Scoping analyses of the coupled thermal–hydrological–mechanical behaviour of the rock mass around a nuclear fuel waste repository

A.P.S. Selvadurai\textsuperscript{a,*,} T.S. Nguyen\textsuperscript{b}

\textsuperscript{a} McGill University, 817 Sherbrooke West Street, Montreal, Canada H3A 2K6
\textsuperscript{b} Atomic Energy Control Board, 280 Slater Street, Ottawa, Canada K1P 5S9

Received 8 January 1996; revision 4 September 1996; accepted 4 September 1996

Abstract

Scoping calculations were performed in order to assess the influence of radiogenic heat on the performance of the rock mass around a nuclear fuel waste repository. The full coupling between the thermal, mechanical and hydrological processes involved was considered by using the finite element code, FRACON, developed through an extension of Biot's classical theory of soil consolidation. By considering the full T–H–M coupling, several important safety features, which would otherwise be omitted in uncoupled analyses, were detected in the present study. In particular, it was shown that the heat-induced pore pressure increase around the repository has the potential to significantly increase the rate of groundwater flow, and affect the structural integrity of the rock mass.

Keywords: Finite element; Nuclear wastes; Coupled processes; Rock stress; Groundwater flow; Thermal effects

1. Introduction

The Canadian concept for the disposal of heat-emitting high level nuclear fuel waste (NFW), currently proposed by Atomic Energy of Canada Ltd. (AECL) involves the deep burial of the wastes in a plutonic rock mass of the Canadian Shield. Due to the longevity of the radio-isotopes, a NFW disposal system is required to provide protection to human health and the environment from the hazards of contaminant release which could last for tens of thousands of years. According to the current conceptual design proposed by AECL (1994a–c), a repository consisting of a series of disposal rooms would be excavated at a depth of 500–1000 m in a granitic rock formation of the Canadian Shield. Three rows of boreholes would be drilled along the length of each room. Corrosion-resistant waste containers would be emplaced in the boreholes. A buffer material, consisting of a mixture of sand and bentonite, would be packed around the containers in the boreholes; after the completion of the emplacement activity, the disposal room would be backfilled with a mixture of clay and crushed granite. It is generally recognized that when such a repository is completely filled and sealed, groundwater is the most important agent that could transport contaminants from the wastes to the surface. The groundwater migration of contaminants would be retarded by several barriers. Due to very low dissolution rates, the waste forms themselves

* Corresponding author.
constitute the first barrier. The waste containers, if properly designed, should be structurally stable, and have a very slow rate of corrosion. The low hydraulic conductivities and high chemical sorption of the buffer and backfill would ensure slow rates of contaminant migration through them. The combined effects of the engineered barriers and the rock formation should be such that by the time contaminants reach the surface, radioactive decay would reduce their dosage to levels harmless to humans and the environment. In the current form of the Canadian concept of NFW disposal, the plutonic rock mass is regarded as a major barrier. The performance of this natural geological barrier ultimately depends on its groundwater regime. Since the wastes will generate heat for hundreds to thousands of years, the stability, deformation and water flow characteristics of the rock mass will be influenced by the introduced thermal pulse. In order to simulate the coupled thermal–hydrological–mechanical response of the rock mass to radiogenic heat, a finite element code, FRACON (FRActured medium CONsolidation) has been developed by the authors (Selvadurai and Nguyen, 1995; Nguyen and Selvadurai, 1995a). The FRACON code was developed from a generalization of Biot’s theory of consolidation, to include the effects of heat conduction and the presence of defects such as rock joints and other discontinuities.

In this paper, we present certain scoping calculations conducted with the FRACON finite element code to assess the influence of radiogenic heat produced from the wastes on the performance of the natural geological barrier. The Nuclear Fuel Waste Disposal program in Canada is in an early stage of concept feasibility studies. A specific site that would host a NFW repository is yet to be selected. Consequently, the scenarios modelled here are meant to be indicative of generic conditions applicable to a hypothetical site. In that context, the use of simple but conservative assumptions for building scenarios that would assess the robustness of the concept is thought to be preferable to sophisticated assumptions which do not have site-specific data to support them. In the Canadian context, the regulatory document R-104 from the Atomic Energy Control Board (1987) requires that the safety of the repository has to be demonstrated for the first 10,000 years. It is with this time frame in mind, that the analyses presented in this paper are performed.

2. Fundamental concepts governing the FRACON code

2.1. Governing equations

The FRACON code numerically solves via the finite element method, the following equations governing the non-isothermal consolidation of saturated porous media (Selvadurai and Nguyen, 1995; Nguyen and Selvadurai, 1995a):

\[
\frac{\partial}{\partial t} \left( \frac{k_{ij}}{\rho} \frac{\partial T}{\partial x_j} \right) = \rho C \frac{\partial T}{\partial t} + G \frac{\partial^2 u_i}{\partial x_i \partial x_j} + \frac{\partial p}{\partial x_i} + \beta_K \frac{\partial T}{\partial x_i} + F_i = 0
\]

(1)

\[
\frac{\partial}{\partial t} \left( k_{ij} \frac{\partial^2 u_i}{\partial x_j \partial x_j} \right) - \left( \frac{n}{K_s} - \frac{n}{K_f} + \frac{\alpha}{K_f} \right) \frac{\partial p}{\partial t} + \alpha \frac{\partial T}{\partial t} \left( (1-a) \beta - (1-a) \beta_s - n \beta_f \right) \frac{\partial T}{\partial t} = 0
\]

(2)

where the unknowns are the displacement \( u_i \) (m), temperature \( T \) (°C) and pore pressure \( p \) (Pa); \( k_{ij} \) is the thermal conductivity tensor of the bulk medium (W m\(^{-1}\) °C\(^{-1}\)); \( k_{ij} \) is the intrinsic permeability tensor (m\(^2\)); \( \rho \) is the density of the bulk medium (kg m\(^{-3}\)); \( \rho_f \) is the density of the fluid (kg m\(^{-3}\)); \( C \) is the specific heat per unit mass of the bulk medium (J kg\(^{-1}\) °C\(^{-1}\)); \( G \) and \( \lambda \) are the Lamé’s constants of the porous skeleton (Pa); \( \alpha = 1 - K_K/K_s \); \( K_D \), \( K_s \) and \( K_f \) are, respectively, the bulk modulus of the drained material, the solid phase and the fluid phase (Pa); \( F_i \) is the volumetric body force (N m\(^{-3}\)); \( \beta, \beta_s \) and \( \beta_f \) are, respectively, the coefficient of thermal expansion of the drained material, the solid phase and the fluid phase (°C\(^{-1}\)); \( n \) is the porosity of the medium (dimensionless); \( \mu \) is the viscosity of the fluid
(kg m\(^{-1}\) s\(^{-1}\)); \(g_i\) is the \(i\)th component corresponding to the acceleration due to gravity (m s\(^{-2}\)).

In the above parameter definitions the bracketed designations are in typical SI units.

In Eqs. (1–3) the Cartesian tensor notation, with Einstein’s summation convention on repeated indices is adopted. For the present, the sign convention for stresses and the fluid pressure adopts tension fields as positive. In developing these equations (Eqs. (1–3)), we invoke the basic principles of continuum mechanics (namely conservation of mass, momentum and energy). These principles are universally applicable, independent of the nature of the medium being considered. In order to complete the formulation (i.e., to develop a set of equations in which the number of unknowns equals the number of equations), the following additional assumptions are necessary:

2.1.1. Representation of the rock mass as a single porosity continuum

Rock masses are in general characterized by the presence of fractures. In order to take this characteristic into account, many researchers utilize the concept of a dual-porosity/dual permeability medium (see, e.g., Huyakorn and Pinder (1983) and Berryman and Wang (1995) for a detailed description of the concept). According to that concept, the rock mass is idealized into a porous matrix partitioned into blocks by a fracture network. For a saturated rock mass, the fluid would be present in two types of void space: the void in the porous blocks constituted by the pores and microcracks in the intact rock; and the voids between the walls of the fractures. A representative elementary volume (REV) is then defined in that dual-porosity medium. An REV is a finite volume in the medium that contains a number of porous blocks and fractures and that surrounds a point mathematically defined in that medium. The mean properties and also the mean parameters in the REV are assigned to the mathematical point. The REV should be large enough to contain a sufficient number of porous blocks and fractures so that the mean value of a given property or parameter has a statistical significance. On the other hand, the REV should be sufficiently small so that the variations of these properties and parameters from one domain to the next may be approximated by continuous functions so that the use of infinitesimal calculus is still appropriate. Two types of fluid pressures are defined for a dual-porosity medium: the fluid pressure in the pore and microcracks of the porous blocks, and the fluid pressure within the fractures.

The dual porosity representation is appropriate for highly fractured rock masses. Rocks at depths beyond a few hundred metres of the Canadian Shield are very sparsely fractured (AECL, 1994a–c) with typical fracture spacings of the order of hundreds of metres. The FRACON code has been developed with this particular application in mind. Consequently, only one type of porosity, associated with the pores and microcracks of the rock matrix, is considered. Discrete fractures that intersect the rock mass are explicitly represented by special joint elements described later in this paper.

2.1.2. Darcy’s law governing pore fluid flow

Darcy’s law is applicable with reasonable accuracy to a variety of geological materials (Freeze and Cherry, 1979) including soils and rocks, provided that the hydraulic gradients are within the laminar flow range, and above a threshold gradient within which the pore fluid is virtually immobile.

For most geotechnical applications, the pore fluid is water at a constant temperature, and the original form of Darcy’s law is appropriate. Where thermal effects are important, and/or when the pore fluid is not water, Darcy’s law has to be modified (Huyakorn and Pinder, 1983), i.e.:

\[
V_{it} - V_{is} = \frac{k_{ij}}{n} \left( \frac{\partial p}{\partial x_j} + \rho_f g_j \right)
\]

\[
V_{it}, V_{is} \text{ are the velocities, respectively, of the fluid and the solid components (m s}^{-1}).
\]

The use of the generalized Darcy’s law (Eq. (4)) is essential when one deals with fluids other than water. It is thus necessary to separate the expression for the hydraulic conductivity \(K_{ij}\) (loosely referred to as the permeability in most geotechnical applications) into a fluid independent component \(k_{ij}\), and a fluid-dependent component characterized
by its viscosity and density, i.e.:

\[ K_{ij} = \frac{\rho g}{\mu} k_{ij} \]  

(5)

The viscosity and density of a particular fluid are also temperature dependent. When thermal effects are considered, appropriate experimentally derived functions of temperature should be used for these two properties.

2.1.3. The principle of effective stress

A generalized principle of effective stress is adopted. Several forms of this principle exist (Terzaghi, 1923; Biot, 1941; Rice and Cleary, 1976; Zienkiewicz et al., 1977). We adopt the form of generalized principle of effective stress formulated by Zienkiewicz et al. (1977). In contrast to Terzaghi's (Terzaghi, 1923) principle of effective stress, this generalized principle takes into consideration the compressibility of the pore fluid and the solid phases. Omission of the compressibility of the pore fluid and the solid phase could lead to an overprediction of pore pressures in competent rocks (Selvadurai and Nguyen, 1995).

2.1.4. Stress strain relationship for the solid matrix

Hooke's law for linear isotropic elastic behaviour of the porous skeleton is adopted. This is a useful first approximation for the study of intact competent rocks which are subjected to stress states lower than those which could initiate fracture, failure or damage. The applicability of the poro-elastic continuum model for the description of the mechanical behaviour of saturated low permeability materials has been discussed in detail by a number of authors including Nur and Byerlee (1971), Rice and Cleary (1976), and Selvadurai (1996). Discrete joints on the other hand could behave in a linear elastic or an elasto-plastic fashion (Nguyen and Selvadurai, 1995b).

2.1.5. Heat transfer mechanism

Heat conduction is assumed to be the predominant mechanism of heat transfer. In the current context, there are two dominant mechanisms of heat transfer in a geological medium: heat conduction and heat convection. Heat conduction is the transfer of heat by the activation of solid and fluid particles, without their bulk movement. The conduction of heat is governed by Fourier's law, which states that the rate of heat flow is proportional to the temperature gradient. Heat convection on the other hand is due to the bulk motion of the particles. In a poro-elastic medium, the movement or displacement of the solid particles could be neglected; thus it is the fluid flow which is primarily responsible for the convective heat transfer. The rate of heat transfer by convection is proportional to the rate of fluid flow. Nguyen (1995) used an analytical solution developed by Ogata (1970) for the one-dimensional convection–diffusion equation to study the relative importance of heat convection in typical granitic formations of the Canadian Shield. The above study showed that the convective heat transfer component could be neglected in most situations. This component becomes important only in fracture zones with high permeability (10^{-14} m^2) that intersect a NFW repository, where heat-induced hydraulic gradients of the order of 100% could be found.

In the current Canadian concept of NFW disposal (AECL, 1994a–c), no fracture zone would be allowed to intersect a repository. Thus, from the above discussion, we assume that conduction is the main mechanism of heat transfer, and that Fourier's law applies. We also assume that a state of thermal equilibrium always exists between the fluid and the solid (i.e., at any point, the temperature of the solid equals the temperature of the fluid).

2.2. Finite element formulation

The governing equations are approximated by matrix equations via a standard Galerkin finite element procedure (see, e.g., Huyakorn and Pinder, 1983). We consider a domain \( R \) with boundary \( B \) where the above equations apply. Considering standard finite element procedures, the domain \( R \) is discretized into \( N_e \) elements. Two types of elements are considered.

2.2.1. Plane isoparametric element

This element (Fig. 1) is used to represent the intact rock mass. Displacements within the element
are interpolated as functions of the displacements at all eight nodes, whereas the pore pressure and temperature are interpolated as functions of the values at the four corner nodes 1, 3, 5 and 7 only. A detailed description of this element is given by Smith and Griffiths (1988).

2.2.2. Joint element

This element (Fig. 2) is used to simulate discontinuities in the rock mass such as joints, fracture zones and fault zones. In finite element terminology (see, e.g., Goodman et al., 1968; Zienkiewicz et al., 1970; Noorishad et al., 1971; Ghaboussi et al., 1973; Desai and Nagaraj, 1986), it is a very thin element, characterized by a thickness \( b \) and length \( L \). Nodal displacements are obtained at all six nodes (Fig. 2), while nodal pore pressures and temperatures are obtained only at the corner nodes 1, 3, 4 and 6. The mechanical behaviour of the element is dictated by its shear and normal stiffnesses \( D_s \) and \( D_n \) respectively, and its hydraulic and thermal behaviour are governed by the transverse and longitudinal permeabilities \( k_{y} \) and \( k_{x} \), and the transverse and longitudinal thermal conductivities \( \kappa_{y} \) and \( \kappa_{x} \) respectively.

With the above two types of elements being fully defined, a Galerkin procedure is applied to the differential Eqs. (1–3) of non-isothermal consolidation. The resulting matrix equations have the forms:

\[
\begin{bmatrix}
\theta [KH] + \rho C/\Delta t [CM]
\end{bmatrix} \{ T \}^1 = \{ FH \} + \{ FQ \} + \{ \theta - 1 \} [KH] + \rho C/\Delta t [CM] \{ T \}^0
\]

\[
\begin{bmatrix}
[K] \quad \alpha [CP]
\end{bmatrix} \{ \{ d \}^1 \}^T - \theta \Delta t [KP] - c_{d}[CM] \{ \{ p \}^1 \} = \{ f \}
\]

\[
\begin{bmatrix}
[K] \quad \alpha [CP]
\end{bmatrix} \{ \{ d \}^0 \}^T - \theta \Delta t [KP] - c_{d}[CM] \{ \{ p \}^0 \}
\]

\[
\begin{bmatrix}
[\beta_{d}][CP] \quad [\theta]
\end{bmatrix} \{ \{ T \}^1 - \{ T \}^0 \} - \beta_{d}[CM] \{ \{ T \}^1 - \{ T \}^0 \}
\]

where: the unknowns are the nodal displacements \( \{ d \}^1 \), the nodal temperatures \( \{ T \}^1 \) and the nodal pore pressures \( \{ p \}^1 \) at the current time step; \( \{ d \}^0 \), \( \{ T \}^0 \) and \( \{ p \}^0 \) are the nodal displacements, nodal temperatures, and nodal pore pressures at the previous time step; \{ \{ f \} \) is the “force” vector, \{ \{ FQ \} \) and \{ \{ FH \} \) are heat flux vectors, \( \theta \) is a time integration constant; all the other matrices, \{ [K], [CP], etc., are assembled from element matrices, which are dependent on thermal, mechanical and hydrological properties of the individual elements and the interpolation functions used. Also,

\[
e_{c} = n/K_{t} - n/K_{s} + \alpha/K_{s}
\]

\[
\beta_{e} = (1 - \alpha) \beta - (1 - n) \beta_{s} - n \beta_{t}
\]

Also \( \Delta t \) is the time increment, and the time integration constant \( \theta \) varies between 0 and 1. Using a value of \( \theta \) close to 1, we observe that after the first three of four timesteps, stability of the solution is generally reliably achieved.
2.3. Verification and comparison with experimental data

The FRACON code was extensively verified against existing analytical solutions for both isothermal and thermal consolidation of porous media (Nguyen and Selvadurai, 1995a). The code was successfully used to interpret a laboratory experiment involving the heating of a partially saturated cementitious material (Nguyen and Selvadurai, 1995a) and in the interpretation of laboratory and field experiments involving the mechanical and coupled hydraulic-mechanical behaviour of rock joints (Nguyen and Selvadurai, 1995b).

3. Conceptual and finite element models of a hypothetical NFW repository

A plutonic rock mass of the Canadian Shield that would contain a NFW repository would ideally be competent, mostly unfractured and any major fracture zones would be easily distinguishable from the competent rock mass. Field data from the Underground Research Laboratory (AECL, 1994a–c) at Whiteshell, Manitoba, indicate that near the ground surface (up to 200–500 m depth), the rock mass is moderately fractured and contains networks of interconnected joints. At greater depths however, the field data suggest that the rock mass is of very good quality and contains few discernible fractures outside the major fracture zones (Fig. 3). This relatively unfractured competent rock is also referred to as “sparsely fractured” rock. We will refer to this sparsely fractured rock mass as “competent” rock in this paper. In the competent rock, water moves in a network of pores, microcracks and sparsely distributed joints. The major fracture zones are defined as zones of fractured, broken rocks, which are hundreds of metres (or more) long and tens of metres (or more) thick. These fracture zones usually have very different mechanical and hydrogeological characteristics when compared with the remaining competent rock mass. Usually they are more hydraulically conductive and prone to shearing under large external loads, such as the weight of a glacier or the heat generated by the wastes.

A hypothetical repository situated at a depth of 1000 m in a typical pluton of the Canadian Shield is considered in this section. The repository occupies an area of 2000 × 2000 m. The total amount of wastes contained in the repository, will result in an initial heat generation rate (per unit area of the repository) of 10.4 W m⁻². This rate decays to 95% after 1 year, 80% after 1000 years and less than 10% after 10,000 years, due to the decay in radioactivity of the wastes (Fig. 4). The above dimensions of the hypothetical repository and its heat characteristics basically follow the conceptual design of AECL (1994b).

We assume that the hypothetical repository is located in a largely competent rock mass containing two vertical fracture zones, 20 m thick, at 100 m from two opposite edges of the repository. Assuming plane strain conditions, the rock mass response was modelled with the FRACON code. The finite element mesh used in the study is shown in Fig. 5. The boundary conditions invoked in the analysis are also shown in Fig. 5. Due to the assumed symmetry conditions, only one half of the repository is considered. The finite element mesh consists of 210 eight-noded isoparametric elements to represent the competent rock mass and 14 six-noded joint elements to represent the fracture zone. The total number of nodes is 718, with three degrees of freedom per node. The time stepping associated with the transient analysis is adjusted to ensure stability of the time marching scheme. The time increments are progressively increased by 25%, according to a geometric progression, and vary from an initial increment of $1 \times 10^7$ s (0.32 year) to a final increment of $60 \times 10^9$ s (1900 years).

4. Properties of rock mass and fracture zones: reference case

For the analysis of the reference case, the following properties of the rock mass and the fracture zone are assumed:
4.1. Rock mass

Permeability $k = 10^{-18}$ m$^2$; Young’s modulus $E = 35 \times 10^9$ Pa; Poisson’s ratio $\nu = 0.2$; effective porosity $n = 0.005$.

4.2. The fracture zone

Permeability $k = 10^{-15}$ m$^2$; shear stiffness $D_s = 35 \times 10^6$ Pa; normal stiffness $D_n = 35 \times 10^9$ Pa.

The thermal properties for both the rock mass and the fracture zone are assumed to be: $\kappa = 3$ W m$^{-1}$ K$^{-1}$; $C = 845$ J kg$^{-1}$ K$^{-1}$.

4.3. Physical properties of pore water, solid grains and solid matrix

Compressibility of water $c_t = 1/K_t = 4.5 \times 10^{-10}$ Pa$^{-1}$; compressibility of the solid grains $c_s = 1/K_s = 2 \times 10^{-11}$ Pa$^{-1}$; density of solid grains $\rho_s = 2700$ kg m$^{-3}$; density of pore water $\rho_t = 1000$ kg m$^{-3}$; coefficient of thermal expansion of solid matrix and solid grains: $\beta = \beta_s = 0.24 \times 10^{-4}$ C$^{-1}$; coefficient of thermal expansion pore water $\beta_t = 0.4 \times 10^{-3}$ C$^{-1}$.

The above thermal/mechanical/hydraulic properties of the rock mass are considered as representative values for competent plutonic rock masses of the Canadian Shield (AECL, 1994a,b; Gale.
Many more uncertainties exist in the definition of properties of the fracture zones. The shear and normal stiffness values of fracture zones in the Canadian Shield are largely unknown because of the lack of field measurements to determine these mechanical properties. Permeability values, on the other hand, which have been estimated for fracture zones at the Underground Research Laboratory site (AECL, 1994c), vary in a range of $10^{-12}$ to $10^{-17}$ m$^2$. The value of permeability for the fracture zone used in the reference case analysis corresponds roughly to an intermediate
value between these limits. For the sake of simplicity, consistent with the generic site discussed earlier, all properties are assumed constant and only linear elastic analyses are performed in this paper. In particular, due to the absence of data on the mechanical properties of the fracture zones, the elasto-plastic joint model discussed in Nguyen and Selvadurai (1995b) is not used in this study.

5. Results for reference case analysis with the FRACON code

For the remainder of this paper, the sign convention adopted previously for stresses and fluid pressure is reversed. Following the usual convention in soil and rock mechanics, compressive stresses and pore pressures will be considered positive.

The temperature and the pore pressure increases at the centre of the repository are shown in Fig. 6. The temperature increase shows two peaks, 50°C at 70 years and 55°C at 5000 years; this is consistent with results of others (AECL. 1994b). The presence of two thermal peaks is due to the nature of the heat output from the fuel wastes. The first peak is due to short-lived radio-isotopes which generate heat at a high rate but for short time periods; the second peak is due to longer-lived isotopes that generate heat at lower rates but for much longer times. Temperature contours are shown in Fig. 7 for the two values of time corresponding to the temperature peaks at the centre of the repository. It can be seen that at 70 years, the perturbation in the temperature is limited to a rock mass approximately 200 m thick surrounding the repository. At 5000 years, the thermal perturbation extends to the ground surface.

The pore pressure increase in the centre of the repository shows a peak of approximately 2.5 MPa at 55 years (Fig. 6). This pore pressure increase is due to the fact that the thermal expansion coefficient of the water is higher than that of the solid matrix. Due to the low permeability of the medium, drainage is slow and the pore water expansion is impeded, resulting in pore pressure increases at the initial stages. At the later stages, migration of water from the heat source takes place gradually allowing the pore pressure to dissipate. Typical contours of pore pressure increases are shown in Fig. 8 (at 55 years). These pore pressure contours suggest that thermally induced high hydraulic gradients can occur in the vicinity of the repository. These gradients can attain values of up to 100% (i.e., several orders of magnitude higher than typical regional gradients in the Canadian Shield which are in the order of 0.1%) resulting in increased groundwater velocities diverging from the repository. The existing groundwater regimes will therefore be significantly modified by the thermal pulse. It can also be observed that the fracture zone acts as a drainage feature and would constitute a preferential pathway for the movement of groundwater to the surface. A further implication of these high pore pressures is that effective stresses will be reduced, possibly resulting in either a reduction of the strength of both the competent rock mass and the fracture zones or in the creation of new fractures.

A typical deformed configuration of the modelled region is shown in Fig. 9. These results indicate that shear movements are induced in the fracture zone, an uplift of the ground surface is induced directly above the repository and thermal expansion of the rock matrix takes place around the repository. These displacements are relatively small (maximum value of 50 cm), but can induce significant disturbances to the stress regime and, as a consequence, the structural integrity of the rock mass in the vicinity of the repository has to be further assessed. We will now have a closer look at the thermally induced perturbations to the stress and groundwater regimes in the rock mass and in the fracture zone.

Herget (1980) reported a compilation of in situ stress measurements in the Canadian Shield. In the majority of cases, the minor principal stress corresponds to the vertical stress, which is primarily due to the weight of the overburden. The major principal stress is oriented in a horizontal direction, and is mainly due to tectonic forces. Herget (1980) proposed the following equations for estimating the in situ stresses:

\[ \sigma_v = 0.0265h \text{ (MPa)} \]  
\[ \sigma_{ha} = 6.67 + 0.0302h \text{ (MPa)} \]  
\[ \sigma_{he} = 12.36 + 0.0586/z \text{ (MPa)} \]

where \( \sigma_v \) is the vertical stress; \( \sigma_{ha} \) is the average value of the horizontal stress for the Canadian
Fig. 6. Time-dependent variations of pore pressure and temperature at the centre of the repository: reference case.

Shield; \( \sigma_{he} \) is the higher values of horizontal stress in the range of values reported by Herget (1980); and \( h \) is the depth below the ground surface (in units of m). In Eqs. (8–10), total stresses (as opposed to effective stresses) are considered.

The heat generated by the wastes will change the above original in situ state of stress. The total vertical and horizontal stresses along a vertical section through the centre of the repository are shown in Fig. 10 for two specific times: 55 years after wastes emplacement, when the thermally induced pore pressure is at its peak, and at 10 000 years when the temperature at the centre of the repository is near its second peak and the thermal perturbation extends to the ground surface. Also, the period of 10 000 years is a reference
from the point of view of safety, associated with regulatory documents (AECB, 1987). In Fig. 10, the \( y \) coordinate corresponds to the vertical direction, and the initial stress distribution is assumed to follow Herget’s values for average conditions, defined by Eqs. (8) and (9). Fig. 10 shows that along a vertical section through the centre of the repository, the vertical stresses are not significantly changed while more important changes are found for the horizontal stresses. The results shown in Fig. 10 are consistent qualitatively and quantitatively to the results given by AECL (1994b). However, in contrast to the analyses by AECL (1994b), in order to assess the rock mass failure conditions, we will consider, in the following, effective stresses instead of total stresses.

Fig. 11 shows that due to thermal effects, along a vertical section through the centre of the repository, the horizontal effective stress increases in the vicinity of the repository, while it decreases near the surface. At 10,000 years, a zone of tensile
stresses could be seen to have formed down to a depth of approximately 25 m from the surface. Horizontally this zone would approximately occupy an area of 200 x 200 m above the centre of the repository. If the tensile strength of rock is negligible, it is likely that vertical fractures will form in this zone. The zone of tensile cracking has a limited extent. This zone is at a distance of 975 m from the repository and is not expected to significantly influence the groundwater flow field in the vicinity of the repository. Fig. 11 also shows that the effective vertical stresses in the rock mass along a vertical section through the centre of the repository decreases at early times (55 years) due to the pore pressure buildup shown in Fig. 8. As the pore pressure dissipates, the effective vertical stresses gradually increase and become more compressive due to thermal effects.

The competent rock mass between the edge of the repository and the fracture zone is of particular importance, since it is part of the groundwater flow path with the minimum travel time to the ground surface. Figs. 12–16 show the evolution of effective stresses at four points located in that envelope of competent rock (point 2 at the edge of the repository; point 3 at a distance of 63 m from the repository and 37 m from the fracture zone; point 4 at 19 m from the fracture zone; and point 5 adjacent to the fracture zone) and at the centre of the repository (point 1). Since the shear stresses are small, it is evident (from Figs. 12–16) that the minor principal stress is practically equal to the vertical stress, while the major principal stress would be practically horizontal, either in the $z$ direction (perpendicular to the plane of the model), in the vicinity of the repository (points 1 and 2), or in the $x$ direction at points closer to the fracture zone (points 3, 4 and 5).

In order to verify whether the above stresses will result in fracturing of the competent rock mass, the empirical Hoek and Brown (1988) failure criterion was adopted: i.e.,

$$
\sigma_{ef}' = \sigma_3' + \sqrt{m \sigma_3' \sigma_3' + s \sigma_c'^2}
$$

(11)

where: $\sigma_{ef}'$ is the effective major principal stress at failure; $\sigma_3'$ is the effective minor principal stress; $\sigma_c'$ is the uniaxial compressive strength of intact samples of the rock mass; $m$ and $s$ are empirical constants.

The above criterion was formulated in terms of effective stresses, since these stresses govern the mechanical behaviour of saturated geological materials. The following values were adopted
(AECL, 1994b) in the computations: $\sigma_c = 190$ MPa; and $m = 17.5$, $s = 0.19$.

The above values suggest a rock mass with a "very good quality" designation (Hoek and Brown, 1988). Using the above values, it is found that the major principal stress at points 1–5 have a maximum value of approximately 45 MPa and at all times are lower than the major principal stress at failure given by the Hoek and Brown criterion (minimum value of approximately...
160 MPa). If the initial in situ horizontal stress is assumed to be in the upper bound (Eq. (10)) of the envelope given by Herget (1980) instead of the average value (Eq. (9)), the maximum value of the major principal stress would be approximately 80 MPa. For this condition, there is still a high margin of safety against failure of the competent rock mass surrounding the repository.

It is assumed that, in the fracture zone, failure is governed by the Mohr-Coulomb failure criterion: i.e.,

$$\tau_f = \sigma' \tan \phi' + c'$$

(12)

where: $\tau_f$ is the shear stress at failure; $\sigma'$ is the effective normal stress acting across the fracture zone; and $c'$ and $\phi'$ are, respectively, the effective
values of the cohesion and the angle of internal friction.

AECL (1994b) has reviewed the data available for the values $c'$ and $\phi'$ for fracture zones in granite and has proposed the following ranges: $\phi'$: 25–40°; $c'$: 0–240 kPa.

As conservative estimates for these parameters, we assume that $c'=0$ and $\phi'=33^\circ$. It is observed that the shear stress levels in the fracture zone are at all times below the shear stress at failure according to the Mohr-Coulomb criterion.

The thermally induced pore pressure triggers outward flow from the repository. In order to assess the rate of migration of potentially contaminated groundwater, the trajectories of water particles from points near the centre and from the
edge of the repository are calculated according to the equations:

\[ x(t) = x_0 + \int_0^t v_x(x,y,t) \, dt \]  

(13)

\[ y(t) = y_0 + \int_0^t v_y(x,y,t) \, dt \]  

(14)

where \( x(t) \) and \( y(t) \) are the coordinates of the particle position at time \( t \), \( x_0 \) and \( y_0 \) are the coordinates of the particle position at time 0, and:

\[ v_x(x,y,t) = -\frac{k}{n\mu} \frac{\partial p}{\partial x} \]  

(15)

\[ v_y(x,y,t) = -\frac{k}{n\mu} \frac{\partial p}{\partial y} \]  

(16)

where \( k \) is the permeability of the rock mass, \( \mu \) is the viscosity of water, \( n \) is the porosity of the rock mass, and \( p \) is the pore pressure (positive in compression).

The calculated trajectories of groundwater movement during 10 000 years are shown in Figs. 17(a) and (b). At 10 000 years, the water particle from near the centre of the repository travels approximately 10 m in an upward direction and 6 m in a horizontal direction (towards the fault zone). The particle from the edge of the repository travels mostly in a horizontal direction towards the fracture zone. Once a water particle has reached a fracture zone, it will migrate relatively quickly to the ground surface. At 10 000 years, the particle from the edge of the repository has travelled a horizontal distance of approximately 30 m but is still 70 m away from the fracture zone. From the above discussion, it is evident that for the rock mass properties assumed in this hypothetical repository scenario, a zone of competent sparsely fractured rock of 100 m between the repository and a major fracture zone would provide an effective barrier for contaminant migration due to thermally induced groundwater flow.

**Parametric study**

The influences of rock mass permeability, fracture zone permeability and rock mass Young’s modulus are assessed by considering the following cases, which are in every way similar to the above reference case except for the following differences:

- **case 1**: rock mass permeability, \( 10^{-20} \text{m}^2 \) (2 orders of magnitude lower than in the reference case);
- case 2: rock mass permeability, $10^{-20} \text{ m}^2$ and $E=70 \text{ GPa}$ (2 times higher than in the reference case);
- case 3: fracture zone permeability, $10^{-13} \text{ m}^2$ (2 orders of magnitude higher than in the reference case);
- case 4: rock mass permeability, $10^{-19}$ m$^2$
  (1 order of magnitude lower than in the reference case).

Fig. 18 presents a comparison of the pore pressure at the centre of the repository for all the separate cases. It can be seen that decreases in the rock mass permeability (cases 1 and 4) results in substantial increases in the peak pore pressure. The thermally induced pore pressure would remain high for longer durations when compared with the reference case. A decrease in the permeability combined with an increase in the Young’s modulus of the rock mass (case 2) results in a further increase in the pore pressure, which would be six times higher than in the reference case. An increase in the permeability of the fracture zone by two orders of magnitude (case 3) does not have any discernible influence on the pore pressure in the centre of the vault.

Case 2 is the most critical for rock mass stability, since the high thermally induced pore pressure (up to 15 MPa) would substantially reduce the minor effective principal stress ($\sigma_{yy}'$). Fig. 19 shows the stress evolution at point 3, at a distance of 37 m from the fracture zone. It may be noted that in this case the effective vertical stress becomes tensile ($\sigma_{yy}' < 0$). This tension zone is found to extend from the fracture zone to approximately a distance of 50 m towards the edge of the repository. Horizontal cracks would form in the tension zone and the original envelope of 100 m of competent

---

![Fig. 18. Effects of permeability and Young's modulus on pore pressure at centre of repository.](image-url)
rock which existed between the repository and the fracture zone could be reduced to 50 m.

In Fig. 20, the flow paths of a particle of water from the edge of the repository are compared for the different cases. Although the pore pressure and the hydraulic gradients are higher for cases 1 and 2 (when compared with the reference case), the water particle has only moved a horizontal distance of approximately 10 m towards the fracture zone in 10 000 years (compared to more than 30 m for the reference case), due to the significantly lower permeability of the rock mass. With an increase in the permeability of the fracture zone (case 3), it exhibits a stronger drainage effect. As a consequence, the flow path becomes more horizontal and the path length is slightly increased compared with the reference case. For case 4, although the permeability of the rock mass is 10 times lower compared to the reference case, the travel distance for a particle of water is not significantly reduced, since the thermally induced hydraulic gradients are much larger.

7. Conclusions

The FRACON code was used for the preliminary assessments of the impact of the heat generated by nuclear fuel wastes on a sparsely fractured plutonic rock mass, representative of conditions that can be encountered in the Canadian Shield. The thermal, mechanical and hydrological disturbances due to these two factors were traditionally analyzed by neglecting the coupling between the T–H–M processes. From the scoping calculations shown in this chapter, where this coupling is considered, several new results were found:

- The heat pulse generated by the wastes has the ability to significantly perturb the groundwater and stress regimes in the host rock.
- The pore pressure induced by the radiogenic heat can accelerate the movement of contaminated water to the ground surface. In 10 000 years, this accelerated rate results in flow distances of tens of metres in addition to any flow distance dictated by the natural hydraulic gradient that existed prior to the thermal loading.
- Very low permeability of the rock mass will not always ensure lower groundwater flow rate since the thermally induced hydraulic gradients are higher for lower permeabilities. In some extreme cases, when a low permeability is combined to a high Young’s modulus of the rock mass, the high pore pressure generated by the waste heat...
can induce tensile cracks in the rock mass, and the buffering distance provided between the repository and a fracture zone could be reduced.

A waste repository should ideally be located in competent sparsely fractured rock, at a “safe” distance from major hydraulic conduits such as highly permeable fracture zones. The basis for the minimum distances between these hydraulic features and the repository should be established by consideration of the thermal/hydraulic disturbances due to the thermal pulse and future geological events such as glaciation. The regulatory document R-104 (Atomic Energy Control Board, 1987) requires that the safety of the repository has to be demonstrated for the first 10 000 years. AECL (1994a–c) has established a minimum thickness of 50 m for an envelope of competent rock between a repository and a fracture zone. It would appear that this minimum thickness was determined without consideration of the full T–H–M coupled processes. Considering coupled T–H–M processes, the analyses performed in this paper, for the effects of radiogenic heat, and the analyses previously performed by the authors for the effects of glaciation (Nguyen et al., 1993), suggest that it would be more prudent to increase the thickness of the envelope of competent rock between the repository and a fracture zone to at least 100 m. However, there are practical limitations to providing such an envelope. It would be difficult to find large regions of competent rock in the Canadian Shield that could contain a 4-km² repository and at the same time provide a minimal distance of 100 m between the repository and major fracture zones. Lower order fractures, of thickness up to 1 cm, cannot be detected by present geophysical site investigation techniques. The undetected fractures in the competent rock envelope could be extended by T–H–M processes to provide preferen-
tial groundwater flow paths and the implications of such contaminant transport processes have to be further assessed. From the above uncertainties pertaining to the competent rock envelope, it would seem prudent to place a greater reliance on engineered barriers such as the container, the buffer and the backfill.

By analyzing the thermal, stress and groundwater flow regimes of a rock mass without considering the influences of coupling between these processes, it is likely that some safety features of importance to a repository could be unwittingly omitted. It is recommended that detailed, site-specific assessment of a future repository should be conducted by taking into account the coupled nature of thermal, mechanical and hydrological processes.

Acknowledgment

The work reported in this paper represents a joint research effort between McGill University and the Atomic Energy Control Board of Canada. The work was supported by the AECB as a part of its ongoing activities related to the regulatory aspects of the Canadian Nuclear Fuel Waste Management Program. The views expressed in the paper are those of the authors and do not necessarily reflect the views or policies of the AECB or McGill University.

References


