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Reference level of the occupational radiation exposure in a deep geological disposal facility for high-level nuclear waste: A Monte Carlo study

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ABSTRACT

In deep geological repositories for high-level nuclear waste, radiation field around the disposed nuclear waste package is characterized by highly scattered radiations due to the surrounding host rock layers or cement liner. Calculation of the reference level of the occupational radiation exposure in such a facility is hence of interest, since geometrical conditions of the occupational exposure in the facility cannot be readily represented by the standard irradiation geometries considered by ICRP. In this study, a horizontal emplacement drift inside rock salt was modeled to represent a deep geological disposal facility. A nuclear waste package, simulated with a shielding cask loaded with spent nuclear fuel, was placed on the ground of the rock salt drift. A "reference worker" inside the drift was represented by the ICRP/ICRU reference adult voxel phantom. The reference level of the occupational radiation exposure was then calculated with a Monte Carlo code in terms of the effective dose based on the ICRP 2007 recommendation. In order to investigate the occupational exposure of a worker during different working scenarios in the drift, the effective dose was calculated with the voxel phantom placed at various distances and different body orientations with respect to the shielding cask. Furthermore, the effective dose obtained with voxel phantom was compared with that obtained with the fluence-to-effective-dose conversion coefficients for the standard irradiation geometries provided by ICRP. It was found out that (1) usage of the dose conversion coefficients for the isotropic (ISO) geometry, which is recommended by ICRP for highly scattered radiation fields, generally underestimates the effective dose in the rock salt emplacement drift; (2) depending on the orientation of the worker in the drift, the dose conversion coefficients for the anterior-to-posterior (AP) or the rotational (ROT) geometry should be used, in order to obtain an adequate estimation of the effective dose in the rock salt drift.

1. Introduction

The effective dose, introduced in ICRP Publication 60 (ICRP, 1991), is recommended by ICRP as a reference quantity to characterize the radiation exposure at a working place (ICRP, 2007). Calculation of the effective dose for external exposure is based on absorbed dose, weighting factors, and reference values for the human body and its organs and tissues, i.e. an anthropomorphic phantom defining a reference person. Effective dose is not based on data from individual persons. Therefore, in its general application, effective dose does not provide an individual-specific dose but rather that for a reference person under a given exposure situation. However, calculation of the effective dose requires a considerable amount of computational resources. Therefore, several standard irradiation geometries, such as the anterior-to-posterior (AP), rotational (ROT) and isotropic (ISO) geometries, were defined by ICRP and the fluence-to-effective-dose conversion coefficients for these standard geometries were also provided (ICRP, 2010). Despite of the fact that these standard irradiation geometries are idealized, they may be used to approximate actual conditions of exposure. For instance, the isotropic (ISO) geometry is recommended by ICRP to approximate a highly scattered radiation field (ICRP, 2010).

In a deep geological repository for high-level nuclear waste, such as a horizontal emplacement drift in rock salt as investigated in a previous study (Saurí Suárez et al., 2015), the radiation field around a nuclear waste package placed in the repository is characterized by scattered radiations due to the surrounding host rock

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layers. Consequently, the geometrical condition of occupational radiation exposure in such a facility cannot be readily represented by the standard irradiation geometries defined by ICRP. Furthermore, the effective dose in a geological repository depends not only on the location of the worker to the shielding cask, but also on the waste inventory, and other geometrical boundary conditions of the facility. It is hence not feasible to provide a complete set of fluence-to-effective-dose conversion coefficients which can be used for all possible working scenarios in a deep geological disposal facility for high-level nuclear waste. Therefore, it is of interest to calculate the effective dose in a representative deep geological facility and compare the calculated effective dose with that obtained with the standard fluence-to-effective-dose conversion coefficients provided by ICRP. The purpose of this comparison is to justify whether a standard irradiation geometry, or a combination of several standard irradiation geometries are suitable to approximate the irradiation situation in a deep geological disposal facility. If this is the case, the dose conversion coefficients for the standard irradiation geometries can then be readily applied in deep geological disposal facilities to obtain the reference level of the occupational radiation exposure in terms of effective dose, provided the fluence distribution of radiations in the facility is provided by simulations.

In the current study, a deep geological disposal facility for high-level nuclear waste was represented by a horizontal emplacement drift in rock salt. A mixture of spent uranium oxide (UOX) fuel and spent mixed oxide (MOX) fuel was defined as a typical high-level nuclear waste inventory. The spent nuclear fuel (SNF) was loaded inside a POLLUX-10 shielding cask (Janberg and Spilker, 1998) designed for deep geological disposal in rock salt. As a simplification, only one nuclear waste package, i.e. a POLLUX-10 cask load with SNF was placed inside the rock salt emplacement drift. The ICRP/ICRU adult voxel phantom defined in ICRP Publication 110 (ICRP, 2009) was chosen to represent a reference worker inside the rock salt drift. Based on the ICRP 2007 recommendation (ICRP, 2007), the effective dose in the vicinity of the shielding cask was then calculated with the general-purpose Monte Carlo N-Particle code MCNP6 (Pelowitz, 2013).

2. Methods and methodology

2.1. The high-level nuclear waste inventory

In the current study, a model pressurized water reactor (PWR) fuel assembly (FA) was considered for disposal in a deep geological facility. This FA contains two-thirds UOX fuel and one-third MOX fuel in correspondence to a typical loading strategy in nuclear power plants. An average burnup of 55 gigawatt-days per metric ton of heavy metal (GWd/tHM) was assumed for both UOX and MOX spent fuel. The age, i.e. the cooling time of the SNF counting from unloading of the FA from the reactor core, was assumed to be 50 years, which corresponds to a possible time of disposal of the SNF in a repository. Mass of isotopes in the SNF in dependence of the age was taken from (Peiffer et al., 2011). As investigated in a previous study (Pang et al., 2016), for the waste inventory considered in this study, neutrons dominate the radiation exposure in the repository. Therefore, out of the hundreds of different radionuclides in the SNF, only those contributing significantly to neutron yield were considered when defining the radiation source for simulation with MCNP6. For the “50-year-old” SNF, ^{244}Cm produces over 95% of the total neutron yield by its spontaneous fission. Neutron production due to (α, n)-reaction stems mainly from interactions with ^{18}O and amounts less than 5% of the total neutron yield. Fig. 1 shows the corresponding neutron spectrum of the “50-year-old” SNF considered in the current study.

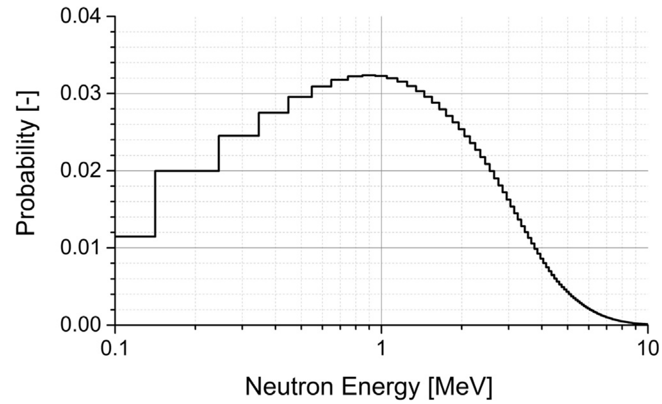

Fig. 1. Spectral neutron energy distribution of the “50-year-old” SNF used as radiation source in MCNP6 simulations.

For geological disposal, SNF is supposed to be loaded inside a shielding cask. In the current study, fuel rods of the spent FAs were stored inside a POLLUX-10 shielding cask (Janberg and Spilker, 1998) that is designed for deep geological disposal in rock salt. The maximum loading capacity of a POLLUX-10 cask is the fuel rods of 10 PWR FAs which contain roughly 5.45 metric tons heavy metal. The total neutron source strength of the “50-year-old” SNF investigated in the current study in a POLLUX-10 cask amounts to 4.723×10^9 n s^{-1}.

2.2. The horizontal emplacement drift in rock salt

Fig. 2 shows the MCNP6 model of a deep geological disposal facility, which is represented in the current study by a horizontal emplacement drift in rock salt. Geometrical parameters of the drift were adopted from a generic reference concept for disposal in rock salt (Stahlmann et al., 2015). An emplacement drift is supposed to be hundreds of meters underground and surrounded by rock salt layers of at least 100 m thickness. As a simplification in the MCNP6 model, the thickness of the rock salt layer was reduced to 1 m, which is sufficient to account for possible interactions of the radiation with the drift materials. A typical rock salt type available in Germany with an average density of 2.2 g cm^{-3} was investigated in the current study. Its materiel composition was taken from (Bernnat et al., 1995). The air inside the rock salt drift was assumed as dry air at near see level. As a simplification, only one POLLUX-10 cask (cylindrical form with a length of 5.5 m and an outer diameter of 1.56 m) loaded with SNF was placed on the ground of the drift with its bottom surface at 2.63 m distance to the drift end side. Detailed modeling of the POLLUX-10 cask with MCNP6 can be found in a previous study (Pang and Becker, 2017).

For calculation of the effective dose, the ICRP/ICRU adult voxel phantom (ICRP, 2009) was applied in the current study to represent a reference worker in the rock salt drift. This phantom consists of the adult male and the adult female reference voxel phantoms, representing Reference Male and Reference Female (ICRP, 2007), respectively. The male reference voxel phantom consists of 1.95 million tissue voxels, each with a slice thickness (corresponding to the voxel height) of 8.0 mm and an in-plane resolution (i.e. voxel width and depth) of 2.137 mm, corresponding to a voxel volume of 36.54 mm^3. The number of slices is 220, resulting in a body height of 1.76 m. The body mass is 73 kg. The female reference voxel phantom consists of 3.89 million tissue voxels, each with a slice thickness of 4.84 mm and an in-plane resolution of 1.775 mm, corresponding to a voxel volume of 15.25 mm^3. The number of slices is 346, the body height is 1.63 m, and the body mass is 60 kg. The