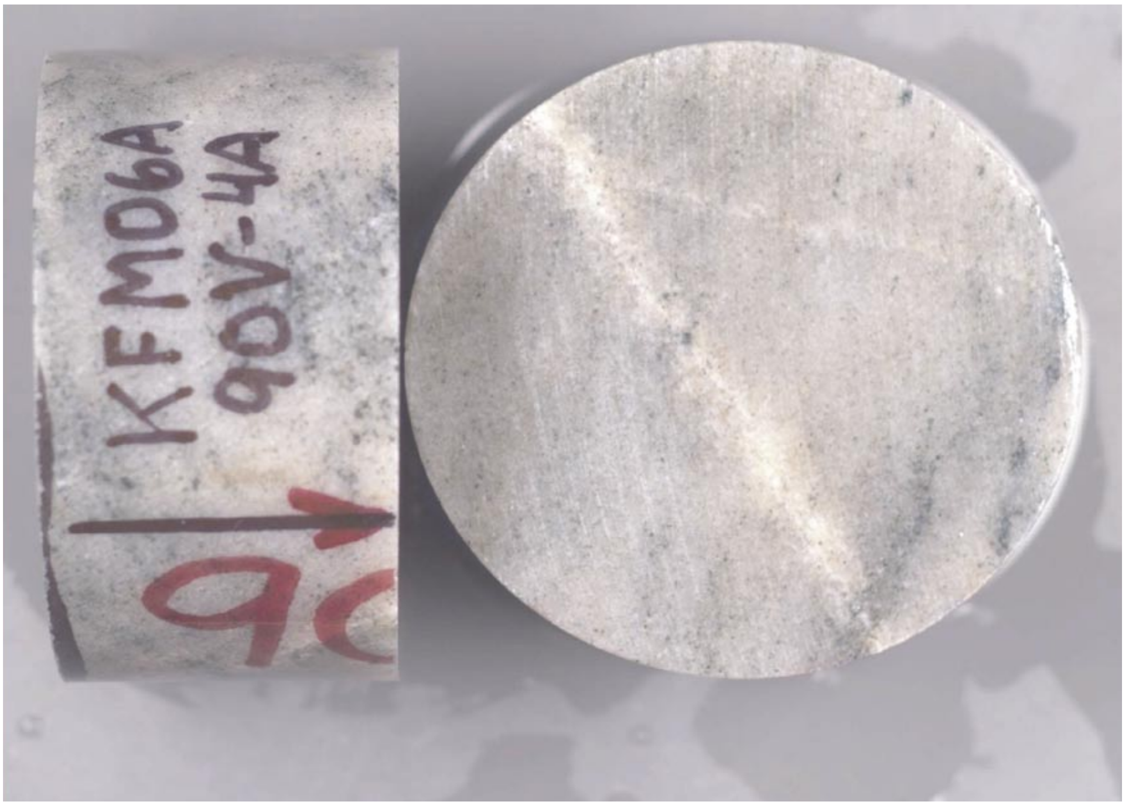

Figure 5-4. *Specimens KFM06A-90V-04.*

Table 5-7. Porosity, wet and dry density of specimens KFM06A-90V-04, average values.

Sample	Density, wet kg/m³	Density, dry kg/m³	Porosity %
KFM06A-90V-04	2,660	2,650	0.4
Adj sec low: 828.89			

Table 5-8. Thermal properties of sample KFM06A-90V-04 at ambient temperature.

KFM06A-90V-04 Adj sec low: 828.89	Conductivity W/(m, K)	Diffusivity mm²/s	Heat capacity MJ/(m³, K)
20°C			
Mean value	3.85	1.68	2.29
Standard deviation	0.008	0.015	0.020

Sample KFM06A-90V-05

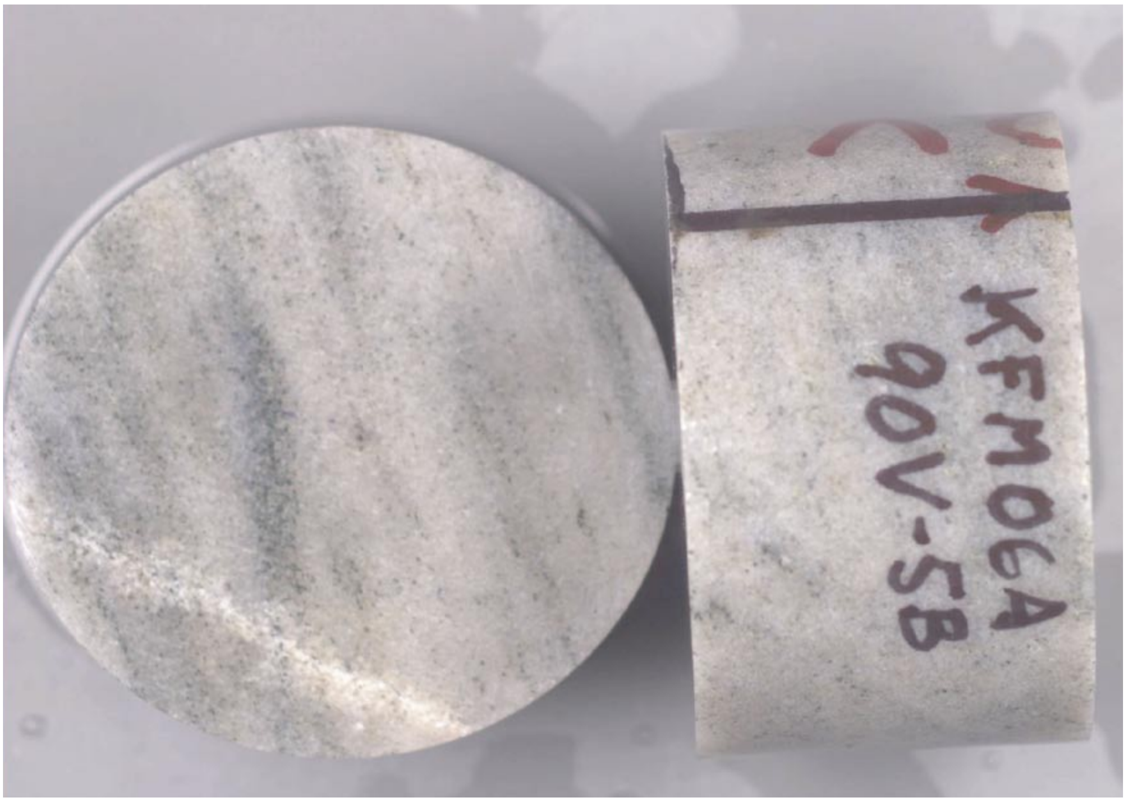

Figure 5-5. *Specimens KFM06A-90V-05.*

Table 5-9. Porosity, wet and dry density of specimens KFM06A-90V-05, average values.

Sample	Density, wet kg/m³	Density, dry kg/m³	Porosity %
KFM06A-90V-05	2,660	2,650	0.4
Adj sec low: 828.96			

Table 5-10. Thermal properties of sample KFM06A-90V-05 at ambient temperature.

KFM06A-90V-05 Adj sec low: 828.96	Conductivity W/(m, K)	Diffusivity mm²/s	Heat capacity MJ/(m³, K)
20°C			
Mean value	3.70	1.83	2.03
Standard deviation	0.006	0.006	0.006

Sample KFM06A-90V-06

Figure 5-6. *Specimens KFM06A-90V-06.*

Table 5-11. Porosity, wet and dry density of specimens KFM06A-90V-06, average values.

Sample	Density, wet kg/m³	Density, dry kg/m³	Porosity %
KFM06A-90V-06	2,660	2,660	0.4
Adj sec low: 829.02			

Table 5-12. Thermal properties of sample KFM06A-90V-06 at ambient temperature.

KFM06A-90V-06 Adj sec low: 829.02	Conductivity W/(m, K)	Diffusivity mm²/s	Heat capacity MJ/(m³, K)
20°C			
Mean value	3.80	1.82	2.09
Standard deviation	0.002	0.005	0.006

5.1.2 Results for the entire test series

Table 5-13 shows the mean value of five repeated measurements of the thermal properties. Standard deviation is presented in Table 5-14.

Thermal conductivity and thermal diffusivity of specimens at 825 m borehole length at 20°C were in the range of 3.70–4.06 W/(m, K) and 1.68–1.97 mm^2/s respectively.

5.1.2.1 Graphical presentation of results

Variation of the thermal conductivity and heat capacity versus borehole length is shown in Figure 5-7.

Table 5-13. Mean value of thermal properties of samples at 20°C.

Sample identification	Conductivity W/(m, K)	Diffusivity mm^2/s	Heat capacity $MJ/(m^3, K)$
KFM06A-90V-01	3.88	1.97	1.97
KFM06A-90V-02	4.03	1.85	2.18
KFM06A-90V-03	4.06	1.88	2.16
KFM06A-90V-04	3.85	1.68	2.29
KFM06A-90V-05	3.70	1.83	2.03
KFM06A-90V-06	3.80	1.82	2.09
Mean value, level 825	3.89	1.84	2.12

Table 5-14. Standard deviation of measured values at 20°C.

Sample identification	Conductivity W/(m, K)	Diffusivity mm^2/s	Heat capacity $MJ/(m^3, K)$
KFM06A-90V-01	0.008	0.034	0.034
KFM06A-90V-02	0.009	0.035	0.045
KFM06A-90V-03	0.003	0.005	0.006
KFM06A-90V-04	0.008	0.015	0.020
KFM06A-90V-05	0.006	0.006	0.006
KFM06A-90V-06	0.002	0.005	0.006

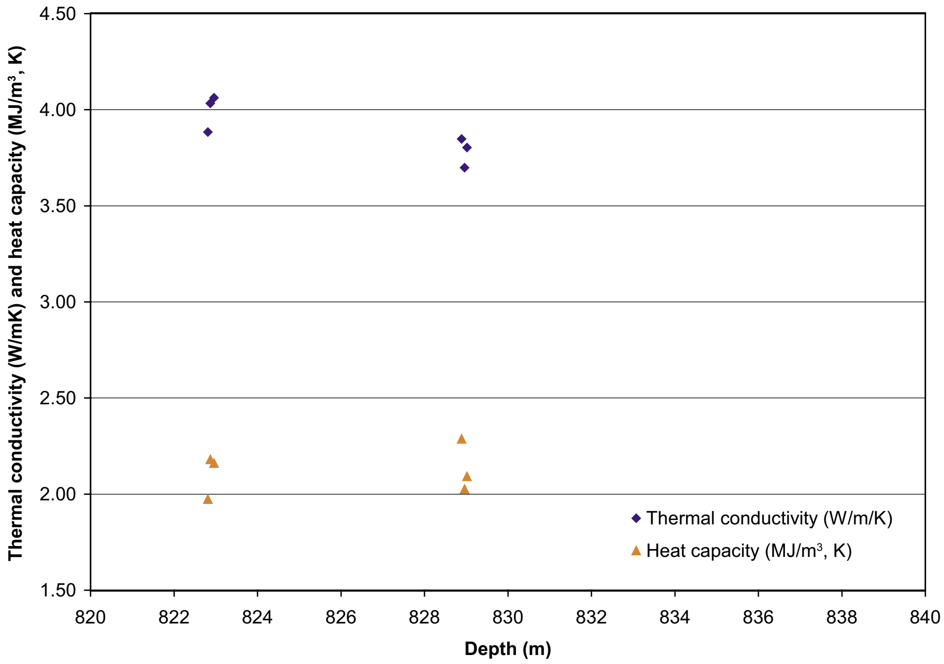

Figure 5-7. *Thermal conductivity and heat capacity versus borehole length at 20°C.*

6 References

/1/ 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.

/2/ Instruction Manual Hot Disc Thermal Constants Analyser Windows 95 Version 5.0, 2001.

/3/ 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:	13.47 W/(m, K)	± 0.05%
Thermal diffusivity:	3.511 mm^2/s	± 0.22%
Heat capacity:	3.837 $MJ/(m^3, K)$	± 0.22%

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

Borås 24/01 2005

Patrik Nilsson

Appendix B

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

Measurement number	Conductivity W/(m, K)	Diffusivity mm²/s	Heat capacity MJ/(m³, K)
KFM06A-90V-01			
1	3.87	1.93	2.01
2	3.89	1.96	1.98
3	3.88	2.02	1.92
4	3.89	1.96	1.99
5	3.88	1.96	1.98
KFM06A-90V-02			
1	4.04	1.87	2.15
2	4.02	1.90	2.11
3	4.04	1.83	2.20
4	4.04	1.82	2.22
5	4.04	1.82	2.21
KFM06A-90V-03			
1	4.06	1.89	2.15
2	4.06	1.88	2.15
3	4.06	1.88	2.16
4	4.06	1.88	2.16
5	4.07	1.88	2.17
KFM06A-90V-04			
1	3.85	1.70	2.26
2	3.86	1.68	2.30
3	3.85	1.68	2.30
4	3.84	1.69	2.27
5	3.84	1.67	2.30
KFM06A-90V-05			
1	3.70	1.84	2.02
2	3.70	1.83	2.03
3	3.70	1.82	2.03
4	3.70	1.83	2.02
5	3.69	1.82	2.03
KFM06A-90V-06			
1	3.80	1.81	2.10
2	3.80	1.82	2.09
3	3.80	1.82	2.09
4	3.80	1.82	2.09
5	3.80	1.82	2.09

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
KFM06A-90V-01			
1	20	0.94	18– 200
2	20	0.86	32– 180
3	20	0.93	51– 190
4	20	0.95	45– 200
5	20	0.95	35– 200
KFM06A-90V-02			
1	20	0.84	24– 185
2	20	0.47	14– 102
3	20	0.76	24– 171
4	20	0.88	31– 200
5	20	0.88	53– 200
KFM06A-90V-03			
1	20	0.91	29– 200
2	20	0.86	29– 188
3	20	0.91	31– 200
4	20	0.90	31– 198
5	20	0.91	32– 200
KFM06A-90V-04			
1	20	0.73	50– 176
2	20	0.81	70– 200
3	20	0.81	62– 200
4	20	0.82	55– 200
5	20	0.81	72– 200
KFM06A-90V-05			
1	20	0.85	30– 191
2	20	0.85	30– 191
3	20	0.84	30– 191
4	20	0.85	30– 191
5	20	0.84	30– 191
KFM06A-90V-06			
1	20	0.87	35– 197
2	20	0.88	35– 200
3	20	0.88	35– 200
4	20	0.88	35– 200
5	20	0.88	35– 200