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Development of Advanced Collimator for Measuring in High Radiation Field

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1. Introduction

After the permanent shutdown of Kori Unit 1 and Wolsong Unit 1, attention has been focused on safety and cost-effectiveness of decommissioning processes of nuclear power plants (NPPs). The Reactor Vessel Internals (RVI) and the Reactor Pressure Vessel (RPV) are the most critical components in the decommissioning of NPPs, as they have the highest content of radioactivity in the plant. Moreover, the quantity of radioactivity of the RPV or RVI varies greatly depending on its location. Therefore, technology that can accurately measure the radioactivity inventory, such as quantities and distribution of the radionuclides, is required before decommissioning work can begin.

When measuring such high radioactivity, the gamma ray flux incident on the detector is high, resulting in a signal pile-up phenomenon in the measurement system, making it difficult to accurately measure radioactivity. The collimator serves to inject only the radiation emitted from a specific location and shields the radiation emitted from other locations to prevent the pile-up phenomenon and enable accurate radioactivity measurement.

The purpose of this study is to investigate the characteristics of collimators and to propose a collimator suitable for radioactivity measurement of highly activated components such as RPV or RVI.

2. Types and Characteristics of Collimators

Collimators are essential components of radiation instruments and gamma cameras, which include pinhole collimators, coded aperture collimators, and Compton scatterer.

The Compton camera utilizes a scatterer to cause gamma rays and elastic scattering instead of a mechanical collimator, and can detect gamma rays within the energy range of several tens of keV to a few MeV. Originally used mainly in astronomy, Compton cameras have recently been utilized in various fields of medicine and for measuring environmental pollution caused by the Fukushima Daiichi Nuclear Plant (FDNP) accident [1]. Compton cameras have relatively high system efficiency, making them useful for measuring low radioactivity, but are not suitable for measuring high radioactivity where the pile-up phenomenon occurs.

The coded aperture collimator utilizes a number of mathematically patterned holes to maximize geometric efficiency. Recently, a hybrid gamma camera combining a coded aperture collimator and Compton scatterer has been developed, but all of them have high geometric efficiency and are used for low-dose radiation measurement or medical equipment [2].

In contrast, the pinhole collimator has relatively low sensitivity compared to other collimators, but it has the advantage of excellent spatial resolution, making it useful in gamma cameras for high radioactivity measurement. Parallel multipoles collimators, diverging collimators, converging collimators, etc., have various spatial resolutions and sensitivities depending on their characteristics and are primarily used in gamma cameras for medical devices.

3. Collimators for High Radiation Field

As described above, to prevent pile-up phenomenon that occurs when measuring high radioactivity and to accurately measure the amount of radioactivity, a pinhole collimator with low efficiency should be used rather than a highly efficient coded aperture collimator or Compton scatterer.

Figure 1 shows a cross-section of a collimator developed to measure the radioactive waste generated during the operation of the research reactor as a preliminary work for dismantling the MR research reactor in Russia [3]. The detector using this collimator measured 760 μSv/h of radioactivity without pile-up. However, it is predicted that accurately measuring radioactivity in high radiation fields of 10 mSv/h or more, which are expected during the dismantling of commercial nuclear power plants, will be difficult.

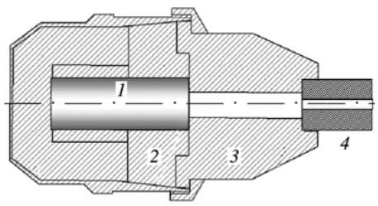


Fig. 1 Schematic diagram of a pinhole collimator designed by Russia [3]

After the FDNP accident in Japan, a gamma camera was developed using a double knife-edge collimator (Figure 2) to be tolerant of high dose rate environments. Figure 3 shows the gamma energy spectrum measured inside the accident nuclear power plant using this gamma camera [4]. This measurement shows the Cs-137 and Cs-134 peaks, and the relative radioactivity can be evaluated. However, due to the serious pile-up phenomenon, not only the peak shape is distorted, but also the radioactivity cannot be accurately measured.

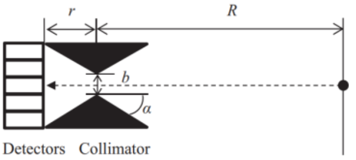


Fig. 2 Double Knife-edge Collimator Used in Japanese Gamma Camera [4]

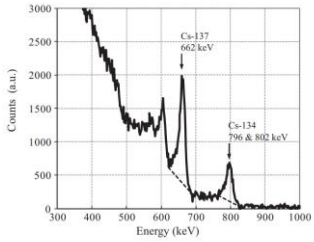


Fig. 3 Gamma Energy Spectrum Measures in the FDNPP Building [4]

4. Advanced Collimator

After reviewing domestic and foreign collimating technologies, it was found that various collimators and gamma cameras have been developed for radiation measurement, but a collimator capable of accurately measuring high radioactivity without pile-up phenomenon has not yet been developed. Figure 4 shows an advanced collimator and shutter set that can solve these problems. Figure 5 shows the measurement concept for RPV and RVI, which are key components during nuclear power plant dismantling. It is predicted that the high radioactivity expected during dismantling of a nuclear power plant can be accurately measured with the optimal combination of collimator and shutter according to the radioactivity of the object.

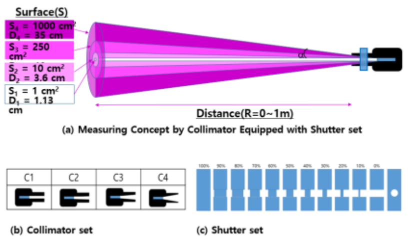


Fig. 4 Advanced Collimator Equipped with Shutter Developed by KAERI

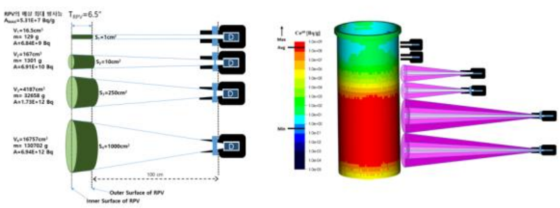
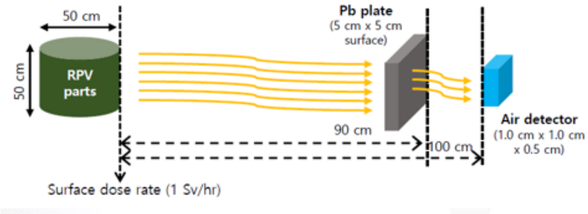


Fig. 5 Measuring Concept for RPV and RVI

Through the preliminary MCNP calculations, the possibility of measuring the radioactivity of RPV without pile-up was confirmed (Figure 6). More precise MCNP calculations will be performed in the future.



(a) Calculation Model

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

(b) MCNP Calculation Results

Fig. 6 Model for Preliminary MCNP Calculation for RPV (a) and calculation Results(b)

5. Conclusion

Currently, technology for accurately measuring high radiation fields without experiencing the pile-up phenomenon has not yet been developed. However, our advanced collimator is expected to contribute to the accurate classification of dismantling waste and the reduction of worker exposure during nuclear power plant dismantling by allowing for the precise measurement without pile-up phenomenon of high radioactivity levels in key parts such as RPV and RVI.

Through the MCNP calculation, the possibility of measuring the radioactivity of RPV without pile-up was confirmed, and more precise MCNP calculation will be performed in the future.

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