〈Technical Note〉

DEPTH AND LAYOUT OPTIMIZATIONS OF A RADIOACTIVE WASTE REPOSITORY IN A DISCONTINUOUS ROCK MASS BASED ON A THERMOMECHANICAL MODEL

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The objective of the present study is the depth and layout optimizations of a single layer, high level radioactive waste repository in a discontinuous rock mass with special joint set arrangements. A single layer repository model, considering variations in the repository depths, pitches, and tunnel spacings, is used to analyze the thermomechanical interaction behavior. It is assumed that the repository is constructed in saturated granite with joints; the PWR spent fuel in a disposal canister is installed in a deposition drift which is then sealed with compacted bentonite; and the backfill material is filled in the repository tunnel. The decay heat generated by the high level radioactive wastes governs the thermomechanical behavior of the near field rock mass of the repository. The temperature and displacement behavior of the repository is influenced more by the pitch variations than the tunnel spacing and repository depth. However, the stress behavior is influenced more by the repository depth variations than the pitch and tunnel spacing. For the final selection of the tunnel spacing, pitch, and repository depth, other aspects such as the nuclide migration through a groundwater flow path, construction costs, operation costs, and so on should be considered.

KEYWORDS : Radioactive Waste Repository, Granite, Thermomechanical Behavior, PWR Spent Fuel, Decay Heat, Bentonite

1. INTRODUCTION

The principle of a deep geological disposal is to isolate the heat generating radioactive wastes from the biosphere using multiple barriers. A rock mass is one of the most important isolation barriers, with granite being the most common and most important repository host rock.

State-of-the-art studies on various coupled processes for rock joints are summarized [1]. The distinct element method has been used to analyze the behavior of the fractured rock masses in a radioactive waste repository to model the coupled thermal and mechanical behaviors [2]. For studying the coupled hydraulic and thermal behavior, the effect of the decay heat emitted from high level radioactive wastes on the groundwater flow around the repository has been studied by many researchers [3, 4]. Hart [3] presented a model that fully describes coupled thermal, hydraulic, and mechanical behaviors in nonlinear porous geological systems using the explicit finite difference method. Kim [5] presented a numerical model to understand the long term thermomechanical interaction behavior on joints adjacent to a high level radioactive waste repository in a saturated and discontinuous granitic rock mass using the distinct element method.

The objective of the present study is the depth and layout optimizations of a single layer repository in a discontinuous rock mass with special joint set arrangements. This optimization will be an important factor of the design and safety evaluation of a disposal system, as well as a key issue in the development of a high level radioactive waste disposal in Korea.

2. REPOSITORY MODEL

The single layer repository model used in this study consisted of multiple tunnels in parallel with each tunnel being equally spaced. Each tunnel was 250 m long, 5 m wide, and spaced at either 30 m or 40 m apart, with a vertical wall height of 4.65 m and an arch shaped roof of 6.15 m above the tunnel floor. Vertical deposition drifts of 7.83 m in depth were located below the tunnel floor along the tunnel at a distance (pitch) of either 6 m or 8 m.

The material properties of the granitic rock mass,

Table 1. Mechanical and Thermal Properties of Granite, Compacted Bentonite, Backfill Material, and Canister Cast iron Insert

Parameter	Granite	Compacted bentonite	Backfill material	Canister cast iron insert
Density, kg/m^3	2650.0	1970.0	2270.0	7200.0
Bulk modulus, GPa	35.45	3.5	0.083	135.0
Shear modulus, GPa	18.28	0.75	0.091	62.0
Thermal conductivity, W/mC	3.2	1.0	2.0	52.0
Thermal expansion coefficient, 1/°C	8.3E-6	1.0E-6	8.3E-6	8.2E-6
Specific heat, J/kg °C	815.0	1380.0	1190.0	504.0
Friction angle, °	35.0	10.0	6.0	-
Cohesion, MPa	30.4	1.1	0.53	-
Dilation	8.0	5.0	0.0	-

Table 2. Mechanical Properties of Joint Sets

Parameter	Joint set 1	Joint set 2
Joint normal stiffness, GPa/m	450	550
Joint shear stiffness, GPa/m	480	500
Joint cohesion, MPa	0.1	0.3
Joint dilation, °	0	0
Joint aperture, mm	2.5	1
Joint permeability, 1/(Pa*sec)	3	1
Joint residual aperture, mm	0.05	0.05
Joint roughness coefficient	5	7
Joint compressive strength, MPa	30	30
Residual angle of friction, °	28	30
Insitu compressive strength, MPa	200	200

joints, compacted bentonite, backfill material, and canister cast iron insert are listed in Tables 1 and 2. The ground water table was assumed to be 10 m beneath the ground surface; its density was also assumed to vary from 1000 kg/m^3 at the ground temperature of 0°C to 800 kg/m^3 at 100°C.

The top and bottom boundaries of the model were selected to be sufficiently far from the heat generating waste. The horizontal displacements on the vertical boundaries and the vertical displacements on the bottom boundary were fixed; however, the vertical and bottom boundaries were free of tangential traction. The thermal boundary conditions were adiabatic on the vertical boundaries and horizontal boundaries of the model, and a constant temperature of 15°C was maintained on the ground surface. From the ground surface, the temperature distribution was assumed to increase by 0.6°C every 20 m in depth. There were two joint sets in the repository model: joint set 1 includes the primary joints throughout the entire repository model, while joint set 2 consists of the secondary joints near the repository.

Due to the symmetry of the repository layout of multiple tunnels in parallel with equal shapes, lengths, and spacings, the central tunnel of the repository was selected as the model for this study of thermomechanical interaction behavior. The vertical length of the model was assumed to be 1500 m, which is sufficiently far from the influence of the decay heat, and the width was either 30 m or 40 m. Six different repository models with repository tunnels located at 200 m, 300 m, 400 m, 500 m, 600 m, and 700 m below the ground surface were studied and compared (see Figures 1, 2, and 3). Due to the symmetry of the model, only half of the model was used in the analysis and symmetric boundary conditions were used.

There were four assemblies of pressurized water reactor (PWR) spent fuels in a canister with each assembly weighing 0.442 ton. The spent fuels that had already been cooled for 40 years were placed in a hollow corrosion resistant cylindrical canister, and then fixed with a cast iron insert between the fuel assemblies and the canister. Each canister containing spent fuels was placed at each deposition drift, which was filled with compacted bentonite.

The spent fuels in the canisters generated decay heat through the radioactive decay process. The generated decay heat can influence its surroundings, such as the canister, bentonite, backfill materials, ground water, adjacent rock mass, and biosphere. Therefore, the behavior of the repository system should be analyzed for the generated decay heat, H(T) in W/tHM, which was obtained

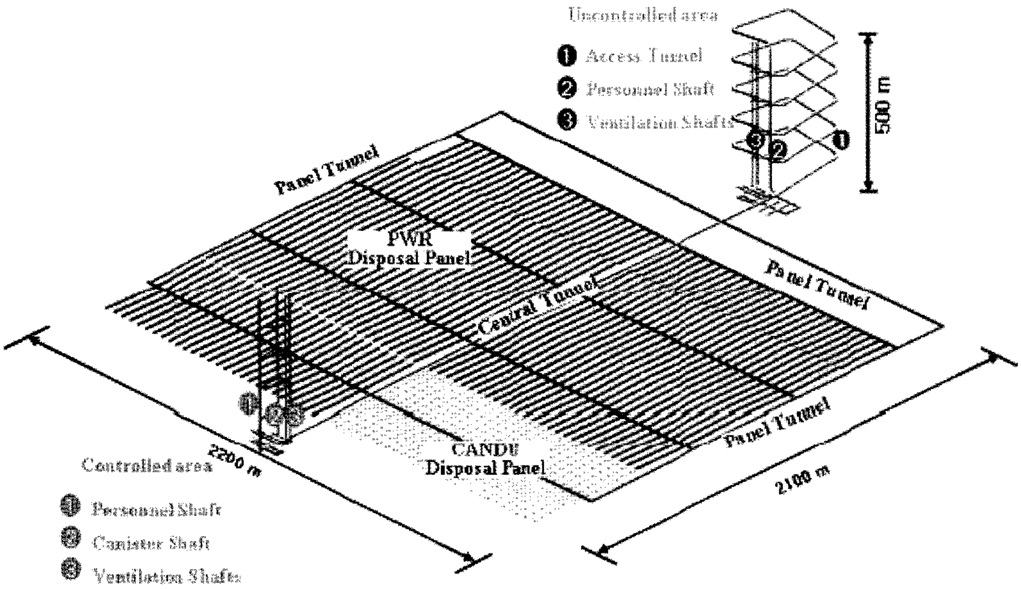


Fig. 1. A single Layer High Level Radioactive Waste Repository at a Depth of 500m Underground

using the experimental data [6]:

$$H(T) = 2201169 \cdot e^{-5.205T} + 1693.22 \cdot e^{-0.018T} + 124.7 \cdot e^{-0.00058T} + 19.134 \cdot e^{-0.0000042T} + 1.429 \cdot e^{-0.000001T}, \quad (1)$$

where T is the time in years after discharging the PWR spent fuels: $0 \leq T \leq 10^6$ years. The PWR spent fuels were cooled for a period of 40 years before disposal in the repository. Then, after shifting the origin to 40 years, the decay heat, H'(T') in W/tHM, is as follows:

$$H'(T') = 824.179 \cdot e^{-0.018T'} + 121.84 \cdot e^{-0.00058T'} + 19.102 \cdot e^{-0.0000042T'} + 1.429 \cdot e^{-0.000001T'}, \quad (2)$$

where T' is $0 \leq T' \leq 10^6$ years, approximately.

It was assumed that the discrete waste locations were distributed uniformly along the disposal tunnel in order to implement a two dimensional approximation. This means that a heat generating trench was located below the tunnel floor and followed the disposal tunnel. The tributary heating area was 7500 m^2 or 10,000 m^2, which is equal to the tunnel length (250 m) multiplied by the tunnel spacing (30 m or 40 m). The decay heat, S_c in W/m^2, is obtained by:

$$S_c = \frac{nu}{ps} H'(T'), \quad (3)$$

where n is the number of spent fuel assemblies in a canister, u is the weight of an assembly, p is the pitch, which is the distance between two adjacent deposition drifts, and s is the tunnel spacing.

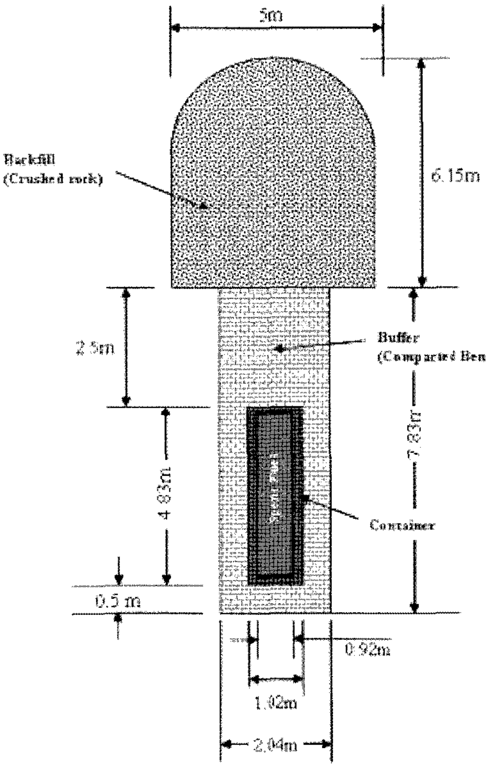
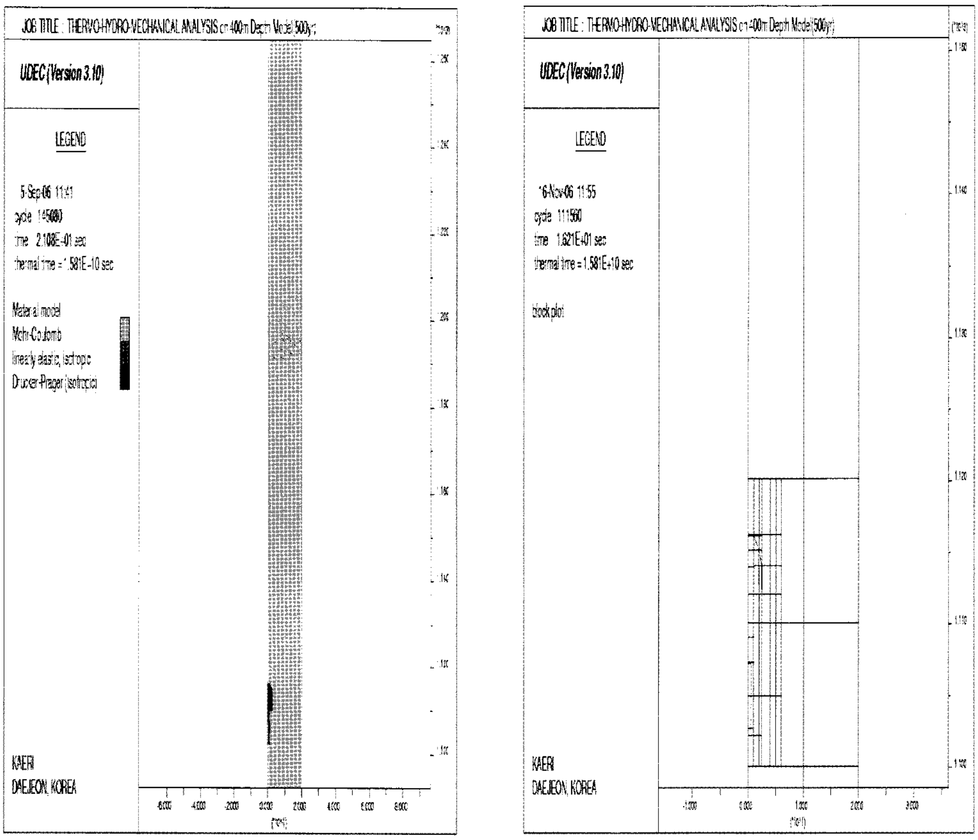


Fig. 2. A Repository Tunnel and a Deposition Drift with Spent Fuels in a Canister



(a) (b)

Fig. 3. (a) A Two Dimensional, Single Layer High Level Radioactive Waste Repository Model, and (b) An Enlarged View of the Repository Model

The heat flux, F in W/m^2, is then obtained by:

$$F = \frac{L}{2p} \cdot \frac{nu}{l(L-e)} H'(t), \tag{4}$$

where L is the length of the tunnel, t is the time in seconds after discharging the spent fuels ($0 \leq t \leq (3.1536E7)(10^6)$ seconds), e is the sum of the tunnel end offsets, which are the distances between both ends of the tunnel and the nearest deposition drifts, and l is the length of the fuel assembly.

The heat flux, F, for the model with a pitch of 6 m and a tunnel spacing of 30 m or 40 m is given as:

$$F = 31.484 \cdot e^{-(5.708E-10) \cdot t} + 4.654 \cdot e^{-(1.839E-11) \cdot t} + 0.730 \cdot e^{-(1.332E-12) \cdot t} + 0.055 \cdot e^{-(3.171E-14) \cdot t}, \tag{5}$$

and for the model with a pitch of 8 m and a tunnel spacing of 40 m:

$$F = 23.572 \cdot e^{-(5.708E-10) \cdot t} + 3.485 \cdot e^{-(1.839E-11) \cdot t} + 0.546 \cdot e^{-(1.332E-12) \cdot t} + 0.041 \cdot e^{-(3.171E-14) \cdot t}, \tag{6}$$

where the heat flux, F, is in W/m^2 and $0 \leq t \leq (3.1536E7)(10^6)$ seconds.

A single repository model, considering the variations of the repository depth, pitch, and tunnel spacing, was used to analyze the thermomechanical interaction behavior of the repository. The two dimensional universal distinct element code, UDEC [7], was used for the analysis. Four different stages of the model, namely, the stages before tunnel excavation, after tunnel excavation, after waste emplacement, and a long time period after waste emplacement, were analyzed and compared.

The tunnel excavation, waste emplacement, and backfill material filling were all assumed to be performed instantaneously, and the initial horizontal stress was assumed to be equal to the initial vertical stress in the analysis. The granitic rock mass was assumed to be homogeneous and isotropic with an elastoplastic behavior (Mohr-Coulomb failure criteria), and the bentonite and backfill material were regarded as elastoplastic materials (Drucker-Prager failure criteria). The canister material was assumed to be homogeneous, isotropic, and linearly elastic. The Barton-Bandis joint constitutive model, a non-linear joint model, was used for the rock joints.

The heat transfer was assumed to occur through conduction. The effect of the heat transfer through convection and radiation was negligible compared with the effect through conduction within the rock mass. The basic equation of conductive heat transfer is Fourier's law:

$$Q_x = -k_x \frac{\partial T}{\partial x} \quad \text{and} \quad Q_y = -k_y \frac{\partial T}{\partial y}, \tag{7}$$

where Q_x and Q_y are the respective fluxes in the x- and y-directions (W/m^2); k_x and k_y are the thermal conductivity in the x- and y- directions (W/m °C), respectively; and T is the temperature.

The change of the temperature for any mass in a two dimensional heat transfer is given as follows:

$$\frac{\partial T}{\partial t} = \frac{1}{C_p \rho}\left(\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y}\right), \tag{8}$$

where C_p is the specific heat (J/kg °C), and ρ is the mass density.

Combining equation (8) with equation (7),

$$\frac{\partial T}{\partial t} = \frac{1}{C_p \rho}\left(k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2}\right). \tag{9}$$

This equation(9) is the standard two-dimensional heat diffusion equation.

The stress is changed due to the temperature changes in equation (9) as follows :

$$\Delta\sigma_{ij} = -3\ \delta_{ij} \cdot k^* \cdot \alpha \cdot \Delta T, \tag{10}$$

where $\Delta\sigma_{ij}$ is the change in stress at ij; δ_{ij} is the Kronecker delta function; k^* is the K for a plane strain and 6 K G / (3K + 4G) for a plane stress, where K is the bulk modulus and G is the shear modulus; α is the linear thermal expansion coefficient; and ΔT is the temperature change. Although mechanical changes cause temperature changes as the energy is dissipated in a system, this effect is usually negligible.

The decay heat generated in the underground repository spreads throughout the surrounding rock mass, consequently causing the rock mass to expand. In general, the heat transfer through the rock mass is dominated by a conduction process. The restriction of the expansion by the surrounding rock results in thermally-induced mechanical stresses; the thermally-induced stress field, in addition to the in situ and excavation-induced stresses, causes normal and shear displacements in the rock joints. Additional displacements increase the potential of failures in the rock mass resulting from excessive joint shear displacement. The thermally-induced stress may also cause microcracks in the rock mass, which can reduce the stiffness of the rock and may lead to the formation or extension of a fractured network through coalescence and further propagation of individual microcracks. The mechanical processes are thought to influence the thermal processes primarily by changing the fracture apertures, hence changing the effective thermal conductivity [1]. This coupling effect is not considered in this study.

3. DEPTH AND LAYOUT OPTIMIZATIONS

A single layer, high level radioactive waste repository in a discontinuous rock mass with special joint set arrangements was analyzed to perform depth and layout optimizations. This model, considering variations of the repository depth, pitch, and tunnel spacing, was used to analyze the thermomechanical interaction behavior. Four different stages were considered in the thermomechanical analysis: before excavation, after excavation, after waste emplacement, and a long time period after waste emplacement.

3.1 Optimization

Three repository models, STM630, STM640, and STM840, were analyzed for their thermomechanical interaction behaviors for a period of 500 years from waste emplacement. The STM630 and STM640 models were single layer repository models with a pitch of 6 m and a tunnel spacing of 30 m and 40 m, respectively. In the STM840 model, the pitch and tunnel spacing were 8 m and 40 m, respectively.

In all models studied, the in situ stresses were calculated and then used in the next analyses, but the calculated displacements were reset to zero before the next analyses. After the instantaneous excavation, the stresses were concentrated near the repository, and the repository periphery showed large deformations toward the excavated area. The stress and displacement behavior

Table 3. Vertical Displacement and Maximum Principal Stress in 4 Different Stages in the Model, STM630, of 500m Depth

Stages	Vertical displacement at the crown of the tunnel, cm	Max. principal stress at the rock below the canister, MPa
Initial stage	0.005	12.6
After excavation	0.167	18.3
After waste emplacement	1.1	18.3
500 years after disposal	16.3	73.5

near the repository were not significant in magnitude in the initially undisturbed stage, the stage after excavation, and the stage after waste emplacement when compared with the stress and displacement behavior for the stage after a long time period after waste emplacement (as shown in Table 3). Therefore, the thermomechanical interaction behavior in the stage of a long time period after waste disposal was analyzed further. Thus, the remainder of this section details this analysis.

The results for the temperature, displacement, and stress behavior near the repository for the stage after a long time period after waste emplacement are shown in Figures 4 to 9 and in Tables 4 to 12. The maximum temperatures at the canister surface of the various models with different depths, pitches, and tunnel spacings, which were reached after 30 to 40 years after waste emplacement, range from 75.9°C to 122.0°C and are shown in Figure 4 and Table 4. For a 500-year period, the temperature distributions at various locations along the horizontal line connecting the canister center of the repository models were asymptotically reduced, and the temperatures after 500 years range from 52.0°C to 102.0°C. The maximum temperature in the STM840 model was the lowest compared with the maximum temperatures from the STM630 and STM640 models for all repository depths considered. For all models studied, the maximum temperatures at the center of the tunnel floor were lower than the maximum temperatures at the canister surface, as shown in Table 4.

Table 4. Maximum Temperature at the Canister Surface

Repository depth, m	Temperature, °C STM630	STM640	STM840
200	109	93.8	75.9
300	110	96.1	78.3
400	113	99	81.2
500	117	102	84.2
600	119	105	87.1
700	122	108	84.1

The maximum temperature allowable at the canister surface was 100°C. The physical and chemical properties changed when the temperatures became higher than 100°C in the compacted bentonite surrounding the canister. Hence, the STM640 model with a depth of 400 m, or less and the STM840 model at all depths considered were thermomechanically acceptable models that satisfied the above criteria.

The vertical displacements at the canister bottom of the various models with different depths, pitches, and tunnel spacings are shown in Figure 5 and Table 6. The lowest displacement was in the STM840 model. The vertical displacements at the tunnel crown, at the center of the

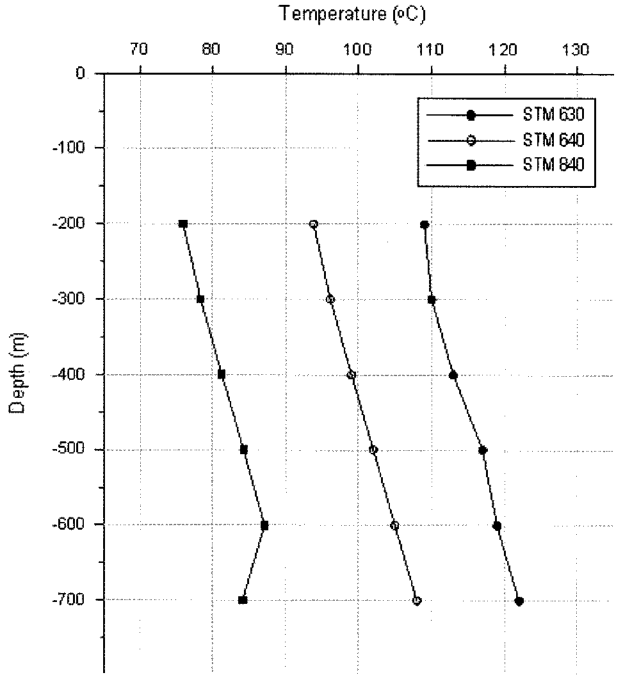


Fig. 4. Maximum Temperature at the Canister Surface of the Models with Different Depth, Pitch, and Tunnel Spacing

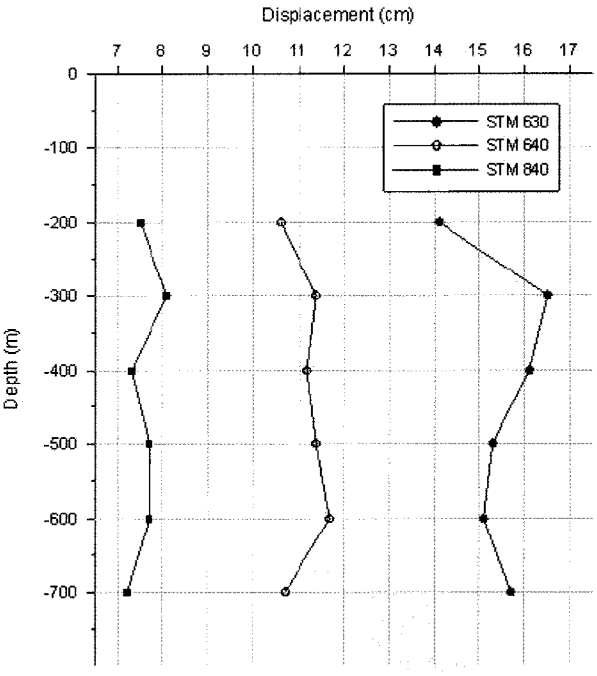


Fig. 5. Vertical Displacements at the Bottom of the Canister of Various Models with a Different Depth, Pitch, and Tunnel Spacing

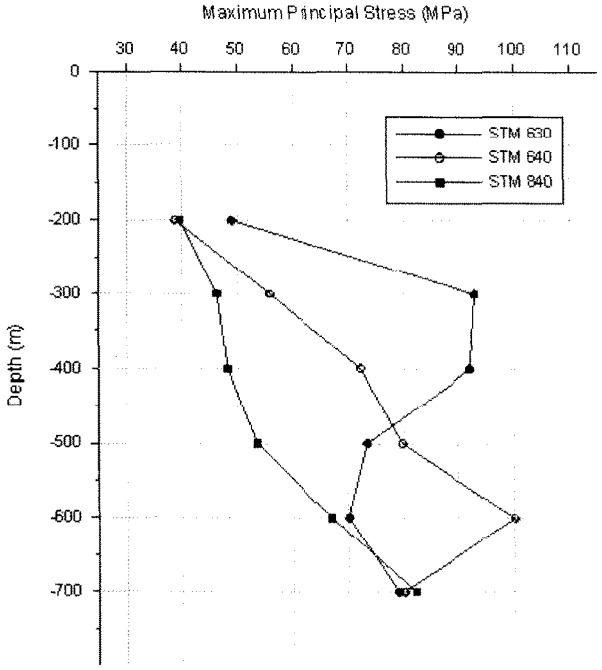


Fig. 6. Maximum Principal Stress on the Rock Below the Deposition Drift

tunnel floor, and at the roof-wall intersection of the tunnel are shown in Tables 7 to 9, respectively. The displacements in the STM840 model showed the lowest value.

The stresses were concentrated around the repository tunnel. The maximum principal stresses on the rock below the deposition hole and on the rock above the tunnel crown were lower than the yield strength of the rock for all models, as shown in Tables 10 and 11. The maximum principal stresses at the center of the backfill in the tunnel were very low and were in the range of 1.9 MPa to 7.3 MPa, as shown in Figure 6 and Table 12.

The thermomechanical behavior near the repository models was dominated by the decay heat generated in the stage after a long time period of waste emplacement when compared with the behavior in the stages of in situ, after excavation, and after waste emplacement. The temperature and displacement behavior were influenced more by pitch variations than by the tunnel spacing and repository depth. Furthermore, the stress behavior was influenced more by repository depth variations than the pitch and tunnel spacing.

Table 5. Maximum Temperature at the Center of the Tunnel Floor

Repository depth,	Temperature, °C		
m	STM630	STM640	STM840
200	93.2	76.7	63
300	95.1	78.7	65.3
400	97.6	81.5	68.1
500	101	84.4	71
600	103	86.9	73.7
700	106	89.9	72.2

Table 6. Vertical Displacement at the Bottom of the Canister

Repository depth,	Vertical displacement, cm		
m	STM630	STM640	STM840
200	14.1	10.6	7.5
300	16.5	11.4	8.1
400	16.1	11.2	7.3
500	15.3	11.4	7.7
600	15.1	11.7	7.7
700	15.7	10.7	7.2

Table 7. Vertical Displacement at the Crown of the Tunnel Floor

Repository depth,	Vertical displacement, cm		
m	STM630	STM640	STM840
200	15.1	9.5	8
300	16.5	12.1	8.6
400	16.2	11.8	7.8
500	16.3	12	8.2
600	15.7	9.4	9.2
700	13.4	10.8	8.7

Table 8. Vertical Displacement at the Center of the Tunnel Floor

Repository depth,	Vertical displacement, cm		
m	STM630	STM640	STM840
200	14.5	10.7	7.3
300	16.7	11.2	7.2
400	15.6	10.4	5.9
500	14.3	10.2	5.7
600	13.5	10.6	5.2
700	13	8.5	4.5

From the repository models studied, by considering variations of the repository depth, pitch, and tunnel spacing,

Table 9. Vertical Displacement at the Roof-Wall Intersection of the Tunnel

Repository depth,	Vertical displacement, cm		
m	STM630	STM640	STM840
200	15	10.7	8
300	17.2	12.1	8.7
400	16.8	11.9	7.9
500	16.3	12.1	8.3
600	16	11.8	8.2
700	15.7	11.3	9.7

Table 10. Maximum Principal Stress on the Rock Below the Deposition Drift

Repository depth,	Max. principal stress, MPa		
m	STM630	STM640	STM840
200	49	38.9	39.8
300	93	55.9	46.4
400	92.1	72.3	48.3
500	73.5	79.8	53.6
600	70.2	100.1	67.1
700	79.1	80.1	82.2

Table 11. Maximum Principal Stress on the Rock Above the Tunnel Crown

Repository depth,	Max. principal stress, MPa		
m	STM630	STM640	STM840
200	48.9	44.2	33.1
300	71.9	50	40
400	73.2	59.7	41.4
500	68.6	68.1	48.4
600	93.8	88.5	52.8
700	94.6	83.4	59.5

Table 12. Maximum Principal Stress at the Center of the Backfill in the Tunnel

Repository depth,	Max. principal stress, MPa		
m	STM630	STM640	STM840
200	1.9	1.9	1.9
300	3.1	2.9	2.9
400	4.5	3.9	4
500	5	5	5
600	6.1	6.2	6.6
700	7.2	7.3	7.3

the following are considered to be the thermomechanically acceptable models: (1) models with a tunnel spacing of 40 m, pitch of 6 m, and repository depth of 400 m, or less and (2) models with a tunnel spacing of 40 m, pitch of 8 m, and all repository depths considered in this study.

3.2 Long Term Behavior of the 400 m Depth Model

The STM840 model at a depth of 400 m was used to analyze the thermomechanical interaction behavior for a period of 500 years after waste emplacement, and the results are shown in Figures 7 to 9. The maximum principal stress contour near the repository is shown in Figure 7 and can be seen near the tunnel. Near the repository models, the maximum principal stress was reached after 50 years after waste disposal. The maximum principal stress below the deposition drift was 74.3 MPa and that above the tunnel crown was 56.8 MPa. The maximum joint shear displacement of 9.4 cm occurred along the periphery of the repository tunnel adjacent to the roof-wall intersection, and the maximum joint aperture was 2.3 cm near the roof-wall intersection of the repository tunnel.

The temperature distribution near the repository showed a high temperature concentration near the heat generating waste, as shown in Figure 8. The temperature histories at several locations along the horizontal axis connected to the center of the canister for the 500-year period from waste emplacement are shown in Figure 9. The temperature increased rapidly in the early period and reached a maximum after 30 to 40 years, after which it decayed quickly.

The temperature at the center of the canister surface reached a maximum of 81.2°C after 30 years, then decayed quickly, and finally cooled to 64.0°C after 500 years.

4. CONCLUSION

A depth and layout optimization was performed for a single layer, high level radioactive waste repository in a discontinuous rock mass with special joint set arrangements. A single layer repository model, subjected to variations in the repository depth, pitch, and tunnel spacing, was used to analyze the thermomechanical interaction behavior. Four different stages were considered in the thermomechanical

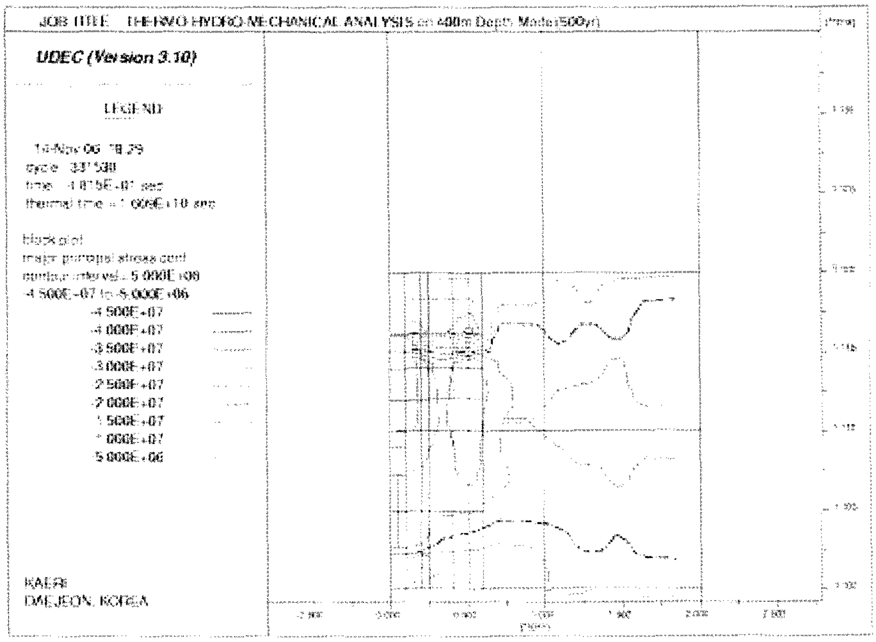


Fig. 7. Maximum Principal Stress Contour in the Vicinity of a Repository

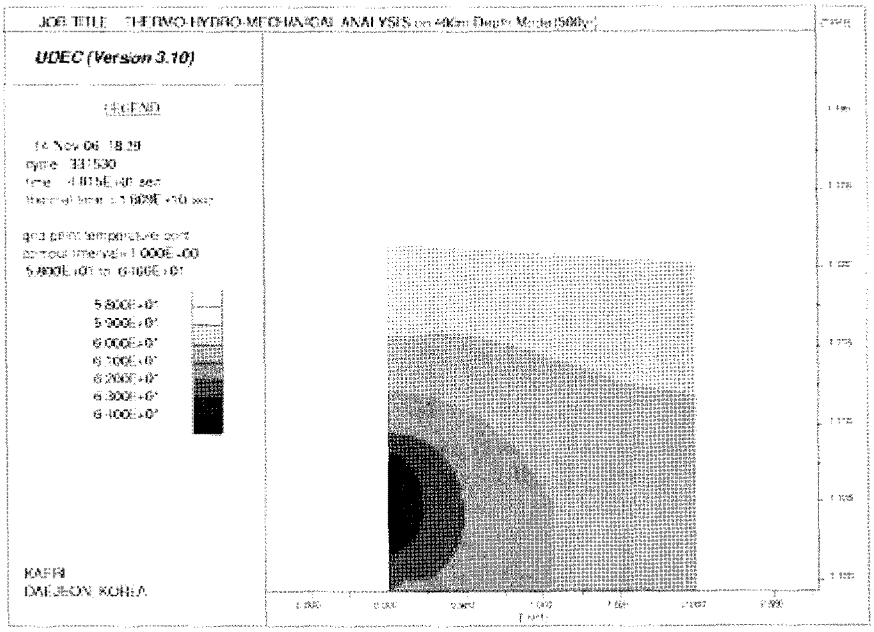


Fig. 8. Temperature Contour in the Vicinity of a Repository

analysis: before excavation, after excavation, after waste emplacement, and after a long time period of waste emplacement. The understanding of the behavior of these stages is an important part of the design and safety evaluation of disposal systems, as well as in the development of a high level radioactive waste disposal concept for Korea.

A single layer repository model with multiple parallel tunnels placed at equal distances apart was analyzed. Each tunnel was 250 m long, 5 m wide, and spaced at either 30 m or 40 m apart with a vertical wall height of 4.65 m and an arch-shaped roof 6.15 m above the tunnel floor. The

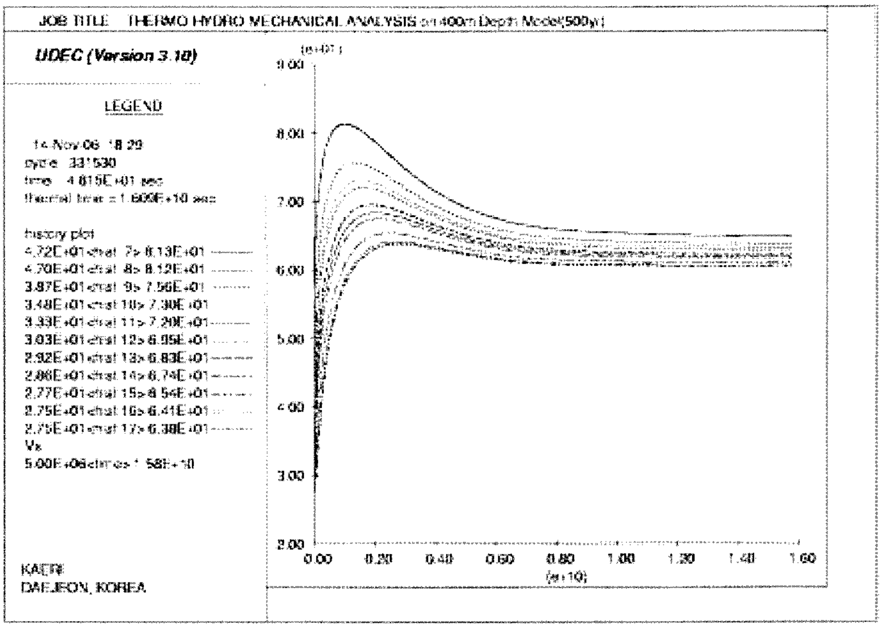


Fig. 9. Temperature Histories at the Locations Along the Horizontal Axis Connecting the Center of the Canister

vertical deposition drifts of 7.83 m in depth were located below the tunnel floor along the centerline of the tunnel at a pitch of either 6 m or 8 m. The length of the model was 1500 m, and the model width was either 30 m or 40 m. Six different repository models with tunnels located at 200 m, 300 m, 400 m, 500 m, 600 m, and 700 m below the ground surface were studied and compared.

The thermomechanical behavior near the repository models was dominated by the decay heat generated by the high level radioactive wastes in the long time period after waste emplacement stage. The thermomechanical behavior of the repository models in the in situ, after excavation, and after waste emplacement stages was not significant: the temperature and displacement behavior was influenced more by the pitch variations than the tunnel spacing and repository depth. Also, the stress behavior was influenced more by the repository depth variations than the pitch and tunnel spacing.

Through the variation of repository depths, pitches, and tunnel spacings in the repository models studied, it is concluded that the thermomechanically acceptable models are models with a tunnel spacing of 40 m, pitch of 6 m, and repository depth of 400 m, or less and models with a tunnel spacing of 40 m, pitch of 8 m, and all considered repository depths. For the final selection of the tunnel spacing, pitch, and repository depth, other aspects such as nuclide migration through the groundwater flow path, construction costs, operation costs, and so on should be considered.

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