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Numerical analysis of thermal process in the near field around vertical disposal of high-level radioactive waste

H.G. Zhao[a,*], H. Shao[b], H. Kunz[b], J. Wang[a], R. Su[a], Y.M. Liu[a]

[a] CNNC Key Laboratory on Geological Disposal of High-level Radioactive Waste, Beijing Research Institute of Uranium Geology (BRIUG), Beijing, China
[b] Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

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ABSTRACT

For deep geological disposal of high-level radioactive waste (HLW) in granite, the temperature on the HLW canisters is commonly designed to be lower than 100 °C. This criterion dictates the dimension of the repository. Based on the concept of HLW disposal in vertical boreholes, thermal process in the near field (host rock and buffer) surrounding HLW canisters has been simulated by using different methods. The results are drawn as follows: (a) the initial heat power of HLW canisters is the most important and sensitive parameter for evolution of temperature field; (b) the thermal properties and variations of the host rock, the engineered buffer, and possible gaps between canister and buffer and host rock are the additional key factors governing the heat transformation; (c) the gaps width and the filling by water or air determine the temperature offsets between them.

1. Introduction

In most of the concepts for deep geological disposal of high-level radioactive waste (HLW), which have been proposed by many countries (such as Sweden, Finland, and China), the potential repositories will be built in depths between −300 m and −1000 m under the ground surface. The decay heat emission from the disposed HLW canisters will be transferred to the surrounding buffer and host rock formation, resulting in high temperatures in the near field. The thermal process and the resultant temperature field are determined by the decay heat emission of the HLW, the initial thermal conditions and the thermal properties of the engineered barrier system (EBS) and host rock, possible gaps in the EBS, and the repository layout, etc.

For disposal of HLW in granite formations, the temperature on the canister surface is set to be less than 100 °C in the repository (Hokmark and Falth, 2003; Kari, 2006; Zhao et al., 2009). The maximum temperature is a criterion dictating the dimension of a repository. The deep repository will basically contain thousands of heat-generating canisters. In order to keep the canister surface temperatures below that limit, the spacing between nearby canisters cannot be arbitrarily small. On the other hand, that spacing must be kept at a minimum value in order to limit the extension of the repository such that it can be accommodated within the given rock volume. This means that it is necessary to derive reliable relations that shall show how the canister surface temperature depends on the canister power, on the thermal resistance between canister, buffer and host rock, on the canister spacing, and on the thermal properties of the buffer and host rock. Consequently, the studies of thermal conductivity properties and temperature evaluation of repository are necessary for the design of long-term safety of HLW repositories.

2. Concept model of HLW repository

This paper aims to analyze the thermal process in the near field of HLW vertical disposal boreholes, which will be excavated vertically from horizontal tunnels in granite. The vitrified HLW canisters are disposed of in vertical holes in the horizontal tunnels. Fig. 1 shows the principal layout of the repository consisting of four parallel panels. Each panel has a central tunnel area, whose width is 60 m measured from canister centers. In one panel there are 300 tunnel pairs, the length of each tunnel pair is 900 m, and the distance is 9.5 m between each tunnel pair. Each tunnel pair can dispose of 80 canisters, and the distance between canisters is 9.5 m. Totally there are 82,630 canisters (Pan and Qian, 2009). In the designed concept, the repository is set at the depth of −500 m (Zhao et al., 2007, 2009; Zhao, 2013).

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* Corresponding author. Tel.: +86 13521800390.
E-mail address: hgz72@sohu.com (H.G. Zhao).

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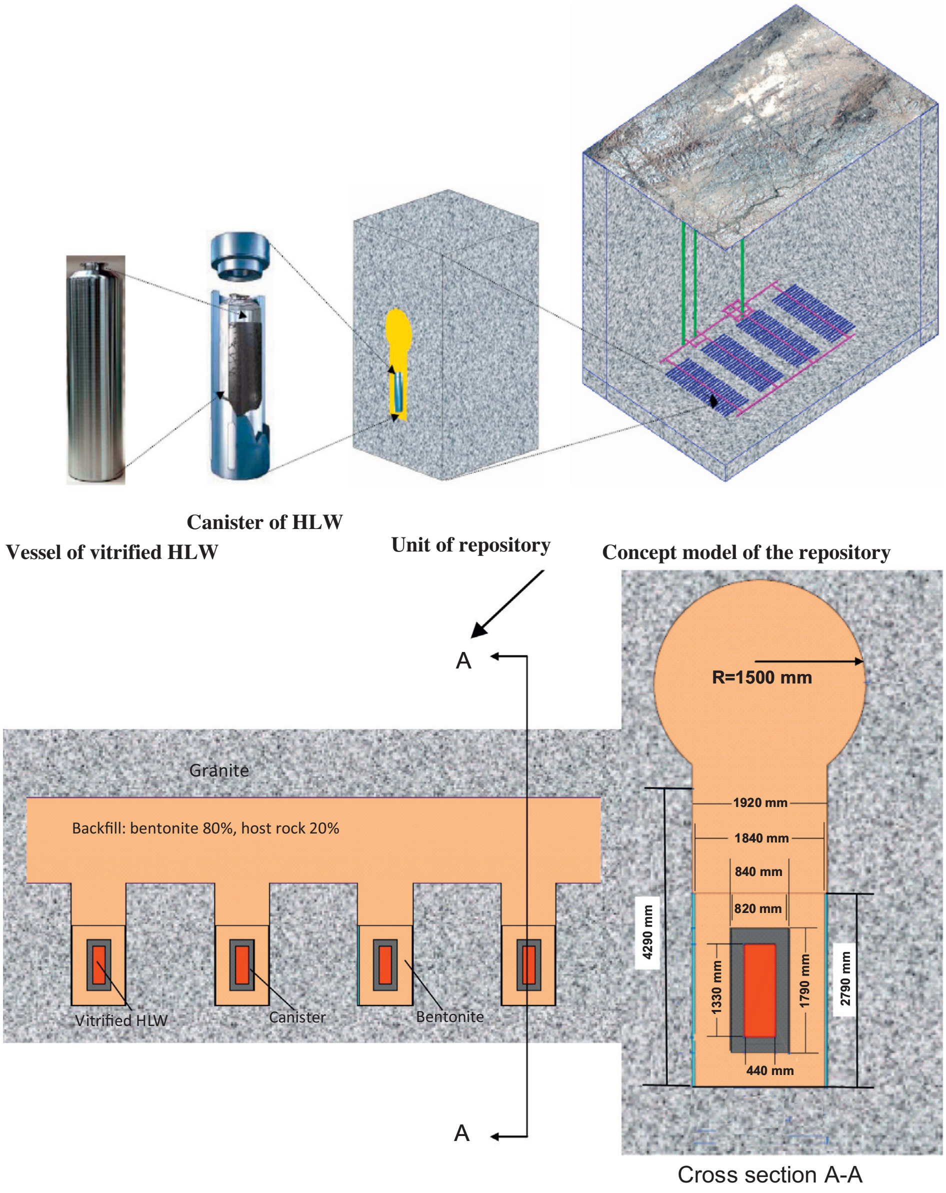

Fig. 1. Concept design of HLW repository.

3. Concept model of EBS

In the designed concept, vitrified HLW will be confined in low carbon–steel canisters. The cylindrical canisters have a size of 820 mm in diameter and 1790 mm in length. They will be disposed of in vertical boreholes with a diameter of 1920 mm and 4310 mm in length. The space between canister and borehole wall will be backfilled with compacted bentonite, and the thickness of bentonite between canister and host rock is 500 mm. Fig. 2 shows schematically the EBS concept for the HLW disposal in vertical boreholes. The previous studies of EBS concept and performance assessment show that the bentonite thickness between 350 mm and 700 mm has the similar function to retard nuclides transportation under the condition of the canister being destroyed (Lennart, 2002). Considering manufacturing and installation tolerances, a clearance (gap) of $r = 5$ mm between the canister and the buffer and $r = 40$ mm between the buffer and the rock wall are assumed to exist (Table 1 and Fig. 2). So the remaining bentonite thickness between the canister and the host rock is 500 mm. The inner gap between the canister and buffer will probably stay dry for a while due to the high temperature at the canister surface. In contrast, the outer gap between the buffer and rock will be filled with water in a relatively short time due to the connection with the saturated host rock. Initially during installation the outer gap is artificially wetted (Kunz et al., 2006, 2009, 2011; Zhao et al., 2009).

4. Decay heat of HLW

The decay heat is a strongly decreasing phenomenon, for example, the decay heat is only a half of the total amount after 50 years. Fig. 3 shows decay power of vitrified HLW, which is based on the ORIGEN2 and ORIGEN-S calculations. Reasonable decay heat level is reached in 30–50 years cooling time depending on the burn-up value of the fuel (Heikki, 2005). The decay power is presented by a sum of exponential terms:

$$P = P_1 \sum_{i=1}^{N} a_i e^{(t_1 - t)/t_i} \tag{1}$$