Thermal Evaluation of Multi-batch Disposal Strategies and Statistical Uncertainty Analysis in Deep Geological Repository

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1. Introduction

Spent Nuclear Fuel (SNF) management is a crucial challenge for nuclear-powered countries. It has led to the development of deep geological repositories (DGR) like Sweden's KBS-3, which employs a multi-barrier concept consisting of natural and engineered barrier systems. The natural barrier consists of the host rock, while the engineered barriers consist of metal canisters that contain SNFs and bentonite as the buffer material. Inspired by KBS-3, Korea has proposed the KAERI Reference disposal System (KRS). These DGR designs need to meet Thermal-Hydraulic-Mechanical-Chemical (THMC) criteria, particularly to maintain the buffer temperature below 100 °C to prevent the degradation of bentonite. This poses a challenge to develop an area-effective DGR, which is particularly important in Korea. To estimate the peak temperature accurately, numerical codes have been developed alongside analytical and semi-analytical solutions. Meanwhile, having helped determine feasible ranges of outcomes, statistical uncertainty studies focusing on THM properties remain limited primarily due to insufficient data.

To address these gaps, this study proposes a multi-batch disposal concept, which can reduce the maximum temperature in the DGR analysis. Analytical solutions are derived to evaluate the thermal effect of multi-batch disposal. Also, thermal conductivity of GTC4 bentonite is measured, and the results are utilized in the analytical solution to incorporate uncertainty of buffer material to the thermal analysis.

2. Methods

2.1 Measurement of thermal conductivity

The thermal properties of bentonite were measured using TPS-M1 (Hot Disk AB, Sweden), which uses the Transient Plane Source (TPS) method. In this approach, the sensor functions as both a heater and a thermometer, generating heat and measuring the resulting temperature change simultaneously. The TPS method allows direct measurement of thermal diffusivity and conductivity. Measurements were conducted 10 times on 10 samples of GTC4 bentonite under consistent environmental conditions at 23 °C.

2.2 One-batch solution [1][2]

Based on the superposition law, analytical solutions are divided into global and local solutions to model heat distribution in a DGR. The global solution describes an overall temperature field derived from a rectangular heat source, while the local solution indicates how far the temperature of a specific point is from the average of the neighboring area. The local solution further consists of three heat source components representing repository tunnels, waste canisters, and the central canister. Equations (1)-(3) incorporate parameters like density, thermal conductivity, thermal diffusivity, and geometric dimensions to model heat conduction. The only time-dependent factor in these equations is the decay heat of SNF, supposing a steady-state condition. The steady-state temperature difference between the rock/buffer interface and the buffer/canister interface at canister mid-height is also determined, helping predict the temperature of buffer at its highest.

$$T_{glb}^{1b}(t) = \frac{1}{\rho c \sqrt{\pi}} \int_0^t \frac{Q_0(t')}{DD'\sqrt{4\alpha(t-t')}} \cdot \mathrm{erf}\left(\frac{L}{\sqrt{4\alpha(t-t')}}\right) \cdot \mathrm{erf}\left(\frac{B}{\sqrt{4\alpha(t-t')}}\right) \cdot \left(1 - e^{-\frac{H^2}{\alpha(t-t')}}\right) \cdot dt' \tag{1}$$

$$T_{loc}^{1b}(t) = \frac{Q_0(t)}{2\pi\lambda D}\left[\gamma + \ln\left(\frac{D'}{4\pi D}\right)\right] + \frac{Q_0(t)}{2\pi\lambda H_c} \ln\left[\frac{H_c}{R} \cdot \left(\sqrt{\left(\frac{R}{H_c}\right)^2 + \left(\frac{1}{2}\right)^2} + \frac{1}{2}\right)\right] \tag{2}$$

$$T_{ben}^{1b}(t) = \frac{Q_0(t)}{2\pi\lambda_b} \cdot \frac{\ln(R/r)}{H_c + r} = Q_0(t) R_{ben} \tag{3}$$

2.3 Multi-batch solution

In multi-batch disposal, fuel canisters within the DGR are divided into two or three groups, named as "batches." Each batch consists of SNF canisters with different cooling periods, resulting in varying levels of decay heat, while canisters within the same batch share identical heat distributions. These batches are arranged alternately in the deposition holes. This multi-batch disposal concept is illustrated in Figure 1 for one-, two-, and three-batch disposal, with the one-batch disposal representing the reference case. As shown in Equations (4) and (5), part of the local solution is modified so that it can be suitable for multi-batch disposal concept.

$$(T_{\equiv}^{2b} + T_{\cdots}^{2b})(t) = \frac{Q_0(t)}{4\pi\lambda D}\left[\gamma + \ln\left(\frac{D'}{2\pi D}\right)\right] + \frac{Q_1(t)}{4\pi\lambda D}\left[\gamma + \ln\left(\frac{D'}{8\pi D}\right)\right] \quad (4)$$

$$(T_{\equiv}^{3b} + T_{\cdots}^{3b})(t) = \frac{Q_0(t)}{6\pi\lambda D}\left[\gamma + \ln\left(\frac{D'}{4\pi D}\right) + \frac{\ln 3}{2}\right] + \frac{Q_1(t)}{6\pi\lambda D}\left[\gamma + \ln\left(\frac{D'}{4\pi D}\right) + \frac{\ln 3}{2}\right] + \frac{Q_2(t)}{6\pi\lambda D}\left[\gamma + \ln\left(\frac{D'}{12\pi D}\right)\right] \quad (5)$$

(a) One-batch disposal (reference case)

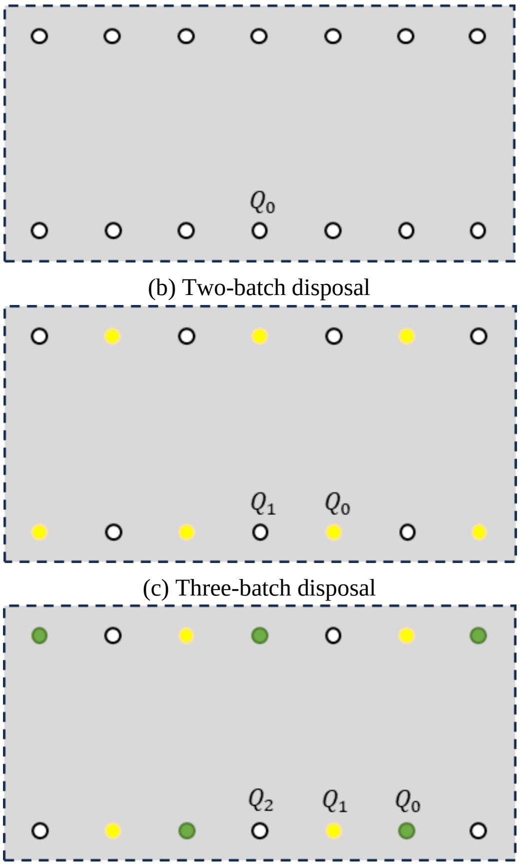

Fig. 1. Visual description of (a) One, (b) Two, and (c) Three - batch disposal.

The repository dimensions in the calculations are based on the KRS+ design [3]. Material properties for the host rock are derived from KAERI Underground Research Tunnel data [4], while the buffer thermal conductivity was measured in this study. The average and standard deviation were utilized in generating 1,000 values of buffer thermal conductivity following normal distribution. The analytical solutions calculate the temperature increases relative to the initial underground temperature of 25 °C, considering a geothermal gradient for 500 m depth and surface conditions. In the multi-batch disposal scenarios, SNF batches differ in the discharge time but are disposed of together. An interval Δt of discharge is set assuming about 2070 beginning of deposition. The decay heat of SNF presented in Eq. (6) implied 4.0 wt.% enrichment of ^{235}U and 45 GWd/MtU burnup, which are the reference SNF values in Korea.

$$Q_1(t) = 2.683 \times 10^4 \times (t + 40)^{-0.758} \quad (6)$$

3. Results and Discussion

3.1 Thermal conductivity of GTC4

Figure 2 presents the thermal conductivity of GTC4 bentonite with a dry density of 1,600 kg/m³ at different water content levels. The result shows that the thermal conductivity varies between 0.44 W/(m·K) and 1.22 W/(m·K), increasing as water content rises. The linear correlation coefficients R^2 between the water content and thermal conductivity is 0.984.

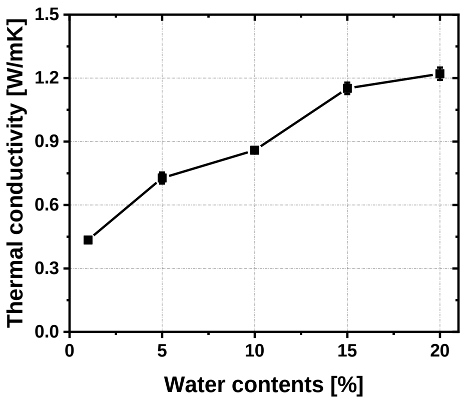

Fig. 2. Thermal conductivity of GTC4 bentonite.

3.2 Thermal and uncertainty analyses

The temperature changes at the mid-height of the central canister are analyzed under multi-batch disposal scenarios. While the overall temperature trend remains consistent, applying the multi-batch approach results in reduced maximum temperatures, leading to the greater decrease observed as the longer time delay Δt becomes. In the two-batch scenario, the maximum temperature decreases from 94.6 °C (reference case) to 92.0 °C, a reduction of 2.6 °C. In the three-batch scenario, it drops further to 91.4 °C, representing a 3.2 °C decline.

Uncertainty analyses were conducted for the multi-batch disposal strategies. The results suggest that if the peak temperature is 94.6 °C, there is 95.0% confidence that it will not exceed 96.4 °C and 99.7% confidence that it will not exceed 97.8 °C. Figure 3 presents the maximum temperature, 95%, and 99.7% confidence levels for two-batch and three-batch disposal scenarios, respectively.

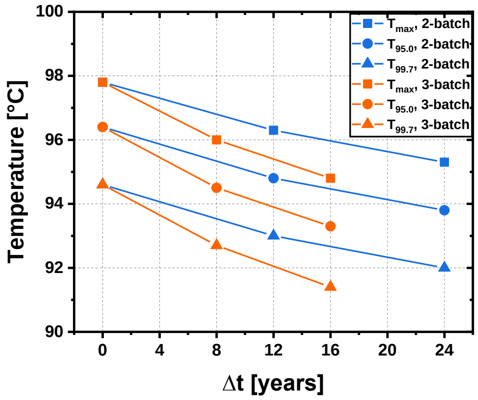

Fig. 3. Peak temperatures at 50, 95, 99.7% confidence levels.

4. Conclusion

This study introduced a multi-batch disposal strategy and developed an analytical method to evaluate the thermal effects of two-batch and three-batch disposal. Compared to the one-batch reference case with a peak temperature of 94.6 °C, the two-batch and three-batch approach lowered the maximum bentonite temperature by 2.6 °C and 3.2 °C, respectively. By reflecting the variability of SNF into repository design, multi-batch disposal may enhance site utilization efficiency. Hence a decrease in the disposal area should be estimated as future work accordingly. Additionally, the analytical solutions facilitated a statistical analysis by modeling thermal conductivity as a normal random variable based on the measured values on GTC4 bentonite. Across all disposal scenarios, the 95% and 99.7% confidence levels indicated temperature increases of approximately 1.8 °C and 3.2 °C above the average, respectively.

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