CALCULATION OF THE THERMAL RESPONSE IN A DEEP GEOLOGICAL REPOSITORY USING THE HORIZONTAL TUNNEL PLACEMENT CONCEPT IN LIMESTONE AT A DEPTH OF 500 M

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ABSTRACT

The Adaptive Phased Management (APM) approach proposed by the Nuclear Waste Management Organization (NWMO) and accepted by the Government of Canada for long term management of Canada's used nuclear fuel includes eventual containment and isolation of the used nuclear fuel in engineered excavations about 500 m deep in plutonic rock or sedimentary rock. The NWMO is evaluating the horizontal tunnel placement (HTP) method for used fuel containers in a deep geological repository (DGR) in sedimentary rock. The approach is similar to the reference NAGRA conceptual design for the Swiss used-fuel/high-level waste repository in sedimentary rock. Some thermal-only or coupled thermal-mechanical simulations are performed using different programs for the near-field modeling. These simulations evaluate the stability of the rock around the placement tunnel for the HTP method in a DGR located at a depth of 500 m in limestone during the excavation stage and after placement of used nuclear fuel. In the near-field modeling, the thermal boundary conditions are based on a dimensionally infinite horizontal repository. The results from these simulations are only considered to be representative for a finite repository for the first 1,000 years after used fuel placement. In order to correct the near-field modeling results to be representative of a DGR of finite horizontal extent, two far-field models (i.e., infinite and finite horizontal extent) are run for the specific repository conditions and dimensions. The thermal results for the volume very near the container from this near-field modeling are modified to represent the results for a finite repository by subtracting the differences between the results from the far-field models for a finite repository and for an infinite repository. The modified results show that the tunnel wall has a peak temperature of 69.6°C at 68 years after placement and a second peak temperature of 71.5°C at 683 years after placement (compared to the original results for second peak temperature 72.5°C at 1,500 years). Modified temperatures for other selected points in the rock along the horizontal line through the container centre are also obtained for one million years to obtain a better estimate of temperature in the near-field of a finite repository.

Key words: Deep geological repository, near-field modeling, far-field modeling, used nuclear fuel, temperature

1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is implementing the Adaptive Phased Management (APM) approach accepted by the Government of Canada [1] for the long-term management of its used nuclear fuel. APM has, as its end point, the containment and isolation of used fuel in a deep repository constructed in a suitable geological formation such as crystalline or sedimentary rocks [2]. Precambrian crystalline rock of the Canadian Shield and Paleozoic sedimentary rock are considered to be potential host geologic media in current Canadian Deep Geological Repository (DGR) concepts.

Sedimentary rock is being studied by some international nuclear waste management organizations (e.g., NAGRA, ANDRA, ONDRAF/NIRAS) as the host medium for their DGRs. NAGRA has proposed a horizontal tunnel placement (HTP) method for a used-fuel/high-level waste repository [3], [4]. A scoping-level investigation was performed by [5] to assess the feasibility of applying a HTP method in a DGR for Canadian used nuclear fuel in representative sedimentary rock formations in Canada.

In order to develop the Canadian capability for modelling using the COMSOL numerical modelling program [6], the latest version at the time of this modelling(COMSOL version 3.5a) is used to assess the thermal response of a used fuel DGR in limestone rock using the HTP method at an assumed depth of 500 m below ground surface.

2. DESCRIPTION OF THE COMSOL PROGRAM

COMSOL is a finite element analysis solver and simulation software package for various physics and engineering applications, especially coupled phenomena or multiphysics.

The heat transfer application mode in the earth science module of COMSOL solves the main governing equation of heat transfer behaviour. Detailed presentation of the governing equations for thermal analysis can be found in the Earth Science Module user guide [6]. In the content of the thermal modeling, the heat transfer control equation is:

$$C \cdot \frac{\partial T}{\partial t} + \nabla(-K \cdot \nabla T) = Q \tag{1}$$

in which C is the specific heat capacity, J/(kg˚C); T is temperature, ˚C; t is time, s; K is the thermal conductivity, W/(m˚C); Q is heat source, W/m^3.

3. DESCRIPTION OF A PROPOSED DGR, MATERIAL PROPERTIES AND SCOPE OF THE ANALYSES

3.1 Description of a proposed DGR

The modelled DGR layout consists of an array of horizontal, circular-shaped placement tunnels with a diameter of 2.5 m (Figure 1). The placement tunnels are connected by access tunnels for moving excavated rock, waste containers and backfilling materials. These tunnels are arranged into eight distinct panels. Four of the panels contain 28 tunnels per panel (spaced at 20 m centre-to-centre) and the remaining four panels contain 27 tunnels each. The tunnels individually hold 50 used fuel containers (UFC). Each container is installed horizontally along the centreline of the placement tunnel at a spacing of 8 m between containers. Each container is 3.909 m long with a diameter of 1.247 m and will accommodate 360 CANDU®[1] fuel bundles. Between the container outer surface and the placement tunnel surface, there is a layer of buffer material composed of bentonite pellets (Figure 2). The container design consists of an outer 25-mm-thick copper corrosion-barrier and an inner, carbon-steel load-bearing component [7]. A DGR has a nominal maximum total capacity of 10,000 UFCs (3,600,000 intact fuel bundles).

[1] CANDU® is a registered trademark of Atomic Energy of Canada Limited.

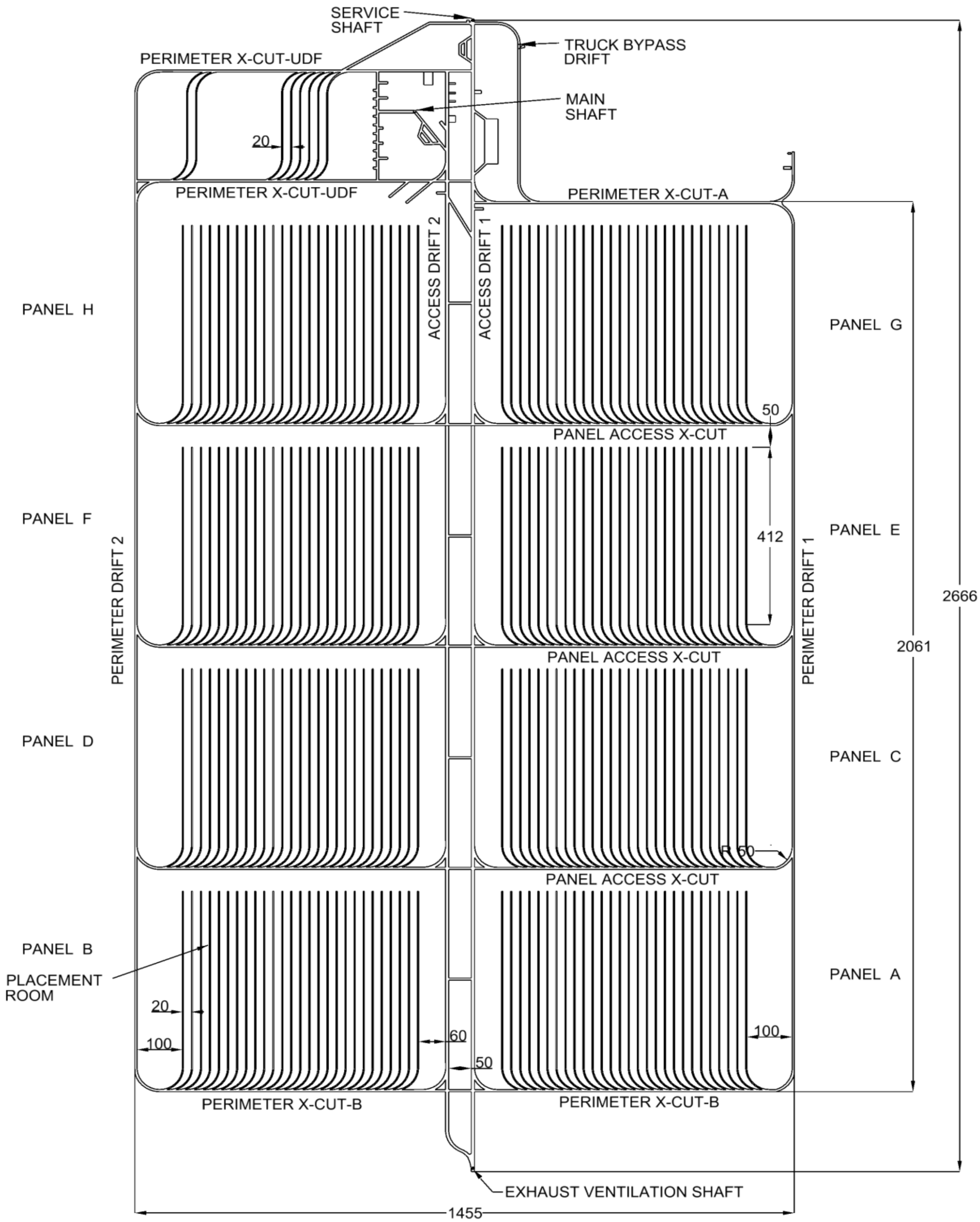

Figure 1. Plan layout of a proposed DGR using the HTP method [8].

For the purposes of this modelling exercise the repository is defined as being located in limestone at a depth of 500 m. The overall dimensions of the UFC placement area in such a repository are 2,061 m by 1,455 m as shown in Figure 1.

3.2 Assumption

As a preliminary modelling for the purpose of a DGR design, each of the materials used in this modelling is assumed to be homogeneous, isotropic, and temperature-independent. The rock mass around the DGR is assumed to be infinite in the horizontal extent.

3.3 Material properties

USED FUEL PROPERTIES

The heat output from the used fuel from each UFC is shown in Table 1. All of used fuel is assumed to undergo an initial cooling period of 30 years in surface facilities prior to placement within the DGR. The DGR model assumes that UFC placement is instantaneous with 30-year-out-of-reactor fuel at the reference conditions.

SEALING-MATERIAL AND USED-FUEL CONTAINER PROPERTIES

Relevant thermal and physical properties of materials are shown in Table 2. The difference of the properties for the highly compacted bentonite pedestal and the bentonite pellets is not considered in this modelling for the purpose of a DGR design. Therefore, both are taken as bentonite sealing material. It is assumed that they have the characteristics of a dry pellet material, which is conservative with regards to thermal characteristics since the pedestal has higher thermal conductivity than the pellets owing to its relative density.

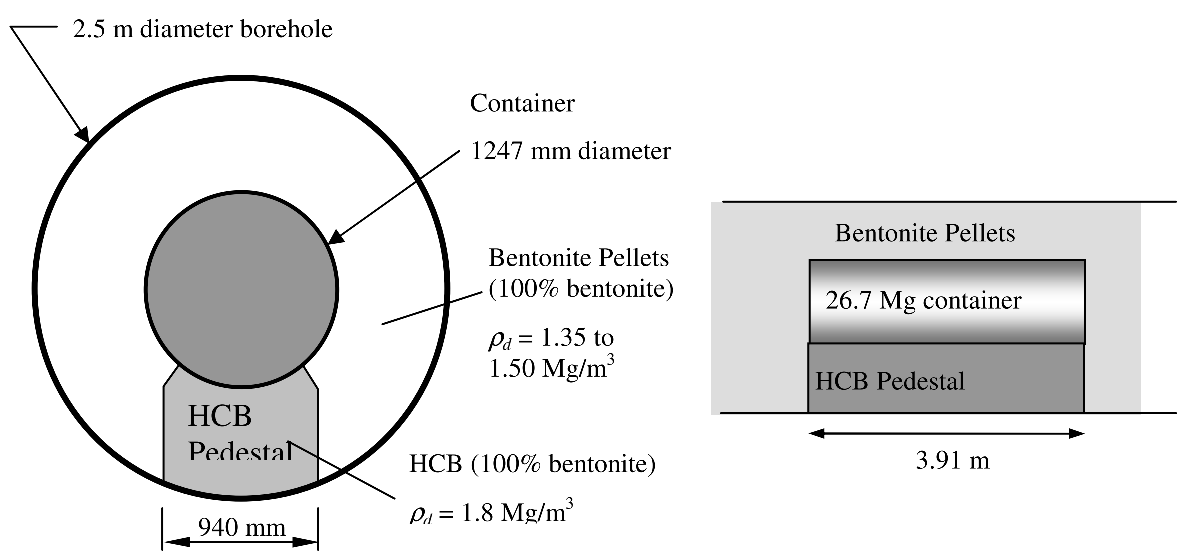

Figure 2. Geometry of the horizontal canister (Container) placement option (Figure provided by NWMO)**.**

Table 1. Heat Output of Containers of Reference Used CANDU® Fuel at Different Times.

Time Out-of-reactor (years)	Heat Generation (220 MWh/kg U Burn-up)			
	Watts per kg U	Watts per bundle	(W/container) (360 bundles)	Heat density (W/m^3) of container
30	1.83E-01	3.52	1268.2	265.6396
35	1.68E-01	3.23	1164.2	243.8659
40	1.54E-01	2.97	1069.2	223.5437
45	1.42E-01	2.74	986.4	206.1247
50	1.32E-01	2.53	910.8	191.6089
55	1.22E-01	2.35	846.0	177.0931
60	1.14E-01	2.19	788.4	165.4804
70	9.91E-02	1.908	686.9	143.8518
75	9.30E-02	1.791	644.8	134.9972
80	8.75E-02	1.685	606.6	127.0135
90	7.82E-02	1.505	541.8	113.5138
100	7.07E-02	1.361	490.0	102.6269
110	6.47E-02	1.245	448.2	93.91739
135	5.41E-02	1.041	374.8	78.53061
150	4.99E-02	0.96	345.6	72.43397
160	4.77E-02	0.918	330.5	69.24049
200	4.19E-02	0.806	290.2	60.82131
300	3.55E-02	0.684	246.2	51.53118
500	2.91E-02	0.56	201.6	42.24105
1,000	2.02E-02	0.388	139.7	29.32197
2,000	1.38E-02	0.265	95.40	20.03184
5,000	1.00E-02	0.1926	69.34	14.51582
10,000	7.19E-03	0.1385	49.86	10.43688
20,000	4.16E-03	0.0801	28.84	6.038583
35,000	2.27E-03	0.0437	15.73	3.295092
50,000	1.43E-03	0.0274	9.864	2.075763
100,000	4.41E-04	0.00849	3.056	0.640148
200,000	1.65E-04	0.00317	1.141	0.239511
250,000	1.52E-04	0.00293	1.055	0.220641
500,000	1.48E-04	0.00285	1.026	0.214834
1,000,000	1.48E-04	0.00285	1.026	0.214834

Table 2. Thermal and physical properties of materials.

Property	Container	Limestone	Bentonite
Thermal conductivity (W/(m˚C))	300	2.3	0.4
Specific heat (J/(kg˚C))	500	830	920
density (kg/m^3)	7800	2600	1410
Geothermal gradient (˚C/m)	NA	0.16	NA

4. NEAR FIELD MODELLING

4.1 Geometry

Figure 3 shows the dimensions of the COMSOL near-field model unit cell, which involves three fundamental component materials, namely rock, buffer and container. All of the rock materials are considered to be limestone. The depth of the crown of the placement tunnel is 500 m. The vertical dimension of the model unit cell is 5,000 m and the horizontal dimensions of a unit cell are 10 m in length and 4 m in width (10 m is a half of the placement tunnel spacing and 4 m is a half of the container spacing). In the COMSOL model, only one quarter of the container is included.

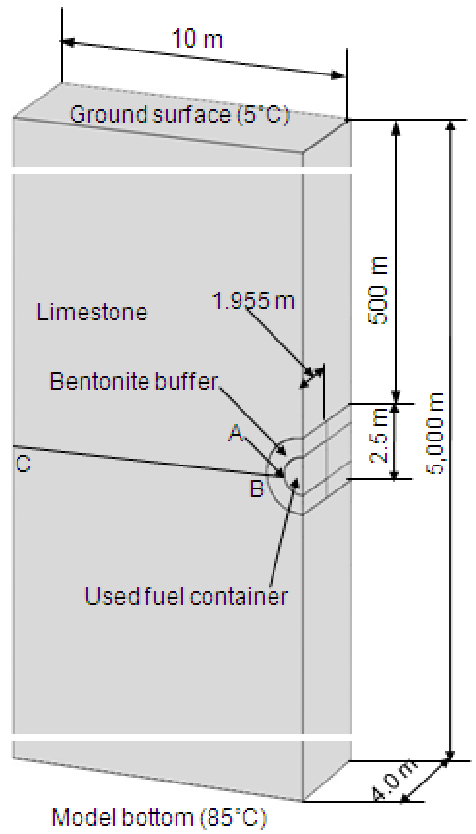

Figure 3. Geometry and dimensions of the near-field model.

4.2 Boundary conditions and initial conditions

Thermal boundary conditions for the model configuration shown in Figure 3 are as follows:

- The temperature on the model's top surface (ground surface) is 5˚C.
- An isothermal condition is applied at the bottom of the model (i.e., 5,000 m below ground surface) at a temperature of 85˚C.
- An adiabatic condition is applied on the four vertical surfaces of the model due to mirror symmetry, which represents the thermal conditions associated with this unit cell within an infinite tabular array of placement tunnels.

- A uniform thermal heat density as shown in Table 1 is applied on the container.

The thermal boundary conditions described above represent boundary conditions for a unit cell in a horizontally infinite repository. Based on the study by [9], the results from the near-field model using the above boundary are accurate for a horizontally finite repository only for the first 1,000 years. After 1,000 years, several degrees of error are developed [9] if the results for a horizontally finite repository are used.

Initial Conditions: Initial boundary conditions are as follows. The initial ambient temperature of the model is based on the geothermal gradient 0.016˚C/m of depth and a ground surface temperature of 5˚C resulting in an ambient temperature of 85˚C at the bottom of the model (i.e., at a depth of 5,000 m).

4.3 Thermal results from the near-field thermal model

The results of the thermal analyses done using the geometry in Figure 3 are shown in Figures 4 and 5. Figure 4 illustrates the calculated temperatures at different locations along the horizontal line ABC. The temperature on the container surface (point A) reaches a peak of 117.4˚C at 10 years after waste placement. The peak temperature on the surface of the tunnel (point B) is 69˚C at 50 years. The temperature at horizontal limit of the model unit cell (point C) achieves a peak of 70.5˚C around 3,500 years following placement. Figure 5 shows the simulated temperature versus distance from the tunnel axis along the horizontal line ABC at five different times. After 1,000 years, the temperature in the rock is uniform at a value of 71~72˚C.

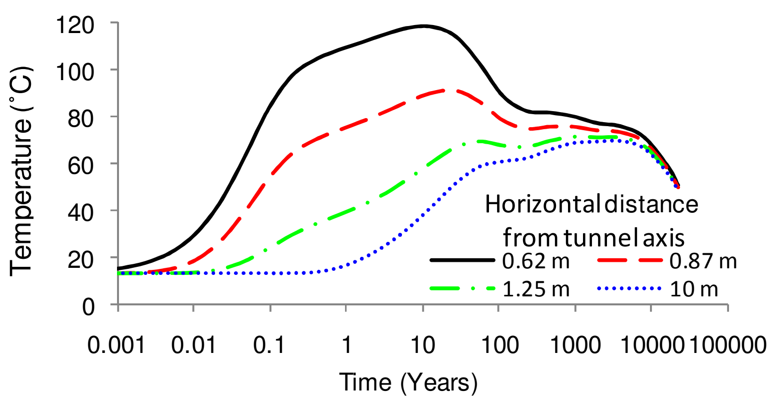

Figure 4. Temperatures versus time at different distances from the tunnel axis along the horizontal line ABC.

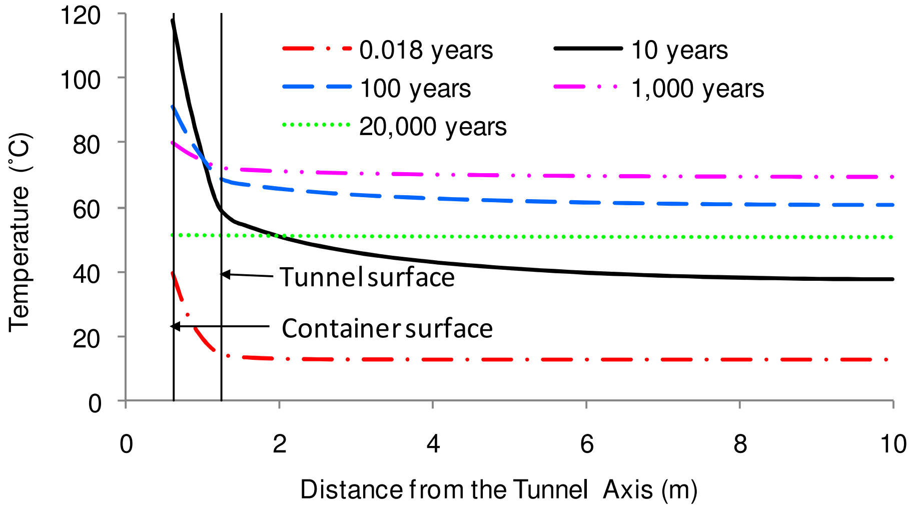

Figure 5. Temperatures versus distance from tunnel axis along the horizontal line ABC (see Figure 3 for location) at five different times.

5. INFLUENCE OF FINITE VERSUS HORIZONTALLY INFINITE REPOSITORY MODEL ON THE CALCULATED THERMAL RESPONSE

In order to examine the influence of thermal boundary conditions on the near-field modelling, two far-field models are simulated, one with a finite-dimension repository and the other with a horizontally infinite repository. These analyses are performed using the far-field model rather than the near-field model because it is not practical to expand the near-field unit cell to the scale of the entire repository.

Figure 6 illustrates the model geometry with a finite repository, in which the thermal load corresponds to the initial panel thermal load (IPTL). The IPTL is defined as the localized initial heating rate at the time of container emplacement without the effect of the nonheating areas of the repository. The IPTL is used in these analyses because this heat load is appropriate for the near-field modelling and the results of these analyses are used to propose a correction to the near-field modelling. In order to make the total thermal load the same as the load in Figure 1, the dimensions of the repository are reduced from those of the model shown in Figure 1, which is used for far-field modelling [10]. Therefore, the horizontal dimensions of one quarter of the repository are 754 m x 530 m due to symmetry. The horizontal dimension of the model is 5,000 m and the vertical dimension is 10,000 m.

The upper surface boundary condition is modelled as an isothermal boundary, with a temperature of 5°C, representing the annual average ground surface temperature. The lower boundary is also modelled as an isothermal boundary with a temperature of 165°C, such that a geothermal gradient of 0.016°C/m of depth is achieved in the absence of a repository. The vertical outer boundaries of the model are modelled as adiabatic planes of symmetry.

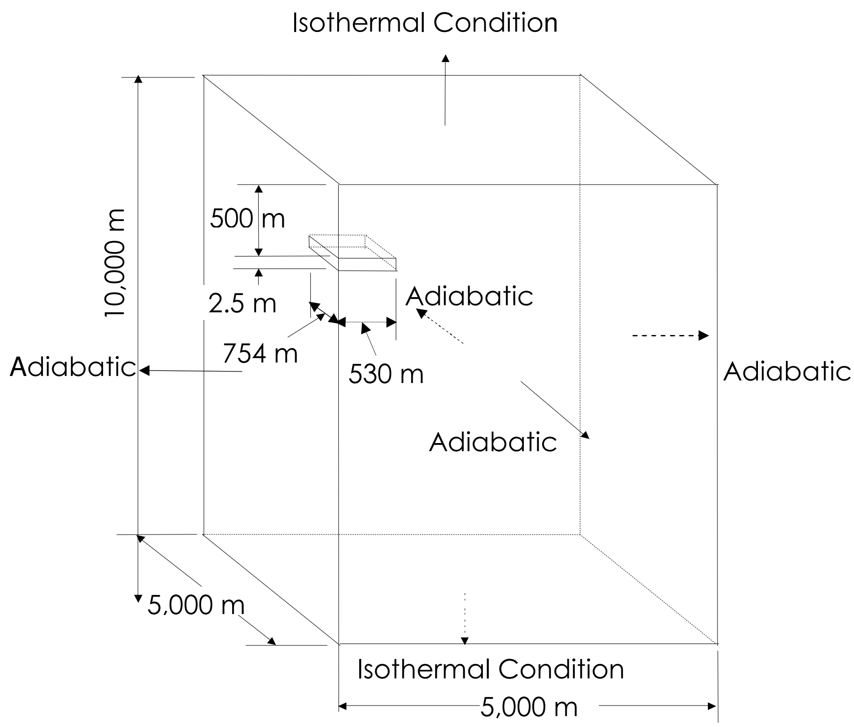

Figure 6. Model geometry for a finite repository with the same total thermal load without considering the auxiliary unheated spaces.

Figure 7 shows the model geometry with a horizontally infinite repository, in which the thermal load corresponds to the IPTL. The horizontal dimensions of the repository are 5,000 m x 5,000 m and the thermal boundary conditions and initial conditions are the same as those for the model shown in Figure 6.

A comparison of the temperature at the centre of the finite repository and a horizontally infinite repository is shown in Figure 8. For the first 1,000 years, there is no obvious difference between the two models. After 1,000 years, the difference between the two models increases until 15,000 years after waste placement, at which time the difference peaks at 17°C. After 15,000 years, the difference decreases as the temperatures from both models converge to the ambient temperature.

Temperature differences along the vertical line through the repository centre between a horizontally infinite repository model and a finite repository model are shown in Figure 9. Using the boundary conditions for a horizontally infinite repository model as those for a finite repository model not only influences the peak temperatures in the host rock around the repository but also influences the temperature of the rock at depth.

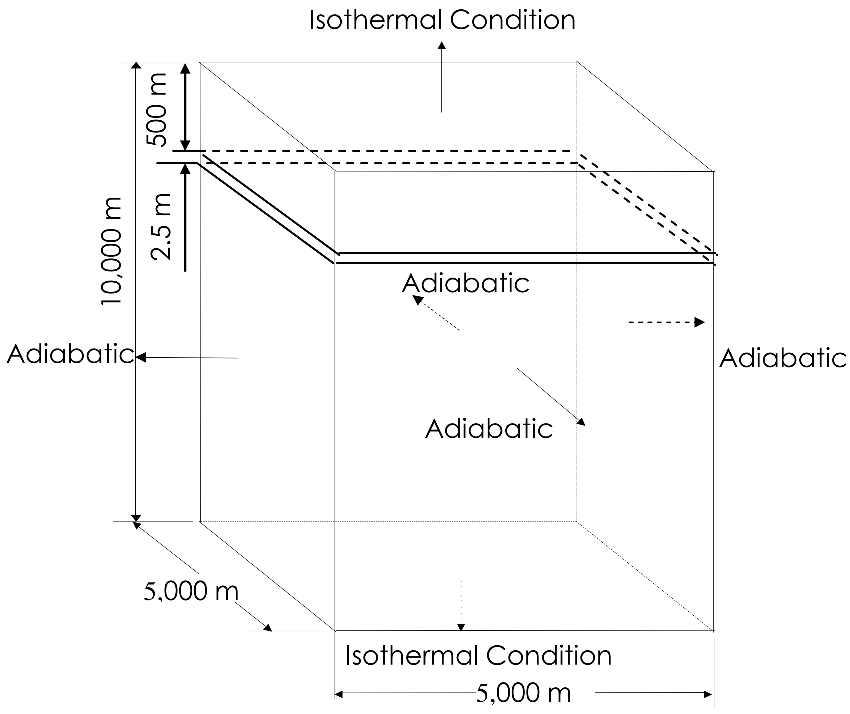

Figure 7. Model geometry for a repository with infinite horizontal dimensions and the same density of thermal load as a repository with a finite horizontal repository.

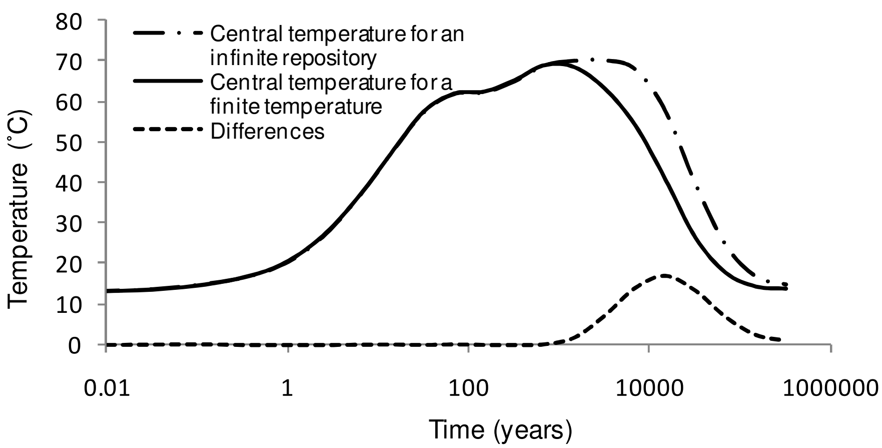

Figure 8. Comparison of the central temperature between a finite repository and a horizontally infinite repository and their difference.

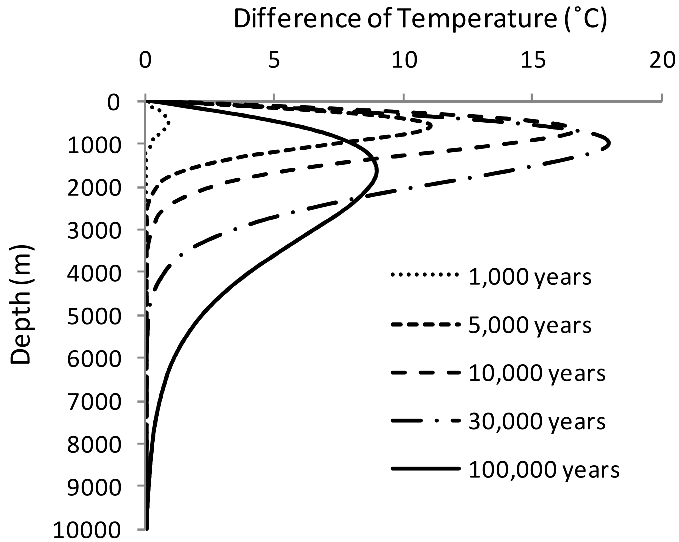

Figure 9. Temperature differences along the vertical axis of the repository between using a horizontally infinite repository model and a finite repository model.

6. MODIFIED NEAR-FIELD THERMAL RESPONSE

The previous section describes modelling that is performed to determine the difference in temperature between a finite repository and a horizontally infinite repository. The temperature differences at the centre of the repository are shown in Figure 8. Since the temperature at all locations at the repository depth are within a few degrees of each other 1,000 years after waste placement, and since these temperatures are close to the temperature at the centre of a horizontally infinite repository, then the same temperature can be subtracted from the temperatures at all locations. Subtracting the temperature difference shown in Figure 8 from temperatures at all locations will result in all these temperatures being representative of the those in a finite repository with a thermal load equal to the IPTL [9]. For times before 1,000 years, the temperature difference in Figure 8 is near zero. Although this may not be a rigorously correct approach for modelling the near-field in a finite repository, it will provide reasonable temperature predictions at the repository depth.

Figure 10 illustrates a comparison of the results using the modified and original approaches at four different locations along a horizontal line of ABC in a finite repository using a thermal load corresponding to the IPTL (refer to Figure 3 for locations). The modified results are obtained by subtracting the differences shown in Figure 8 from the results of the near-field modelling where the temperature is defined as being uniform 1,000 years after waste placement. Figure 10 shows that the temperature at different locations approaches uniformity. The maximum temperature of the container surface predicted using the modified temperature assumptions is 117°C at 6.8 years and 69°C at 3,200 years after waste placement. The modified temperature at Point B has exhibits a first peak value of 69.6°C occurring 68 years after waste placement and a second peak value of 71.5°C occurring approximately 683 years after waste placement.

Figure 11 shows the modified near-field temperatures along the horizontal line ABC, compared to the originally predicted temperatures at the same locations. During the first 1,000 years after waste placement, the modified temperatures are the same as the original temperature from the near-field modelling. The modified temperatures have a significant difference from the original temperatures after 1,000 years of waste placement, but they are very uniform.

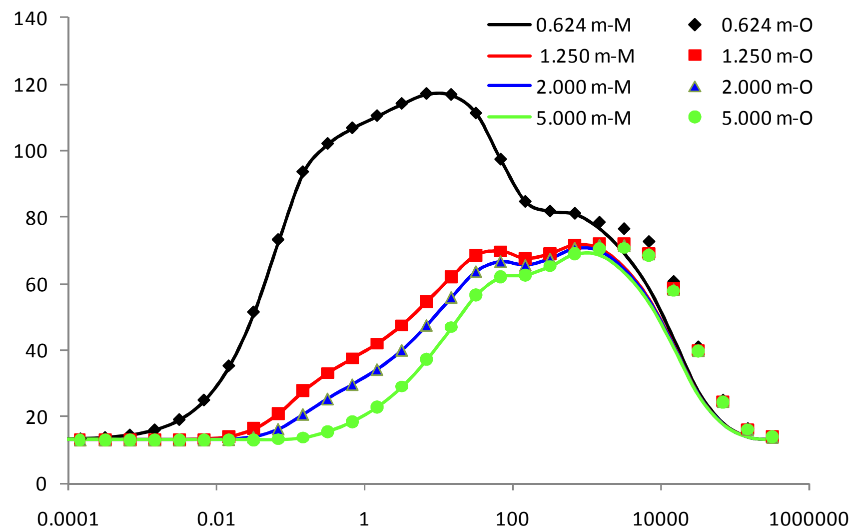

Figure 10. Comparison of original and modified near-field temperatures at four different locations for a finite repository (In the legend: -M is modified, -O is original).

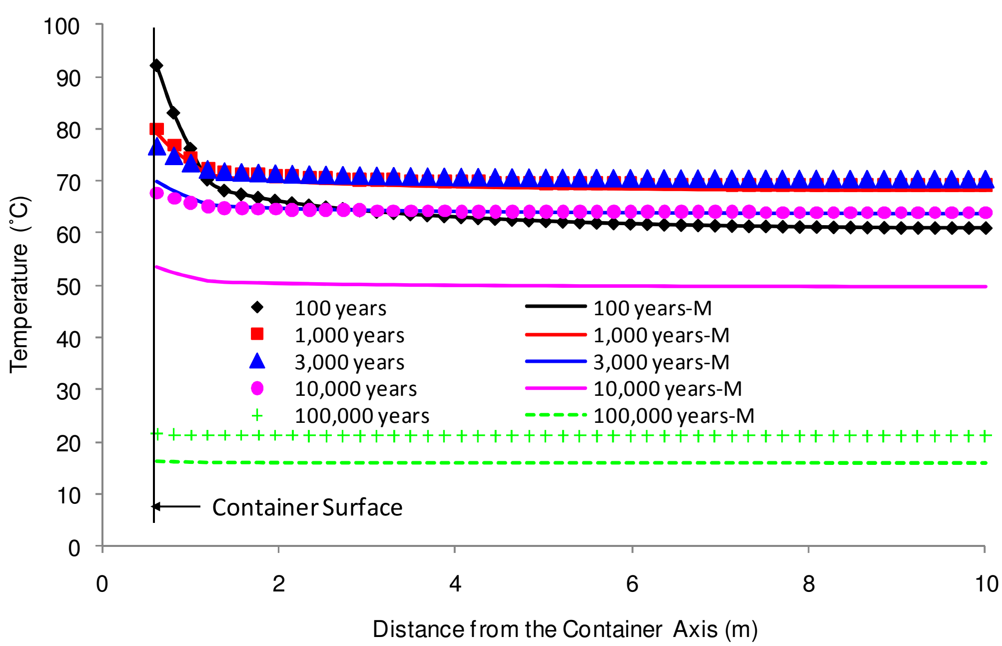

Figure 11. Original and modified temperature profiles along the horizontal line ABC at different times (see Figure 3 for locations) (In the legend: -M is modified)

7. CONCLUSIONS

A series of three-dimensional finite-element, thermal transient analyses is performed to gain a better understanding of the thermal behaviour of the rock mass in the near-field of a radioactive waste repository using an HTP method.

A thermal far-field model is established for a smaller repository with horizontal dimensions of 754 m x 530 m (for one quarter of a DGR), having the same total thermal load as the larger DGR for far-field modelling. In this model, the thermal load density is equivalent to the IPTL, while the load in the far-field analysis is equivalent to the initial gross thermal load (IGTL), which is defined as the localized initial heating rate at the time of container emplacement with the effect of the non-heating areas of the repository. The smaller DGR represents the dimensions of the larger DGR with the non-heat-generating area removed. A third thermal far-field model with the same thermal load density as the smaller DGR (i.e., the IPTL) is established to represent a horizontally infinite repository. The comparison of the thermal results between the two far-field models indicates that the peak difference of the temperatures between the two models is 17°C approximately 15,000 years after waste placement. At the centre of the repository, the results derived from two models are the same for the first 1,000 years after waste placement, indicating that the results from near-field modelling using the boundary conditions that represent a repository with infinite horizontal extent can be used to determine the temperature results for a finite repository for this period.

A near-field model (i.e., a model for a repository of infinite horizontal extent) is used to simulate the temperatures for 1,000,000 years following waste placement. The thermal results for the volume very near the container from this near-field modelling are modified to represent the results for a finite repository. This modification is performed by subtracting the differences between the results from the far-field models for a finite repository and for an infinite repository. The modified results show that the container surface develops a peak temperature of 117°C at 6.8 years after waste placement and a second peak temperature of 69°C at 3,200 years after waste placement. Modified temperatures for other selected points near the container are also determined for a million years following placement in order to obtain a better estimate of temperature in the near-field of a finite repository. To correct the near-field modelling results (i.e., for a DGR with infinite horizontal extent) so that they are representative of a DGR of finite horizontal extent, the two far-field models (i.e., infinite and finite horizontal extent) must be run for the specific repository conditions and dimensions.

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