Monte Carlo Simulation Study for Optimizing Detection Efficiency of Inorganic Scintillators

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1. Introduction

In the process of decommissioning a nuclear facility, radioactivity information on groundwater that may have caused contamination at the site of nuclear decommissioning is important. In particular, it is necessary to determine whether the level of radioactive contamination is sufficiently low in order to perform the decommissioning. Therefore, the on-site gamma-ray monitoring system for groundwater at the decommissioning site was conceptually designed. Minimum detectable activity (MDA) is important for establishing an on-site monitoring system, especially in determining the level of radioactive contamination in low-level radioactive environments. MDA is affected by background counting rate, sample and background measurement time, sample volume and detection efficiency [1]. Therefore, before establishing a monitoring system, it is necessary to select a detector with good detection efficiency and derive the detector geometry. In this study, Monte Carlo simulations were used to derive the detection efficiency and geometry of of five inorganic scintillators.

2. Materials and methods

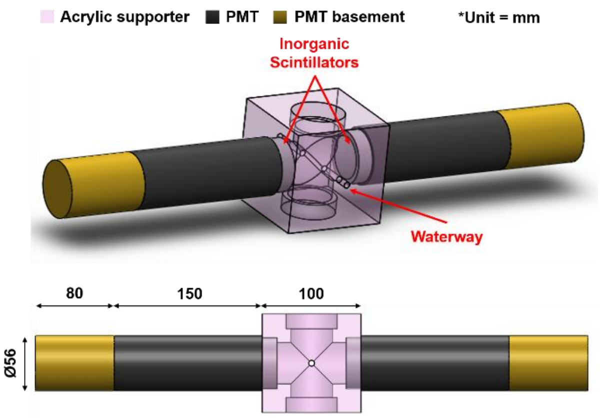

Fig. 1. Conceptually designed detection system.

A conceptually designed detection system consists of two pairs of inorganic scintillation detectors. Fig. 1 shows the three-dimensional image and dimensions of a conceptually designed detection system. A high voltage supply is used to apply an operating voltage to the photomultiplier (PMT) to obtain the incident radiation signal. The two output signals of the PMT are amplified simultaneously using a dual amplifier. The amplified signal uses a timing single-channel analyzer and a time-amplitude converter-based coincidence method to minimize background effects. The signal acquired using the coincidence method is digitized using a multi-channel analyzer.

To select the inorganic scintillator to be used in the conceptually designed detection system, five inorganic scintillator candidates were selected: GAGG(Ce), LYSO(Ce), $LaBr_3$(Ce), $CeBr_3$, and NaI(Tl). Table I is the properties of the candidates.

Table I: Properties of the inorganic scintillators

Materials	Decay constant [μs]	Light yield [photons/MeV]	Hygro scopicity
GAGG(Ce)	0.05-0.15	40,000-60,000	X
LYSO(Ce)	0.05	25,000	X
$LaBr_3$(Ce)	0.02	60,000	O
$CeBr_3$	0.02	60,000	O
NaI(Tl)	0.23	55,000	O

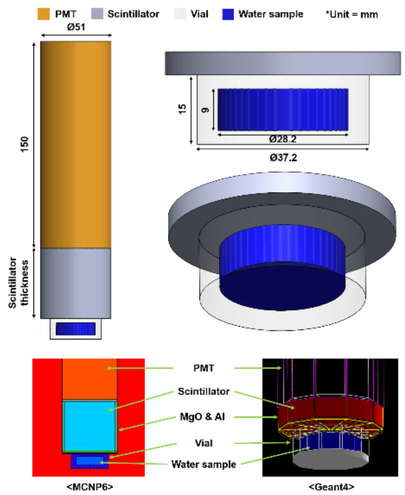

Fig. 2. Dimensions and modeling in simulations.

Monte Carlo simulations were performed using MCNP6 (version 6.2) and Geant4 toolkit (version 10.03) to evaluate the detection efficiency of inorganic scintillators with varying thickness and source-to-detector distance (SDD). Fig. 2 shows the dimensions used in both simulations and the modeling of MCNP6 and Geant4. The source is homogeneously distributed in the water sample. To confirm the detection efficiency by energy, the source emits a monoenergetic gamma rays of 0.1, 0.2, 0.5, 0.8, 1.0, 1.5, and 2.0 MeV. SDD varied from 0 to 5 cm (every 1 cm) and was evaluated only for inorganic scintillators with a thickness of 1 cm. SDD is the distance from the top of the sample to the front of the detector structure. For thickness evaluation, the range of high detection efficiency was determined by changing the scintillator thickness from 1 to 7 cm (every 1 cm) in the optimal SDD. The thickness range was chosen to take into account the attenuation in the scintillator that was too thick except for the thickness (mm) with low interaction. The detection efficiency in MCNP6 was determined by the number of gamma rays deposited on the scintillator using the F8 tally. Geant4 simulated the optical photon process caused by the interaction of gamma rays with the scintillator and determined the detection efficiency using the number of gamma rays deposited on the scintillator.

3. Results and discussion

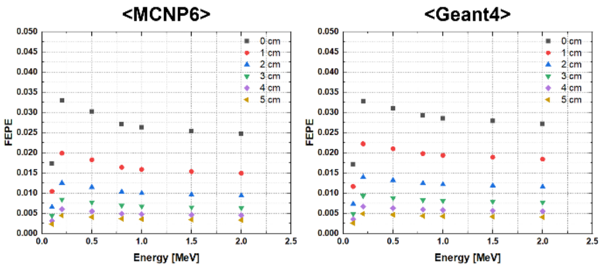

Fig. 3. Detection efficiency of GAGG(Ce) according to SDD.

Fig. 3 shows full energy peak efficiency (FEPE) of GAGG(Ce) according to SDD change of MCNP6 and Geant4 when the thickness is 1 cm. The relative error between MCNP6 and Geant4 results is less than 10%. The detection efficiency shows two regions with different tendencies due to attenuation and absorption. In the region of less than 0.2 MeV, the aluminum packing, the dead layer of the detector, or the attenuation of the source decreases, so the detection efficiency increases as the energy increases. In the region of 0.2 MeV or more, the detection efficiency gradually decreases [2]. In both simulations, the closer to the water sample, the exponentially higher detection efficiency. In addition, since the water sample has a large attenuation coefficient compared to the source in the air, it is necessary to keep a close distance in terms of detection efficiency. These trends were commonly followed by the evaluated scintillator candidates. Therefore, the SDD was determined to be 0 cm.

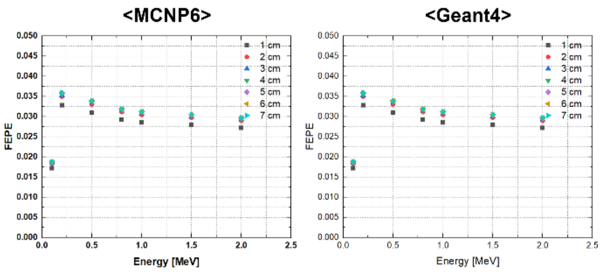

Fig. 4. Detection efficiency of GAGG(Ce) according to thickness.

Fig. 4 shows the detection efficiency according to the thickness change of GAGG(Ce) in MCNP6 and Geant4 when SDD is 0 cm. The relative error between MCNP6 and Geant4 results is less than 10%. In both simulations, FEPE of GAGG(Ce) began to saturate when the thickness was 3 cm. Saturation refers to the case where the increase in FEPE is less than 1% as the scintillator thickness increases by 1 cm. The detection efficiency increased as an exponential decay function with increasing thickness. As a result of evaluating other scintillators, FEPE of LYSO(Ce) began to saturate at 3 cm, and FEPE of $LaBr_3$(Ce), $CeBr_3$ and NaI(Tl) began to saturate when the thickness was 5 cm. Among scintillator candidates, GAGG(Ce) and LYSO(Ce) showed the highest FEPE in most energy regions. In addition, the variation of FEPE according to the energy region was the least.

4. Conclusion

In this study, a detection system was conceptually designed to monitor the gamma rays of groundwater in the decommissioning site. The MDA, which determines the level of radioactive contamination, is affected by the detection efficiency of the detection system and is important in field monitoring systems. In order to establish a detection system with excellent detection efficiency, the detection efficiency of five inorganic scintillator candidates was evaluated by MCNP6 and Geant4 Monte Carlo simulations. The detection efficiency according to SDD and scintillator thickness was calculated for five inorganic scintillators. The 3cm thick GAGG(Ce) and LYSO(Ce) showed the highest detection efficiency, and the smaller the SDD, the higher the detection efficiency. In addition, GAGG(Ce) and LYSO(Ce) are resistant to hygroscopicity among considerations. However, LYSO(Ce) has the influence of background noise due to the self-radioactivity of ^{176}Lu contained in the constituent elements. Therefore, GAGG(Ce) is considered the most suitable scintillators for this study. In future studies, it is necessary to experimentally evaluate FEPE in consideration of the effect of the wavelength of the scintillator and the PMT.

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