Keynote Paper
Geotechnical Engineering for Geoenvironmental Applications

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ABSTRACT This keynote paper discusses a major geotechnical engineering application associated with the determination of long term performance of engineered barrier systems. The particular waste containment problem considered is the isolation of high level nuclear wastes in underground repositories. A typical underground prototype repository is used to highlight geotechnical engineering application in the engineered barrier system and the *Performance Assessment* requirement for reliable analytical-computer models to predict the buffer barrier behaviour under thermal, hydraulic, and mechanical stresses.

Introduction – problem description

The following discussion of a particular waste disposal problem is presented to illustrate the need for application of geotechnical engineering techniques in support of the long term solution of the problem. The selection of the problem of nuclear waste disposal as a geoenvironmental problem for discussion is deliberate not only because it occupies a most prominent position in the research agenda in Europe, but also because of the significant effort being expended in seeking solutions to the safe containment of the nuclear wastes. At the present time, in Europe, because of the immensity and complexity of the many issues that need to be addressed, the various nations are undertaking cooperative research in various consortia, working with underground prototype repositories in an effort to find tractable solutions. The disposal problem is rendered difficult because of: (a) the very complex disposal specifications and conditions, and (b) the very large requirement for not only geotechnical input to the solution of the problem, but also inputs from various other disciplines in earth sciences, and physical, chemical and biological sciences.

Regulatory requirements in most countries expect that disposal of high-level long-lived radioactive wastes in secure disposal facilities must be designed to isolate the wastes for a long period of time. This is to ensure protection of the environment and biotic receptors from errant radionuclides for at least 100,000 years. The reason for this demanding requirement is that not only are the fission products and transuranic wastes highly radioactive, the amount of heat generated in the canister containing the spent fuel rods will be active over a long period of time, as seen in Fig. 1. Note that the axes for the diagramme are in log. scale.

The information given in Fig. 1 is for changes in radioactivity of the fuel rods given in units of Becquerel (Bq) with a burnup of 38 MWd/kg (megawatt days per kg.). Initially, activity is by fissions and activation products. However, this decays rapidly after 100 years, after which, activity appears to be contributed primarily by actinides and actinide daughters. For comparison, the horizontal line shown at a radioactivity level of 10^{12} Bq represents the radioactivity for eight tonnes of natural uranium with daughters. It is useful to see for example, that the half lives of uranium 235 (U235), U236, U238 and iodine 129 (I-129) are 7.0 x 10^8, 2.3 x 10^7, 4.5 x 10^9 and 1.6 x 10^7 years respectively. Whilst some countries had originally opted for a million year assured period of safe disposal, this has now been reduced to 100,000 years. It is reasoned by some (and contradicted by others) that the levels reached after about 100,000 years are reasonably low and are consistent with natural levels in natural uranium deposits.

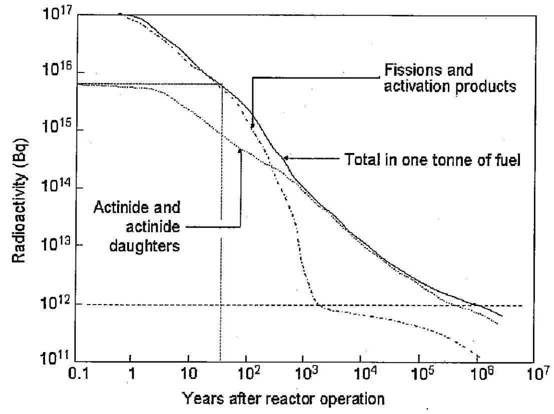

Fig. 1. Activity of fuel with a burn up of 38 MWd/kg in relation to years after operation. (Adapted from Hedin, 1997)

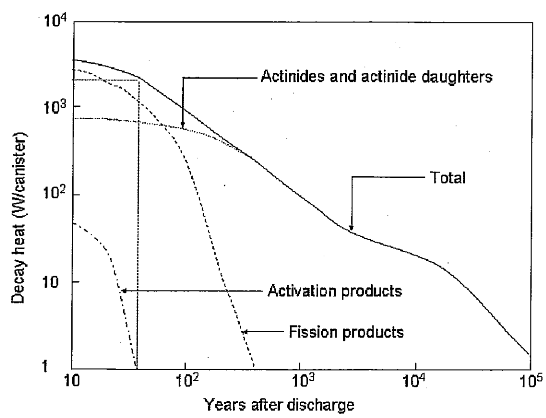

Fig. 2. Reduction in decay heat in relation to time after discharge or cessation of operation.

The heat generated by the decay heat, which is the residual power or the heat generated in the fuel after cessation of operation, is shown in Fig. 2 in relation to the time after discharge. Note again that the axes are in log. scale. As in the radioactivity diagramme, the fission and activation products contribute to the heat in the canister in the first 100 plus years, after which time, the main contributor to the total heat is from the actinides and actinide daughters. As can be seen, the heat generated by the decay heat is still significant after 10,000 years.

Given the high level of radioactivity and heat generated by the spent fuel rods, it is evident that this is a waste disposal problem that requires special attention. Schemes underway to isolate these high level radioactive wastes take the form of deep underground burial – in specially constructed tunnels and boreholes. Depths of burial vary between a few hundred metres to a kilometre or so. Fig. 3 shows a typical tunnel and borehole scheme to containment of the canisters.

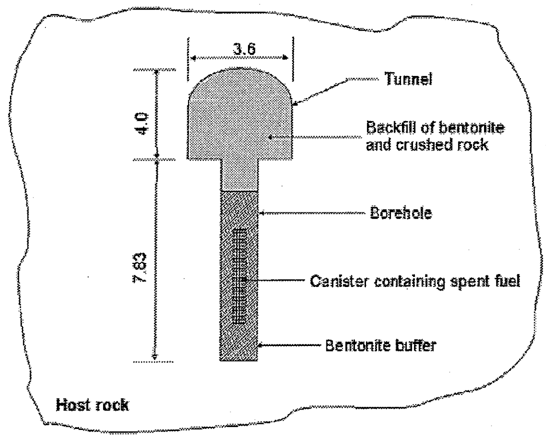

Fig. 3. Tunnel and borehole scheme for canister disposal in host rock. Dimensions shown are approximate and are given to demonstrate the relative size of the disposal scheme.

Underground research laboratories

To investigate field-test schemes for safe containment and isolation of the high level nuclear wastes, large underground chambers and facilities have been constructed in several countries to serve as underground research laboratories (URLs). These facilities are utilized by a host of other countries acting as consortia to solve a common problem. Various aspects of the containment and isolation schemes are studied using prototypes of the various elements under investigation. The URLs in the different countries differ in some respects, but not in the final sets of objective, i.e. to provide facilities that permit the study of safe disposal of high level nuclear wastes.

Active facilities in Europe with crystalline rock as host material are in Aspo (Sweden), Grimsel (Switzerland) and Olikiluoto (Finland). Facilities with dense clay beds as host material are in Mol (Belgium) whilst Mt. Terri (Switzerland) and Bure (France) utilize clay shale as the host material. The present active salt dome facility is in Asse (Germany). These are described in many documents in CLUSTER (2002). The crystalline rock URL in Canada is in Pinawa, Manitoba. However, it needs to be noted that at the time of preparation of this discussion, it was announced that the URL at Pinawa will be closed by mid-summer of this year. This will deprive Canada of its only underground facility to investigate and test methods for isolation of high level nuclear wastes in underground repositories.

Typical isolation scheme

In the typical isolation scheme, the canister which contains the spent fuel rods is shown in Fig. 3 in a borehole located in a tunnel radiating from and underground chamber. There are several variants to some of the details of this typical scheme – e.g. type of host material, borehole or chamber emplacement of canister, tunnel emplacement, buffer-barrier system surrounding the canister, etc.

The generic drawing in Fig. 4 shows the typical canister embedded in a buffer material within a borehole in the host material (crystalline rock). In most instances, the buffer material consists of a composite clay which is either bentonite or proportions of bentonite and fine grained material.

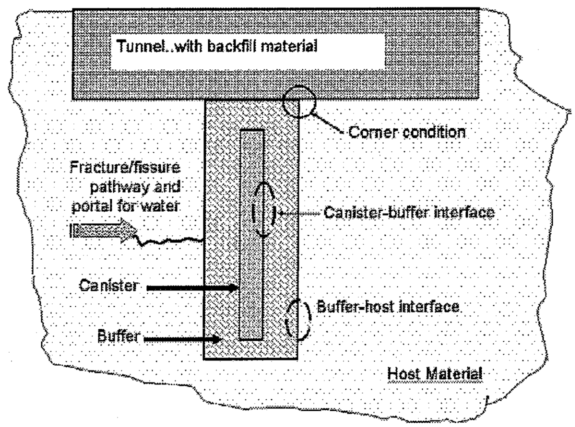

Fig. 4. Schematic of elements of the canister and borehole scheme of high level nuclear waste isolation in underground repository.

The chamber with backfill material will vary in depth dependent upon the concept model of different countries. As indicated previously, a one kilometre depth is not an unusual depth for this repository. Since the present focus is on the canister and bore-hole problem, the several other parts of the repository problem will not be shown or discussed. Suffice to say that these in themselves are also problems that require considerable application of geotechnical expertise and input.

The geoenvironmental problem

An overriding concern in the repository disposal schemes in all the countries faced with the problem of isolation of nuclear fuel wastes is *Performance Assessment*. Given that assurance of complete and secure isolation of the nuclear waste for 100,000 years is required, one of the tools used in performance assessment (PA) exercises is predictive or performance models. It is this aspect of the high level nuclear waste isolation problem that presents one of the more challenging tasks for geotechnical engineering. The challenges include all aspects of analyses and investigation, ranging from: (a) proper characterization of the various physical and geometric features of borehole emplacement (b) laboratory and field experiments for determination of pertinent input properties and parameters, (c) performance monitoring, and (d) modelling for assessment and prediction of performance.

In the scheme shown in Fig. 4, we can identify some of the more prominent basic factors and processes that contribute to the long term performance of the canister-buffer and borehole system. These include:

- Continuous canister heat source as shown in Fig. 2;

- Heat transfer in the buffer and host rock;
- Liquid and vapour transfer in buffer and host rock;
- Constitutive behaviour of buffer and host rock;
- Geochemical processes;
- Biogeochemical processes;
- Illitization and other transformations.

Whilst there have been some discussions in one or two countries in regard to placement of spent fuel rods with higher temperatures in the canisters, present tests and prototype experiments are being conducted with simulated canisters at close to 100 °C. Since the canister will remain "hot" for hundreds of years (Fig. 2) in the actual disposal scenario, one of the many problems that confront the geotechnical engineer is the performance of the buffer placed around the canister.

Of the many countless studies, tests, and prototype experiments, it is generally agreed that the buffer should possess the following as minimum qualities:

- low hydraulic conductivity to minimize groundwater transport,
- high sorption capability to sorb errant nuclides and to restrict solute transport via partitioning mechanisms,
- good chemical buffering capability to counter contaminant interactions,
- self-sealing ability to ensure no development of preferred pathways because of shrinkage cracks and other fissures,
- good thermal conductivity so as to be able to transfer heat effectively to the host rock,
- good mechanical properties to provide a stable platform, and
- ability to creep without fracture.

The aim of this discussion does not include a debate of the reasons for the requirements for the qualities listed above. Instead, this presentation addresses the geotechnical problem of predictions of long term performance of the buffer-barrier system in a typical full-scale repository, using a prototype isolation-disposal system and inputs from specific laboratory experiments. Site specific conditions can vary from crystalline rock as host material, to rock salt, or deep clay deposits. It is useful to note also that the fracture-fissure presence and distribution will also vary considerably between the various crystalline rocks used as host material. These buffer performance predictions fall into the class of "near-field" predictions, and together with far field performance predictions, they constitute a vital part of the programme for safety assessment of the repository.

Performance predictions

Regulatory requirements for performance and safety assurance of the canister isolation disposal system can be met if one had a means to accurately predict long term system performance. Several numerical models have been developed to address the isolation-disposal scenario represented by the schematic shown in Fig. 4. The main elements of the disposal scheme shown in the figure, known as the canister-borehole emplacement problem, include the following:

- The buffer is placed in an almost dry state – with water contents at around 5% to 7% depending on the composition of the buffer;
- Groundwater is expected enter into the borehole through the fractures and fissures. The nature, size, and extent of fractures, cracks and fissures are not easily established. Furthermore, the extent, distribution and rate of groundwater inflow through these fractures and fissures cannot be truly established;
- Wetting occurs at the cooler end, i.e. at the buffer-rock interface, and drying occurs at the canister-buffer interface;
- Swelling of the bentonite buffer occurs upon water entry;
- Shrinkage can occur at canister-buffer interface due to drying.

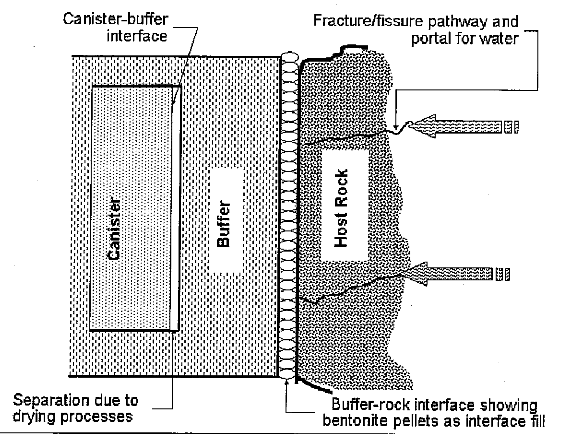

Fig. 5. Schematic of simplified system showing canister and buffer in borehole with bentonite pellets as infill between the buffer and the host rock.

The schematic diagram in Fig. 5 shows the principal elements of the canister-buffer system in the borehole emplacement scenario that needs to be modeled. It should be noted that there are other emplacement techniques. The bentonite pellets shown at the interface between the buffer and the host rock is one of the schemes proposed to ensure that intimate contact between buffer and host rock is achieved.

The system shown in Fig. 5 can be represented as a geomechanics problem of heat and mass transfer in the bentonite-sand buffer – with some added features. These include swelling pressures developed as water enters into the composite-bentonite buffer from the host rock, and vapour transport from the canister-buffer interface. The schematic process diagram is shown in Fig. 6.

The geotechnical problem

Whilst the canister-buffer system shown in Fig. 6 fits within the framework of a classical geoenvironmental waste containment system, analysis and prediction of system performance is best sought using techniques in geotechnical engineering.

Given the system shown in Figs. 4 to 6, the basic elements of the geotechnical problem are described in capsule form as follows:

- When the canister is placed in the borehole and surrounded by the partly saturated buffer, canister heat is turned on and is considered to be instantly peak temperature at time t = 0.

- Because the borehole walls are not smooth, and because the buffer is not expected to make solid full-face contact with the borehole wall, a bentonite powder or pellet filler is emplaced in the interface between buffer blocks and borehole wall.
- Groundwater is expected to be drawn into the filler and buffer as point-source flow from the fractures and fissures. The hydraulic head and osmotic or solute potential of the buffer material are the driving gradients. This means that water uptake will occur at the cold end of the buffer.
- Vapour and liquid transport from the hot end to the cold end would occur.
- Buffer swelling will occur in the wetted portion, resulting in pressures developed against the borehole wall and canister.
- Separation of the buffer from the canister is expected to occur at the canister-buffer interface because of the drying effects from the canister.
- Solute transport in the buffer will occur.

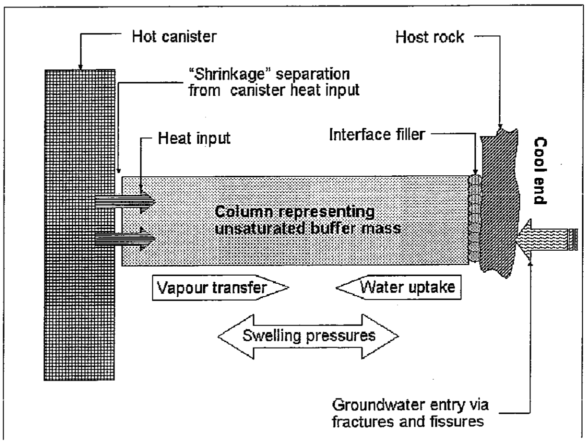

Fig. 6. Schematic showing processes in a column representing the unsaturated composite bentonite buffer mass.

It is important to recognize that there are several coupled processes, e.g. heat and liquid moisture flow, liquid and vapour flow, liquid flow and swelling pressures. These are shown in Fig. 7 in respect to the fluxes generated. The diagramme shows a regular three-phase solid-liquid-gas representation of the buffer material with the various fluxes in the respective phases. Evaporation and condensation of the pore water are shown by the vertical arrows. The water drawn into the buffer is a combination of the hydraulic head and the osmotic potential of the buffer material. What makes the problem complicated is that all of the fluxes generated, and the couplings established, are dependent on the transmission properties of the buffer, which in turn will be dependent on the temperature at any point in the buffer and the amount of liquid moisture and pressure. The challenge which presents itself is to be able to properly assess the effects of the couplings in development of numerical models to predict buffer performance in the near field (Stephansson and Min, 2002).

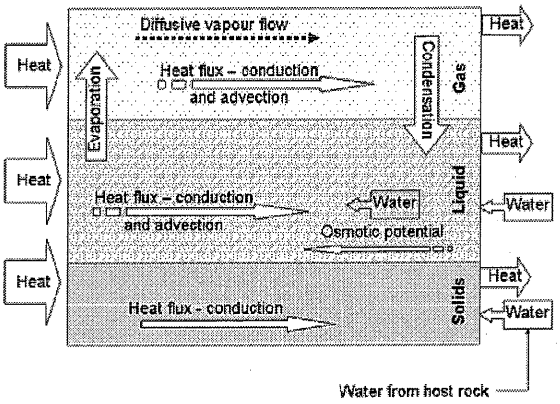

Fig. 7. Fluxes and couplings generated in the buffer material in contact with the hot canister on the left and the host rock on the right.

Models and basic approaches

The majority of the models developed to address the problem have taken a mechanistic approach. There is agreement between almost all the models in the structure of the basis functions used to describe the various processes involved in the overall system performance. Many of these processes are well defined as separate individual processes, e.g. heat transfer, liquid moisture transfer, vapour transfer, and constitutive performance of the material.

For most of the numerical models developed, the relationships governing liquid, vapour, and heat flow are cast in terms of the respective flux laws: (a) Darcy's law for liquid and gas flow, (b) Fick's law for vapour flow, and (c) Fourrier's law for heat conduction. Some differences in expression of the constitutive performance exist between many of the models, ranging from, for example: (a) effective stress relationship for partly saturated soils, (b) elasto-plastic relationship, to (c) state surface representation.

Many of the models developed utilize some of the basic relationships first proposed by Philip and De Vries (1957). Their basic formulations for coupled heat and moisture flow through porous media have been extended to suit the problem under consideration. In the most basic form, the coupled heat and moisture flow relationships are obtained as follows:

$$[1] \quad \frac{\partial \theta}{\partial t} = \nabla\left(D_T \nabla T\right) + \nabla\left(D_\theta \nabla \theta\right) + \frac{\partial k}{\partial z}$$

$$[2] \quad C\frac{\partial T}{\partial t} = \nabla\left(\lambda \nabla T\right) + L\nabla\left(D_{\theta vap} \nabla \theta\right)$$

where θ is the volumetric water content, C = volumetric heat capacity, T = temperature, t = time, λ = thermal conductivity, L = latent heat of water, D_T = thermal moisture diffusivity, D_θ = isothermal moisture diffusivity, and $D_{\theta vap}$ = isothermal vapour diffusivity.

The thermal moisture diffusivity D_T consists of the thermal vapour diffusivity D_{TV} and the thermal liquid diffusivity D_{TL}.

[3] $$D_{TV} = \frac{D_o}{\rho_w}\alpha v h \beta \frac{\partial \rho_o}{\partial T} \; ; \; D_{TL} = k_\theta \frac{\psi}{\sigma}\frac{\partial \sigma}{\partial T}$$

Similarly, the isothermal moisture diffusivity D_θ consists of the isothermal vapour diffusivity $D_{\theta v}$ and the isothermal liquid diffusivity $D_{\theta L}$.

[4] $$D_{\theta v} = \frac{D_o}{\rho_w}\alpha v \beta \frac{\rho_o g h}{RT}\frac{\partial \psi}{\partial \theta} \; ; \; D_{\theta L} = k_\theta \frac{\partial \psi}{\partial \theta}$$

where D_0 = molecular diffusivity of water in air, v = mass flow factor, ρ_o = density of saturated water vapour, α = tortuosity factor, β = volumetric air content, σ = surface tension of water, ψ = total potential, and h = relative humidity.

This approach has been adopted by Thomas and his co-workers in their development of the COMPASS code which extends the Philip and de Vries formulations to include the other processes involved in system performance. As reported by Thomas *et al*, (1996), in addition to the adoption of the flux laws for water and air, the heat transfer process includes the effects of conduction, convection and latent heat of vapourization. For the resultant pressures, the incremental form of the stress-strain relationship was adopted. Temperature effects on suction were considered in terms of their effect on surface energy and the basic unknowns were pore water pressure, pore air pressure, temperature, and displacements. The continuity condition for moisture transfer in fully coupled form given by Thomas *et al*, (1996) shows:

[5] $$\frac{\partial(\rho_w \theta_w)}{\partial t} + \frac{\partial(\rho_w \theta_v)}{\partial t} + \nabla\cdot(\rho_w V_w) + \nabla\cdot(\rho_w V_v) + \nabla\cdot(\rho_v V_a) = 0$$

The stress equilibrium relationship used was:

[6] $$\frac{\partial(\sigma_{ij} - \delta_{ij}u_a)}{\partial x_j} + \frac{\partial u_a}{\partial x_i} + b_i = 0$$

where the subscripts associated with the symbols are given as w = water, v = vapour, and a = air.

The THAMES finite element code developed by Ohnishi *et al*, (1985) also extends the Philip and de Vries work for treatment of coupled heat and mass transfer. The model also considers water movement due to osmotic potentials – in addition to the thermally driven fluid flow process. Accordingly, the continuity condition for moisture transfer is expressed as:

[7] $$\left[\xi \rho_w D_\theta \frac{\partial \theta}{\partial \psi}(h,_i - z,_i) + (1-\xi)\frac{\rho_w^2 g K}{\mu_w}h,_i\right]_{,i} + \left[\rho_w D_T T,_i\right]_{,i} - \rho_{wo} n S_r \rho_w g \beta_p \frac{\partial h}{\partial t} - \rho_w \frac{\partial \theta}{\partial \psi}\frac{\partial \psi}{\partial t} - \rho_w S_r \frac{\partial u_{i,j}}{\partial t} + \rho_{wo} n S_r \beta_T \frac{\partial T}{\partial t} = 0$$

where ξ is the saturation parameter and is zero in the unsaturated zone and equal to unity in the saturated zone; ψ = soil moisture potential, ρ_w = density of water, S_r = degree of saturation, β_p = compressibility of water, β_T = thermal expansion coefficient of water, μ_w = viscosity of water, and subscript o = reference state.

It is interesting to observe from the preceding two expressions for moisture transfer that: (a) the Thomas model considers the transfer in respect to storage of pore liquid and vapour, and movement of both the liquid and vapour masses, whilst (b) the Ohnishi model considers the transfer in terms of the internal driving force expressed by the gradient of the moisture potential ψ, and external driving forces. In addition, the Ohnishi model considers moisture transfer in the unsaturated zone to be a diffusion process, and transfer in the saturated zone to be governed by the Darcy relationship.

In the report by Chijimatsu *et al*, (1998) on the use of the THAMES code, the mechanical performance of the buffer in respect to pressures developed from the swelling of the buffer material has been considered. They provide the equilibrium relationship in terms of the swelling behaviour of the buffer material as follows:

[8] $$\left[\frac{1}{2}C_{ijkl}\left(u_{k,l} + u_{l,k}\right) - F\pi\delta_{ij} - \beta\delta_{ij}\left(T - T_0\right) + \chi\delta_{ij}\rho_w h\right]_{,j} + \rho b_i = 0$$

where C_{ijkl} = elastic matrix, F = coefficient related to swelling pressure in the buffer, π = swelling pressure and χ = effective stress parameter which varies from 0 for the unsaturated zone and is equal to unity in the saturated zone. The swelling pressure in the buffer π is assumed to be a function of the soil water potential ψ. It is useful and interesting to note that in equation [7], the movement of moisture in the unsaturated zone which is considered as diffusive flow, the water potential is assumed to be a single-valued function of the volumetric water content θ. The relationship for swelling pressure in the buffer is given as follows:

[9] $$\pi(\theta_1) = \rho_w g(\Delta\psi) = \rho_w g\{\psi(\theta_1) - \psi(\theta_o)\} = \rho_w g \int_{\theta_o}^{\theta_1} \frac{\partial \psi}{\partial \theta} d\theta$$

The modelling approach adopted in CODE_BRIGHT (Olivella *et al*, 1996) also uses the various constitutive relationships for air, water and heat. In recognition of the unsaturated state of the buffer, the hydraulic conductivity of the material is considered to be dependent on the degree of saturation. Thermal conductivity is also considered to be a function of the hydration state of the material. The effect of vapour diffusion in the buffer material is considered in terms of a coefficient of tortuosity. For the mechanical behaviour of the buffer, a thermo-plastic model is used wherein deformations are a function of net stresses, suction and temperature.

The equilibrium restrictions used in the Olivella *et al.* model (Gens *et al*, 2002) are similar to those used in the Thomas *et al* model code. These include control: (a) of mass fraction of water in the vapour phase from psychrometric principles, and (b) of the amount of air dissolved in water from Henry's law. The Olivella *et al.* model considers all the interacting processes by simultaneous solution of the equations of: (a) enthalpy conservation, (b) water mass conservation, (c) air mass conservation, and (d) linear momentum conservation.

Technical auditing and processes

In the context of a geotechnical assessment of the geoenvironmental problem under discussion, *technical auditing* refers to the examination of the adequacy of the technical tools used to perform the assessment. In this instance, the geotechnical tool used consists of a combination of: (a) a prototype experiment, (b) laboratory tests on buffer material for determination of material properties and performance under specified conditions, and (c) models developed to predict long term system performance under specified scenarios.

A full examination of all the audit protocols and requirements is not possible within the scope of this presentation. Instead, we focus on a few of the main questions and some specific problem areas that require more geotechnical input and study. Many of the questions asked include (Yong, 2002):

- whether the nature of the interactions between the various processes and their dependencies on the controlling system factors are well understood,
- whether the simple and higher order coupled processes can be properly distinguished, and
- how these can be systematically represented and tested in the model-building process.

Coupled processes and their interdependencies are serious issues that require attention, not only to the strength of the couplings but also to the manner in which the couplings are expressed. A simple case in point can be demonstrated in looking at the problem of vapour transport in the buffer. Vapour is produced at the hot end of the buffer where the buffer meets the canister (Figs. 6 and 7) and is transported to the cold end by diffusion. The use of two separate diffusivity D coefficients (water and vapour) to represent individual moisture movement requires one to specify the coupling relationship between vapour and fluid transport and also be sufficiently sagacious in describing the coupling between vapour and liquid moisture transfer, and also the intimate evaporation-condensation relationships.

We can learn from studying the moisture distribution in a surface soil layer in a field-drying situation. In an initially moist stage, the moisture profile demonstrates a concave shape. As drying and evaporation continues, the moisture profile changes that occur will eventually show a shape change from concave to convex, as seen in Fig. 8. As continued drying occurs, the convexity in the moisture content curve becomes more pronounced. The presence of an inflection region (shown in the diagramme) where this changeover occurs suggest very strongly that the total moisture diffusion process is a complex mixture of both vapour and liquid moisture movement.

The superposed diffusion coefficient (D) curve shown in Fig. 8 represents the D coefficient for total (combined vapour and liquid moisture) movement. As has been reported by Philip (1974), at the very dry stage, one observes that moisture movement is dominantly via vapour transport processes. As moisture content in the soil increases, the movement of moisture becomes more a liquid moisture movement phenomenon.

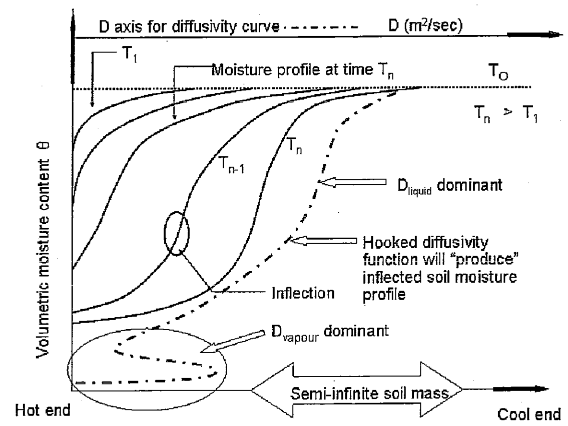

Fig. 8. Dominant diffusion processes in moisture transfer and their influence on the development of the moisture profile in a field soil under drying conditions.

Total moisture movement consists of both vapour and liquid moisture movement. The "hooked" diffusivity coefficient shown in Fig. 8, which represents the combined processes involved in the total moisture movement, testifies to the very strong coupling between vapour and liquid moisture transport processes. Included in this coupling is the intimate relationship between evaporation and condensation – a cross-coupled process that occurs in various degrees and proportions throughout the soil mass under the influence of a temperature gradient.

If one examines the schematic diagramme shown as Figs. 5 and 6, two sets of problems can be identified. These relate to:

- Boundary conditions – nature of physical contact between buffer material and host rock, and also with canister; nature of access to groundwater and distribution, condition of host rock interface and influence on contact and distribution of access to groundwater; etc...
- Maturation of the buffer – processes associated with thermal, fluid, vapour, solute and gas transport in processes associated with saturation of the buffer; swelling, swelling pressures and resultant constitutive performance of buffer material; geochemical reactions; abiotic and biotic reactions and kinetics of reactions; alterations and transformations etc...

Most of the predictive models use a continuum approach and the appropriate flux laws when they consider water and solute uptake, i.e. water and solute entry and movement in the buffer material. On the understanding that the primary clay minerals in the buffer material are 2:1 layer-lattice type minerals, one might perhaps want to anticipate the long term effects of oxidation-reduction reactions. The reduction of the structural Fe^{3+} in the octahedral and tetrahedral sheets to Fe^{2+} will undoubtedly alter the nature and performance characteristics of the mineral. Collapse of the mineral is likely, resulting in the loss of the swelling capacity of the mineral (Yong, 2000).

Other processes could also transform the bentonite material in the buffer to a non-swelling type of material. Conversion of smectite, which is the primary mineral in bentonite to illite occurs when the following conditions exist (Pusch and Karnland, 1996): (a) sufficient heat for reorganization of the lattice structure, and (b) sufficient potassium available for reactions. This problem becomes particularly acute if the disposal temperature of the canister is set at 150°C, as has been the subject of some discussion.

Even without the very high canister temperature, alteration of the smectite minerals in the bentonite in the long term can occur due to interactions with Fe and also because of exposure to a high pH environment. Corrosion of the carbon steel overpack, i.e. the outer casing of the canister, which is not expected to occur until a thousand years or more, will release Fe into the pore water. When the dissolved Fe interacts with the smectites, although one will not perceive any change in the 2:1 layer lattice arrangement, a non-swelling smectite will be obtained. In effect, one obtains a pseudo chlorite. Accordingly, the qualities that a swelling clay buffer provided would be lost. The effect of maturation processes, i.e. processes contributing to the evolution of the buffer material over a period of thousands of years, will impact on all of the processes initially considered in the development of the model. How these changes are incorporated into the models is something that has yet to be resolved.

Most, if not all, of the major elements of the boundary condition problem shown in Figs. 5 and 6 have been considered in the models. Several options for choice of physical contact between the buffer and host rock are available; – ranging from the simplest (intimate contact) to the more complex contact scenarios such as pellets, sporadic contact because of consequences of excavation damages in the host rock, etc. Concomitant with physical contact are assumptions or options pertaining to the nature and/or sources of entry of groundwater from the host rock and its distribution.

Information on how the interface pellets shown in Fig. 5 will wet or hydrate is not available, principally because of the lack of field measurements. Techniques for measurement of water movement and saturation in the interface pellets and in the buffer in contact with the pellets are not available. Furthermore simulation of point-source entry of water in laboratory experimentation for determination of the wetting phenomenon of the interface pellets is not sufficiently realistic because of scaling problems. For purposes of model calculations, one has the choice of assumptions for water entry into or water availability. The simple choice of uniform distribution at the interface has been a popular one. There are some instances where specified points of entry into the buffer have also been discussed. However, the absence of supporting data or inputs has not allowed for proper examination and implementation of the protocols as required in the technical audit.

The geotechnical tests needed to provide information on buffer performance in the short term are adaptations of normal tests for strength, water uptake, hydraulic conductivity, solute transport, etc. Two particular situations come immediately to mind: (a) Because of the high temperature environment, more studies are required to determine buffer properties and characteristics, as for example in the work performed by Graham and his co-workers (Lingnau *et al*, 1995, Tanaka *et al*, 1997) and De Bruyn and Thimus (1996); and (b) Because of the swelling nature of the buffer material, more work is needed to fully establish the role of structure on water uptake and subsequent buffer performance, as for example in the work reported by Yong (1999a, 1999b) and Pusch and Yong (2003).

Concluding remarks

It would not be proper to conclude the discussion without making reference to the many uncertainties that attend the problem of long term prediction of the near field buffer performance. Perhaps the most visible one would be the contact between the host rock and the buffer. Borehole excavation in the crystalline rock could produce a highly disturbed, rough and fractured surface. The uncertainties associated with this event relate to the hydraulic gradients of the groundwater, the nature or distribution of the "groundwater load".

Water uptake at the interface and transport into the buffer depends not only on the nature of the groundwater contact, but also on the chemistry of the groundwater. Uncertainty in the chemistry of the groundwater is a concern in the longer term because of the various processes that occur as normal processes of evolution (Yong, 2003). Reaction kinetics in the face of high temperatures and pressures, and resultant mineral transformations due to abiotic and biotic redox reactions (Fukue and Sato, 2003; Plötz and Kahr, 2003) create complicated scenarios that have yet to be fully determined. Until such time as these are fully evaluated, uncertainties in material performance will exist.

With the existence of nuclear power stations, and with the inevitable production of spent fuel rods, long term safe disposal of these is needed. Because of the highly radioactive nature of the waste and because of its long active life, ordinary and normal precautions used in the construction of solid waste or hazardous waste landfills are not sufficient to provide the level of safety and protection needed. Deep isolation-disposal of the spent fuel has been considered in many countries as a logical disposal scheme. The extent of geotechnical engineering input and participation in the design and analysis of long term safe disposal, assurance of performance and safety of the disposal facility is almost limitless.

This brief discussion which has focused on the buffer surrounding the waste canister, has only considered one small part of the near field performance assessment problem. To say that this is one very small part of a very complex geotechnical, geochemical, biogeochemical, radioactive, geological and chemical problem is perhaps a vast understatement. The challenges for geotechnical engineers are not only in the determination of the various properties and performance characteristics of the buffer in the hostile environment, but also to provide analytical capability in modelling the complex interdependent processes that contribute to long term performance in the near and far fields.

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