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Effectiveness of source term optimization for higher disposal density of spent fuels in a deep geological repository

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ABSTRACT

Spent fuels to be disposed of have various initial ^{235}U enrichments, discharge burnups, and cooling times, and consequently each type of spent fuel has a different decay heat. Because a disposal system design considering respective spent fuel characteristics was not previously possible in Korea, a system was developed based on a conservative reference spent fuel nominated through historical data analyses on the relation of spent fuel inventory with the initial ^{235}U enrichment, discharge burnup, and cooling time. Recently, ASOURCE, an advanced source-term calculation system, was developed by the Korea Atomic Energy Research Institute, making it possible to design a disposal system considering the respective source terms of the spent fuels. In this study, the benefits resulting from a consideration of the individual decay heat for entire spent fuels were evaluated in terms of the footprint of a repository. As a result, it was seen that conservativeness in the disposal system design can be remarkably avoided, revealing a roughly 50% decrease in the footprint of the repository, considering the respective irradiation and cooling profile. It is therefore concluded that optimization of the source term is a viable option in a deep geological disposal system design.

1. Introduction

For the efficient design of a disposal system for spent fuels (SFs), it is necessary to consider the exact decay heat, because it is one of the most important factors affecting the disposal area. The decay heat is a complicated function that is highly dependent on the discharge burnup and cooling time of the spent fuel. The discharge burnup depends on the initial ^{235}U enrichment and neutronic features of the reactor in which the spent fuel was depleted. Even if the discharge burnup is the same, there are many spent fuels with different cooling times. It should be noted that if spent fuels have different discharge burnups or cooling times, they present a variety of source terms such as decay heat, radioactivity, nuclide concentration, and radiotoxicity.

When the Korean Reference disposal System (KRS) was developed, a disposal system design considering the respective spent fuel characteristics was not possible in Korea due to the absence of a suitable code to estimate the source terms that takes into account each source term from entire spent fuels. Therefore, a disposal system was developed on the basis of conservative reference spent fuel determined by historical data analyses of the spent fuel inventory for the initial ^{235}U enrichment, discharge burnup, and cooling time (Cho et al., 2007; Lee et al., 2007).

Recently, an advanced source-term calculation system, called ASOURCE, was developed by the Korea Atomic Energy Research Institute. This code has a powerful capability to characterize the source terms considering respective fuel design, irradiation history, and cooling history. This means that a disposal system can be designed without inclusion of conservatism induced by unrealistic source term calculations for spent fuels (Cho et al., 2013a, 2013b).

In this study, the benefits resulting from consideration of individual decay heat for entire spent fuels were evaluated in terms of the footprint of a deep geological repository to assess the viability of source term optimization in the disposal system design.

2. Description of Korean reference disposal system

The KRS was designed to accommodate the spent fuels from Korea's 4 CANDU and 16 PWR reactors. In this paper, only a disposal system for PWR spent fuel is introduced, because the effectiveness of the source term optimization was investigated only for a disposal system for PWR spent fuel.

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2.1. Source terms and inventory

As described earlier, when the KRS was developed, source terms were estimated for the reference spent fuel determined based on a statistical analysis of the initial ^{235}U enrichment, discharge burnup, and cooling time discharged by the end of 2006. The reference fuel has an initial ^{235}U enrichment of 4.0 wt.%, discharge burnup of 45,000 MWd/tU, and cooling time of 40 years (Cho et al., 2007; Lee et al., 2007).

The regression equation of decay heat for the reference spent fuel is given in Eq. (1), which was used as input data for a thermal-mechanical analysis for a disposal system design.

$$P(t) = 4545.68 \times t^{-0.75756}\ [\mathrm{W/tHM}] \quad (30 \leqslant t \leqslant 10^6 \text{ years}) \tag{1}$$

According to Eq. (1), the decay heat from the reference spent fuel is approximately 890 W/tHM at 40 years after a reactor discharge, which is equivalent to a 1.6 kW/canister.

The total amount of spent fuel, 20,000 MtU, expected from the 16 PWR reactors was considered as a design basis when the KRS was developed.

2.2. The disposal system

2.2.1. General site assumption

Since a repository site for spent fuel has not been discussed in Korea, the design of the KRS was performed on the basis of geological data on granite, which is considered a candidate rock for a disposal system in the R&D discipline (Korea Atomic Energy Research Institute, 2011). It was assumed that the repository would be constructed in a granite rock foundation. A geothermal gradient of 30 °C/km was used in the thermal analysis (Lee et al., 2007).

2.2.2. Disposal canister and buffer

The main role of the canister is to confine radionuclides during the specified period. The canisters consist of two parts, an outer shell made of copper for corrosion resistance and an insert made of nodular cast iron for structural integrity. The thickness of the outer shell is 5 cm. Fig. 1 shows a disposal canister called KDC-1 to accommodate PWR spent fuel. A conceptual design of the KRS was proposed based on the KDC-1, which contains four PWR spent fuel assemblies. The insert was designed to withstand the hydrostatic pressure and swelling pressure caused by the bentonite buffer. The dimensions for the KDC-1 canister are summarized in Fig. 1.

In a geological disposal system, one of the major roles of a buffer is to protect the disposal canister under the given geological conditions. Generally, the buffer material is introduced to prevent seepage of groundwater into the disposal canister. Domestic Korean Ca-bentonite with a dry density of 1.6 g/cm^3, which gives a thermal conductivity of 1.0 W/m °C, was chosen as a candidate buffer material for the KRS. The thickness of the buffer was determined to be 50 cm to provide adequate retardation and adsorption of the radionuclides. Fig. 2 shows the configuration of the disposal hole, including the buffer and canister.

2.2.3. Layout of the disposal system

The depth of the repository is set to be 500 m below the surface. The repository consists of three sections: a disposal area, technical rooms in the controlled area, and technical rooms in the uncontrolled area. The disposal area consists of disposal tunnels, panel tunnels, and a central tunnel. Fig. 3 shows the configuration of the deposition tunnel and holes. The distance between the deposition holes was determined through a thermal analysis. The constraint of the peak temperature in the buffer was 100 °C. The buffer should be kept below the limit temperature to maintain performance of swelling pressure. The spacing of 40 m for tunnels and a distance of 6 m between deposition holes satisfied the contraints, revealing a peak temperature of 98.6 °C.

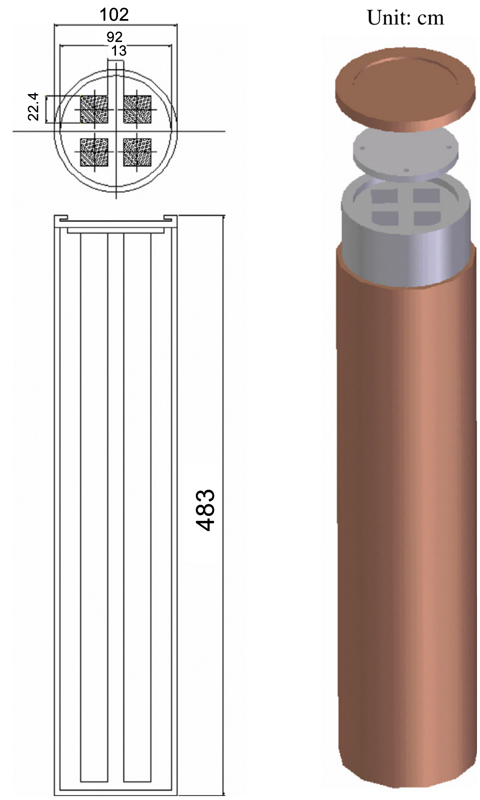

Fig. 1. Schematic illustration of a KDC-1 canister.

For more detailed information, please refer to a study by Lee et al. (2007).

3. Effectiveness of source term optimization

3.1. Source term evaluation tool

ORIGEN2 (Croff, 1980) or ORIGEN-ARP (Gauld et al., 2009) is generally used to estimate the source term needed for the facility design for the storage or disposal of spent fuels. These codes can only estimate the single irradiation and decay history for a specified assembly design. Therefore, a disposal system design considering the respective source terms of entire spent fuels is impossible with these codes.

However, an advanced source-term evaluation program, called ASOURCE, was developed by the Korea Atomic Energy Research Institute for a source term analysis to accomplish the advanced fuel cycle being considered in the Republic of Korea. ASOURCE has the following features: (a) estimation of inflow and outflow source terms in each unit process for the design of the pyroprocess facility; (b) overall inventory calculation for long-lived nuclides and transuranics in SFs stored at each or all reactor sites; and (c) evaluation of grand source terms for a batch of SFs with different irradiation and cooling characteristics to avoid conservative design of a storage or disposal facility. Currently, functional modules, called *Screening*, *DeplDec*, *DecRes*, *ReproRun*, *MetalRun*, and *Batch*, are also available within the system.

The *Screening* module selects SFs, for which the calculations are to be done, from a SF database according to a user definition. The SF database includes the fuel design characteristics, irradiation