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Dose calculation according to collimator design for high radiation measurement

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1. Introduction

Accurate radiation measurement is crucial during the decommissioning of a nuclear power plant (NPP), particularly in high radiation environments. However, the presence of high levels of radiation can interfere with the performance of radiation measurement systems, leading to inaccurate readings and potential risks to workers. Therefore, ensuring the performance of radiation measurement systems in such environments is of utmost importance.

One critical aspect of radiation measurement system design is the collimator. Collimators play a critical role in shaping and directing the flow of radiation, which is essential for accurate measurement. Also, collimators are particularly important in high radiation environments, where they help to reduce impacts of dead time with pile-up of radiation signals on the measurement system, though pile-up restoration algorithm is integrated.

An effective collimator can ensure the safety of workers and the efficient decommissioning of nuclear power plants, while also enabling the precise measurement of radiation levels and doses for safe and efficient waste disposal. Therefore, in this work, such geometric parameters of a collimator and resultant dose rate were investigated, using Monte Carlo simulations, to satisfy performance requirement of radiation measurement for a sectioning area of reactor pressure vessel (RPV) without its internals (e.g., former, baffle, core barrel) [1].

2. Methodology

2.1. Detector validation

To ensure the reliability of simulation tools in comparison to experimental results, a LaBr3(Ce) detector with a diameter of 1.5 inches and a thickness of 1.5 inches was used in conjunction with a specific setup (780 voltage supplied, DT-5730B digitizer, DPP-PSD) to measure Cs-137 (661.7 keV γ-ray emitter) and Co-60 (1173, 1333 keV γ-ray emitter) point sources at varying source-detector distances (30-60 cm at 10 cm intervals) to avoid distortion due to dead time. The gamma energy spectrum was then simulated using a Gaussian Energy Broadening (GEB) card to match the experimental measurements as closely as possible. The energy resolution at each peak showed differences ranging from 0.00% to 2.98%, and the count rates of experiments over simulations (Experiment/Simulation) at each distance ranged from 90.48% to 92.73%. Figure 1 shows the validated gamma spectra from the simulation (left) and the measurement (right).

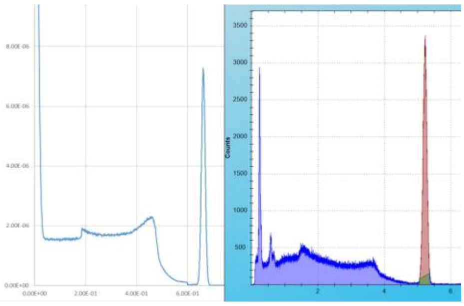

Fig. 1. Simulated(left) and experimentally measured gamma-ray spectra for Cs-137 point source

2.2. Source term definition

Several factors were considered and assumptions made to investigate the dose rate according to the geometric parameters (thickness and diameter of the pinhole) of a collimator. The target sample, which would be a sectioning area of the reactor pressure vessel (RPV) measurable by a detector system, was assumed to be a cylindrical shape (diameter: 20 cm, height: 50 cm) made of carbon steel (density: 7.86 g/cc), considering the structural information of Kori Unit 1, a nuclear power plant that has been permanently shut down in South Korea. The dominant nuclide of a radioactive RPV after 10 years of cooling period was determined to be Co-60. Although the amounts of Fe-55, Ni-59, and Ni-60 are significant compared to Co-60, they emit X-rays in the range of 0.64 – 6.9 keV and β-rays [3]. Based on these facts, a sectioning area of the RPV was modeled as a source term for MCNP6.2, and the total activity of the area was set so that the dose rate at the surface of the area was 1 Gy/hr to a cylindrical air detector (diameter: 1.5 in, length: 1.5 in).

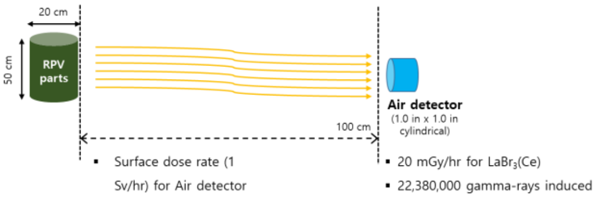

Fig 2. Simplified illustration of MCNP simulation

3. Results and Discussion

Under the previously described source conditions, the calculated dose rates and incident gamma rates to an air detector (diameter: 1.5 in, thickness: 1.5 in) were found to be approximately 20 mGy/hr and 22,380,000 photons/sec at 1 m distance from the source. These rates are high enough to paralyze a normal measurement system incapable of functioning properly due to limited pulse width and the specifications (e.g., memory) of commercial DAQ devices, even for a few hundred nano-seconds pulse width of analog signal from PMT anode. Therefore, the number of γ-rays incident to the detector per unit time needs to be suppressed below 1 million scales.

To achieve this, a collimator of 5 cm thickness was installed between the source and detector, with its width (10 cm x 10 cm) set to cover γ-rays incident to the detector side. Dose rates and induced gamma rates were then calculated with varying collimator diameter from 38.1 mm (1 inch) to 1 mm, as shown in Table 1. Both rates decreased as the diameter became narrower, but the incident rate was saturated around 1 million. This is because the pinhole becomes identical to a fully filled Pb shield as the diameter approaches 1 mm. Accordingly, dose rates and induced gamma rates were calculated with varying the thickness of the Pb shield, and it was confirmed that over 5 cm of thickness is needed to suppress gamma rates below 1 million, as shown in Table 2.

Consequently, pinhole diameter was varied from 2 mm to 10 mm for each 5 cm and 10 cm thickness of collimator (Width: 50 cm x 50 cm), as shown in Table 3. In further studies, it will be necessary to improve the collimator design in terms of pinhole structure (e.g., diameter, slope) to reduce spectrum distortion caused by internal scattering, to examine a more extensive area of targets, to optimize thickness and minimize the weight of the collimator, and to cover the detector side from external radiation in field applications.

Table 1. Calculated dose rates and incident gamma-rays to a 1.5” x 1.5” cylindrical air detector per unit time according to the diameter of the pinhole collimator of 5 cm thick (width: 10 cm x 10 cm)

phDia (mm)	Dose rate (mGy/hr)	#gamma/sec
38.1	12.374	15,195,609
10	1.738	1,875,826
8	1.424	1,508,651
6	1.172	1,235,255
5	1.090	1,140,032
4	1.055	1,105,857
3	1.018	1,063,901
2	0.996	1,041,920
1	0.986	1,033,016

Table 2. Calculated dose rates and incident gamma-rays to a 1.5” x 1.5” cylindrical air detector per unit time according to the thickness of Pb shield (width: 10 cm x 10 cm)

irisThick (cm)	Dose rate (mGy/hr)	#gamma/sec
0	19.843	22,381,073
1	9.035	9,113,194
2	5.002	5,058,625
3	2.766	2,889,027
4	1.565	1,696,931
5	0.877	999,403
6	0.539	575,318
7	0.340	346,959
8	0.273	261,242
9	0.190	215,845
10	0.158	169,404

Table 3. Calculated dose rates and incident gamma-rays to a 1.5” x 1.5” cylindrical air detector per unit time according to the pinhole diameter of 5 cm thick Pb shield (width: 50 cm x 50 cm)

	Dose Rate (uGy/hr)		Gamma Rate (#gamma/sec)	
Pin-hole Dia	5 cm Thick	10 cm Thick	5 cm Thick	10 cm Thick
2 mm	1,038	85	1,013,522	76,412
4 mm	1,091	94	1,069,116	85,196
6 mm	1,221	127	1,206,054	121,953
8 mm	1,449	204	1,458,031	198,084
10 mm	1,777	346	1,836,036	348,195

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Acknowledgements

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