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Reconsideration of thermal criteria for Korean spent fuel repository

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ABSTRACT

In this study, the appropriateness of the current thermal criteria for a geological repository for Korean spent fuel is reviewed based on the reported technical information, and the possibility of the elevation of the maximum temperature limit is assessed. The results show that even if the maximum temperature limit at the interface between the canister surface and the surrounding buffer is elevated from 100 °C to 125 °C, there is no significant influence on the integrity of the canister and the buffer. This elevation of the maximum temperature limit can improve the disposal density by about double, and contribute greatly to finding a suitable site for a spent fuel repository.

1. Introduction

A geological repository has been considered the most probable option to protect the public health and environment from the radiological effects of spent fuel during its harmful period. The geological repository will be constructed in a host rock at the depth of several hundred meters below the ground surface. A geological repository consists of a network of disposal tunnel, and the spent fuel packed in a canister will be deposited in an array of large-diameter deposition holes drilled into the floor of the disposal tunnel. After the emplacement of a canister, the space between the canister and inner wall of a deposition hole will be filled with a compacted bentonite buffer. When all deposition holes in a disposal tunnel are filled, the tunnel is backfilled with a compacted bentonite–sand mixture. Since the spent fuel generates decay heat for long periods of time, there are thermal criteria for the geological repository.

The thermal criteria act as a constraint on the design of a geological repository because they restrict the amount of spent fuel to be disposed of in any given area of the repository, namely the disposal density. The typical thermal criterion widely used for the repository constructed in saturated hard rock is that the maximum temperature at the interface between the canister surface and the surrounding buffer should not exceed 100 °C. However, when this temperature limit is applied to the design of a geological repository, a considerably large area is required for the site of the geological repository because it includes an excess safety margin for the deposition hole spacing and the distance between disposal tunnels. This over-conservatism makes it difficult to find a suitable site for a spent fuel repository in a small country with a high population density where a sufficient site area is unavailable, and may act as the main obstacle to the sustainable utilization of nuclear power for supplying electricity.

Therefore it is necessary to review the appropriateness of the thermal criteria for a geological repository to improve the site availability for spent fuel disposal and to ensure the sustainable utilization of nuclear power. Wersin et al. (2007) reviewed experimental and natural analog data on thermally-exposed bentonite and concluded that available information supports temperature criterion for the bentonite buffer of at least 120 °C. In PEBS project Case 2, the performance of a bentonite barrier exposed to temperatures above 100 °C under variable saturated conditions was investigated. No significant changes in the properties were observed, and related requirements are still expected to be met (Gaus et al., 2014).

In this paper, the technical backgrounds of a temperature limit of 100 °C which is currently applied to determine the lay-out of Korean spent fuel repository are analyzed, and their reasonability is reexamined to remove the over-conservatism involved in the temperature criterion.

2. Thermal criteria for a geological repository in hard rock

The typical thermal criteria for the geological repository in a hard rock formation is that the maximum temperature at the

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interface between the canister and the buffer should not exceed 100 °C (SKB, 2009; Ikonen, 2005; JNC, 1999; Simmons and Baumgartner, 1994). Although the temperatures at the canister–buffer interface above 100 °C were accepted by the regulators in Swiss safety analysis (Nagra, 1985), and the duration of the thermal transient needs to be considered, the temperature limit of 100 °C has been established to guarantee the long-term integrity of a canister and a buffer in the repository environment in several countries.

The candidate materials for a waste canister are copper, titanium, steel and high nickel alloy (SKB, 2009; Simmons and Baumgartner, 1994; JNC, 1999; Nagra, 1985; Richard and Voegele, 2014). Among them, there is no thermal constraint for steel and nickel alloy canisters. For a copper canister, the possibility of groundwater vaporization and subsequent enrichment of precipitated substances such as salts on the canister surface during the initial unsaturated phase was considered. This enrichment of the precipitated substances might make the water chemistry around the canister aggressive and have a bad influence on the canister material when the repository is saturated with groundwater (Werme, 1998). For a Grade-2 titanium canister, the occurrence of crevice corrosion at high temperature was considered. To prevent the possibility of crevice corrosion, the maximum temperature of the canister surface should be maintained below 100 °C (Simmons and Baumgartner, 1994).

The principal ingredient of bentonite which is a candidate material for the buffer, is smectite. Smectite which is swelling clay, can be chemically converted into a non-swelling illite at high temperature when potassium ions are present in the groundwater. This conversion process is the so-called illitization, and can deteriorate the sealing properties of the buffer. To avoid the possibility of illitization, the temperature of the buffer is set to be maintained below 100 °C (Simmons and Baumgartner, 1994; JNC, 1999).

3. Temperature history at the interface between canister and buffer

The temperature limit restricts the amount of spent fuel to be disposed of in any given area of the repository, and determines the layout of the disposal tunnel and the deposition hole. If the temperature limit is set to too conservative value and contains an excessive safety margin, its application to the design of a repository may require a repository site with a larger area than is needed. In a small country with a high population density, finding a site for a spent fuel repository is a difficult problem to be solved. If the required site area is larger than it needs to be, the site for a spent fuel repository might be unavailable, and looking for a suitable repository site will be a main obstacle for the sustainable utilization of nuclear power. Therefore, it is necessary to remove the excess safety margin involved in the temperature limit to reduce the site area required for a spent fuel repository.

The thermal criteria presented in the previous section are based on the assumption that the temperatures at the canister surface and in the buffer are constant throughout the post-closure period of a spent fuel repository. However the temperatures at the canister surface and in the buffer are changed with time because the decay heat from a spent fuel decreases with an increase in time. Moreover the temperature in the buffer becomes different with the locations. Therefore the estimation of the temperature history at the canister surface and in the buffer is necessary to review the appropriateness of the thermal criteria.

To estimate the temperature history in the repository, the configuration and dimension of the repository are set based on the Korean reference repository concept (Choi et al., 2008). The disposal of spent fuel after cooling for 30 years is assumed. The time-dependent decay heat, $Q(t)$ (W/MTHM) from the PWR spent fuel with an average specific power of 37.5 MW/MTHM, and an average fuel burn-up of 45,000 MWd/MTHM can be expressed as:

$$Q(t) = 1.455 \times 10^4 (t + 30)^{-0.758} \quad (1)$$

where t is the time in years after the disposal in a repository. The decrease of the decay heat with time is shown in Fig 1. Four PWR spent fuel assemblies are packed in the disposal canister with an outer diameter of 1.02 m and a length of 4.83 m. The disposal canister is emplaced in a vertical deposition hole with a diameter of 2.02 m. The space between the canister and the inner wall of the deposition hole will be filled by a compacted bentonite buffer with a dry density of 1.6 Mg/m^3. The disposal tunnel is backfilled with a compacted bentonite–sand (30:70) mixture with a dry density of 1.6 Mg/m^3. The analysis domain of the hydrothermal model for the thermal analysis of a geological repository is shown in Fig. 2. The analysis domain is limited by vertical planes passing through the center of the canister, half of the distance between the adjacent tunnels, and half spacing between the centerlines of the adjacent deposition holes. This implies that the analysis domain is at the center of the repository and surrounded by the domains with equal decay heat source. This means that all canisters are assumed to be deposited in the repository simultaneously and the domain in the center of the repository has a higher temperature than the domains located at the boundaries of the repository. The repository is located in a granite host rock at a depth of 500 m below the ground surface, and the top of the analysis domain is the ground surface. The bottom of the domain extends to a depth of 200 m below the repository level because there is no effect of the boundary at more than 200 m (Cho et al., 2014; JNC, 1999). For the boundary and the initial conditions, the lateral sides of the analysis domain are assumed to be adiabatic boundaries because of a symmetrical geometry, and the ground surface is considered as a constant temperature boundary of 10 °C. The bottom of the domain is assumed to be a constant temperature boundary considering the geothermal gradient of 3 °C/100 m. It is assumed that the aquifer exists near the ground surface (at the depth of 10 m below), and the atmospheric pressure works on the top of the aquifer. Under the top of the aquifer, the hydrostatic pressure increases with a gradient of 1.013×10^6 Pa/100 m with an increase in depth. The analysis was performed using the TOUGH2 computer code (Pruess et al., 1990). The buffer and backfill were assumed to be initially at a

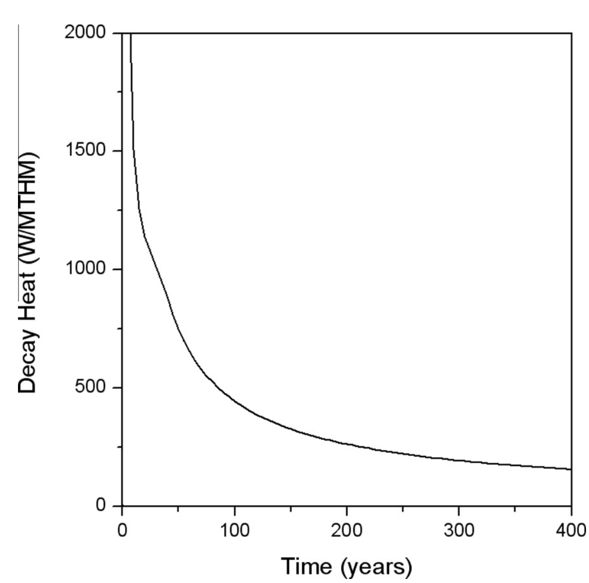

Fig. 1. Decay heat of PWR spent fuel.