P-05-219

Forsmark site investigation

Borehole KFM08A

Thermal conductivity and thermal diffusivity determined using the TPS method

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September 2006

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Keywords: Thermal properties, Thermal conductivity, Thermal diffusivity, Heat capacity, Transient Plane Source method, AP PF 400-05-058.

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 of sixteen specimens from borehole KFM08A, Forsmark, Sweden, were determined at ambient temperature (20°C) by a direct measurement method, the so called Transient Plane Source Method (TPS), Gustafsson, 1991. The samples were collected partly from the dominant rock type metamorphic, medium-grained granite to granodiorite (101057) at intervals of c. 75 m within the section 200–650 m borehole length. Samples were also taken between c. 257–813 m of the following minority rock types: amphibolite (102017), metamorphic, fine- to medium-grained granite, granodiorite and tonalite (101051), metamorphic felsic to intermediate volcanic rock (103076), pegmatite, pegmatitic granite (101061), and metamorphic, aplitic granite (101058).

Thermal conductivity and thermal diffusivity at 20°C were in the range of 2.30–3.98 W/(m, K) respectively 0.93–1.95 mm^2/s. The heat capacity, which was calculated from the thermal conductivity and diffusivity, ranged between 1.89 and 2.48 $MJ/(m^3, K)$.

Sammanfattning

Termiska egenskaper hos sexton provkroppar från borrhål KFM08A, Forsmark, bestämdes vid rumstemperatur (20°C) med den s.k. TPS metoden (”Transient Plane Source”), Gustafsson 1991. Proverna från borrhålet hade tagits dels från den dominerande bergarten metamorf, medelkorning granit till granodiorit (101057) på ca 75 m avstånd från varandra inom intervallet 200–650 m (borrhålslängd). Proverna var också tagna i intervalket 257–813 m från följande minoritetsbergarter: amfibolit (102017), metamorf, fin- till medelkorning granit, granodiorit och tonalit (101051), metamorf, sur till intermediär vulkanit (103076), pegmatit, pegmatitisk granit (101061) och metamorf, aplitisk granit (101058).

Den termiska konduktiviteten och den termiska diffusiviteten hos provkropparna vid 20°C uppgick till 2,30–3,98 W/(m, K) respektive 0,93–1,95 mm^2/s. Från värdena på dessa parametrar kunde värmekapaciteten beräknas och befanns ligga i intervallet 1,89–2,48 $MJ/(m^3, K)$.

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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 KFM08A 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 densities, as well as porosity of the samples, were determined within the scope of parallel activity /3/.

Borehole KFM08A, see Figure 1-1, is a telescopic drilled borehole inclined c. 60° from the horizontal plane and with a total length of c. 1,000 m. The borehole section 0–100.55 m is percussion drilled, whereas the section 100.55–1,000 m is core drilled.

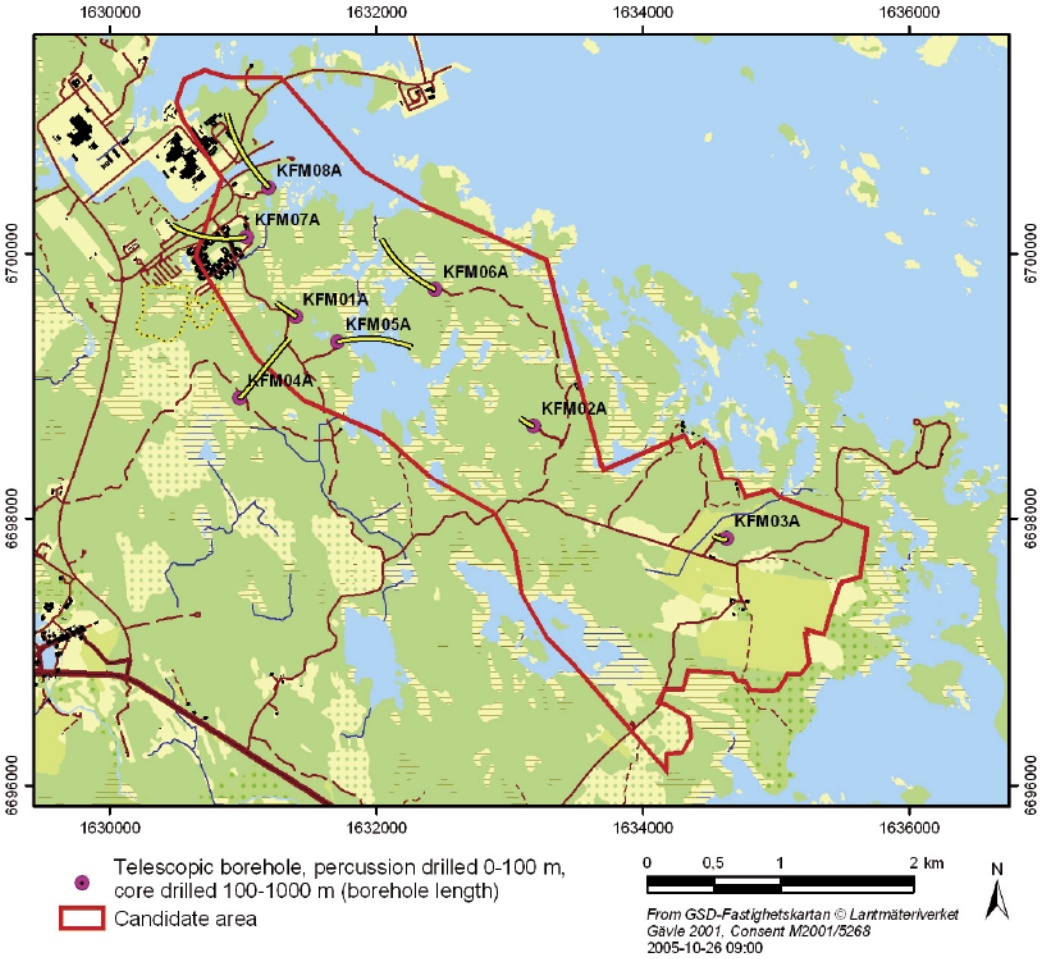

Figure 1-1. *Location of all telescopic boreholes drilled up to December 2005 within and close to the Forsmark candidate area. The projection of each borehole on the horizontal plane at top of casing is also shown in the figure.*

Rock samples were selected at Forsmark based on the preliminary core logging with the strategy to investigate the properties of the dominant rock type, metamorphic, medium-grained granite to granodiorite, as well as of a number of minority rock types: amphibolite, metamorphic, fine- to medium-grained granite, granodiorite and tonalite, metamorphic, felsic to intermediate volcanite, pegmatite and pegmatitic granite and metamorphic, aplitic granite. The specimens to be tested were cut from the rock samples in the shape of circular discs. The rock samples arrived at SP in August 2005. The thermal properties were determined on water-saturated specimens. Testing was performed during October 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. Also SP's (Swedish National Testing and Research Institute) Quality Plan (SP-QD 13.1) served as a controlling document.

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

Activity Plan	**Number**	**Version**
KFM08A. Bergmekaniska och termiska laboratoriebestämningar	AP PF 400-05-058	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 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.

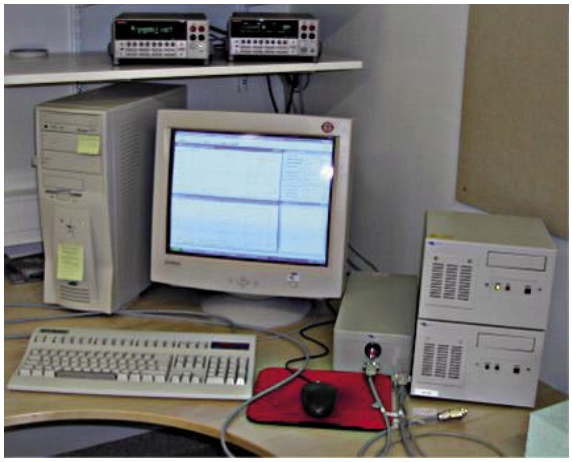

Figure 3-1. *TPS-apparatus with source meter, multi-meter, bridge, and computer.*

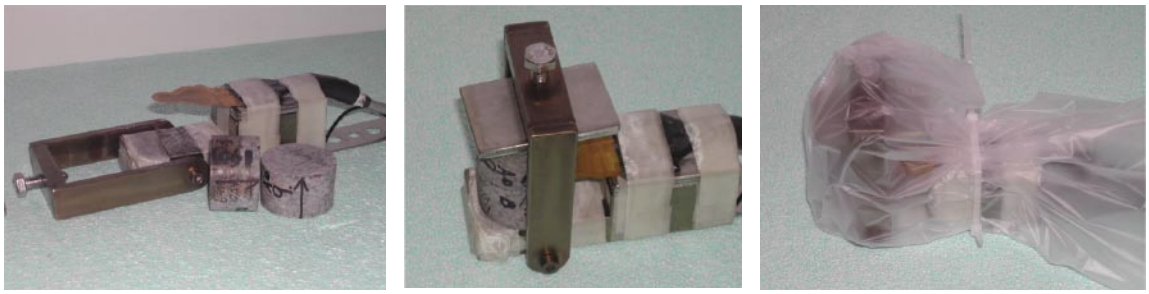

Figure 3-2. *Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).*

4 Execution

Determination of 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 Fire Technology, see SP-QD 13.1.

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 /5/.

4.1 Description of the samples

Sixteen pairs of cores (designated A and B) were sampled from borehole KFM08A, Forsmark, Sweden. The cores were collected within the interval 200–813 m. The thirty-two specimens with a thickness of 25 mm each (see) 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 KFM08A 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 KFM08A 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/occurrence	Sampling level, (m borehole length) (Adj Sec low)
KFM08A-90V-01	Granite to granodiorite, metamorphic, medium-grained (101057)	200,896
KFM08A-90V-02	Amphibolite (102017)	257,312
KFM08A-90V-03	Granite to granodiorite, metamorphic, medium-grained (101057)	288,798
KFM08A-90V-04	Granite to granodiorite, metamorphic, medium-grained (101057)	350,193
KFM08A-90V-05	Granite to granodiorite, metamorphic, medium-grained (101057)	424,299
KFM08A-90V-06	Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained (101051)	460,258
KFM08A-90V-07	Amphibolite (102017)	478,476
KFM08A-90V-08	Felsic to intermediate volcanic rock, metamorphic (103076)	494,625
KFM08A-90V-09	Granite to granodiorite, metamorphic, medium-grained (101057)	503,615
KFM08A-90V-10	Granite to granodiorite, metamorphic, medium-grained (101057)	576,502
KFM08A-90V-11	Granite to granodiorite, metamorphic, medium-grained (101057)	650,050
KFM08A-90V-12	Pegmatite, pegmatitic granite (101061)	668,600
KFM08A-90V-13	Pegmatite, pegmatitic granite (101061)	670,376
KFM08A-90V-14	Granite, metamorphic, aplitic (101058)	783,895
KFM08A-90V-15	Granite, metamorphic, aplitic (101058)	807,613
KFM08A-90V-16	Granite, metamorphic, aplitic (101058)	812,795

4.2 Test procedure

The present activity was performed parallel to another activity /3/, conducted by SP Building Technology and Mechanics, 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 /3/.
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 the SKB catalogue at the 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 September–October 2005.

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 5.1 and 5.2. Values of each separate measurement as described in Chapter 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 is 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 KFM08A-90V-01A and B

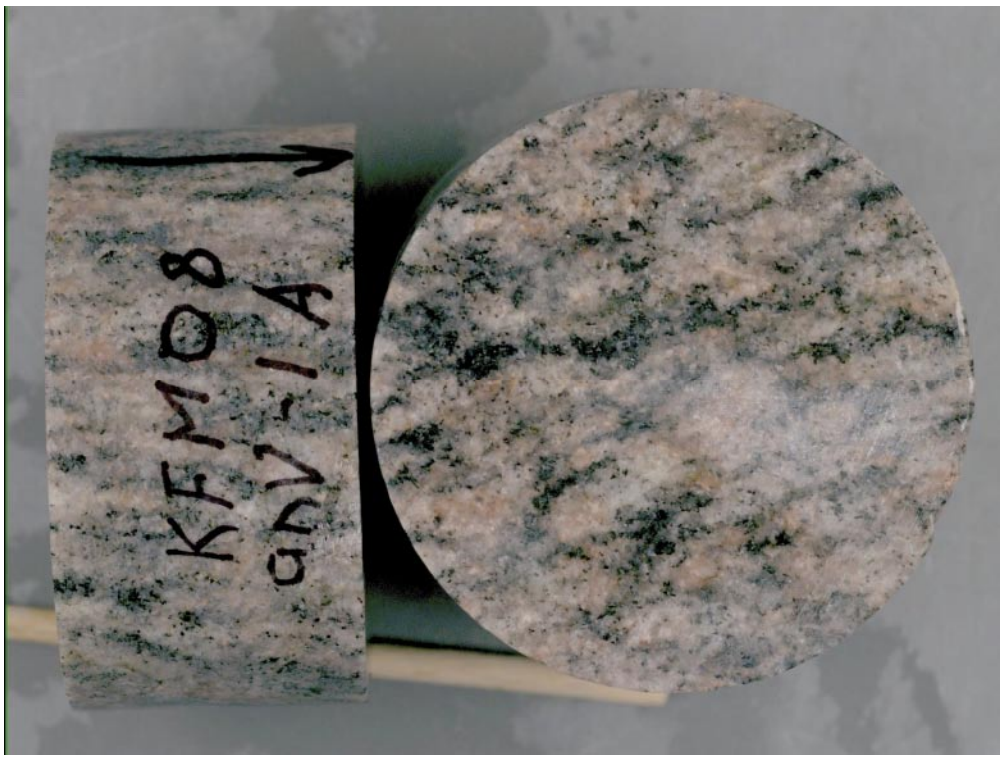

Figure 5-1. *Specimens KFM08A-90V-01.*

Table 5-1. Porosity, wet and dry density of specimens KFM08A-90V-01, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-01 Sec low: 200.90	2,650	2,650	0.5

Table 5-2. Thermal properties of specimens KFM08A-90V-01 at ambient temperature, average values.

KFM08A-90V-01 Sec low: 200.90	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.67	1.68	2.19
Standard deviation	0.018	0.031	0.043

Specimens KFM08A-90V-02A and B

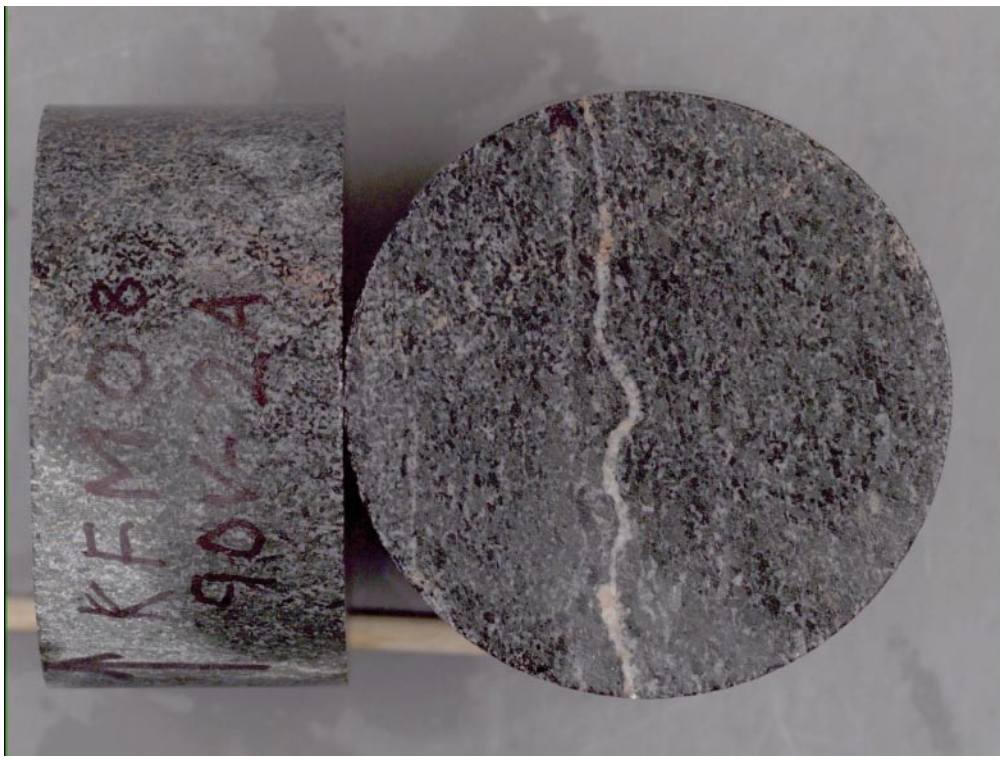

Figure 5-2. *Specimens KFM08A-90V-02A and B.*

Table 5-3. Porosity, wet and dry density of specimens KFM08A-90V-02, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-02 Sec low: 257.31	3,000	2,990	0.4

Table 5-4. Thermal properties of specimens KFM08A-90V-02 at ambient temperature, average values.

KFM08A-90V-02 Sec low: 257.31	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	2.36	1.03	2.30
Standard deviation	0.002	0.005	0.012

Specimens KFM08A-90V-03A and B

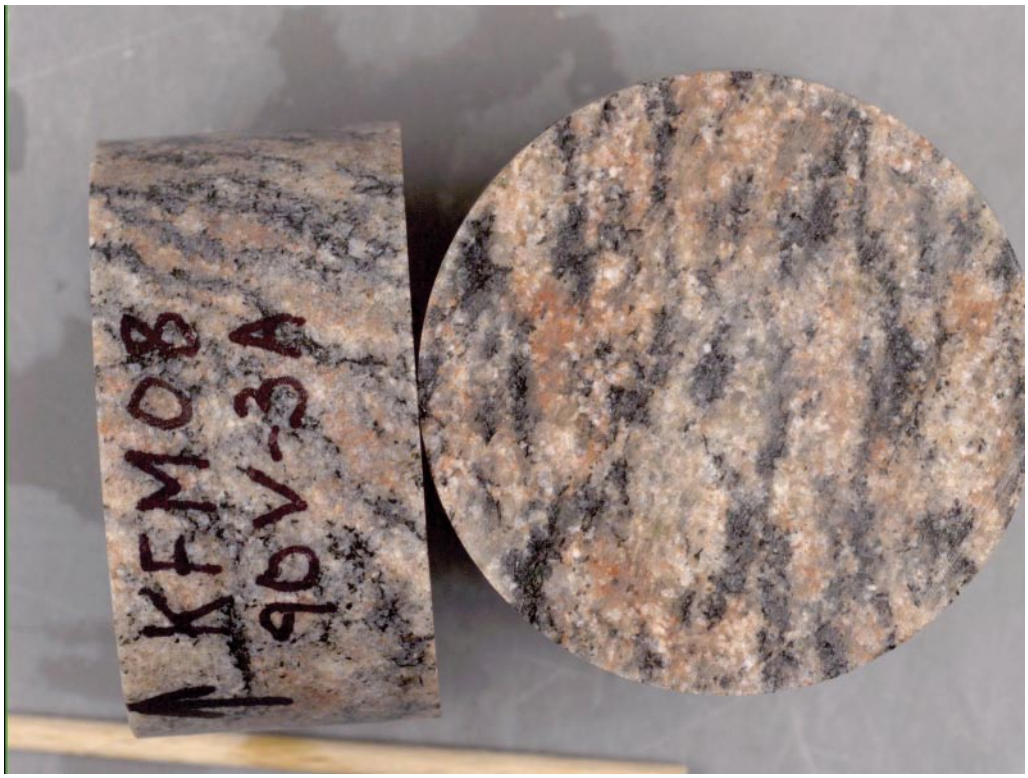

Figure 5-3. *Specimens KFM08A-90V-03A and B.*

Table 5-5. Porosity, wet and dry density of specimens KFM08A-90V-03, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-03 Sec low: 288.80	2,660	2,650	0.4

Table 5-6. Thermal properties of specimens KFM08A-90V-03 at ambient temperature, average values.

KFM08A-90V-03 Sec low: 288.80	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.55	1.77	2.01
Standard deviation	0.005	0.012	0.016

Specimens KFM08A-90V-04A and B

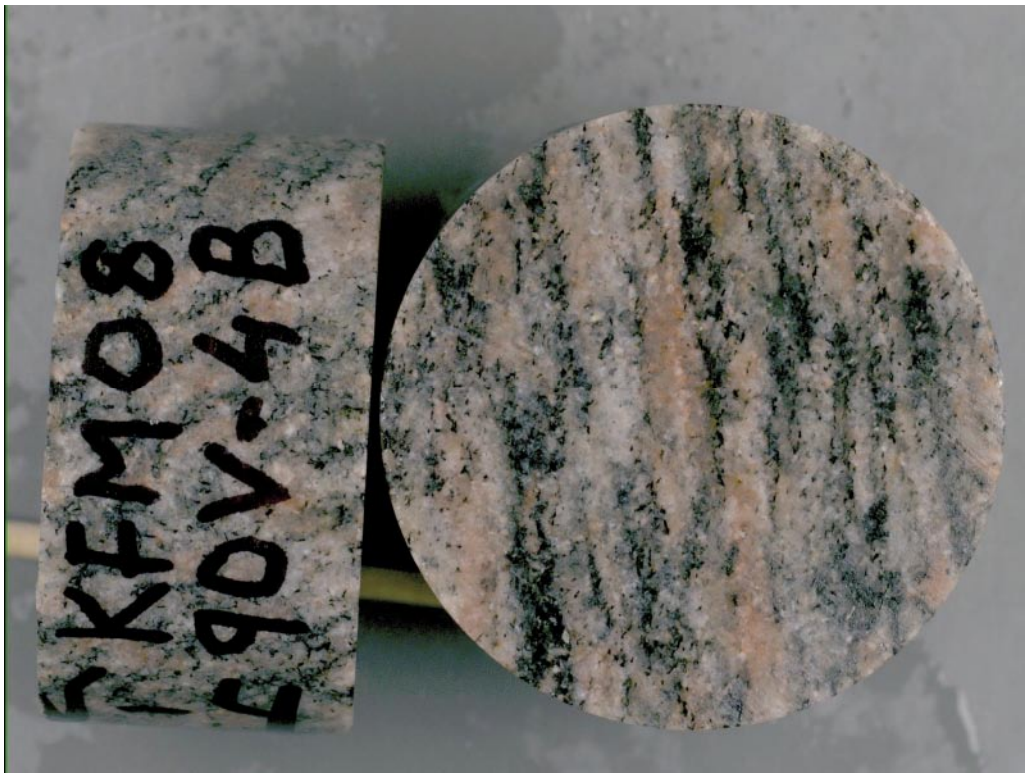

Figure 5-4. *Specimens KFM08A-90V-04A and B.*

Table 5-7. Porosity, wet and dry density of specimens KFM08A-90V-04, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-04 Sec low: 350.19	2,660	2,660	0.3

Table 5-8. Thermal properties of specimens KFM08A-90V-04 at ambient temperature, average values.

KFM08A-90V-04 Sec low: 350.19	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.49	1.67	2.09
Standard deviation	0.007	0.008	0.006

Specimens KFM08A-90V-05A and B

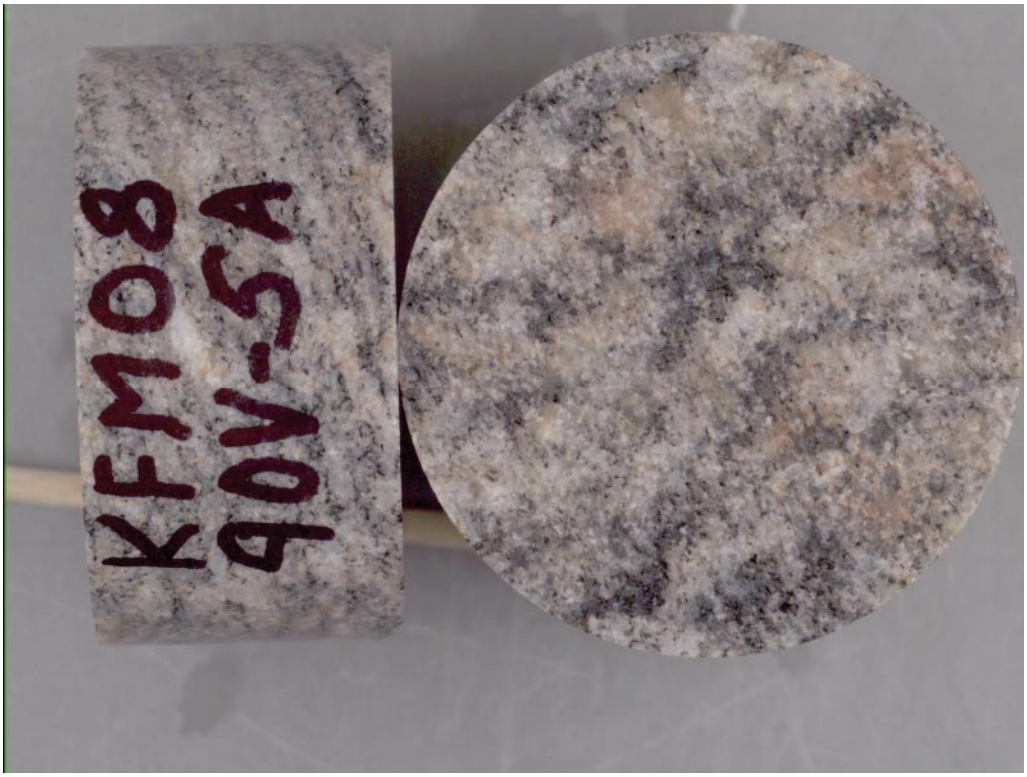

Figure 5-5. *Specimens KFM08A-90V-05A and B.*

Table 5-9. Porosity, wet and dry density of specimens KFM08A-90V-05, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-05 Sec low: 424.30	2,650	2,650	0.3

Table 5-10. Thermal properties of specimens KFM08A-90V-05 at ambient temperature, average values.

KFM08A-90V-05 Sec low: 424.30	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.57	1.73	2.07
Standard deviation	0.004	0.005	0.007

Specimens KFM08A-90V-06A and B

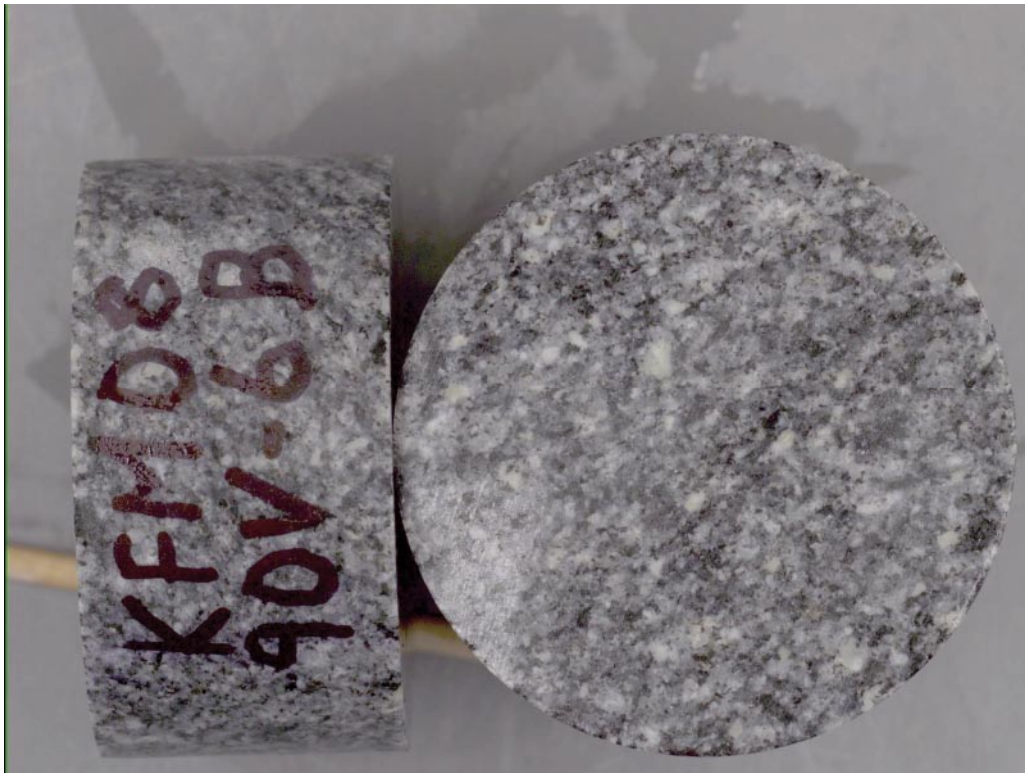

Figure 5-6. *Specimens KFM08A-90V-06A and B.*

Table 5-11. Porosity, wet and dry density of specimens KFM08A-90V-06, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KFM08A-90V-06 Sec low: 460.26	2,720	2,720	0.3

Table 5-12. Thermal properties of specimens KFM08A-90V-06 at ambient temperature, average values.

KFM08A-90V-06 Sec low: 460.26	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
	20°C		
Mean value	2.86	1.37	2.09
Standard deviation	0.002	0.006	0.010

Specimens KFM08A-90V-07A and B

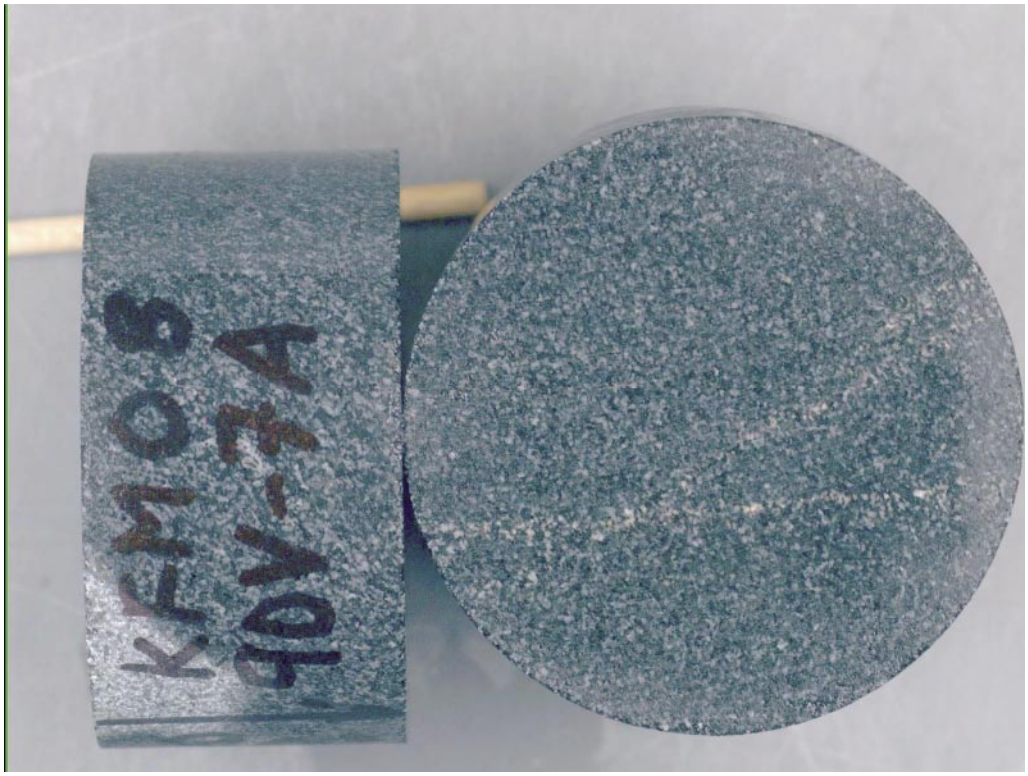

Figure 5-7. *Specimens KFM08A-90V-07A and B.*

Table 5-13. Porosity, wet and dry density of specimens KFM08A-90V-07, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-07 Sec low: 478.48	2,980	2,970	0.5

Table 5-14. Thermal properties of specimens KFM08A-90V-07 at ambient temperature, average values.

KFM08A-90V-07 Sec low: 478.48	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	2.30	0.93	2.48
Standard deviation	0.002	0.001	0.003

Specimens KFM08A-90V-08A and B

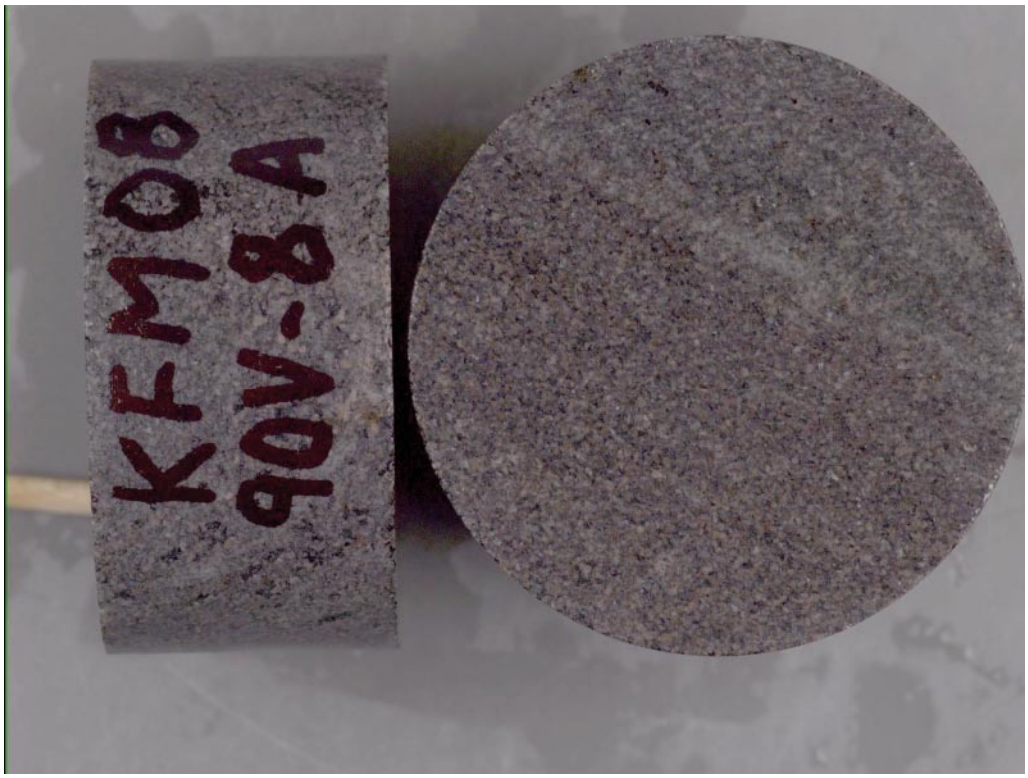

Figure 5-8. *Specimens KFM08A-90V-08A and B.*

Table 5-15. Porosity, wet and dry density of specimens KFM08A-90V-08, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KFM08A-90V-08 Sec low: 494.63	2,700	2,700	0.4

Table 5-16. Thermal properties of specimens KFM08A-90V-08 at ambient temperature, average values.

KFM08A-90V-08 Sec low: 494.63	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
	20°C		
Mean value	2.99	1.36	2.19
Standard deviation	0.002	0.004	0.007

Specimens KFM08A-90V-09A and B

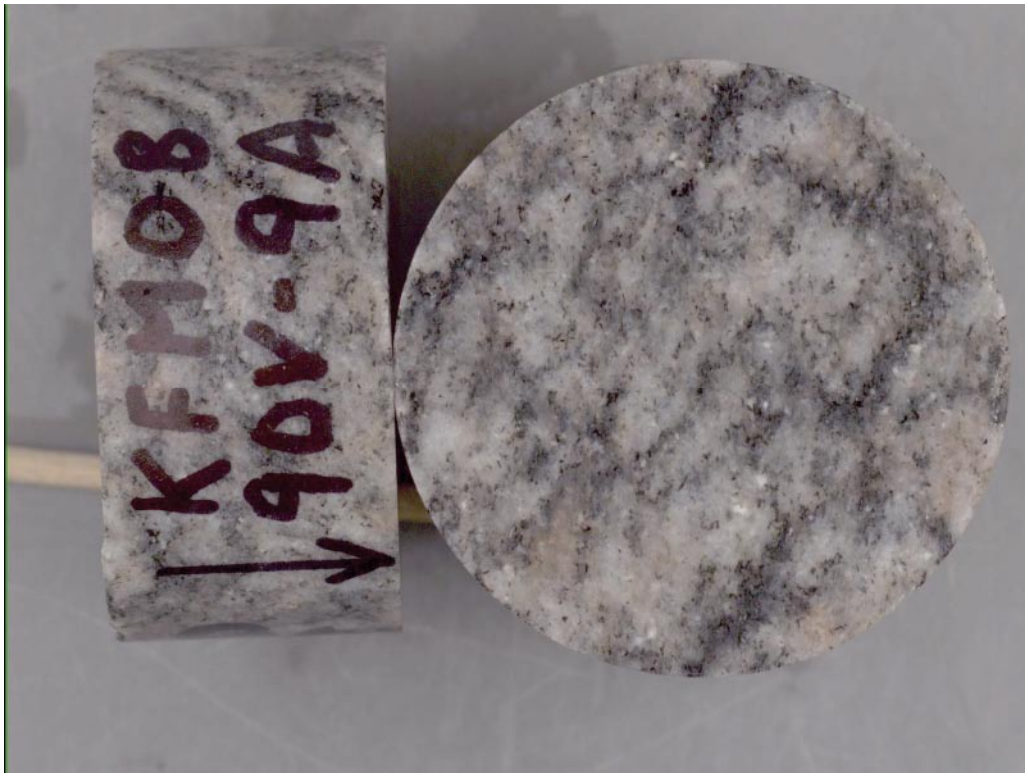

Figure 5-9. *Specimens KFM08A-90V-09A and B.*

Table 5-17. Porosity, wet and dry density of specimens KFM08A-90V-09, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-09 Sec low: 503.62	2,660	2,650	0.3

Table 5-18. Thermal properties of specimens KFM08A-90V-09 at ambient temperature, average values.

KFM08A-90V-09 Sec low: 503.62	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.48	1.71	2.03
Standard deviation	0.014	0.012	0.022

Specimens KFM08A-90V-10A and B

Figure 5-10. *Specimens KFM08A-90V-10A and B.*

Table 5-19. Porosity, wet and dry density of specimens KFM08A-90V-10, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KFM08A-90V-10 Sec low: 576.50	2,650	2,650	0.3

Table 5-20. Thermal properties of specimens KFM08A-90V-10 at ambient temperature, average values.

KFM08A-90V-10 Sec low: 576.50	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
		20°C	
Mean value	3.44	1.78	1.94
Standard deviation	0.009	0.010	0.015

Specimens KFM08A-90V-11A and B

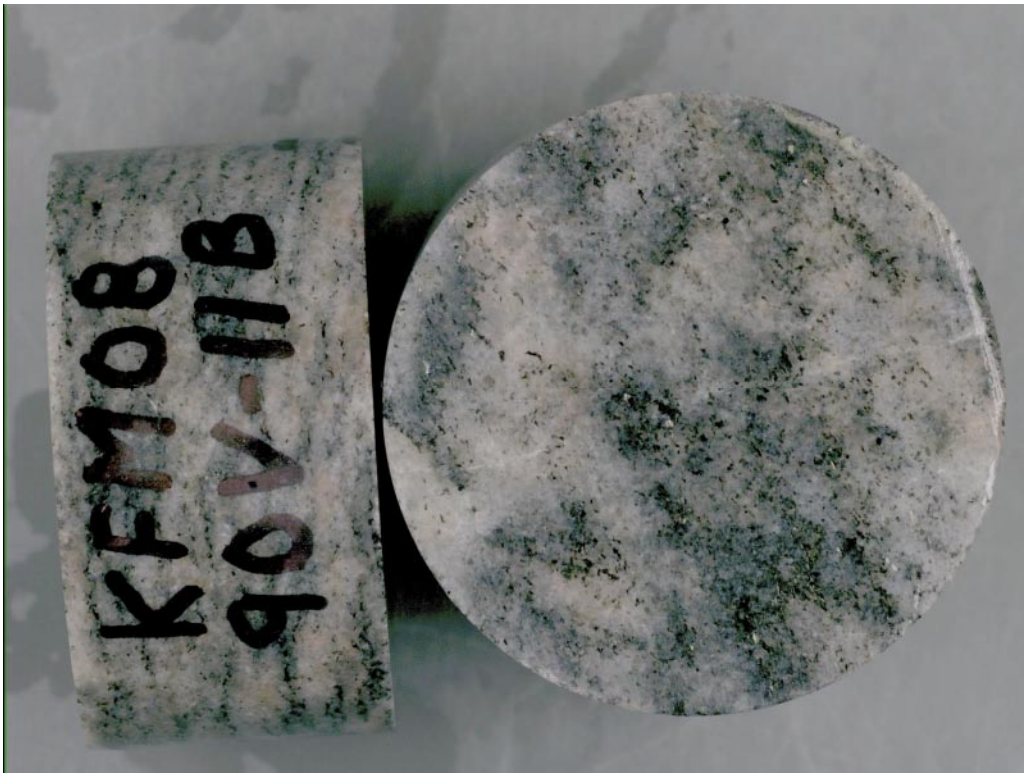

Figure 5-11. *Specimens KFM08A-90V-11A and B.*

Table 5-21. Porosity, wet and dry density of specimens KFM08A-90V-11, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-11 Sec low: 650.05	2,660	2,650	0.3

Table 5-22. Thermal properties of specimens KFM08A-90V-11 at ambient temperature, average values.

KFM08A-90V-11 Sec low: 650.05	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.43	1.82	1.89
Standard deviation	0.009	0.014	0.019

Specimens KFM08A-90V-12A and B

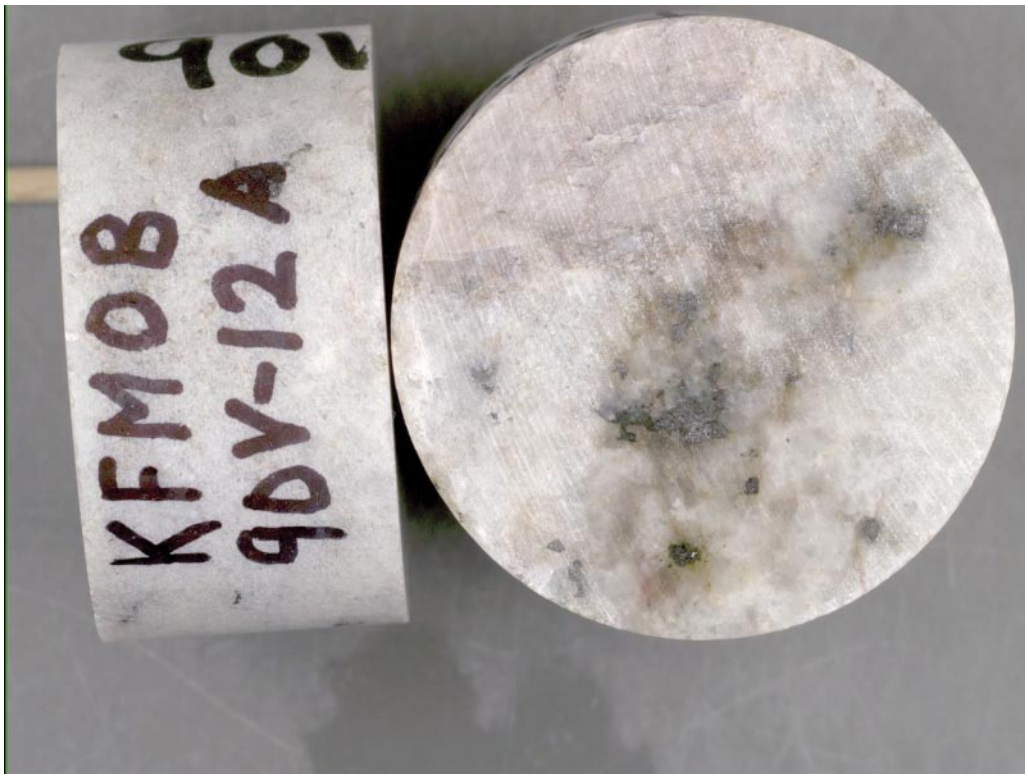

Figure 5-12. *Specimens KFM08A-90V-12A and B.*

Table 5-23. Porosity, wet and dry density of specimens KFM08A-90V-12, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-12 Sec low: 668.60	2,630	2,620	0.3

Table 5-24. Thermal properties of specimens KFM08A-90V-12 at ambient temperature, average values.

KFM08A-90V-12 Sec low: 668.60	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.47	1.83	1.90
Standard deviation	0.012	0.014	0.020

Specimens KFM08A-90V-13A and B

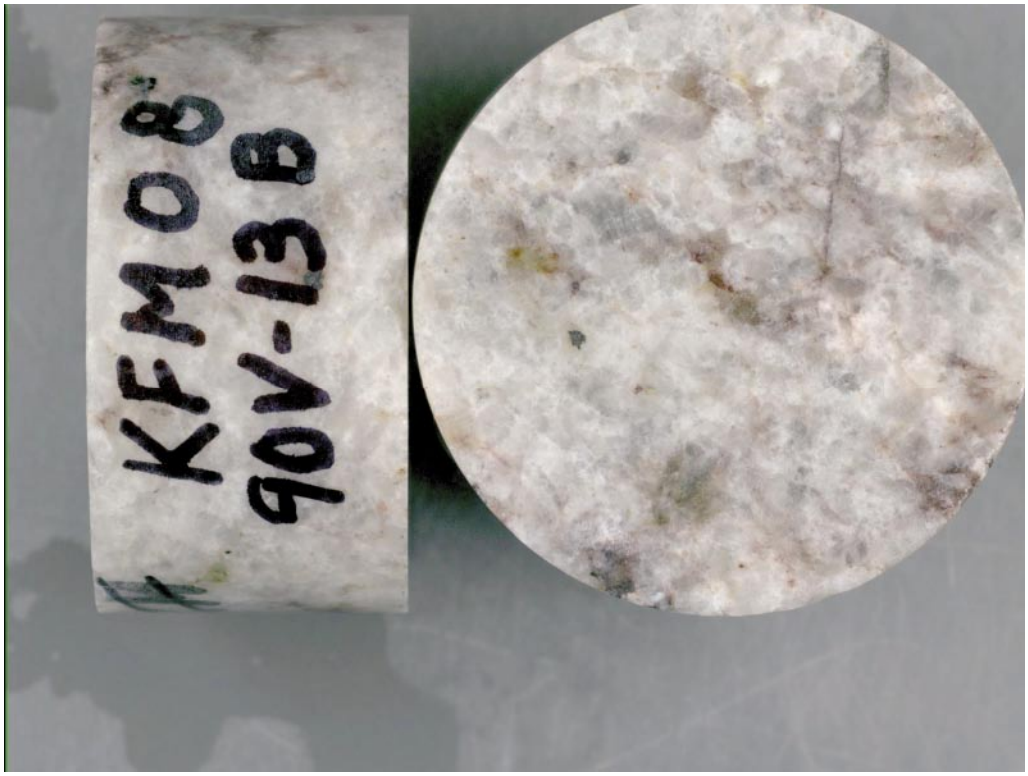

Figure 5-13. *Specimens KFM08A-90V-13A and B.*

Table 5-25. Porosity, wet and dry density of specimens KFM08A-90V-13, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-13 Sec low: 670.38	2,640	2,640	0.3

Table 5-26. Thermal properties of specimens KFM08A-90V-13 at ambient temperature.

KFM08A-90V-13 Sec low: 670.38	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.50	1.76	1.98
Standard deviation	0.009	0.012	0.017

Specimens KFM08A-90V-14A and B

Figure 5-14. *Specimens KFM08A-90V-14A and B.*

Table 5-27. Porosity, wet and dry density of specimens KFM08A-90V-14, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KFM08A-90V-14 Sec low: 783.90	2,630	2,630	0.2

Table 5-28. Thermal properties of specimens KFM08A-90V-14 at ambient temperature, average values.

KFM08A-90V-14 Sec low: 783.90	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
	20°C		
Mean value	3.74	1.90	1.98
Standard deviation	0.006	0.009	0.010

Specimens KFM08A-90V-15A and B

Figure 5-15. *Specimens KFM08A-90V-15A and B.*

Table 5-29. Porosity, wet and dry density of specimens KFM08A-90V-15, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-15 Sec low: 807.61	2,630	2,620	0.4

Table 5-30. Thermal properties of specimens KFM08A-90V-15 at ambient temperature, average values.

KFM08A-90V-15 Sec low: 807.61	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.98	1.90	2.10
Standard deviation	0.019	0.026	0.039

Specimens KFM08A-90V-16A and B

Figure 5-16. *Specimens KFM08A-90V-16A and B.*

Table 5-31. Porosity, wet and dry density of specimens KFM08A-90V-16, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KFM08A-90V-16 Sec low: 812.80	2,630	2,630	0.3

Table 5-32. Thermal properties of specimens KFM08A-90V-16 at ambient temperature, average values.

KFM08A-90V-16 Sec low: 812.80	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.80	1.95	1.95
Standard deviation	0.009	0.017	0.014

5.2 Results for the entire test series

Table 5-33 displays the mean value of five repeated measurements of the thermal properties. Standard deviation is shown in Table 5-34. The results are in both tables grouped according to rock type. Thus the mean values are in this report given “per rock type “instead of as in previous reports “per level”.

Thermal conductivity and thermal diffusivity of specimens representing different depths at 20°C were in the range 2.30–3.98 W/(m, K) respectively 0.93–1.95 mm^2/s. From these results the heat capacity was calculated and appeared to range between 1.89 and 2.48 MJ//(m^3, K). A graphical representation of the heat conductivity and heat capacity versus borehole length is given in Figure 5-17.

Table 5-33. 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)]
Rock type 101057			
KFM08A-90V-01	3.67	1.68	2.19
KFM08A-90V-03	3.55	1.77	2.01
KFM08A-90V-04	3.49	1.67	2.09
KFM08A-90V-05	3.57	1.73	2.07
KFM08A-90V-09	3.48	1.71	2.03
KFM08A-90V-10	3.44	1.78	1.94
KFM08A-90V-11	3.43	1.82	1.89
Mean value	**3.52**	**1.74**	**2.03**
Rock type 102017			
KFM08A-90V-02	2.36	1.03	2.30
KFM08A-90V-07	2.30	0.93	2.48
Mean value	**2.33**	**0.98**	**2.39**
Rock type 101051, single value			
KFM08A-90V-06	2.86	1.37	2.09
Rock type 103076, single value			
KFM08A-90V-08	2.99	1.36	2.19
Rock type 101061			
KFM08A-90V-12	3.47	1.83	1.90
KFM08A-90V-13	3.50	1.76	1.98
Mean value	**3.48**	**1.80**	**1.94**
Rock type 101058			
KFM08A-90V-14	3.74	1.90	1.98
KFM08A-90V-15	3.98	1.90	2.10
KFM08A-90V-16	3.80	1.95	1.95
Mean value	**3.84**	**1.92**	**2.01**

Table 5-34. Standard deviation of measured values at 20°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Rock type 101057			
KFM08A-90V-01	0.018	0.031	0.043
KFM08A-90V-03	0.005	0.012	0.016
KFM08A-90V-04	0.007	0.008	0.006
KFM08A-90V-05	0.004	0.005	0.007
KFM08A-90V-09	0.014	0.012	0.022
KFM08A-90V-10	0.009	0.010	0.015
KFM08A-90V-11	0.009	0.014	0.019
Rock type 102017			
KFM08A-90V-02	0.002	0.005	0.012
KFM08A-90V-07	0.002	0.001	0.003
Rock type 101051			
KFM08A-90V-06	0.002	0.006	0.010
Rock type 103076			
KFM08A-90V-08	0.002	0.004	0.007
Rock type 101061			
KFM08A-90V-12	0.012	0.014	0.020
KFM08A-90V-13	0.009	0.012	0.017
Rock type 101058			
KFM08A-90V-14	0.006	0.009	0.010
KFM08A-90V-15	0.019	0.026	0.039
KFM08A-90V-16	0.009	0.017	0.014

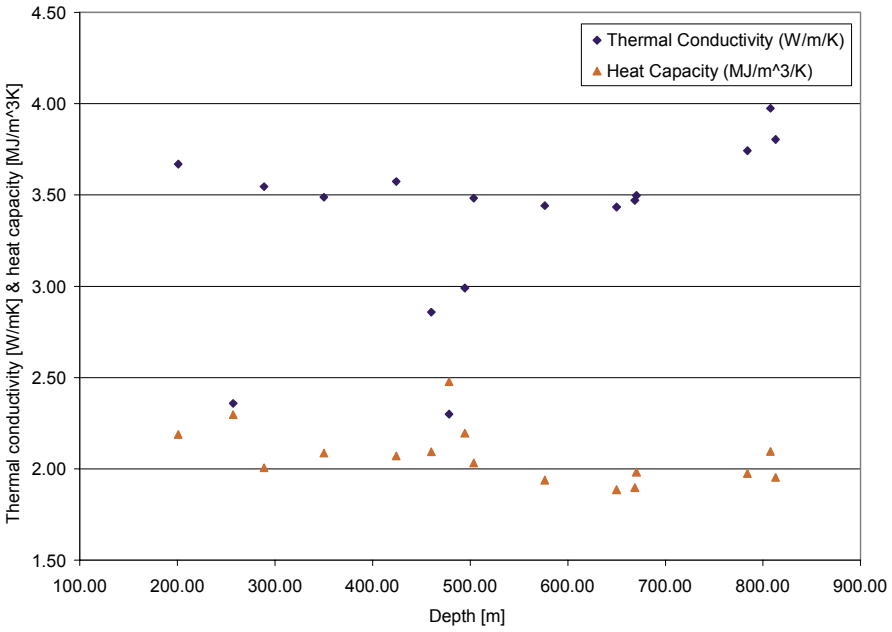

Figure 5-17. *Thermal conductivity and heat capacity versus borehole length at 20°C.*

6 References

/1/ **SKB, 2001.** Site investigations. Investigation methods and general execution 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/ **Liedberg L, 2005.** Forsmark site investigation. Borehole KFM08A. Determination of porosity by water saturation and density by buoyancy technique. SKB P-05-220. Svensk Kärnbränslehantering AB.

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

/5/ **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)	±0.04%
Thermal Diffusivity:	3.516 mm^2/s	±0.12%
Heat Capacity:	3.842 $MJ/(m^3. K)$	±0.15%

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

Borås 29/09 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)]
KFM08A-90V-01			
1	3.64	1.71	2.13
2	3.69	1.69	2.19
3	3.68	1.70	2.17
4	3.67	1.65	2.22
5	3.67	1.64	2.24
KFM08A 90V-02			
1	2.36	1.02	2.32
2	2.36	1.03	2.29
3	2.36	1.03	2.30
4	2.36	1.03	2.29
5	2.36	1.03	2.29
KFM08A 90V-03			
1	3.54	1.77	2.01
2	3.55	1.78	1.99
3	3.54	1.78	1.99
4	3.55	1.76	2.01
5	3.55	1.75	2.03
KFM08A 90V-04			
1	3.49	1.68	2.08
2	3.50	1.68	2.08
3	3.49	1.67	2.08
4	3.49	1.66	2.10
5	3.48	1.66	2.09
KFM08A 90V-05			
1	3.58	1.73	2.07
2	3.58	1.72	2.08
3	3.57	1.73	2.07
4	3.57	1.72	2.07
5	3.57	1.73	2.06
KFM08A 90V-06			
1	2.86	1.37	2.08
2	2.86	1.37	2.09
3	2.86	1.37	2.09
4	2.86	1.36	2.11
5	2.86	1.36	2.10
KFM08A 90V-07			
1	2.30	0.93	2.48
2	2.30	0.93	2.48
3	2.30	0.93	2.47
4	2.30	0.93	2.48
5	2.30	0.93	2.48

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
KFM08A 90V-08			
1	2.99	1.36	2.20
2	2.99	1.36	2.20
3	2.99	1.36	2.19
4	2.99	1.36	2.20
5	2.99	1.37	2.19
KFM08A 90V-09			
1	3.50	1.70	2.06
2	3.47	1.73	2.00
3	3.49	1.70	2.05
4	3.48	1.72	2.02
5	3.47	1.72	2.02
KFM08A 90V-10			
1	3.45	1.76	1.96
2	3.45	1.77	1.94
3	3.44	1.78	1.93
4	3.43	1.79	1.92
5	3.44	1.78	1.94
KFM08A 90V-11			
1	3.43	1.82	1.88
2	3.42	1.84	1.85
3	3.44	1.81	1.90
4	3.43	1.82	1.89
5	3.44	1.81	1.91
KFM08A 90V-12			
1	3.49	1.81	1.93
2	3.47	1.84	1.89
3	3.46	1.84	1.88
4	3.46	1.84	1.88
5	3.47	1.82	1.91
KFM08A 90V-13			
1	3.50	1.76	1.98
2	3.51	1.75	2.01
3	3.50	1.78	1.97
4	3.49	1.77	1.97
5	3.49	1.76	1.98
KFM08A 90V-14			
1	3.74	1.91	1.96
2	3.75	1.89	1.98
3	3.74	1.89	1.97
4	3.75	1.89	1.99
5	3.74	1.89	1.97
KFM08A 90V-15			
1	3.96	1.93	2.05
2	3.97	1.91	2.08
3	3.98	1.88	2.11
4	3.96	1.91	2.08
5	4.00	1.86	2.16

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
KFM08A 90V-16			
1	3.80	1.95	1.95
2	3.82	1.97	1.94
3	3.80	1.94	1.96
4	3.80	1.95	1.95
5	3.80	1.93	1.97

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
KFM08A-90V-01			
1	20	0.78	52–189
2	20	0.72	52–175
3	20	0.68	52–164
4	20	0.70	75–176
5	20	0.73	76–183
KFM08A 90V-02			
1	20	0.49	36–199
2	20	0.50	36–199
3	20	0.50	36–199
4	20	0.50	36–199
5	20	0.50	36–199
KFM08A 90V-03			
1	20	0.77	62–180
2	20	0.76	67–175
3	20	0.78	66–180
4	20	0.75	66–176
5	20	0.73	64–171
KFM08A 90V-04			
1	20	0.74	32–183
2	20	0.75	34–183
3	20	0.71	32–174
4	20	0.74	32–183
5	20	0.73	32–181
KFM08A 90V-05			
1	20	0.84	28–200
2	20	0.83	30–200
3	20	0.84	28–200
4	20	0.84	28–200
5	20	0.84	28–200
KFM08A 90V-06			
1	20	0.67	37–200
2	20	0.66	42–200
3	20	0.66	37–200
4	20	0.66	37–200
5	20	0.66	37–200
KFM08A 90V-07			
1	20	0.45	27–200
2	20	0.45	27–200
3	20	0.45	27–200
4	20	0.45	27–200
5	20	0.45	27–200

Measurement number	Total time (s)	Total/char. time	Points
KFM08A 90V-08			
1	20	0.66	20–200
2	20	0.66	23–200
3	20	0.66	23–200
4	20	0.66	23–200
5	20	0.66	23–200
KFM08A 90V-09			
1	20	0.83	75–200
2	20	0.83	75–198
3	20	0.83	76–200
4	20	0.83	75–200
5	20	0.83	75–200
KFM08A 90V-10			
1	20	0.79	65–185
2	20	0.80	72–185
3	20	0.80	65–185
4	20	0.80	70–185
5	20	0.80	65–185
KFM08A 90V-11			
1	20	0.88	29–200
2	20	0.90	29–200
3	20	0.88	29–200
4	20	0.88	33–200
5	20	0.87	29–199
KFM08A 90V-12			
1	20	0.88	69–200
2	20	0.89	69–200
3	20	0.89	71–200
4	20	0.89	73–200
5	20	0.88	69–200
KFM08A 90V-13			
1	20	0.86	28–200
2	20	0.85	28–200
3	20	0.86	28–200
4	20	0.86	28–200
5	20	0.85	28–200
KFM08A 90V-14			
1	20	0.92	44–198
2	20	0.91	44–198
3	20	0.91	44–198
4	20	0.91	44–198
5	20	0.91	44–198
KFM08A 90V-15			
1	20	0.93	35–200
2	20	0.93	35–200
3	20	0.91	35–200
4	20	0.93	35–200
5	20	0.90	35–200

Measurement number	Total time (s)	Total/char. time	Points
KFM08A 90V-16			
1	20	0.95	86–200
2	20	0.96	86–200
3	20	0.94	86–200
4	20	0.95	88–200
5	20	0.93	87–200