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The impact of low and intermediate-level radioactive waste on humans and the environment over the next one hundred thousand years

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A B S T R A C T

In order to assess the potential radiological risk to humans and the environment from a geological repository for radioactive waste, a safety assessment must be performed. This implies that the release and transfer of radionuclides from the repository into the surface environment are calculated and that the effects in the biosphere are evaluated for an assessment period up to one hundred thousand years according to Swedish regulations. This paper discusses the challenges associated with the modelling of surface ecosystems over such long time scales, using the recently completed assessment for the extension of the existing repository for the low- and intermediate-level nuclear waste (called SFR) in Forsmark, Sweden as an applied example.

In the assessment, natural variation and uncertainties in climate during the assessment period were captured by using a set of climate cases, primarily reflecting different expectations on the effects of global warming. Development of the landscape at the site, due to post-glacial isostatic rebound, was modelled, and areas where modelling indicated that radionuclides could discharge into the biosphere were identified. Transfers of surface water and groundwater were described with spatially distributed hydrological models. The projected release of radionuclides from the bedrock was then fed into a biosphere radionuclide transport model, simulating the transport and fate of radionuclides within and between ecosystems in the landscape. Annual doses for human inhabitants were calculated by combining activity concentrations in environmental media (soil, water, air and plants) with assumptions on habits and land-use of future human inhabitants. Similarly, dose rates to representative organisms of non-human biota were calculated from activity concentrations in relevant habitats, following the ERICA methodology.

In the main scenario, the calculated risk for humans did not exceed the risk criteria or the screening dose rate for non-human biota, indicating that the repository design is sufficient to protect future populations and the environment. Although the combination of radionuclides, land-uses/habitats, type of most exposed population and area of exposure that contribute most to the total dose shifts over time, the total calculated dose shows limited variability. Significant reductions in the dose only occur during submerged periods and under periglacial climate conditions. As several different water and food pathways were equally important for endpoint results, it is concluded that it would be difficult to represent the biosphere with one or a set of simplified models. Instead, we found that it is important to maintain a diversity of food and water pathways, as key pathways for radionuclide accumulation and exposure partly worked in parallel.

1. Introduction[2]

When addressing the potential effects from a geological repository for low- and intermediate-level nuclear waste in Sweden, time frames of up to 100,000 years are of interest. For a geological repository for spent nuclear fuel even longer time frames, up to one

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million years, have to be considered according to the Swedish regulations (SSM, 2008). In Sweden the Forsmark site has an existing low- and intermediate-level waste repository (LILW), 'Slutförvaret för kortlivat radioaktivt avfall' (a.k.a. SFR), and the location has been selected for a permanent geological repository for spent nuclear fuel (high-level waste; HLW). Depending on if it is a HLW or LILW repository, the focus and time-frames in safety assessments can be different. This and other differences between assessing a HLW repository (SR-Site, cf. Kautsky et al., 2013a) and a LILW (SKB, 2014a) are discussed in this article.

SFR has been operated by the Swedish Nuclear Fuel and Waste Management Co (SKB) since 1988. A number of safety assessments have been performed for the repository since SKB received permission to start building SFR in 1983. The purpose of a safety assessment is to evaluate if human health and the environment are protected from harmful effects of ionising radiation caused by the repository. In December 2014 a new license application was submitted to the authorities containing a safety assessment for an extended repository (SKB, 2014a). The key findings regarding the biosphere part of this safety assessment (SKB, 2014b) are highlighted in this paper.

Regulations from the Swedish authorities require a safety assessment covering one hundred thousand years following repository closure (SSM, 2008). In that time frame, the state of the repository system and its surrounding environment can be expected to change. Due to the very long time-scales considered, uncertainties concerning the properties of future surface ecosystems, and the characteristics and habits of future human inhabitants and non-human biota can only be taken into account by using simplifying assumptions. Intentionally, the assessment is reasonably cautious for a sufficiently robust demonstration of compliance aiming at over-rather than underestimating radiological consequences without being unrealistic.

The biosphere part of the safety assessment of the extended SFR builds on those made previously, for SFR and for the planned repository for spent nuclear fuel in Sweden. Between 2002 and 2008, SKB performed site investigations for a repository for high-level waste (HLW) in Forsmark (SKB, 2008). Thereby, the past and present biosphere conditions at Forsmark have been described thoroughly in a number of papers and reports. Several adaptations and improvements were necessary to better handle certain radionuclides (e.g. C-14) and scenarios specific to the 2014 safety assessment of SFR, which is called SR-PSU. Additional site investigations were performed 2010–2012 for the SFR extension project (SKB, 2013).

The present paper summarises some of the challenges met within the biosphere part of the SR-PSU safety assessment (Fig. 1), the methods and models developed to calculate transport and dose in surface ecosystems, and presents selected results from the main scenario. The intention is to give an overview and some highlights of the biosphere program in the most recent safety assessment performed in Sweden, thereby providing both a brief state of the art on radionuclide transport and dose modelling in surface ecosystems within the Swedish program and an illustration of some aspects specific to this assessment of low- and intermediate-level waste (LILW).

2. Input data and models

The Forsmark site represents a typical coastal area at the shoreline of the Baltic Sea in northern Uppland, Sweden, with a small-scale topographic variation The majority of the landscape is covered by a thin regolith layer mainly consisting of till. The rapid shoreline displacement has strongly affected landscape development, and still causes a continuous and relatively predictable change in the abiotic and biotic environment. The first parts of Forsmark emerged from the sea around 500 BC resulting in a young terrestrial system that contains a number of new-born shallow lakes and wetlands. At the site the LILW repository is operating as well as the three Forsmark nuclear power reactors. Details concerning the Forsmark site can be found in Lindborg (2008) and SKB (2008).

2.1. The SFR repository

SFR consists of a set of disposal chambers situated in rock at c. 60 m depth beneath the present-day sea floor (Fig. 2). It is built as a passive repository for the storage of short-lived low- and intermediate-level radioactive waste. The radioactive waste is operational waste from the Swedish nuclear power plants and from the interim storage facility for spent nuclear fuel, Clab, and radioactive waste from other industries, research institutions and medical care. An extension with rock vaults at c. 120 m depth is planned, in order to enable storage of decommissioning waste from the Swedish nuclear power plants (Fig. 2; see SKB, 2014a for details).

The radioactive inventory of the waste to be disposed of in SFR is dominated by short-lived radionuclides. This means that a large portion of the radioactivity deposited in SFR will decay substantially during the operational phase, i.e. up to about 2075AD. After 1000 years only 2% remains of the total activity content. Initially, Ni-63 dominates the activity, but after about 600 years Ni-59 and C-14 will become dominant (SKB, 2014a).

2.2. Climate change

During the long time period covered by the safety assessment (100,000 years), the climate is expected to vary, and both warmer and colder periods than the present are anticipated. Current scientific understanding of the climate system suggests that the climate evolution during the coming 100,000 years will differ from the past climate variability. It is very likely that the anthropogenic release of CO_2 into the atmosphere, together with the future natural variation in insolation, will result in the present Holocene interglacial being considerably longer than previous interglacials (e.g. Berger and Loutre, 2002; Näslund et al., 2013; SKB, 2014c).

In order to include uncertainties in climate evolution for the coming 100,000 years, a number of climate cases are considered as a basis for the safety assessment (Näslund et al., 2013). Three climate cases are defined to span the range in future climate evolution associated with low, medium and high human carbon emissions (i.e. different degrees of global warming): *the early periglacial climate case* with a periglacial period at 17,000 AD; *the global warming climate case* with the earliest periglacial period at 52,000 AD; and *the extended global warming climate case* without periglacial periods in the assessment period. Among them, *the global warming climate case*, which describes a climate evolution with a medium degree of global warming, is used in this article. The climate cases used in the assessment of the SFR repository are described in detail in SKB (2014c).

Information from the various climate cases is used to define parameters in the landscape development models, radionuclide transport models, and for determining presence and land-use of human inhabitants and non-human biota at the site for the calculation of radioactive dose. Since the coming one hundred thousand years are expected to be affected by global warming, processes such as leaching of soils and periglacial environments in general are comparatively more important in the SR-PSU LILW assessment than in the one million year time frame of the HLW assessment (Näslund et al., 2013), where processes related to glaciation (erosion, isostatic changes) are additional factors of high importance.

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