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A global sensitivity analysis of two-phase flow between fractured crystalline rock and bentonite with application to spent nuclear fuel disposal

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ABSTRACT

Geological disposal of spent nuclear fuel in deep crystalline rock is investigated as a possible long term solution in Sweden and Finland. The fuel rods would be cased in copper canisters and deposited in vertical holes in the floor of deep underground tunnels, embedded within an engineered bentonite buffer. Recent experiments at the Äspö Hard Rock Laboratory (Sweden) showed that the high suction of unsaturated bentonite causes a de-saturation of the adjacent rock at the time of installation, which was also independently predicted in model experiments. Remaining air can affect the flow patterns and alter bio-geochemical conditions, influencing for instance the transport of radionuclides in the case of canister failure. However, thus far, observations and model realizations are limited in number and do not capture the conceivable range and combination of parameter values and boundary conditions that are relevant for the thousands of deposition holes envisioned in an operational final repository.

In order to decrease this knowledge gap, we introduce here a formalized, systematic and fully integrated approach to study the combined impact of multiple factors on air saturation and dissolution predictions, investigating the impact of variability in parameter values, geometry and boundary conditions on bentonite buffer saturation times and on occurrences of rock de-saturation. Results showed that four parameters consistently appear in the top six influential factors for all considered output (target) variables: the position of the fracture intersecting the deposition hole, the background rock permeability, the suction representing the relative humidity in the open tunnel and the far field pressure value. The combined influence of these compared to the other parameters increases as one targets a larger fraction of the buffer reaching near-saturation. Strong interaction effects were found, which means that some parameter combinations yielded results (e.g., time to saturation) far outside the range of results obtained by the rest of the scenarios. This study also addresses potential air trapping by dissolution of part of the initial air content of the bentonite, showing that neglecting gas flow effects and trapping could lead to significant underestimation of the remaining air content and the duration of the initial aerobic phase of the repository.

1. Introduction

A final repository for storage of long lived high level nuclear waste would have to guarantee the confinement of the waste for hundreds of millennia, remaining undisturbed through climate changes, including glaciations. It should furthermore not jeopardize resources such as groundwater, ecosystems, valuable ore deposits or geothermal fields (Berglund et al., 2009; Jarsjö et al., 2008; Mathurin et al., 2012; Raguž et al., 2013; Selroos and Follin, 2014), minimizing the risk of future accidental interactions. Surface storage facilities that are presently used throughout the world do not meet such criteria, and therefore constitute a concern for human safety and the environment, in particular if

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the waste would remain in surface storage for extended time periods. Deep geological disposal is currently investigated in many countries as a long-term solution to assess its compliance with all these requirements (Johannesson et al., 2007; Trotignon et al., 2007).

In Sweden and Finland, a multi-barrier confinement strategy called KBS-3 is under development for spent nuclear fuel (Fig. 1). It comprises both natural and engineered barriers. The former consists of sparsely fractured crystalline bedrock (granite or gneiss). A network of deposition tunnels approximately 500 m below ground surface would allow to drill and test vertical deposition holes (height ~ 8 m, radius 1.75 m, minimum spacing ~ 6 m). Each qualified hole would receive a copper canister (first engineered barrier, height ~ 5 m, radius 1.05 m) containing spent fuel rods. Pre-packed, high-density, low moisture content bentonite blocks are under study to serve as an engineered buffer to embed the canisters as a second engineered barrier. Bentonite is also entering in the design of the material intended to backfill the tunnels. This method is designed to be unmonitored and maintenance-free after construction. The focus here will be to characterize the groundwater and air flow interactions between the second engineered barrier, the bentonite blocks, and the natural barrier, the host rock.

Bentonite is a porous material with low permeability under water-saturated conditions. Groundwater flow and particle transport around the canisters would consequently be very slow, which is ideal for confinement (Alonso et al., 2005). When unsaturated, it exerts a high water suction and undergoes a micro-structural change as it gets hydrated, resulting in an overall swelling behavior. This last trait is appropriate for a buffer and backfilling material since it would swell after installation to seal any potential gap as it sucks up water from the neighboring rock domain (Alonso et al., 2005). The high swelling pressure that develops would also toughen the conditions for microbial life in the vicinity of the canister and thus decrease the risk for biological corrosion of the canisters (Pedersen, 2010). Bentonite can be used in different forms, including dry powder, pellets, slurry and compacted blocks. This study will focus on the latter, namely high-density (dry density ~ 1600 kg/m^3), low moisture content (~10% or liquid saturation ~ 0.36) blocks, as it is the form that is intended to embed the canisters in the KBS-3 method (Johannesson et al., 2007).

The host formation consists of crystalline bedrock described as sparsely fractured i.e. with lower fracture density than in other geological formations (Painter and Cvetkovic, 2005). Fracture openings offer a primary network for fluid flow. Flow can also occur in intact rock mass within the inter-grain “matrix” porosity of the rock, however such flow is generally considered to be extremely small in comparison (Cvetkovic et al., 2007). Connected fractures are typically subject to moderate flow rates and yield the dominant flow of the subsurface system. Fractured rock exhibits a strong solute retention capacity through diffusion and retardation into the rock matrix (Cvetkovic et al., 1999; Cvetkovic and Haggerty, 2002; Cvetkovic and Frampton, 2010; Frampton and Cvetkovic, 2011), although some evidence has shown that this retention is neither complete nor definite. For example, cesium can be extensively mobilized from cation-exchange sites if marine water intrudes (Mathurin et al., 2014b) and lanthanides can be mobilized via organic complexation (Mathurin et al., 2014a). Despite these occurrences, sparsely fractured bedrock is regarded as a suitable environment due to its long term stability and low average flow rates combined with overall strong retention capacity (Nguyen et al., 2009).

Towards the end of the operational phase the tunnel system will successively be backfilled, allowing groundwater to re-saturate the site. The time scale of the re-saturation process for the bentonite buffer inserted into a deposition hole is hard to predict with certainty. The high suction of unsaturated bentonite causes de-saturation also of adjacent rock at the time of installation, which increases the complexity of the problem (Dessirier et al., 2014). In addition, the lowering of pressure may induce groundwater degassing of dissolved gasses such as nitrogen, methane, hydrogen and carbon dioxide near the deposition hole (Jarsjö and Destouni, 2000; Rosdahl

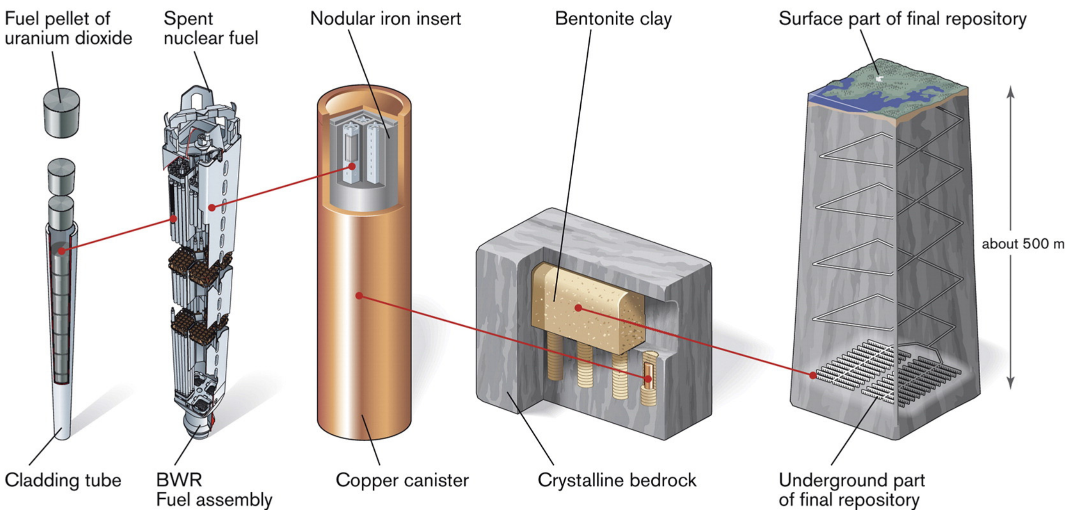

Fig. 1. Representation of the repository concept considered in the Swedish program for spent nuclear fuel disposal (denoted as the KBS-3 method). The main features of the multiple barrier design are: the host crystalline rock (to provide a long term stable environment and the final barrier to the surface biosphere), the engineered barriers, i.e., the copper canister, bentonite clay buffer and tunnel backfill. (Source SKB. Illustrator: Mats Jerndahl.)