

# Near-Field Thermo-Mechanical Coupled Processes in Host Rocks of High-Level Waste Deep Geological Repositories

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## ABSTRACT

Deep geological repositories (DGR) is considered the most preferred option for long-term management of all levels of radioactive waste, including used nuclear fuel containers (UNFC). The radioactive decay of spent fuel typically continues to generate heat for durations exceeding tens of thousands of years. Post closure safety assessments require comprehensive analyses of coupled thermal, hydraulic, and mechanical responses from the DGR system. The temperature, stress, and pore pressure in the vicinity of the multiple barrier systems of a DGR need to be investigated to ensure an adequate level of safety is met. This study contributes to the evaluation of potential changes in the material properties of near-field natural barrier systems, such as strength, which might impact the overall safety. Few studies are available on the numerical evaluation of coupled thermo-hydro-mechanical (THM) processes at a detailed near field scale. This work will expand the current understanding of thermo-mechanical responses of the DGR system.

## RÉSUMÉ

Le stockage en couches géologiques profondes (DGR) est considéré comme l'option privilégié pour la gestion à long terme des déchets radioactifs de tous les niveaux, y compris les conteneurs de combustible nucléaire irradié (UNFC). La désintégration radioactive du combustible irradié continue généralement de générer de la chaleur au delà de dizaines de milliers d'années. Les évaluations de la sécurité après la fermeture nécessitent des analyses approfondies des comportements thermiques, hydrauliques et mécaniques couplées du système DGR. La température, le stress et la pression interstitielle dans le voisinage des systèmes à barrières multiples d'un DGR doivent être examinés afin de garantir un niveau de sécurité adéquat. Cette étude contribue à l'évaluation des changements potentiels des propriétés matérielles des systèmes des barrières naturelles immédiates, telle que la résistance qui est susceptible de perturber la sécurité globale. Il existe peu d'études sur l'évaluation numérique des processus couplés en thermo-hydro-mécaniques (THM) à une échelle détaillée en grandeur nature. Ce travail élargira la compréhension actuelle du comportement MT du système DGR.

## 1 INTRODUCTION

Generating electricity via nuclear fission is considered a clean energy source in terms of greenhouse gas emissions as compared to traditional fossil fuel power generation methods (IPCC 2014). However, proper disposal of nuclear waste, and in particular, spent fuel, is still considered a main challenge due to its long term radioactivity and ability to persist in the environment. As such, nuclear waste must be managed accordingly to ensure long-term safety of present and future societies and the environment. Among the different management methods, disposing spent fuel in deep geological repositories (DGR) is considered to be the most acceptable approach. The performance of a DGR depends mainly on its capability to safely isolate and contain radioactive waste. The containment performance is a function of both natural and engineered barrier systems. The natural barrier system is comprised of low permeability host rock greatly extending above and below the storage rooms. The engineered barrier system is the man-made low permeability filling materials that encapsulate the containers. Spent fuel is characterized by its radioactivity and heat generation; the latter can cause an increase in temperature within the engineered and natural components of the DGR. Characterization of the barrier materials' thermal properties within a DGR containing high-level waste is an essential component of a system-wide safety assessment.

Advancing the understanding of thermo-mechanical processes in rocks has drawn the attention of researchers for various geoscience applications, particularly, in the fields of geothermal energy and nuclear waste disposal. The influence of thermal stresses on rock has been investigated showing that both permeability and strength of the rock matrix are affected (Tarasovs 2012; Hakala et al. 2014). Additional studies related to the impact of thermal stresses on DGR can be found in the literature, including the DECOVALEX project (Tsang et al. 2004). The DECOVALEX project investigated numerical modelling techniques and the development of computer codes describing coupled processes and validated with experimental data that included results from in situ tests on host rock at an underground rock laboratory (Garitte 2017). In Canada, several studies have investigated the thermal response of sedimentary and crystalline rocks subjected to thermal gradients emanating from DGR containing spent fuel (Guo 2010, 2016).

In this work, a numerical analysis is used to study thermal stresses imposed by a DGR and the consequential reduction of strength in hypothetical crystalline rock adopted from Guo (2016) using FLAC3D 6.0 (Itasca Consulting Group Inc. 2017).

## 2 CONCEPTUAL MODEL

The primary goal of this work is to investigate the impact of elevated temperature on near field host rock resulting from heat generated by spent fuel in a DGR. Conceptually, the following steps and assumptions are required:

- The hypothetical DGR is located at a depth of 500 m within a homogenous granite rock.
- The DGR includes rooms with an approximate length of 300 m and 3.2 m width by 2.2 m height placed at a spacing of 20 m center to center as shown in Figure 1a).
- UNFC center to center spacing of 0.75 m as shown in Figure 1a).
- The spent fuel is 30 years since being removed from a reactor
- The DGR houses UNFC similar to the cylindrical Mark II container (Guo 2016) whereby the hemispherical ends of the Mark II are simplified with an equivalent cuboid shape.
- Maximum temperature at the tunnel occurs within the first 200 years (Guo 2016) thus heat transfer and temperature distribution are only evaluated for 200 years.
- The host rock conforms to a Hoek-Brown failure envelope.
- The stress-strength ratio is used to evaluate stability of the host rock.
- All computations are done using FLAC3D 6.0 software (Itasca 2017).
- There are three vertical planes of symmetry:
  - z-x plane transversely bisecting the “long” rooms.
  - z-y plane midway between two long rooms.
  - z-y plane longitudinally bisecting a room passing through the center of the containers.

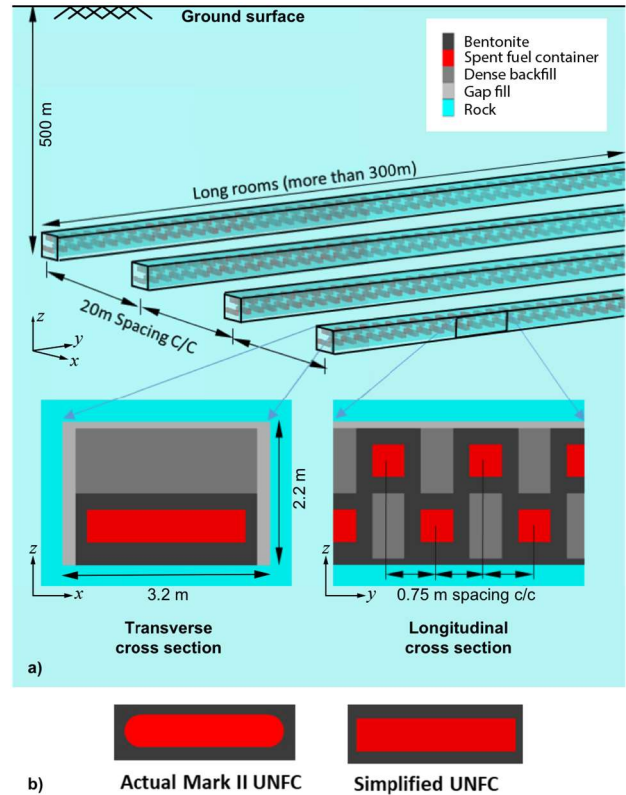


Figure 1. a) Hypothetical DGR; b) Actual vs simplified UNFC. (Note: the thickness of the bottom UNFC is 0.1m higher due to bentonite leveling layer).

### 2.1 Model Geometry

The aforementioned conceptualized model and assumptions are reflected in the analyzed model. The planes of symmetry are used to reduce the size of the analyzed geometry to  $10 \times 0.75 \times 1000$  m as shown in Figure 2. The 10 m dimension represents half of the 20 m room spacing including the half-length of the containers; 0.75 m represents the spacing between two adjacent containers, and 1000 m is the height of the analyzed geometry corresponding to a 500 m vertical depth of the DGR below ground surface level, and another 500 m of rock below the DGR.

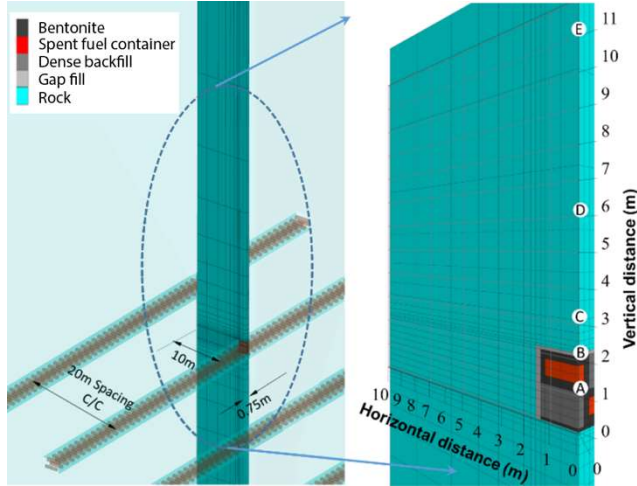


Figure 2. Model domain showing the analyzed geometry.

## 2.2 Thermal and Mechanical Equations

Thermal and mechanical coupled processes are analysed in FLAC3D by solving the energy balance and the mechanical constitutive models for both temperature (T) and stresses ( $\sigma$ ) as shown in Equation 1 and Equation 2, respectively:

$$C^T \frac{\partial T}{\partial t} + \nabla \cdot q^T - qv^T = 0 \quad [1]$$

$$\frac{\partial \sigma_{ij}}{\partial t} = 2G \left( \frac{\partial \epsilon_{ij}}{\partial t} - \alpha_t \frac{\partial T}{\partial t} \delta_{ij} \right) + \left( K - \frac{2}{3}G \right) \cdot \left( \frac{\partial k_k}{\partial t} - 3\alpha_t \frac{\partial T}{\partial t} \right) \delta_{ij} \quad [2]$$

Where: T is temperature,  $q^T$  is thermal flux,  $qv^T$  is volumetric heat source intensity, and  $C^T$  is the effective specific heat,  $\sigma_{ij}$  and  $\epsilon_{ij}$  are the total stresses and strains, K and G are bulk and shear moduli,  $\alpha_t$  is linear thermal expansion coefficient of the solid matrix, and  $\delta_{ij}$  is the Kronecker delta.

## 2.3 Material Properties

Table 1 summarizes the mechanical and thermal properties of materials used in the analysis of a hypothetical site. Values were adopted from comparable research (Guo 2010, 2016) which serve as part of this study's validation.

Table 1. Mechanical and thermal properties

Mechanical properties	Bulk modulus	Shear modulus		
Rocks	30 GPa	18 GPa		
Hoek-Brown parameters: constant-mb = 11.5, constant-s = 0.5, constant-a = 0.619 and constant-sci = 210 MPa				
Thermal properties	Density kg/m <sup>3</sup>	Thermal expansion coefficient K <sup>-1</sup>	Specific-heat J/K	Thermal conductivity W/(m·K)
Rock	2700	10E-6	845	3.0
DBF <sup>a</sup>	2276	10E-6	1060	2.0
Bentonite	1995	10E-6	1280	1.0
Gap Fill	1439	10E-6	870	0.4
Container	7800	10E-6	434	60.5

<sup>a</sup> Dense backfill blocks – 70% aggregate, 25% clay, 5% bentonite

The Hoek-Brown model is used to define the strength failure envelope of the rock as shown in Equation 3:

$$\sigma_{1f} = \sigma_3 + \sigma_{ci} \left( m_b \frac{\sigma_3}{\sigma_{ci}} + s \right)^a \quad [3]$$

Where:  $\sigma_{1f}$  is the major principal stress at failure;  $\sigma_3$  is the minor principal stress;  $\sigma_{ci}$  is the uniaxial compressive strength of intact rock material; and  $m_b$ ,  $s$  and  $a$  are empirical constants.

The state of stress with respect to failure is evaluated by calculating the stress-strength ratio:

$$\text{stress-strength ratio} = \frac{\sigma_{1f}}{\sigma_1} \quad [4]$$

Where:  $\sigma_1$  is the major principal stress.

Thermal strain resulted from thermal expansion (Equation 2) due to changes in temperature generated by the spent fuel (Equation 1) will cause changes in all stresses, including  $\sigma_1$  and  $\sigma_3$ , hence, changes in stress-strength ratio (Equation 3 and 4). A stress-strength ratio greater than one represents a stable and safe rock; values close to one indicate a small margin of safety against failure.

## 2.4 Heat Generation

Heat generated by the spent fuel was modelled from data adopted from Tait et al. (2000) under the assumption that it was placed in the DGR after a cooling period of thirty years since removed from a reactor. Figure 3 shows the heat output per container used in this work.

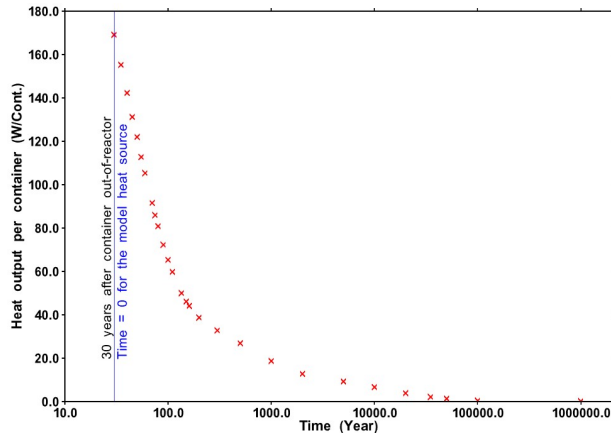


Figure 3. Heat output of a container with time (original data source Tait et al. 2000 as reported in Guo 2016).

To implement the function shown in Figure 3 as a heat source in FLAC3D, the data was converted to an equivalent source per unit volume of the container.

## 2.5 Initial and Boundary Conditions

Table 2 summarizes the thermal and mechanical initial and boundary conditions used in this work.

Table 2. Thermal and mechanical initial and boundary conditions

	Initial conditions	Boundary conditions
Thermal	Linear geothermal gradient with 5°C at the ground surface and 125°C at a depth of 10,000m <sup>a</sup> , and 11°C at the room elevation.	Top and bottom boundaries are fixed with 5°C and 125°C, respectively. No flux on sides (symmetry).
Mechanical	15.6 MPa and 23.3 MPa in the X- and Y-directions, respectively, which are the in situ stresses at the repository depth of 500 m <sup>b</sup> .	Top boundary is free Bottom boundary is fixed Side boundaries are roller (free vertically and fixed horizontally).

a : Baumgartner et. al. 1994

b : Guo 2010

## 3 RESULTS

Two groups of results are presented in this paper:

- The first details the temperature development in the rock. Results are compared with those of Guo (2016) for validation.
- The second group of results describes changes in the stress-strength ratio resulting from changes in rock temperature.

### 3.1 Temperature

Temperature development in the rock was determined for a period of 200 years following the placement of containers in the DGR. This duration was selected to investigate the

impact of peak temperature on the mechanical stability of the rock. Figure 4 shows temperature variation with time at four locations (A to E as shown in Figure 2). The locations of the selected points are the same as those used by Guo (2016) for comparison. The results show good agreement in terms of temperature history, peak values and time of maximum temperature.

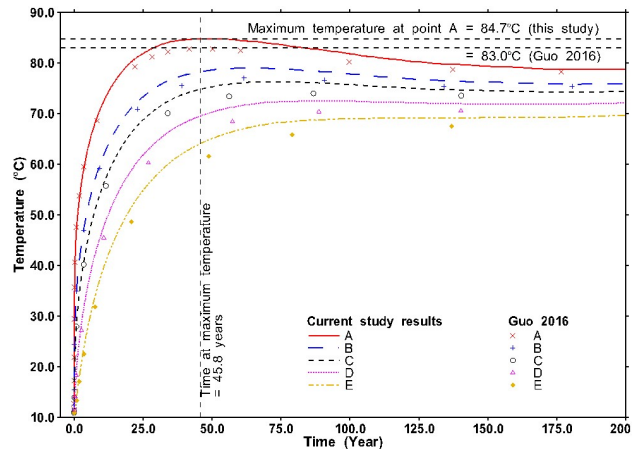


Figure 4. Temperature history at different locations (A to E shown in Figure 2) compared with Guo (2016).

Figure 5 depicts the temperature distribution in the host rock surrounding the room opening at different times from 0 to 100 years.

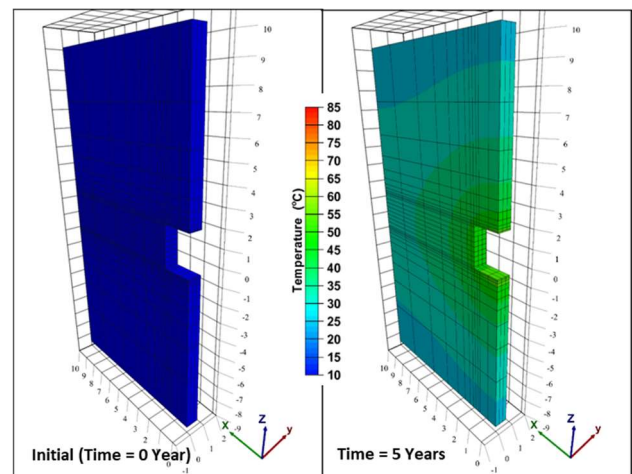


Figure 5a. Near field temperature distribution at 0 and 5 years.

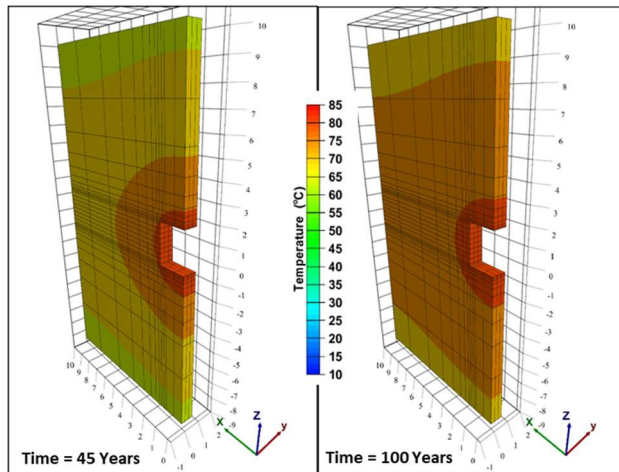


Figure 5b. Near field temperature distribution at 45 and 100 years.

It can be seen from Figure 4 and Figure 5 that the peak temperature at Point B is around 80°C and occurred within a period ranging from 50 to 100 years as compared to the maximum temperature attained within the room (Point A) of 84.7°C at 45.8 years.

### 3.2 Stress-strength ratio

Figure 6 shows the stress-strength ratio at the initial time and at the approximate moment of maximum temperature. A significant reduction in the stress-strength ratio was observed (indicated in blue in Figure 6) demonstrating the severity of the influence thermal stress has on the integrity of host rock; particularly, in close proximity to the DGR where values approach unity (i.e. failure). A reduction of this magnitude can have damaging effects on the host rock as it changes its properties (e.g. permeability) in the region immediately adjacent to the room and outwardly extending to approximately one metre.

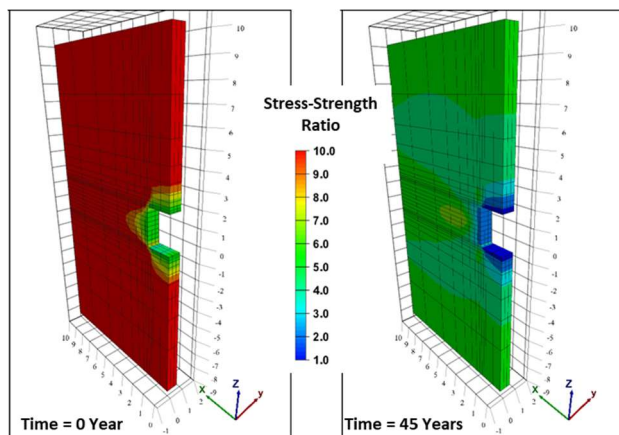


Figure 6. Stress-strength ratio at 0 and 45 years.

## 4 CONCLUSIONS

Thermal response and changes in the stress-strength ratio due to near field thermal stresses caused by a DGR were modelled using FLAC3D as a preliminary investigation and precursor to more complicated future work. The model covered simulated a period of only 200 years by assuming the maximum temperature occurs within this time frame. Temperature development was in good agreement with similar work performed by others using equivalent model constraints and conditions solved using other computer codes producing a maximum temperature of 84.7°C. The thickness of the rock subjected to significant thermally induced damage and reduction in the stress-strength ratio was not more than one metre.

Further studies are required including the investigation of coupled hydraulic processes and changes in host rock permeability and its impact on the overall safety of the system.

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## 5. AKNOWLEGMENTS

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