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# MODELLING INDOOR EXPOSURE TO NATURAL RADIATION

K. Brown, P. J. Dimbylow and P. Wilkinson
National Radiological Protection Board
Chilton, Didcot
Oxfordshire OX11 0RQ

**Abstract** – Models have been developed to enable prediction to be made of the dose incurred indoors from gamma radiation and from inhalation of radon decay products.

The gamma model takes account of attenuation and build-up of the photon fluence and involves a three-dimensional point kernel integration. The model is divided into three parts: calculation of the dose rate from the walls, ceiling and floor slab (walls can be multilayered and may also include windows and doors); calculation of that part of the dose rate from the ground which is attenuated by the floor slab, and calculation of that part of the dose rate from the ground which is attenuated by the walls.

The radon model assumes that the diffusion pathway is the important route for radon transfer when average air concentrations are to be predicted, and assumes that the rate of diffusion is only significant in the direction perpendicular to the surface of the building element. Thus the radon flux into the room is predicted by solving the one dimensional diffusion equation under the boundary conditions appropriate to the particular wall or floor structure (e.g. cavity wall or multi-layer). The equilibrium decay product concentration is then found by considering the ventilation rate and the concentration of the decay products in the ventilating air. The one dimensional approach is inappropriate for predicting the flux through the floor when there are discontinuities such as cracks and service ducts present, since these introduce a radon concentration gradient in the horizontal as well as the vertical plane. A two-dimensional model using numerical techniques is being developed which will help to overcome this problem.

Preliminary results from an experimental programme designed to test the models are presented.

## INTRODUCTION

All rocks, soils and minerals contain to a greater or lesser extent the radionuclides potassium-40 and those in the uranium-238 and thorium-232 series. Since building materials are extracted from the earth, they too contain these radionuclides and thus contribute to the population's radiation exposure. To assess the radiological significance of building materials and building practices, models are required which relate measurable parameters to dose. Such models would also be necessary should radiological protection standards be introduced to limit indoor exposure.

We present here models for estimating the effective dose equivalent from the two major exposure routes: whole body irradiation by gamma rays and irradiation of the lung tissues by radon decay products.

## GAMMA RADIATION

The fluence rate, $\dot{\emptyset}$, at a target in a vacuum from an isotropic point source of energy $E_i$ in a medium is given by:-

$$\dot{\emptyset}(E_i) = \frac{B(E_i,d)\dot{A}(E_i)}{4\pi L^2} \exp(-\mu_m(E_i)d) \qquad (1)$$

where d is the distance travelled in the medium, L is the distance from source to target, $\mu_m(E_i)$ is the linear attenuation coefficient of the medium, $B(E_i,d)$ is a build-up factor and $\dot{A}(E_i)$ is the activity of the source.

If the source is at (X,Y,Z), the target at $(X_T,Y_T,Z_T)$ and the line joining them crosses the medium/vacuum interface at $(X^1,Y^1,Z^1)$ then L and d are given by:-

$$L = [(X_T - X)^2 + (Y_T - Y)^2 + (Z_T - Z)^2]^{1/2} \qquad (2)$$

$$d = \frac{(Z^1 - Z)}{(Z_T - Z)} L \qquad (3)$$

If the source is spread uniformly through the material volume, V, then the effective dose equivalent rate at the target position will be:

$$\dot{H} = \sum_i f(E_i) \int_V \dot{\emptyset}(E_i)\, dV \qquad (4)$$

where $f(E_i)$ is a conversion factor from fluence to effective dose equivalent.

The build-up factor reflects the contribution of secondary radiation (mostly Compton scattered photons) to the total photon flux. It varies rather slowly with respect to changes in attenuation distance, source photon energy and average atomic composition. Build-up factors can therefore be obtained by interpolation.

In modern houses walls are usually multi-layer systems. Build-up factors for such systems can be constructed using Broder's[1] direct synthesis model. This assumes the build-up at each layer to be the sum

of individual differences in the build-up. If we define $S_m$ as the sum of the attenuation distances:

$$S_m = \sum_{i=1}^{m} \mu_i x_i .$$

where $\mu_i$, is the attenuation coefficient in layer i and $x_i$ is the distance travelled in layer i, then

$$B(S_m) = B(S_{m-1}) + [b_m(S_m) - b_m(S_{m-1})] \quad (5)$$

where $B(S_m)$ is the total build-up after traversing layer m and $b_m(S_m)$ is the build-up in layer m for a traversal of $S_m$ in material m.

From this recurrence formula, the total build-up can be derived as

$$B(S_N) = b_1(S_1) + \sum_{m=2}^{N} [b_m(S_m) - b_m(S_{m-1})] \quad (6)$$

The point kernel integral for the fluence rate from a multilayer system is then given by:

$$\int \dot{\emptyset}(E_i)dV = \sum_N \frac{\dot{A}_N(E_i)}{4\pi} \int_V \frac{B(E_i, S_N)}{L^2} \exp(-S_N)dxdydz \quad (7)$$

Our computer model, GRIND (*G*amma *R*ay *IN*door *D*ose rate) uses standard numerical integration methods to calculate this fluence rate for a rectangular block geometry. The gamma ray energies and emission probabilities[2] for the natural radionuclides are held in a data library (lines with an emission probability of less than 0.001 are excluded) along with elemental attenuation cross-sections[3]. For convenience, lines of similar energy are grouped together (the number and boundary energies of the groups being specified by the user) and the mid point energy of each group is used in the calculations. Conversion factors from fluence to effective dose equivalent for anterior-posterior incidence[4] are also held in the library. These will produce upper values of effective dose equivalent because anterior-posterior irradiation conditions give the maximum dose.

For each building material to be considered users of the model must specify the density, elemental composition, build-up factors and the specific activity of the radionuclides. The activity of each radionuclide in the decay chains may be specified independently, thus allowing for any disequilibrium.

For each building element the data required include the dimensions, the number of layers, the material from which each layer is constructed, the thickness of each layer, the position and size of any holes (i.e. doors or windows) and the position(s) of the target(s) at which the dose rate is to be calculated.

The contribution to the indoor dose rate from the activity in the subjacent ground can also be calculated. Two modified versions of GRIND are used, one to calculate that part of the dose rate from the ground which is attenuated by the floor slab, and the other to calculate that part which is attenuated by the walls.

## RADON DECAY PRODUCTS

Radon gas generated in porous media such as rock, soil or building materials, may be transported through the air filled pore system to be exhaled at the surface. When radon is exhaled into a dwelling, either from the building elements or from the subjacent ground, the concentration increases because dispersion is restricted by the limited ventilation.

Transport of radon through porous media occurs by two mechanisms[5]: diffusion under the influence of a radon concentration gradient between the pore air and the external air, and convective transport (i.e. movement of radon along with the pore air) occasioned by the existence of a pressure difference. The effect of the latter was ignored in this assessment. Building elements are effectively semi-infinite slabs and the diffusion of radon may thus be represented by the one-dimensional diffusion equation[6]:

$$\frac{dC(x)}{dt} = f - \lambda C(x) + \frac{ke}{p}\frac{d^2C(x)}{dx^2} \quad (8)$$

where C is the activity concentration per unit volume of pore space, $k_e$ is the effective bulk diffusion coefficient, p is the porosity of the medium, $\lambda$ is the radioactive decay constant for radon and f is the production rate of radon per unit volume of interstitial space. The flux is given by Fick's Law:

$$J(x) = -k_e \frac{dC(x)}{dx} \quad (9)$$

where J is the activity flux per unit time per unit area of the porous medium.

If the central point of the element is taken as the origin, then for the symmetric case, the radon flux is equal to zero at x = 0.

$$J(0) = -k_e \left.\frac{dC}{dx}\right|_{x=0} = 0 \quad (10)$$

For diffusion occurring from a wall '2d' thick into a room 't' deep at the steady state (dC/dt = 0), the flux into the room compensates the volume decay rate of radon in the room:

$$-k_e \left.\frac{dC}{dx}\right|_{x=d} = C(d)\, t\lambda \quad (11)$$

The steady state solution of Equation 8 under the boundary conditions shown in Equations 10 and 11 has the form:

$$C(x) = \frac{f}{\lambda}\left[1 - \frac{\cosh(x/t_o)}{\cosh\beta + \frac{1}{\alpha\beta}\sinh\beta}\right] \quad (12)$$

where $t_o = (Ke/\lambda p)^{1/2}$ the diffusion length, $\alpha = t/dp$, the ratio of the room volume to the pore volume, $\beta = d/t_o$ and the flux of radon into the room is given by:

$$J = k_e \left.\frac{dC}{dx}\right|_{x=d} = fp\, t_o \tanh\beta/((1 + \tanh\beta)/\alpha\beta) \quad (13)$$

For rooms $\alpha$ is large and the radon flux may be approximated by:

$$j = fpt_o\tanh\beta \quad (14)$$

In our computer model, REXIN (*R*adon *EX*posure *IN*doors), we have extended this analysis, by varying the boundary conditions, to cover the radon flux from several wall geometries. For multi-layer walls, the boundary conditions allow for the requirement that the radon concentration and the radon flux vary continuously at the layer interface. For cavity walls, steady state conditions are assumed, such that the diffusive flux into the cavity is balanced by radioactive decay and removal by ventilation. The analysis may also be extended to estimate the contribution to the total flux from the ground and floor. A typical floor structure is that of a concrete slab resting on the ground for which the flux is given by:

$$J = \frac{p_s t_{o,s}\,[(f_g - f_s)\,Ke^{-\beta s}\,(1 + \tanh\beta_s) + f_s\,(K + \tanh\beta_s)]}{1 + K\tanh\beta_s} \quad (15)$$

where subscripts s and g refer to the slab and to the ground, respectively, and

$$K = \frac{p_g t_{o,g}}{p_s t_{o,s}} \quad (16)$$

The model uses standard expressions[6] to derive the steady state radon and decay product con-centrations at a given ventilation rate:

$$C_R = \frac{\dfrac{\Sigma_m J_m S_m}{V} + C_o\lambda_v}{\lambda + \lambda_v} \quad (17)$$

where $C_R$ is the activity concentration of radon, $J_m$ is the exhalation rate from element m, $S_m$ is the exhaling surface area of element m, V is the volume of indoor space, $C_o$ is the activity concentration of radon in ventilating air, $\lambda_v$ is the ventilation or air exchange rate and

$$C_i = \frac{\lambda_i C_{i-1} + \lambda_v C_{i,o}}{\lambda_v + \lambda_i} \quad (i=1 \text{ to } 3) \quad (18)$$

where i = 0 is $^{222}Rn$, i = 1 is $^{218}Po$, i = 2 is $^{214}Pb$ and i=3 is $^{214}Bi$.

This will be a maximum value, however, as the predicted decay product concentrations will be reduced by plateout, i.e. the attachment of decay products to indoor surfaces. The importance of plateout varies considerably with ventilation rate and the aerosol concentration[7], and it is therefore necessary to specify a reduction factor appropriate to the particular circumstances.

A major inadequacy of this model is that it takes account of radon diffusion through intact floor slabs only. In most dwellings the concrete floor slabs are interrupted by service ducts and are subject to cracking. This provides an easy route for ingress of radon from the ground[8]. Such discontinuities produce a radon concentration gradient in both the horizontal and vertical planes and a one-dimensional diffusion model is no longer appropriate. We are currently developing a computer program based on finite difference schemes, and the finite element code HEATRAN[9] is being prepared for application to this problem. The initial work is based on a two-dimensional periodic floor crack geometry[10], but future work will include the construction of a more realistic model of a house.

## EVALUATION OF MODELS

As a preliminary evaluation of the models, we have compared results obtained with GRIND and REXIN against measured values for one house for which samples of some of the building materials were available.

The house is a traditionally constructed, detached, two storey dwelling. The external cavity walls are of brick and block construction with plasterboard linings. The internal walls are of block and plasterboard on the lower floor and of plasterboard mounted on wooden frames on the upper floor.

Samples of brick, block and plasterboard were available for which measurements of specific activity, density, porosity and radon emanating fraction were made. Radon diffusion coefficients were estimated from literature values[11], as were all parameters for the concrete slab floor and subjacent ground. The values are shown in Table 1.

Build-up factors for aluminium[12] were used for all construction materials. This is a reasonable approximation since replacing the build-up factors by those for iron or water changes the dose rate by only a few percent.

The gamma dose rate in air was measured at the centre of the living room at a height of 1 metre. After subtraction of the cosmic ray contribution, the absorbed dose rate in air was found to be 0.06 $\mu$Gy.h$^{-1}$ [13], which corresponds to an effective dose equivalent rate of 0.04 $\mu$Sv.h$^{-1}$ using a conversion

**Table 1. Parameters used to test the models**

| Parameter | Brick | Block | Plasterboard | Concrete | Ground |
|---|---|---|---|---|---|
| Specific activity $^{226}$Ra, Bq.kg$^{-1}$ | 14 | 39 | 2.5 | 40 | 25 |
| Specific activity $^{232}$Th.Bq.kg$^{-1}$ | 30 | 30 | 2.5 | 30 | 25 |
| Specific activity $^{40}$K, Bq.kg$^{-1}$ | 546 | 336 | 52 | 400 | 370 |
| Density, kg.m$^{-3}$ | 1600 | 1200 | 960 | 2000 | 1500 |
| $^{222}$Rn emanating fraction, % | 5 | 4 | 20 | 5 | 20 |
| Effective diffusion coefficient, m$^2$.s$^{-1}$ | $1.5 \times 10^{-8}$ | $3 \times 10^{-8}$ | $2 \times 10^{-8}$ | $5 \times 10^{-9}$ | $5 \times 10^{-7}$ |
| Thickness, m | 0.1 | 0.1 | 0.01 | 0.1 | 0.1 |

factor of 0.7[14]. The effective dose equivalent rate predicted by GRIND for the same position is 0.05 $\mu$Sv.h$^{-1}$.

Radon decay product concentrations and ventilation rates were measured in the house over a period of several days. The mean concentration was 5 mWL with a mean ventilation rate of 0.2 air changes per hour[13]. With this value for the ventilation rate the decay product concentration predicted by REXIN is 3 mWL.

## CONCLUSION

Both models are in encouraging agreement with the measured values when the experimental uncertainties are taken into account. The rather low value predicted for the radon decay product concentration probably reflects the omission from the model of radon ingress through cracks in the floor. Our future work will include the development and experimental validation of models to cover this pathway.

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