# Technical note

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Subject : Dose assessment from radon progeny in a concrete based room using CFD calculation

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## 1 Radon simulation and boundary conditions

**Geometry, material and ventilation conditions**

Based on information provided by the customer the following conditions of the room have been agreed:

***Geometry and material features of the room***

Dimensions : length 3 m; width 3 m; height 2.7 m
Inner area : 50.4 $m^2$
Volume : 24.3 $m^3$
Window : 1.2 x 1.2 $m^2$ (1.4 $m^2$)
Door : 2.0 x 0.8 $m^2$ (1.6 $m^2$)
Area concrete : 47.4 $m^2$
Concrete thickness : 0.2 m
Concrete density : 2300 $kg \cdot m^{-3}$
Furniture : Unfurnished room

***Flow conditions and $^{222}$Rn background***

Air exchange rate : 0.5 $h^{-1}$
$^{222}$Rn background concentration : 10 $Bq \cdot m^{-3}$
$^{222}$Rn background equilibrium factor : 0.4

**$^{222}$Rn source**

According to exhalation measurements carried out by NRG[1] the $^{222}$Rn exhalation rate is determined as $4.8 \cdot 10^{-6}$ and $6.8 \cdot 10^{-6}$ $Bq \cdot kg^{-1} \cdot s^{-1}$ for the concrete samples with and without fly ash, respectively. In building materials the diffusion of $^{222}$Rn is often described as a one-dimensional process, i.e. directed to the living space and its opposite side. The $^{222}$Rn source for the considered room follows from the multiplication of the exhalation rates by the total area in the room taken by concrete and the surface density, the product of the thickness of the building parts and their density. In formula:

$$S = E_m \; A \; \rho \; L \tag{1}$$

In this equation $S$ represents the $^{222}$Rn source in the room ($Bq \cdot s^{-1}$); $E_m$ the $^{222}$Rn exhalation rate ($Bq \cdot kg^{-1} \cdot s^{-1}$); $A$ the area in the room taken by concrete ($m^2$); $\rho$ the density of concrete ($kg \cdot m^{-3}$); and $L$ the half-thickness of the construction parts (m). In this way the $^{222}$Rn source in the room is calculated at $7.4 \cdot 10^{-2}$ $Bq \cdot s^{-1}$ for the room constructed with concrete to which no fly ash is added and $5.2 \cdot 10^{-2}$ $Bq \cdot s^{-1}$ for the concrete with fly ash.

These values, however, have to considered as a maximum. The exhalation from the test specimen takes place from all sides instead of one-dimensional as in a practical situation. This may lead to an overestimation of the $^{222}$Rn source in the room under investigation. Berkvens et al.[2] have introduced a formalism to calculate the one-dimensional exhalation rate from the experimentally determined results. Therefore, they defined an equivalent sample geometry with a reduced thickness to compensate for the $^{222}$Rn diffusion to the planes other than the front and backside. With the x-axis directed towards the room, the shortest mean distance is given by:

$$\frac{L'_x}{2} = \frac{L_x}{2} - \frac{1}{6}\left(\frac{L_x^{\,2}}{L_y} + \frac{L_x^{\,2}}{L_z} - \frac{1}{2}\frac{L_x^{\,3}}{L_y L_z}\right) \tag{2}$$

In this expression $L_x$, $L_y$ and $L_z$ represent half of the sample thickness of the test specimen in the x-, y- and z-direction. As the dimensions of the present test samples are 0.10 x 0.10 x 0.20 m$^3$, $L'_x$ is calculated at 0.33 m. Subsequently the exhalation rate from a wall in practice is calculated from the measured exhalation rate according to:

$$\frac{E_m^{(1)}}{E_m} = \frac{L'_x}{L_x}\,\frac{\tanh\,(L_x/l)}{\tanh\,(L'_x/l)} \tag{3}$$

$E_m^{(1)}$ is this equation is the one-dimensional exhalation rate; $E_m$ the experimental determined exhalation rate; and $l$ the diffusion length of $^{222}$Rn in concrete. As reported by Kovler et al.[3] the literature data on the diffusion length in concrete ranges from 0.06 m for heavy concretes to 0.30 m for light-weight species. If for the present concretes a diffusion coefficient of 0.10 m is assumed, a correction factor of 0.79 can be calculated from equation (3). With that the $^{222}$Rn source in the considered room comes to $5.9 \cdot 10^{-2}$ Bq·s$^{-1}$ (no fly ash added) and $4.1 \cdot 10^{-2}$ Bq·s$^{-1}$ (with fly ash), respectively. Since these values are supposed to be more realistic, these are applied in the model calculations.

### Radon and radon progeny modelling

The modelling of the $^{222}$Rn concentration and the concentrations of the short-lived $^{222}$Rn progeny nuclides $^{218}$Po, $^{214}$Pb and $^{214}$Bi follows the method as described De With and De Jong[4]. In this work, a Computational Fluid Dynamics (CFD) model is used to simulate the concentration of thoron and thoron progeny products in a typical Dutch living room. The dispersion is computed using the fundamental flow equations for gas and aerosols, which enables detailed simulation of the three-dimensional flow structures from ventilation and buoyancy. Extra algorithms are developed and coupled with the CFD model to take account of all relevant physical processes. These include the formation and attachment of the progeny products to aerosol particles as well as their dispersion and deposition.

The computed concentrations for radon and its progeny are as follows:

**Table 1 Concentrations radon and radon progeny.**

| | $^{222}$Rn (Bq·m$^{-3}$) | $^{218}$Po (Bq·m$^{-3}$) | $^{214}$Pb (Bq·m$^{-3}$) | $^{214}$Bi (Bq·m$^{-3}$) |
|---|---|---|---|---|
| Concrete without fly ash | 27.3 | 23.3 | 9.9 | 5.1 |
| Concrete with fly ash | 22.2 | 19.0 | 8.2 | 4.3 |

These concentration levels also include the radon background concentration of 10 Bq·m$^{-3}$ and its background progeny.

## 2 Dose assessment

**Calculation of internal dose**

The effective dose to residents due to inhalation of the short-lived $^{222}$Rn progeny is based on the so-called equilibrium equivalent $^{222}$Rn concentration. This concentration is calculated according to the following expression:

$$C_{eq}^{222} = 0.105\,C_1 + 0.515\,C_2 + 0.380\,C_3 \tag{4}$$

in which $C_1$, $C_2$ and $C_3$ are the activity concentrations in the indoor environment of $^{218}$Po, $^{214}$Pb and $^{214}$Bi (Bq·m$^{-3}$), respectively, as found by the model computations. The constants in the equation are the relative contributions of each decay product to the total potential alpha energy from the decay of a unit $^{222}$Rn gas. To convert the equilibrium equivalent concentration into an effective dose rate, a conversion factor of 9 nSv·h$^{-1}$ per Bq·m$^{-3}$ is applied[5]. The time spent indoors is taken as 7000 h per year (80% of the total time).

Based on the findings reported in Table 1, the above conversion factor and the hours spent indoors the internal dose is as follows:

**Table 2 Annual internal dose from radon exposure.**

| | Internal dose (mSv·a$^{-1}$) |
|---|---|
| Concrete without fly ash | 0.60 |
| Concrete with fly ash | 0.50 |

**Calculation of external dose**

The external dose due to gamma radiation from the building materials in the room is calculated according to the method described by De Jong et al.[6,7]. The standard geometry as defined by Koblinger[8] is taken as starting point for our calculation model. This geometry has dimensions of 5 x 4 m$^2$ and 2.8 m in height, with each construction part (i.e. floor, walls and ceiling) made of 20 cm thick concrete and no doors or windows. Correction factors have been deduced for alternative situations. The absorbed dose rate in air (unit: Gy·h$^{-1}$) in a particular room is than calculated according to:

$$\dot{D}_{air} = \left\{ \sum_{i=1}^{6} \left[ F_{dose} \cdot F_1 \cdot F_2 \cdot F_3 \cdot \cdots \cdot F_n \right]_i \right\} F_{zoning} \cdot F_{adjac} \tag{5}$$

in which $i$ is the index for a construction part, $F_1$ to $F_n$ are the correction factors for construction part $i$, $F_{zoning}$ is a correction factor which takes internal zoning of the construction into account, and $F_{adjac}$ is the contribution from adjacent floors and dwellings. $F_{dose}$ is the so-called dose factor, defined as:

$$F_{dose,i} = k_1 a_{1,i} + k_2 a_{2,i} + k_3 a_{3,i} \tag{6}$$

In this equation $k_1$, $k_2$ and $k_3$ represent the specific absorbed dose rates, defined as the absorbed dose rate in air due to an activity concentration of 1 Bq·kg$^{-1}$ of each of the primordial radionuclides in equilibrium with its decay products (Gy·h$^{-1}$ per Bq·kg$^{-1}$); and $a_{1,i}$ to $a_{3,i}$ the activity concentration of $^{226}$Ra, $^{232}$Th and $^{40}$K of construction part $i$ (Bq·kg$^{-1}$), respectively. The values of the specific absorbed dose rate depend amongst others on the thickness, density and dimensions of the various construction parts.

Several researchers have determined the specific absorbed dose rate for the standard Koblinger-construction, using various codes. Averaged over all data the specific absorbed dose rates are[9]:

| | | |
|---|---|---|
| $^{226}$Ra | 0.90 | nGy·h$^{-1}$ per Bq·kg$^{-1}$ |
| $^{232}$Th | 1.10 | nGy·h$^{-1}$ per Bq·kg$^{-1}$ |
| $^{40}$K | 0.08 | nGy·h$^{-1}$ per Bq·kg$^{-1}$ |

For the calculation of the annual indoor effective dose to the residents due to external radiation the absorbed dose as found from equation (5) is multiplied by a conversion factor of 0.7 Sv·Gy$^{-1}$ and the annual number of hours spent indoors, taken as 7000. The required activities for each of the three radionuclides are based on measurements performed by NRG[1]. The mean activity concentrations for both types of concrete are as follows:

**Table 3 Activity concentrations.**

| | $^{226}$Ra (Bq·kg$^{-1}$) | $^{232}$Th (Bq·kg$^{-1}$) | $^{40}$K (Bq·kg$^{-1}$) |
|---|---|---|---|
| Concrete without fly ash | 29.4 | 8.6 | 56.1 |
| Concrete with fly ash | 37.9 | 18.1 | 60.9 |

Based on those experimental results the annual external dose for is as follows:

**Table 4 Annual external dose from primordial radionuclides.**

| | Internal dose (mSv·a$^{-1}$) |
|---|---|
| Concrete without fly ash | 0.20 |
| Concrete with fly ash | 0.29 |

## Calculation of total dose

Based on the calculated internal and external dose as presented in Table 2 and Table 4 the total annual dose per year is:

**Table 5 Annual total dose from primordial radionuclides.**

| | Total dose (mSv·a$^{-1}$) |
|---|---|
| Concrete without fly ash | 0.80 |
| Concrete with fly ash | 0.78 |

# 3 References

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