Feasibility Study of Simplification of Radiation Source Shape Using Monte Carlo N-Particle Transport(MCNP)

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***Abstract*—In real radiation work environments, radiation sources can exist in various shapes (line, surface, or volume) and forms (gas or liquid). It is difficult to calculate the worker's exposure dose under all these conditions. Therefore, the source shape needs to be simplified. The Electric Power Research Institute (EPRI) algorithm suggests converting line or volume sources into point sources, and some studies report that this simplification is acceptable when the measurement point is far enough from the source. In this study, we analyzed the relative error in dose rate when a line source is simplified as a point source. Both theoretical methods and Monte Carlo N-Particle Transport (MCNP) simulations were used. Cesium was used as the source, and the dose rate was calculated at various positions. The results showed that the relative error was less than 10% when the distance was more than one source length, and less than 1% when the distance was more than twice the source length.**

Keywords-Source Simplification; Monte Carlo Simulation;

I. INTRODUCTION

Radiation sources can exist in various forms such as lines, surfaces, and volumes, and may also change in real time when in liquid or gas states. When theoretically calculating the dose received by radiation workers, it is not practical to consider all these complex source geometries. Therefore, simplifying the shape of the radiation source is necessary.

The EPRI developed an algorithm that estimates radiation dose by approximating extended sources (such as line or volume sources) as a series of point sources. The method recommends representing line and volume sources as multiple point sources spaced approximately 1 foot apart [1]. In addition, previous research has shown that when the measurement point is more than three times the length of a line source away, treating the source as a point source is acceptable without significant error [2].

In this study, we analyzed the relative error caused by this simplification process using both a theoretical approach and MCNP simulation. MCNP was developed at Los Alamos National Laboratory for radiation transport studies [3]. Its origin goes back to the late 1940s when the Monte Carlo method was first applied to nuclear research [4]. The code simulates the transport of neutrons, photons, and electrons by tracing random particle histories. At each step, interactions such as scattering, absorption, or collision are sampled statistically using random number [3]. This probabilistic approach allows accurate calculations even in complex geometries and material conditions. The relationship between the distance from the source and the resulting dose rate error was examined to evaluate the validity of approximating line sources as point sources in practical dose assessment scenarios.

In this study, both theoretical calculations and Monte Carlo simulations were used to evaluate the error introduced when a line source is approximated as a point source. This approach aimed to determine the distance from the line source at which the point source approximation becomes acceptable.

The Materials and Methods section explains the theoretical approach and the Monte Carlo simulation used to calculate the dose rate of an actual line source and approximated as a point source at various positions. The Results and Conclusion sections provide criteria for the distance at which a line source can be approximated as a point source.

II. MATERIALS AND METHODS

This section describes the theoretical methods for calculating the dose rate when a line source is approximated as a point source. It also presents the procedure of MCNP simulation under this assumption.

A. *Theoretical Method [5]*

The dose rate at different positions from a line source can be calculated using the following equation (1).

$$\text{Dose rate} = \Gamma(A / r^2) \tag{1}$$

Γ is the gamma constant for Cesium, A represents the activity, and r is the distance between the source and the measurement point.

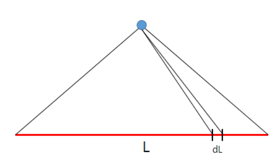

Figure 1. Radiation dose rate calculation from a linear source

A line source can be regarded as a collection of infinitely many point sources. Based on this logic, Figure 1 illustrates the method used to calculate the dose rate from a linear source.

A line source of length L can be divided into infinitesimal segments of length dL. The total dose rate from the entire source can be obtained by integrating the dose rate contributions from each segment (2).

$$\text{Dose rate} = \Gamma(A_l / h)(\theta_1 + \theta_2) \quad (2)$$

A_l is the total activity of the line source of length L, and h is the perpendicular distance from the line source to the measurement point. The angle θ is defined by the geometry formed by the measurement point, the foot of the perpendicular to the source, and both ends of the line source.

Using this equation, we calculated the dose rate under 4 different geometric conditions: (a) measurement point is perpendicular to the center of the source, (b) perpendicular to one end, (c) perpendicular to an off-center segment, (d) not perpendicular to any part of the source (Figure 2).

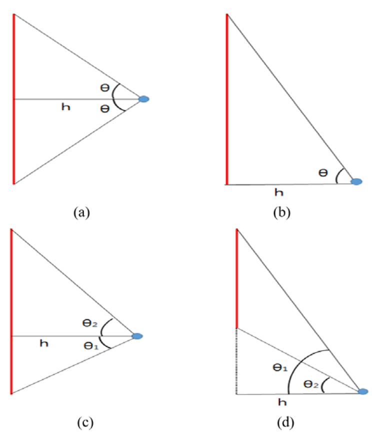

Figure 2. Dose rate calculation under four geometric conditions: (a) center, (b) end, (c) off-center, (d) non-perpendicular

B. Monte Carlo Simulation

The MCNP simulation was performed using a monoenergetic gamma source of 0.662 MeV, representing Cesium. The results of MCNP are presented with statistical uncertainties. When the number of particle simulations is small, the statistical error is large, while increasing the number of particles reduces the error. In this study, results were considered reliable when the statistical uncertainty was less than 10%. To achieve this, a total of 1,000,000 simulations were performed, where the number of simulations corresponds to the number of photons. The increase in dose at the measurement point due to scattered secondary gamma rays originating from the unscattered primary 0.662 MeV gamma rays is referred to as the build-up factor. This effect depends on factors such as the geometric structure of the source, the thickness and material of the shielding, and the energy of the gamma rays. In this study, the dose contribution from this effect was excluded; therefore, the attenuated dose rate was not considered. The simulation environment was set up on a 6 m × 6 m xy-plane, with the point source located at the origin. A 1-meter-long line source was placed along the y-axis, centered at the origin. Dose rates were calculated at intervals of 10 cm throughout the plane.

To convert photon fluence to ambient dose equivalent, the conversion coefficients from International Commission on Radiological Protection (ICRP) Publication 74 [H*(10)/Φ] were used. Figure 3 shows the MCNP simulation setup used for the dose rate calculation.

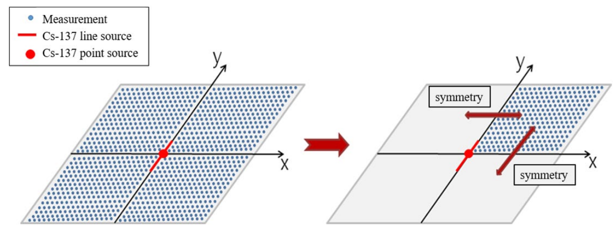

Figure 3. MCNP simulation setup for dose rate calculation

For each case, the relative error was calculated by comparing the result to the assumption that the line source is modeled as a single point source.

III. RESULTS

Table I shows the relative error at each measurement position calculated using the theoretical method.

TABLE I. RELATIVE ERROR BY POSITION (THEORETICAL CALCULATION)

Distance from source (multiples of source length)	Relative error (%)			
	(a)	(b)	(c)	(d)
0.1 times	264	74	48	61
0.2 times	110	50	12	46
0.3 times	62	31	4	32
0.4 times	40	18	10	21
0.5 times	27	10	11	13
0.6 times	20	5	10	8
0.7 times	15	1.4	9	4
0.8 times	12	0.3	8	2
0.9 times	10	1.3	7	0.7
1 times	8	2	6	0.3
3 times	0.9	0.8	0.9	0.7

In this study, relative error of 10% or less was considered a meaningful simplification, and an error below 1% was assumed to be practically error-free. Under condition (a) in Figure 2, the relative error was less than 10% when the measurement point was located at 0.9 times the source length from the source. For condition (b), the threshold was 0.5 times the source length, and for conditions (c) and (d), it was 0.6 times. Additionally, the relative error was below 1% when the distance was 3 times the source length for conditions (a) to (c), and 0.9 times for condition (d).

In the Monte Carlo simulation, the linear source was placed along the y-axis, and the point source was positioned at the origin. Since the dose distributions from both sources are symmetric with respect to the first quadrant of the xy-plane, the simulation focused on this region (Figure 4).

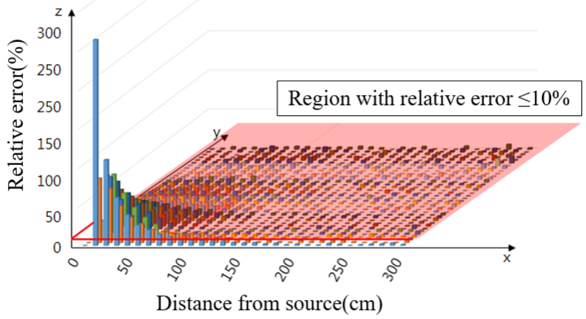

Figure 4. Relative error from approximating a line source as a point source

The results showed that the relative error was less than 10% at distances equal to the source length and less than 1% at twice the source length. These findings are consistent with the theoretical calculations.

IV. Conclusion

In this study, the relative dose rate error caused by approximating a line source as a point source was evaluated using both theoretical calculations and Monte Carlo transport simulations. The results showed that when the distance from the source exceeded the length of the line source, the relative error remained below 10%, and when the distance was more than twice the source length, the error was within 1%. This indicates that at distances of 2–3 times the source length, the line source can be reasonably simplified as a point source without significantly affecting the calculated worker dose. Based on these findings, users can construct an appropriate point source model depending on the allowable error margin in practical applications.

References

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