P-07-162

Forsmark site investigation

Rock matrix permeability measurements on core samples from borehole KFM01D

Peter Vilks, Atomic Energy of Canada Ltd

August 2007

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

ISSN 1651-4416
SKB P-07-162

Forsmark site investigation

Rock matrix permeability measurements on core samples from borehole KFM01D

Peter Vilks, Atomic Energy of Canada Ltd

August 2007

Keywords: Matrix permeability, Granite, Forsmark, AP PF 400-06-101.

Abstract

This report presents the results of matrix permeability measurements performed on rock samples from the Forsmark site investigation area. The rock samples were taken from core KFM01D drilled at drill site 1. Permeability measurements were made at AECL's Whiteshell Laboratories Canada, using a range of confining pressures to simulate in situ burial conditions. Measured permeability values ranged from $6 \cdot 10^{-22}$ to $6 \cdot 10^{-19}$ m^2, corresponding to hydraulic conductivity values of $4 \cdot 0^{-14}$ to $5 \cdot 10^{-12}$ m/s. Increasing the confining pressure from 2 MPa to 15 MPa resulted in a reduction of measured permeability that ranged from a factor 2 to 130. Permeability measured normal to the core axis was a factor 3 to 5 lower than measured parallel to the core axis.

Sammanfattning

Denna rapport presenterar resultaten från mätningar av matrispermeabilitet på bergprover från Forsmarks undersökningsområde. Bergproverna togs från borrkärnan KFM01D borrad på borrplats 1. Permeabilitetsmätningar utfördes på AECL, Whiteshell Laboratories, Kanada, med varierande omgivningstryck i syfte att simulera in situ tryckförhållanden i berget. De uppmätta permeabiliteterna varierade från $6 \cdot 10^{-22}$ till $6 \cdot 10^{-19}$ m^2, motsvarande hydrauliska konduktiviteter på $4 \cdot 10^{-14}$ till $5 \cdot 10^{-12}$ m/s. Ökning av omgivningstrycket från 2 MPa till 15 MPa medförde en reduktion av uppmätt permeabilitet av en faktor 2 till 130. Permeabiliteter på prover mätta vinkelrätt mot borrhålsaxeln var en faktor 3–5 lägre än motsvarande mätta parallellt med borrhålsaxeln.

Contents

1 Introduction

This document reports the results of permeability measurements performed at Whiteshell Laboratories, Canada, using the High Pressure Radioisotope Migration (HPRM) apparatus /Vilks et al. 2004/. The work was carried out in accordance with activity plan AP PF 400-06-101. In Table 1-1 the controlling documents for performing this activity are listed. The activity plan is an SKB's internal controlling document.

This activity consisted of determining the rock matrix permeability of core samples from borehole KFM01D, see Figure 1-1. The purpose is to get data on intact rock to be included in the safety assessment of the site.

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

Activity plan	Number	Version
Determination of rock matrix permeability on core samples from KFM01D	AP PF 400-06-101	1.0

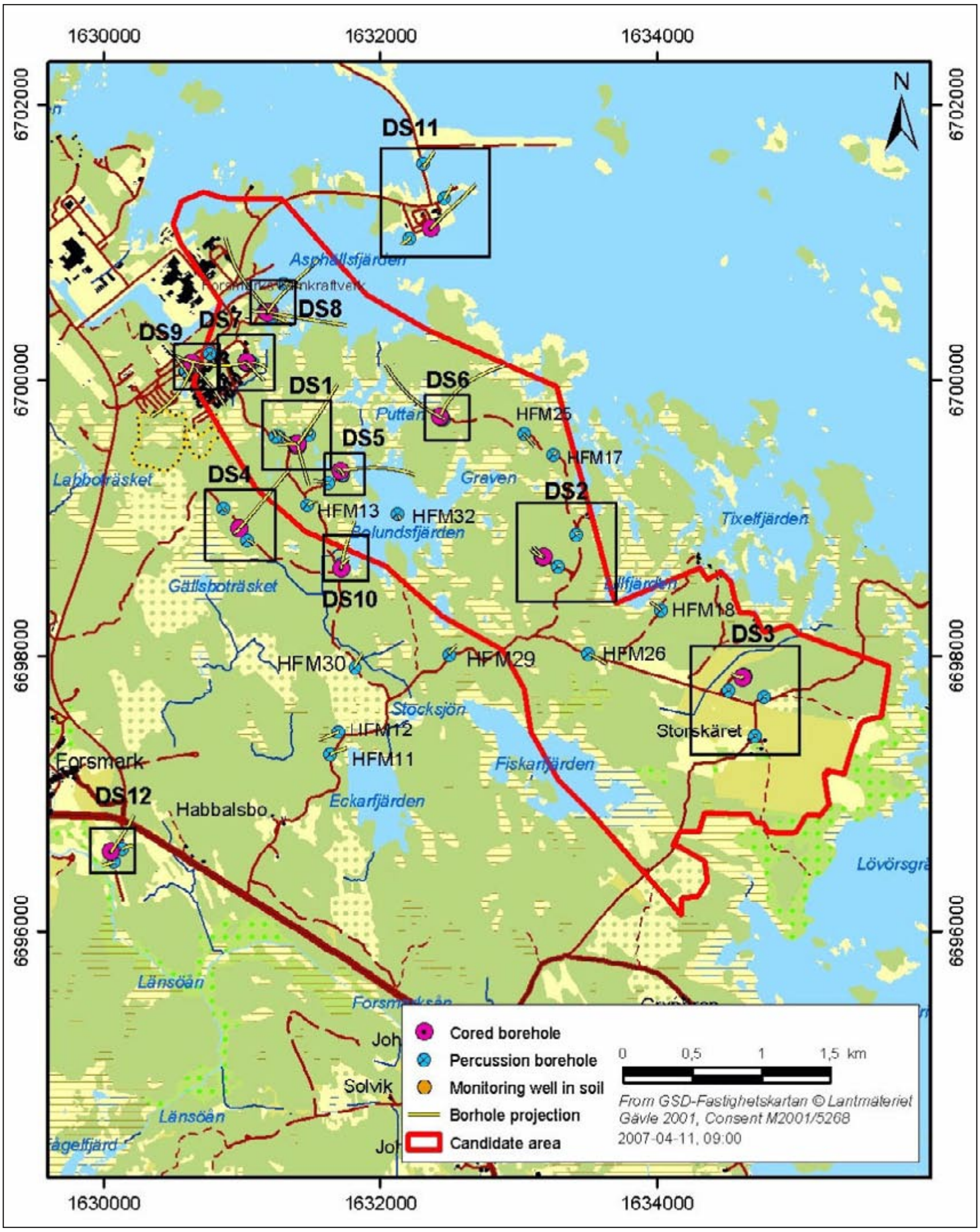

Figure 1-1. *Map of the investigation area showing borehole locations. Borehole KFM01D is located at Drill site 1 (DS1) and is oriented towards NE.*

2 Objective and scope

The objective of the work is to obtain data on the matrix permeability of rock formations at the Forsmark site. Matrix permeability is a measure of the ability of the rock's unfractured matrix to conduct water under a hydraulic gradient. The work scope consisted of measuring permeabilities of 6 core samples delivered to AECL by Geosigma. Permeabilities were determined by at least four confining pressures to evaluate the effects of sample alteration during drilling and to simulate the effect of litho static load. In selected samples permeability values were determined in two directions.

3 Equipment

3.1 Description of equipment/interpretation tools

Permeabilities of core samples are estimated at various confining pressures using the HPRM apparatus, described by /Drew and Vandergraaf 1989/. The HPRM consists of a core holder assembly, which is placed in a pressure vessel that can be operated with a maximum pressure of about 17 MPa. Core samples, with lengths of 0.5 to 2.0 cm, are placed between two stainless steel cylinders (Figure 3-1), each containing a centre drilled hole. The core samples and stainless steel cylinders are coated with a pliable RTV 108 silicon rubber adhesive (Figure 3-2) to isolate the core from the water used as the pressure medium in the pressure vessel. Once the core and stainless steel cylinders are connected to the lines used to pass sample fluid through the core, the pressure vessel is assembled and partially filled with water. A confining pressure is applied to the pressure vessel, which subjects the core sample to a tri-axial pressure along its length and both ends. Water is then pumped through the core at a constant flow rate and the pressure differential between the inlet and outlet side of the core is measured. Provided that the inlet pressure is not allowed to exceed the confining pressure, water flow is always from one end of the core to the other end, following the interconnected pore spacings. Once a steady water flow through the sample is established, the flow rate is determined by measuring the mass of water collected at the outlet over a given time interval. The entire HPRM facility is illustrated in (Figure 3-3).

Rock samples used for permeability estimation have a 25 mm diameter. These can be drilled from selected core samples using an orientation that is either parallel or perpendicular to the bedding planes.

Figure 3-1. *Rock core sample enclosed by end pieces to be used in a permeability measurement.*

Figure 3-2. *Rock core sample coated with silicon and ready to be loaded in pressure vessel for permeability measurement.*

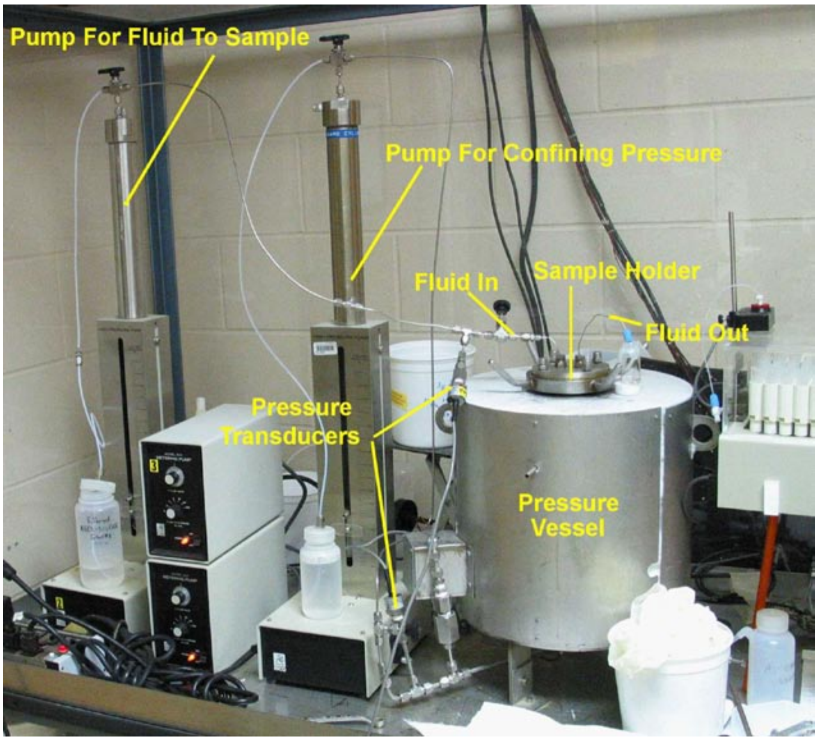

Figure 3-3. *HPRM facility for measuring permeability.*

The permeability of the core is given by

$$k = \frac{QL\mu}{A\Delta P} \quad \text{(Equation 1)}$$

where

k is the permeability in m^2,

Q is the volumetric flow rate in m^3/s,

L is the length of the core in m,

μ is the viscosity of the transport solution in $N{\cdot}s/m^2$,

A is the cross sectional area of the core in m^2, and

ΔP is the pressure differential between the inlet and outlet of the core in N/m^2.

In addition to sample dimensions, the parameters measured to calculate permeability consist of:

- The volumetric flow rate, Q, which is determined by collecting water for a measured time period. The volume of collected water is determined gravimetrically using a balance that is checked with weights that have their mass traceable to an ASTM Class 1 calibrated weight set.
- Pressure drop across sample, DP, is determined by a pressure transducer measuring the pressure of water being applied to one end of the sample. The pressure transducer is calibrated with a deadweight tester on a regular basis.

The error associated with a permeability measurement is the sum of errors from (1) the area of the sample cross section, (2) the sample length, (3) the pressure drop across the sample, and (4) the measured flow rate. The error attributed to the area of the cross section is about 1.6 percent. The error associated with sample length depends upon the total sample length, and varies between 4 and 5 percent for the samples used in this study. The error attributed to the pressure drop across the sample also depends on the magnitude of the pressure drop, typically varying between 1 and 20 percent. The error associated with the flow rate measurement is influenced by the total measured mass of fluid, as well as the time used to collect a given volume of fluid. Errors associated with flow rate measurements varied from 0.4 to 20 percent.

3.2 Rock samples

The rock samples were received from Eva Gustavsson (Geosigma AB, Sweden) on February 13, 2007. Table 3-1 summarizes the samples sent to AECL, as well as their locations in borehole KFM01D. Figure 3-4 documents the core samples received from Geosigma, showing the variation in rock textures.

Table 3-1. List of rock samples from KFM01D for permeability measurements.

Sample ID	Borehole length (m)	Rock type
KFM01D-3	254.93–255.03	Granite
KFM01D-8	499.90–500.00	Granite
KFM01D-11	642.92–643.02	Granite
KFM01D-12	700.07–700.17	Granite
KFM01D-13	747.09–747.19	Granite
KFM01D-14	790.38–790.48	Granite

Figure 3-4. *KFM01D core samples received from Geosigma.*

4 Execution

4.1 Sample preparation

The rock samples were cored with a water cooled diamond drill (Figure 4-1) to produce core samples with a 25 mm diameter. Every rock sample had one sample core drilled parallel to the core axis (Figure 4-2). Two rock samples were also drilled normal to the core axis to test the effect of sample orientation on permeability. Table 4-1 lists the samples cut for permeability measurements. The sample cores were cut into 5 mm thick slices to be used for the actual permeability measurements. A thickness of 5 mm was chosen because the matrix permeability was expected to be low and thicker samples would have resulted in excessively long measurement times.

Table 4-1. List of rock samples cored for permeability measurements.

Sample ID	Comment
KFM01D-3A	Cut parallel to core axis
KFM01D-3B	Cut normal to core axis
KFM01D-8	Cut parallel to core axis
KFM01D-11A	Cut parallel to core axis
KFM01D-12	Cut parallel to core axis
KFM01D-13A	Cut parallel to core axis
KFM01D-13B	Cut normal to core axis
KFM01D-14	Cut parallel to core axis

Figure 4-1. *KFM01D core samples cut for permeability measurements.*

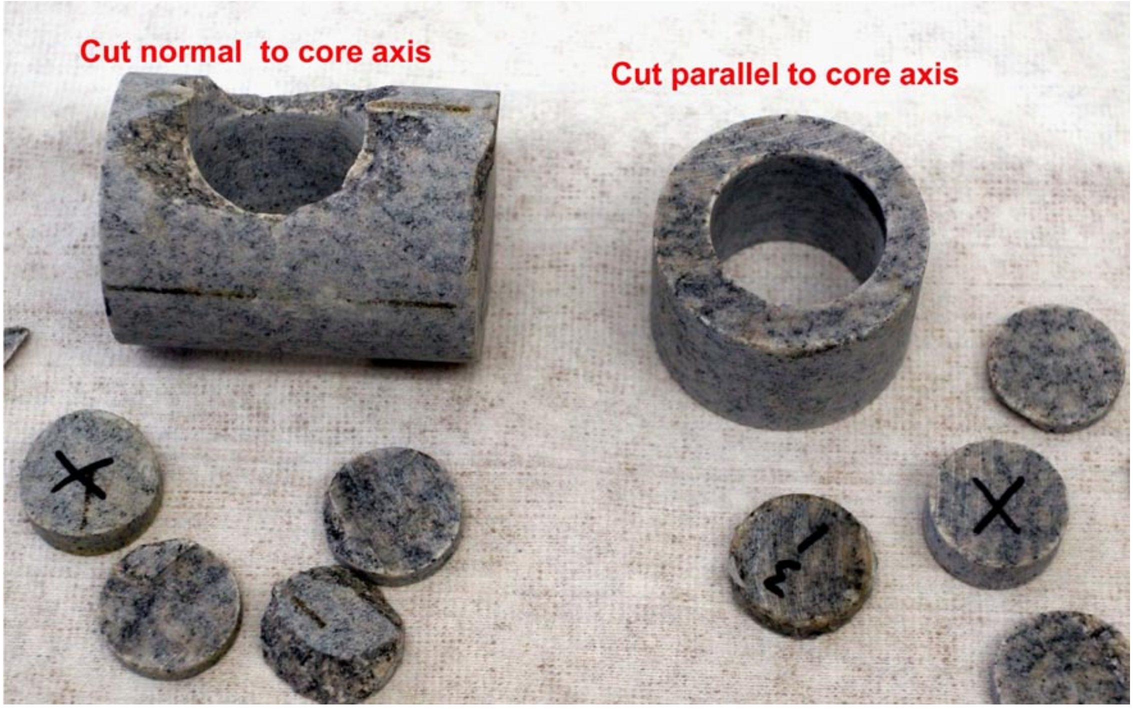

Figure 4-2. Sample core cut parallel and normal to core axis. The core slices used for permeability measurements had a 25 mm diameter.

4.2 Permeability measurements

After the rock samples were placed between two end fittings, coated with silicon and placed into the pressure vessel, the confining pressure was initially increased to between 1.3 and 2.7 MPa. Once it was confirmed that the silicon coating isolating the sample from the confining high pressure fluid did not leak, distilled water was pumped into one end of the sample core using hydraulic pressures ranging from 0.2 to 4.2 MPa. Permeability measurements could begin once a steady flow of water was observed across the sample core. In some cases the time to reach a steady flow was up to one or two weeks. The flow rate was determined by gravimetrically measuring the amount of water collected over time periods ranging from 1 hour to several days. Once several permeability measurements were performed at a given confining pressure, the confining pressure was increased up to values as high as 15.7 MPa to produce permeability measurements over a range of confining pressures.

4.3 Data handling/post processing

The raw data was recorded on data sheets stored in a binder dedicated to the HPRM. The raw data was transferred to an Excel spreadsheet to calculate permeability, conductivity and associated error using Equation 1.

4.4 Nonconformities

The sample core from KFM01D-14 may have had a fracture which opened up when the flow rate across the sample was increased. The final measurements on this sample were performed with high flow rates and low pressure drops because the permeability appeared to have increased by two orders of magnitude. Sample KFM01D-11 appeared to contain an open fracture as indicated by high flow rates through the sample. The test with KFM01D-11 was terminated without permeability measurements.

5 Results

Original data from the reported activity are stored in the primary database Sicada. Data are traceable in Sicada by the Activity Plan number (AP PF 400-06-101). Only data in databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. However, such revision of the database will not necessarily result in a revision of this report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

The results of permeability measurements of rock samples from core KFM01D are tabulated in Table 5-1. The results for each core sample are given in the order of measurement. The data for each measurement include the confining pressure, the pressure drop across the sample and the observed flow rate. Using the measured pressure drop and flow rate, and the sample length and surface area, the permeability was calculated using Equation 1. The table also includes values of hydraulic conductivity (m/s) corresponding to the calculated permeability values (m^2). The reported error values were estimated for each measurement.

The effect of confining pressure on permeability measurements is illustrated in Figure 5-1. Note that sample KFM01D-14 was not included in this figure because this sample displayed a significant change in permeability during the experiments which may have resulted from the opening of a fast flow path. When the confining pressure was increased from 2 MPa to 15 MPa most samples displayed reductions in permeability that ranged from a factor 2 to 130. This suggests that rock samples may have been altered by stress relief during drilling. With the application of a high confining pressure a portion of the additional porosity created by sample alteration was closed to flow.

Assuming that permeability values measured at high confining pressures are more representative of in situ conditions, average permeability values obtained at confining pressures above 14 MPa are given in Table 5-2. Note that sample KFM01D-14 is an exception because permeability values at high confining pressure were not available for this sample. The results in Table 5-2 suggest that matrix permeability may not be isotropic. The permeability measured normal to the core axis was a factor 5 lower in KFM01D-3, and a factor 3 lower in KFM01D-13.

Table 5-1. Permeability results.

Sample	Confining pressure (MPa)	Pressure drop (MPa)	Flow rate (m^3/s)	Permeability m^2	Conductivity m/s
KFM01D-3A	1.8	0.5	$1.1 \cdot 10^{-11}$	$(2.0 \pm 0.4) \cdot 10^{-19}$	$(1.8 \pm 0.3) \cdot 10^{-12}$
	1.8	0.4	$1.1 \cdot 10^{-11}$	$(2.8 \pm 0.6) \cdot 10^{-19}$	$(2.5 \pm 0.6) \cdot 10^{-12}$
	1.7	0.4	$1.1 \cdot 10^{-11}$	$(2.6 \pm 0.6) \cdot 10^{-19}$	$(2.3 \pm 0.5) \cdot 10^{-12}$
Parallel to Core	4.2	0.5	$1.1 \cdot 10^{-11}$	$(2.2 \pm 0.4) \cdot 10^{-19}$	$(1.9 \pm 0.3) \cdot 10^{-12}$
Axis	4.3	0.5	$1.0 \cdot 10^{-11}$	$(1.9 \pm 0.4) \cdot 10^{-19}$	$(1.6 \pm 0.3) \cdot 10^{-12}$
	8.4	0.6	$8.5 \cdot 10^{-12}$	$(1.3 \pm 0.2) \cdot 10^{-19}$	$(1.1 \pm 0.2) \cdot 10^{-12}$
Diameter: 25 mm	8.6	0.6	$9.2 \cdot 10^{-12}$	$(1.4 \pm 0.3) \cdot 10^{-19}$	$(1.2 \pm 0.2) \cdot 10^{-12}$
Area: 491 mm^2	12.0	0.7	$7.1 \cdot 10^{-12}$	$(1.0 \pm 0.2) \cdot 10^{-19}$	$(8.7 \pm 1.5) \cdot 10^{-13}$
Length: 4 mm	14.5	0.7	$6.6 \cdot 10^{-12}$	$(8.7 \pm 1.8) \cdot 10^{-20}$	$(7.5 \pm 1.6) \cdot 10^{-13}$
	14.5	0.7	$5.4 \cdot 10^{-12}$	$(7.0 \pm 1.5) \cdot 10^{-20}$	$(6.1 \pm 1.3) \cdot 10^{-13}$
	14.8	0.7	$5.3 \cdot 10^{-12}$	$(6.9 \pm 1.3) \cdot 10^{-20}$	$(6.0 \pm 1.1) \cdot 10^{-13}$
	12.5	1.3	$9.7 \cdot 10^{-12}$	$(7.1 \pm 0.8) \cdot 10^{-20}$	$(6.2 \pm 0.7) \cdot 10^{-13}$
	10.2	1.8	$1.2 \cdot 10^{-11}$	$(6.0 \pm 0.7) \cdot 10^{-20}$	$(5.2 \pm 0.6) \cdot 10^{-13}$
	10.1	1.8	$1.1 \cdot 10^{-11}$	$(5.6 \pm 0.7) \cdot 10^{-20}$	$(4.9 \pm 0.6) \cdot 10^{-13}$
	15.2	1.9	$9.8 \cdot 10^{-12}$	$(4.7 \pm 0.5) \cdot 10^{-20}$	$(4.1 \pm 0.4) \cdot 10^{-13}$

Sample	Confining pressure (MPa)	Pressure drop (MPa)	Flow rate (m^3/s)	Permeability m^2	Conductivity m/s
	13.4	2.3	$9.0\cdot10^{-12}$	$(3.6 \pm 0.3)\cdot10^{-20}$	$(3.1 \pm 0.3)\cdot10^{-13}$
KFM01D-3B	2.3	0.6	$8.9\cdot10^{-12}$	$(1.7 \pm 0.3)\cdot10^{-19}$	$(1.5 \pm 0.2)\cdot10^{-12}$
	5.0	0.7	$8.0\cdot10^{-12}$	$(1.4 \pm 0.2)\cdot10^{-19}$	$(1.2 \pm 0.2)\cdot10^{-12}$
	5.2	0.7	$7.0\cdot10^{-12}$	$(1.1 \pm 0.2)\cdot10^{-19}$	$(1.0 \pm 1.4)\cdot10^{-13}$
Normal to core	5.3	0.7	$5.8\cdot10^{-12}$	$(9.4 \pm 1.6)\cdot10^{-20}$	$(8.2 \pm 1.4)\cdot10^{-13}$
Axis	9.0	0.7	$4.7\cdot10^{-12}$	$(7.7 \pm 1.5)\cdot10^{-20}$	$(6.7 \pm 1.3)\cdot10^{-13}$
	10.2	1.0	$4.2\cdot10^{-12}$	$(5.0 \pm 0.6)\cdot10^{-20}$	$(4.4 \pm 0.5)\cdot10^{-13}$
Diameter: 25 mm	11.4	1.2	$3.2\cdot10^{-12}$	$(3.2 \pm 0.4)\cdot10^{-20}$	$(2.8 \pm 0.3)\cdot10^{-13}$
Area: 491 mm^2	14.2	1.0	$2.4\cdot10^{-12}$	$(2.7 \pm 0.3)\cdot10^{-20}$	$(2.4 \pm 0.3)\cdot10^{-13}$
Length: 5 mm	14.5	0.7	$1.2\cdot10^{-12}$	$(2.2 \pm 0.3)\cdot10^{-20}$	$(1.9 \pm 0.3)\cdot10^{-13}$
	14.4	1.0	$9.2\cdot10^{-13}$	$(1.1 \pm 0.2)\cdot10^{-20}$	$(9.1 \pm 1.6)\cdot10^{-14}$
	14.9	1.1	$1.2\cdot10^{-12}$	$(1.3 \pm 0.2)\cdot10^{-20}$	$(1.1 \pm 0.2)\cdot10^{-13}$
	15.3	1.3	$1.1\cdot10^{-12}$	$(1.0 \pm 0.1)\cdot10^{-20}$	$(9.0 \pm 1.2)\cdot10^{-14}$
	14.4	1.0	$5.3\cdot10^{-13}$	$(6.0 \pm 1.5)\cdot10^{-21}$	$(5.3 \pm 1.3)\cdot10^{-14}$
	14.9	1.6	$3.0\cdot10^{-13}$	$(2.2 \pm 0.2)\cdot10^{-21}$	$(1.9 \pm 0.2)\cdot10^{-14}$
KFM01D-8	1.3	0.8	$6.3\cdot10^{-12}$	$(9.7 \pm 1.1)\cdot10^{-20}$	$(8.4 \pm 1.0)\cdot10^{-13}$
	3.1	0.9	$2.4\cdot10^{-12}$	$(3.0 \pm 0.4)\cdot10^{-20}$	$(2.6 \pm 0.3)\cdot10^{-13}$
	6.3	1.0	$6.4\cdot10^{-12}$	$(7.3 \pm 0.9)\cdot10^{-20}$	$(6.4 \pm 0.7)\cdot10^{-13}$
Parallel to core	7.6	1.8	$8.3\cdot10^{-12}$	$(5.3 \pm 0.4)\cdot10^{-20}$	$(4.6 \pm 0.4)\cdot10^{-13}$
Axis	8.8	2.4	$8.4\cdot10^{-12}$	$(4.0 \pm 0.3)\cdot10^{-20}$	$(3.5 \pm 0.3)\cdot10^{-13}$
	8.8	2.1	$8.2\cdot10^{-12}$	$(4.6 \pm 0.5)\cdot10^{-20}$	$(4.0 \pm 0.5)\cdot10^{-13}$
Diameter: 25 mm	12.0	2.0	$1.0\cdot10^{-11}$	$(5.9 \pm 0.9)\cdot10^{-20}$	$(5.1 \pm 0.8)\cdot10^{-13}$
Area: 491 mm^2	8.8	2.4	$1.0\cdot10^{-11}$	$(4.9 \pm 0.4)\cdot10^{-20}$	$(4.3 \pm 0.4)\cdot10^{-13}$
Length: 5 mm	12.9	1.8	$2.8\cdot10^{-12}$	$(1.8 \pm 0.2)\cdot10^{-20}$	$(1.6 \pm 0.2)\cdot10^{-13}$
	14.4	2.1	$1.3\cdot10^{-13}$	$(7.4 \pm 0.7)\cdot10^{-22}$	$(6.4 \pm 0.6)\cdot10^{-15}$
KFM01D-12	1.6	0.2	$7.7\cdot10^{-12}$	$(4.4 \pm 1.4)\cdot10^{-19}$	$(3.9 \pm 1.2)\cdot10^{-12}$
Parallel to core	2.0	0.3	$9.0\cdot10^{-12}$	$(3.4 \pm 0.9)\cdot10^{-19}$	$(3.0 \pm 0.7)\cdot10^{-12}$
Axis	4.1	0.3	$1.3\cdot10^{-11}$	$(5.8 \pm 1.5)\cdot10^{-19}$	$(5.1 \pm 1.3)\cdot10^{-12}$
	4.4	0.3	$9.9\cdot10^{-12}$	$(4.5 \pm 1.2)\cdot10^{-19}$	$(4.0 \pm 1.0)\cdot10^{-12}$
Diameter: 25 mm	6.3	0.3	$1.2\cdot10^{-11}$	$(5.5 \pm 1.4)\cdot10^{-19}$	$(4.8 \pm 1.3)\cdot10^{-12}$
Area: 491 mm^2	6.6	0.2	$8.9\cdot10^{-12}$	$(5.1 \pm 1.7)\cdot10^{-19}$	$(4.5 \pm 1.5)\cdot10^{-12}$
Length: 5 mm	11.4	0.3	$1.1\cdot10^{-11}$	$(5.0 \pm 1.3)\cdot10^{-19}$	$(4.4 \pm 1.1)\cdot10^{-12}$
	13.0	0.3	$7.5\cdot10^{-12}$	$(2.9 \pm 0.7)\cdot10^{-19}$	$(2.5 \pm 0.6)\cdot10^{-12}$
	13.3	0.3	$9.1\cdot10^{-12}$	$(3.5 \pm 0.8)\cdot10^{-19}$	$(3.0 \pm 0.7)\cdot10^{-12}$
	14.7	0.3	$9.2\cdot10^{-12}$	$(3.5 \pm 0.9)\cdot10^{-19}$	$(3.1 \pm 0.8)\cdot10^{-12}$
	14.6	0.4	$8.1\cdot10^{-12}$	$(2.6 \pm 0.5)\cdot10^{-19}$	$(2.3 \pm 0.5)\cdot10^{-12}$
	14.7	0.4	$7.2\cdot10^{-12}$	$(2.1 \pm 0.4)\cdot10^{-19}$	$(1.8 \pm 0.4)\cdot10^{-12}$
	15.0	0.4	$6.9\cdot10^{-12}$	$(2.0 \pm 0.4)\cdot10^{-19}$	$(1.7 \pm 0.4)\cdot10^{-12}$
KFM01D-13A	2.0	0.4	$1.6\cdot10^{-12}$	$(5.4 \pm 1.1)\cdot10^{-20}$	$(4.7 \pm 1.0)\cdot10^{-13}$
	2.7	0.3	$8.7\cdot10^{-13}$	$(4.0 \pm 1.1)\cdot10^{-20}$	$(3.5 \pm 1.0)\cdot10^{-13}$
	2.7	0.4	$1.5\cdot10^{-12}$	$(4.4 \pm 0.9)\cdot10^{-20}$	$(3.8 \pm 0.8)\cdot10^{-13}$
Parallel to core	2.8	0.6	$1.9\cdot10^{-12}$	$(3.6 \pm 0.5)\cdot10^{-20}$	$(3.2 \pm 0.8)\cdot10^{-13}$
Axis	3.0	0.7	$3.0\cdot10^{-12}$	$(4.9 \pm 0.7)\cdot10^{-20}$	$(4.2 \pm 0.6)\cdot10^{-13}$
	6.1	0.7	$2.4\ 10^{-12}$	$(4.0 \pm 0.6)\cdot10^{-20}$	$(3.5 \pm 0.5)\cdot10^{-13}$
Diameter: 25 mm	6.2	0.8	$2.2\cdot10^{-12}$	$(3.3 \pm 0.5)\cdot10^{-20}$	$(2.9 \pm 0.5)\cdot10^{-13}$
Area: 491 mm^2	10.4	0.8	$1.8\cdot10^{-12}$	$(2.6 \pm 0.5)\cdot10^{-20}$	$(2.2 \pm 0.4)\cdot10^{-13}$
Length: 5 mm	10.8	0.9	$1.1\cdot10^{-12}$	$(1.5 \pm 0.3)\cdot10^{-20}$	$(1.3 \pm 0.3)\cdot10^{-13}$
	10.9	1.1	$1.6\cdot10^{-12}$	$(1.7 \pm 0.2)\cdot10^{-20}$	$(1.5 \pm 0.3)\cdot10^{-13}$
	14.9	1.3	$1.1\cdot10^{-12}$	$(1.0 \pm 0.1)\cdot10^{-20}$	$(9.1 \pm 1.0)\cdot10^{-14}$
	15.0	1.3	$8.6\cdot10^{-13}$	$(7.4 \pm 1.0)\cdot10^{-21}$	$(6.4 \pm 0.8)\cdot10^{-14}$
	15.1	1.4	$1.4\cdot10^{-12}$	$(1.2 \pm 0.2)\cdot10^{-20}$	$(1.0 \pm 0.1)\cdot10^{-13}$
	14.4	2.8	$2.2\cdot10^{-12}$	$(9.0 \pm 0.7)\cdot10^{-21}$	$(7.8 \pm 1.1)\cdot10^{-14}$

Sample	Confining pressure (MPa)	Pressure drop (MPa)	Flow rate (m^3/s)	Permeability m^2	Conductivity m/s
	14.2	4.2	$3.3 \cdot 10^{-12}$	$(8.9 \pm 1.0) \cdot 10^{-21}$	$(7.8 \pm 0.6) \cdot 10^{-14}$
	14.5	4.2	$3.0 \cdot 10^{-12}$	$(8.2 \pm 0.9) \cdot 10^{-21}$	$(7.1 \pm 0.8) \cdot 10^{-14}$
KFM01D-13B	2.0	0.9	$7.4 \cdot 10^{-13}$	$(9.4 \pm 1.8) \cdot 10^{-21}$	$(8.2 \pm 1.6) \cdot 10^{-14}$
Normal to core	1.9	0.8	$1.2 \cdot 10^{-12}$	$(1.7 \pm 0.2) \cdot 10^{-20}$	$(1.4 \pm 0.2) \cdot 10^{-13}$
Axis	1.7	0.7	$1.5 \cdot 10^{-12}$	$(2.4 \pm 0.4) \cdot 10^{-20}$	$(2.1 \pm 0.3) \cdot 10^{-13}$
	4.8	0.7	$3.8 \cdot 10^{-13}$	$(6.2 \pm 1.6) \cdot 10^{-21}$	$(5.4 \pm 1.4) \cdot 10^{-14}$
Diameter: 25 mm	4.7	0.7	$9.6 \cdot 10^{-13}$	$(1.6 \pm 0.3) \cdot 10^{-20}$	$(1.4 \pm 0.2) \cdot 10^{-13}$
Area: 491 mm^2	4.9	0.7	$8.0 \cdot 10^{-13}$	$(1.3 \pm 0.3) \cdot 10^{-20}$	$(1.1 \pm 0.2) \cdot 10^{-13}$
Length: 5 mm	9.7	0.8	$7.2 \cdot 10^{-13}$	$(1.0 \pm 0.1) \cdot 10^{-20}$	$(9.0 \pm 1.1) \cdot 10^{-14}$
	9.7	1.0	$3.8 \cdot 10^{-13}$	$(4.5 \pm 0.9) \cdot 10^{-21}$	$(4.0 \pm 0.8) \cdot 10^{-14}$
	15.2	1.1	$2.3 \cdot 10^{-13}$	$(2.5 \pm 0.5) \cdot 10^{-21}$	$(2.2 \pm 0.4) \cdot 10^{-14}$
	14.3	1.0	$3.1 \cdot 10^{-13}$	$(3.7 \pm 0.5) \cdot 10^{-21}$	$(3.2 \pm 0.4) \cdot 10^{-14}$
	14.3	1.6	$6.5 \cdot 10^{-13}$	$(4.7 \pm 1.1) \cdot 10^{-21}$	$(4.1 \pm 1.0) \cdot 10^{-14}$
	14.2	1.7	$8.6 \cdot 10^{-14}$	$(6.0 \pm 1.4) \cdot 10^{-22}$	$(5.2 \pm 1.2) \cdot 10^{-15}$
KFM01D-14	2.7	1.7	$1.6 \cdot 10^{-12}$	$(1.1 \pm 0.1) \cdot 10^{-20}$	$(9.4 \pm 0.1) \cdot 10^{-14}$
	2.6	1.5	$5.3 \cdot 10^{-13}$	$(4.2 \pm 0.5) \cdot 10^{-21}$	$(3.6 \pm 0.3) \cdot 10^{-14}$
	2.2	1.4	$1.1 \cdot 10^{-13}$	$(9.1 \pm 4.1) \cdot 10^{-22}$	$(7.9 \pm 1.0) \cdot 10^{-15}$
Parallel to core	2.3	1.3	$9.3 \cdot 10^{-14}$	$(8.5 \pm 1.1) \cdot 10^{-22}$	$(7.5 \pm 3.3) \cdot 10^{-15}$
Axis	4.0	2.8	$2.4 \cdot 10^{-10}$	$(9.9 \pm 2.7) \cdot 10^{-19}$	$(8.6 \pm 1.2) \cdot 10^{-12}$
	4.0	2.4	$4.5 \cdot 10^{-11}$	$(2.2 \pm 0.3) \cdot 10^{-19}$	$(1.9 \pm 0.5) \cdot 10^{-12}$
Diameter: 25 mm	4.0	2.2	$3.6 \cdot 10^{-11}$	$(1.9 \pm 0.2) \cdot 10^{-19}$	$(1.6 \pm 0.2) \cdot 10^{-12}$
Area: 491 mm^2	4.0	2.3	$2.5 \cdot 10^{-11}$	$(1.2 \pm 0.1) \cdot 10^{-19}$	$(1.1 \pm 0.1) \cdot 10^{-12}$
Length: 5 mm	6.7	2.5	$1.1 \cdot 10^{-11}$	$(4.9 \pm 0.4) \cdot 10^{-20}$	$(4.3 \pm 0.3) \cdot 10^{-13}$
	9.8	0.3	$3.6 \cdot 10^{-10}$	$(1.4 \pm 0.4) \cdot 10^{-17}$	$(1.2 \pm 0.1) \cdot 10^{-10}$
	10.0	0.4	$3.9 \cdot 10^{-10}$	$(1.1 \pm 0.2) \cdot 10^{-17}$	$(9.7 \pm 3.0) \cdot 10^{-11}$
	9.9	0.5	$3.9 \cdot 10^{-10}$	$(8.9 \pm 1.6) \cdot 10^{-18}$	$(7.7 \pm 1.5) \cdot 10^{-11}$
	15.3	0.3	$4.2 \cdot 10^{-10}$	$(1.6 \pm 0.4) \cdot 10^{-17}$	$(1.4 \pm 0.3) \cdot 10^{-10}$
	15.7	0.3	$4.2 \cdot 10^{-10}$	$(1.6 \pm 0.4) \cdot 10^{-17}$	$(1.4 \pm 0.4) \cdot 10^{-10}$

Table 5-2. Average permeability and conductivity values for confining pressures greater than 14 MPa.

Sample	Permeability m^2	Conductivity m/s
KFM01D-3A	$(6.8 \pm 1.6) \cdot 10^{-20}$	$(5.9 \pm 1.4) \cdot 10^{-13}$
KFM01D-3B	$(1.3 \pm 0.9) \cdot 10^{-20}$	$(1.1 \pm 0.8) \cdot 10^{-13}$
KFM01D-8	$7.4 \cdot 10^{-22}$	$6.4 \cdot 10^{-15}$
KFM01D-12	$(2.5 \pm 0.7) \cdot 10^{-19}$	$(2.2 \pm 0.6) \cdot 10^{-12}$
KFM01D-13A	$(9.2 \pm 1.5) \cdot 10^{-21}$	$(8.0 \pm 1.3) \cdot 10^{-14}$
KFM01D-13B	$(2.9 \pm 1.8) \cdot 10^{-21}$	$(2.5 \pm 1.3) \cdot 10^{-14}$
KFM01D-14*	$(4 \pm 5) \cdot 10^{-21}$	$(4 \pm 4) \cdot 10^{-14}$

* Average for confining pressures from 2.2 to 2.7 MPa.

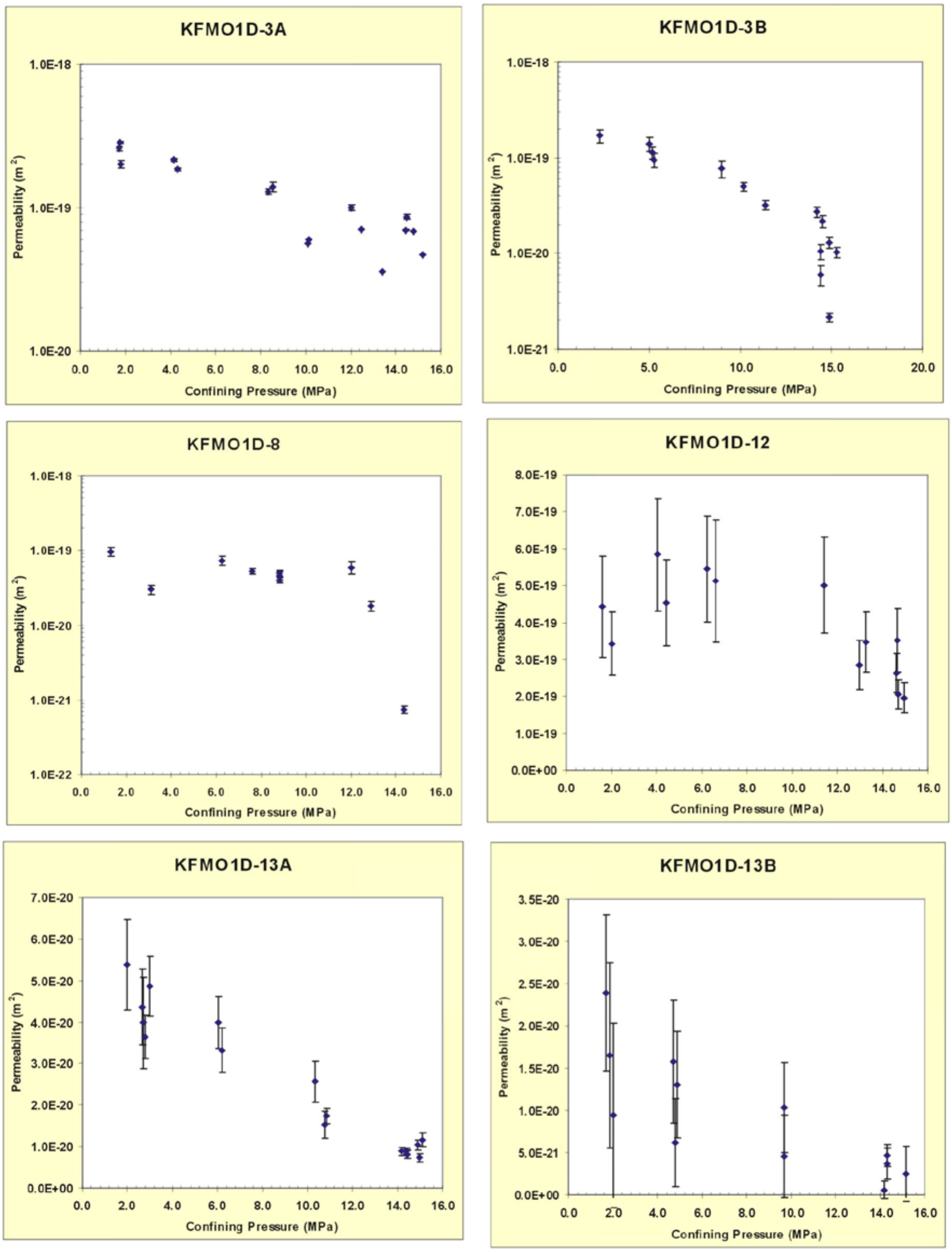

Figure 5-1. *Effect of confining pressure on permeability values.*

References

Drew D J, Vandergraaf T T, 1989. Construction and operation of a high-pressure radioisotope migration apparatus. Atomic Energy of Canada Limited Technical Record, TR-476.

Vilks P, Miller N H, Stanchell F W, 2004. Phase II in situ diffusion experiment. AECL Report no: 06819-Rep-01200-10128-R00.