Analysis of Arrangement of Domestic High Burn-up PWR Spent Nuclear Fuel in Deep Geological Disposal

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1. Introduction

Recently, the deep geological disposal system isolating a spent nuclear fuel (SNF) is considered a disposal method of high-level radioactive waste for the safety of humans or the natural environment. The one of important requirements for maintaining the thermal stability of these systems is that the temperature of the buffer does not exceed 100 °C even though the decay heat is emitted from high-level radioactive wastes loaded in the disposal container.[1] In 2007, a deep geological disposal system based on the Swedish disposal concept was developed for the SNF in Korea.[2] To respond to the development process, lee et al. (2019) developed a deep geological disposal system that ensures thermal stability for domestic pressurized light water reactor (PWR) SNF with 55 GWD/MTU of discharged burn-up.[3]

The thing is that the recent fuel activity is pursuing to operate further high burn-up fuel conditions, and it leads to emergency core cooling system (ECCS) revision for extending the license above 60 GWD/MTU in the world. In order to maintain thermal stability when spent nuclear fuel with discharged burn-up of 60 GWD/MTU or higher is disposed, a spacing of deposition hole should be wider than that of disposal system with 55 GWD/MTU. However, in countries with a large amount of waste and limited land area, such as Korea, it is necessary to appropriately set a spacing of deposition hole to maximize available space.

In this regard, this study performs two tasks: first, it calculates decay heat at 60 GWD/MTU of discharged burn-up and performs thermal analysis of existing systems to calculate a spacing of deposition holes satisfying thermal stability; second, it proposes an arrangement that considers disposal efficiency and calculates a spacing of deposition holes compared to existing systems.

2. Numerical method

2.1 Decay heat

This study used PLUS7 with 4.5 wt.% of initial concentration of U-235 as the reference nuclear fuel to calculate the decay heat of SNF with 60 GWD/MTU of discharged burn-up, following Lee et al. (2019). The source term evaluation was performed with the ORIGEN-ARP module of SCALE 6.2, assuming a power density of 41.5 MW/MTU, a three-cycle operation and a reload period of 60 days.

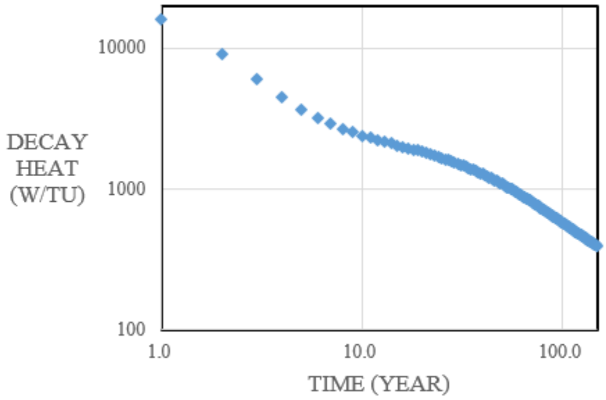

Fig. 1. Decay heat over time

Figure 1 shows the decay heat value calculated for R-SF (Regular-Spent Fuel) and S-SF (Short-Spent Fuel), which have cooling periods of 45 and 50 years respectively at the time of disposal, following Lee et al. (2019). R-SF denotes 453cm-long nuclear fuel from the OPR 1000 and APR 1400 reactors, while S-SF denotes 406cm-long nuclear fuel from the WH type reactor.

2.2 Thermal analysis

The thermal analysis was evaluated for thermal stability that the maximum temperature of the buffer over time met the thermal design requirements. Conduction heat transfer is the dominant mechanism of heat transfer in the disposal system, which is mainly composed of solid materials and receives decay heat. Convection and radiation heat transfer can be neglected due to the small gaps of tens of mm between components and the slow groundwater flow velocity. Thus, the energy balance of the system is governed by conduction heat transfer and decay heat, and the governing equation is expressed by:

$$\frac{\partial}{\partial t}(\rho c T) = \nabla \cdot (k \cdot \nabla T) + \ddot{Q}$$

ANSYS Mechanical, a finite element method program, was used to perform thermal analysis of the disposal system. As shown in Figure 2, the analysis model included the entire depth of 1000 m on the surface and 1/4 of one disposal hole at a depth of 500 m. The initial temperature was set to 10°C at 0m on the surface and a temperature gradient of 3°C/100m was applied with respect to depth.

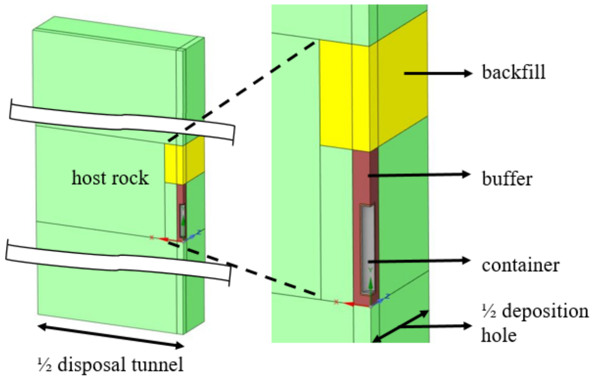

Fig. 2. Analysis model

3. Case 1 : Existing arrangement

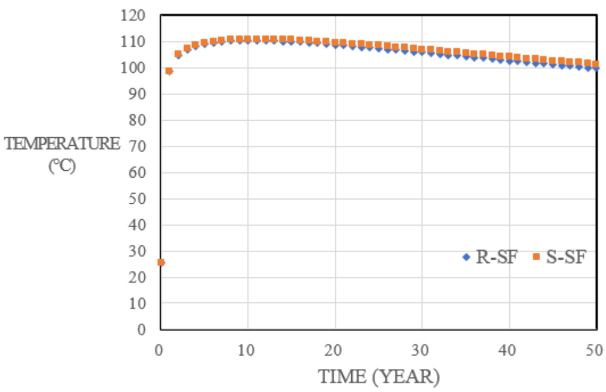

Fig. 3. Maximum temperature of buffer over time

As shown in Figure 3, the buffer exceeded its thermal design requirement of 100 °C after 11 years of disposal for both R-SF and S-SF at 60 GWD/MTU, reaching 110.4 °C and 111.0 °C respectively in existing systems.

We investigated the effect of varying the spacing of deposition hole on the maximum temperature of the buffer to meet the thermal design requirements.

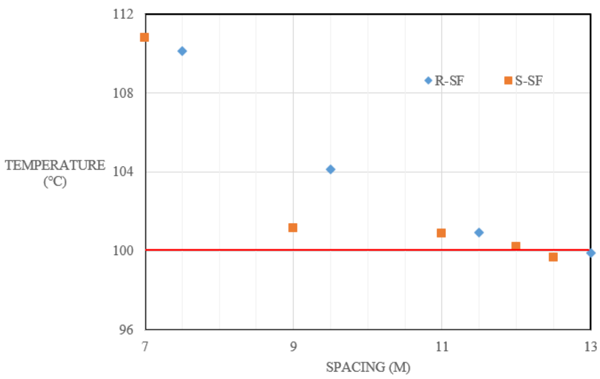

Fig. 4. Spacing of deposition hole according to maximum temperature of buffer

Figure 4 shows that the spacing of deposition holes required to meet the thermal design requirements is 13 m for R-SF and 12.5 m for S-SF, which is 5.5 m larger than the existing spacing.

3. Case 2 : A modified arrangement

Korea has a large amount of nuclear waste and a limited land area, requiring an efficient disposal system design. The area per deposition hole is determined by the product of the spacing of deposition hole and the spacing of disposition tunnel. To reduce the disposal space for a large amount of waste, we explored ways to decrease the spacing of deposition hole compared to a disposal system design.

Cho et al. (2019) estimated that 62,500 SNF assemblies from domestic PWRs would be generated by 2082, of which only about 30% had been discharged by 2018. Moreover, 99% of the SNF so far had a discharged burn-up of less than 55 GWD/MTU.[4] Based on the current government's second roadmap for high-level waste management, which expects the disposal system to start operation in 2037, we assumed that there would be no significant impact on the disposal system design if we alternately arranged 55 GWD/MTU SNF and 60 GWD/MTU SNF as shown in Figure 5.[5]

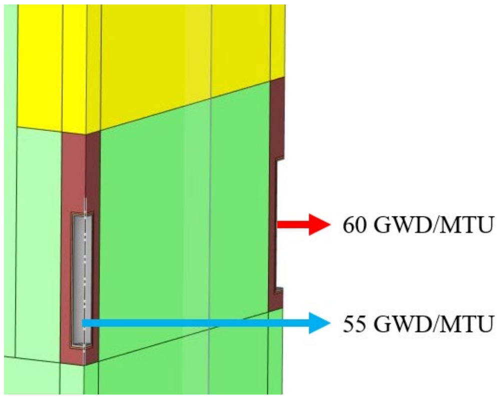

Fig. 5. Analysis model at a modified arrangement

We used ANSYS to perform thermal analysis on the geometry in Figure 5, as in case 1, to calculate the maximum temperature of the buffer. We applied different decay heat values for 55 GWD/MTU SNF and 60 GWD/MTU SNF, using the value from lee et al.(2019) for 55 GWD/MTU SNF.

Fig. 6 shows that the minimum spacing of deposition hole ensuring thermal stability in a modified arrangement is 12.5m for R-SF and 11.5m for S-SF. This represents a reduction of 0.5m for R-SF and 1m for S-SF compared to the existing arrangement. Compared to the disposal of only SNF of burn-up of 60 GWD/MTU, a modified arrangement reduces the area ratio per deposition hole by about 4-8% compared to the existing one: 0.96 for R-SF and 0.92 for S-SF.

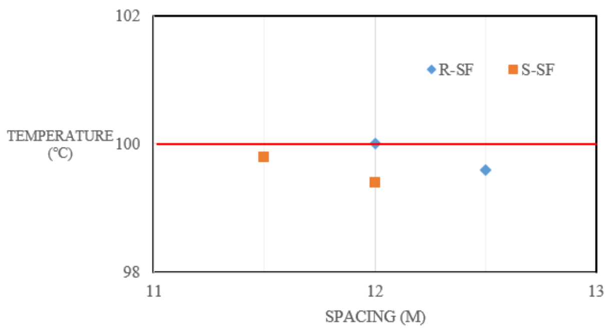

Fig. 6. Spacing of deposition hole according to maximum temperature of buffer at a modified arrangement

Nevertheless, following the previous suggestion that alternately arranged SNFs of different burn-up, 55 GWD/MTU SNF would have a considerably larger temperature margin than 60 GWD/MTU SNF. Consequently, the deposition hole spacing could be significantly wider, and 55 GWD/MTU SNF in this study would occupy a greater area per deposition hole than 55 GWD/MTU SNF in lee et al (2019).

4. Conclusions

This study showed that the existing design system failed to achieve thermal stability for SNF disposal of 60 GWD/MTU, and we calculated the spacing of deposition hole required to achieve it. We also proposed a modified arrangement considering the domestic environment, and we showed that it reduced the spacing of deposition holes ensuring thermal stability compared to the disposal of only SNF of burn-up of 60 GWD/MTU.

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