Journal of Radiation Industry 15 (3) : 199 ~ 205 (2021) https://doi.org/10.23042/radin.2021.15.3.199

Technical Paper

Thermal Safety Evaluation of Buffer for Preliminary Conceptual Design of SNF Disposal System

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Abstract - The conceptual design of the spent nuclear fuel (SNF) disposal system is significant in that it must maintain the safety for a very long period in consideration of geological characteristics. A buffer, one of the important components of the SNF disposal system, minimizes the inflow of groundwater and relieves the shock caused by a mechanical factor. In order to construct an optimal disposal system, as decay heat of SNF causes temperature variation in the buffer that affects the mechanical performance of the system, it is substantial to estimate accurately the temperature variation. Therefore, in this study, the disposal environment required for thermal evaluation of buffer was established by reflecting domestic conditions. Using this setting value, the thermal evaluation of buffer was performed according to the distance between disposal pits and the change of overpack material in the disposal cask. As a result of the evaluation, it was confirmed that most of the cases had satisfied the criteria of thermal safety, but some of the cases had not.

Key words : Disposal cask, Finite element method, High-level radioactive waste, Spent nuclear fuel

INTRODUCTION

These SNFs are generally stored temporarily in Nuclear Power Plant (NPP), transported to storage facilities, stored for a certain period of time, and then permanently disposed of if their heat/radiation is reduced. Permanent disposal is the last step in the management of SNF, which means that they do not rely on being monitored or maintained and remain in disposal facilities that can safely isolate SNF for a long time. Although the Korean government's for managing SNF has not been established, it is absolutely certain that the permanent disposal of SNF generated by nuclear power generation is the only way to protect all mankind and nature in the present and the future.

SNF disposal system considering deep geological disposal consists of natural barriers such as rocks and soils, and engineering barriers such as a disposal cask, backfill, and a buffer. These natural and engineering barriers are composed of multiple barriers, and serve to delay nuclide leakage for long-term radioactive decay. So, proper material selection and placement of the engineering barriers loaded with SNF is essential in order to (so as to) safely dispose of SNF. As shown above, it has to be sure that a disposal cask should be designed to maintain the temperature of the buffer of the engineering barrier and it should not exceed 100°C because it would be affected by decay heat generated from SNF (Lennart 1988).

Analyzing the research cases of countries, Sweden (Okmark and Claesson 2005; KORAD 2018) plans to dispose of SNF directly in crystalline rock about 500 m deep underground, and developed the KBS-3 concept to isolate SNF protected by the multi-barrier system. Japan (JNCDI 1999) divided the light and soft rocks into a variety of disposal tunnels and a disposal pit(s) intervals in accordance with the structural inte-

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grity and the maximum buffer temperature limit, and suggested the optimal placement method. In Canada (Baumgartner 2005), the distance between the disposal tunnel and the disposal pit was set up according to the cooling period of the SNF of CANDU. In addition, a study was conducted to derive the optimal conditions by analyzing the heat load per unit area at the disposal site and the density of uranium. Finally, in the United States (Sander 2013; Energysolutions and NAC international 2015), although the Yucca Mountain disposal project became a blank, a canister that can be used simultaneously for transport, storage and disposal, which can increase safety and economy, was developed. In addition, various studies concerning safety, such as evaluation of material properties of disposal overpack, are being conducted.

The research and development on the disposal of SNF in Korea have developed disposal system by benchmarking the Swedish KBS-3 concept of disposing on stable rock 500 m underground (Lee *et al*. 2007; KAERI 2008). In addition, it was confirmed that a number of studies were conducted on the structural integrity evaluation of the disposal cask (Choi *et al*. 2006) and the evaluation of the heat of bentonite.

Looking at the above research trends, it can be seen that diverse basic studies on disposal have been conducted. However, the research of leading foreign countries was performed in accordance with the geological environment of the country's disposal site, but in the case of Korea, the site of disposal was not determined, so the research was carried out without considering the geological environment of Korea, and the results were also insufficient.

In this study, given the specifications of the SNF dual purposed cask developed in Korea, the specifications of the canisters that can be commonly used in the process of transportation, storage, and disposal are determined, and we will conduct a thermal safety assessment of buffers, one of the main components of the disposal system.

SELECTION OF SNF DISPOSAL SYSTEM

1. Selection of standard SNF

In 2007, a standard deep geological disposal system was developed for SNF in PWR in Korea, and the standard SNF for the development of this system has an initial enrichment of 4.0 wt%, an burn up rate of 45 GWD·MTU^{-1}, and a cooling time of 40 years (Lee and Choi 2005; Lee *et al*. 2007). Subsequently, with the advancement in nuclear power technology, the characteristics of SNF emitted from domestic nuclear reactors have also changed. Since 2010, most of the plus-7 type SNF with an initial enrichment of 4.5 wt% and burn up the rate of 55 GWD·MTU^{-1} has been generated, and it is estimated that this fuel will account for more than 70% of the total generation in the future. It is proposed to set such high burn up SNF as a standard for the design of deep geological disposal systems (Cho *et al*. 2008). Therefore, in this study, the SNF with the highest burn up rate generated from nuclear power plants 1 and 2 was selected as the standard SNF.

The standard spent fuel is WH 17×17 type, the initial enrichment of which is 4.0wt%, and the burn up rate of 60 GWD·MTU^{-1}. The decay heat of SNF that was cooling time for 40 years after the nuclear reactor was released was calculated, and the period for obtaining the amount of heat was 10,000 years. The decay heat was obtained by utilizing ORIGEN-ARP of commercial software SCALE 6.1. The equation for the tendency of SNF to decay heat is shown below (Malbrain and Lester 1982).

$$\mathrm{P(t)} = C_1 EXP\left(\frac{1}{C_2} + C_3 t\right) \quad for \;\; 1 < t < 30 \;\; yr \tag{1}$$

$$\mathrm{P(t)} = C_1 t^{C_2} \quad for \;\; 30 \le t \le 1{,}000{,}000 \;\; yr \tag{2}$$

In the previous study (KAERI 2005), the relative error between the decay heat calculated by the above formula and the decay heat calculated through ORIGEN-ARP was verified to be 0.001%. Therefore, the decay heat calculated by ORIGEN-ARP was applied to the safety evaluation of this study. The decay heat of an assembly of SNF in this study is shown in Fig. 1.

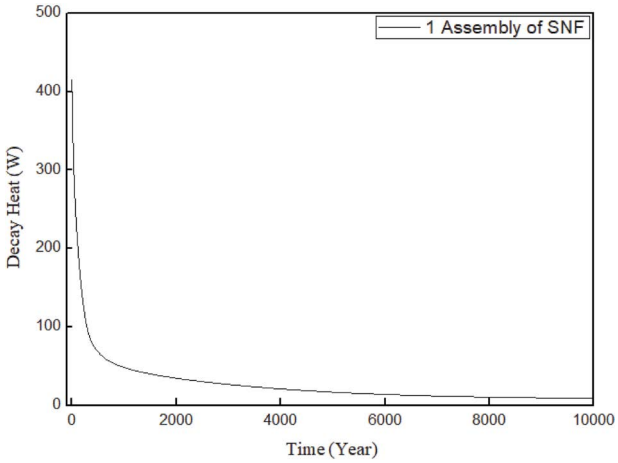


Fig. 1. Decay heat of one assembly of SNF.

2. Determination of engineered barrier system specifications

In order to isolate the spent fuel from the ecosystem, the deep geological disposal is composed of a multi-barrier system that includes natural barriers such as rocks and engineered barrier system (EBS) such as a disposal cask and a buffer. Natural barriers are unreliable due to the heterogeneity and uncertainty of the rocks. Therefore, so as to secure high safety, the concept of an EBS composed of a disposal cask, buffer, backfill and a disposal tunnel is introduced as shown in Fig. 2.

Factors influencing the specifications and arrangement of the disposal tunnel and disposal pit should be determined by considering the structural integrity, thermal safety, construction, operation, closure, and economics (Choi *et al*. 2006).

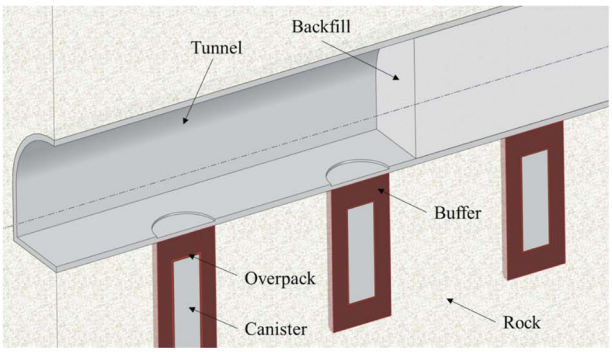


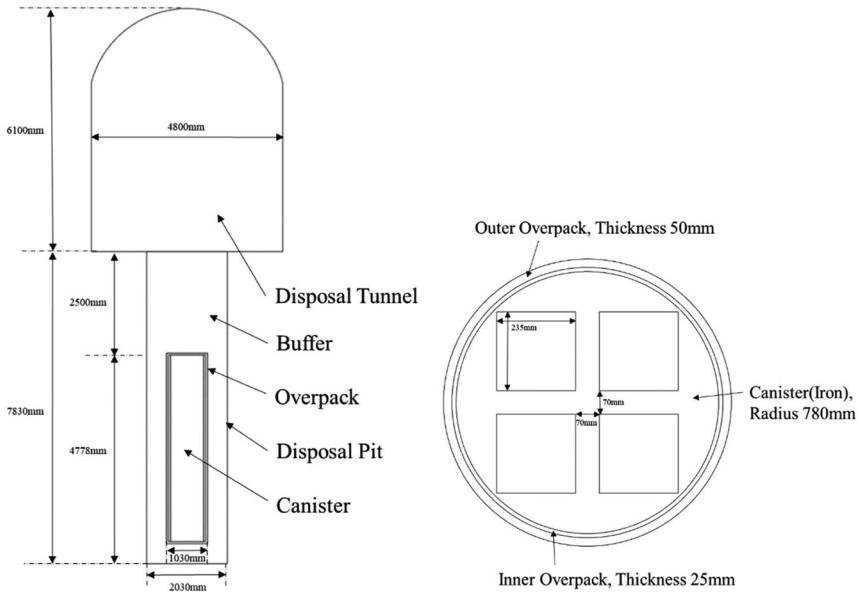
Fig. 2. Conceptual diagram of engineering barrier system.

In this study, taking the above condition into account, the disposal tunnel was selected as 4.8 m wide and 6.1 m high, and 2.03 m wide and 7.83 m high for disposal pit (KORAD 2014). Additionally, the distance between the disposal tunnel and the disposal pit is also a very significant factor in evaluation the safety of EBS. The distance between disposal tunnels was determined to be 25 m, which is the minimum interval for construction and operation (Kari 2003), and in the case of disposal pit, from 5 m to 15 m, the interval between disposal pits to ensure thermal safety of the buffer was evaluated. The disposal cask can accommodate 4 assemblies of SNF. Considering the size of the canister that can be commonly used for transportation, storage, and disposal, it was determined as a canister type container having a diameter of 780 mm, a height of 4,778 mm, and a distance between spent fuel bundles of 70 mm. In addition, the overpack located on the outside of the canister consists of a double layer. The inner overpack is 25 mm thickness and the outer overpack is 50 mm thickness. Fig. 3 shows the specifications of the EBS selected in this study.

THERMAL SAFETY EVALUATION OF BUFFER

1. Evaluation target

SNF has a cooling period of time before disposal in the



(a) Engineering barrier system (b) Disposal cask

Fig. 3. Determination of engineering barrier system specifications in this study.

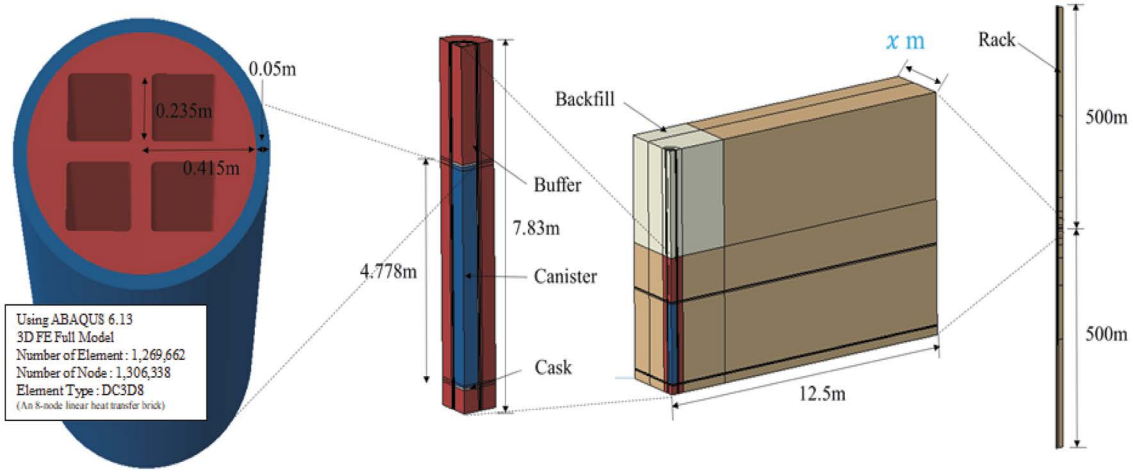


Fig. 4. Finite element model of SNF disposal system for heat transfer analysis.

Table 1. Thermal material properties of SNF disposal system

Items	Density ($kg \cdot m^{-3}$)	Thermal conductivity ($W \cdot m^{-1}\,°C = J \cdot s^{-1} \cdot m^{-1}\,°C$)	Specific heat ($J \cdot kg^{-1}\,°C$)
Overpack (Copper)	8,900	386	383
Overpack (Titanium)	4,500	17	520
Cast insert	7,200	52	504
Buffer (Na-bentonite)	1,970	1.0	1,380
Backfill	2,270	2	1,190
Rock	2,650	3.2	815

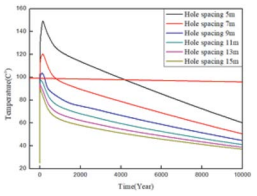
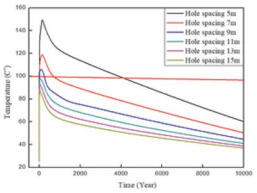
cask. However, even after disposal is completed, decay heat is continuously generated, which affects the performance of the EBS and also affects the behavior of rocks and groundwater. The thermal effects of decay heat are very important considerations for the safe disposal of SNF. Because it would be affected by the decay heat, the buffer of the engineering barrier system should be designed to maintain the temperature of the buffer and it should not exceed 100°C (Lee *et al*. 2011; Kim *et al*. 2018). This is to maintain sufficient performance without changing the components of bentonite, a buffer material that inhibits inflow into the disposal cask caused by submersion of groundwater and the leakage of the disposed of radioactive material outside the disposal cask. Therefore, in this part, the thermal effect on the buffer is analyzed according to the change in the overpack material outside the disposal cask and the change in the distance between the disposal pits.

2. Analysis model and material properties

The scope of the analytical model for the thermal safety evaluation of the buffer is shown in Fig. 4. Modeling was performed up to 500 m and 500 m on the basis of the disposal cask, and the disposal tunnel and the disposal pit are arranged at regular intervals. As mentioned above, the distance between the disposal tunnels was determined to be 25 m, and the distance between the disposal pits was 5 m, 7 m, 9 m, 11 m, 13 m and 15 m. While modeling, total of 6 cases were considered. A finite element model of the deep geological disposal system was generated by 8-node quadrilateral elements (Type DC3D8 for the heat transfer analysis and C3D8R for the stress analysis in ABAQUS element library). It was composed of 1,269,662 elements and 1,306,338 nodes.

In order to perform the thermal analysis, it is necessary to secure thermal property data for the disposal cask, buffer, backfill and the rock constituting the disposal system. Thermal properties data include density, thermal conductivity and specific heat. Once the disposal site is confirmed later, it is necessary to obtain accurate material property data and perform analysis. In this study, as shown in Table 1, material properties were applied to each structure by reflecting the

Table 2. Temperature analysis results of buffer

Material of outer overpack	The distance between the disposal pit (m)	Max. temperature of buffer (°C)	Safety margin	Figure
Copper	5	149.5	0.67	
	7	120.9	0.83	
	9	105.5	0.95	
	11	96.7	1.03	
	13	92.3	1.08	
	15	89.7	1.11	
Titanium	5	150.7	0.66	
	7	122.0	0.82	
	9	107.1	0.93	
	11	98.6	1.01	
	13	94.1	1.06	
	15	91.8	1.09	

existing reference (Cho *et al*. 2007).

3. Design criteria and analysis conditions

For thermal analysis conditions of the spent fuel disposal system, initial conditions and boundary conditions should be set up appropriately. The boundary conditions were set up in the analysis area where the decay heat of SNF in the disposal cask was not affected. In addition, the initial temperature (3°C/100 m) for thermal analysis was configured as a fixed value by setting the surface temperature and the temperature of underground 1,000 m to 10°C and 40°C, and the insulation condition was set up for the vertical section. When disposal cask is loaded, decay heat of the SNF diffuses in the order of disposal cask, buffer, backfill and rocks. Therefore, in this study, the heat released by the decay heat of SNF selected in section 2.1 was applied to this analysis.

In order to increase the efficiency of the analysis, convection and radiation were not applied in that the main heat transfer method is heat conduction because the disposal tunnel is closed with backfill material. The computer program for this analysis was evaluated using ABAQUS 2018 (ABAQUS 2018), a commercial computer code used for the finite element method.

4. Analysis results

Table 2 shows the results of the thermal analysis of the buffer. Regardless of the material of the outer overpack, the limit temperature of the buffer was exceeded at 100°C at a distance of 9 m or less. The difference was slight, however, the maximum temperature of the buffer was found to be higher in the order of titanium and copper in the outer overpack material. Although the distance between the disposal holes was 15 m, the safety factor of the two materials did not exceed 1.2, but the difference was insignificant. Fig. 5 shows the maximum distance between disposal pits to ensure thermal safety for each candidate material of the outer overpack. With 10 m of copper and 10.8 m of titanium, copper ensures thermal safety at the shortest distance between the disposal pits.

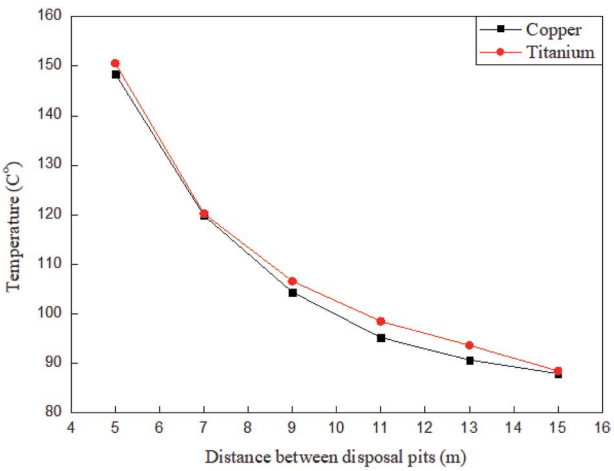


Fig. 5. Minimum allowable distance between disposal pits.

Summarizing the results of the thermal analysis of the buffer, the influence of the material of the outer overpack on the thermal stability of the buffer was very low. On the other

hand, it was confirmed that the distance between the disposal pits is a very significant factor for the thermal safety of the buffer.

CONCLUSIONS

In this study, a disposal system suitable for domestic conditions was selected, and thermal safety evaluation of the buffer was performed based on the above results. The following key findings have been derived.

(1) In order to evaluate the safety of the buffer in the SNF disposal system, this study analyzed the standard SNF, disposal environment, and EBS and derived representative values to be applied to the analysis.
(2) As a result of the thermal evaluation of the buffer, it was confirmed that the thermal safety effect of the overpack material was at most 5%, very small, and the change in the distance between the disposal pits was dominant in the thermal effect.
(3) The results of the thermal analysis of the buffer conducted in this study reflected the SNF generated in Korea and the geological environment in Korea. Buffer and disposal cask are the most important factors in EBS. Therefore, a structural integrity evaluation of the disposal cask will be carried out later to complete the safety assessment of the overall EBS.

ACKNOWLEDGEMENTS

This work was supported by the Korean Nuclear R&D Program organized by the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20181710201770).

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Received: 23 July 2021
Revised: 13 August 2021
Revision accepted: 16 August 2021