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Original Article

Detection of voluminous gamma-ray source with a collimation beam geometry and comparison with peak efficiency calculations of EXVol

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ABSTRACT

In this study, we expanded the performance of the existing EXVol code and performed empirical experiments and calculations. A high-resolution gamma spectroscopy system was constructed, and a standard point source and a standard volume source were measured with an HPGe detector with 43.1% relative efficiency. EXVol was verified by quantitative comparison of the detection efficiencies determined by measurements and calculations.

To introduce the concept of the detector scanning that occurs in the actual measurement into the EXVol code, a collimator was placed between the source and detector. The detection efficiency was determined in the asymmetric arrangement of the source and detector with a collimator. A collimator made of lead with a diameter of 15 mm and a thickness of 50 mm was installed between the source and the detector to determine the detection efficiency at a specific location. The calculation result was contour plotted so that the distribution of detection efficiency could be visually confirmed. The relative deviation between the measurements and calculations for the coaxial and asymmetric structures was 10%, and that for the collimation structure was 20%. The results of this study can be applied to research using γ-ray measurements.

1. Introduction

Large volume radioactive materials in radioactive waste drums removed from nuclear power plants or in spent fuel assemblies or fuel rods are always at high risk of radiation dose. They have difficulty identifying radionuclides and quantifying their concentration due to their large volume or high doses. Collimation technology is convenient and straightforward to reduce the dead time of measurement equipment including semiconductor detectors and related spectral modules. In a nondestructive analysis of highly surveyed and bulky structures, studies on detection efficiency and radioactive concentrations make sense because it can improve worker safety and shorten work time.

Codes such as MCNP [1] and GESPECOR [2] based on Monte Carlo simulation and EXVol [3], SOLANG [4], ESOLAN [5], SOLIDANG [6], ANGLE [7] and LabSOCS [8] based on the principle of the effective solid angle method [9] have been developed to calculate the absolute full-energy peak (FEP) efficiency (below, detection efficiency) of a voluminous source. However, most of these codes can only be calculated for limited geometries and arrangements of the source and detector. In most cases, calculation is possible only for the coaxial arrangement of the source and the detector, and the calculations for a voluminous source can only be performed for a small volume source that is smaller than the detector crystal diameter.

With ANGLE and LabSOCS, which are recently developed and commercialized detection efficiency determination codes based on the effective solid angle method, it is possible to calculate the detection efficiency for cylindrical and Marinelli beaker-type sources. However, these codes return the detection efficiency calculation results only for the entire volume of a source. Performance comparison between commercial code and EXVol is shown in Table 1.

In this study, we extended and verified the performance of the EXVol (Efficiency calculator for eXtended Voluminous source) code, which is a detection efficiency calculation code that uses the effective solid angle method. The previous EXVol only determined

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Table 1
Performance comparison between commercial code and EXVol.

Category	License	Computable Shape		Output (Detection Efficiency)		Collimator	Contour plot for specific position and Energy
		Marinelli	Cylinder	Entire volume	Specific position		
ANGLE	ORTEC	O	O	O	X	X	X
LabSOCS	CANBERRA	O	O	O	X	X	X
EXVol	Seoul National University	O	O	O	O	O	O

the detection efficiency of the source-detector coaxial arrangement for the whole volume source. After expansion of the performance, EXVol can calculate the perpendicular and asymmetric arrangement of the source and detector. Besides, the introduction of a collimator made it possible to reduce the radiation intensity and counting rate of a high radiation source. It is possible to determine the precise detection efficiency according to the energy of a γ-ray at a specific position of a volume source.

To verify the performance of EXVol, a high-resolution gamma spectroscopy system was constructed, and measurement and analysis were performed. Measurements were performed on coaxial, asymmetric and collimated structures with standard point source and standard volume source (1 L, liquid medium with ^{152}Eu, cylindrical, 64 kBq) and HPGe detector (relative efficiency 43.1%, N-type). The detector was shielded with lead and a collimator. The volume source was divided into 5 equal parts in the height direction to measure the detection efficiency at a specific location.

The methodology of this study and the performance of EXVol were verified by quantitative comparison of the detection efficiency determined by the calculated and measured peak efficiency. The introduction of a collimator has made it possible to reduce the radiation intensity of a high radiation source. And it is possible to determine the precise detection efficiency according to the energy of a gamma-ray at a specific position of the volume source.

2. Method

The equation for calculating the effective solid angle, including the geometric solid angle, attenuation factor and efficiency factor, for a standard point source can be expressed by Equation (1) [9].

$$\overline{\Omega}_{ref} = \iint_{S_d} d\overline{\Omega} = \iint_{S_d} F_{eff}F_{att}d\Omega = \iint_{S_d} F_{eff}F_{att}\frac{cos\theta d\sigma}{r^2} \tag{1}$$

where F_{att} is the attenuation factor on the gamma-ray path, F_{eff} is the efficiency factor, dσ is the normal vector for the surface element of the detector volume sensitive to the incident γ-rays and S_d is the detector surface on which γ-rays are incident. For the curved surface of the detector sensitive region, the unit vector $\overrightarrow{n_u}$ for the surface element dσ at a point on the detector crystal surface and the direction cosine of the detector and standard point source are included in the integral term. Where r is the distance between the detector and the standard point source. This geometry is shown in Fig. 1. In the case of a volume source, the effective solid angle is given as a mean value of integral, which is shown in Equation (2).

$$\overline{\Omega}_{vol} = \frac{1}{V_s}\int_{V_s} dV \iint_{S_d} d\overline{\Omega} = \frac{1}{V_s}\int_{V_s} dV \iint_{S_d} F_{eff}F_{att}d\Omega \tag{2}$$

On the other hand, for a volume source with a nonuniform nuclide concentration, Equation (1) can be converted to the mean value of the integral containing the nuclide concentration distribution function ($\rho = \rho(\overrightarrow{r})$). In this case, it is difficult to determine the analytical concentration distribution function to directly perform the analytical integration. For realistic calculations, the concentration distribution function can be replaced by dividing the volume source into sufficiently small volume elements (V_i (i = 1, …,K)) and obtaining the average value ($\Delta\overline{\Omega_i}$) for each differential volume element. Hence, Equation (1) is represented by Equation (3).

$$\Delta\overline{\Omega_i} = \frac{1}{(\Delta V_s)_i}\int_{(\Delta V_s)_i} dV \iint F_{eff}F_{att}d\Omega \tag{3}$$

The detection efficiency for the differential volume element ($(\Delta V_s)_i$) is given as Equation (4).

$$(\Delta\varepsilon_{p,x})_i = \varepsilon_{p,ref}\Delta\frac{\Delta\overline{\Omega}_{x,i}}{\Delta\overline{\overline{\Omega}}_{ref}} \tag{4}$$

$(\Delta\varepsilon_{p,x})_i$ is the distribution of the detection efficiency according to the specific position in the source (x). The average detection efficiency ($\overline{\varepsilon_{p,x}}$) for the entire volume source using the nuclide concentration distribution function is shown in Equation (5).

$$\overline{\varepsilon_{p,x}} = \sum_{i=1}^{K}\frac{(\Delta\varepsilon_{p,x})_i\rho(\overrightarrow{r_i})(\Delta V_s)_i}{\sum_{i=1}^{K}\rho(\overrightarrow{r_i})(\Delta V_s)_i} \tag{5}$$

When $(\Delta V_s)_i$ is set to be the same regardless of i, the formula is simplified as Equation (6).

$$\overline{\varepsilon_{p,x}} = \sum_{i=1}^{K}\frac{(\Delta\varepsilon_{p,x})_i\rho(\overrightarrow{r_i})}{\sum_{i=1}^{K}\rho(\overrightarrow{r_i})} \tag{6}$$

Therefore, Equation (4) is the finite volume average of the point distribution function of the detection efficiency. For a sufficiently small volume element, if the number of particles generated within the differential volume is large enough, it is asymptotic with the actual distribution.

We have established a method for calculating the detection efficiency of the differential volume corresponding to a specific position in the source. It is possible to describe the source area as a nonuniform two-dimensional (r,z) source when the source and detector are coaxial. In addition, the source area can be decomposed and divided into several sets of volume units. Users can equally divide the (r,z) coordinate system to calculate the detection efficiency at a specific position of a cylindrical volume source. The coordinates of the radius of the central position of the volume source are set to 0, and the cylindrical source is limited to a symmetrical structure. The differential volumes are created for each location by dividing the entire volume source into equal parts in the radial (r) and height (z) directions. The generated differential volumes are set according to the corresponding position. The calculation results for the γ-rays generated in each differential volume are recorded in the representative coordinates of each differential volume.

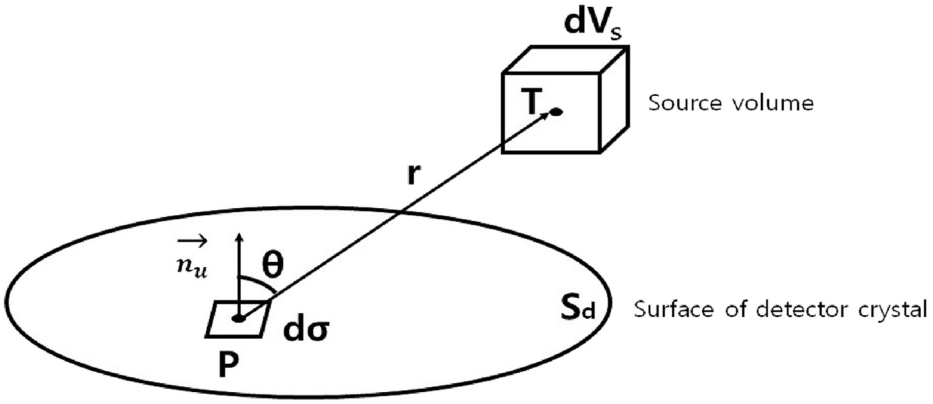

Fig. 1. Calculation of the effective solid angle for an arbitrarily shaped source.

Table 2
Information on the source used in this study.

Type	Circular casing [Point]	Cylindrical beaker [Volume]
Authority	IAEA	KRISS
Volume [ml]	–	1000
Medium	Al	Liquid HCl
Nuclides and Eγ [keV]	^{241}Am 59.357, 125.3 ^{133}Ba 53.16, 79.613, 80.998, 276.4, 302.853, 356.015, 383.851 ^{60}Co 1173.238, 1332.502 ^{137}Cs 661.66 ^{152}Eu Same as Volume Source	^{152}Eu 45.5, 121.782, 244.699, 344.281, 411.126, 443.965, 778.92, 867.39, 964.055, 1085.842, 1089.767, 1112.087, 1212.97, 1299.152, 1408.022

Table 3
Specifications of the detectors used in this study.

Parameter	Contents
Type	N
Model	GMX 30190-S (ORTEC)
Relative Efficiency [%]	43.1
FWHM [keV]	1.83
Crystal Length/Diameter [mm]	79.0/58.2
Window Thickness [mm] and Material	0.5 Be
Dead Layer [μm]	Ge/B: 0.3, Ge/Li: 700
Detector Bias Voltage [V]	- 3900

In the case of large volume sources, a perpendicular arrangement of the source and detector can be considered to reduce the attenuation effect in the source. For asymmetric and perpendicular arrangements of the source and detector, the coordinates are changed from (r, z) to (x, y, z). For a coaxial arrangement, it is possible to divide the source evenly in two dimensions (r, z) since the symmetrical structure is established. However, for a perpendicular arrangement, even if it is uniform in the radial direction, an asymmetric arrangement is generated depending on the positions of the source and detector. Therefore, the volume source is described as a 3-dimensional (x,y,z) cylindrical source with a perpendicular and asymmetric geometry. The x-coordination of the detector centre is set to 0, and translation of the detector is considered by the direction and distance of movement. Except for the geometry of the source and detector, the same algorithm is applied to the calculation methods for the attenuation coefficient, γ-ray generation, pathlength, effective solid angle and detection efficiency.

3. Experiments for validation of EXVol

To verify the performance of EXVol, a high-resolution gamma spectroscopy system was constructed, and measurement and analysis were performed. Measurements were performed on coaxial, asymmetric and collimated geometries with a standard point source and standard volume source with an HPGe detector. The source used for the measurement was an IAEA standard point source and a standard volume source (CRM) produced and certified by the Korea Institute of Standards and Science (KRISS). A total of 64 kBq of ^{152}Eu was dissolved in 0.1 ml of 1000 ml dilute HCl, and the solution was placed in a cylindrical polyethylene container with a diameter of 101.04 mm, a height of 149.17 mm and a thickness of 1.61 mm. The detector used for the measurements had a relative efficiency of 43.1% and was an N-type HPGe detector. A collimator with a diameter of 15 mm and a thickness of 50 mm was installed between the source and the detector. The standard source information used in the experiment is shown in Table 2, and the detector information is shown in Table 3. The arrangement of the source, detector, and collimator performed in the experiment is shown in Fig. 2. The experiment was carried out in a general detection room. The centre of the source and detector was arranged perpendicular, the detector was shielded with lead, and a collimator made of lead was installed to determine the detection efficiency at a specific location. A comparative experiment to confirm the effectiveness of the collimator was performed in the same environment without a collimator and a lead shield.

The volume source was divided into 5 equal parts in the height direction to measure the detection efficiency at each location. The spectrum was obtained by GammaVision. The acquisition times of the standard point source and standard volume source were 14,400 and 86,400 s, respectively. This was a live time with a statistical error of less than 1% for all the gamma sources. The collimator was

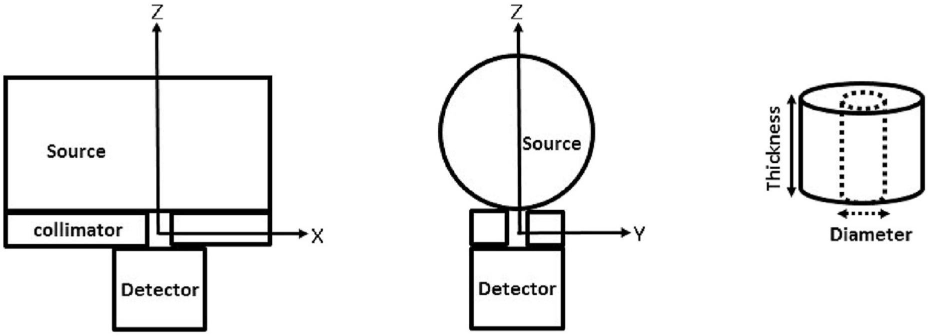

Fig. 2. Coordinate system of the perpendicular geometry of the source, detector and collimator (left and middle) and definition of the collimator (right).

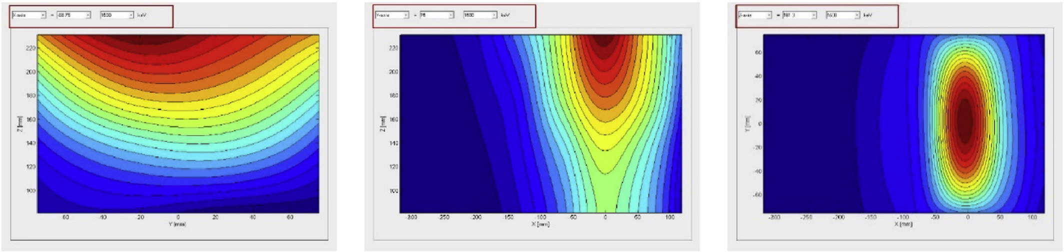

Fig. 3. The contour plot window of EXVol. Users can change the information of axis, coordinate and energy which they have interest. The information can be changed in the red box position at the top left in figures. As a result, EXVol shows the distribution of the detection efficiency.

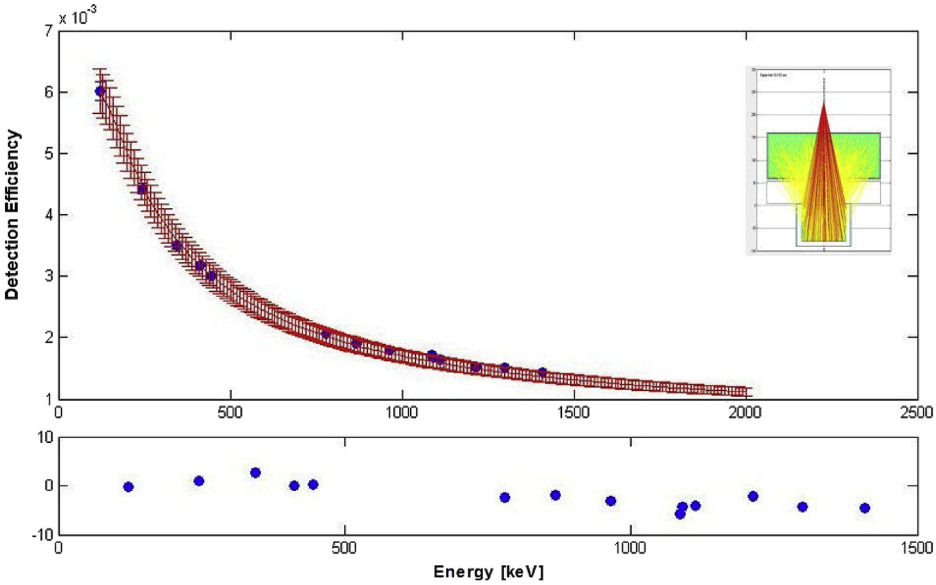

Fig. 4. The detection efficiency (upper box) and a relative deviation (lower box) of the EXVol calculation (red line) and the experimental value (blue dot) for the geometry without a collimator.

installed between the standard volume source and the detector, so the source-to-detector distance was 50 mm. Considering the distance from the centre position of the standard volume source to the window of the detector, the source-detector distance of the standard point source was set to 100 mm. The average count rate at every location was 0.3 cps, and the dead time did not exceed 0.6% for the collimation geometry. The average count rate at every location was 3 cps, and the dead time did not exceed 1.6% for the without collimation geometry. The spectrum analysis and determination of the peak area were performed with the HyperGam [10] program.

4. Results and discussion

EXVol calculation was performed for the experimental geometry and a part of the contour plot is shown in Fig. 3. A comparison of the results for the detection efficiency was performed based on the influence of the measurement position of the volume source and the placement of the collimator. The results are shown in Figs. 4–7. The measurement and calculation results for the case without a collimator are shown in Fig. 4. In this case, it was confirmed that the relative deviation was less than ±10% in all energy regions.

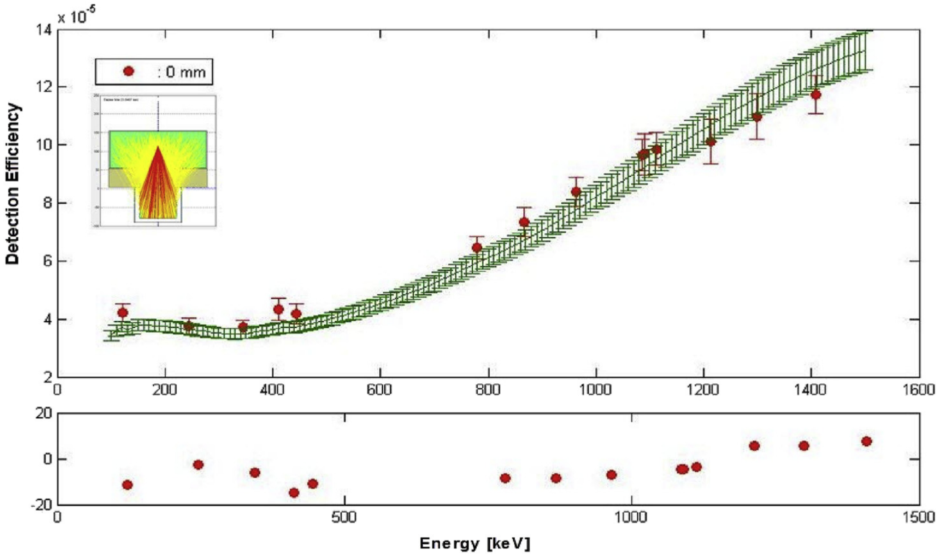

Fig. 5. The detection efficiency (upper box) and a relative deviation (lower box) of the EXVol calculation (green line) and the experimental value (red dot) at the centre height position for the geometry with a collimator.

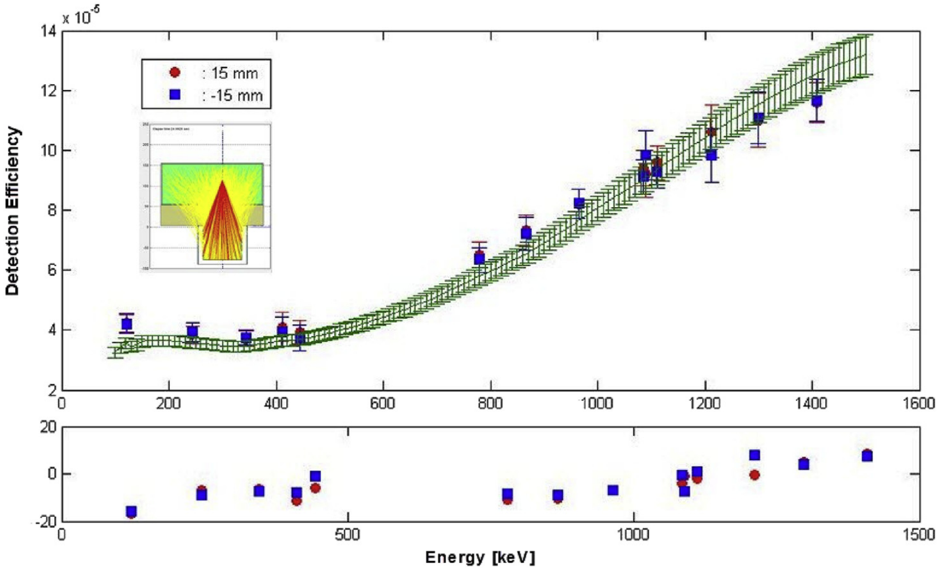

Fig. 6. The detection efficiency (upper box) and a relative deviation (lower box) of the EXVol calculation (green line) and the experimental value (blue square and red dot) for the geometry with a collimator at the ±15 mm translated from centre position.

Commercial programs such as ANGLE and LabSOCS that calculate the detection efficiency of volume sources using the same methodology as this study guarantee uncertainty of ±15%. It can be confirmed that the performance of EXVol is similar to that of commercial codes. Accordingly, calculations with a collimator were conducted under the assumption that the performance of the EXVol code is reliable.

Based on the centre position of the height of the source, the detector and collimator were moved by 15 mm and 30 mm in the up and down directions, respectively. Measurements and calculations were performed for these cases, and the results are compared in Figs. 5–7.

It was confirmed that the measurement and calculation results showed symmetry based on the centre position of the source height, and the data of the symmetry set are shown in the same figure. The analysis results for the detection efficiency curve with the collimation geometry are notable. The results show a trend opposite of that of the existing detection efficiency curve. The attenuation effect increases exponentially as the energy decreases, and the probability of low-energy γ-rays reaching the detector shielded by the collimator is reduced. The relative deviation between the experimental and calculated results is approximately ±20%.

In this study, the total calculation case of EXVol on a PC with a 3.6 GHz CPU with 1 core and 8 GB of RAM is 93 s for 10^4 event numbers, 207 s for 10^5 event numbers and 1950 s for 10^6 event numbers. As the number of events increases, the calculation time increases linearly, but the numerical fluctuations are less than 1%. Therefore, it is possible to calculate the detection efficiency within a few minutes regardless of the type of experimental case to be analysed.

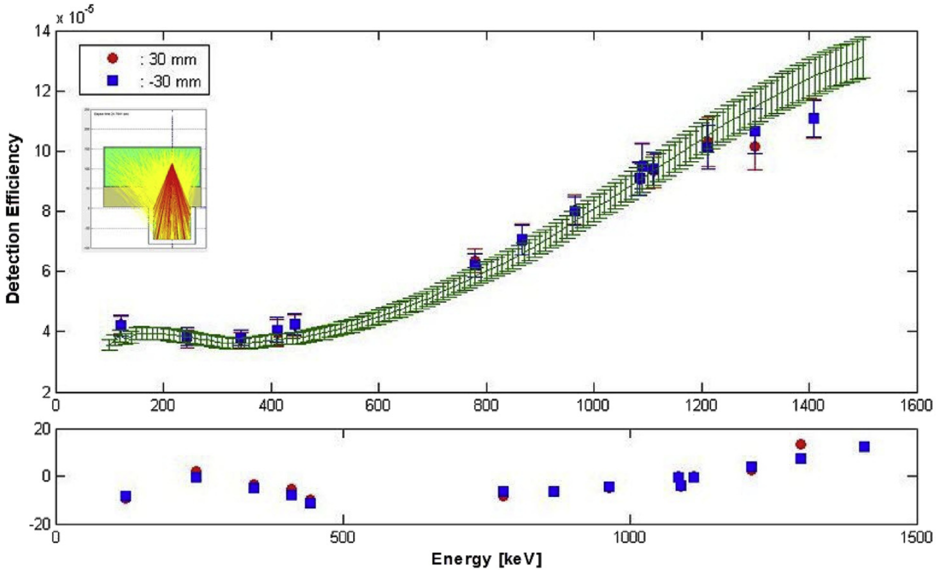

Fig. 7. The detection efficiency (upper box) and a relative deviation (lower box) of the EXVol calculation (green line) and the experimental value (blue square and red dot) for the geometry with a collimator at the ±30 mm translated from centre position.

5. Conclusion and further work

We established a method for calculating the detection efficiency of the differential volume corresponding to a specific position in a large volume source. As a result of this study, γ-ray detection efficiency and radiation distributions were obtained.

The difference in the detection efficiency depending on the placement of the collimator was greater than 100-fold. In addition, it was confirmed that when γ-rays were measured through the collimator, the detection efficiency increased as the incident rays entered the high-energy region.

The relative deviation in the measurements and calculations for the coaxial and asymmetric structures was 10% and that for the collimation structure was 20%. To confirm the possibility of improving the performance of the EXVol code, we plan to perform calculations considering the true coincidence summing correction. In this study, only for the cylindrical type of collimator was measured and compared with EXVol calculation result. However, we plan to further verification of EXVol performance by manufacturing collimators of various shapes (slit, corn etc.) and diameter in the future.

The results of this study can be used in the analysis of environmental radiation samples and applied research using γ-ray measurements. In addition, the results can also be used for nondestructive assays and the radioactivity analysis of high-level radiation and large volume structures such as nuclear fuel rods and radioactive waste drums.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.05.004.

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