Coupled thermo-hydraulic-mechanical analysis for a high efficiency high-level radioactive waste repository in South Korea

Kwang-Il Kim
Korea Atomic Energy Research Institute, Daejeon, Republic of Korea

Changsoo Lee
Korea Atomic Energy Research Institute, Daejeon, Republic of Korea

Dong-Keun Cho
Korea Atomic Energy Research Institute, Daejeon, Republic of Korea

ABSTRACT: This study analyzes enhancement of disposal efficiency inversely proportional to disposal area based on three design factors for the high-level radioactive waste (HLW) repository such as decay heat optimization, increased thermal limit of buffer, and double-layer concept. If the repository is designed with the optimized decay heat model, the disposal efficiency increases to 2.3 times of the improved Korean Reference disposal System (KRS^+). Additional to the decay heat optimization, increasing thermal limit of buffer to 130 °C or using the double-layer concept provides extra 50 % improvement of the disposal efficiency. If the three design factors are applied all together, disposal efficiency can be enhanced to the five times of the KRS^+ repository. Rock mass stability analysis indicates that failure of rock is focused at the corner between the disposal tunnel and deposition hole, and rock spalling failure is generated in the wider area if the thermal limit of buffer is increased.

Keywords: Coupled thermo-hydraulic-mechanical analysis, High-level radioactive waste repository, Disposal efficiency, Rock mass stability.

1 INTRODUCTION

As Korea has relatively small land area and large population density compared to other countries considering the DGD concept such as Finland and Sweden, improvements of disposal efficiency which is inversely proportional to the disposal area might be needed for the current reference disposal system called KRS^+ (Lee et al., 2020a) to alleviate the difficulties of site selection for the HLW repository (Lee et al., 2020b). In this context, several studies have discussed alternative disposal concepts including multi-layer and multi-canister repositories (Cho et al., 2017; Lee et al., 2020b). Adjusting design constraints of the repository from overly conservative to reasonable level (e.g. increase of thermal limit of buffer) can be an additional method to enhance the disposal efficiency. Performance evaluation of bentonite at high temperature above the 100 °C has been investigated through laboratory and numerical studies (Yoon et al., 2022; Cho and Kim, 2016, Wersin et al., 2007; Zheng et al., 2015; Couture, 1985), and various studies indicate that changes in safety performance of bentonite around 125 °C are not significant (Cho and Kim, 2016; Wersin et al., 2007; Pusch et al., 2003). Disposal efficiency can also be improved through the optimization of the decay heat per canister. Cho and Jeong (2014) presented that the disposal efficiency is enhanced by using the respective decay heat of an individual SNF instead of using the uniform decay heat. Jeong et al (2022) developed a computer program, called ACom (Assembly Combination) by which the SNFs with the maximum and minimum decay heat are iteratively emplaced in a canister, and the decay heat of a canister calculated by ACom was relatively lower than that used for designing KRS.

This study presents a numerical study to investigate the enhancement of disposal efficiency based on three design factors for the HLW repository, i.e. decay heat optimization, increased thermal limit of buffer, and double-layer concept. First, thermal performance of the repository using the optimized decay heat model is compared to the KRS^+ repository with the identical disposal spacings. Subsequently, disposal spacings of four high-efficiency repositories generated based on the three design factors are determined by conducting coupled thermo-hydraulic (TH) numerical simulations, and the amount of enhanced disposal efficiency of four high-efficiency repositories compared to the KRS^+ was evaluated. Additional coupled THM numerical simulations were conducted to analyze the mechanical stability of four high-efficiency repositories with the determined disposal spacings.

2 NUMERICAL MODEL SETUP

2.1 Simulation cases

Five simulation cases are generated to investigate the increase of disposal efficiency depending on the three design factors of the HLW repository, i.e., decay heat model, thermal limit of buffer and the number of layers (Table 1). Case 1 is set as a reference case representing the conditions of the KRS^+ repository. Case 2 uses the optimized decay heat model with the identical thermal limit of buffer and the number of layers to the KRS^+ repository to identify the effect of decay heat optimization on the enhancement of disposal efficiency. In addition to the decay heat optimization, the increased thermal limit of buffer to 130 °C and double-layer concept are considered in case 3 and case 4, respectively. Lastly, case 5 takes advantage of the three design factors all together.

Table 1. Decay heat model, thermal limit of buffer and the number of layers for five simulation cases.

Case	Decay heat model	Thermal limit of buffer	Single- or double- layer
Case 1	KRS^+	100 °C	Single
Case 2	Optimized	100 °C	Single
Case 3	Optimized	130 °C	Single
Case 4	Optimized	100 °C	Double
Case 5	Optimized	130 °C	Double

2.2 Geometry and initial and boundary conditions

A quarter section of a symmetrical disposal module is generated for single- and double-layer concepts with data monitoring points at buffer and rock mass (Figure 1). In double-layer concept, data monitoring points are located at the lower layer as temperature of buffer at the lower layer is higher than that at the upper layer due to effect of the geothermal gradient. Sizes of disposal tunnel and deposition hole refer to the geometry of the unit disposal modules shown in Lee et al. (2023). The canister is assumed as an equivalent single material emitting a quarter of the decay heat per canister. Heights of the single- and double-layer models are set as 3 km and 4 km, respectively to eliminate the boundary effects from the fixed temperature at the bottom of the models. For case 1, spacings of disposal tunnel (d) and deposition hole (s) are 40 m and 7.5 m, respectively which are identical to those of the KRS^+ repository. For cases 2 to 5, however, various values of the deposition hole spacings are used to identify the optimal disposal spacing satisfying the thermal limit of buffer. Distance between the upper and bottom layers in the double-layer concept is fixed as 300 m.

No fluid flow and heat transfer occur at all lateral boundaries, which indicates the numerical domains are surrounded by the identical decay heat sources. The displacement normal to the lateral and bottom boundaries is fixed, whereas the free displacement condition is applied at the upper boundary which indicates the ground surface. Temperature and pressure are fixed as 10 °C and 0.1 MPa, respectively at the ground surface, and geothermal gradient of 0.03 °C/m and hydrostatic condition are considered at the remaining domain other than the EBS materials. Initial temperature and pressure of the EBS materials are set as 15 °C and 0.1 MPa, respectively considering the excavation and ventilation of the repository. Initial liquid saturation of the EBS materials is 0.507 converted from initial water content of 13 % according to Choi et al. (2008) except a canister assumed as dry condition. In-situ stress condition representing the regional stress in the Korean peninsula (Synn et al., 2013) is applied. Z indicates the depth using a negative value, and the compressive stress is expressed by a negative value.

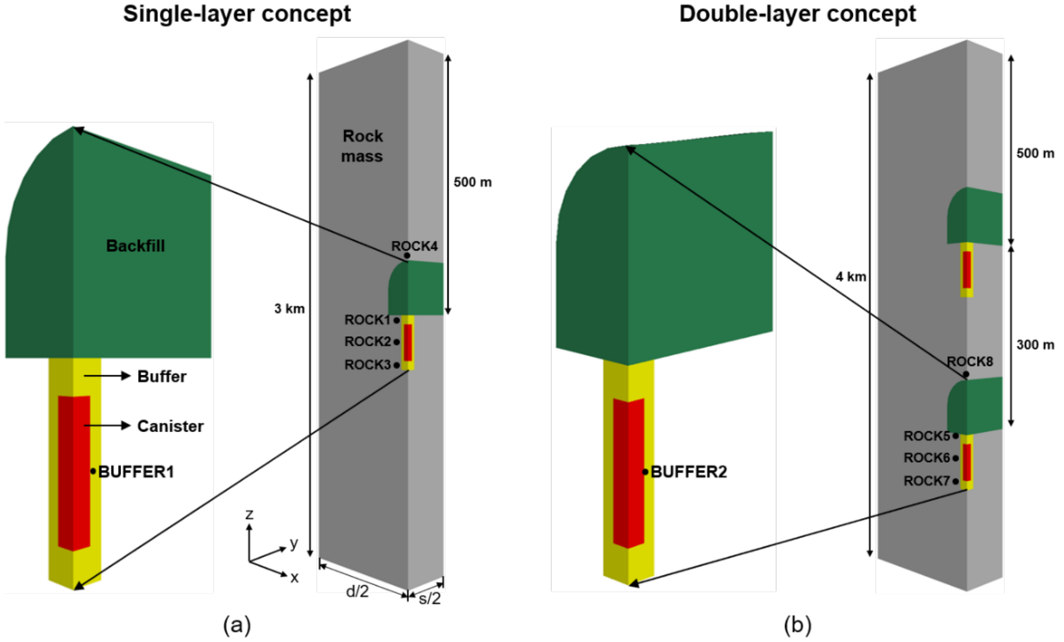

Figure 1. A quarter section of symmetrical disposal modules for (a) single- and (b) double-layer concepts.

3 SIMULATION RESULTS

3.1 Estimation of the deposition hole spacing

Figure 2 shows the variations of temperature after disposal and thermal limit of buffer for cases 2 to 5. The temperature is calculated at BUFFER1 and BUFFER2 in Figure 1 for single- and double-layer concepts, respectively. For case 2, the maximum temperatures of buffer are calculated as 100.6 °C, 96.1 °C and 92.2 °C when the deposition hole spacings are 7.0 m, 7.5 m and 8.0 m, respectively, so 7.5 m is an optimal value for the deposition hole spacing with the observance of the thermal limit of buffer. Using the similar approach, the deposition hole spacings for cases 3, 4 and 5 are determined as 5.0 m, 10.0 m and 7.0 m corresponding to the maximum temperatures of buffer of 128.0 °C, 97.6 °C and 123.9 °C, respectively.

The disposal efficiency of each case normalized by the KRS^+ is shown in the Figure 3. By optimizing the decay heat per canister (case 2), the disposal efficiency can be increased to 2.3 times of that of the KRS^+ repository. In addition to the decay heat optimization, increasing thermal limit of buffer to 130 °C (case 3) or using the double-layer concept (case 4) provides extra 50 % improvement of the disposal efficiency. If the three design factors are applied to the repository all together (case 5), disposal efficiency can be enhanced to the five times of that of the KRS^+ repository, which might significantly alleviate the difficulties of site selection for the HLW repository.

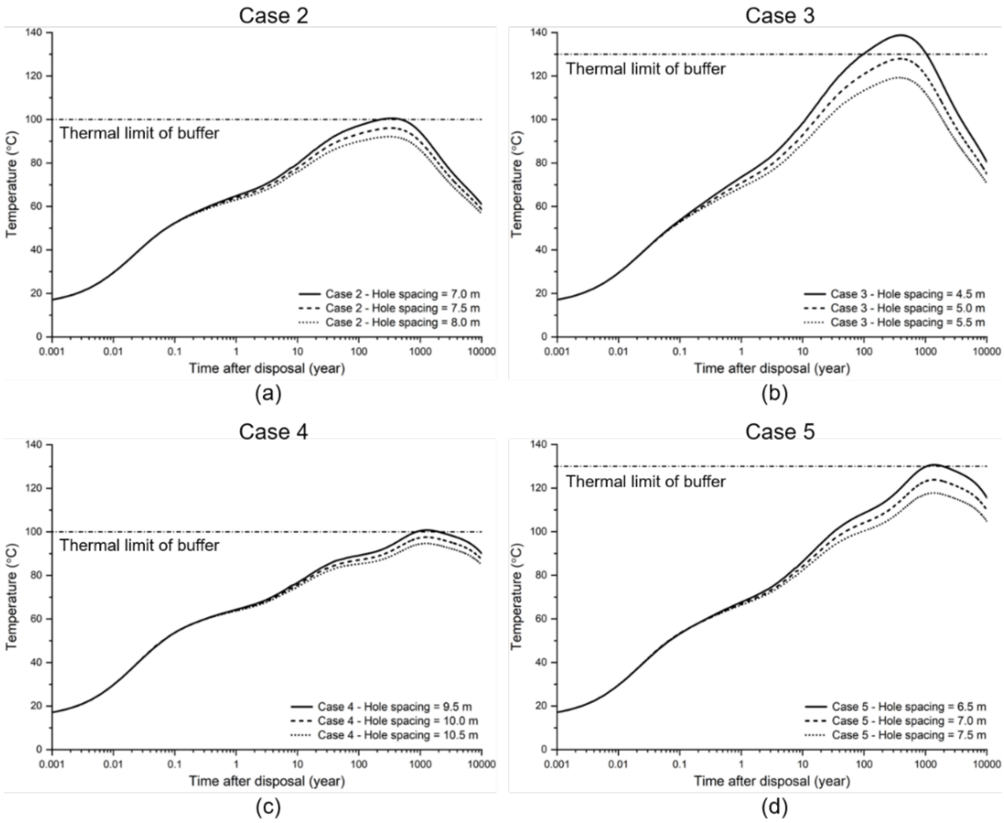

Figure 2. Variations of temperature of buffer with various deposition hole spacings for (a-d) cases 2 to 5.

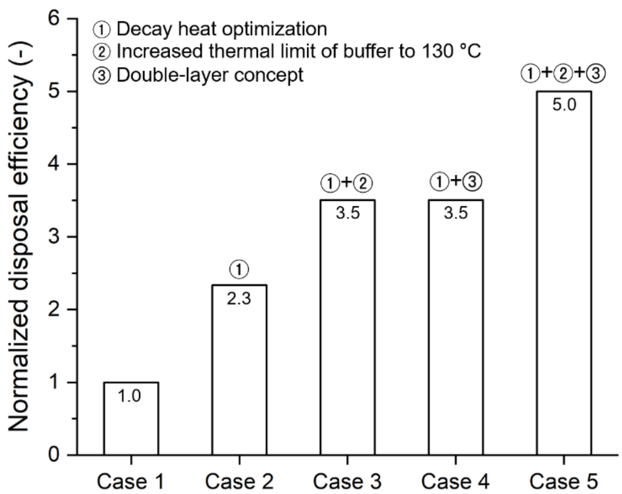

Figure 3. Bar charts of the normalized disposal efficiency by the KRS$^+$ repository for cases 1 to 5.

3.2 Mechanical stability of rock mass

Fig. 9 shows variations of the maximum principal stresses of rock mass near the disposal tunnel and the deposition hole for cases 2 to 5 with the failure criterion of rock spalling calculated as 50 % of the UCS of intact rock specimens from KURT (Lee et al., 2019). Comparing the cases with the identical thermal limit of buffer (cases 2 and 4 or cases 3 and 5), the magnitudes of stress changes at each monitoring points are comparable regardless of the single- or double-layer concept. On the other hand, the peak stresses are numerically observed relatively late in cases of the double-layer concept due to the superposition of the heat from the upper and lower layers. Comparing the cases with different thermal limit of buffer (cases 2 and 3 or cases 4 and 5), the increase of thermal limit of buffer from 100 °C to 130 °C induces larger amount of thermal stress at rock mass and thereby wider area of rock spalling failure. In particular, the peak maximum principal stresses at ROCK2 and ROCK6 are calculated as 49.8 MPa and 52.5 MPa for cases 2 and 4, respectively which are below the spalling failure criterion, but those are increased to 73.4 MPa and 66.4 MPa at the corresponding locations for cases 3 and 5, respectively resulting in the possible spalling failure. However, the area of rock spalling failure might be overestimated as increase of rock mass strength due to confining stress by swelling of buffer and backfill is not considered in this analysis.

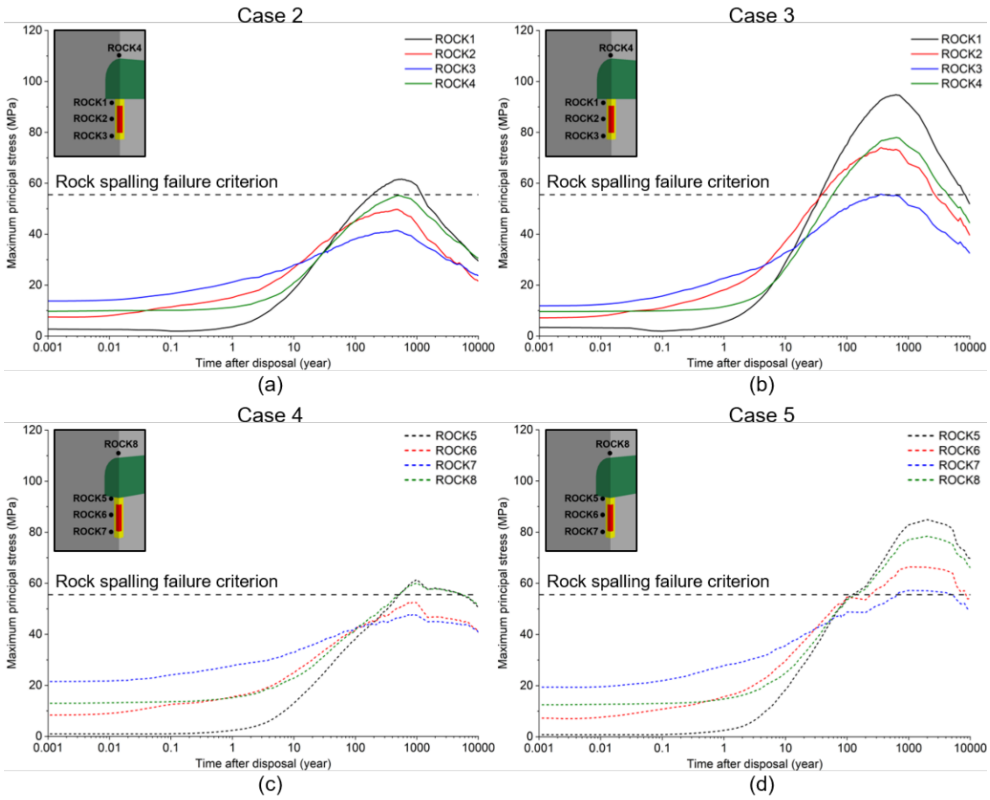

Figure 4. Variations of the maximum principal stresses of rock mass near the disposal tunnel and the deposition hole for (a-d) cases 2 to 5 with the rock spalling failure criterion.

4 CONCLUSION

This study presents the enhancement of disposal efficiency of the HLW repository in the viewpoint of disposal area considering three design factors such as optimization of decay heat, increased thermal limit of buffer, and double-layer concept using coupled TH simulations, and additional coupled THM simulations are conducted to analyze the rock mass stability in the high-efficiency repositories. If the repository is designed with the optimized decay heat model, thermal limit of buffer of 100 °C and single-layer concept, the disposal efficiency can be increased to 2.3 times of that of the KRS^+ repository. In addition to the decay heat optimization, increasing thermal limit of buffer to 130 °C or using the double-layer concept provides extra 50 % improvement of the disposal efficiency. If the three design factors are applied to the repository all together, disposal efficiency can be enhanced to the 5 times of that of the KRS^+ repository, which might significantly alleviate the difficulties of site selection for the HLW repository.

Analysis of rock mass stability indicates that the thermal stress induced by the decay heat mainly contributes to the potential failure of rock mass. Thus, the rock spalling failure can be generated in the wider area if the thermal limit of buffer is increased from 100 °C to 130 °C. However, the area of rock spalling failure might be overestimated as increase of rock mass strength due to confining stress by swelling of buffer and backfill is not considered in this analysis. The results given in this study can provide various options for designing the high-efficiency repository in accordance with the target disposal area and quality of the rock mass in the potential repository site.

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