Variation of the Air Kerma Rate from Natural Radionuclides in the Ground Due to the Change of Source Configurations

Kimiaki Saito
Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken, Japan

Abstract - The kerma rate in air from natural radionuclides of $^{238}$U series, $^{232}$Th series, and $^{40}$K changes according to the source configurations in the environment. In this study, the tendency and degree of the change were investigated using Monte Carlo calculations assuming several kinds of typical terrain having different source configurations. The kerma rate was confirmed to be related deeply with the solid angle subtended by gamma source, but to change less than the solid angle does.

INTRODUCTION

The gamma rays from natural radionuclides in ground and artificial structures are among the major sources for external exposure of public. It is well known that the kerma rate in air due to natural gamma rays changes according to conditions. Especially, in urban environments like in Tokyo it has been observed that the air kerma rate changes variously with place (1, 2). The main factor of the changes is the difference in radionuclide concentrations in materials constituting the environment. Further, the configurations of gamma-ray sources and shielding effects of various constructions vary the radiation level apparently.

The purpose of this paper is to investigate the relationship of gamma-source configurations to the kerma rate in air. The kerma rate in a tunnel or a cut in the ground is higher than the kerma rate on a plain field at the same concentrations of radionuclides because of difference in solid angle subtended by soil containing gamma sources. On the contrary, the kerma rate decreases on a water body like a river which hardly contains radionuclides. It has been reported by some researchers that for $4\pi$ source geometry the kerma rate becomes approximately twice as much as that for $2\pi$ geometry (3, 4). However, the features of the change in kerma rate due to source configurations have not been thoroughly investigated.

In this study, kerma rates in air due to natural radionuclides were calculated using Monte Carlo simulation assuming typical terrain, that is typical source configurations. The considered terrain was 1) spherical hollow in the ground, 2) cylindrical tunnel in the ground, 3) slab-shaped hollow in the ground, 4) angled ground, 5) rectangular cut in the ground, and 6) straight river. The natural radionuclides of the $^{238}$U series, $^{232}$Th series, and $^{40}$K were assumed to distribute uniformly in soil at some typical concentration ratios. The calculated kerma rates were normalized to the value for infinite plain ground geometry.

CALCULATIONAL METHOD

The environmental gamma-ray transport calculation were performed using the Monte Carlo program YURI (5) which has been verified by comparisons with experimental and theoretical data under various conditions. Three photon interaction processes of photoelectric absorption, Compton scattering and pair production followed by annihilation of two 0.511 MeV gamma rays were considered.

In this research, the natural radionuclides of $^{238}$U series, $^{232}$Th series, and $^{40}$K were assumed to be in radiation equilibrium and distribute uniformly in soil. The nuclides in the $^{238}$U series and $^{232}$Th series emit a great number of gamma rays with different energies. All photon lines compiled in the JEF-2.2 file (6) were taken into account. The radionuclides that release energy less than one percent of the energy released from the series were omitted. The summation of the energy released from the omitted nuclides is still less than one percent of the total released energy for each series. The concentration ratios among $^{238}$U, $^{232}$Th, and $^{40}$K in the soil were assumed to be 1:1:10. Water was taken not to contain any radioactivity. The elementary compositions and density of air and soil were the same used in ref.(5). In this calculation, the changes in elementary compositions and density do not affect the results significantly.

The following six kinds of typical source configurations were considered in this study: a) spherical hollow in the ground; b) cylindrical tunnel in the ground; c) slab-shaped hollow in the ground; d) angled ground; e) rectangular cut in the ground; and f) straight river. The considered source configurations are shown in Figure 1. Except the spherical hollow, the configurations are infinite in one dimension or in two dimensions. The cylindrical tunnel has infinite length; the slab-shaped hollow is infinite in the plane directions; configurations d), e), and f) are infinite in the direction perpendicular to the cross sections shown in the figures.

A photon history was determined for each calculation so that the standard deviation of the calculated kerma rates would be within several percent. The calculated kerma rates per unit source intensity were normalized...
to the value for infinite plain ground geometry to investigate the relative effects of source configurations. The absolute values of kerma rate conversion factors for $^{238}$U series, $^{232}$Th series, $^{40}$K taken from ref. (7) are shown in Table 1. The results in this paper can be converted absolute kerma rate values using the tabulated data.

RESULTS AND DISCUSSIONS

4 source geometry

The normalized kerma rates for configurations a), b), and c) are shown in Figure 2. All of the configurations have $4\pi$ source geometries, and the tendency of relative kerma rate as a function of radius $R$ or height $H$ are similar for all configurations. When the radius or height is very small, the normalized kerma rate is close to 2 but never reach 2. This is because the portion of kerma rate due to scattered gamma rays in the total kerma rate is smaller than that for plain ground geometry.

The soil consists of heavy elements compared with air; therefore, the absorption rate for photons in soil is higher than that in air. The soil acts as scatterer as well as source, but the reduction by absorption is greater than that for air resulting in a smaller scattered component. In configuration c), the normalized kerma rate gets close to 2.0 most among the three configurations, because the amount of air working as scatterer is relatively large.

The kerma rate decreases as the radius $R$ or height $H$ increases, and the kerma rate goes down nearly to 1as $R$ or $H$ reaches 1000 m. The kerma rate as a function of $H$ in the slab-shaped hollow decreases rapidly compared with that as a function of $R$ in the other configurations. In the spherical hollow at a radius of 100 m the relative kerma is about 1.7; while in the slab-shaped hollow at a height of 100 m about 1.4.

This could be explained by the fact that the amount of source existing in the vicinity of the detector are substantially the largest for spherical hollow, the second for the cylindrical tunnel, and the smallest for the slab-shaped hollow according the curvature of the ground.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Kerma rate per unit activity ( (\text{nGy.h}^{-1}\text{per Bq.kg}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U series</td>
<td>0.463</td>
</tr>
<tr>
<td>$^{232}$Th series</td>
<td>0.604</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>0.0417</td>
</tr>
</tbody>
</table>
The representative dimension (corresponding to \( R \) or \( H \) in the simulation) of such hollows where the public spend their daily lives seldom exceed some tens meter. Thus, the kerma rate in \( 4\pi \) source geometry is usually expected to be 1.8 – 2.0 times as much as that in \( 2\pi \) source geometry, provided the nuclide concentrations are the same.

Angled ground

The relationship of the normalized dose rate on angled ground to the angle \( \theta \) between two planes is shown in Figure 3. In the figure, the solid angle subtended by the source normalized at 180 degree is shown together. It is obvious that the relative kerma rate has a close relation with the solid angle. However, the change in kerma rate is a little smaller that the change in solid angle.

This is explained by the difference in the rate of photon absorption between air and soil. As discussed before, the frequency for absorbing photon is smaller for air. Therefore, the increase in relative amount of air leads to the increase in the fraction of scattered gamma rays, resulting in the increase in the total kerma rate. In fact, the fraction of scattered gamma rays contribution in the total kerma rate is nearly 0.6 at \( \theta = 90 \) degree while it is usually 0.5. On the contrary, for \( \theta \) greater than 180 degree the scattered-gamma ray component is reduced by the increment of soil acting as absorber.

Figure 2. The change of normalized kerma rates for \( 4\pi \) geometry sources as functions of \( R \) and \( H \).
Rectangular cut

Figures 4 and 5 show the kerma rates in the rectangular cuts in the ground at different dimension. The width of rectangular cut $W$ was changed from 5 m to 40 m, and the depth $H$ was from 5 m to 20 m. The change of air kerma in the cuts is shown in the figures as a function of distance $D$ from the center line of the cut as shown in Figure 1. The kerma rate profile is symmetric to the plane perpendicular to the ground at the center line; therefore, the kerma rates in the right half space in the cut are shown. In the figures, the solid angle subtended by the source is shown together.

In summary, the relative kerma rate changes between 1 - 2 according to the dimensions. It is clear that the relative kerma rate has a relation with the solid angle, but does not exceed the value of relative solid angle. This can be explained also by the decrease of the scattered

Figure 3. Kerma rate on angled ground as a function of angle between two plane ground.
Figure 4. Kerma rates in rectangular cuts at different dimensions.

Figure 5. Kerma rates in rectangular cuts at different width $W$ from 5 m to 40 m, the depth $H$ being fixed to be 10 m.
Figure 6. Kerma rate on the rivers at different widths from 5 m to 100 m. The detector height was changed from 1 m to 100 m.
Figure 7. The relation of kerma rate to the solid angle viewing source. The portion of kerma rate due to scattered gamma rays is also shown.
The kerma rate at 1 m height changes drastically with distance $D$ even for a river at 5 m width. On the contrary, the kerma rate at 100 m height, the kerma rate is insensitive to the position; it seems difficult to find out the existence of river at 100 m width from an air-borne survey. In actual air-borne survey, we have experienced that the existence of a river can be recognized by the decrease in air absorbed dose rate measured. In this case, the river is considered to have a larger width than that simulated in the calculation.

In Figure 7 the relationship between the kerma rate at 1 m and the solid angle is demonstrated. The relative kerma rate on a river is obviously greater than the relative solid angle. For example, on the river at 100 m width, the solid angle subtended by the source is very small; however, still some amount of kerma rate is observed on the river due to scattered gamma rays. In fact, on rivers the portion of scattered gamma rays is dominant as shown in Figure 7.

CONCLUSIONS

The kerma rate from natural radionuclides is almost proportional to the solid angle subtended by the soil, but the change in kerma rate due to source configuration is generally smaller than that expected from the solid angle. This is explained by the difference in absorption properties for photons between air and soil. Soil absorbs photons at a higher rate than air. Therefore, the increment of soil in the environment leads to the decrement in the scattered gamma-ray component in the kerma rate: the increment of air leads to the opposite tendency. As a result, the normalized kerma rate never exceeds two even $4\pi$ source geometry. One a river, the kerma rate decreases as the position gets close to the middle, but the decreasing tendency is much slower than the decrease of the solid angle for source since the contribution rate of scattered gamma-ray to the kerma rate increases largely.

REFERENCES


