TECHNICAL
REPORT

96-16

Diffusion of I^-, Cs^+ and Sr^{2+} in compacted bentonite

– Anion exclusion and surface diffusion

Trygve E Eriksen, Mats Jansson

Royal Institute of Technology, Department of Chemistry,
Nuclear Chemistry, Stockholm

November 1996

SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

P.O.BOX 5864 S-102 40 STOCKHOLM SWEDEN
PHONE +46 8 665 28 00
FAX +46 8 661 57 19

DIFFUSION OF I^-, Cs^+ AND Sr^{2+} IN COMPACTED BENTONITE

ANION EXCLUSION AND SURFACE DIFFUSION

Trygve E Eriksen, Mats Jansson

**Royal Institute of Technology, Department of Chemistry,
Nuclear Chemistry, Stockholm**

November 1996

Information on SKB technical reports from1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32), 1989 (TR 89-40), 1990 (TR 90-46), 1991 (TR 91-64), 1992 (TR 92-46), 1993 (TR 93-34), 1994 (TR 94-33) and 1995 (TR 95-37) is available through SKB.

Diffusion of I^-, Cs^+ and Sr^{2+} in Compacted Bentonite.

Anion exclusion and surface diffusion.

Trygve E. Eriksen and Mats Jansson

Royal Institute of Technology, Department of Chemistry
Nuclear Chemistry, S-100 44 Stockholm 70

ABSTRACT

The diffusion of I^-, Cs^+ and Sr^{2+} in bentonite compacted to a dry density of 1.8 g cm^{-3} and saturated with two ground waters of different ionic strength have been studied experimentally using the through diffusion technique.

The I^- diffusivity and diffusion porosity were found to be concentration independent in the concentration range 10^{-8} to 10^{-2} mol dm^{-3}. The diffusion porosity, being only a fraction of the water porosity for normal ground waters, is strongly ionic strength dependent due to anion exclusion.

The dependence of the diffusion of Cs^+ and Sr^{2+} on the sorption intensity is accommodated by a model encompassing diffusion of the sorbed cations within the electrical double layer next to the mineral surface in addition to diffusion in the pore water.

SAMMANFATTNING

Rapporten beskriver diffusionsförsök i bentonit kompakterad till tätheten 1.8 g cm^{-3} och jämviktad med NaCl och simulerade grundvattenlösningar.

Diffusionskonstanter och fördelningskoefficienter (K_d) har beräknats genom att simulera genombrottskurvor och koncentrationsprofiler i bentoniten.

Diffusionens beroende av lösningarnas jonstyrka kan för katjonerna Cs^+, Sr^{2+} bäst förklaras av en modell som omfattar två diffusionsmekanismer, diffusion i porvattnet och diffusion av sorberade katjoner.

Jodid-diffusionens jonstyrkeberoende, ökande diffusionsporositet med ökande jonstyrka, förklaras av anjonförträngning från små porer i den vattenmättade bentoniten.

TABLE OF CONTENTS

SUMMARY AND CONCLUSIONS

The diffusion of I^-, Cs^+ and Sr^{2+} in Wyoming MX-80 Na-bentonite, compacted to 1.8 g cm^{-3} dry density and saturated with NaCl solutions or synthetic groundwater solutions with different ionic strength, was studied experimentally by a through diffusion technique.

The apparent and effective diffusivity of I^- were found to be concentration independent in the concentration range 10^{-8} to 10^{-2} mol dm^{-3}. The diffusivities are increasing with increasing ionic strength of the ground water, due to anion exclusion which is ionic strength dependent.
The apparent and effective diffusion constant in bentonite equilibrated with saline ground water (NASK-solution) were found to be $D_a = 9.2(+/- 1.3)\cdot 10^{-7}$ and $D_e = 7.0(+/- 1.7)\cdot 10^{-8}$ $cm^2\ s^{-1}$, respectively.
The corresponding diffusivities in bentonite equilibrated with granitic ground water (Allard-solution) are $D_a = 3.5\cdot 10^{-7}$, $D_e = 2.1\cdot 10^{-9}$ $cm^2\ s^{-1}$.

The distribution coefficients K_d ($cm^3\ g^{-1}$) for Cs^+ and Sr^{2+}, calculated by simulation of the break through curves and concentration profiles from the diffusion experiments, fall well within the range of distribution coefficients observed in batch sorption experiments with bentonite suspensions and compacted bentonite and can be calculated for groundwaters with different ionic strength I (mol dm^{-3}) using the equations.

$$\log K_d (Sr^{2+}) = 0.6(+/-0.3) - 1.28(+/- 0.06) \log I$$
$$\log K_d (Cs^+) = 1.54(+/-0.3) - 0.58(+/- 0.09) \log I.$$

The observed dependence of the diffusivity of Cs^+ and Sr^{2+} on the distribution coefficient is best accommodated by a model based on the assumption of diffusion within the electrical double layer next to the mineral surface in addition to pore water diffusion i.e. the diffusion constants are given by the equations

$$D_a = \varepsilon D_p / (\varepsilon + K_d \rho) + K_d \rho D_s / (\varepsilon + K_d \rho)$$
$$D_e = D_a (\varepsilon + K_d \rho).$$

By using the water porosity, 0.32 for bentonite compacted to the dry density $\rho = 1.8$ g cm^{-3}, the pore water and surface diffusivities were found to be $D_p = 8\cdot 10^{-6}$, $D_s = 6\cdot 10^{-9}$ and $D_p = 3\cdot 10^{-6}$, $D_s = 1\cdot 10^{-7}$ $cm^2\ s^{-1}$ for Cs^+ and Sr^{2+} respectively.

The Sr^{2+} and Cs^{+} diffusivities in bentonite compacted to dry density 1.8 cm^{-3} and equilibrated with granite (Allard) and saline ground water are accordingly

Water	Ionic strength	Sr^{2+}		Cs^{+}	
		D_a cm^2s^{-1}	D_e cm^2s^{-1}	D_a cm^2s^{-1}	D_e cm^2s^{-1}
Allard	0.018	$1.2 \cdot 10^{-7}$	$6.7 \cdot 10^{-5}$	$1.0 \cdot 10^{-8}$	$6.4 \cdot 10^{-6}$
NASK	0.218	$1.0 \cdot 10^{-7}$	$6.0 \cdot 10^{-6}$	$2.3 \cdot 10^{-8}$	$3.5 \cdot 10^{-6}$

1. INTRODUCTION

Characteristic features of the clay to be used as buffer material in repositories for spent nuclear fuel are low permeability, high sorptivity and long term stability. The low permeability of compacted bentonite prevents material transport by hydraulic flow and makes diffusion the principal mechanism for transport of corrosive solutes to the surface of the waste canister and migration of radionuclides released on failure of a waste canister.

The diffusive transport of solutes through compacted bentonite is governed by the geometrical microstructure of the pore network i.e. the parameters porosity, tortuosity, constrictivity, and the interaction between the three components diffusing solute, water and clay. Despite extensive studies several of the processes involved are not, due to the complicated microstructure of the bentonite, fully understood. The diffusion of some sorbing solutes e.g. the cations Na^+, Cs^+ and Sr^{2+} has repeatedly been reported to be faster than predicted from a model based on diffusion in the aqueous phase and immobilisation by sorption on the solid phase. Diffusion within the electrical double layer next to the mineral surface, referred to surface diffusion, or less sorption, i.e. a lower K_d value in the compacted than in freely expanded clay, have been offered to explain the experimental results. Van Schaik et al (1966), Rasmuson and Neretnieks (1983), Torstenfelt (1983), Eriksen and Jacobsson (1981,1984), Soudek et al (1984), Jahnke and Radke (1987), Muurinen et al (1985,1987, 1990,1994), Cheung (1989), Cook (1989), Choi et al (1992), Berry and Bond (1992), Kim et al (1993).

To shed some light on surface diffusion, if it exists, in bentonite clay and its relative importance to the function of bentonite as a barrier to radionuclide diffusion, we have studied the diffusive transport of Sr^{2+} and Cs^+ in compacted bentonite using a through diffusion technique. Apparent diffusivity and transport K_d are, in each experiment, obtained by computer simulation of the experimentally measured cumulative flux through a plug of compacted bentonite and the concentration profile within the bentonite. Due to the particular interest in Cs^+ and I^- which can possibly be released from a damaged spent fuel canister we have also studied the diffusion of these ions in the concentration range 10^{-2} to 10^{-8} mol dm^{-3}.

2. EXPERIMENTAL

2.1 Materials

The bentonite used in this investigation is the American Colloid Co. type MX-80 (Wyoming Na-bentonite). The bentonite (MX-80) has a clay content (< 2μm) of approximately 85% and a montmorillonite content of 80-90 wt% of this fraction. The remaining silt fraction contains quartz, feldspar and some micas, sulphides and oxides (Pusch and Karnland 1986). Two different synthetic groundwater solutions (Allard and NASK) were used in the diffusion experiments, see Table 1.

Table 1

Composition of ground water solutions used in the sorption and diffusion experiments.

NASK		Allard	
NaCl	140 mM	$NaHCO_3$	2 mM
$KHCO_3$	2 mM	$CaCl_2$	0.45 mM
$CaCl_2$	20 mM	KCl	0.1mM
$MgSO_4$	4 mM	$NaSiO_4$	0.2 mM
pH	7.7	$MgSO_4$	0.1mM
Ionic strength	0.218	$MgCl_2$	0.78 mM
		NaCl	10 mM
		pH	8 - 8.2
		Ionic strength	0.0182

Simulated ground waters and NaCl solutions with different concentration were used to vary the ionic strength in the sorption experiments. The solutions were prepared from analytical grade chemicals and Millipore deionized, triple distilled water. The radionuclides used, ^{134}Cs (Amersham) and ^{85}Sr, ^{125}I (DuPont Scandinavia) were purchased in aqueous solution. Tracer solutions were prepared by adding small aliquots of the stock solution to the solutions used in the experiments. The overall diffusant concentration was obtained by adding small volumes of standardized inactive solutions.

2.2 Diffusion experiments

The diffusion cell, made of PEEK, is shown schematically in Figure 1. Bentonite was statically compacted in the diffusion cylinder (internal diameter 10 mm and 5 mm long) to a dry density of 1.8 kg dm^{-3}. The diffusion cylinder and endplates containing in and outlet channels fitted with metallic filters (0.82 mm thick) were assembled and the clay equilibrated with the aqueous solution for at least three weeks by pumping solution from reservoirs through the end plate channels, see Figure 2. After water saturation a small volume of diffusant solution, containing the tracer and inactive carrier required to give the chosen diffusant concentration, was added to the reservoir at the inlet side of the diffusion cell. The activity of the solutions in inlet and outlet reservoirs were monitored by γ-spectrometry on small sample volumes using a germanium detector and multichannel analyzer. The volume of the inlet reservoir was sufficient to keep the concentration nearly constant (within a few percent) throughout the experiments. At the end of the Cs^+ and Sr^{2+} experiments the diffusion cell was dismantled and the bentonite sliced into thin sections. Each section was weighed and the activity measured by γ-counting.

The diffusion properties of the filters were measured in separate through diffusion experiments, using a package of five filters, and the filter porosity was measured by weighing dry and water saturated filters.

2.3 Sorption

Sorption was measured in batch experiments with 0.1 g bentonite and 20 cm^3 spiked diffusant solutions.

3. DATA EVALUATION

3.1 Iodide diffusion

The filters, being thin (0.82 mm) and with porosity (0.26) comparable to the water porosity of the compacted bentonite (0.32), were judged to have but a slight effect on the diffusion of iodide through the diffusion cell. The effective and apparent diffusion constants were therefore evaluated using equations (1) and (2) respectively (Eriksen and Jacobsson 1984).

$$D_e = J\,L \,/\, A[C_o - C_t] \qquad (1)$$

$$D_a = L^2 \,/\, 6\,t_e \qquad (2)$$

D_e	effective diffusion constant	($cm^2\ s^{-1}$)
D_a	apparent diffusion constant	($cm^2\ s^{-1}$)
J	flux through the diffusion cell	($Bq\ s^{-1}$)
L	thickness of the bentonite plug	(cm)
A	surface area perpendicular to the diffusion direction	(cm^2)
C_o	concentration in the inlet reservoir (const)	($Bq\ cm^{-3}$)
C_t	concentration in the outlet reservoir	($Bq\ cm^{-3}$)
t_e	time lag, the point where the asymptote of the break through curve intercepts the time axis (See Figure 3)	

3.2 Cesium and strontium diffusion.

For sorbing diffusants, e.g. Cs^+ and Sr^{2+}, evaluation of diffusion parameters using Equations 1 and 2 will be strongly influenced by the presence of filters in the diffusion cell. In evaluating the experimental diffusion data for Cs^+ and Sr^{2+} an analysis of the complete diffusion system, as represented schematically in Figure 4 is required.

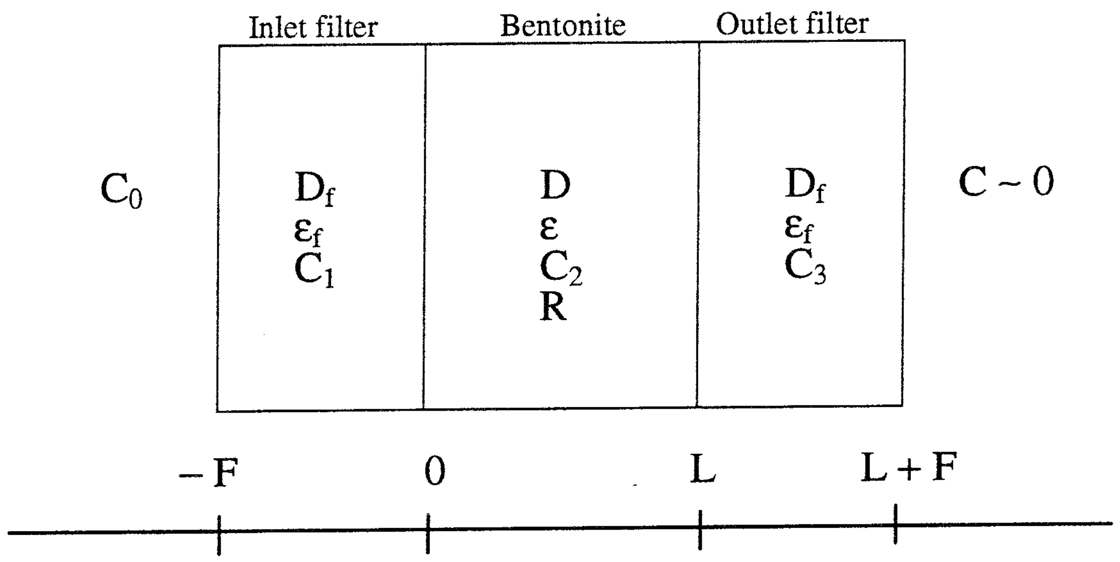

Figure 4

Schematic representation of the barriers in the diffusion cell.

The diffusive transport through the inlet filter ($-F < x < 0$) is given by equation (3)

$$J = -A\, \varepsilon_f\, D_f\, (\partial C_1 / \partial x) \qquad (3)$$

and the boundary conditions

$$C(-F, t) = C_0$$

ε_f	filter porosity
D_f	apparent diffusion constant in filter ($cm^2\ s^{-1}$)
F	filter thickness (cm)
C_1	concentration in filter ($Bq\ cm^{-3}$)
C_0	concentration in inlet solution ($Bq\ cm^{-3}$)

The diffusive transport through the compacted bentonite ($0 < x < L$) is given by equation (4)

$$J = -A\, \varepsilon\, D_a\, R\, (\partial C_2 / \partial x) \qquad (4)$$

R	capacity (retardation) factor defined as the ratio of the overall concentration of diffusant in the compacted bentonite to the concentration in the solution accessible for diffusion ($R = \varepsilon + \rho K_d / \varepsilon$)
C_2	concentration in pore solution ($Bq\ cm^{-3}$).

At the boundary between the inlet filter and the compacted bentonite we have the following conditions

$$C_1\,(0,t) = C_2\,(0,t)$$

$$\varepsilon_f\, D_f (\partial C_1 / \partial x\,)_{x=0} = \varepsilon\, D_a\, R\, (\partial C_2 / \partial t\,)_{x=0} \qquad \text{(no storage in the boundary)}$$

The corresponding transport equation and boundary conditions for the outlet filter are given by

$$J = -A\, \varepsilon_f\, D_f\, (\partial C_3 / \partial x) \qquad (5)$$

$$C_2\,(L,t) = C_3\,(L,t)$$

$$\varepsilon\, D_a\, R\, (\partial C_2 / \partial x)_{x=L} = \varepsilon_f\, D_f\, (\partial C_3 / \partial x)_{x=L}$$

$$C_3\,(L+F,\, t) = 0$$

The accumulated flow of diffusant through the outlet filter Q(t) is given by the flux through the boundary x = L+ F integrated from time zero to t

$$Q(t) = A\, \varepsilon_f\, D_f \int_0^t (\partial C_3\,(x,t) / \partial x)_{x=L+F}\, dt \qquad (6)$$

An analytical solution to equation (6), defining the break through curve, can be obtained by the Laplace transform method (Put 1991). However, to make use of all the experimental data i.e. the accumulated flow and the concentration profile within the compacted bentonite, we have chosen to use a finite difference based simulation code (ANADIFF). The code ANADIFF calculates the apparent diffusion coefficient D_a and the sorption coefficient for transport K_d. In the simulations A, ε_f, ε, D_f, C_0, F, L and ρ are kept constant while D_a and K_d are varied.

4. RESULTS AND DISCUSSION

4.1 Iodide

Measured apparent and effective diffusion constants for I^- in compacted ($\rho_{dry} = 1.8$ g cm^{-3}) NASK-water equilibrated bentonite are given in Table 2 together with corresponding diffusion constants measured in an earlier study with Allard-water saturated bentonite. As can be seen, there in no concentration dependence within the concentration range 10^{-2} to 10^{-6} mol dm^{-3} for the NASK-water equilibrated bentonite. In Allard-water saturated bentonite the apparent and effective diffusion constants are approximately 2-3 and 30 times respectively smaller than the corresponding diffusion constants in Allard-water saturated bentonite.

Neglecting possible slight sorption effects the I^- transport can be assumed to take place by pore water diffusion only. The relation between the apparent and effective diffusion constant is thus given by $D_e = D_a\, \varepsilon_p$. The calculated diffusion porosities (ε_p) are given in Table 2.

Table 2.

Diffusion constants and porosities for I^- in compacted bentonite ($\rho_{dry} = 1.8$ g cm^{-3}) equilibrated with NASK and Allard ground water solutions.

Solution	I^--conc mol dm^{-3}	D_a $cm^2\ s^{-1}$	D_e $cm^2\ s^{-1}$	ε_d
NASK	10^{-2}	$8.6 \cdot 10^{-7}$	$5.3 \cdot 10^{-8}$	0.06
	10^{-3}	$1.1 \cdot 10^{-6}$	$6.5 \cdot 10^{-8}$	0.06
	10^{-4}	$8.7 \cdot 10^{-7}$	$9.4 \cdot 10^{-8}$	0.11
	10^{-6}	$8.6 \cdot 10^{-7}$	$6.8 \cdot 10^{-8}$	0.08
Allard*	10^{-8}	$3.5 \cdot 10^{-7}$	$2.1 \cdot 10^{-9}$	0.006

* Eriksen and Jacobsson (1984)

The variations in diffusivity and diffusion porosity can be explained by the difference in ionic strength of the ground water solutions used (Allard 0.018 and NASK 0.218 mol dm^{-3}) and anion exclusion from the small pores. Increasing the iodide concentration in Allard water to 10^{-2} mol dm^{-3} may thus be expected to give a small increase in the apparent and effective diffusion constants as well as diffusion porosity given in Table 2 due to the increase in ionic strength on addition of iodide to the solution.

4.2. Cesium and strontium

Typical experimental and simulated accumulated flux and concentration profile plots are shown in Figures 5 a, b and 6 a, b. Apparent diffusion constants and diffusion K_d values obtained by simulation calculations are given in Table 3.

Table 3

Apparent diffusivities and distribution coefficients for Cs^+ and Sr^{2+} in compacted bentonite ($\rho_{dry} = 1.8$ g cm^{-3}) equilibrated with Allard and NASK groundwater solutions.

Solution	Ion	Conc. mol dm^{-3}	D_a $cm^2\ s^{-1}$	K_d $cm^3\ g^{-1}$
NASK	Sr^{2+}	10^{-4}	$1.05 \cdot 10^{-7}$	11
		10^{-6}	$1.4 \cdot 10^{-7}$	8.5
	Cs^+	10^{-2}	$5.0 \cdot 10^{-8}$	40.5
		10^{-4}	$2.6 \cdot 10^{-8}$	46.6
		10^{-6}	$3.2 \cdot 10^{-8}$	46.8
		10^{-8}	$2.0 \cdot 10^{-8}$	80
Allard	Cs^+	10^{-2}	$2.0 \cdot 10^{-8}$	85
		10^{-4}	$0.8 \cdot 10^{-8}$	270
		10^{-6}	$1.4 \cdot 10^{-8}$	270
		10^{-8}	$1.1 \cdot 10^{-8}$	450

Distribution coefficients for Cs^+ and Sr^{2+} measured in batch experiments using bentonite suspended in NaCl solutions and ground waters with different ionic strength (I) are shown in Log K_d versus Log I plots in Figures 7 and 8 respectively. In the strontium plot (Figure 8) we have included data from ionic-strength dependence studies by Muurinen (1994) and Oscarson (1984).

We have also plotted the K_d-values obtained by simulation of the diffusion break through curves and concentration profiles in the solid phase into Figures 7 and 8. Inspection of the plots in Figures 7 and 8 reveals that the diffusion K_d-values fall well within the range of distribution coefficients obtained in batch sorption experiments. The assumption of lower K_d-values for diffusitive transport in compacted bentonite than for sorption in suspensions is therefore not borne out in this study.

The apparent diffusion constants for Cs^+ and Sr^{2+} are, together with data from earlier studies by Muurinen (1994) and Eriksen and Jacobsson (1984), shown in Log D_a versus Log K_d plots in Figures 9 and 10, respectively. Inspection of these plots shows that in the K_d interval 10 to 1000 the apparent Cs^+ diffusivity decreases by approximately one order of magnitude whereas the apparent Sr^{2+} diffusivity is virtually constant. This is clearly not in accordance with a diffusion model for porous media encompassing diffusion in the pore water and complete immobilization of sorbed species, yielding equation (7)

$$D_a = \varepsilon\, D_p / (\varepsilon + K_d\, \rho) \qquad (7)$$

where D_p is the pore diffusion constant, D_a the apparent diffusion constant, K_d the distribution coefficient and ρ the dry bulk density of the porous medium. According to equation (7) the apparent diffusivity should decrease nearly linearly with increasing K_d. Instead assuming diffusion of sorbed cations to take place and to be Fickian, equation (7) can be modified to read

$$D_a = \varepsilon D_p / (\varepsilon + K_d \rho) + K_d \rho D_s / (\varepsilon + K_d \rho) \qquad (8)$$

where D_s is the surface diffusivity.
The effective diffusivity is given by equation (9)

$$D_e = D_a (\varepsilon + K_d \rho) \qquad (9)$$

Fitted D_a and D_e curves calculated using equations (8) and (9) are plotted into Figures 9 and 10. As can be seen, good fits to experimental data were obtained using $D_p = 8\cdot10^{-6}$, $D_s = 6\cdot10^{-9}$ $cm^2\ s^{-1}$ for Cs^+ and $D_p = 3\cdot10^{-6}$ and $D_s = 1\cdot10^{-7}$ $cm^2\ s^{-1}$ for Sr^{2+}. These surface diffusivities are in fair agreement with results obtained by Muurinen (1994) and Choi et al (1992).

It should be pointed out that our calculations are based on the water porosity of the bentonite ($\varepsilon \pm 0.32$). It may be argued that the diffusion porosity is smaller than the water porosity, but we have presently not sufficient information on the ionic strength dependent diffusion porosity. The different diffusion constants for Cs^+ and Sr^{2+} are summarized in Table 4.

Table 4
Diffusion constants for Cs^+ and Sr^{2+} in aqueous solution and compacted bentonite.

Ion	D_w $cm^2\ s^{-1}$	D_p $cm^2\ s^{-1}$	D_s $cm^2\ s^{-1}$
Cs^+	$2.1\cdot10^{-5}$	$8.0\cdot10^{-6}$	$6.0\cdot10^{-9}$
Sr^{2+}	$0.78\cdot10^{-5}$	$3.0\cdot10^{-6}$	$1.0\cdot10^{-7}$

The ratio D_p / D_w is found to be the same for both ions indicating that the overall effect of tortuosity and constrictivity is the same.

The ionic strength dependence of the distribution coefficients clearly points at ion exchange as the main sorption mechanism. The Cs^+ ion, having a larger radius than Sr^{2+}, is very weakly solvated and may be expected to be more specifically bound closer to the solid surface and thereby less mobile than the strongly solvated Sr^{2+} which is separated from the surface by at least one molecule of water.

5. ACKNOWLEDGEMENTS

Dr Daichao Sheng, Luleå University of Technology is gratefully acknowledged for developing the computer code ANADIFF.

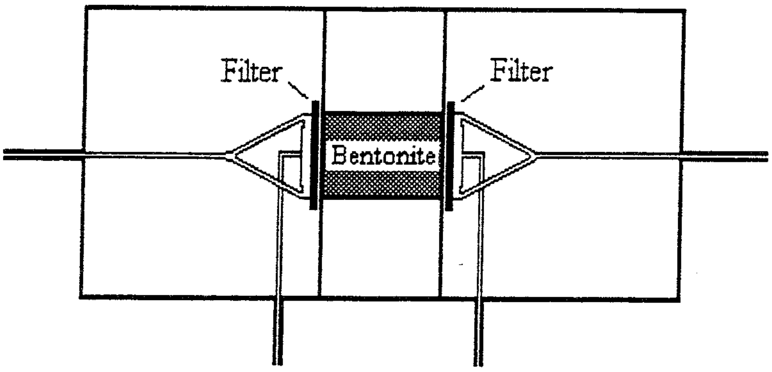

Figure 1

Schematic drawing of diffusion cell.

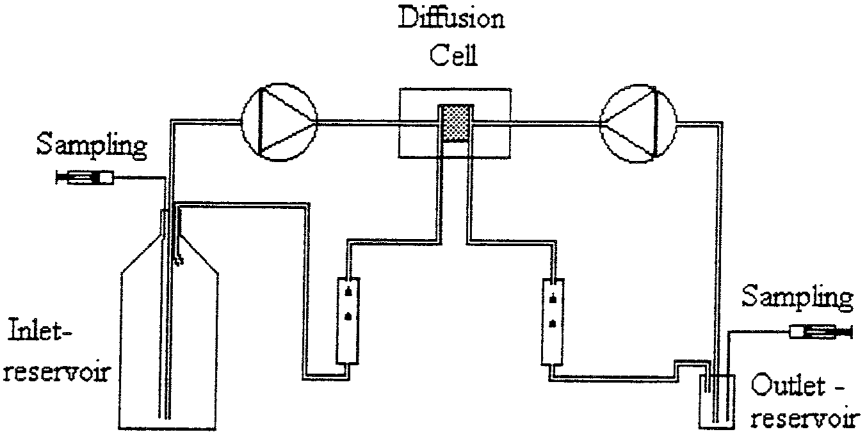

Figure 2

Arrangement of through diffusion experiments.

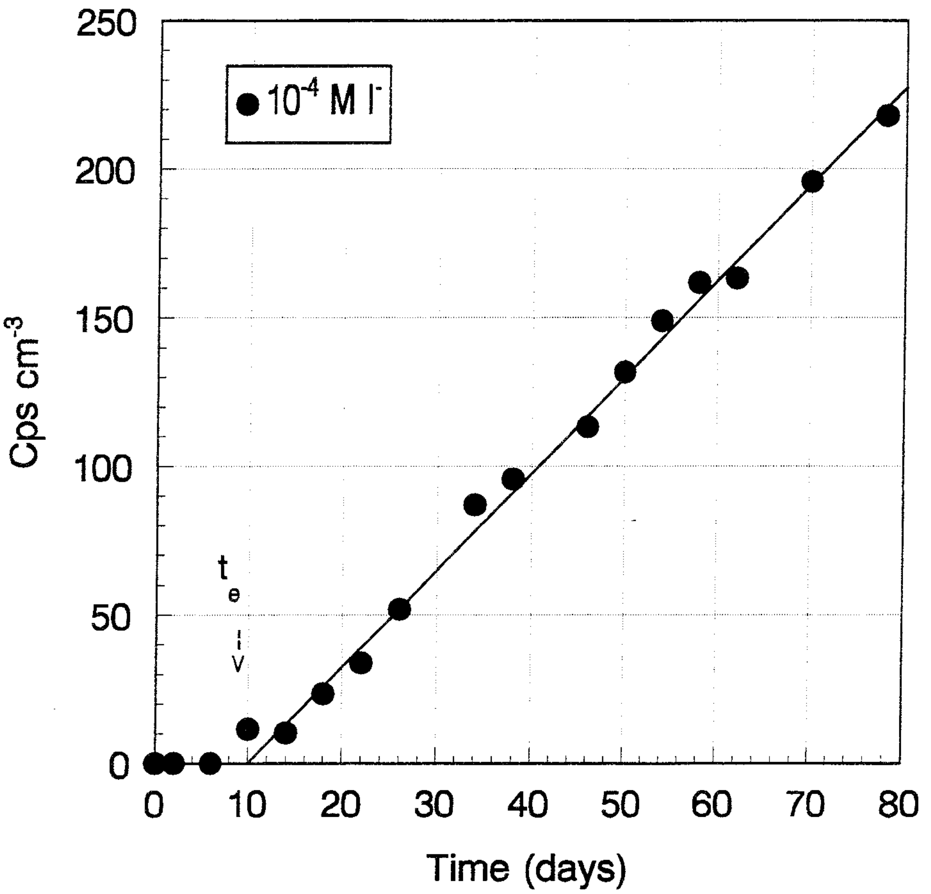

Figure 3.

Cumulative flux plot from I$^-$ through diffusion experiment. Dry density 1.8 g cm^{-3}, NASK-solution.

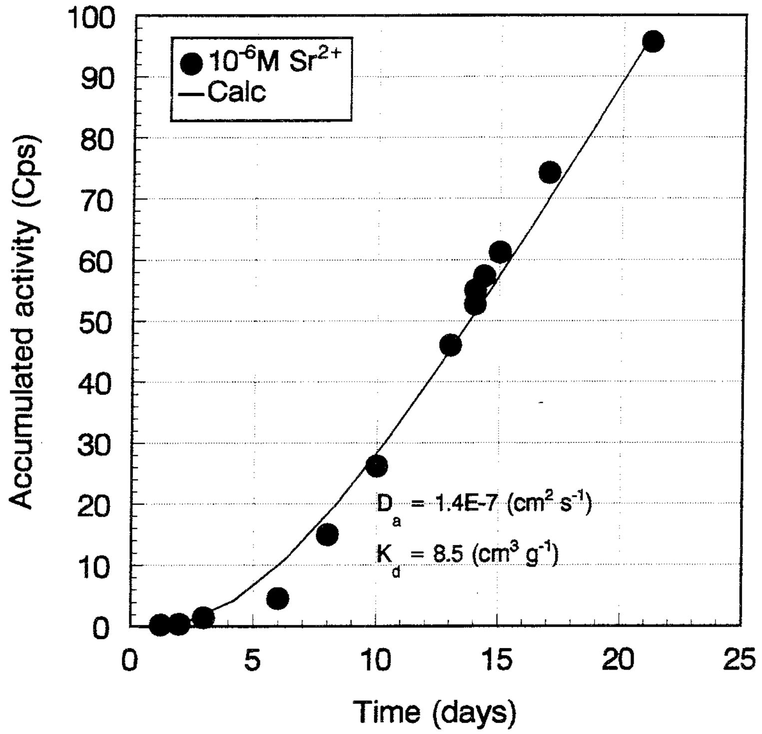

Figure 5a.

Experimental and calculated break through curves for 10^{-6} M Sr^{2+}. Dry density 1.8 g cm^{-3}, NASK-solution.

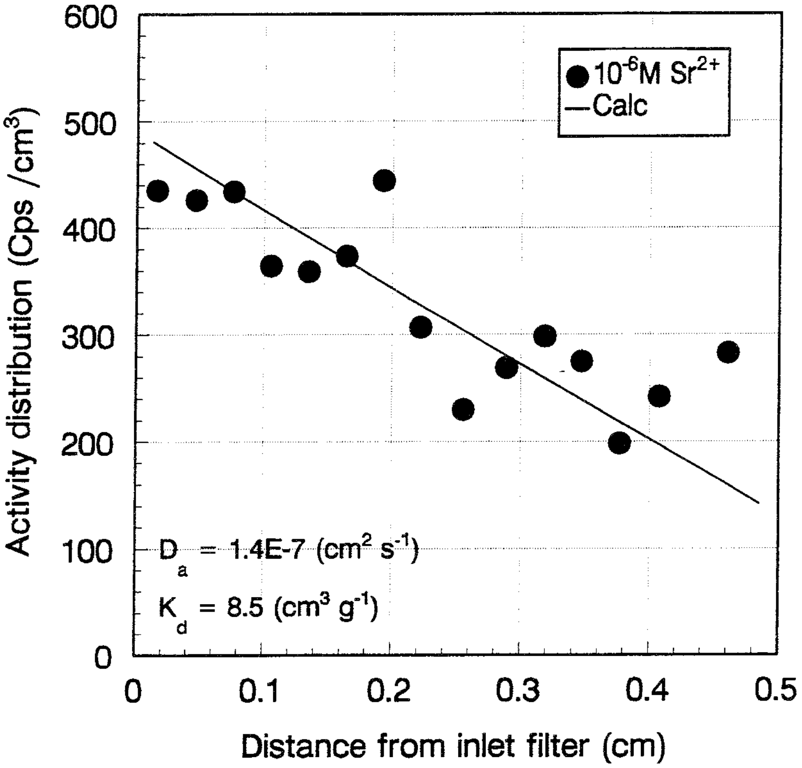

Figure 5b.

Experimental and calculated activity profiles in bentonite plug. 10^{-6} M Sr^{2+}, dry density 1.8 g cm^{-3}, NASK-solution.

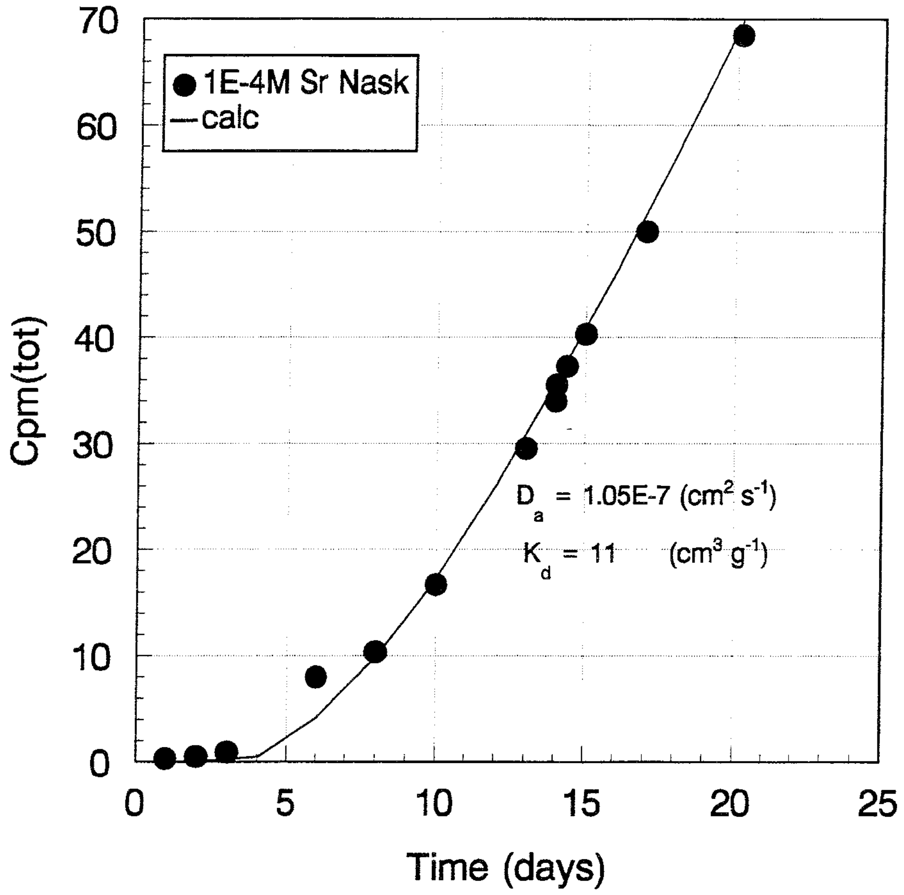

Figure 6a.

Experimental and calculated break through curves for 10^{-4} M Sr^{2+}. Dry density 1.8 g cm^{-3}, NASK-solution.

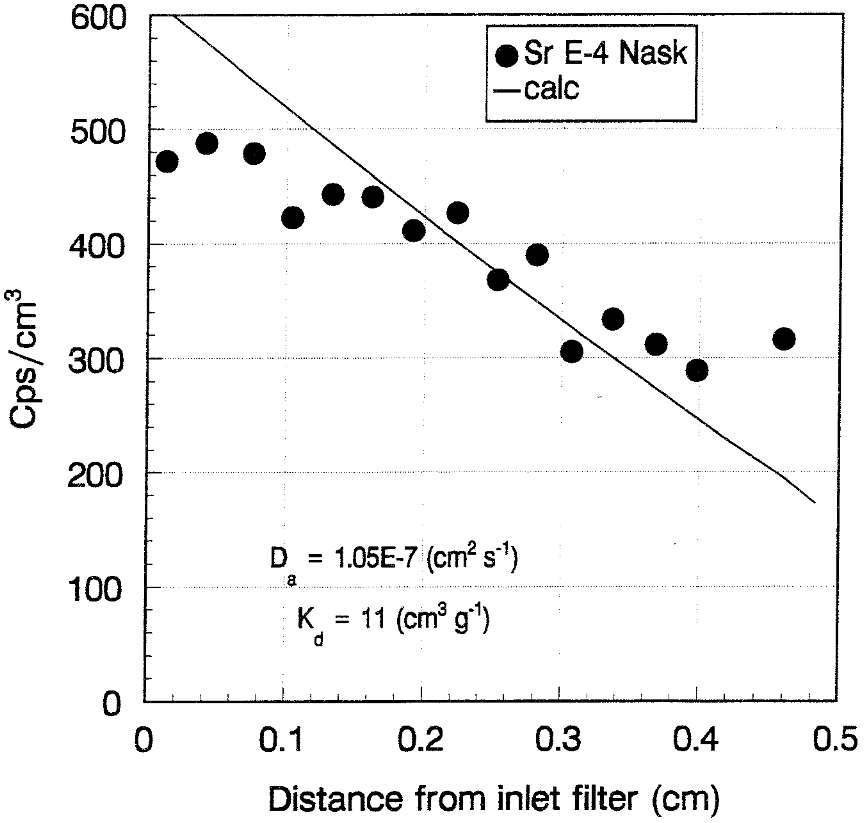

Figure 6b.

Experimental and calculated activity profiles in bentonite plug.
10^{-4} M Sr^{2+}, dry density 1.8 g cm^{-3}, NASK-solution.

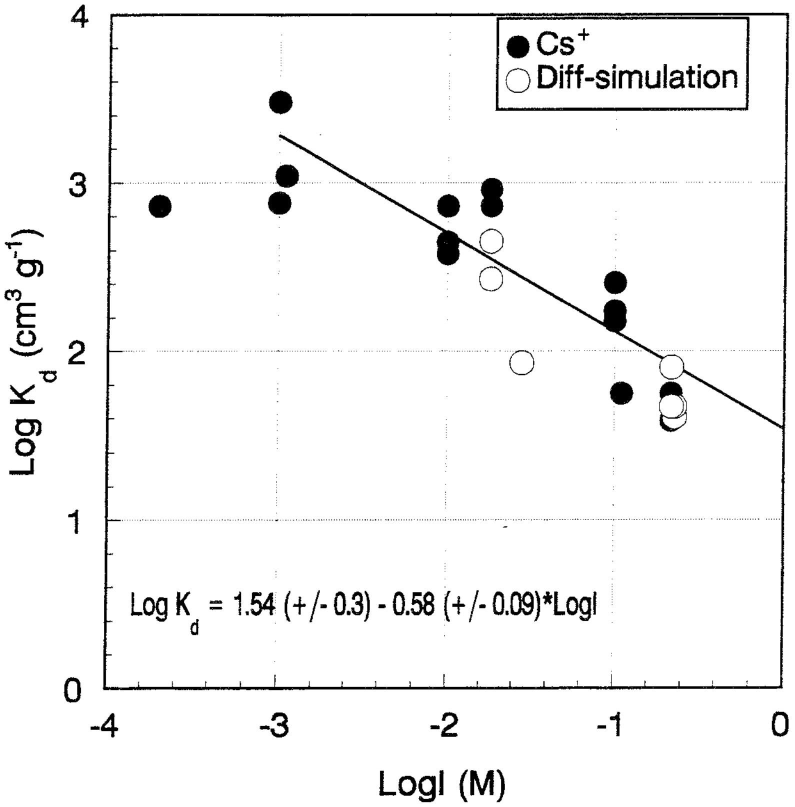

Figure 7.

Logarithmic plot of distribution coefficients (K_d) as function of ionic strength of solutions used in Cs^+ sorption and diffusion experiments. Cs^+ concentrations 10^{-2} to 10^{-8} mol dm^{-3}.

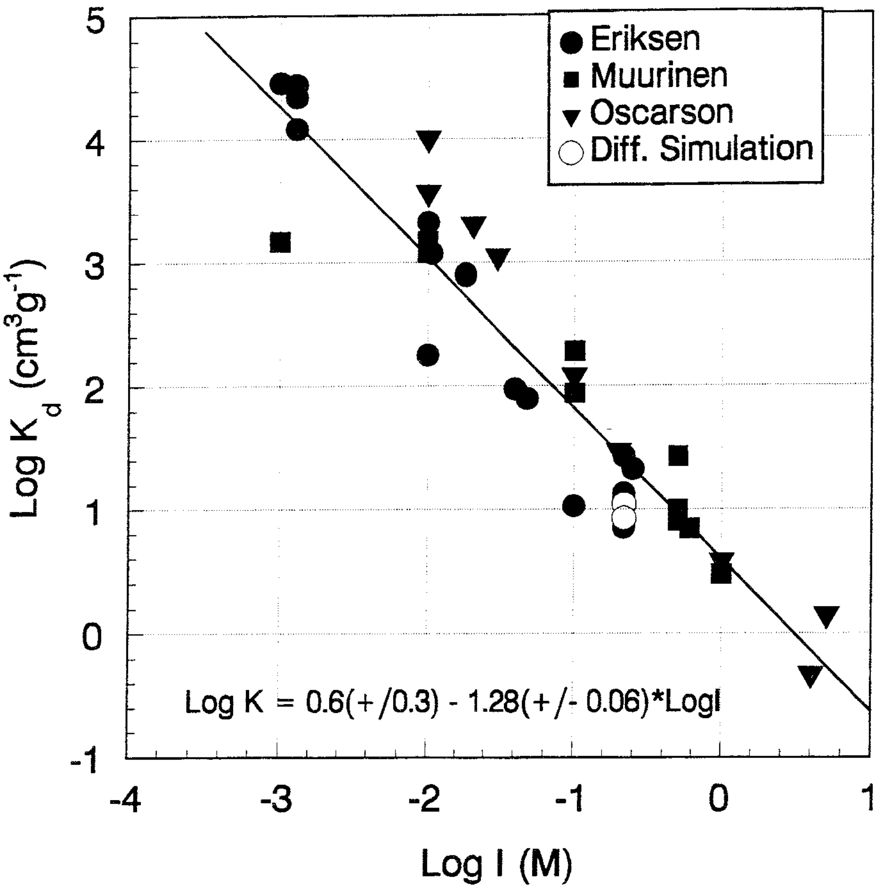

Figure 8.

Logarithmic plot of distribution coefficients (K_d) as function of ionic strength of solutions used in Sr^{2+} sorption and diffusion experiments.

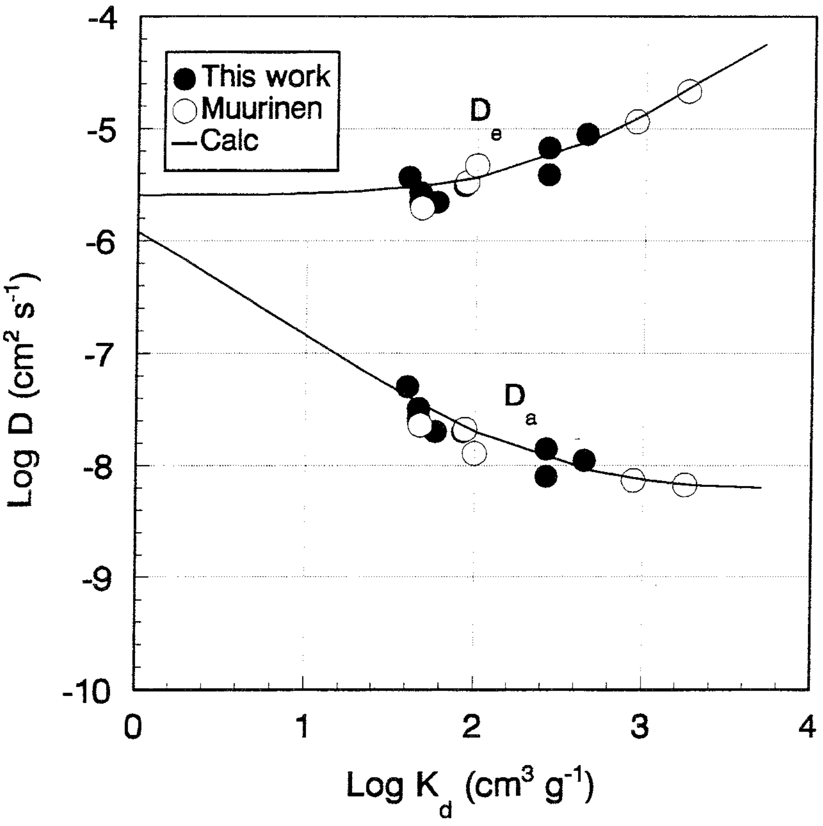

Figure 9.

Logarithmic plot of apparent and effective Cs^+ diffusivity as function of distribution coefficient (K_d).
The lines are calculated using $D_p = 8 \cdot 10^{-6}$ and $D_s = 6 \cdot 10^{-9}$ $cm^2 \cdot s^{-1}$.

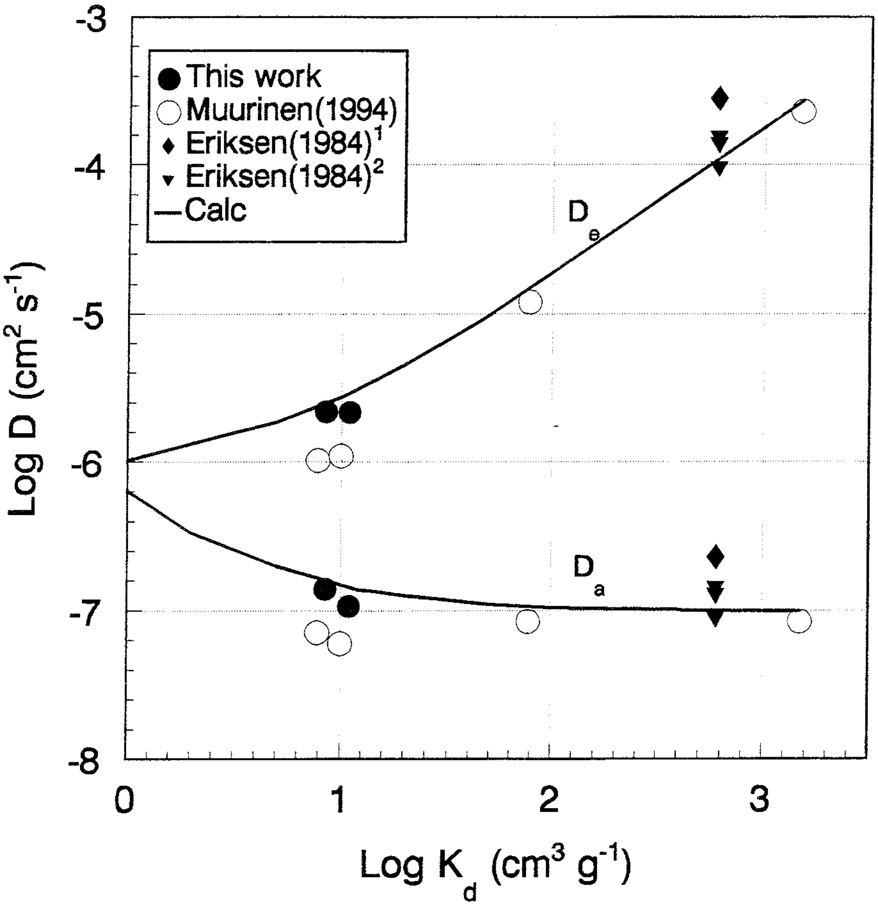

Figure 10.

Logarithmic plot of apparent and effective Sr^{2+} diffusivity as function of distribution coefficient (K_d). The lines are calculated using $D_p = 3 \cdot 10^{-6}$ and $D_s = 1 \cdot 10^{-7}$ cm$^2 \cdot$s^{-1}. The data from Eriksen (1984) are from experiments with different techniques.

6. REFERENCES

Berry, J. A. and Bond, K. A. 1992. Studies on the extent of surface diffusion in the migration of radionuclides through geological materials: Radiochim. Acta 58/59, 329-335.

Cheung, S. C. H. and Gray, M. N. 1989. Mechanisms of ionic diffusion in dense bentonite. In: Lutze, W. and Ewing, R. C. (eds) Scientific basis for nuclear waste management XII. MRS Symp. Proc., vol 127. Pittsburg: MRS. pp 677-681.

Choi, J. W., Jung, C. H., Chun,.C. H., Park, H. S., Whang, J. H. and Lee, B. H. 1992. Diffusion of radionuclides in compacted bentonite. Proc. Conf. on high level radioactive waste management. (CONF-920430). La Grande Park, IL; Am. Nucl. Soc., pp 2278 2283.

Cook, A. J. 1989. A desk study of surface diffusion and mass transport in clay. Report EUR 12381.

Eriksen, T. E., Jacobsson, A. and Pusch, R. 1981. Ion diffusion through highly compacted bentonite. KBS TR 81-06, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden

Eriksen, T. E. and Jacobsson, A. 1981. Ion diffusion in compacted Na and Ca bentonites. KBS TR 91-12, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Eriksen, T. E. and Jacobsson, A. 1984. Diffusion in clay. Experimental techniques and theoretical models. KBS TR 84-05, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Jahnke, F. M. and Radke, C. J.. Electrolyte diffusion in compacted montmorillonite engineered barrier. In: Coupled Processes Associated with Nuclear Waste Repositories, San Diego. Academic Press, pp 287-297.

Kim, H. T, Suk, T.W. and Parks, S. H. 1993. Diffusivities for ions through compacted Na-bentonite with varying dry bulk density. Waste Management, vol 13, pp 303-308.

Muurinen, A., Rantanen, J. and Penttilä-Hiltunen, P. 1985. Diffusion mechanisms of strontium, cesium and cobalt in compacted sodium bentonite. In. Werme,.L O.(ed) Scientific basis for nuclear waste management IX, MRS Symp. Proc: vol 50, pp 617-624.

Muurinen, A., Penttilä-Hiltunen, P. and Rantanen, J. 1987. Diffusion mechanisms of strontium and cesium in compacted sodium bentonite. In Bates, J. K and Seefeldt, W. B. (eds) Scientific basis for nuclear waste management X, MRS Symp. Proc., vol 84, pp803-812.

Muurinen, A. 1994. Diffusion of anions and cations in compacted sodium bentonite. Espoo, Technical Centre of Finland, VTT Publication No 168.

Oscarson, D. W., Watson, R. L. and LeNeveu, D. M. 1984. Compilation of distribution coefficients for radioactive and other toxic contaminants with bentonite for use in SYVAC, AECL TR-288, Whiteshell Nucl. Res. Est., Pinawa, Manitoba, Canada.

Put, M. J. An improved mathematical model for the interpretation of the flow-through type diffusion tests with influence of filterplates. 1991. Rad. Waste. Management and the Nuclear Fuel Cycle, vol 16(1). pp 69-81.

Rasmuson, A. and Neretnieks, I.1983. Surface migration in sorption processes. SKB TR 83-37, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Soudek, A., Jahnke, F. M. and Radke, C. J. 1984. Ion- exchange equilibria and diffusion in engineered backfill. Techn.Rep. NUREG/ CP-0052, pp 172-203.

Torstenfelt B. et al. 1983. Radionuclide diffusion and mobilities in compacted bentonite. KBS TR 83-34. Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

van Schaik, J. C, Kemper,.W. D. and Olsen, S. R. 1966: Contribution of adsorbed cations to diffusion in clay-water systems. Soil Sci. Soc. Amer. Proc., vol 30, pp17-22.

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

1992
TR 92-46
SKB Annual Report 1992
Including Summaries of Technical Reports Issued during 1992
Stockholm, May 1993

1993
TR 93-34
SKB Annual Report 1993
Including Summaries of Technical Reports Issued during 1993
Stockholm, May 1994

1994

TR 94-33

SKB Annual Report 1994

Including Summaries of Technical Reports Issued during 1994.
Stockholm, May 1995

1995

TR 95-37

SKB Annual Report 1995

Including Summaries of Technical Reports Issued during 1995.
Stockholm, May 1996

List of SKB Technical Reports 1996

TR 96-01

Bacteria, colloids and organic carbon in groundwater at the Bangombé site in the Oklo area

Karsten Pedersen (editor)
Department of General and Marine Microbiology,
The Lundberg Institute, Göteborg University,
Göteborg, Sweden
February 1996

TR 96-02

Microbial analysis of the buffer/container experiment at AECL´s Underground Research Laboratory

S Stroes-Gascoyne[1], K Pedersen[2], S Daumas[3],
C J Hamon[1], S A Haveman[1], T L Delaney[1],
S Ekendahl[2], N Jahromi[2], J Arlinger[2], L Hallbeck[2],
K Dekeyser[3]
[1] AECL, Whiteshell Laboratories, Pinawa, Manitoba, Canada
[2] University of Göteborg, Department of General and Marine Microbiology, Göteborg, Sweden
[3] Guigues Recherche Appliquée en Microbiologie (GRAM), Aix-en-Provence, France
1996

TR 96-03

Reduction of Tc (VII) and Np (V) in solution by ferrous iron. A laboratory study of homogeneous and heterogeneous redox processes

Daqing Cui, Trygve E Eriksen
Department of Chemistry, Nuclear Chemistry,
Royal Institute of Technology, Stockholm, Sweden
March 1996

TR 96-04

Revisiting Poços de Caldas. Application of the co-precipitation approach to establish realistic solubility limits for performance assessment

Jordi Bruno, Lara Duro, Salvador Jordana,
Esther Cera
QuantiSci, Barcelona, Spain
February 1996

TR 96-05

SR 95

Template for safety reports with descriptive example
SKB
December 1995

TR 96-06

Äspö Hard Rock Laboratory Annual Report 1995

SKB
April 1996

TR 96-07

Criticality in a high level waste repository. A review of some important factors and an assessment of the lessons that can be learned from the Oklo reactors

Virginia M Oversby
VMO Konsult
June 1996

TR 96-08

A reappraisal of some Cigar Lake issues of importance to performance assessment

John Smellie[1], Fred Karlsson[2]
[1] Conterra AB
[2] SKB
July 1996

TR 96-09

The long-term stability of cement. Leaching tests

Ingemar Engkvist, Yngve Albinsson,
Wanda Johansson Engkvist
Chalmers University of Technology,
Göteborg, Sweden
June 1996

TR 96-10

Lake-tilting investigations in southern Sweden

Tore Påsse
Sveriges geologiska undersökning,
Göteborg, Sweden
April 1996

TR 96-11
Thermoelastic stress due to an instantaneous finite line heat source in an infinite medium
Johan Claesson, Göran Hellström
Depts. of Building Physics and Mathematical Physics, Lund University, Lund, Sweden
September 1995

TR 96-12
Temperature field due to time-dependent heat sources in a large rectangular grid
– Derivation of analytical solution
Johan Claesson, Thomas Probert
Depts. of Building Physics and Mathematical Physics, Lund University, Lund, Sweden
January 1996

TR 96-13
Thermoelastic stress due to a rectangular heat source in a semi-infinite medium
– Derivation of an analytical solution
Johan Claesson, Thomas Probert
Depts. of Building Physics and Mathematical Physics, Lund University, Lund, Sweden
May 1996

TR 96-14
Oklo: Des reacteurs nucleaires fossiles (Oklo: The fossil nuclear reactors). Physics study (R Naudet, CEA)
– Translation of chapters 6, 13, and conclusions
V O Oversby
VMO Konsult
September 1996

TR 96-15
PLAN 96
Costs for management of the radioactive waste from nuclear power production
Swedish Nuclear Fuel and Waste Management Co
June 1996