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# Development of a simulation model for estimating the indoor gamma radiation dose

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## ABSTRACT

A simulation model to calculate the indoor γ radiation doses has previously been established. The basic factors that control the dose rates are studied. Some of the factors like the detection point, the dimensions, the thickness and the density have previously been taken into account. In this article, new factors are included. These are the existence of a neighboring room and the division of a wall to two segments. The dose rates are calculated for wide ranges of the considered factors. The calculations are carried out by using the MCNP simulation code. A demonstrative application of the model is given.

## 1. Introduction

During the recent decades many studies have been showing concerns about the natural radioactivity from building materials (Ackers et al., 1985; Ademola and Farai, 2005; Ahmad et al., 1998; De Jong et al., 1998; Koblinger, 1978; Máduar and Hiromoto, 2004; Malanca et al., 1993; Mustonen, 1984; O'Brien et al., 1995; O'Brien, 1997; Othman and Mahrouka, 1994; Stranden, 1979). Many of them report elevated radiation doses calculated inside rooms of different styles built with different materials. It is important therefore to have a method that can easily calculate the doses while clearly emphasizes the weight of each factor that affects the indoor radiation doses. This is the main purpose of this paper. This can also help in trying to reduce the indoor radiation doses.

In a previous study, the model's basis has been stablished (Orabi, 2016). Some of the basic factors have been determined. Here the model is being developed by including more factors. The previously studied factors are the wall's thickness, the building material's density, and the room's dimensions. Another important factor - the uncertainty in the equilibrium of a radioactive decay series - has also been investigated (Orabi, 2017). The new factors here are the existence of a neighboring room and the division of a wall to two segments.

## 2. The model's summary

The aim of the model is to simplify the calculation of the indoor absorbed gamma dose rate inside a room. Some reference calculations are made on a room with a certain specifications that we call 'the normal specifications'. The room is made of concrete (2.35 g/cm$^3$), with dimensions $5 \times 4 \times 2.8\,\mathrm{m}^3$, thickness 20 cm. The normal rate of the radiation dose is estimated at the central point. The normal specifications are the ones used by most of the studies on the radiation dose estimations (Ahmad et al., 1998; Ademola and Farai, 2005; Koblinger, 1978; Máduar and Hiromoto, 2004; Malanca et al., 1993; Mirza et al., 1991; Mustonen, 1984; Sherif et al., 2016; Stranden, 1979). Having a room with different specifications, the model can easily give the corresponding dose rate, if the relative changes of the room specifications are provided with respect to the normal ones. This is the convenience offered by the model.

The MCNP code (Los Alamos, 2005) is used to simulate motion of particles inside materials and to calculate different relevant physical quantities. We use it here to calculate the indoor radiation doses. The geometry of the system is defined first thing in the code. This includes the dimensions of the room and the used substances with their densities. Secondly, the source is taken as a homogeneous volume gamma source inside the walls. The gamma energies, and their probabilities, of the $^{238}$U series or the $^{232}$Th series or $^{40}$K are written in the source definition. These are shown in Table (1) (Mustonen, 1984). The gamma flux is calculated at the central point of the room. The conversion of the flux into a dose rate is done by using the ANSI/ANS 6.1.1-1977 factors. This requires the inclusion of the energy-dose functions. The dose rates are given in the units (rem/h)/(Bq/Kg). This is converted to (nGy/h)/(Bq/Kg). Compositions of concrete and air are in accordance with ref. (Hubbell and Seltzer, 1995).

The indoor specific radiation dose rate is calculated as

$$d = \sum_{i=1}^{6} d_i, \tag{1}$$

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**Table 1**
Gamma energies and probabilities for $^{238}$U, $^{232}$Th and $^{40}$K.

| $^{238}$U series E (MeV) | Intensity | $^{232}$Th series E (MeV) | Intensity | $^{40}$K E (MeV) | Intensity |
|---|---|---|---|---|---|
| 0.047 | 0.040 | 0.040 | 0.015 | 1.460 | 0.107 |
| 0.053 | 0.022 | 0.100 | 0.023 | | |
| 0.186 | 0.040 | 0.129 | 0.034 | | |
| 0.242 | 0.084 | 0.209 | 0.045 | | |
| 0.273 | 0.059 | 0.239 | 0.450 | | |
| 0.295 | 0.207 | 0.270 | 0.032 | | |
| 0.352 | 0.348 | 0.289 | 0.057 | | |
| 0.395 | 0.012 | 0.331 | 0.190 | | |
| 0.470 | 0.021 | 0.409 | 0.019 | | |
| 0.609 | 0.430 | 0.463 | 0.046 | | |
| 0.666 | 0.029 | 0.511 | 0.086 | | |
| 0.773 | 0.077 | 0.583 | 0.300 | | |
| 0.806 | 0.021 | 0.727 | 0.072 | | |
| 0.934 | 0.036 | 0.782 | 0.091 | | |
| 1.120 | 0.159 | 0.860 | 0.051 | | |
| 1.246 | 0.083 | 0.911 | 0.260 | | |
| 1.390 | 0.092 | 0.969 | 0.172 | | |
| 1.509 | 0.037 | 1.588 | 0.066 | | |
| 1.661 | 0.020 | 1.626 | 0.041 | | |
| 1.760 | 0.180 | 2.615 | 0.352 | | |
| 1.848 | 0.027 | | | | |
| 2.118 | 0.011 | | | | |
| 2.204 | 0.062 | | | | |
| 2.435 | 0.024 | | | | |

where the summation is over the composing 6 parts of the room; 4 walls plus a floor and a ceiling. $d_i$ is the dose rate from one of the parts and it calculated by multiplying its normal value $d_{io}$ with the correction factors $d_{ij}$

$$d_i = d_{io}.\prod_{j=1}^{n} d_{ij}, \tag{2}$$

where $n$ is the number of the correction factors involved. These correction numbers correspond to the different factors that affect the radiation dose rate inside the room, e.g. thickness, density, etc. They are obtained by dividing the dose rates at the normal values by the dose rates at other values. They are therefore unit-less with values $< 1$ or $\geq 1$. Having the value of one means that they are just normal. The numbers $d_{i1}$, $d_{i2}$, and $d_{i3}$ correct for changes in the wall's thickness, the building material's density, and the room's dimensions, respectively. They are given in ref (Orabi, 2016). In that reference, it has been shown that the central point of the room is a good representation for the indoor dose rates. Accordingly, all the dose rates are calculated at the central point.

## 3. New factors

### 3.1. A neighboring room

Having a neighboring room can significantly increase the absorbed dose rate especially if the room in question is surrounded by more than one room. Only that wall (adjacent) right next to the neighboring room can shield some of the radiation coming from the neighboring room. As the radiation dose rate is more than the normal, the corresponding correction numbers $d_{i4}$ are expected to be bigger than one.

We simulate the change of the correction numbers $d_{i4}$ with the change of the thickness of the adjacent wall. First, the neighboring room's dose share is estimated. Naming that $X_{ni}$, the correction number $d_{i4}$ to the radiation dose rate ($d_i$) is calculated as $d_{i4} = (X_{ni} + d_i)/d_i$. This is plotted in Fig. (1). $X_{ni}$ decreases as the thickness of the adjacent wall increases until almost $d_i$ only remains. The correction number $d_{i4}$ starts with a value $\geq 1$, and this value depends on the specifications of the neighboring room. It then decreases till it reaches 1 when the thickness of the wall is big enough to block all the neighboring radiation. A similar trend is achieved for the change of $X_{ni}$ with the density of the adjacent wall (Orabi, 2016). As the dose share from the neighboring room changes with both the density and the thickness of the adjacent wall, it is more adequate to use the surface density (the density times the thickness) as in Fig. (1).

Two scenarios going in parallel control the curve in Fig. (1). First is that the increase of the surface density shields some of the neighboring radiation. This action is continuous. The second scenario, on the other hand, has a kind of overturning behavior. When the surface density increases at first, more radiation adds up to the indoor dose rate, however later on, the surface density increment will begin to block its own radiation. This will lead at the end to the saturation of the radiation increase. The total effect that happens when the surface density of the adjacent wall increases is just the sum of the two scenarios. This continues till some value of the surface density is reached after which just the first scenario remains. This will then go on until the dose share from the neighboring room disappears completely and only that from the adjacent wall remains, which was already saturated. This is the reason for the shown stability in Fig. (1).

### 3.2. Wall division to two segments

Dividing a wall into two segments is used in some cases to make the wall more strongly standing on the ground, in particular if the room is constructed just on the ground without any underground basis. The wall's external segment will of course contribute to the indoor radiation dose. This contribution can be calculated in exact same way as the one from the internal segment, except that some of the radiation from the external segment is blocked by the internal one. This effect can be taken into account by just subtracting the blocked radiation.

The proportion of the radiation from the external segment that crosses the internal segment and shares to the indoor dose rate is simulated as a function of the surface density of the internal segment. This gives the correction number $d_{i5}$, which is plotted in Fig. (2). If the density or the thickness of the internal segment is zero, the external segment can share with all of its radiation (100% or 1) as shown in Fig. (2). Moreover, in agreement with ref (Orabi, 2016), the share from the external segment is very little when the surface density of the internal segment reaches 50 g/cm$^2$. After calculating the radiation dose rate from the external segment, we use Fig. (2) to estimate the real (reduced) amount by multiplication with the correction number $d_{i5}$ that corresponds to the given value of the surface density of the internal segment. Adding this result to the dose rate from the internal segment, we get the overall dose share from the wall.

## 4. The normal dose rates

The different factors are studied at domains that are sufficient to include different rooms' specifications. This means that all the correction numbers that could be required in the calculation of the dose rate inside any room would be found in the figures of ref (Orabi, 2016) in addition to those here. All we need now is the normal specific rates. The MCNP5 code (Los Alamos, 2005) is utilized to configure the normal room and calculate the specific dose rates from the two radioactive series $^{238}$U and $^{232}$Th, and from the radionuclide $^{40}$K. Table (2) shows the results in the last line. This is given in comparison with other methods. The results of the present model are comparable to those from the other methods. By entering the normal specific rates in the equations of the model, together with the correction numbers, we can calculate the radiation dose rate inside any room. This requires only three steps: 1) find where the differences of the given room from the normal one are, 2) find the corresponding correction numbers from the figures and 3) put the correction numbers in the model's equations and do the math. This gives the specific rates that after multiplication with the radioactivity concentrations we get the total radiation dose rate D