SKB
TECHNICAL
REPORT
89-24

Some notes on diffusion of radionuclides through compacted clays

Trygve E Eriksen

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

May 1989

SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

BOX 5864 S-102 48 STOCKHOLM
TEL 08-665 28 00 TELEX 13108-SKB

SOME NOTES ON DIFFUSION OF RADIONUCLIDES THROUGH COMPACTED CLAYS

Trygve E Eriksen

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

May 1989

Information on SKB technical reports from
1977-1978 (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) and 1988 (TR 88-32) is available
through SKB.

Some notes on diffusion of radionuclides through compacted clays.

Trygve E Eriksen
The Royal Institute of Technology,
Department of Nuclear Chemistry,
S-100 44 Stockholm 70

Abstract.

The apparent diffusivities of some simple cations i.e. Sr^{2+}, Cs^{+} in water saturated bentonite indicates that diffusion takes place both in the pore solution and within the solvation sheath of the exchangeable cations. Data from some earlier diffusion experiments have been re-evaluated and the results suggest that diffusion within the solvation sheath of the exchangeable cations is the dominating mechanism for Sr^{2+} and Cs^{+}.

Content.

1. Introduction.

To make possible the assessment of long term storage of high level nuclear wastes in underground repositories understanding of the migration mechanisms in porous water containing materials is of great importance.

A clay backfill is generally assumed to create a first barrier to the transport of radionuclides when the canisters fail and diffusion through compacted water saturated bentonite clays has been the subject of several studies (1-12).

The experimental techniques used and the results obtained have earlier been discussed in some detail by Eriksen and Jacobsson (13). Methods of measuring diffusion properties of porous media have also recently been discussed by Lever (14).

The transport of solutes is of great importance for many soil processes and the diffusion of ions and uncharged solutes through soil and clays have recently been comprehensively reviewed by Nye (15).

Applying Fick's first law $F = -D \cdot \delta c/\delta x$, where F is the flux, D the diffusion coefficient and $\delta c/\delta x$ the concentration gradient, to a complex medium such as water saturated bentonite may be regarded as giving an operational definition of the diffusion coefficient. To explain the results obtained at varying experimental conditions a thorough understanding of the clay/water system is, therefore, required.

Some of the models used to describe the diffusion in compacted bentonite will be discussed below.

2. Components of diffusion coefficients.

In the overall movement of solutes through a water containing porous medium both solid and water play a part.If the diffusion is assumed to take place in the pore water only the flux per unit area of of the porous medium is linked to the concentration gradient in the pore water by the intrinsic diffusion coefficient for the pore water D_{ip}

$$F = -D_{ip} \cdot \nabla C_p \qquad /1/$$

If it is assumed that the solute is sorbed on the surface of the porous medium by a sorption reaction that is instantaneous and reversible the diffusion in one dimension is described by the equation

$$\theta \cdot \delta C_p / \delta t = D_{ip} \cdot \delta^2 C_{p} / \delta x^2 - \delta C_s / \delta t \qquad /2/$$

where C_p is the concentration of solute in pore water, C_s is the concentration of sorbed solute and θ is the volume fraction of the pore water.

The quantity of solute sorbed is frequently measured per unit mass of porous medium and the ratio of the concentration of solute bound to the solid phase relative to the concentration in solution is given by the distribution coefficient K_d. Based on the assumptions given above the concentration of sorbed solute is related to the solute concentration in the pore water by the density of the porous medium and the distribution coefficient.

$$C_s = (K_d \cdot \rho) C_p \qquad /3/$$

and equation /2/ can be rewritten as

$$\alpha \cdot \delta C_p / \delta t = D_{ip} \cdot \delta^2 C_p / \delta x^2 \qquad /4/$$

where $\alpha = \theta + K_d \cdot \rho$ is the capacity factor of the porous medium. The total quantity of solute per unit volume of the porous medium is thus $\alpha \cdot C_p$ and the total flux per unit area is $D_{ip} \cdot \delta C_p / \delta x$

The apparent diffusivity is a measure of the distance that the solute has diffused and the appropriate diffusion coefficient is

$$D_a = D_{ip} / \alpha \qquad /5/$$

For weakly or non sorbing solutes

$$D_a = D_{ip} / \theta = D_p \qquad /6/$$

where D_p is the pore-water diffusion coefficient.

The experimental data on cation diffusion in compacted clays can not be easily accommodated by this pore diffusion model and several researchers (16,17) have recently argued for the inclusion of an additional surface flux F_s that arises from the diffusion of the solute sorbed on the surface of the porous solid.

The total flux is in this case given by

$$F = -D_{ip} \cdot \nabla C_p - D_s \cdot \nabla C_s \qquad /7/$$

where D_s is the surface diffusion coefficient and equations 4 and 5 are modified to read

$$\alpha \cdot \delta C_p/\delta t = D_i \cdot \delta^2 C_p/\delta x^2 \qquad /8/$$

where $D_i = D_{ip} + K_d \cdot \rho \cdot D_s$ is the total intrinsic diffusion coefficient and

$$D_a = (D_{ip} + K_d \cdot \rho \cdot D_s)/\alpha \qquad /9/$$

3. Clay- water interaction.

The clay used in many of the studies cited is the American Colloid Co type Mx-80 granulated Na bentonite, containing about 75% montmorillonite.

The mechanism of hydration and the structure of smectite-adsorbed water have recently been reviewed (18-19). It seems clear that the first stage in water adsorption involves solvation of the exchangeable cations (mainly in the interlamellar positions), the degree of solvation depending on the ability of the cations to solvate themselves. The ordered arrangement thus obtained for the first 1-3 first layers of water in contact with the surface remains unaltered even on addition of further water. As the water content is increased water is adsorbed on external surfaces and in micropores and the behaviour of the hydrated cations becomes gradually more similar to that of cations in aqueous solution. At a given water content the water adsorbed by smectites can thus be found in two different states. A general relationship between bulk density and content of internal water in percent of the total water volume in smectite clay is given in a recent paper by Pusch (20).

4. Experimental techniques.

Several different techniques have been used for measuring diffusion properties of porous media. In this section we give a short description of some tracer techniques used to study diffusion in highly compacted bentonites.

4.1 Through diffusion.

A compacted water saturated bentonite is sandwiched between two reservoirs (Fig 1).

The tracer is added to one of the reservoirs and the temporal change in the tracer concentration in the other reservoir monitored. The total amount of tracer $Q(t) = C_2(t)V_2$, accumulated in the initially tracer free reservoir is given by

$$Q/A \cdot l \cdot C_1 = D_i t/l^2 - \alpha/6 - (2\alpha/\pi)\sum_{n=1}^{\infty} (-1)^n/n^2 \exp -D_i n^2 \pi^2 t/l^2 \qquad /10/$$

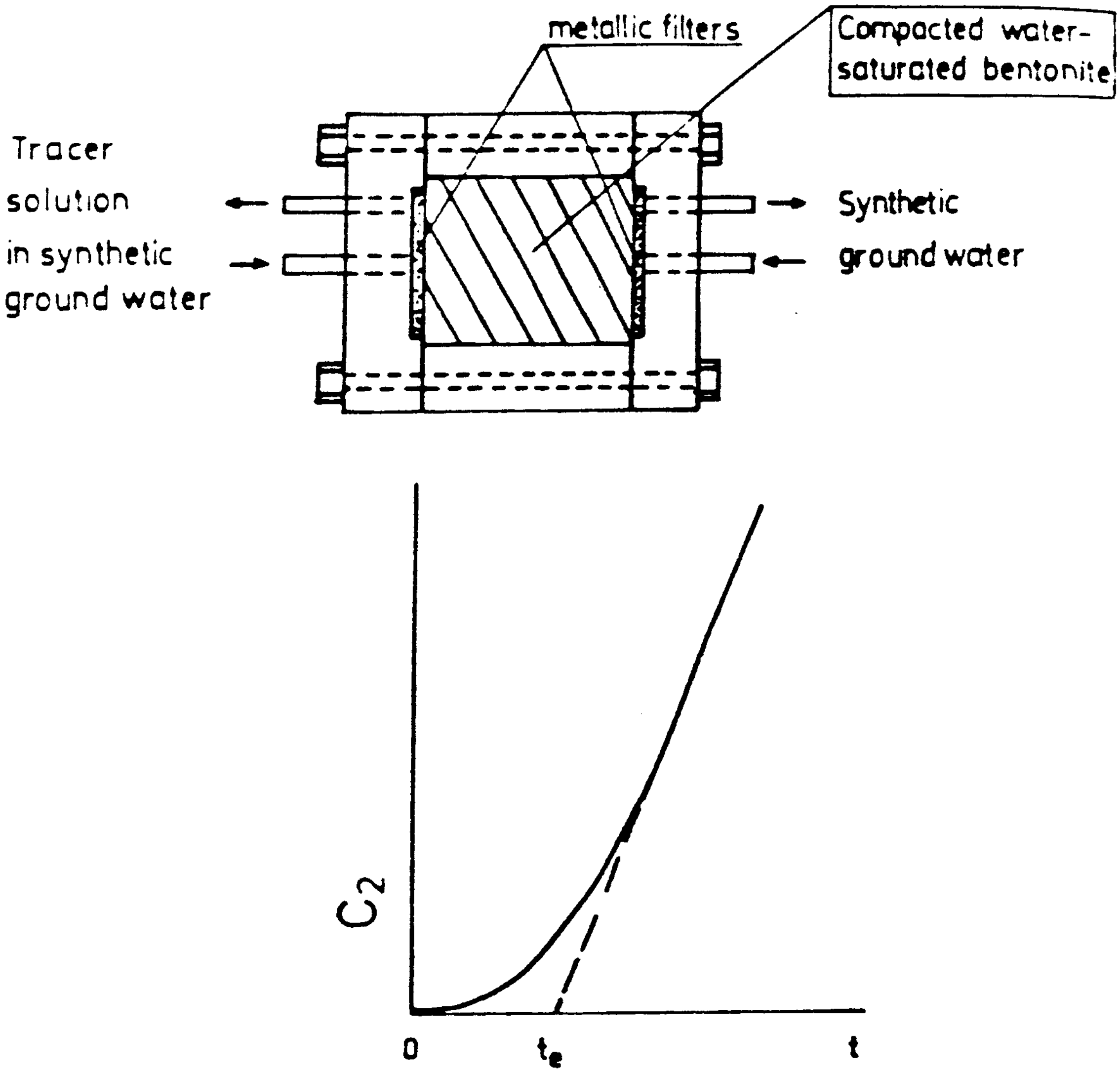

Fig 1

With increasing t the exponential term rapidly decreases leaving the asymptotic solution

$$C_2 = (AC_1/V_2 l)(D_i t - \alpha l^2/6) \qquad /11/$$

where D_i is the intrinsic diffusion coefficient, C_1 the inlet concentration, C_2 the concentration in the outlet reservoir with volume V_2, A the cross-sectional area of the clay sample, l the sample thickness and α the capacity factor.

The asymptotic solution thus gives a straight line with slope $D_i(AC_1/V_2l)$ and an intercept on the t-axis at $t_e = \alpha l^2/6D_i$. The capacity factor can be obtained from the intercept of the extrapolated asymptote with the C_2-axis. i.e.$C_2(0) = (AC_1l/6V_2)\cdot\alpha$.

4.2 Back to back experiments.

A water saturated compacted clay sample is pressed in contact with a corresponding clay sample containing the tracer.

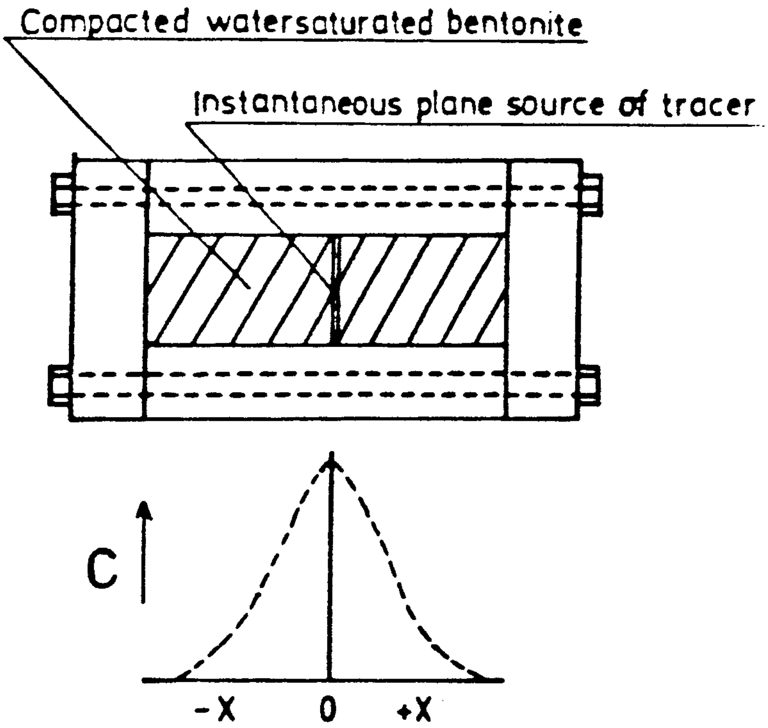

Fig 2

If the tracer is applied to a thin layer and the total amount of tracer is M then the tracer concentration at a distance x from the initial source at time t is

$$C(t)=[M/2A(\pi D_a t)^{1/2}]\cdot \exp(-x^2/4D_a t) \qquad /12/$$

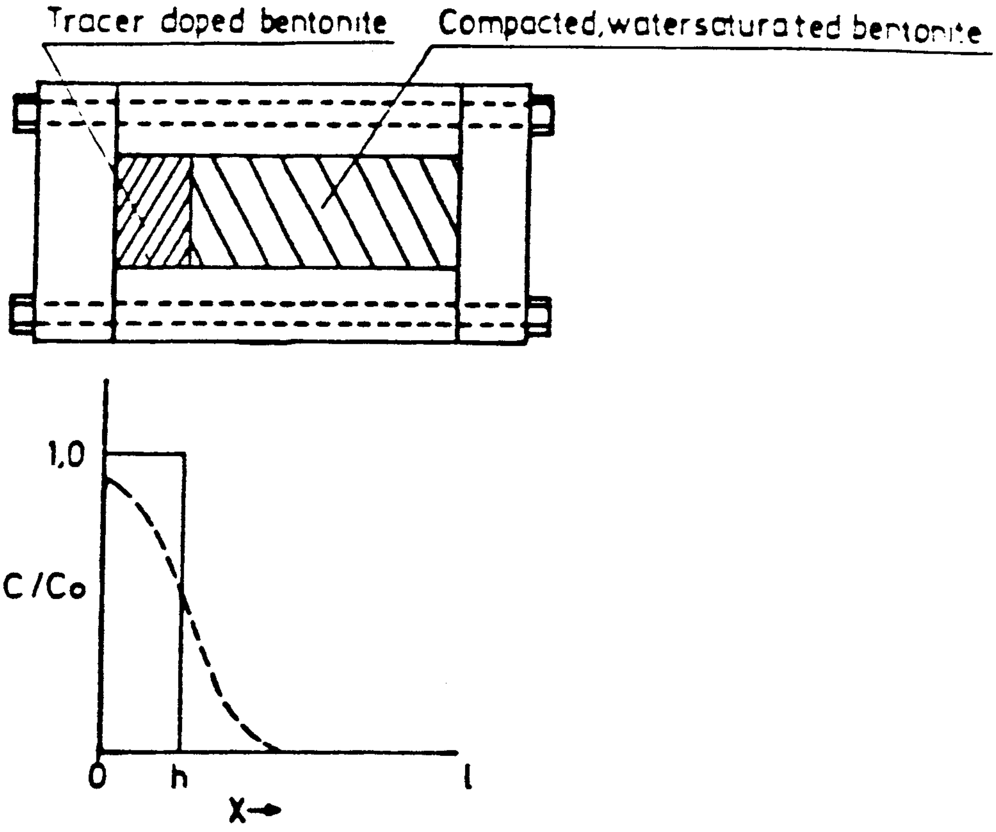

Fig 3

If one half is uniformly loaded with the tracer i.e extended initial distribution the tracer distribution is given by the equation

$$C/C_o = 1/2\ \mathrm{erf}[(l-x/h)/(2/h)\cdot(D_a t)^{1/2}] + 1/2\ \mathrm{erf}[(l+x/h)/(2/h)(D_a t)^{1/2}] \qquad /13/$$

where C_o is the initial tracer concentration in the loaded sample of thickness h and l the overall thickness of the clay samples.

In both cases only the apparent diffusion coefficient can be calculated directly from the diffusion data and the capacity factor must be determined in separate sorption experiments.

4.3 Material.

The clay used in the experiments was the American Colloid Co type MX-80 granulated Na bentonite. The bentonite was dried at 105°C, compacted and thereafter water saturated. The experimental conditions are given in table 1.

Table 1.

Properties of diffusing medium.

Dry density $g \cdot cm^{-3}$	Bulk density $g \cdot cm^{-3}$	V_w/V_w+V_s %	Water ratio %
1.8	2.12	32	17.7

5.1 Anion diffusion.

The experiments were carried out using the through diffusion technique and the experimental results are given in table 2.

Table 2.

Anion diffusion in compacted Mx-80. (Bulk density 2.12 $g \cdot cm^{-3}$)

Ion	D_a 10^{12} $m^2 \cdot sec^{-1}$	D_i 10^{14} $m^2 \cdot sec^{-1}$	α	V_w/V_w+V_s	$\alpha/(V_w/V_w+V_s)$
Cl^-	92	31	0.0034	0.32	0.011
I^-	35	21	0.0060	0.32	0.019
HS^-	4.8	1.14	0.0024	0.32	0.008
AQS^{-*}	8.2	0.23	0.0003	0.32	0.001
$LS^{-\$}$	5.6	0.075	0.00013	0.32	0.0004

* AQS = Antraquinone sulfonate

$ LS = Lignosulfonate (Mw 30 000)

Assuming no sorption the relation between the pore diffusion coefficient D_p and the free water diffusion coefficient D_w can be written $D_p = f \cdot D_w$ where f is an impedance factor.

In the case of uncharged solutes the impedance factor takes account primarily of tortuosity (τ^2) and constrictivity (δ) and can be written $f = \delta/\tau^2$. In the case of anion diffusion the impedance factor also allows for Donnan exclusion.

Taking the free water diffusion coefficient of Cl^- to be $2.03 \cdot 10^{-9}$ m^2s^{-1} the impedance factor is 0.045, indicating marked constrictivity and/or tortuosity. The capacity factor is also very low compared to the volumetric water ratio. It is thus very clear that very little, if any, interlamellar anion diffusion takes place. If the anion "diffusion porosity" is assumed to represent the external pore-water (as described by Pusch) the Cl^-,I^- and HS^- data indicate that with the exception of a few percent, the water is present as interlamellar water.

5.2 Cation diffusion.

Diffusion coefficients for Sr^{2+} and Cs^+ are given in table 3.

Table 3.

Sr^{2+} and Cs^+ diffusion in compacted Na- bentonite.
(Bulk density 2.1 $g \cdot cm^{-3}$).

Ion	Ref	$D_a \cdot 10^{12}$ $m^2 \cdot s^{-1}$	V_w/V_w+V_s	K_d $cm^3 \cdot g^{-1}$	$D_w \cdot 10^9$ $m^2 \cdot s^{-1}$
Sr^{2+}	6	15+/-2	0.32	604	0.78
	5.9	1.5-12		2900	
Cs^+	6	2.5+/-0.5	0.32	645	2.11
	9	1.4-2		1400	
	10	5.0			

According to the pore diffusion model, assuming no diffusion of sorbed exchangeable ions, the apparent diffusivity is described by $D_a = D_{ip}/\alpha$ where $\alpha = \theta + K_d \cdot \rho$.
The impedance factor $f = \delta/\tau^2$ is not known, but as we have not used oriented samples it is not likely to be higher than 0.5. Based on the free water diffusivities and K_d values given in table 3, the upper limits for D_a are calculated to be $0.34 \cdot 10^{-12}$ and $0.9 \cdot 10^{-12}$ $cm^2 \cdot s^{-1}$ for $Sr^{2+}$and Cs^+ respectively, i.e lower than the experimentally measured apparent diffusivities. The experimental data can thus not be accommodated by the pore diffusion model.
In a study on Sr^{2+}, Cs^+ and Co^+ diffusion in compacted bentonite Murinen and co-workers varied the the Kd values by changing the ionic strength of the solutions used for water saturation of the bentonite. The electrolyte used was NaCl and the highest concentration was 0.6 $mol \cdot dm^{-3}$. By fitting the data to a model with surface diffusion included they calculated $\theta \cdot D_p$ and D_s. The surface diffusion was found to account for 70-90 percent of the total transport in their experiments.

The idea of separating the cation migration in clays into two components i.e. the flux through the pore solution alone and the flux of exchangeable cations on the solid is not a new one. The overall cation transport in suspensions with low clay content (21, 22) as well as on water saturated clay films (23) have been explained by a model based on the assumption of diffusion taking place both in a solution phase and in the adsorbed state. The application of this concept does, however, require knowledge of the volume fraction occupied by the pore solution. It ought to be emphasized that the water associated with the sorbed exchangeable ions is not to be included. Mott (24) measured the diffusion coefficients of Na^+ and Sr^{2+} in oriented homoionic bentonite flakes with varying water content. He found the diffusion in dry clay to be very slow ($D_a < 10^{-15}$ m^2s^{-1}) and to increase with several orders of magnitude on addition of 0.15-0.3 g water/g dry clay. This water content corresponds to 1-3 molecule layers of water.

A detailed study on diffusion of the exchangeable cations Na^+, Rb^+, Cs^+ and Ca^{2+} in montmorillonite containing 0-0.25 g water/ g dry clay was carried out by Calvet (24). He found the mobility of Na^+ to be much reduced on addition of Ca^{2+} to a homoionic clay and that the effect was enhanced at low water content. According to Calvet this effect is due to the higher water affinity of Ca^{2+} as compared to Na^+, i.e competition for water in the slightly hydrated clay.

In the highly compacted bentonite (ρ = 2.12 $g \cdot cm^3$) used in our experiments the water content corresponds to 2-3 molecule layers of water. Most of this water is associated with the exchangeable cations and is thereby situated in interlamellar positions. Pusch (20) estimates that 75-85 percent of the water is present as "internal" water at the bulk density used in our experiment.

If it is assumed that the impedance factor for the cation transport in the pore solution (i.e interlamellar water not included) is the same as for the anions Cl^- and I^- and that the interlamellar water is totally associated with the exchangeable cations the diffusion coefficients in pore solution and in the solvated cation phase can be calculated. The results are tabulated in table 4.

Table 4.

Calculated diffusion coefficients for pore solution and solvated-cation phase.

Ion	$D_a \cdot 10^{12}$ m^2s^{-1}	f	$D_w \cdot 10^9$ m^2s^{-1}	$D_{ip} \cdot 10^{11}$ m^2s^{-1}	$D_s \cdot 10^{12}$ m^2s^{-1}	
Sr^{2+}	15	0.045	0.78	3.5	15^a	$12\text{-}13.5^b$
Cs^+	2.5	0.045	2.1	9.5	2.1^a	$0.5\text{-}1.3^b$

a : based on pore solution porosity of 0.0045

b : based on pore solution porosity of 15-25% of total water volume fraction (according to Pusch, ref 20).

The diffusion coefficients, calculated in this way, are somewhat higher, but of the same order of magnitude as those obtained by Murinen el al (17).

Some objections can be raised against the use of solutions with varying concentrations of electrolytes and complexing agents to vary the K_d-value in diffusion experiments. At low water ratios a redistribution of the water on the clay surface probably takes place which, according to the work of Calvet (25), may influence the diffusivity of the exchangeable ions.

All the experimental data indicate that diffusion within the solvation sheath of the exchangeable ions is a dominating transport process in highly compacted bentonite with low water content.

References.

1. Neretnieks I, Skagius K
   Diffusionsmätningar i våt lera.
   KBS TR-87

2. Neretnieks I, Skagius K
   Diffusionsmätningar av metan och väte i våt lera.
   KBS TR 86

3. Allard B, Kipatsi H
   Mätning av diffusionshastigheter för silver i lera-sandblandning.
   KBS TR 53

4. Eriksen T E, Jacobsson A, Pusch R
   Ion diffusion through highly compacted bentonite.
   KBS TR 81-06

5. Torstenfelt B, Andersson K, Kipatsi H, Allard B, Olofsson U
   Diffusion measurements in compacted bentonite.
   Topp S (Ed): Scientific Basis for Nuclear Waste Management lV, Elsevier 1982.

6. Eriksen T E, Jacobsson A
   Ion diffusion in compacted sodium and calcium bentonites.
   KBS TR 81-12.

7. Eriksen T E and Jacobsson A
Diffusion of hydrogen,hydrogensulfide and large molecular weight anions in bentonite.
KBS TR 81-17

8. Pusch R, Eriksen T E and Jacobsson A
Ion/water migration phenomena in dense bentonites.
Lutze W (Ed): Scientific Basis for Nuclear Waste Management V, Elsevier 1982 p.649

9. Torstenfelt B, Kipatsi H, Andersson K, Allard B, Olofsson U.
Transport of actinides through a bentonite backfill.
ibid p.659

10. Murinen A,Rantanen R,Ovaskinen R, Heinonen O J
Diffusion measurements in concrete and compacted bentonite.
Brookins D G (Ed): Scientific Basis for Nuclear Waste Management VI, Elsevier

11. Kipatsi H
Sorption behaviour of long lived fission products and actinides in clay and rock.
Dissertation, Univ. Gothenburgh 1983.

12. Neretnieks I
Diffusivities of some dissolved constituents in compacted wet bentonite clay-MX 80 and the impact on radionuclide migration in the buffer.
KBS TR 82-27

13. Eriksen T E, Jacobsson A
Diffusion in clay, experimental techniques and theoretical models.
KBS TR 84-05

14. Lever D A
Some notes on experiments measuring diffusion of sorbed nuclides through porous media.
AERE R 12 321 (1986)

15. Nye P H
Diffusion of ions and uncharged solutes in soils and soil clay.
Adv in Agronomy Vol 31,P 225-272. A.P 1979.

16. Rasmusson A, Neretnieks I
Surface migration in sorption processes.
KBS TR 83-37.

17. Murinen A, Rantanen J, Hiltunen P P
Diffusion mechanisms of strontium,cesium and cobalt in compacted sodium bentonite.
Werme L (Ed): Scientific Basis for Nuclear Waste Management IX, Material Research Society Symposia Proceedings Vol 50, p 617 (1985).

18. Fripiat J J, Stone W E E
Water on the surface of clay minerals: orientation, diffusion and proton exchange.
Rev. Chem. Liq. Vol 7, p 349-374 Gordon and Breach 1978.

19. Sposito G, Prost R
Structure of water adsorbed on smectites
Chem.Rev: 1982,86:6,553

20. Pusch R, Karnland O
Aspects of the physical state of smectite- adsorbed water.
SKB TR-86-27

21. Duffey J E, Landelout H G
Self diffusion of anions in clay- gels
J.Colloid. Interface Sci. 1975, 51, 278

22. Duffey J E, Landelout H G
Self diffusion of sodium on clay surfaces as influenced
by two other alkali cations.
J. Colloid. Interface Sci. 1975, 52,340

23. Ellis J H, Bornhisel R I, Phillips R E
The diffusion of copper,manganese and zinc as affected by
concentration,clay mineralogy and associated anions.
Soil.Sci.Soc.Amer.Proc 1970,34,866

24. Mott G J B
Thesis, Univ Oxford 1967 (see p 241 in ref 15)

25. Calvet R
Ann Agron 1973,24,77-217

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

Technical Reports

1989

TR 89-01
Near-distance seismological monitoring of the Lansjärv neotectonic fault region Part II: 1988
Rutger Wahlström, Sven-Olof Linder,
Conny Holmqvist, Hans-Edy Mårtensson
Seismological Department, Uppsala University, Uppsala
January 1989

TR 89-02
Description of background data in SKB database GEOTAB
Ebbe Eriksson, Stefan Sehlstedt
SGAB, Luleå
February 1989

TR 89-03
Characterization of the morphology, basement rock and tectonics in Sweden
Kennert Röshoff
August 1988

TR 89-04
SKB WP-Cave Project
Radionuclide release from the near-field in a WP-Cave repository
Maria Lindgren, Kristina Skagius
Kemakta Consultants Co, Stockholm
April 1989

TR 89-05
SKB WP-Cave Project
Transport of escaping radionuclides from the WP-Cave repository to the biosphere
Luis Moreno, Sue Arve, Ivars Neretnieks
Royal Institute of Technology, Stockholm
April 1989

TR 89-06
SKB WP-Cave Project
Individual radiation doses from nuclides contained in a WP-Cave repository for spent fuel
Sture Nordlinder, Ulla Bergström
Studsvik Nuclear, Studsvik
April 1989

TR 89-07
SKB WP-Cave Project
Some Notes on Technical Issues
Part 1: Temperature distribution in WP-Cave: when shafts are filled with sand/water mixtures
Stefan Björklund, Lennart Josefson
Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden
Part 2: Gas and water transport from WP-Cave repository Luis Moreno, Ivars Neretnieks
Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden
Part 3: Transport of escaping nuclides from the WP-Cave repository to the biosphere. Influence of the hydraulic cage
Luis Moreno, Ivars Neretnieks
Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden
August 1989

TR 89-08
SKB WP-Cave Project
Thermally incuded convective motion in groundwater in the near field of the WP-Cave after filling and closure
Polydynamics Limited, Zürich
April 1989

TR 89-09
An evaluation of tracer tests performed at Studsvik
Luis Moreno[1], Ivars Neretnieks[1], Ove Landström[2]
[1] The Royal Institute of Technology, Department of Chemical Engineering, Stockholm
[2] Studsvik Nuclear, Nyköping
March 1989

TR 89-10
Copper produced from powder by HIP to encapsulate nuclear fuel elements
Lars B Ekbom, Sven Bogegård
Swedish National Defence Research Establishment
Materials department, Stockholm
February 1989

TR 89-11
Prediction of hydraulic conductivity and conductive fracture frequency by multivariate analysis of data from the Klipperås study site
Jan-Erik Andersson[1], Lennart Lindqvist[2]
[1] Swedish Geological Co, Uppsala
[2] EMX-system AB, Luleå
February 1988

TR 89-12
Hydraulic interference tests and tracer tests within the Brändan area, Finnsjön study site
The Fracture Zone Project – Phase 3
Jan-Erik Andersson, Lennart Ekman, Erik Gustafsson, Rune Nordqvist, Sven Tirén
Swedish Geological Co, Division of Engineering Geology
June 1988

TR 89-13
Spent fuel
Dissolution and oxidation
An evaluation of literature data
Bernd Grambow
Hanh-Meitner-Institut, Berlin
March 1989

TR 89-14
The SKB spent fuel corrosion program
Status report 1988
Lars O Werme[1], Roy S Forsyth[2]
[1] SKB, Stockholm
[2] Studsvik AB, Nyköping
May 1989

TR 89-15
Comparison between radar data and geophysical, geological and hydrological borehole parameters by multivariate analysis of data
Serje Carlsten, Lennart Lindqvist, Olle Olsson
Swedish Geological Company, Uppsala
March 1989

TR 89-16
Swedish Hard Rock Laboratory – Evaluation of 1988 year pre-investigations and description of the target area, the island of Äspö
Gunnar Gustafsson, Roy Stanfors, Peter Wikberg
June 1989

TR 89-17
Field instrumentation for hydrofracturing stress measurements
Documentation of the 1000 m hydrofracturing unit at Luleå University of Technology
Bjarni Bjarnason, Arne Torikka
August 1989

TR 89-18
Radar investigations at the Saltsjötunnel – predicitions and validation
Olle Olsson[1] and Kai Palmqvist[2]
[1] Abem AB, Uppsala, Sweden
[2] Bergab, Göteborg
June 1989

TR 89-19
Characterization of fracture zone 2, Finnsjön study-site
Editors: **K. Ahlbom, J.A.T. Smellie, Swedish Geological Co, Uppsala**
Part 1: Overview of the fracture zone project at Finnsjön, Sweden
K. Ahlbom and J.A.T. Smellie. Swedish Geological Company, Uppsala, Sweden.
Part 2: Geological setting and deformation history of a low angle fracture zone at Finnsjön, Sweden
Sven A. Tirén. Swedish Geological Company, Uppsala, Sweden.
Part 3: Hydraulic testing and modelling of a low-angle fracture zone at Finnsjön, Sweden
J-E. Andersson[1], L. Ekman[1], R. Nordqvist[1] and A. Winberg[2]
[1] Swedish Geological Company, Uppsala, Sweden
[2] Swedish Geological Company, Göteborg, Sweden
Part 4: Groundwater flow conditions in a low angle fracture zone at Finnsjön, Sweden
E. Gustafsson and P. Andersson. Swedish Geological Company, Uppsala, Sweden
Part 5: Hydrochemical investigations at Finnsjön, Sweden
J.A.T. Smellie[1] and P. Wikberg[2]
[1] Swedish Geological Company, Uppsala, Sweden
[2] Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden
Part 6: Effects of gas-lift pumping on hydraulic borehole conditions at Finnsjön, Sweden
J-E- Andersson, P. Andersson and E. Gustafsson. Swedish Geological Company, Uppsala, Sweden
August 1989

TR 89-20
WP-Cave - Assessment of feasibility, safety and development potential
Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden
September 1989

TR 89-21
Rock quality designation of the hydraulic properties in the near field of a final repository for spent nuclear fuel
Hans Carlsson[1], Leif Carlsson[1], Roland Pusch[2]
[1] Swedish Geological Co, SGAB, Gothenburg, Sweden
[2] Clay Technology AB, Lund, Sweden
June 1989

TR 89-22
Diffusion of Am, Pu, U, Np, Cs, I and Tc in compacted sand-bentonite mixture
Department of Nuclear Chemistry, Chalmers University of Technology, Gothenburg, Sweden
August 1989

TR 89-23
Deep ground water microbiology in Swedish granitic rock and it's relevance for radionuclide migration from a Swedish high level nuclear waste repository
Karsten Pedersen
University of Göteborg, Department of Marine microbiology, Gothenburg, Sweden
March 1989