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# Optimization of the Layout of a Radioactive Waste Repository Based on Thermal Analysis

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# 열해석에 기초한 방사성폐기물 처분장 배치 최적화

권상기, 최종원, 조원진

**초 록** 국내 원전에서 발생되는 36,000톤의 사용후핵연료를 처분하기 위해서는 약 4km$^2$의 지하 처분장이 필요하다. 본 연구에서는 굴착량과 처분장 면적을 최소화하기 위한 지하 심부 처분장 배치의 최적화를 실시하였다. 열 해석 결과를 토대로 처분 터널과 처분공 간격이 처분장 배치에 미치는 영향을 고려한 결과, 처분장 면적과 굴착량은 처분 터널의 길이가 길어짐에 따라 감소하였다. 주어진 열적 기준을 만족하면서 처분장 면적을 줄이기 위해서는 처분 터널의 간격을 줄이고 처분공 간격을 늘리는 것이 유리하였으며, 반면에 굴착량을 최소화하는 경우 처분공 간격을 줄이고 처분 터널 간격을 늘려주는 것이 효과적인 것으로 나타났다

**핵심어** 지하처분장, 고준위폐기물, 최적화, 열해석

**Abstract** The deep underground High Level Waste (HLW) repository to dispose of 36,000tons of spent fuel from the reactors in Korea needs about 4km$^2$ repository area. In this study, the deep underground repository layout was optimized to minimize the excavation rock volume as well as the underground repository area. In the optimization, the results from thermal analysis were used to define the influence of tunnel and deposition hole spacings on repository layout. The repository area and excavation rock volume could be reduced with longer disposal tunnel length. When it is necessary to reduce the repository area with satisfying thermal criteria, it is better to reduce tunnel spacing and increase deposition hole spacing. In contrast, the excavation rock volume can be reduced by increasing the tunnel spacing and decreasing the hole spacing.

**KeyWords** Underground repository, High-level waste, Optimization, Thermal analysis

## 1. Introduction

In Korea, 15 Pressuized Water Reactors (PWR) and 4 Canadian Deuterium Uranium(CANDU) reactors are now in operation and additional 7 reactors will be operated by 2015. The cumulative amount of spent fuel from the operating nuclear power plants is about 6,000 MTU by 2003. The total inventories of spent fuel to be disposed of with the assumption that 26 PWR and 4 CANDU reactors will be operated for their life time is estimated to be 36,000 tons, which consists of PWR spent fuel of 20,000 tons and CANDU spent fuel of 16,000 tons. In this estimation, the life times of the reactors are assumed to be 40 years.

A long term R&D program for developing a reference concept for disposing the spent fuels in an underground rock mass have been carrying by Korea Atomic Energy Research Institute(KAERI) since 1997. According to the previously determined disposal concept, the PWR and CANDU spent fuels in corrosion resistant canisters will be emplaced in a several hundred meters deep underground repository constructed in crystalline rock such as granite. The waste packages are assumed to be emplaced in vertical deposition holes in the floor of deposition tunnels. In order to dispose of the whole spent fuel, 13,904 spent fuel canisters consisting of 11,375 PWR canisters and 2,529 CANDU canisters are required.

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With a consideration of the thermal and mechanical criteria for assuring the safety and stability of the underground repository, the disposal tunnel spacing and deposition hole need to be decided. The mechanical stability of the underground repository was investigated in the previous studies. Kwon et al.(1999) used UDEC and 3DEC to determine the mechanical stability of underground excavations in deep underground. From the modeling, it was found that the mechanical stability could be maintained even though the deposition hole spacing was reduced to 3 m. Park and Kwon (2000) calculated the factor of safety for different repository layouts using ABAQUS. The factor of safety for the case with 40m tunnel spacing and 3m hole spacing was found to be over 1.0 even in the high in situ stress ratio, K=2.6, which was measured in Canada. From the studies, it is possible to estimate that the mechanical stability can be more or less easily achieved if the deposition hole spacing is over 3 m. The next thing to be considered for determining the underground repository layout is thermal stability.

The most critical criteria is that the maximum buffer temperature should be lower than 100°C to guarantee the performance of bentonite buffer, which is one of the most important engineered barriers protecting the leakage of radionuclides from the repository. In order to select the adequate tunnel spacing and deposition hole spacing, which can satisfy the thermal criteria, an extensive thermal analysis had been carried out by Kuh et al.(1999). Based on the thermal analysis, tunnel spacing of 40 m and hole spacings of 6m and 3m for PWR and CANDU canisters, respectively, were suggested. In that case, the underground repository area was estimated to be about 2 km x 2 km.

The thermal analysis was useful to find out the optimum tunnel and hole spacing to minimize the underground deposition area. In order to determine the optimum underground layout, however, the excavation rock volume needs to be considered too, since it is closely related to excavation cost, hoisting cost, and backfilling cost. In this study, a Fortran program was developed to optimize the repository layout by minimizing the excavation rock volume as well as the repository area.

## 2. Conceptual Repository Design

KAERI have been carrying a R&D program to develop a reference disposal concept, which is adequate for the disposal of the spent fuels generated from Korean nuclear power plants. From the comparison of the proposed alternative disposal concepts based on technical aspects, a disposal concept could be developed (Choi, et al., 1999). The followings are brief descriptions of the disposal concept:

- The underground repository is located in crystalline rock mass at about 500 meters below surface.
- 4 PWR assemblies are assumed to be inserted in a canister and the total number of PWR canisters is 11,375. The total number of CANDU canisters is 2,529.
- The dimensions and material type of the canisters for the two different spent fuels are designed to be exactly identical to make the encapsulation and handling processes in the repository simple.
- PWR and CANDU spent fuels are emplaced in the vertical boreholes drilled with the spacing of 6 m and 3 m, respectively, in the floor.
- Because of the different characteristics of the two spent fuels, PWR and CANDU spent fuels are disposed of in separate areas.
- The migration of radionuclides from spent fuel needs to be delayed by natural barriers and the engineered barriers consisted of waste form, canister, buffer, and backfill.
- Vertical shafts for different sizes will be excavated to connect the surface facilities and the underground repository.

In order to embody the disposal concept, KAERI carried out an international collaboration research with Sandia National Laboratory(SNL). Fig. 1 shows the reference repository layout developed from the collaboration. The deposition tunnels were temporarily decided as to be 6 m wide and 7 m high. The deposition holes with a diameter of about 2.2 m are filled with canister and bentonite buffer. The buffer has the roles of dissipating the decay heat from the waste into the surrounding rock and protecting the canister from possible mechanical damage due to rock movement into the deposition hole. It also acts as a barrier to suppress the detrimental effects of the corrosive water in the host rock, to increase the life span of the canister, and to serve as a geochemical filter for the sorption of the radionuclides (Selvadurai and Pang, 1990). The bentonite buffer will be compressed up to a specific density, which is optimum to achieve the above functions.

Backfilling of the disposal tunnels is planned to be done immediately after the emplacement of canister and buffer. The mixture of bentonite and crushed rock is considered as the backfilling material. The recommended layout of PWR deposition tunnel and deposition hole is illustrated in Fig. 2. Further description of the Korean reference disposal concept can be found in published reports(Choi, et al., 1999, Kang et al., 2000, Lee et al., 2002) and papers(Kwon et al., 2002).

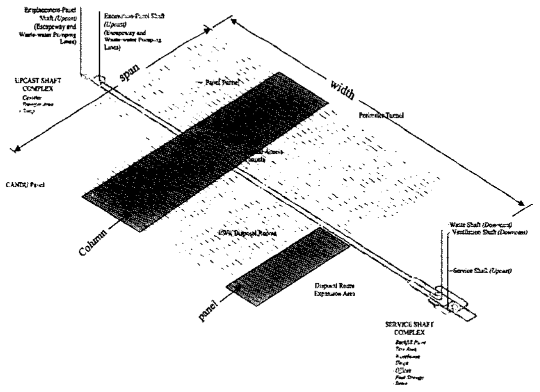



**Fig. 1.** Overview of the underground HLW repository considered in Korea(Kang et al, 2000).

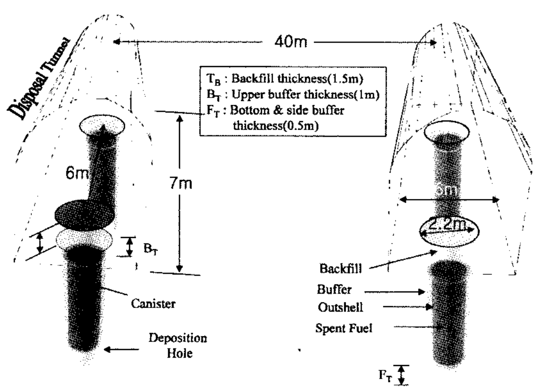



**Fig. 2.** Preliminary layout of PWR disposal tunnel and deposition hole

## 3. Relationship Between Tunnel and Borehole Spacings from Thermal Analysis

### 3.1 Thermal analysis using ABAQUS

In order to determine the underground repository layout, extensive thermal analysis using ABAQUS, which is a general purposed finite element code, had been carried out by Kuh et al. (1999). In the study, sensitivity study for different deposition hole spcaings and tunnel spacings was performed. Fig. 3 shows the model mesh used for the thermal analysis. The material properties used in the thermal analysis are listed in Table 1. In the study, the boundaries except the top surface of the model were regarded as adiabatic surfaces. The top surface was assumed to be thermally free and heat transfer through heat convection was allowed. In order to consider the geothermal temperature effect, the typical geothermal gradient of 3°C/100 m and initial surface temperature of 20°C were used. The decay heat from the waste was determined from the following equation for the reference PWR spent fuel with a burnup of 45,000 MWd/MtU(Choi, et al., 1997):

$$P(t) = 14548.7t^{-0.76204} \text{ (W/ton)} \quad t \geq 30 \text{ years}$$

In one PWR canister, 4 assemblies are emplaced after 40 years cooling in temporary storage pools. Thermal analysis for CANDU deposition holes was not included in the study, because the decay heat from CANDU spent fuel is much lower than that from PWR spent fuel and thus the buffer temperature in CANDU hole is not a concern in the evaluation of repository layout.

Selection of the deposition holes and tunnels spacings needs to be done to ensure that the maximum buffer temperature can be maintained below 100°C. Table 2 lists the maximum buffer temperature at different repository layouts. The maximum temperature at a position near the heat source is reached in a relatively short time about 20 years after the emplacement. The maximum buffer temperature is normally recorded at the contact point with the canister around the middle of the borehole. The deposition hole spacing varies from 3 m to 10 m, and the disposal tunnel spacing varies from 15 m to 60 m. When the tunnel spacing is 15 m, it was not able to get the maximum buffer temperature below 100°C even though the hole spacing is increased up to 10 m. As expected, the maximum buffer temperature decreases with increase of deposition hole spacing. When the tunnel spacing is 30 m, the decrease of buffer temperature due to the increase of deposition hole spacing from 6 m to 10 m is 16.2°C, while it is only 8.5°C when the tunnel spacing is 60 m. For the reference disposal concept, in which the PWR disposal tunnel and deposition hole spacing are 40 m and 6 m, respectively, the buffer temperature is calculated as 95.8°C.

Fig. 4 shows the effect of tunnel and hole spacings on buffer temperature. The maximum buffer temperature decreases exponentially with increase of hole spacing. When the tunnel spacing is narrower, the variation of buffer temperature in the range of hole spacing from 3 m to 10 m becomes larger. For instance, the maximum buffer temperature decreases about 143°C with increase of hole spacing from 3 m to 10m, when the tunnel spacing is 15 m, while it is only about 38°C for 60 m tunnel spacing.

In order to determine the required tunnel and hole spacings to get a specific buffer temperature, curve fitting using third-order polynomial equations was carried out. The six curves could fit the relationship for different tunnel spacings with the coefficient of correlation R2 over 0.999 as shown in Fig. 4. After fitting the curves, the correlation between tunnel spacing and deposition hole spacing to get a specific

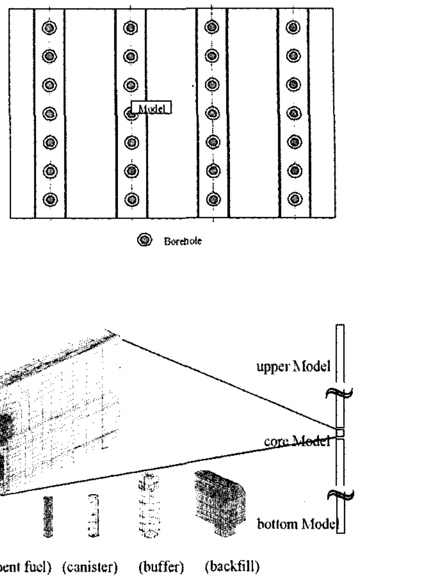



**Fig. 3.** Model meshes for thermal analysis(Kuh et al., 1999)

**Table 1.** Material properties used in the thermal analysis (Kuh et al., 1999)

| Properties | Rock | Backfill | Buffer | Canister | Spent fuel |
|---|---|---|---|---|---|
| Density (kg/m$^3$) | 2700 | 2100 | 2100 | 8000 | 10960 |
| Heat conductivity (W/m.K) | 3.2 | 2 | 1.2 | 15.2 | 7 |
| Specific heat (J/kg.K) | 815 | 800 | 1000 | 504 | 275 |

**Table 2.** Influence of tunnel and hole spacing on maximum buffer temperature(°C) in PWR holes

| Spacings | | Tunnel spacing (m) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 15 | 20 | 30 | 40 | 50 | 60 |
| Hole spacing (m) | 3 | 251.7 | 202.3 | 155.2 | 135 | 126.1 | 122.4 |
| | 4 | 199.5 | 162.7 | 128.2 | 114.4 | 108.6 | 106.5 |
| | 5 | 168.5 | 139.4 | 112.8 | 102.9 | 99 | 97.73 |
| | 6 | 148 | 124.2 | 103.1 | 95.81 | 93.14 | 92.34 |
| | 7 | 133.7 | 113.7 | 96.74 | 91.2 | 89.44 | 88.99 |
| | 8 | 123.1 | 106.2 | 92.28 | 88.11 | 86.9 | 86.57 |
| | 9 | 115.1 | 100.4 | 89.18 | 85.92 | 85.2 | 85.04 |
| | 10 | 108.8 | 96.18 | 86.92 | 84.42 | 83.97 | 83.83 |

buffer temperature could be plotted. In Fig. 5, the lower curves shows the combination of tunnel spacing and deposition hole spacing to get the maximum buffer temperature of 100°C, while the lower curve is for 95.8°C. The two temperatures, 100°C and 95.8 °C, were chosen, because the first one is the thermal criteria for assuring the performance of buffer and the second one is from the reference disposal concept described in Fig. 2. The fitting equations for the two curves are also shown in Fig. 5 and the coefficients of correlation of the curves are 1.0.

When the tunnel spacing is 30m, deposition hole spacings to make the maximum buffer temperatures 100°C and 95.8°C are 6.5 m and 7.3 m, respectively. Even though the tunnel spacing increases twice from 30 m to 60 m, the hole spacings allowable for getting the maximum buffer temperatures are about 2 m.

### 3.2 Influence of tunnel and hole spacings on

With the two fitting equations in Fig. possible to determine the influence of tunn deposition hole spacings on repository area. In to do that, a new parameter, plane area, was introduc Plane area represents the area calculated by multiplying the tunnel spacing and hole spacing. As shown in Fig. 6, the plane area for a certain buffer temperature increases more or less exponentially with increase of tunnel spacing. Fig. 7 shows the plane area for the two buffer temperatures when deposition hole spacing is varying. From Fig. 6 and Fig. 7, it is possible to conclude that the plane area for a certain buffer

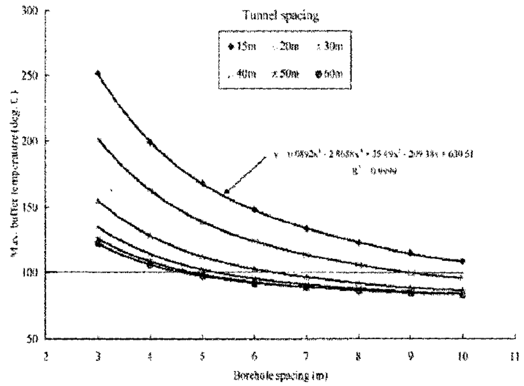



**Fig. 4.** Variation of maximum buffer temperature with variation of hole and tunnel spacings and fitting curves

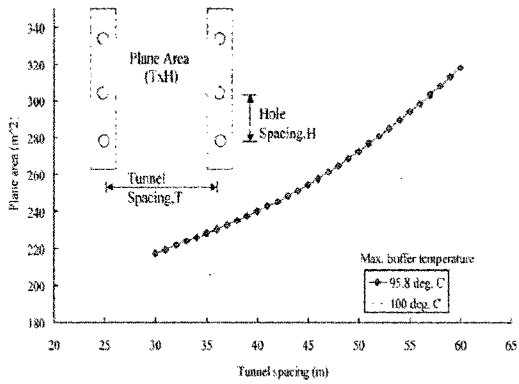
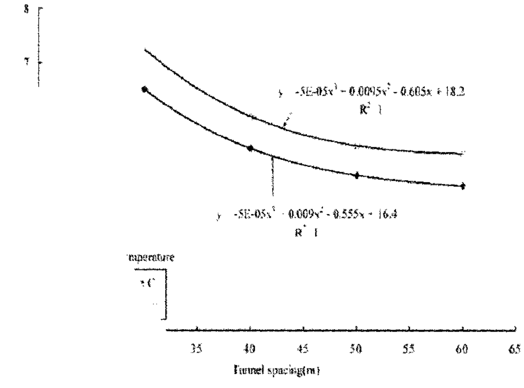



**Fig. 6.** Required plane area to get the buffer temperatures with variation of tunnel spacing




hole spacing and tunnel spacing to nperatures of 100°C and 95.8°C

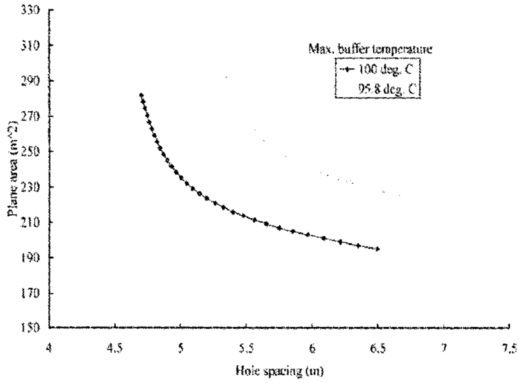



**Fig. 7.** Required plane area to get the buffer temperat with variation of borehole spacing

temperature can be minimized by decreasing tunnel spacing, while increasing hole spacing as much as required for maintaining the buffer temperature.

## 4. Selection of the Optimum Repository Layout

### 4.1 Inputs and outputs for optimization

Since the area of several $km^2$ is required for the underground repository, the optimization of the underground layout based on repository area is also needed to make the siting processes for an HLW repository in Korea easy. It is needed to minimize the excavation rock volume, because it is closely related to the excavation cost as well as hoisting cost. Minimizing the excavated rock volume is also needed to reduce the rock disposal area in surface and the backfilling volume.

It was possible to derive the general trend of the repository area and excavation rock volume from the calculation of plane area as described in the previous section. The selection of optimum repository layout, however, should be done with a consideration of overall repository layout, which can satisfy the requirements such as CANDU and PWR should be disposed of in separate areas. In the optimization process, the variation of outputs is to be monitored with variation of input parameters. In this case excavated rock volume and repository area are the outputs. The excavation rock volume for a certain repository layout is calculated from the volumes of disposal tunnels, access tunnels, panel tunnels, perimeter tunnels, shafts, and deposition holes. The following design parameters were used as inputs in the optimization process: (a) disposal tunnel length : 200~300 m; (b) disposal tunnel spacing : 30~60 m; and (c) deposition hole spacing : 4~10 m. The selection of the ranges for the design parameters were based on the reference disposal concept and thermal analysis.

### 4.2 Assumptions for optimization

In the optimization, 11,375 PWR canisters and 2,529 CANDU canisters are assumed to be disposed of in a single level repository. The diameter of deposition holes is 2.24m and the depth of the holes is 8m. The dimensions of different tunnels and shafts are listed in Table 3.

The repository is assumed to be located at 500m. Tunnel excavation is done by drill and blasting and it is assumed that right-angled intersections are achievable. As commented earlier, CANDU and PWR canisters need to be disposed of in separate areas. In order to do that, all of CANDU spent fuels are required to be disposed of in even number of panels. The waste handling shaft, the service shaft, and the intake ventilation shaft in the service shaft complex were included in the excavation volume calculation.

Overbreak of the rock around the tunnels due to the blasting impact is not considered in the excavation volume calculation, since it does not influence on the optimization of the repository layout.

**Table 3.** Dimensions of tunnels and shafts(Kang et al., 2000)

| Tunnels | | Shafts | |
|---|---|---|---|
| Name | Dimension (width x height) | Name | Dimension (diameter) |
| Access | 6 m x 5 m | Service | 7.9 m |
| Panel | 6 m x 6.5 m | Waste handling | 5.5 m |
| Disposal | 6 m x 7 m | Emplacement panel ventilation | 4.6 m |
| Perimeter | 6 m x 5 m | Downcast ventilation | 4.6 m |
| | | Panel ventilation | 4.9 m |

### 4.3 Calculation for the base repository layout

The excavation volume for different tunnels, deposition holes, and shafts and the required repository area for emplacing the CANDU and PWR spent fuels in separate areas were calculated using a Fortran program developed in this study. The repository layout with disposal tunnel length of 250 m, disposal tunnel spacing of 40 m, PWR hole spacing of 6 m, and CANDU hole spacing of 4 m was considered as the base layout. CANDU hole spacing of 4m instead of 3 m was selected, because of the possible mechanical instability of the rock web between the deposition holes when the spacing is only 3 m.

The maximum buffer temperature for the base layout is 95.8°C. The calculation results for the base case are listed in Table 4. The total excavated rock volume and the required repository area were calculated as 4.54E6 $m^3$ and 4.58E6 $m^2$, respectively. The repository width was 2.35 km and the span was 1.95 km.

For comparison, calculation for the maximum buffer temperature of 100°C was carried out. If the layout is set for 100°C, the PWR hole spacing could be reduced from 6m to 5.4 m as shown in Fig. 5. With the narrower PWR hole spacing, the total excavation rock volume and repository area could be reduced about 9% and 22%, respectively, compared to the base layout. The significant decrease of repository area is mainly due to the reduction of PWR panels from 14 to 12 and the increase of PWR holes per each disposal tunnel from 38 to 42. The more or less square repository layout with the buffer temperature of 100°C is also contributed to the area reduction.

**4.4 Layout for minimizing the excavation volume**

The optimum disposal tunnel length, disposal tunnel spacing, and deposition hole spacing, which can minimize the excavation volume were determined by using the Fortran program. During the optimization process using the program, the tunnel and borehole spacings were adjusted to satisfy the thermal criteria, which is 95.8°C in this case. The calculation results are listed in Table 5. When the tunnel spacing is 55 m and the tunnel length is 297 m, the excavation volume could be minimized to 4.07E6 $m^3$. The reduced rock volume with the optimization is about 0.47E6 $m^3$, which is about 10% less than that for the base layout. The repository width is 2.11 km, while the repository span is 2.23 km. The total repository area is 4.69E6 $m^2$ and increased about 2% compared to the base layout.

**Table 4.** Calculation results for the repository layouts with different maximum buffer temperatures

| Types | Item | Unit | Max. buffer temperature | |
|---|---|---|---|---|
| | | | 95.8°C | 100°C |
| Input | . Tunnel spacing | M | 40 | 40 |
| | . PWR deposition hole spacing | M | 6 | 5.4 |
| | . CANDU deposition hole spacing | M | 4 | 4 |
| | . Disposal tunnel length | M | 250 | 250 |
| Output | Total excavated rock volume | $M^3$ | 4,538,208 | 4,128,745 |
| | - Deposition tunnels | $M^3$ | 3,451,375 | 3,165,350 |
| | - Access tunnels | $M^3$ | 138,524 | 111,028 |
| | - Perimeter tunnels | $M^3$ | 173,757 | 146,261 |
| | - Panel tunnels | $M^3$ | 273,785 | 205,339 |
| | - Shafts | $M^3$ | 62,433 | 62,433 |
| | - Deposition holes | $M^3$ | 438,331 | 438,331 |
| | Total required underground area | $M^2$ | 4,577,800 | 3,553,152 |
| | - Width | M | 2,350 | 1,824 |
| | - Span | M | 1,948 | 1,948 |
| | Total Deposition tunnel length | M | 90,500 | 83,000 |
| | Total access tunnel length | M | 5,300 | 4,248 |
| | Total perimeter tunnel length | M | 6,648 | 5,596 |
| | Total panel tunnel length | M | 7,792 | 5,844 |
| | Number of PWR tunnels in a panel | | 24 | 24 |
| | Number of PWR panels | | 14 | 12 |
| | Number of holes in a PWR tunnel | | 38 | 42 |
| | Number of required PWR tunnels | | 315 | 285 |
| | Number of CANDU tunnels in a panel | | 24 | 24 |
| | Number of CANDU panels | | 2 | 2 |
| | Number of holes in a CANDU tunnel | | 57 | 57 |
| | Number of required CANDU tunnels | | 47 | 47 |

### 4.5 Layout for minimizing the repository area

Using the Fortran program, the repository layout to minimize the repository area could be suggested. The repository layout with tunnel spacing of 30 m, PWR hole spacing of 7.2 m, CANDU hole spacing of 4m, and tunnel length of 293 m were suggested to minimize the repository area. In this case, the total excavated rock volume is 4.96E6 $m^3$ and the required repository area is 3.31E6 $m^2$. Compared to the base repository layout, the repository area could be reduced about 28%. The repository width and span are also changed to 2.69 km and 1.23 km, respectively.

### 4.6 Optimum repository layout

To determine the optimum repository layout, it is needed to consider the repository area as well as the excavation volume. When weighting for the two outputs was not considered, the optimum layout to minimize the excavation volume and the repository area could be calculated as Table 5. The excavation rock volume and repository area are 4.15E6 $m^3$ and 3.95E6 $m^2$, respectively, when the tunnel spacing is 46m, PWR hole spacing is 6.8 m, and the tunnel length is 299 m. By the optimization, the repository area could be reduced about 14%, while the excavation rock volume was reduced about 9% compared to the base case. It would be possible to check the influence of weighting value on the optimum repository layout, but the variation of the layout would be limited within the two optimum layouts, one is for minimizing the repository area and the other is for minimizing the excavation volume.

## 5. Sensitivity of the Parameters on Rock Volume and Area

Using the Fortran program to calculate the excavation rock volume and required repository area for a certain tunnel and deposition hole dimensions, it is possible to conduct sensitivity analysis for the design parameters:

### 5.1 Tunnel spacing

Fig. 8 shows the influence of tunnel spacing on excavation rock volume and repository area, when the tunnel length is 250 m and CANDU hole spacing is 4 m. The PWR tunnel spacing is calculated using the fitting equation of the curve for the maximum buffer temperature of 95.8°C in Fig. 5. With increase of the tunnel spacing, the excavation volume decreases more or less exponentially. In contrast, the required repository area increases almost linearly with increase of tunnel length, when the tunnel spacing is up to 48 m. When the tunnel spacing is 49 m, the required area dropped suddenly from 5.48E6 $m^2$ to 4.34E6 $m^2$. The sudden change is resulted from the sequential change of the repository layout from hole spacing to column number. At first the deposition hole spacing was reduced a little bit with increase of tunnel spacing. When the tunnel spacing changed from 48m to 49m, the hole spacing decreased and the number of deposition holes in a 250 m disposal tunnel was increased from 41 to 42. This results in the change of the total number of PWR disposal tunnels from 292 to 285. Finally, the required number of the columns could be reduced from 4 to 3 and that was the reason of the sudden decrease of repository area.

**Table 5.** Optimum repository layouts for different goals

| Types | Item | Base case | Optimization | | |
|---|---|---|---|---|---|
| | | | Excavationvolume | Repository area | Volume and Area |
| Input | Tunnel spacing (m) | 40 | 55 | 30 | 46 |
| | PWR hole spacing (m) | 6.0 | 5.3 | 7.2 | 5.6 |
| | CANDU hole spacing (m) | 4.0 | 4.0 | 4.0 | 4.0 |
| | Tunnel length (m) | 250 | 297 | 293 | 299 |
| Output | Excavated rock volume ($10^6$ $m^3$) | 4.54 | 4.07 | 4.96 | 4.15 |
| | Repository area($10^6$ $m^2$) | 4.58 | 4.69 | 3.31 | 3.95 |
| | Width (km) | 2.35 | 2.11 | 2.69 | 2.12 |
| | Span (km) | 1.95 | 2.23 | 1.23 | 1.87 |

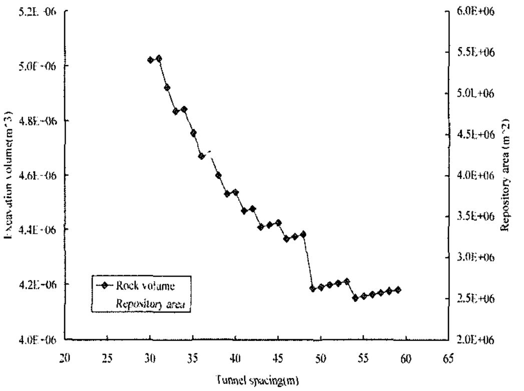



**Fig. 8.** Variation of excavation volume and repository area with tunnel spacing change, when tunnel length is 250 m and the maximum buffer temperature is 95.8°C

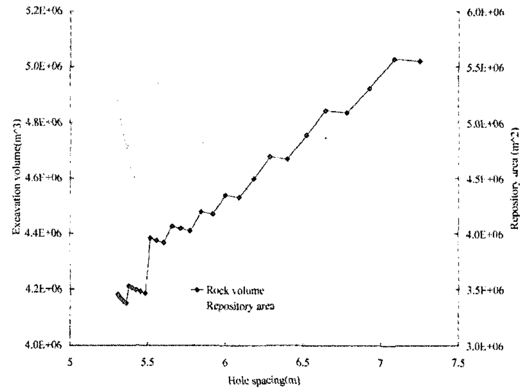



**Fig. 9.** Variation of excavation volume and repository area with hole spacing change, when tunnel length is 250 m and the maximum buffer temperature is 95.8°C

Because of such a nonlinear variation of excavation rock volume and repository area, any code for linear optimization would not be applied for optimizing the repository layout.

### 5.2 Deposition hole spacing

Fig. 9 shows the variation of excavated rock volume and repository area with different PWR deposition hole spacings when the tunnel length is 250 m. The excavated rock volume increases almost linearly with increase of hole spacing, while the required repository area decreases exponentially with increase of hole spacing. The general trends of the excavation volume and repository area change with variation of hole spacing are opposite to those from the variation of tunnel spacing. This is due to the fact that PWR hole spacing is dependent on tunnel spacing to satisfy the thermal criteria. From Fig. 8 and Fig. 9, it can be concluded that when it is necessary to reduce the repository area, it is better to reduce tunnel spacing, while deposition hole spacing should be increased to meet the thermal constraint. In contrast, the excavation volume can be reduced by increasing tunnel spacing and decreasing hole spacing.

### 5.3 Disposal tunnel length

When tunnel length varies from 200 m to 300 m and the other parameters are the same as the base repository layout, the repository area and excavation volume are changing as shown in Fig. 10. The

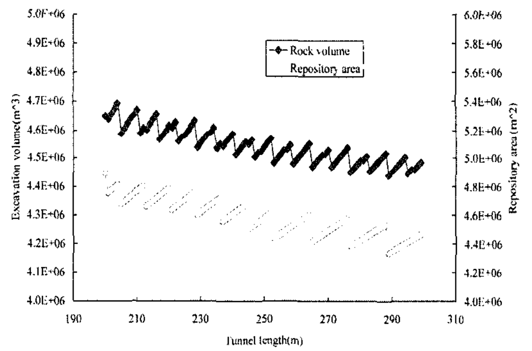



**Fig. 10.** Variation of excavation volume and repository area with tunnel length change, when the maximum buffer temperature is 95.8°C

stepwise decrease in the two curves is due to that the number of deposition holes in a tunnel changes stepwise pattern with increase of disposal tunnel length. It is interesting to find that the excavation volume and repository area have the same pattern of decreasing with increase of tunnel length. Therefore, it would be better to select longer tunnel length to reduce the excavation volume and repository area, if there is no technical problem with long disposal tunnels.

## 6. Conclusions

In this study, the layout of the underground HLW repository was optimized to minimize the excavated rock volume as well as repository area. In the optimization process, thermal analysis using ABAQUS were used to define the influence of tunnel and deposition hole spacings on repository layout. A Fortran program was developed for calculating the excavated rock volume and repository area for emplacing the whole spent fuels from Korean nuclear reactors. From the study, the following conclusions could be drawn:

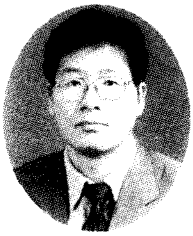
1) Quite different repository layouts could be developed for different buffer temperatures. When the maximum buffer temperature of 100°C is used in the calculation, the calculated repository area is about 22% less than that for 95.8°C case.
2) With the increase of the tunnel spacing from 30 m to 60 m, the excavation rock volume decreases more or less exponentially. Repository area increases with increase of tunnel spacing almost linearly until the sudden drop at 49 m.
3) The excavation volume and repository area have a pattern decreasing with increase of tunnel length. Therefore, it is recommended to select a longer tunnel length to reduce the excavation volume and repository area.
4) When the tunnel spacing is 55 m, PWR hole spacing is 5.3 m, and the tunnel length is 297 m, the excavation rock volume could be minimized. The repository area could be minimized when the tunnel spacing is 30 m, PWR hole spacing is 7.2 m, and tunnel spacing is 293 m.
5) When the weightings for excavation rock volume and repository area are the same, the optimum repository layout could be achieved when the tunnel spacing is 46 m, PWR hole spacing is 5.6m, and the tunnel length is 299 m. At the optimum layout, the excavation rock volume could be reduced about 9% and the repository area was reduced about 14% compared to the base repository layout.
6) If it is necessary to reduce the repository area without losing safety, it is recommended to reduce tunnel spacing, while deposition hole spacing should be increased to meet the thermal constraint. In contrast, the excavation volume can be reduced by increasing the tunnel spacing and decreasing the hole spacing.

As a next step for the optimization of the underground HLW repository layout, it is highly recommended to optimize the repository layout based on various parameters including cost analysis, mechanical stability, and groundwater flow. It is also recommended to consider multi-layer repository concept as an alternative layout in the future study.

## References


1. Choi, J.W et al., 1997. Reference spent fuel and its characteristics for the concept development of a deep geological disposal system, KAERI report, KAERI/TR-914/97.
2. Choi, J.W, C.H., Kang, S., Kwon, and Y.S., Choi, 1999, Technology assessments of disposal alternatives to determine a reference geological repository system for HLW, KAERI report, KAERI-1361/99.
3. Lee, M.Y., S.R., Sobolic, S.W, Webb, S., Kwon, J.H., Park, J.W., Choi, and C.H., Kang, 2002, Coupled thermal-hydrological-mechanical modeling for the development of the underground high level nuclear waste repository in the republic of Korea, Sandia National Lab.
4. Kang, C.H. et al., 2000, Preliminary conceptual design and performance assessment of a deep geological repository for high-level waste in the republic of Korea, KAERI-SANDIA final report.
5. Kuh, J.E., C.H., Kang, and J., Park. 1999, Thermal analysis for the near field of the high level radioactive waste repository using ABAQUS, Proc., ABAQUS users' conference, May 26-28, Chester, UK, 410-426.
6. Kwon, S, K.M. Chang, and C.H., Kang, 1999, Structural analysis for the conceptual design of a high level radioactive waste repository in a deep deposit, Tunnel and Underground, Vol. 9, 102-113.
7. Kwon, S., Park, J.H., J.W., Choi, C.H., Kang, 2002, HLW deposition hole design with thermal-mechanical analysis, Proc. of the ISRM regional symposium, Seoul National University, Seoul, Korea, July 22-24, 731-738.
8. Park, B.Y. and S., Kwon, 2000, Mechanical stability analysis of a High-level waste repository for determining optimum cavern and deposition hole spacing, Tunnel and Underground, 10, 237-248.
9. Selvadurai, P.S. and S., Pang, 1990, Mechanics of the interaction between a nuclear waste disposal container and a buffer during discontinuous rock movement, Engineering Geology, 28, 405-417.

**권 상 기**



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