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Evaluation of gamma and alpha doses due to natural radioactivity of building materials

L Bruzzi , R Mele and F Padoani

Abstract. A method of calculation was developed for evaluating the contributions of external (gamma) and internal (alpha) doses due to the natural radioactivity of building materials. The radionuclides examined are ^{40}K and members of the ^{235}U , ^{238}U and ^{232}Th radioactive decay chains. The method makes it possible to correlate the specific activities of these radionuclides in material used for constructing the walls of a room with the alpha and gamma dose absorbed by an individual at the centre of the room. The results obtained are in agreement with the experimental data and with values calculated by other authors.

1. Introduction

In recent years, there has been a considerable increase in the level estimated by the United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR) of the effective dose equivalent absorbed on average by members of the public because of exposure to natural sources of radiation. Until a few years ago, the dose evaluated by UNSCEAR was 1 mSv y^{-1} ; later, more accurate estimates also taking the revaluation of the alpha particle quality factor into consideration attributed a value of 2 mSv y^{-1} to the average per capita dose due to natural radiation [1], and, more recently, 2.4 mSv y^{-1} [2]. These dose values include contributions deriving from cosmic radiation, cosmogenic and primordial radionuclides; however, UNSCEAR attributes a preponderant contribution (ca. 2 mSv y^{-1}) to the primordial radionuclides rather than to the others.

Primordial radionuclides belong for the most part to natural radioactive decay chains, the parent isotopes of which (^{232}Th , ^{235}U and ^{238}U) are present in the earth's crust in variable concentrations, with mean values of the order of those shown in table 1 [3]. According to UNSCEAR estimates, the overall contribution of the radionuclides belonging to natural radioactive decay chains to the external dose is 0.26 mSv y^{-1} , and to the internal dose 1.42 mSv y^{-1} . Among the primordial radio-

Table 1. Mean concentrations of the parent isotopes of natural radioactive decay chains in the earth's crust [3].

Nuclide	Half-life (10^9 years)	Concentration	
		(ppm)	(Bq kg^{-1})
^{232}Th	14.1	8.5	34
^{235}U	0.7	0.02	1.5
^{238}U	4.5	2.7	33

nuclides not belonging to these decay chains, the most important from a radiological point of view is ^{40}K , which is to be found in natural potassium in an isotopic concentration of 0.0118% and, according to UNSCEAR, is responsible for a contribution to the external dose of 0.15 mSv y^{-1} , and a contribution to the internal dose estimated at 0.18 mSv y^{-1} (equivalent to a body burden of ca. 4 kBq). Since all these radionuclides are to be found in the earth's crust, they are also present in building materials, which are therefore partly responsible for the dose absorbed by the population due to natural radiation.

Studies of the radioactivity of the most commonly used building materials have been carried out all over the world; the data relating to Italy, summarised in table 2 [4], show in particular the high radioactive content of certain building materials which are widely used in three Italian regions (Lazio, Campania and

Table 2. Concentrations of uranium, thorium and potassium (Bq kg^{-1}) in building materials in Italy [4].

Material	Origin	^{40}K	^{238}U	^{232}Th
Tuffs	Lazio	1900–2370	350–390	275–350
	Campania	1950–2250	130–390	85–135
	Umbria	1468–1925	136–242	468–541
Pozzolana	Lazio			
	Campania			
	Umbria			
Stone	Various regions	4–68	1–38	–
Bricks	Various regions	365–1060	28–81	40–148
Concrete	Various regions	4–780	10–100	10–240

Umbria). However, to characterise a building material from a radiological point of view, it is necessary to identify not only the uranium, thorium and potassium content, but also the efficiency with which radon isotopes are emanated. In fact, the three radon isotopes (^{219}Rn , ^{220}Rn , ^{222}Rn) are members of the three natural radioactive decay chains. Since they are gaseous, they may be released from the ground, rocks, and also from building materials, and accumulate, with their short-lived daughters, in closed spaces, and in particular in dwellings. ^{220}Rn and ^{219}Rn , mainly because of their short half-life, are not as important as ^{222}Rn , which may reach levels of concentration in the air which are significant in terms of radiological protection. The dose deriving from the presence in the air of ^{222}Rn is linked to the inhalation of its short-lived daughters, which are deposited in the respiratory organs: two of them (^{218}Po and ^{214}Po), if deeply inhaled, emit alpha particles in direct contact with the bronchial and pulmonary epithelium. For these reasons, the dose deriving from exposure to ^{222}Rn in closed spaces has been placed in direct relation to the risk of onset of lung cancer [5].

One of the sources of radon in buildings (together with the ground, water and natural gas for domestic use) consists of building materials themselves. In order to characterise these materials from the point of view of the dose which may derive from them, it is necessary to identify not only the quantity of radionuclides which are to be found in them, but also the value of the emanation ratio of ^{222}Rn , e , defined as the quantity of ^{222}Rn emanated in a unit of time divided by the quantity which, in the same time, is formed in the material. The e values of certain building materials are shown in table 3

[6], which also shows the concentration of ^{226}Ra (direct parent of ^{222}Rn).

Before proceeding to an evaluation of the doses due to natural radionuclides it may be useful to note that the International Commission on Radiological Protection (ICRP) recommends that the limits for such doses be set according to different criteria from those adopted for artificial radionuclides. The two fundamental points on which the criteria for natural radioactive sources are based are the degree to which such sources may be controlled and the distinction between existing and future situations [7]. For existing situations, the ICRP recommends that levels be set, above which remedial action is to be taken; in any case, the costs of that action are to be justified by the risk reduction deriving from it. Future situations, on the other hand, may be subject to limits and controls at a planning stage.

With regard to the accumulation of radon in buildings the radiological protection bodies of various nations have implemented the recommendations of the ICRP, setting action levels and limits for the concentration of ^{222}Rn in dwellings; these are intended to refer respectively to existing and future buildings, as shown in table 4 [8]. The Commission of the European Communities has recently adopted an action level of 400 Bq m^{-3} of ^{222}Rn , corresponding to an effective dose equivalent of 20 mSv y^{-1} , and a design limit of 200 Bq m^{-3} , corresponding to an effective dose equivalent of 10 mSv y^{-1} [9]. With regard to such limits, it is important to note that such high levels may not be attributed, except in very rare cases, to radon emanation from building materials, but refer mainly to radon emanating from the ground underneath the building. As shown in table 4, in certain countries

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Table 3. Values of concentration of ^{226}Ra , of ^{222}Rn emanation rate and emanation ratio, for some building materials [6].

Country Material	Number of samples	^{226}Ra (Bq kg^{-1})	^{222}Rn emanation rate ($10^{-5} \text{ Bq kg}^{-1} \text{ s}^{-1}$)	Emanation coefficient
USSR				
Heavy concrete	18	66	0.32	0.035
Lightweight concrete	19	141	0.41	0.021
Red brick	12	50	0.16	0.017
Hungary				
Concrete	100	13	0.78	0.28
Red brick	200	55	0.39	0.036
Poland				
Fly ash	33	96	—	0.0054
Slag	11	67	—	0.0070
Phosphorite	6	705	—	0.20
Red brick	3	18	—	0.023
Denmark				
Concrete	4	—	0.47	—
Alum-shale concrete	1	—	44	—
Brick	2	—	0.017	—
Gypsum board	1	—	0.023	—
Norway				
Concrete	137	28	—	0.01–0.20
Brick	18	63	—	0.01
LECA	12	52	—	0.01–0.20
United States				
Concrete	106/21†	9–32	0.43–1.26	0.13–0.25
Fly-ash concrete	8	19	1.04	0.26
Red brick	6	45	0.10	0.01
Gypsum	12	12	0.63	0.28

† Radon-222 emanation rate measured for 106 samples from 10 cities; radium-226 and emanation ratio measured for 21 samples from 7 cities.

levels have been proposed or set for building materials. In particular, for each of the most commonly used building materials, the Health Council of the Netherlands has set a lower and an upper limit for the sum of the specific activities of ^{226}Ra and ^{232}Th : if the activity of the material is below the lower limit, it may be used without limitation; for intermediate levels, its use is subject to a cost-benefit analysis, whilst a material with a specific activity higher than the maximum limit may not be used [10]. The approach has the undoubted advantage of setting a limit on the quantity of gamma-emitting radionuclides (and, therefore on the subsequent gamma dose) and on the quantity of ^{222}Rn produced.

A more complete approach is that proposed by a Commission of the Swedish National Institute of Radiological Protection: in order to establish alpha and gamma dose limits, it is recommended that the specific activities of ^{40}K , ^{238}U and ^{232}Th in any building material be such that the levels of a specially designed 'gamma index' and of a 'radium index' are not greater than one [11]. In this way, the condition laid down for the use of any material is that neither the alpha nor the gamma dose be greater than a set limit, in agreement with the general criteria proposed by the ICRP [7]. Finally, as shown in table 4, the Swedish government also lays down limits for the concentration of ^{222}Rn in the air, taking account of all sources. It should be noted

Table 4. Recommended action levels and planning limits set by certain countries for ^{222}Rn concentration in the air in dwellings (Bq m^{-3}) [8].

Country	Government policy adopted	Action levels (existing buildings)	Limits (future buildings)
Belgium	No	250	125
Denmark	No	800	200
FR Germany	No	250	250
Spain	No	—	—
France	No	—	—
Greece	No	—	—
Ireland	No	not yet decided	—
Italy	No	not yet decided	—
Luxembourg	No	levels for building materials proposed	—
Netherlands	No	levels for building materials proposed	—
Portugal	No	—	—
United Kingdom	Yes (NRPB)	400	100
Canada	No	200	200
Sweden	Yes	800	—
United States	Yes (EPA)	800	140
	No (NCRP)	150	150
		400	—

that with this method the contribution of the gamma dose due to ^{40}K is also taken into account.

In the present report a model of calculation is described which makes it possible to establish, on the lines of the Swedish proposal described above, a relationship between the concentration of radionuclides to be found in the most widely used building materials (bricks, concrete) and the dose deriving from them.

2. Description of the model

The nuclides to be found in building materials which are relevant for the purposes of calculating the gamma radiation dose are ^{40}K and the members of natural radioactive decay chains. Potassium-40 decays with a half-life of 1.3×10^9 years, and in 11% of disintegrations emits 1.46 MeV photons; the radionuclides of the natural radioactive decay chains, on the other hand, emit photons of different energy with a different degree of probability. The assessment of the spectrum of photons emitted by these nuclides was carried out by means of the ORIGEN-2 computer code [12], on the basis of the following hypotheses: (i) the members of

each decay chain are in secular equilibrium; (ii) the isotopic abundance of ^{235}U is the natural one (0.7%).

Eighteen energy groups in the range between 10 keV and 11 MeV were taken into consideration [12].

In order to evaluate the effect which the emanation of radon has on the gamma dose, the same procedure was used to evaluate the spectrum of photons which are emitted by radionuclides of the ^{238}U series which are to be found downstream of ^{222}Rn . The model utilised for the calculation of the alpha dose due to ^{222}Rn is based on the correlations between the concentration of radon in air and the effective dose equivalent to be found in the literature [5,9,13]. The concentration in the air of ^{222}Rn was determined by means of a model which describes the release of such gas from a porous solid. With regard to the geometric model, a 'standard' $4 \times 4 \times 2.8 \text{ m}^3$ room was considered; it was presumed that the four walls, the floor and the ceiling had the same thickness; the presence of doors and windows was not taken into consideration; the walls were considered to be homogeneous and the distribution of radionuclides in the material uniform. The building materials taken into consideration were bricks and concrete of known composition [14,15].

3. Calculation of the gamma dose

The contribution of the gamma dose deriving from the decay of radionuclides of the ^{238}U and ^{232}Th series and from the decay of ^{40}K were evaluated separately with reference to the unit specific activity (1 Bq kg^{-1}) of the three nuclides cited; for ^{235}U , the activity is defined by its natural isotopic abundance. The calculation of the dose was carried out by means of MCNP code (Monte Carlo Neutron and Photon Transport Code System) [16], starting from the emission spectra previously calculated. For a point at the centre of the room, a calculation was made of the influence on the dose calculated of the thickness of the walls, with a variation of the thickness from 0.12 m to 1.0 m. The results obtained in the case of brick walls are shown in figure 1: the greater the thickness, the higher the dose in the centre of the room, though not in a uniform manner. In fact, in the initial section of the curves in figure 1, when the thickness of the walls increases from 0.12 m to 0.50 m, there is an increase greater than 50% in the dose for all

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Figure 1. Gamma dose rate at the centre of a 'standard' room with brick walls: contributions of (a) uranium, (b) thorium and (c) potassium.

three contributions, whereas in the second part of the curves, the dose increases more gradually. More precisely, as the thickness increases from 0.50 m to 1.0 m, the increases in the three contributions range from 9.6% to 14.1%. This phenomenon is due to the presence of two contrasting effects: in fact, the increase in thickness, at the same level of specific activity and

density, results in an increase of the overall activity of the source, but also a higher self-shielding. From the results in figure 1, it may be noted that, as the thickness increases, there tends to be a trade-off between these effects, so that the dose at the centre of the room reaches a level of saturation for a wall thickness of ca. 1 m. The same phenomenon may be noted in the case in which the walls of the room are in concrete. The largest values of the thickness which were taken into consideration may not appear realistic: it must be borne in mind, however, that the photons emitted by the walls of the adjacent rooms and of the lower and upper floors also contribute to the gamma dose at the centre of the room. In order to take account of these contributions, it appears to be reasonable to assume an equivalent wall thickness of 1.0 m.

The calculations carried out showed that the dose increases as the distance from the walls decreases: this increase was found to be of the order of 10% for all the cases examined, when the distance was reduced from 2.0 m to 0.5 m. The effect of the emanation of ²²²Rn from the walls on the gamma dose was also found to be limited: it was calculated in fact that for the levels of the emanation ratio commonly found (1–10%), neglecting release of radon from the walls is equivalent to overestimating the gamma dose due to radionuclides of the uranium series by less than 10%. A calculation was also made of the gamma dose deriving from the presence in the air of ²²²Rn, presumed to be in secular equilibrium with its daughters: the gamma dose corresponding to a concentration of 1 Bq m⁻³ of ²²²Rn was found to be 0.12 μSv y⁻¹, for a 100% residence probability.

From this point on, reference will be made to the dose at the centre of the 'standard' room calculated with a wall thickness of 1.0 m, on the hypothesis that radon is not released; the results are presented in table 5. These figures were reported on an annual basis with reference to a residence probability of 100% and were found

Table 5. Calculated values of the dose rate at the centre of a 'standard' room (μSv y⁻¹ Bq⁻¹ kg).

Contribution	Brick walls	Concrete walls
Uranium	16.0	14.2
Thorium	19.5	17.2
Potassium	1.12	1.07

to be generally in agreement with the results obtained by other authors [17]. Using these results, it is possible for the two cases considered (bricks, concrete) to calculate the gamma dose in the 'standard' room starting from the specific activity (Bq kg^{-1}) of ^{238}U (C_U), ^{232}Th (C_{Th}) and ^{40}K (C_K) in the material. With reference to a mean residence probability of 80% [2] and to the levels in table 5, the following is obtained:

$$H_E = 12.8C_U + 15.6C_{Th} + 0.9C_K, \quad (1)$$

in the case of brick wall, and:

$$H_E = 11.4C_U + 13.8C_{Th} + 0.9C_K, \quad (2)$$

in the case of a concrete wall; in both cases, the level of the effective dose equivalent, H_E , is expressed in $\mu\text{Sv y}^{-1}$.

Based on the data for the natural radioactivity of building materials used in Italy which are shown in table 2, it may be concluded that the gamma dose attributable to such materials is between 1.3 mSv y^{-1} and 4.3 mSv y^{-1} for bricks, and between 0.3 mSv y^{-1} and 5.2 mSv y^{-1} for concrete. These levels appear on average to be quite high, considerably higher than the levels observed experimentally which are around 0.4 mSv y^{-1} (UNSCEAR [2]). This apparent discrepancy may be explained by the fact that 'real' buildings are constructed with materials with a limited specific activity on average, and moreover with apertures (doors, windows). It may, however, be noted that the levels of exposure to gamma radiation measured in buildings [18] fall within the ranges stated above, and this provides evidence of the validity of the method of calculation adopted.

4. Release of radon

The release of ^{222}Rn from a porous solid is a process which takes place in two steps: the gas which is emanated from individual grains goes into the pore system of the solid matter; radon then migrates to the surface through the pores and fissures present in the material. The correct phenomenological description of these two processes is quite difficult and complex, because of the numerous parameters which it is necessary to take into consideration at the same time: the most important of these include the shape of the internal and external surface, the degree of compaction and the rate of humidity present within the pores [19]. The emanation of ^{222}Rn

from the solid matrix can be studied, however, in a simple way, by means of the equivalent sphere model, taking into account two different mechanisms: release by recoil and by diffusion [21–23]. On the basis of this model, the emanation ratio can be expressed by the following:

$$e = e_r + e_d = \frac{3R}{4r_0} + \frac{3L}{r_0}, \quad (3)$$

where r_0 is the equivalent radius, L is the diffusion length of ^{222}Rn in the solid matrix, and R its recoil range, the values of which can be calculated with a semi-empirical formula, and for the solid matrices under consideration are of the order of 10^{-8} m [20]. Equation (3) applies under the hypotheses that the concentration of ^{226}Ra in the grain be uniform, and that $R \ll r_0$ and $L \ll r_0$ [21]. The last two conditions appear to be the case for common building materials [20,22]. Moreover, when $L \ll R$ [20], the second term of the right side of equation (3) is negligible, and it may therefore be concluded that:

$$e = \frac{3R}{4r_0}. \quad (4)$$

The results thus obtained for the materials examined are not, however, in agreement with certain experimental data. In fact, for concrete, the value of r_0 is about $1.5 \times 10^{-6} \text{ m}$ and that of R is $4 \times 10^{-8} \text{ m}$ [23]. The resulting level of e is 2%, a result which is found in many cases experimentally. In other cases, the results were found to be higher (see table 3). To explain these experimental results, certain authors [24] put forward the hypothesis that the uranium and thorium minerals are not distributed homogeneously in the solid matrix, but are to be found in thin superficial layers. On the basis of this hypothesis, if it is assumed that the thickness of such layers may be compared with the recoil range of radon, the level of e_r may reach 25%. If the contribution of diffusion in this thin superficial layer is added, results higher than 25% can be explained. The diffusion of radon in the pores may be studied, in the case of a flat wall, by means of a one-dimensional diffusion model [25]. In the stationary case, and on the hypothesis that the diffusion length of ^{222}Rn in the porous mass is much greater than half of the thickness [26–29], the number of radon atoms which are emanated from the surfaces which

delimit a flat porous slab (to which the wall of a room may be assimilated) in a given unit of time is stated by:

$$A_{Ra}em - \lambda pVN \quad (5)$$

where A_{Ra} (Bq kg⁻¹) is the specific activity of ²²⁶Ra, m (kg) is the mass of the wall, λ (s⁻¹) is the decay constant of ²²²Rn, V (m³) is the volume of the wall, p the porosity, N (atoms m⁻³) the concentration of external ²²²Rn. It should be noted that the first term in expression (5) represents the emanation rate of ²²²Rn from the single grains.

5. Calculation of the alpha dose

The alpha dose deriving from the inhalation of the short-lived daughters of ²²²Rn present in the air may be calculated on the basis of the level of concentration of ²²²Rn. The value of this concentration may be calculated by means of a balance equation written for the volume of the 'standard' room considered: in fact, in stationary conditions the number of ²²²Rn atoms which are removed in a given unit of time from such a volume must be equal to the number of atoms which at the same time enter it. Taking account only of the ²²²Rn emanated from the walls, it is therefore possible to state:

$$\lambda N + \lambda_v N = \lambda_v N_0 + (S_p/V_a), \quad (6)$$

where λ (s⁻¹) is the decay constant of ²²²Rn, λ_v (s⁻¹) the ventilation rate constant, N (atoms m⁻³) the concentration of ²²²Rn in the room with a volume V_a (m³), N_0 (atoms m⁻³) its concentration in the external air, and S_p (atoms s⁻¹) the number of radon atoms which in a given unit of time enter the volume V_a solely by effect of emanation from the walls. Reference to a stationary condition is legitimate since these conditions are reached in a short time, thanks to the relatively low values of the time constant, which is expressed in practical terms by the ventilation rate constant which in real cases is found to be of the order of 1 h⁻¹. The contribution of each single wall as a source may be written, for expression (5) as:

$$S'_p = \frac{1}{2} V (edA_{Ra} - pA_{Rn}), \quad (7)$$

where V (m³) represents the volume of a wall and d (kg m⁻³) its density; A_{Ra} (Bq kg⁻¹) and $A_{Rn} = \lambda N$ (Bq m⁻³) are the specific activities of ²²⁶Ra and ²²²Rn respectively in the material and

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in the air contained in the room. Since the walls are all of the same thickness, the following may be stated for the source term of equation (6):

$$S_p/V_a = (S/V_a)^{1/2} s (edA_{Ra} - pA_{Rn}), \quad (8)$$

in which S/V_a (m⁻¹) is the surface/volume ratio inside the room, whereas s (m) is the thickness of the walls. Substituting (8) in (6) and bearing in mind that $\lambda N = A_{Rn}$, the result is:

$$A_{Rn} = [(S/V_a)^{1/2} s (edA_{Ra}) + (\lambda_v/\lambda) A_0] / [(\lambda_v/\lambda) + 1 + (S/V_a)^{1/2} sp] \quad (9)$$

where $A_0 = \lambda N_0$ (Bq m⁻³) is the specific activity of ²²²Rn in the outside air. It is interesting to note that (9), in the conditions which are most frequently encountered in buildings, takes the following simplified form:

$$A_{Rn} = \{[(S/V_a)^{1/2} s (edA_{Ra})] / (\lambda_v/\lambda)\} + A_0. \quad (9')$$

The level of the alpha dose attributable to the presence in air of the short-lived daughters of ²²²Rn may be related to the exposure to radon (integral of the concentration over time) and to the 'equilibrium factor', which characterises the removal of the mixture of ²²²Rn and its daughters from the condition of secular equilibrium [5]. Recent studies, however, have shown that the dose due to radon in the conditions which are normally to be found in dwellings may be more readily correlated to the concentration of ²²²Rn itself [13], i.e. to A_{Rn} . The Commission of the European Communities recommends the use of a conversion ratio by which 1 Bq m⁻³ of ²²²Rn corresponds to an effective dose equivalent of 0.05 mSv y⁻¹ [9]. Using this conversion factor, by means of expression (9) it is possible to calculate the alpha dose on the basis of the specific activity of ²²⁶Ra, which on the hypothesis of secular equilibrium is equal to that of ²³⁸U. Taking as the parameters of the material the following figures: $S/V_a = 1.71$ m⁻¹; $s = 0.2$ m†; $p = 0.1$; $\lambda_v = 0.7$ h⁻¹ [5] $eA_0 = 9$ Bq m⁻³ [3], the result for bricks ($d = 1750$ kg m⁻³) is the following:

$$H_E = 0.16eC_U + 0.45, \quad (10)$$

and for concrete ($d = 2000$ kg m⁻³):

$$H_E = 0.18eC_U + 0.45, \quad (11)$$

† In this case, the value of s is realistic, unlike that assumed previously for calculating the gamma dose.

Figure 2. Calculated gamma and alpha doses from building materials as a function of ^{238}U concentration.

where the contribution of radon to the effective dose equivalent, H_E , is expressed in mSv y^{-1} and the concentration of ^{238}U in the material, C_U , in Bq kg^{-1} .

At this point it is worth specifying that the level of the calculated contribution of gamma dose due to the presence in air of ^{222}Rn and daughters (see para 3) is found, at equal concentration (A_{Rn}), to be about 0.2% of the corresponding alpha dose, and therefore it will not be taken into consideration. Relations (10) and (11), on the basis of the natural radioactivity data of the building materials used in Italy (table 2) and the emanation ratio figures (table 3), make it possible to calculate H_E levels in a range from 0.5 mSv y^{-1} to 1.7 mSv y^{-1} , in the case of bricks, and from 0.5 mSv y^{-1} to 5.8 mSv y^{-1} for concrete. Also in this case, the doses calculated appear on average to be quite high, if it is considered that they do not include the contribution of radon emanated from the ground. This is due in part to the role of radon contained in the air outdoors, which adds considerably to the lower dose levels; with regard to the higher levels, it must be made clear that they were obtained by attributing very high levels to the emanation ratio and to the specific activity, levels not usually found in practice.

In figure 2 values of the alpha dose calculated by means of (10) are shown, as a function of the concentration of ^{238}U , assuming emanation ratio levels between 0.01 and 0.1. By way

of comparison, figure 2 also shows the variation with C_U of the gamma dose, obtained with equation (1), on the hypothesis that $C_U = C_{Th}$ and for C_K levels between 300 Bq kg^{-1} and 1000 Bq kg^{-1} . As may be noted, the level of the alpha dose is generally lower than that of the gamma dose.

6. Conclusions

On the basis of the results obtained, it may be stated that the model proposed makes it possible to calculate with a sufficient degree of reliability the contribution of building materials both to the external (gamma) and to the internal (alpha) dose, based on the concentrations of uranium, thorium and potassium present in the materials themselves. In fact, there is substantial agreement between the levels of gamma dose calculated and those measured experimentally. Moreover, because of the particularly low concentrations of radionuclides normally to be found in the most commonly used building materials, the alpha and gamma contributions were both found to be extremely modest. The fact that the dose due to radon, for high levels of specific activity of the materials was found to be considerably lower than the gamma dose (see figure 2), shows that it is necessary to take account of both contributions in characterising building materials from the point of view of

radiological protection.

One possible method for applying this approach consists of comparing the levels of both the doses calculated with the limit of 10 mSv y^{-1} , recommended for new buildings in relation to radon [5,9]. For this purpose, if the expressions of the gamma dose (1) and (2) and those of the alpha dose (10) and (11) are compared to the level of 10 mSv y^{-1} , the following relations are obtained:

$$\frac{C_U}{780} + \frac{C_{Th}}{640} + \frac{C_K}{11100} < 1 \quad (12)$$

$$C_U d e < 1 \times 10^5 \quad (13)$$

in which the concentrations are all expressed in Bq kg^{-1} and d in kg m^{-3} . The close agreement between these expressions and the limitation scheme proposed by the Swedish National Institute of Radiological Protection [11] provides further confirmation of the validity of the model proposed, both with regard to the calculation of the dose and with regard to the differential evaluation of the alpha and gamma contributions. Moreover, the levels calculated for the specific activity in the air of radon emanated from the most widely used building materials were found to be in keeping with the measured data, of the order of $1\text{--}10 \text{ Bq kg}^{-1}$ [30], and in any case well below the limits proposed for the concentration of radon in air (see table 4). It must therefore be stated that, where the levels of specific activity of ^{222}Rn are considerably higher, the greatest contribution to its accumulation in buildings, apart from exceptional cases, is due to emanation from the ground. More generally, on the basis of the model proposed, it is possible to conclude that the gamma and alpha dose deriving from the most widely used building materials is much lower than the limits recommended by the radiological protection organisations, and in any case at a level which does not give cause for concern.

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Résumé

Les auteurs ont développé une méthode de calcul pour évaluer les contributions des doses externe (gamma) et interne (alpha) dues à la radioactivité naturelle des matériaux de construction. Ils ont examiné ^{40}K et les membres des familles radioactives de ^{235}U , ^{238}U et ^{232}Th . Cette méthode permet de relier les activités spécifiques de ces radionucléides dans le matériau employé pour construire les murs d'une pièce, aux doses alpha et gamma absorbées par un individu situé au centre de la pièce. Les résultats obtenus sont en accord avec les données expérimentales et avec les valeurs calculées par d'autres auteurs.

Zusammenfassung

Es wurde ein Rechenverfahren entwickelt, um die Anteile von externen (Gamma) und internen (Alpha) Dosen infolge der natürlichen Radioaktivität in Baumaterialien zu bestimmen. Die untersuchten Radionuklide sind ^{40}K und die Glieder der radioaktiven Zerfallsketten von ^{235}U , ^{238}U und ^{232}Th . Die Methode ermöglicht, die Alpha- und Gammadosen einer im Zentrum eines Raumes befindlichen Person den spezifischen Aktivitäten dieser Radionuklide im Baumaterial der Wände dieses Raumes zuzuordnen. Die erhaltenen Resultate sind in Übereinstimmung mit den experimentellen Daten und mit berechneten Werten anderer Autoren.

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