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Note

Calculation of Dose Rates and Buildup Factors in Air at 1 m above Ground for ^{134}Cs and ^{137}Cs Sources Having Different Types of Depth Profile

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Monte Carlo calculations were carried out to evaluate absorbed dose rates in air and dose buildup factors at a height of 1 m above the air-ground interface for underground ^{134}Cs and ^{137}Cs sources having three typical types of depth profile, i.e. slab, exponential and triangular sources. The calculated results showed that the respective dose rates and buildup factors were relatively different one another. In addition, a linear relationship was found between mean source depths expressed in natural logarithm and the corresponding dose rates.

Key words: Monte Carlo calculation, dose rate, ^{134}Cs, ^{137}Cs, source depth profile

1. Introduction

One of applications of field gamma ray dosimetry is to determine radionuclide activity levels in the ground. When calculating dose rates due to fallout radionuclides, a good approximation of the source distribution is that of an infinite half space with a homogeneous source distribution in the horizontal plane and where variations occur only with depth in the soil. A decreasing "exponential" profile with depth in the soil has so far been used in general[1]. In reality, however, there must be a variety of complicated profiles under the ground in actual fallout fields. It would be worth calculating cases of some other profiles not only to check the versatility of the exponential assumption but also to examine the possibility of applying the other profiles to data collected in the environment.
Application of the basic data to be given in this paper will be also described as an example in a later section.

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2. Model

The three profiles of radioactivity under the ground s(z) to be treated in this paper are illustrated in Figure1, where A_a represents the maximum activity and z_m the mean depth, which is defined as

$$z_m = \int_0^\infty \frac{z \cdot s(z)\,dz}{s(z)\,dz} \qquad (1)$$

Dose rates at a height of 1 m above the ground will be calculated for various values of z_m for each profile in the following sections. The respective profiles are expressed by:

A. Slab source

$$s(z) = \begin{cases} A_a & (0 < z < z_m) \\ 0 & (z_m \leq z) \end{cases} \qquad (2)$$

B. Exponential source

$$s(z) = A_a\, e^{\frac{z}{z_m}} \qquad (3)$$

In this case, the mean depth z_m is called "relaxation mass per unit area"[1].

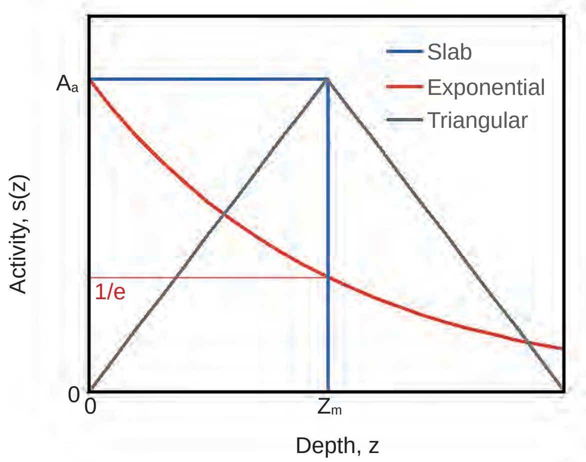

Fig. 1. Source distributions under the ground. The term z_m represents a mean depth, which is defined in the text.

C. Triangular source

$$s(z) = \begin{cases} A_a \dfrac{Z}{Zm} & (0 < z < z_m) \\ A_a \left(2 - \dfrac{Z}{Zm}\right) & (z_m \leq z < 2\, z_m) \\ 0 & (2\, z_m \leq z) \end{cases} \qquad (4)$$

The calculation procedure is a straightforward application of the Monte Carlo method. A detailed description on the one-dimensional Monte Carlo gamma transport code, MONARIZA/G2, used in this paper and its validity has been given in references 2) and 3).

3. Results and Discussion

The dose rates at 1 m above the ground were calculated for ^{134}Cs and ^{137}Cs sources under the ground for various mean depths, and 100,000 histories were traced for each mean depth. The source intensities were normalized so that the integral of s(z) over z might yield the unit activity per unit area.

$$\int_0^\infty s(z)\,dz = z_m \cdot A_a = 1 \qquad (5)$$

Figure 2 shows the results. The unit "Bq/cm^2" means 1 Bq in the soil column having a cross-sectional area of 1 cm^2. The dose rate decreases gradually with increasing mean depth as shown in the figure.

It is seen from the figure that the respective source profiles give relatively different curves one another, i.e. the slab geometry reveals the highest values and the triangular the lowest for the same mean depths.

Figure 3 shows the relationship between dose rate due to ^{137}Cs and mean depth expressed in natural logarithm (ln). It should be noted that the dose rate varies almost linearly with mean depth expressed in natural logarithm

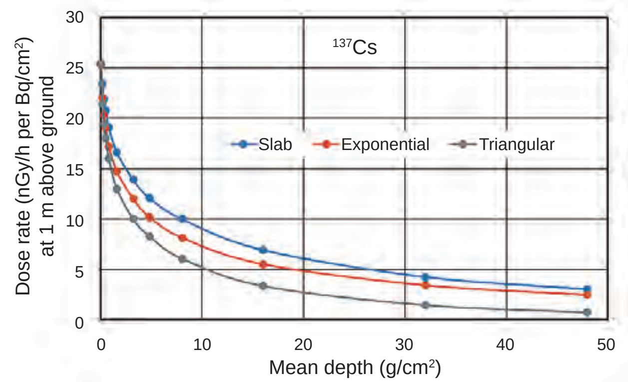

Fig. 2. Dose rates as a function of mean depth for ^{137}Cs sources having different types of depth profile.

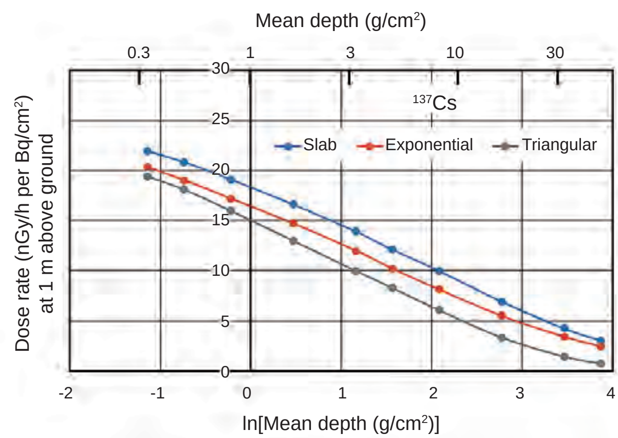

Fig. 3. Dose rates as a function of mean depth expressed in natural logarithm for ^{137}Cs sources having different types of depth profile.

for every profile in the range from around 0.3 to 30 g/cm^2, which correspond to around 0.19 and 19 cm, respectively, for a soil density of 1.6 g/cm^3.

Figure 4 shows the calculated dose buildup factors, i.e. the ratio of dose rate due to total gamma ray flux to that due to primary flux. A method of discrimination in dose rate between total and primary fluxes obtained in field spectroscopy has been briefly described by Yoshida-O *et al.*[4]. It is noticed that the buildup factor for the triangular source is great at any mean depth compared to the other two profiles.

Although the three profiles result in somewhat different values of both dose rate and buildup factor one another, a plane source on the ground corresponding to $z_m = 0$ becomes the same values for these three profiles. Table 1 gives the values.

Figure 5 shows the relationship between dose rates due to ^{134}Cs and ^{137}Cs and mean depth expressed in natural logarithm.

The ICRU Report 53 gives the dose rate values only for the exponential sources[1]. The Monte Carlo calculated curves for the exponential sources of both ^{134}Cs and ^{137}Cs

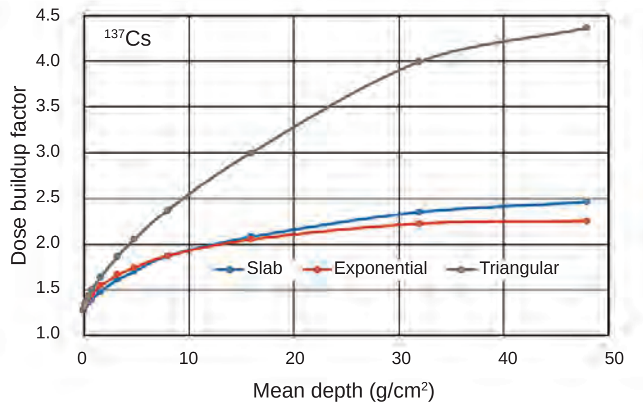

Fig. 4. Dose buildup factors as a function of mean depth for ^{137}Cs sources having different types of depth profile.

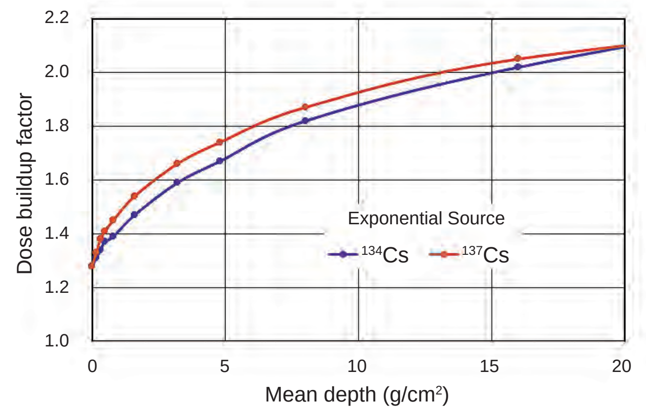

Fig. 6. Dose buildup factors as a function of mean depth for ^{134}Cs and ^{137}Cs exponential sources.

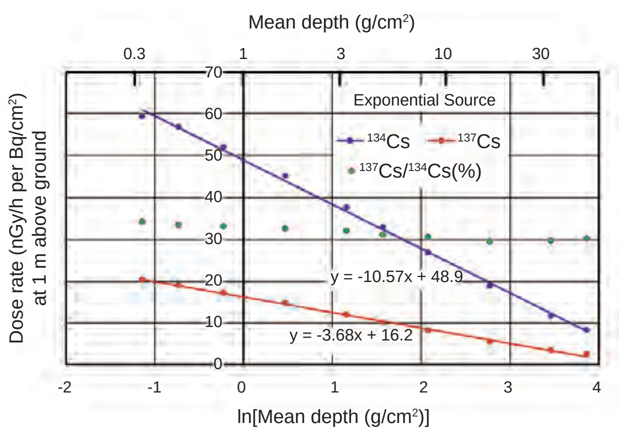

Fig. 5. Dose rates as a function of mean depth expressed in natural logarithm for ^{134}Cs and ^{137}Cs exponential sources.

Table 1. Dose rate and buildup factor for an infinite plane source (zm=0)

Nuclide	^{134}Cs	^{137}Cs
Dose rate (nGy/h per Bq/cm^2)	69.2	25.4
Dose buildup factor	1.27	1.28

At a height of 1 m above ground

shown in Figure. 5 agree fairly well with the ICRU values.

As to dose buildup factors, we can derive the values only for the exponential ^{137}Cs source from ICRU Report 53. The deduced values give a good agreement with our data.

The linear relation to mean depth expressed in natural logarithm are also seen both for ^{134}Cs and ^{137}Cs sources in the figure. Furthermore, it is noted that the dose rate ratio of ^{134}Cs to ^{137}Cs is almost constant within this range.

Figure 6 shows the buildup factors for exponential ^{134}Cs and ^{137}Cs sources. The values are close to each other.

4. Example of Application

Yoshida-O *et al.*[4] measured outdoor dose rates due to primary and scattered components separately on June 11, 2012 (15 months after the Fukushima Daiichi nuclear power plant accident) at a site in Marumori Town, Miyagi Prefecture and the evaluated values were 356 and 270 nGy/h, respectively. Namely, the dose buildup factor amounts to (356+270)/356 ≒ 1.76 and total dose rate is equal to 626 nGy/h.

The buildup factor 1.76 corresponds to the mean depths of about 5 g/cm^2 for the slab and exponential sources, and of about 2.5 g/cm^2 for the triangular source (See Figure 4).

Here, we assume that the buildup factor for ^{134}Cs is nearly the same as that for ^{137}Cs for the other two depth profiles. The activity ratio of ^{134}Cs to ^{137}Cs was approximately unity just after the accident[5], i.e. the initial dose ratio of ^{134}Cs to ^{137}Cs is calculated to be 69.2/25.4 = 2.72 from Table 1. The total dose rates of ^{134}Cs (half-life = 2.06 years) and ^{137}Cs (30.0 years) at the time of the measurement are estimated by correcting for radioactive decay to be 408 and 218 nGy/h, respectively.

We apply the values of the mean depth and corresponding total dose rate mentioned in Figure 2. Then, we obtain the following approximate values for ^{137}Cs of 218/12 = 18 for slab ($z_m \fallingdotseq 5$ g/cm^2), 218/10 = 22 for exponential ($z_m \fallingdotseq 5$ g/cm^2) and 218/12 = 18 Bq/cm^2 for triangular source ($z_m \fallingdotseq 2.5$ g/cm^2). According to a radioactivity map obtained through airborne surveys[6], the activity of ^{137}Cs in Marumori Town cited by Yoshida-O *et al*[4]. was reported to be 100～300 kBq/m^2, which are consistent with the values just mentioned. The airborne survey technique requires an assumption[6] of an exponential distribution with $z_m = 1$ g/cm^2. In other words, if z_m is different from 1, an error inevitably occurs depending on the difference. On the other hand, our method needs no assumption for the mean depth, since it is determined from Figure 4.

5. Conclusion

We compared dose rates in air due to slab, exponential and triangular sources underground and obtained the result that the respective source profiles gave relatively different dose rates one another for the same mean depth. The result just mentioned indicates that evaluation of radioactivity for the real profile would be possibly accompanied by errors to some extent if we rely only on the exponential assumption.

We found a linear relationship between mean depth expressed in natural logarithm and dose rate for the three types of source profile. This means that the combinations of these profiles also have a linear relationship. This fact suggests that the dose rate due to many other profiles than the three treated in this study might also vary linearly with mean depth expressed in natural logarithm.

We also found that the variation in buildup factor with mean depth were peculiar to the source profile.

It is hoped that the calculated data given in this study would be a useful tool to interpret the data collected through in-situ measurements and to analyze those obtained through long-term continuous monitoring in ^{134}Cs and ^{137}Cs fallout fields.

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