Gas transport processes in crystalline rocks and engineered barriers within the EDZ: BGS contribution to NF-PRO WP4.4.1

Chemical & Biological Hazards Programme

Commissioned Report CR/06/244N

BRITISH GEOLOGICAL SURVEY

CHEMICAL & BIOLOGICAL HAZARDS PROGRAMME

COMMISSIONED REPORT CR/06/244N

Gas transport processes in crystalline rocks and engineered barriers within the EDZ: BGS contribution to NF-PRO WP4.4.1

H J Reeves, R J Cuss, and D J Noy

The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office.
Ordnance Survey licence number Licence No:100017897/2006.

Keywords

Gas transport; crystalline rocks; EDZ; waste disposal; engineered barrier.

Bibliographical reference

REEVES, HJ, CUSS, RJ, AND NOY DJ. 2006. Gas transport processes in crystalline rocks and engineered barriers within the EDZ: BGS contribution to NF-PRO WP4.4.1. *British Geological Survey Commissioned Report*, CR/06/244N. 26pp.

Copyright in materials derived from the British Geological Survey's work is owned by the Natural Environment Research Council (NERC) and/or the authority that commissioned the work. You may not copy or adapt this publication without first obtaining permission.
Contact the BGS Intellectual Property Rights Section, British Geological Survey, Keyworth, e-mail ipr@bgs.ac.uk You may quote extracts of a reasonable length without prior permission, provided a full acknowledgement is given of the source of the extract.

© NERC 2006. All rights reserved

Keyworth, Nottingham British Geological Survey 2006

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham, Edinburgh and London; see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast, BT9 5BF

☎ 028-9038 8462 Fax 028-9038 8461

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Sophia House, 28 Cathedral Road, Cardiff, CF11 9LJ

☎ 029–2066 0147 Fax 029–2066 0159

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Contents

FIGURES

TABLES

Summary

This report outlines the contribution made by BGS to the NF-PRO (Key processes in the Near Field) project; part of the *EC Euratom Research and training Programme on Nuclear Energy.* BGS was asked to contribute to Work Package 4.4.1 examining EDZ Characterisation and Evolution. This work package included a state-of-the-art report on the gas flow properties within the Engineered Damaged/Disturbed Zone (EDZ); BGS was requested to contribute to the chapters on clay (Cuss *et al.*, 2006) and crystalline rock (this report). This work was co-funded by United Kingdom Nirex Limited (Nirex).

1 Introduction

The NF-PRO (Key processes in the Near Field) project is part of the *EC Euratom Research and training Programme on Nuclear Energy (call 2003).* BGS is contributing to Work Package 4.4.1 examining EDZ Characterisation and Evolution.

The construction of a tunnel in any type of rock results in the creation of new free surfaces and therefore leads to a redistribution of stresses resulting in a damaged or disturbed zone around the opening, referred to as the engineered damage zone (EDZ). The size and the properties of this zone depend on the state of stress, the pore water pressure and the hydro-mechanical properties of the rock (as well as the excavation methods; not considered in this study).

The most important change in the EDZ compared to that of the intact rock is the creation of discontinuities, which could result in an interconnected fracture network and an increase in hydraulic conductivity. This could lead to preferential flow along emplacement tunnels, access tunnels (e.g. ramps) or shafts to the biosphere. In the preliminary French Safety Analyses (dossier (Anon) 2001) for instance, treatment of scenarios considering an early seal failure, highlighted the hydraulic role of the damaged zone as a potential radionuclide transport path. Therefore, the presence of an EDZ represents an important issue in repository performance and safety assessment.

In addition to its hydraulic significance, the role of the EDZ in gas transport remains unclear and needs to be investigated. Repositories of some types of wastes combined with the corrosion of the repository infrastructure could generate significant gas overpressures in the repository (if the gas cannot be released through the intact host rock or along tunnels). The EDZ could become a transport path for gas and act as a vent, limiting the gas overpressure in the repository. Processes including diffusive or advective transport of gas, 2-phase flow mechanisms, pathway dilation and creation of micro- or macro-fractures need to be investigated.

Work Package 4.4 of NF-PRO (Near Field Processes) concerns the migration of gas through the EDZ. The material contained within this report was submitted to partners in Nagra and GRS towards the state-of-the-art report on gas transport processes within clays, shales, mudstones and crystalline rocks. This report covers the aspects of gas transport in crystalline rocks; transport within clay-rich rocks is covered in an accompanying report (Cuss *et al.*, 2006).

2 Gas transport in Crystalline Rock

The development of a conceptual model is the first step to understanding how gas can be transported in a tunnel nearfield/EDZ within a crystalline repository. A conceptual model describes the main "natural" materials, geological and hydrogeological features of the rock mass, as well as the engineered materials that control the transport behaviour of the nearfield/EDZ. This section will briefly outline the main mechanisms and features that contribute to gas transport within this region and highlight some of the potential safety issues.

2.1 BASIC CONCEPTS OF GAS TRANSPORT IN CRYSTALLINE ROCK

When Low Level Waste (LLW) and Intermediate Level Waste (ILW) are disposed of in a repository, particularly when there is an availability of water, significant quantities of gas are expected to be produced and their effects in migrating from the repository have to be addressed. The disposal of waste and its containers may produce significant quantities of gas by various processes (radiolysis, alpha decay, corrosion, microbial degradation and degassing from solution of naturally present gas due to thermal or radiation impact), which need to escape from the repository area (IAEA, 2001).

For repositories in fractured crystalline rock it is generally thought that there is sufficient transport capacity in the discontinuity network to accommodate the expected flux of gas from the radioactive wastes without mechanical disruption to the surrounding rock mass. Surrounding the repository the mechanical, hydraulic and geochemical properties of the rock mass will be disturbed, due to the excavation of the rock. This zone is called the Engineered Disturbed Zone (EDZ). In crystalline rock, the EDZ is simply a zone with irreversible deformation, caused by stress redistribution giving rise to tension, compression, and shear stresses forming in different parts of the rock opening. For the stronger crystalline rocks with naturally occurring discontinuities, permeability is very sensitive to the rock strength relative to the new stress state. If the rock does not fail, tangential compression occurs near the opening, thus reducing its radial permeability by a factor of five (Tsang *et al.*, 2005a). However, the permeability parallel to the drift wall is increased by one order of magnitude, because of radial tensile stresses working to open existing fractures. Shear stresses also act to open fractures or create new ones through shear displacement and dilation. For hard and brittle crystalline rocks, the excavation activity could by itself induce significant damage, depending on the excavation method used. Thus, if drill and blast methods are used, the EDZ could extend 0.1 to 0.75 m into the rock, increasing permeability by two or three orders of magnitude (Tsang *et al.*, 2005a). If a tunnel boring machine (TBM) is used, the EDZ could be about 1 cm thick, with permeability increased by one order of magnitude (Tsang *et al.*, 2005a). As a result of the EDZ the transport of gas from the nearfield to the farfield geosphere within a crystalline rock mass will alter within this zone. The processes (Figure 2-1) and factors that will determine the transport of gas within this zone are:

- Transport mechanisms (diffusion, advection);
- Physical properties of engineered and natural material (hydraulic conductivity, porosity, diffusion coefficient, discontinuities, wetting characteristics of phases);
- Retardation/retention properties of engineered and natural barriers (sorption, filtration);
- Coupling of processes, such as flow and chemical reaction (Pigford and Chambre, 1988).

Although these processes and factors have been described for argillaceous formations the basic descriptions and definitions are similar although specific definitions related to crystalline rock masses are presented below.

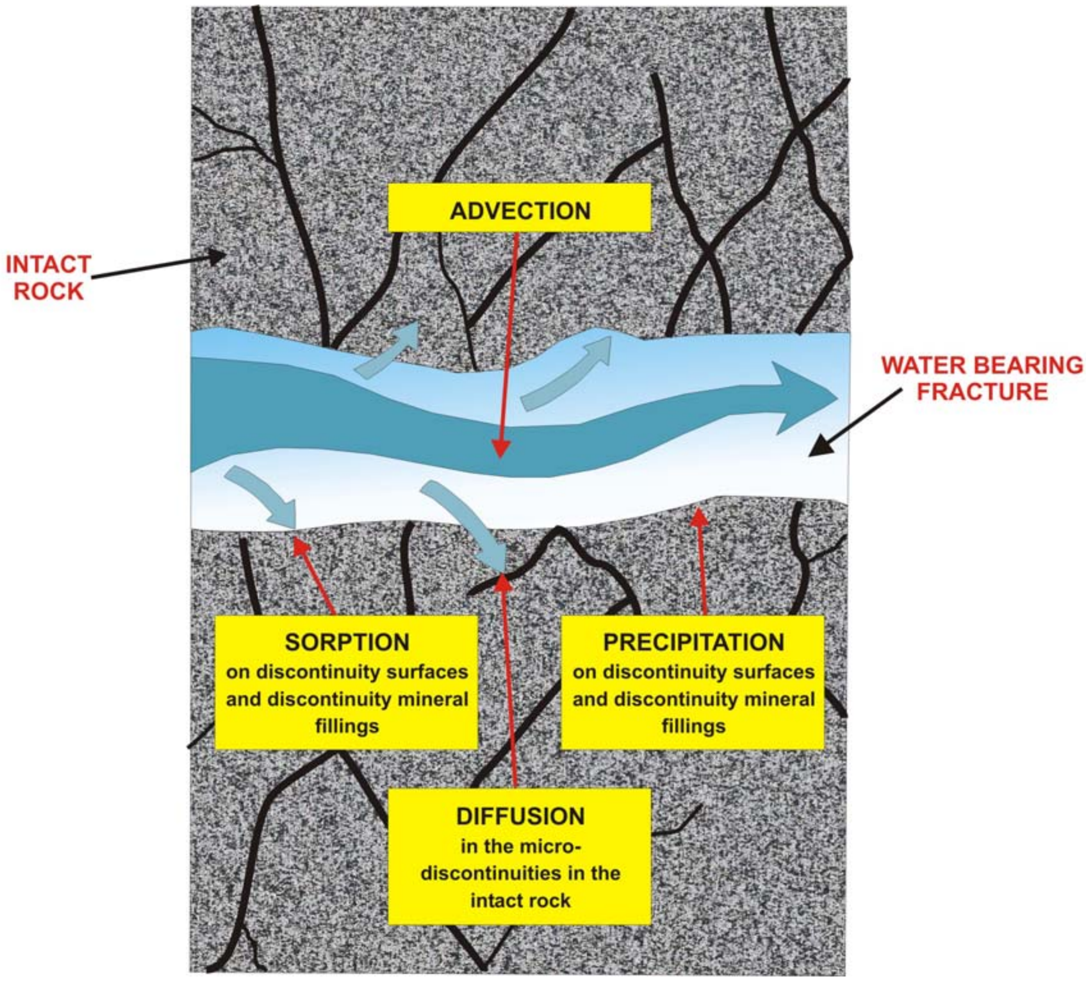

Figure 2-1 – An illustration of the potential mechanisms that influence the transport of gas from a repository into the biosphere (adapted from SKB, 2001).

3 Gas transport mechanisms

3.1 SINGLE PHASE FLOW

Some of the gases generated in a crystalline repository, in a water-saturated rock, may dissolve into the local groundwater and be transported away in solution from the repository by either advection or diffusion.

3.1.1 Advection

Advection is a significant gas transport mechanism when discontinuities are present in a crystalline rock mass. It is a process that transports fluid/gas by a pressure gradient in the bulk mass of flowing fluid within a water-saturated crystalline rock mass (Freeze and Cherry, 1979). For advection, flow through a medium is governed by Darcy's law that relates the total volumetric flow rate through a cross-sectional (unit) area normal to the direction of flow (q), to the permeability (k) and the pressure gradient. It can be expressed in a vector form as:

$$\overline{q} = -\frac{k}{\mu}\left(\nabla p - \rho \overline{g}\right) \qquad \text{(Eq.3.1)}$$

where q is the Darcy velocity, specific discharge, or rate of transmission of the fluid/gas through the medium ($m.s^{-1}$), k is the permeability of the medium (m^2), μ is the viscosity of the liquid (Pa.s), ρ is the fluid density ($kg.m^{-3}$), g is the acceleration due to gravity ($m.s^{-2}$) and ∇p is the pressure gradient (Apted *et al.*, 1995). The Darcy is an alternative unit of permeability favoured by the oil industry. One Darcy is defined as the permeability of a medium for which a flow of 1 cm^3s^{-1} is obtained through a section of 1 cm^2, for a fluid of viscosity 1 cP, and a pressure gradient of $1 atm.cm^{-1}$, or 760 mm Hg cm^{-1} (de Marsily, 1986). One Darcy is equivalent to 9.87×10^{-13} m^2.

When observed in detail this movement is extremely complicated, as gas velocities can vary on all scales: across the aperture of a discontinuity; in a discontinuity plane; from one discontinuity to another; and from one part of discontinuity network to another part. To describe every detail of this movement is impractical as mechanical mixing and spreading out of the gas usually cause these small-scale velocity variations. The classical approach to modelling advection only describes the average velocity fluid/gas. This average is taken over an appropriate volume; so small-scale variations are smoothed out (Anon, 1996).

3.1.2 Diffusion

Diffusion is the process whereby ionic or molecular constituents move under the influence of their kinetic activity in the direction of their concentration gradient (Freeze and Cherry, 1979).

Fick's first law of diffusion states that a substance diffuses in the direction of decreasing concentration:

$$J_D = -D\left(\nabla C\right) \qquad \text{(Eq.3.2)}$$

where J_D is the flux of solutes ($mol.m^{-2}.s^{-1}$), D is the diffusion coefficient ($m^2.s^{-1}$) and ∇C is the concentration gradient. When the transport is instationary and the solute accumulates or is depleted from the system, Fick's second law describes the transport and accumulation (Widestrand et al., 2003):

$$\frac{\partial C}{\partial t} = D\left(\nabla C\right) \qquad \text{(Eq.3.3)}$$

The diffusion of one chemical species at low chemical concentration into another is known as tracer diffusion. The term self-diffusion is understood to mean the diffusion of a molecule or ion within a system comprising the same molecules or ions, where no distinction is made between isotopes (e.g. water in water, HTO in water). Self-diffusion is essentially Brownian motion.

In porous media dissolved gases move by diffusion in the pore water. The tortuosity of the pores increases the diffusion path. The diffusion is also hindered by the constrictivity of the pores. Therefore the pore diffusivity will be less than that in unconfined water:

$$D_P = D\left(\frac{\delta_D}{\tau^2}\right) \quad \text{(Eq.3.4)}$$

δ_D is the constrictivity, τ^2 the tortuosity and D_p the pore diffusivity. The porosity, (ε - m^3 pore volume/m^3 rock), of a porous medium is made up of a transport porosity (ε_t) and a storage porosity (ε_d). The transport porosity consists of the pores that are utilised in transporting the substance. Storage porosity refers to pores that have a dead end, and therefore contribute little or nothing to the transport, but can affect the capacity to hold the dissolved species.

$$\varepsilon = \varepsilon_t + \varepsilon_d \quad \text{(Eq.3.5)}$$

Fick's first law for transport through porous media can then be described as follows:

$$J_D = -D_p \varepsilon_t \left(\nabla C_p\right) \quad \text{(Eq.3.6)}$$

where C_p is the solute concentration in the pore water. $D_p\varepsilon_t$=D_e, and is often called the effective diffusivity (D_e). The porosity, constrictivity and tortuosity can be lumped into an entity, F_f, known as the formation factor. The effective diffusivity can then be expressed as the product of the formation factor and the diffusivity in the free bulk carrier water, D_w:

$$D_e = D_w \varepsilon_t \left(\frac{\delta_D}{\tau^2}\right) = D_w F_f \quad \text{(Eq.3.7)}$$

It should be noted that in the literature the formation factor is sometimes described as the inverse of that described by Equation 3.7. The definition used here is, however, widely used in the nuclear waste management community (Widestrand et al., 2003).

Based on these simple diffusional process, the physical characteristics of the rock that are responsible for slowing down molecular diffusion are generally considered to be the porosity, the pore size distribution (represented by a constrictivity term) and the tortuosity (t) of the diffusional path. The effective diffusion coefficient is a property of the whole system being studied: the porous medium, the porewater and the diffusing species. (Autio *et al.*, 2005) present examples of the effective diffusion coefficient, permeability and porosity results from varying degrees of damaged granitic and gneissic rocks (**Figure** 3-1). From this study it was conclude that in a sensitively engineered tunnel (smooth blasting technique used) the EDZ was unlikely to be a significant migration route for gas out of a waste canister because the ‘enhanced’ discontinuities in the EDZ were poorly connected the porosity only increased slightly.

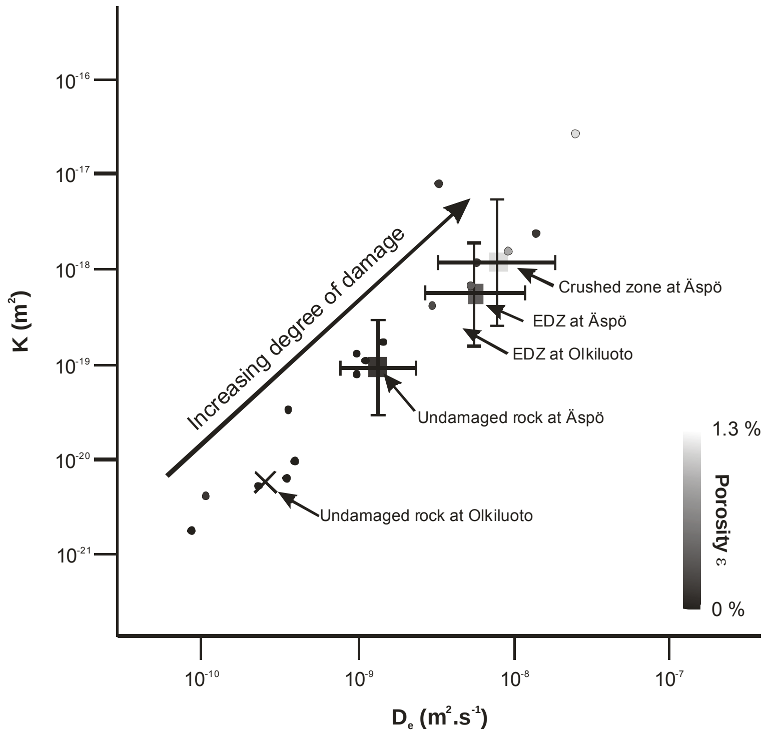

Figure 3-1 Measured values of the effective diffusion coefficient (D_e), permeability (k) and porosity (ε) for varying degrees of damaged granitic rocks using 14C-PMMA and He-gas diffusion method (from Autio *et al.*, 2005).

3.2 TWO PHASE FLOW

If gas is generated faster than it can be dissolved and advected and/or diffused away from the source zone then it may form a separate phase. Transport of the gas will then be affected by its interaction with the aqueous phase. A generalisation of the single phase Darcy's law is usually assumed with the form

$$\overline{q}_f = -\frac{kk_{rf}\left(S_f\right)}{\mu_f}\left(\nabla p - \rho\overline{g}\right): \qquad f = w,g \qquad \text{(Eq.3.8)}$$

where f is the phase, water (w) or gas (g), k_{rf} is the relative permeability of phase f, and S_f is the saturation of phase f, or fraction of the pore space occupied by the phase. Gas and water pressures are related by the capillary pressure, p_c, which is a function of the gas saturation:

$$p_g - p_w = p_c\left(S_g\right) \qquad \text{(Eq.3.9)}$$

Gas and water saturations are related by

$$S_g + S_w = 1 \qquad \text{(Eq.3.10)}$$

The functional dependencies of k_{rf} and p_c on the phase saturations cannot in general be determined from first principles and many parameterised functions have been introduced in the literature. Amongst those most commonly applied to granular porous media are the Brooks-Corey (Brooks and Corey, 1964) and the van Genuchten (van Genuchten, 1980, Luckner et al., 1989) functions which are described in more detail below. It should be noted, however, that all such functions are necessarily approximations and ideally explicit data for permeability verses saturation etc. for specific rocks should be used where possible.

The full transport equations are obtained by combining the above flow law equations with continuity equations for fluid and solid components. The formulation is completed with additional constitutive relations that describe the compressibility of solid and fluid phases, usually combined with an assumption that solid phase displacements are small.

3.2.1 Brooks-Corey functions

The Brooks-Corey relative permeability for the aqueous phase is defined in terms of an effective saturation, S_e, given by

$$S_e = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{gr}} \qquad \text{(Eq.3.11)}$$

where S_{wr} is the residual water saturation, below which the water is immobile, and S_{gr} is the residual gas saturation. The aqueous phase relative permeability is then given by

$$k_{rw} = S_e^{(2+3m)/m} \qquad \text{(Eq.3.12)}$$

where m is a fitting parameter, which may be set to m=2 to give the simpler equations of Corey(1954). The gas phase relative permeability is given by

$$k_{rg} = \left(1 - {}^*S_e\right)^2 \left(1 - {}^*S_e^{(2+m)/m}\right) \qquad \text{(Eq.3.13)}$$

The dependence of the capillary pressure on the effective water saturation is given by

$$p_c = \frac{p_d}{S_e^{1/m}} \qquad \text{(Eq.3.14)}$$

where p_d is the air entry pressure.

3.2.2 van Genuchten functions

The aqueous and gas phase relative permeabilities are given by

$$k_{rw} = S_e^{\eta}\left[1 - \left(1 - S_e^{1/n}\right)^n\right]^2 \qquad \text{(Eq.3.15)}$$

and

$$k_{rg} = \left(1 - S_e\right)^{\varsigma}\left[1 - S_e^{1/n}\right]^{2n} \qquad \text{(Eq.3.16)}$$

where S_e is given by Eq.3.11, n is a parameter related to the pore-size distribution of the porous medium and η and ζ are pore connectivity parameters, often taken to be equal to 0.5. The capillary pressure function is given by

$$p_c = \frac{1}{\alpha}\left(1 - S_e^{-1/n}\right)^{(1-n)} \qquad \text{(Eq.3.17)}$$

where α is the reciprocal of the air entry pressure. An important difference between the Brooks-Corey and van Genuchten models is that in the latter the capillary pressure goes to zero as saturation approaches unity. It may be noted that neither of these models include any hysteretic effects, but other authors have suggested modifications to accommodate this (e.g Parker and Lenhard, 1987).

3.2.3 Application to fractured rocks

The above formulations for two-phase flow were originally developed for and applied to granular porous rocks for which they have been found to provide good approximations of the processes involved. When gas and water flow mainly in networks of fractures the application of these equations becomes more questionable. In particular, the scale of the fractures and their interconnections may be such that the averaging implicit in the derivation of continuum models becomes inappropriate in that the size of a representative volume is no longer small compared to size of the total region being modelled. To try to overcome these problems various approaches have been used that separate the fracture and matrix components of the system either using explicitly specified fractures or some form of dual porosity model in which fracture and matrix continua overlap in space with some form of exchange of fluids between them. In these models separate parameterisations of the relative permeability and capillary pressure functions can be chosen for each continuum, or specifically for individual fractures.

4 Physical properties of crystalline rock mass and engineered barrier

With most repository concepts there are two forms of barrier: an engineered barrier and the natural host rock. Below a brief outline of the physical properties that influence the gas transport properties in each of these barriers will be discussed.

4.1 CRYSTALLINE ROCK MASS

Crystalline rock masses are commonly described as low permeability rocks (average permeabilities range from 10^{-11} to 10^{-17}) that almost entirely obtain their permeability and flowing porosity from their discontinuity network (Rodwell *et al.*, 1999). Although the permeability of these rocks are considered to be generally low they cannot be considered as impermeable barriers because tectonic forces may have create discontinuities (faults and fractures) within the rock mass. Given the highly heterogeneous nature of a discontinuous rock mass, flow paths are likely to be highly complex. The nature of discontinuities and discontinuity networks need to be understood as they provide the bulk permeability of the rock, and help to understand the nature of flow.

The migration of gas through a saturated porous medium is influenced by a large number of physical phenomena, the most important of these are:

- Two-phase flow;
- Relative permeability and capillary pressure effects;
- Solubility limited dissolution of the gas phase in the liquid phase;
- Reaction-diffusion-advection behaviour of dissolved species;
- Mixing or diffusion of vapour in the gas phase;
- Viscous fingering (instability of simple geometrical configurations);
- Dynamic response of the medium to pressure conditions (Apted *et al.*, 1995).

The extent to which each of these phenomena influence transport is very dependant on the gas generation rate, pressure conditions and physical properties of the medium through which the gas may move (Apted *et al.*, 1995).

Many of the key physical properties that need to be assessed and in some way quantified to help develop a conceptual model of a gases transport behaviour in the nearfield/EDZ are outlined in Table 4-1.

Within a crystalline repository concept it is also necessary to understand the distinction between a saturated and unsaturated hydrogeological environment. Most repository concepts that have been proposed within a crystalline rock mass are mainly located in saturated (below the water table) hydrogeological environments where the chief pathway through which gaseous radionuclides could escape from the repository is through dissolution and transport in the groundwater. At the Yucca Mountain site the repository is sited in the unsaturated zone (above the water table), the main interest in this site is thermally driven vapour flows and the behaviour of infiltrating water. Although the chief concerns differ, a common area of research exists in trying to understand the interaction between flow in discontinuities and fluid retention in the matrix of the rock mass (Rodwell *et al.*, 1999).

	Parameter	Description or examples
Structural Data	Discontinuity type	Fissures, Joints, Fractures, Minor shears and slickensides, Bedding plane shears, Faults and major shears, Bedding planes and bedding disturbances, Laminations and fissility
	Discontinuity orientation	Dip and dip direction of the discontinuity
	Discontinuity spacing	Spacing between discontinuities
	Discontinuity persistence	Length of discontinuity
	Discontinuity planarity	Shape of discontinuity surface
	Discontinuity roughness	Nature of discontinuity surface (also referred to as Joint roughness coefficient)
	Discontinuity aperture	Perpendicular distance between walls of discontinuity
	Filling/gouge composition	Material separating walls of discontinuity
	Discontinuity throw	Relative movement along discontinuity
	Discontinuity slip sense	Direction of movement including extension
	Discontinuity relative age	Relative age of the discontinuity, be it pre-tunnelling, result of tunnel face advancement, or late post-boring.
	Seepage	Water flow or free moisture visible in discontinuity
	Weathering	Wall strength
	Normal stress across fracture	The normal stress that is acting across an identified discontinuity
	Shear stress along discontinuity	The shear stress that is acting along an identified discontinuity
	Tunnel geometry	Measure of tunnel length and diameter
	EDZ thickness	Measure of depth of disturbance into the wall-rock
	Discontinuity density	Number of fractures per unit volume of rock
	Discontinuity connectivity	Expression of connection of fracture network
	Facies architecture	This family of parameters describe rock complexity; including heterogeneities, bedding, purity of clay (i.e. does it include silt, nodules, etc)
	Specific storage	The quantity of water that a unit volume of porous rock releases from storage under the effect of a unit decline in hydraulic head.
Hydro Data	Intrinsic permeability	Intrinsic permeability is considered as a property of the geological medium and is not affected by the nature and properties of the fluid.
	Capillary pressure	The difference in the pressure between two immiscible fluid phases separated by a curved meniscus and occupying the pores of a solid rock.
	Diffusivity coefficient	Measure of the diffusion properties of pore fluids
	Total porosity	The total amount of porosity present within a rock. Defined as the ratio of the total pore volume to the bulk volume
	Effective/kinetic porosity	The amount of porosity that is available for fluid flow. This will be less than the total porosity as isolated/disconnected pores are not part of the transport network.
	Bulk volume	Total volume of a block of material.
	Volume of pores	The total volume of the effective pore network.
	Average grain density of mineral solids (ρ_s)	Density of the mineral constituents of a rock.
	Bulk rock dry density (ρ_b)	Density of a unit block of rock after drying.
	Darcy velocity/specific discharge	The volume rate of flow through a porous medium divided by the cross-sectional area normal to the direction of flow.
	Fluid viscosity	The viscosity of the transport fluid or gas.
	Hydraulic radius (R_H)	The radius of a capillary that is able to transmit fluid.
	Tortuosity (τ)	Defined as the average ratio of the microscopic path length to the macroscopic path length in the medium. This is because within an actual porous medium, the interconnected void space can be assumed to be a number of tortuous pore channels.
	Relative permeability	The permeability of a rock, gas, or water with respect to each other when more than two are present
	Wettability	Process when a liquid spreads on (wets) a solid substrate
	Surface tension	The property of the surface between water and gas

	Contact angle	quantitative measure of the wetting of a solid by a liquid. It is the angle formed by the liquid at the three phase boundary where a liquid, gas (or a second immiscible liquid) and solid intersect.
	Entry pressure	The pore fluid pressure for which fluid flow initiates. Below this pressure, the rock behaves impermeably.
	Hydraulic conductivity	The constant of proportionality in Darcy's law. The volume of water that will move through a porous medium in unit time, under a unit hydraulic gradient, through a cross-section of unit area normal to the direction of flow.
	Dispersion	When contaminated water moves into freshwater, not only is it carried along by the movement of the freashwater (advection), but also the contaminent tends to spread out into the surrounding freshwater. Dispersion is a complex and poorly understood process.
	Transmissivity	The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths (Lohman et al., 1972; USGS, 2001)
	In situ stress	Cartesian stress orientation: Stress in a geographic sense is denoted σ_h, σH, σv, stress is usually denoted σ_1, σ_2, σ_3 (where $\sigma_1 > \sigma_2 > \sigma_3$) Polar stress orientation: Stress around a circular opening is denoted radial stress (σ_r) and circumferential/hoop stress (σ_θ)
Geomechanical	Stress (σ)	Deviatoric stress, effective stress, mean stress, octahedral stress, normal stress, shear stress
	Strain (ε, γ)	Change in shape or volume of a body as a result of stress. Defined as the ratio of original length to deformed length.
	k	Ratio of average horizontal to vertical stress
	K0	Stress path coefficient defined as the constant ratio of change in effective minimum (horizontal) stress to effective maximum (vertical) stress from initial reservoir conditions.
	Pore pressure	The pressure within the fluid contained within the pore network of a prous rock.
	Unconfined compressive strength (q_u)	The strength of a sample of rock at rupture when measured in the standard uniaxial compression strength. It indicated strength at surface with no lateral confinement.
	Modulus of elasticity (E)	Defined as the ratio of the stress applied to a body to the strain produced. This parameter refers to elastic (recoverable) deformation.
	Poisson's ratio (ν)	Defined as the ratio of the lateral strain to the longitudinal strain. This parameter refers to elastic (recoverable) deformation and describes howmuch axial compression is translated into radial strain.
	Tensile strength	A measure of the resistance that a material offers to tensile stress. It is defined as the stress required to cause rupture.
	Shear strength	The internal resistance of a body to shear stress, typically including a frictional component and cohesion.
	Shear Modulus (G)	Defined as the tangential force per unit area divided by the angular deformation in radians. This parameter refers to elastic (recoverable) deformation
	Friction Angle (ϕ)	Tangent of the coefficient of friction
	Cohesion	Shear strength of a rock not related to interparticle friction.
	Void ratio	Ratio of the volume of void space to that of solid material in a sediment.
	P-wave sonic velocity	Seismic wave velocity that involves particle motion of alternating compression and expansion in the direction of propagation (Primary or Push wave).
	Specific volume	The volume of a substance per unit mass. The reciprocal of density.
	Bulk modulus (K)	Defined as the ratio of the pressure on a body to its fractional decrease in volume. This parameter refers to elastic (recoverable) deformation.
	Anisotropy	Many of the mechanical and hydraulic parameters listed in this table are directional and have strong anisotropy. For a thorough understanding, each parameter should be quantified for anisotropy.
	f P	Effect of confining pressure on porosity, permeability, strength
	f T	Effect of temperature on porosity, permeability, strength
	f Chemistry	Effect of fluid composition on permeability, strength
	$f\ \dot{\varepsilon}$	Effect of strain rate on strength, permeability
	f Shear	Effect of shearing on permeability
	Temperature	Temperature of the system.

	Coefficient of friction (μ)	Friction is the force that resists the motion of one surface relative to another with which it is in contact.
	Effective pressure coefficient (χ)	Description of whether a rock perfectly obeys the law of effective stress, which states that effective stress = total stress – pore pressure. Perfect conditions occur for $\chi = 1$.
	Mineral composition	Detailed mineralogy of the rock.
	pH	A measure of the acidity or alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity. The pH scale commonly in use ranges from 0 to 14.
	Eh (Redox)	Standard oxidation-reduction potential.

Table 4-1 - The key physical properties that need to be assessed to help develop a conceptual model of the gas transport behaviour in the nearfield/EDZ of a crystalline repository.

4.2 ENGINEERED BARRIER

Within the crystalline repository concepts there are two types of engineered barrier (backfill or buffer materials) that are considered:

- Clays (generally clays are of the bentonite type);
- Cementitious materials (grout) based on Portland cement.

For both engineered barrier options the generation of gas within the repository presents a problem, due for the need for any generated gas to be able to escape through the barrier without degrading the subsequent performance of the barrier (Rodwell *et al.*, 1999).

4.2.1 Clay

Bentonite clay barriers are generally formed from pre-compacted high dry density bentonite clay. This material will resaturate after the closure of the repository forming a significant swelling pressure that will act against the host rock aiding the closure of fractures in the EDZ (Tsang *et al.*, 2005a). The passage of a gas phase through an initially water-saturated clay buffer is only possible if the gas pressure (related to the sum of the external water pressure and the swelling pressure) exceeds the threshold value of the buffer clay (Horseman *et al.* 2004; 1999; 1996; Pusch *et al.* 1987).

4.2.2 Cementitious materials

Cements more closely resemble a porous medium than clay buffers, since the pore structure is defined by a relative rigid solid phase. Cementitious materials are complicated reactive microporous materials with complex pore structures in which pore sizes are distributed between 1nm and 1 μm (or larger if unconnected voids are included). Cements are also reactive with certain gases such as carbon dioxide (CO_2). The connectivity of the pore space is complicated and commonly larger pores are linked by finer pores. The gas migration properties of cementitious materials depends on the formulation of the material. Recorded gas permeability values cover a range of at least eight orders of magnitude between 10^{-20} and 10^{-12} m^2 (Rodwell *et al.*, 1999). The basic features of observed two-phase flow behaviour in cements are generally described by conventional models of two-phase flow in porous media.

4.3 RETARDATION/RETENTION PROPERTIES OF ENGINEERED AND NATURAL BARRIERS

The transport of gas by both advection and diffusion will be modified by various modes of retardation/retention. Retardation/retention capability of engineered and natural barriers is controlled by a number of physical and chemical processes.

Retardation is a reversible processes (sorption and matrix diffusion) that delay the time taken for solutes to traverse the geosphere. Retardation processes can be subdivided into two fundamentally distinct categories:

- Physical restriction of solute transport (e.g. filtration, ion-exculsion, precipitation, reaction);
- Direct uptake with solids (sorption) (Apted *et al.*, 1995).

Retardation of radionuclides dissolved in groundwater is an important barrier function of the repository. Retardation is provided by the physical and chemical processes (e.g. sorption, complexation and precipitation), which occur in the repository and the geosphere (IAEA, 2001). In the safety assessment time scale, the effective rock matrix diffusivity (D_e) and the mass related sorption coefficient (K_d) of the intact rock mass are usually regarded as the most important retardation properties when modeling gas migration through intact rock. Qualitative and quantitative retardation properties on a detailed discontinuity (or discontinuity zone) scale are needed to provide support for modelling tracer field experiments. Such experiments are in turn performed to support the models used in the long-term safety analysis. The detailed fracture properties description (Table 3-1; Cuss *et al.*, 2006) is also important for the general understanding of the long-term solute-rock interactions (Widestrand *et al.*, 2003).

Retention is the combined effect of retardation and immobilisation processes that in combination leads to a decreased net flow rate of solutes through the geosphere (Widestrand *et al.*, 2003).

4.4 COUPLING OF PROCESSES

There may be a strong coupling between any number of processes in the nearfield, e.g. thermo-mechanical, flow and chemical reaction. In solving such problems it is necessary to model the interaction between chemical reactions, chemical transport, gas/fluid flow and temperature distribution. A number of coupled thermal, hydrological, chemical, and mechanical non-linear processes have been investigated within crystalline repository concepts such as: the Thermal-Hydraulic Experiment at the Underground Research Laboratory (URL), Pinawa, Canada; the Drift Scale Test at the Exploratory Studies Facility, Yucca Mountain, United States or the FEBEX experiment at the Grimsel Underground Testing Facility, Switzerland (Martino and Chandler, 1999; Sonnenthala *et al.*, 2005; Tsang *et al.*, 2005b).

5 Gas related characterisation methods

5.1 IN SITU AND LABORATORY CHARACTERISATION METHODS

In order to understand fully the transport properties of a rock mass and the fracture surfaces that occur in an EDZ, it is necessary to conduct a large number of experiments on 'intact' material and on the EDZ in the Underground Research Laboratories (URL). On site investigations, matrix diffusivity and matrix porosity can be determined via laboratory experiments on drill cores and also from *in situ* measurements in boreholes. If the method works, *in situ* measurements can provide opportunities to distribute the matrix diffusivity spatially. This method however requires support from laboratory measurements. Ideally, matrix diffusivity and matrix porosity can then be extrapolated to the entire rock mass based on the rock type and hydrogeochemical conditions (SKB, 2001). Table 5-1 outlines a summary of the methods that are used to characterize the transport properties in the laboratory and within the field.

Investigation methods	Parameters (information)	Comment (reference)
Laboratory measurements		
Through diffusion measurements	Sorption coefficients (Ka,Kd)	Ohlsson & Neretnieks, 1995, 1997; Byegård et al, 1998;
	Matrix diffusivity (De)	
	Matrix porosity (εp)	
Gas diffusion measurements	Matrix diffusivity (De)	Hartikainen et al, 1996; Autio,1997; Laajalahti et al, 2000; Maaranen et al, 2000
	Matrix porosity (εp)	
Porosity measurements	Matrix porosity (εp)	Byegård et al, 1998, 2001; Ohlsson & Neretnieks, 1995, 1997; Siitari-Kauppi, 2002
Batch sorption measurements	Sorption coefficients (Ka,Kd)	Ohlsson & Neretnieks, 1995, 1997; Byegård et al, 1998;
BET surface	Surface area	Ohlsson & Neretnieks, 1995, 1997; Byegård et al, 1998;
Cation exchange capacity	Cation exchange capacity	Ohlsson & Neretnieks, 1995, 1997; Byegård et al, 1998;
Field measurements		
Resistivity measurement	Matrix diffusivity (De)	Ohlsson, 2001; Lövgren and Neretnieks, 2002a; SKB, 2003d
Radon measurement	Flow wetted surface (a_r, a_w)	Glynn & Voss, 1999
Groundwater flow measurement	Groundwater flow (Q)	Winberg et al, 2000
	Darcy velocity (q)	
Packer tests (Two Phase Flow)	Capillary pressure on fracture and matrix	Jarsjö et al., 2001
Single-hole tracer test (push-pull)	Flow porosity (ε_f)	McNeish et al, 1990; Meigs et al (eds), 2000;
	Flow wetted surface (a_r, a_w)	
	Dispersivity (D)	
	Indication of matrix diffusion Comparative sorption data	
Single-hole tracer (in-situ sorption)	Sorption coefficient (K_d)	
	Matrix diffusivity (De (T))	
Multi-hole tracer test	Travel time (t_p)	Gustafson et al, 1992; Winberg et al, 2000
	Dispersivity (D)	
	Flow porosity (ε_f)	
	Flow wetted surface (a_r, a_w)	
	Verification of structural model	
	Comparative sorption data (connectivity) Indication of matrix diffusion	

Table 5-1 – Summary of the discipline's methods, evaluated parameters, and literature references (adapted from Widestrand *et al*., 2003).

5.2 GAS TRANSPORT MODELS

A numerical gas transport model provides a quantitative estimate of flow and the transport behaviour of a system described by a conceptual model. The hydraulic properties of a discontinuous rock mass are likely to be highly heterogeneous even within a single lithological unit. The main difficulty in modelling gas flow in a discontinuous rock is to describe this heterogeneity. Flow paths are controlled by the geometry of discontinuities and their open void spaces (Anon, 1996). The characterization level should give enough detail to enable specific mass transfer models for different major types of discontinuities or discontinuity zones within a site to be used for modelling in the tracer test time scale (Widestrand *et al.*, 2003).

Continuum models of flow and transport in porous medium have been used to provide predictions for the performance assessment of underground radioactive waste disposal for many years. This approach is based on an extended version of Darcy's law, in which two-phase flow effects are represented by the introduction of relative permeability and capillary pressure functions. These models have the advantage of allowing the straightforward representation of a range of macroscopic processes, such as diffusion, dispersion and solution of gas in groundwater, in addition to advective flow. As awareness of relevant host rock processes have increased, these models have become increasingly sophisticated. Their structure and parameterization typically reflects data collected at spatial scales that are usually orders of magnitude smaller in volume than those over which the prediction of radionuclide migration is required. Upscaling is, therefore, required by default for the successful application of the models. Formal upscaling methods are increasingly used to transform the small-scale data into large-scale values required as input to numerical models. Although many upscaling strategies have been proposed, the problem of translating the information contained in field data into meaningful continuum model parameters remains controversial (Bluma *et al.*, 2005).

Heat flow and transport, which is particularly important for the disposal of high-level waste and spent fuel can also be included in these models. This enables the complex phase behaviour induced by the presence of a strong heat source to be incorporated into the model. In a crystalline discontinuious rock mass the coupled behaviour between fluid flow in the rock matrix and the discontinuity network may be an important interaction and it will therefore be necessary to apply a dual permeability or dual porosity approach, in which the average properties of the matrix and the discontinuities are separately represented. However, if the rock matrix can be regarded as essentially inaccessible to gas, then this complication is not necessary. Part of the reason that this modelling approach has been applied is it is the only one currently available that allows reasonably detailed field-scale simulations. Although there is extensive literature on empirical observations and mathematical modelling concepts for multiphase flow, on scales ranging from pore level to megascopic level (kilometers), there are also serious limitations in the range and scope of phenomena that can be addressed. To try and meet these difficulties other modelling approaches have been explored. These include fracture network models, numerical studies of two-phase flow in single discontinuities (Rodwell *et al.*, 1999).

There are a number of issues are that are not generally covered by this modelling approach, such as:

- Determining what the appropriate scale on which to represent processes (e.g. fracture models);
- How to deal with viscous and capillary instabilities;
- How to characterise the system in sufficient detail to make predictions;
- How to determine suitable two-phase flow parameters on an appropriate scale;
- How to provide macroscopic conceptual models that will bridge the gap between microscopic understanding and the prediction of scale behaviour (Rodwell *et al.*, 1999).

6 Potential Safety Issues

The investigation and understanding of gas migration in a repository study is largely required to provide data for the safety assessment. Some of the potential safety issues related to gas migration that have been highlighted from the studies at Stripa (Sweden), Pinawa (Canada), Äspö Hard Rock Laboratory (Sweden), Grimsel-FEBEX (Switzerland), Kamaishi (Japan), and the Sellafield assessment as part of Nirex97 (UK) are briefly outlined below.

6.1 GAS GENERATION

The disposed of radioactive waste in a crystalline repository will produce a number of gases that could cause potential safety issues. These include:

- Radioactive gases such as ^{14}C, ^{3}H, ^{222}Rn, ^{85}Kr or ^{129}I that may be transported to the surface by the larger volumes of inactive gases produced in a water-saturated repository.
- Large quantities of hydrogen and methane may be produced in a water-saturated repository which could compromise the integrity of the engineered barrier system and intact host rock resulting in the movement of contaminants. Discharge of flammable gases may also present a flammability hazard when released to the biosphere.
- Carbon dioxide (some of which is likely to contain ^{14}C) that will be consumed in carbonation reactions with the engineered barrier, and whether the gas may furnish transport mechanisms for water-borne contaminants that would allow near-field chemical conditioning to be bypassed (Rodwell *et al.*, 1999).

6.2 OVER-PRESSURISATION

If gas cannot escape from a repository as fast as it is generated, the pressure will rise. If the pressure were to rise to a level at which the gas hydro-fractured the engineered barrier or host rock, then there would be a concern that this would leave 'preferential' pathways along which radionuclides might be transported more quickly. The consensus from published work is that gas migration from a repository in a typically discontinuous crystalline host is likely to proceed without developing an excessive overpressure in the repository. At potential repository depths, the rock permeability is not likely to be sufficiently low or the capillary pressure sufficiently high to provide major impediments to gas migration at the rates required by anticipated gas generation rates (Rodwell *et al.*, 1999). However, where cement is used as a backfill or to grout fractures the resulting interactions generally lower permeability as could impede gas migration.

6.3 GAS GENERATION CAUSING MOVEMENT OF CONTAMINATED GROUNDWATER

Three mechanisms could induce the movement of potentially contaminated groundwater due to gas generation in a water-saturated host rock repository. These are:

- Forcing water from a repository by the accumulation of a gas cushion within the repository (or within the disposal canister).
- Displacement of water from saturated fractures by advancing gas phase.
- Entrainment of groundwater in streams of gas bubbles (for this to occur, gas migration from a repository must involve some form of migration as gas bubbles).
- Induced movement of groundwater as a consequence of instabilities in gas pathways, with pathways continually collapsing and reforming (Rodwell *et al.*, 1999).

6.4 CONCEPTUAL UNCERTAINTIES

Conceptual uncertainty concerns the uncertainty originating from a lack of understanding of the processes and their interrelationships. Although conceptual uncertainty is an issue for the safety assessment, it is discussed here since it effects all phases of the investigation into gas transport, from drilling, sampling, sample treatment and measurements to evaluation methods, modelling concepts etc. These uncertainties have to be accounted for and documented to provide confidence in the end result (Widestrand *et al.*, 2003). Andersson (2003) has documented in detail how uncertainties were handled by SKB when constructing a site descriptive model. The conceptual uncertainties that are considered to be of particular relevance are listed below:

- Processes understanding at a range of scales for different transport mechanisms and repository concepts.
- Spatial variability of rock properties such as: discontinuities, permeability, matrix diffusivity and sorption properties etc within the rock mass.
- Temporal development of parameters e.g. sorption reaction kinetics, mineral weathering (dissolution and alteration), diffusion kinetics etc.
- Scale concerns over the spatial resolution of parameters. Extrapolation of data from the measurement scale (parts of millimetres to centimetres) to larger scales requires attention to the combination of the time and scale effects.
- Data uncertainty in the values of the parameters of a model e.g. measurement errors, interpretation errors or extrapolation of parameters that varies in time and/or space.
- Sample disturbances caused by e.g. drilling (pressure release, porosity generation), sawing, crushing etc. causing changes in physical properties of the rock mass such as porosity (Widestrand *et al.*, 2003).

In performance assessment terms, the major uncertainties to do with gas are:

- Generation rates
- Reaction of CO_2 with cement
- Migration/retardation in geosphere
- Rate of migration
- Extent of dilution/dispersion
- Degree of localization/dispersion at surface
- Reversible and non-reversible interaction with the engineered barrier and host rock

7 Conclusions

Gas produced by the radiolysis, alpha decay, corrosion, microbial degradation and degassing of radioactive waste within a water-saturated crystalline radioactive waste repository will be transported away through the tunnel nearfield/(EDZ), by the combined processes of molecular diffusion and advection. The physical properties of the rock mass (in particular the porosity, pore size distribution, tortuosity of the diffusional path and retardation/retention properties) will affect the speed at which the gas and hence radionuclides are transported. Due to the heterogeneous nature of a discontinuous crystalline rock the nature of the discontinuities and their networks need to be fully understood, as they provide the bulk permeability of the rock and the flow paths for the migrating gas. The excavation of a repository within a crystalline rock mass will cause an engineered damage zone (EDZ) to form. This will cause mechanical, hydraulic and geochemical properties of the rock mass to alter surrounded the repository opening. By conducting a large number of *in situ* and laboratory experiments the transport properties of the crystalline EDZ can be investigated and modelled to highlight the potential safety issues that could arise from the migrating gas. Through studies at Stripa (Sweden), URL Pinawa (Canada), Aspö Hard Rock Laboratory (Sweden), Grimsel-FEBEX (Switzerland), and Kamaishi (Japan) it has been highlighted that a crystalline repository generally has sufficient transport capacity in the discontinuity network to accommodate the expected flux of gas from the radioactive wastes without mechanical disruption to the surrounding rock mass. However, transit times from the repository to the biosphere must be considered in any safety assessment exercise. Of particular interest to repository safety assessment in relation to gas generation is: the role of gas over-pressuring the engineered barrier and or host rock; gas generation causing movement of contaminated groundwater and dealing with conceptual uncertainties associated with our understanding of system processes (e.g. transport mechanisms), the interaction and interrelationships of the system processes and the description of the physical environment (e.g. spatial and temporal evolution of material properties).

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

Andersson, J. (2003) Site descriptive modelling – strategy for integrated evaluation. **SKB R-03-05** *Swedish Nuclear fuel and Waste Management Company*.

Anon (2001) Progress Report on Feasibility Studies and Research into Deep Geological Disposal of High-level, Long-lived Waste. *Dossier 2001 Argile*. Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA), Châtenay-Malabry, France, 157pp.

Anon (1996) *Rock Fractures and Fluid Flow: Contemporary Understanding and Applications*. National Academy Press , Washington.

Apted, M., Grindrod, P., and Savage, D. (1995) The near-field. *In: The scientific and regulatory basis for the geological disposal of radioactive waste*. Savage, D. (Ed) John Wiley & Sons. UK pp.75-118.

Autio, J., Hjerpe, T., and Siitari-Kauppi, M. (2005) Porosity, diffusivity and permeability of EDZ in crystalline rock and effect on migration in a KBS-3 type repository. *In: Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories.* Proceedings of a European Commission Cluster conference and workshop, Luxembourg, 3 to 5 November 2003. Davies, C., and Bernier, F. (editors). **EUR 21028 EN.** (Luxembourg: European Commission - nuclear science and technology.) pp. 149-155.

Autio, J. (1997) Characterization of the excavation disturbance caused by boring of the experimental full scale deposition holes in the Research tunnel at Olkiluoto. **SKB TR 97-24.** *Svensk Kärnbränslehantering AB.*

Bluma, P., Mackay, R., Rileya, M.S., and Knight, J.L. (2005) Performance assessment of a nuclear waste repository: Upscaling coupled hydro-mechanical properties for far-field transport analysis. *International Journal of Rock Mechanics & Mining Sciences*, **42**, pp.781–792.

Brooks, R.H., and A.J. Corey. (1964) Hydraulic properties of porous media. *Hydrol.* Paper 3, Colo. State Univ., Fort Collins, CO.

Byegård J., Widestrand H., Skålberg M., Tullborg E.-L., Siitari-Kauppi M., (2001) Complimentary investigation of diffusivity, porosity and sorptivity of Feature A-site specific geologic material. **SKB ICR 01-04**. *Swedish Nuclear Fuel and Waste Management Company*.

Byegård, J., Johansson, H., and Skålberg M., (1998) The interaction of sorbing and nonsorbing tracers with different Äspö rock types. **SKB Technical Report TR 98-18**, *Swedish Nuclear Fuel and Waste Management Company*.

Corey, A.T. (1954) The interrelation between gas and oil relative permeabilities. *Producers Monthly*, November 1954, pp.38-41

Cuss, R.J., Reeves, H.J., Harrington, J.F., and Noy, D.J. (2006) State-of-the-art report on gas transport processes in argillaceous rocks within the EDZ: BGS contribution to NF-PRO WP4.4.1. *British Geological Survey Commissioned Report*, CR/06/243. 28pp.

Freeze, R.A., and Cherry, J.A. (1979) *Groundwater*. Prentice-Hall.

Glynn, P., and Voss, C. (1999) Site-94 – Geochemical characterization of Simpevarp groundwaters near the Äspö Hard Rock Laboratory. **SKI Report 96:29** *Swedish Nuclear Power Inspectorate.*

Gustafson, G., Ström, A., and Vira, J. (1997) The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. Evaluation report on Task No 3, the Äspö Tunnel drawdown experiment. **SKB ICR 97-06**. *Svensk Kärnbränslehantering AB.*

Hartikainen, J., Hartikainen, K., Hautojärvi, A., Kuoppamäki, K., and Timonen, J. (1996) Helium gas methods for rock characteristics and matrix diffusion. **POSIVA-96-22**, *POSIVA OY*, Helsinki.

Horseman, S.T., Harrington, J.F. and Sellin, P. (2004) Water and gas flow in Mx80 bentonite buffer clay. In: Symposium on the Scientific Basis for Nuclear Waste Management XXVII (Kalmar), Materials Research Society, Vol. 807. 715-720.

Horseman, S.T., Harrington, J.F. and Sellin, P. (1999) Gas migration in clay barriers. In: Pusch, R. and Yong, R.N. (eds) Microstructural Modelling of Natural and Artificially Prepared Clay Soils with Special Emphasis on the Use of Clays for Waste Isolation (1999 Special Edition), Engineering Geology, Vol 54, pp 139-149, Elsevier, Amsterdam.

Horseman, S.T., Harrington, J.F. and Sellin, P. (1996) Gas migration in Mx80 buffer bentonite. In: Symposium on the Scientific Basis for Nuclear Waste Management XX (Boston), Materials Research Society, Vol. 465. 1003-1010.

IAEA (2001) The use of scientific and technical results from underground research laboratory investigations for the geological disposal of radioactive waste. **IAEA-TECDOC-1243**. *International Atomic Energy Agency*.

Jarsjö, J., Destouni, G., and Gale, J. (2001) Groundwater degassing and two-phase flow in fractured rock: Summary of results and conclusions achieved during the period 1994–2000. **Technical Report TR-01-13**. *Swedish Nuclear fuel and Waste Management Company*, Laajalahti, M., Aaltonen, T., Kuoppamäki, K., Maaranen, J., Timonen, J. (2000) Measurements with the He-gas methods of the disturbed zone caused by boring. **SKB IPR-00-12**. *Swedish Nuclear fuel and Waste Management Company*.

Lövgren M., and Neretnieks, I. (2002) Formation factor logging in situ by electrical methods. Background and methodology. **SKB TR-02-27**. *Swedish Nuclear fuel and Waste Management Company*.

Luckner, L., van Genuchten, M.T., and Nielsen, D.R. (1989) A consistent set of parametric models for the two-phase flow of immiscible fluids in the subsurface**.** *Water Resources Research*. **25**; 10, pp.2187-2193.

Maaranen, J., Lehtioksa, J., and Timonen, J. (2001) Determination of porosity, permeability and diffusivity of rock samples from Äspö HRL using the helium gas method. **SKB IPR-02-17**. *Swedish Nuclear Fuel and Waste Management Company*.

Marsily, G. de (1986) *Quantitative Hydrogeology for Engineers*. San Diego: Academic Press Inc.

Martino, J.B., and Chandler, N.A. (1999) Summary report on thermal-hydraulic studies 1994 to 1999. *Ontario Hydro Nuclear Waste Management Division.*

McNeish, J.A., Andrews, R.W., and Vomvoris, S. (1990) Interpretation of the tracer testing conducted in the Leuggern borehole. **NAGRA Technical Report 89-27**.

Ohlsson, Y. (2001) Studies of Ionic Diffusion in Crystalline Rock. *Doctoral thesis*, Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm.

Ohlsson, Y., and Neretnieks, I. (1995) Literature survey of matrix diffusion theory and of experiments and data including natural analogues. **SKB TR-95-12**. *Swedish Nuclear fuel and Waste Management Company*.

Ohlsson, Y., and Neretnieks, I. (1997) Diffusion data in granite – recommended values. **SKB TR 97-20**. *Swedish Nuclear fuel and Waste Management Company.*

Parker, J.C. and Lenhard, R.J. (1987) A model for hysteretic constitutive relations governing multiphase flow: 1. Saturation-pressure relations. *Water Resour. Res*. **23**(12) pp.2187-2196.

Pigford, T.H., and Chambre, P.L. (1988) Near-field mass transfer in geologic disposal systems: A review. *In: Scientific Basis for Nuclear Waste Management*. Apted, M.J., and Westerman, R.E. (editors). Materials Research Society. pp. 125-141

Pusch, R., Ranhagen, L. and Nilsson, K. (1985) Gas migration through Mx-80 bentonite. Nagra Technical Report NTB 85-36, Wettingen, Switzerland.

Rodwell, W.R., Harris, A.W., Horseman, S.T., Lalieux, P., Muller, W., Ortiz Amaya, L., and Pruess, K. (1999) Gas Migration and Two-Phase Flow through Engineered and Geological Barriers for a Deep Repository for Radioactive Waste. *A Joint EC/NEA Status Report*, **EUR 19122 EN**.

SKB (2003) Method description for "measurement of petrophysical properties of rock types" (in Swedish). **SKB MD 230 001**. *Swedish Nuclear fuel and Waste Management Company.*

SKB (2001) Site investigations: Investigation methods and general execution programme. **SKB TR-01-29**. *Swedish Nuclear fuel and Waste Management Company.*

Sonnenthala, E., Itob, A., Spychera, N., Yuib, M., Appsa, J., Sugitab, Y., Conrada, M., and Kawakamib, S. (2005) Approaches to modeling coupled thermal, hydrological, and chemical processes in the drift scale heater test at Yucca Mountain. *International Journal of Rock Mechanics & Mining Sciences*, **42**, pp.698–719.

Tsang, C.F., Bernier, F., and Davies, C. (2005[a]) Geohydromechanical processes in the excavation damaged zone in crystalline rock, rock salt, and indurated and plastic clays - in the context of radioactive waste disposal. *International Journal of Rock Mechanics & Mining Sciences*, **42**, pp.109-125.

Tsang, C.F., Jing, L., Stephansson, O., and Kautsky, F. (2005[b]) The DECOVALEX III project: A summary of activities

van Genuchten, M.Th. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J*. **44**, pp.892–898.

Widestrand, H., Byegård, J., Ohlsson, Y., and Tullborg, E. (2003) Strategy for the use of laboratory methods in the site investigations programme for the transport properties of the rock. **SKB R-03-20**. *Swedish Nuclear fuel and Waste Management Company.*

Winberg, A.E. (ed.), Andersson, P., Hermanson, J., Byegård, J., Cvetkovic, V., and Birgersson, L., (2000) Final Report of the first stage of the Tracer Retention Understanding Experiments. **SKB TR-00-07**, *Swedish Nuclear Fuel and Waste Management Company.*