THE EFFECT OF MESH DIVISION OF A VOLUME SOURCE ON CALCULATED RADIATION FLUX DISTRIBUTION

by

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A sensitivity analysis of a point kernel code was performed to investigate the effect of mesh division of a volume source on the radiation flux at points of interest. The QAD-CGGP, known as a representative point kernel code, was employed for a series of calculations and these calculation results compared with the reference data obtained from the MCNP5-1.60 code. The spherical volume source widely used in radiation shielding was also considered in this work and the mesh division along the radius was performed in two ways (regular and irregular). In addition, an approximate equation was defined to correct the significant error that occurs as an outcome of the point source assumption. As a result, in the case of a regular mesh division, a minimum mesh size of 1 cm is required to produce accurate results in comparison to the MCNP ones, while in the other instance, a half-level mesh division is sufficient to obtain the same result from the standpoint of the level of accuracy. In addition, by introducing the approximate equation presented in this paper, a significant error resulting from the point source assumption is exponentially reduced from a maximum of ~30% to a maximum of ~11%. Therefore, it is to be expected that the appropriate level of mesh division is required so as to increase the accuracy of the calculation using a point kernel method.

Key words: spherical volume source, point kernel method, QAD-CGGP, radiation shielding

INTRODUCTION

The evaluation of radiation shielding for the design and maintenance of facilities using radioactive sources (accelerators, radionuclides, nuclear fuel) is presented here. The research required a considerable amount of numerical calculations to analyze the radiation flux and dose rate distribution around the said facilities. For this reason, various computational codes and methods were introduced into the field of radiation shielding and the most widely used methods classified into two main groups: Monte Carlo [1-3] and point kernel methods [4-6]. The Monte Carlo method can provide an accurate result for the radiation transport calculation in a complex geometry. However, this method requires a lot of computing time and the computational burden significantly increases with geometric complexity, source diversity, and shielding thickness. On the other hand, the point kernel method requires much less computing time than the other method, although it may lack the desired accuracy under complex geometry and beam streaming conditions. Hence, the point kernel method can be regarded as an optimal tool for repeated calculations, allowing the optimization of radiation shielding.

Using a point kernel method, some researchers have even tried to increase the accuracy of the calculation. More specifically, they have focused on the reevaluation of existing buildup factors, because existing data (ANS-6.4.3) [7] only include single-material buildup factors which were evaluated about 20 years ago [8-10]. However, the level of mesh division can influence the computing time and calculation accuracy because most codes, *e. g*., QAD-CGGP [11], MICROSHIELD [12], and MARMER [13], based on a point kernel method, use the central points of the divided meshes to define the radiation source. Using the QAD-CGGP code, a simple calculation is conducted to investigate the effect of the level of mesh division on calculation time (see fig. 1). In particular, QAD-CGGP used in this work is a representative three-dimensional point kernel code which uses a double-precision combinatorial geometry scheme and a more accurate geometric progression fitting function for the gamma-ray buildup factor. In addition, the radiation source assumes a spherical volume source with a 10 cm radius. As shown in the figure, the calculating time is continually increased with an increase in the mesh division for the radius of the sphere, as well as the number of calculation positions. That is, it is necessary

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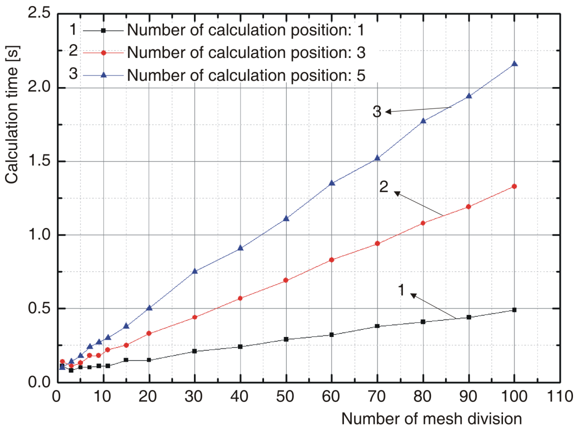

Figure 1. Run time as a function of the mesh division and calculation quantity

to determine the appropriate level of mesh division to perform an efficient calculation with respect to the calculation time.

In this study, the relation between the mesh division of the volume source and radiation flux distribution is analyzed to determine the appropriate level of mesh division. A series of calculations are conducted on a spherical volume source widely used in radiation shielding. In addition, an approximate equation is defined to derive the calculation results (radiation flux and dose rate) with a spherical volume source from results obtained with a point source.

ANALYSIS OF RADIATION FLUX DISTRIBUTION

The point kernel method is a typical macroscopic approach used for the calculation of radiation (especially, gamma ray) flux and dose rate distributions. In this method, the volume of the radiation source is divided into elementary cells, and each cell (point kernel) contributes to the radiation flux and dose rate at the points of interest. The radiation flux and dose rate at specific points are primarily determined by using the uncollided radiations that have streamed directly from the source without interaction in the surrounding medium. The effect of radiation interactions (*e. g.*, Compton scattering, photoelectric effect, pair production, Rayleigh scattering, *etc.*) with the medium is considered using the linear attenuation and buildup factors later. The basic theory of the point kernel method can be defined as follows [14]

$$D(r,E) \quad \frac{S(r,E)}{4\pi r^2} e^{\mu r} B(r,E) DCF(E) \qquad (1)$$

where r is the distance from the radiation source to the detection point, E – the attenuation coefficient, $S(r, E)$ – the incident radiation energy, $S(r, E)$ – the source strength, $B(r, E)$ – the buildup factor, and $DCF(E)$ – the radiation flux to dose conversion factor.

The spherical volume source is important for two reasons: (1) it is effective in making rough calculations and, (2) it is representative of many practical sources. Hence, the calculations in this study are based on a spherical volume source (^{60}Co), which is executed using a QAD-CGGP code. The source emission is assumed to have a uniform strength of S_v (4189 Bq), and the energies of the two gamma-rays are 1.1732 MeV and 1.3324 MeV, respectively (see fig. 2). The volume of the radiation source is divided into 5 to 100 meshes along the radius (R), while being divided into 100 meshes along the polar (θ) and azimuthal (φ) angles, respectively. In particular, the mesh division along the radius is performed in two ways (regular and irregular types), as shown in fig. 3.

In the case of a regular division, the meshes are evenly spaced along the radius and the size of each mesh equals the radius of the spherical volume source divided by the number of meshes (N). In the other case, the meshes are mainly distributed at the edge of the spherical volume source, while the edge of each mesh is defined as $(2^N–1)R/2^N$. Figure 4 shows the ratio of the effective radius determined from the mesh division to the real radius of the spherical volume source. As shown in the figure, if the level of mesh division is insufficient, the volume of the radiation source can be decreased to ~40% of its original volume, due to the 25% reduction of the sphere radius. An irregular mesh division is a more effective way for defining the radiation source in a point kernel method.

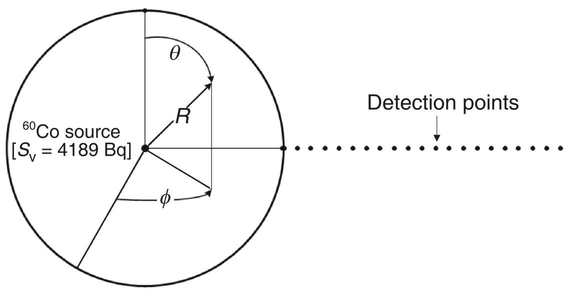

Figure 2. Calculation model for analyzing the relation between the mesh division of volume source and radiation flux distribution

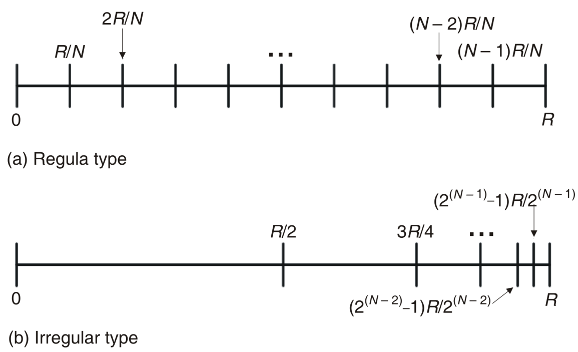

Figure 3. Method of mesh division for volume source

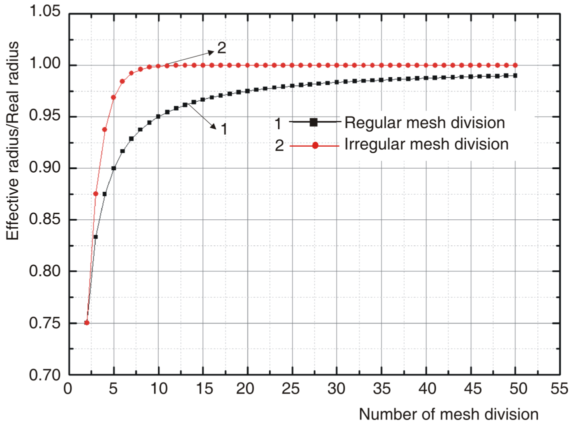

Figure 4. Ratio of the effective radius to the real radius of a spherical volume source

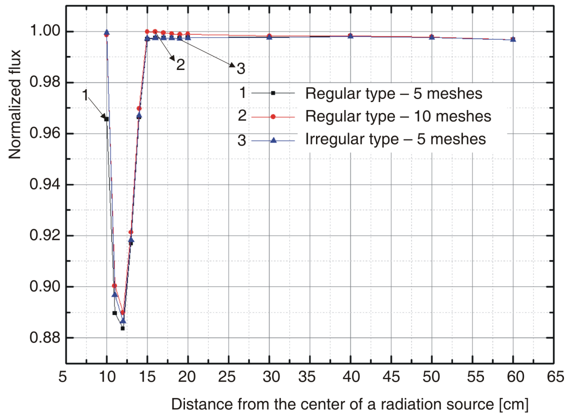

Figure 5. Gamma ray flux normalized by MCNP5 results (OAD-CGGP/MCNP5)

The gamma ray flux distribution around the spherical volume source is analyzed using the MCNP5-1.60 [15] and QAD-CGGP codes and the results presented in tab. 1. As shown in the table, the gamma ray flux exponentially decreases with an increase in the distance from the radiation source to the detection point, regardless of the calculation code and the level of mesh division. In the case of a regular mesh division, the radiation flux becomes more underestimated in comparison to the reference data (MCNP5), as the number of the dividing volume source is smaller. However, in the second case there are no significant changes in the radiation flux, despite the variation in mesh division. Figure 5 shows the gamma ray flux normalized by reference data, in order to easily understand the calculation results. As shown in the figure, the gamma ray flux around the radiation source ($r < 15$ cm) has a large uncertainty, regardless of the mesh division method. However, under the same condition, an irregular mesh division can produce a slightly more accurate result than the other one. From these results, it is expected that a sufficient mesh division (regular type: ~1 cm mesh size and irregular type: ~2 cm mesh size) is required for point kernel calculation with the spherical volume source.

APPROXIMATE EQUATION TO CORRECT POINT SOURCE ASSUMPTION

When a specific source as a spherical volume that emits the radiations to be isotropically moved over the 4 solid angle is placed in a simple structure, the evaluation of radiation shielding can be easily conducted by introducing certain assumptions. In particular, if the size of the source volume is small in comparison with the distance from the radiation source to the detection point, the source can be assumed an equiva-

Table 1. Change of gamma flux [$cm^{-2}s^{-1}$] following the level and way of dividing volume source

r*[cm]	QAD-CGGP Regular mesh division 5 meshes	10 meshes	20 meshes	Irregular mesh division 5 meshes	10 meshes	20 meshes	MCNP5
10	9.290E+00	9.606E+00	9.717E+00	9.615E+00	9.620E+00	9.619E+00	9.621E+00
11	6.962E+00	7.046E+00	7.070E+00	7.018E+00	7.024E+00	7.023E+00	7.826E+00
12	5.542E+00	5.581E+00	5.591E+00	5.560E+00	5.562E+00	5.561E+00	6.272E+00
13	4.559E+00	4.581E+00	4.586E+00	4.565E+00	4.566E+00	4.566E+00	4.972E+00
14	3.834E+00	3.848E+00	3.851E+00	3.836E+00	3.837E+00	3.836E+00	3.967E+00
15	3.278E+00	3.287E+00	3.290E+00	3.279E+00	3.279E+00	3.279E+00	3.288E+00
16	2.840E+00	2.847E+00	2.848E+00	2.840E+00	2.840E+00	2.840E+00	2.847E+00
17	2.487E+00	2.492E+00	2.493E+00	2.487E+00	2.487E+00	2.487E+00	2.493E+00
18	2.198E+00	2.202E+00	2.203E+00	2.198E+00	2.198E+00	2.198E+00	2.204E+00
19	1.958E+00	1.961E+00	1.961E+00	1.958E+00	1.958E+00	1.958E+00	1.963E+00
20	1.756E+00	1.758E+00	1.759E+00	1.756E+00	1.756E+00	1.756E+00	1.760E+00
30	7.569E-01	7.573E-01	7.573E-01	7.568E-01	7.568E-01	7.568E-01	7.586E-01
40	4.215E-01	4.216E-01	4.216E-01	4.214E-01	4.214E-01	4.214E-01	4.223E-01
50	2.685E-01	2.685E-01	2.685E-01	2.685E-01	2.685E-01	2.685E-01	2.691E-01
60	1.860E-01	1.860E-01	1.860E-01	1.860E-01	1.860E-01	1.860E-01	1.866E-01

**r* is the distance from the center of a radiation source to the detection point

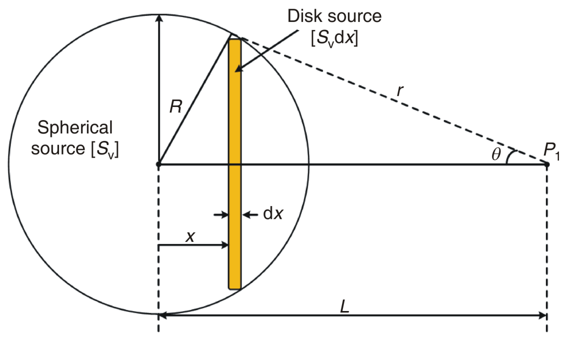

Figure 6. Spherical volume source without radiation shielding

lent point source. That is, this assumption ignoring the source volume can lead to a significant error for the radiation flux (dose) distribution near the radiation source. In this study, an approximate equation is defined to correct significant errors produced by employing a point source assumption, and a spherical volume source without the radiation shield is assumed, as shown in fig. 6.

A spherical volume source of radius R emits isotropically S_v particles per unit volume, a detector is positioned at point P_1, and the distance from the sphere center to the detection point is L. In this case, the differential uncollided flux ($d\phi_u^{sph}$) of particles emitted in dx about x can be defined using the total uncollided flux for the finite disc source [16]

$$d\phi_u^{sph} \quad \frac{S_v dx}{2}\ln(\sec\theta) \tag{2}$$

and thus the total uncollided flux (ϕ_u^{sph}) at P_1 becomes

$$\phi_u^{sph} \quad \frac{S_v}{2}\,{}_{-R}^{\;R}\ln(\sec\theta)dx$$

$$\frac{S_v}{2}\,{}_{R}^{R}\ln\frac{\sqrt{R^2 \quad L^2 \quad 2Lx}}{L \quad x}\,dx$$

$$\frac{S_v}{8L}\;\begin{matrix} 2(L^2 \quad R^2)\{\ln 2 \quad \ln[L(L \quad x)]\} \\ (L^2 \quad R^2 \quad 2Lx) \\ 2\ln\frac{\sqrt{L^2 \quad R^2 \quad 2Lx}}{L \quad x} \quad 1 \end{matrix}\;{}_{R}^{R}$$

$$\frac{S_v}{4L}\;(L^2 \quad R^2)\ln\frac{L \quad R}{L \quad R} \quad 2LR \tag{3}$$

Also, the total uncollided flux (ϕ_u^{pnt}) of the equivalent point source considering the sphere volume can be simply defined as

$$\phi_u^{pnt} \quad \frac{S_v}{4\pi L^2} \quad \frac{4}{3}\pi R^3 \quad \frac{S_v R^3}{3L^2} \tag{4}$$

and an approximate equation to correct the point source assumption is finally derived from those equations

$$\frac{\phi_u^{sph}}{\phi_u^{pnt}} \quad \frac{3L}{4R^3} \quad (L^2 \quad R^2)\ln\frac{L \quad R}{L \quad R} \quad 2LR \tag{5}$$

In addition, the reactions between the emitted radiations and the sphere source (*i. e*., self-shielding effect) are not considered to derive a simplified equation.

The gamma ray flux under the same conditions as shown in fig. 2 is re-analyzed to confirm the effect of correcting the point source assumption and the results are presented in tab. 2. As shown in the table, the results applied with the point source assumption have a maximum difference of ~30% in a radiation flux near the source, compared with the MCNP5 result. On the other hand, this difference is sharply reduced from ~30% up to ~11% by correcting the point source assumption (fig. 7).

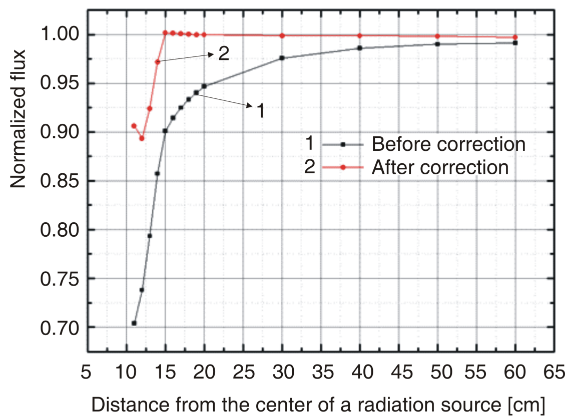

Figure 7. Correction before and after gamma ray flux normalized by MCNP5 results (QAD-CGGP/MCNP5)

CONCLUSION

Using the point kernel method, an analysis of the relation between the mesh division of the volume source and radiation flux distribution was conducted to increase the accuracy of the calculation. In this process, the spherical volume source widely used in radiation shielding is considered to determine the appropriate level of mesh division, while the mesh division is performed in two ways: regular and irregular. As a result, in a regular mesh division, at least a 1cm mesh size along the radius is required to obtain accurate results, compared with the MCNP5 data, while a half-level of the mesh division in an irregular mesh division is sufficient to obtain the same result regarding the level of accuracy. In addition, an approximate

Table 2. Point source assumption correction before and after gamma flux [$cm^{-2}s^{-1}$]

r* [cm]	QAD-CGGP			MCNP5
	Before correction	Correction factor	After correction	
11	5.509E+00	1.288E+00	7.092E+00	7.826E+00
12	4.629E+00	1.210E+00	5.603E+00	6.272E+00
13	3.944E+00	1.165E+00	4.593E+00	4.972E+00
14	3.400E+00	1.134E+00	3.856E+00	3.967E+00
15	2.962E+00	1.112E+00	3.293E+00	3.288E+00
16	2.603E+00	1.095E+00	2.851E+00	2.847E+00
17	2.306E+00	1.082E+00	2.495E+00	2.493E+00
18	2.057E+00	1.072E+00	2.204E+00	2.204E+00
19	1.846E+00	1.063E+00	1.963E+00	1.963E+00
20	1.666E+00	1.056E+00	1.760E+00	1.760E+00
30	7.403E-01	1.023E+00	7.576E-01	7.586E-01
40	4.163E-01	1.013E+00	4.217E-01	4.223E-01
50	2.664E-01	1.008E+00	2.686E-01	2.691E-01
60	1.850E-01	1.006E+00	1.860E-01	1.866E-01

*r is the distance from the center of a radiation source to the detection point

equation is defined to correct significant errors that occur from introducing a point source assumption. By applying this equation, the difference in the calculation results derived from MCNP5 and QAD-CGGP codes is sharply reduced from a maximum of ~30% up to a maximum of ~11%. Therefore, it is to be expected that an appropriate level of mesh division is required to increase the accuracy of the calculation when using a point kernel method. The approximate equation for correcting the point source assumption can, therefore, be successfully applied in various evaluations for radiation shielding.

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AUTHOR CONTRIBUTIONS

A series of simulation works were carried out by K.-O. Kim and C.-G. Seo, the manuscript and figures prepared by K.-O. Kim. All authors reviewed the final manuscript.

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Кјунг-О КИМ, Чул-Ђо СЕО, Бјунг Чул ЛИ

УТИЦАЈ БРОЈА ТАЧАКА МРЕЖЕ У ЗАПРЕМИНСКОМ ИЗВОРУ НА ИЗРАЧУНАТУ РАСПОДЕЛУ ФЛУКСА ЗРАЧЕЊА

Извршена је анализа осетљивости кода са моделом тачкастог језгра ради процене утицаја густине мреже запреминског извора на флукс зрачења у тачкама од интереса. За серију прорачуна употребљен је QAD-CGGP код, познат као репрезентативан код са тачкастим језгром, и резултати прорачуна упоређени су са референтним подацима добијеним MCNP5-1.60 кодом. У раду је такође коришћен сверни запремински извор уобичајен у заштити од зрачења, са правилном и неправилном деобном мрежом дуж полупречника. Додатно, дефинисана је једна апроксимативна једначина да се исправи значајна грешка која се јавља као последица претпоставке о тачкастом извору. У погледу нивоа тачности, у случају правилне мреже, захтева се минимално растојање мрежних тачака од 1 cm да би се постигли упоредиви резултати са MCNP кодом, док је у другом случају довољна половина претходног броја деобних тачака да се добију резултати истог нивоа тачности. Применом апроксимативне једначине приказане у овом раду, додатно је експоненцијално умањена максимална грешка која следи из претпоставке тачкастог извора – од 30% до 11%. Отуда се може сматрати да је потребан одговарајући број тачака мреже да се постигне тачност прорачуна коришћењем методе тачкастог језгра.

Кључне речи: сверни запремински извор, метода тачкастог језгра, QAD-CGGP, флукс зрачења, заштита од зрачења