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Numerical investigation of high level nuclear waste disposal in deep anisotropic geologic repositories

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ABSTRACT

One of the techniques that have been proposed to dispose high level nuclear waste (HLW) has been to bury them in deep geologic formations, which offer relatively enough space to accommodate the large volume of HLW accumulated over the years since the dawn of nuclear era. Albeit the relatively large number of research works that have been conducted to investigate temperature distribution surrounding waste canisters, they all abide to consider the host formations as homogeneous and isotropic. While this could be the case in some subsurface settings, in most cases, this is not true. In other words, subsurface formations are, in most cases, inherently anisotropic and heterogeneous. In this research, we show that even a slight difference in anisotropy of thermal conductivity of host rock with direction could have interesting effects on temperature fields. We investigate the effect of anisotropy angle (the angle the principal direction of anisotropy is making with the coordinate system) on the temperature field as well as on the maximum temperature attained in different barrier systems. This includes 0°, 30°, 45°, 60°, and 90° in addition to the isotropic case as a reference. We also consider the effect of anisotropy ratio (the ratio between the principal direction anisotropies) on the temperature fields and maximum temperature history. This includes ratios ranging between 1.5 and 4. Interesting patterns of temperature fields and profiles are obtained. It is found that the temperature contours are aligned more towards the principal direction of anisotropy. Furthermore the peak temperature in the buffer zone is found to be larger the smaller the anisotropy angle and vice versa.

1. Introduction

Nuclear reactors are systems where energy stored in the nucleus of some radioactive materials are unleashed under highly controlled processes. The fuel used in nuclear reactors are assemblies of fuel pins grouped together to facilitate handling during fueling and defueling operations. Each fuel pin is stack of uranium oxide (in most cases) in the form of ceramic pellets. Fuel pellets are encapsulated in metallic tubes. The useful lifespan of a fuel element in a functioning reactor core ranges between 3 and 5 years. Upon depleting useful energy, fuel elements are removed from the core. They are characterized by high radioactivity and heat energy that continuously decays in time. Once spent fuels are taken away from the core, they are stored primarily under water which provides enough radiation shielding and cooling capacity. On the other hand, liquid high level waste from reprocessing of spent fuel is usually solidified by mixing with melted glass material at high temperatures such that upon consolidation they are incorporated into the glass structure. The melted mixture is then poured into stainless steel containers. Since the shielding requirements of spent fuel remain for thousands of years, a more viable, permanent storage facility needs to be devised. Given the longer period of time where radioactivity of spent fuel need to be contained, the search for safe repository has been a challenge. The fact is that, over the past fifty years, the total amount of spent fuel generated worldwide amounts to approximately 300,000 tHM (IAEA Report, 2006). Out of this amount, approximately one third has been reprocessed. This implies that approximately 200,000 tHM of high level nuclear wastes are still, mostly, in wet storage pools waiting to be transferred to safe permanent repositories. One of the major requirements that need to be fulfilled in a reliable permanent disposal facility for HLW is that it must provide adequate long-term safety without reliance

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on continuous controls or ongoing maintenance. This requirement is mostly satisfied in subsurface geologic repositories, which makes this option attractive. In subsurface geologic repositories, it has been determined that spent fuel is encapsulated in tight canisters that can maintain integrity for a very long lifetime. The repository must be designed to allow the canister intact and tight and should be backfilled with appropriate materials to limit any possible migration of groundwater. Several countries have developed their own HLW disposal strategies which suites their own policy and interest. Although no subsurface repository for HLW has yet been in operation, researchers have identified three principal designs. These are: in-floor disposal, in-room disposal and disposal in deep drill holes (EUR-9909 EN/FR, 1985; EUR-8179 EN/FR, 1982; Ringwood, 1980; RingwoodKesson et al., 1988). In the in-floor type disposal concept, which is the focus of this research, a tunnel network is constructed deep underground and boreholes are drilled at suitable intervals into the tunnel floor (Ahlstrom, 1997; Thunvik and Braester, 1991a; Pettersson and Widing, 2003). In the in-room disposal, the HLW is placed inside the tunnel (Hopkirk and Wagner, 1986; Sasaki et al., 1997). The in-floor disposal method has several advantages including flexibility to arrange the waste units vertically or horizontally while each waste unit is shielded (Sizgek, 2005).

A large number of research works has been conducted to predict the behavior of these systems once in operation [(Thunvik and Braester, 1991b; Nuclear Energy Agency, 2003; Svensk, 2006; Cho et al., 2010) to add but a few]. In particular, the cooling capacity of the host rock to accommodate the decay heat from the HLW has attracted the focus of researchers in the last decade. For example, Sizgek (2005) investigated the temperature distribution in an in-floor disposal system. He conducted transient calculations for a three-dimensional conduction model. The surface cooling times, he considered, varies between 5 and 40 years before subsurface disposal. A single borehole is subject to a 3D numerical investigation of a hypothetical tunnel to optimize the best combination of geometrical settings. He concluded that decreasing the spacing between spent fuel canisters has a more pronounced effect on the temperature field than decreasing the space between the tunnels. Choi et al. (2011) introduced the Korean reference disposal system for spent fuel. This system is estimated to accommodate approximately 20,000 MtU of PWR spent fuels and 16,000 MtU of CANDU spent fuels. They indicated that an area of approximately 4 km^2 was required to dispose 20,000 MtU of spent fuel after 40 years cooling time. They performed thermal analysis to determine the optimum spacing of deposition holes. Lee et al. (2011) analyzed the spacing of the disposal tunnels and boreholes numerically. They highlighted that the spacing between boreholes may be more critical than tunnels' spacing to ensure meeting the allowable thermal criteria in the repository. On the other hand, Lee et al. (2014) conducted numerical study to investigate the effect of partially saturated buffer and backfill regions on thermal behavior of this system. They indicated that the temperature distribution was sensitive to the degree of saturation. The design criteria based on these studies require that the peak temperature does not exceed certain predetermined limit. Such limit, apparently, determines the time required to keep the waste under water before they are released to permanent deep repositories and also the geometric spacing between pit holes and between tunnels.

Albeit the interesting results obtained from these and other research works, they considered, in most cases that the host rock properties are homogeneous and isotropic which are far from being the case in subsurface formations. It is almost rare to find such large piece of rock suitable to accommodate such large amount of waste and the rock is homogeneous, isotropic and fracture-free. Many rocks are thermally anisotropic, showing a preferred direction of thermal conductivity. Apparently this will affect the design criteria mentioned earlier and therefore worth investigation. Anisotropy of thermal conductivity in rock systems arise in two main forms: 1) mineral-anisotropy, or microanisotropy, which refers to anisotropy in rock thermal conductivity that arises from a dominant orientation of an anisotropic mineral, 2) macroanisotropy, which arises from bedding and foliation. For example, a metamorphic rock may have alternating layers of quartz and feldspar, causing a dependence on the direction of foliation, Vosteen and Schellschmidt (2003). In sedimentary rocks, due to stratification and layering processes that took place over the longer geologic time scale, granulometry and mineralogy changes contribute largely towards anisotropy of thermal properties, Brigaud and Vasseur (1989), Deming (1994), Cho and Kwon (2010). Cermak and Rybach (1982) define the anisotropy factor as the ratio of parallel thermal conductivity to normal thermal conductivity, or

$$k = \frac{\lambda_{11}}{\lambda_{22}} \tag{1}$$

Such anisotropy of thermal conductivity is expected to have significant effect on the temperature distribution surrounding the disposal site. In particular, it is known that when thermal conductivity is anisotropic, the heat flux vector is not any more coincident with the temperature gradient vector as it is in isotropic media, Salama et al. (2013, 2014a, 2014b). Since none of the previously mentioned HLW disposal techniques has yet been in operation, and since different countries have different subsurface formation settings, it is worth to investigate the effect of anisotropy of thermal conductivity of the host formations on the generated temperature field, which is primary focus of this research.

2. Problem description

The efficiency of the subsurface disposal facility in isolating dangerous radioactivity from getting released to the environment is based on the existence of two kinds of barriers; namely an engineered barrier system and the host rock. However, as Lee et al. (2011) pointed out, there is a large degree of uncertainty associated with the properties of the host rock, which makes it difficult to accurately predict the fate of radioactivity and decay heat. It is, therefore, always beneficial to consider conservative scenarios when designing and operating such facilities. This again brings up the concern about the possibility that the thermal conductivity of the host rock may be anisotropic and in this case it worth to investigate its effects on the temperature field surrounding the HLW. As indicated earlier, design criteria have been set by different research institutes. For example the design limit suggested by the Korean reference disposal system has been based on the peak temperature of the buffer zone surrounding the HLW canisters, which have been determined not to exceed 100 °C. This limit clearly affect many factors including the time required for surface cooling before disposal, the spacing between canisters' holes, the spacing between tunnels and the overall capacity of the site. Whereas, according to this design limit, they were able to test cases of different disposal conditions as outlined before, their studies have been based on the assumption that the host formations are homogeneous and isotropic. While this may be the case in some settings, it may not be the case in other settings where the disposal host formations may likely be heterogeneous and/or anisotropic. In this case, many of the factors attributed to the design limit have to be re-evaluated to meet the safety criteria (e.g., the time required for surface cooling, the spacing between canisters' holes, etc.). In this research, we show that even a slight anisotropy in thermal conductivity of the host formation can make the peak temperature to