Paper

MONTE CARLO CALCULATIONS OF LR115 DETECTOR RESPONSE TO ^{222}Rn IN THE PRESENCE OF ^{220}Rn

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Abstract—**The sensitivities (in m) of bare LR115 detectors and detectors in diffusion chambers to ^{222}Rn and ^{220}Rn chains are calculated by the Monte Carlo method. The partial sensitivities of bare detectors to the ^{222}Rn chain are larger than those to the ^{220}Rn chain, which is due to the higher energies of alpha particles in the ^{220}Rn chain and the upper energy limit for detection for the LR115 detector. However, the total sensitivities are approximately equal because ^{220}Rn is always in equilibrium with its first progeny, which is not the case for the ^{222}Rn chain. The total sensitivity of bare LR115 detectors to ^{222}Rn chain depends linearly on the equilibrium factor. The overestimation in ^{222}Rn measurements with bare detectors caused by ^{220}Rn in air can reach 10% in normal environmental conditions. An analytical relationship between the equilibrium factor and the ratio between track densities on the bare detector and the detector enclosed in chamber is given in the last part of the paper. This ratio is also affected by ^{220}Rn, which can disturb the determination of the equilibrium factor.**
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Key words: Monte Carlo; radon progeny; detector, alpha-track; thoron

INTRODUCTION

THE LR115 detector is commonly used for measurements of indoor ^{222}Rn concentrations. The detector is used either bare or in a diffusion chamber (hereafter referred to as an enclosed detector). Both techniques are well-known and fully described in the literature. In addition, methods employing the ratio between the track densities on the bare detector and the enclosed detector for estimation of the equilibrium factor between ^{222}Rn and its short-lived progeny were developed (Planinić and Faj 1990).

However, alpha emitting nuclides belonging to the ^{220}Rn chain are also present in air. These are detected by the LR115 detector and can lead to incorrect results for measurements of ^{222}Rn concentrations and progeny equilibrium factors.

The overestimate in ^{222}Rn measurements caused by ^{220}Rn is analyzed. The bare detector and enclosed detector are considered separately. In addition, the ratio between the track densities on the bare and enclosed detector, and the relationship between this ratio and the equilibrium factor are studied.

BARE LR115 DETECTOR

The bare detector is simply immersed in air at the place where the ^{222}Rn concentration is measured. Alpha particles emitted by ^{222}Rn and ^{220}Rn hit the detector and leave latent tracks in it. The tracks are made visible by chemical or electrochemical etching. An advantage of the bare LR115 detector, in comparison with another commonly used solid state detector, CR39, is that it does not detect those ^{222}Rn progeny deposited onto the detector itself. However, the sensitivity of LR115 detector is 0.2 to 0.25 of the CR39 detector because only those alpha particles striking the surface with energies lower than a certain limit leave visible tracks.

The track density on the bare detector is proportional to the average ^{222}Rn concentration during the period of exposure. The proportionality constant, denoted here by ϵ, is called the sensitivity, of which the reciprocal $k = 1/\epsilon$ is the calibration coefficient. It has been shown that the sensitivity of the bare LR115 detector depends on the equilibrium factor, as well as on the thickness of the layer removed during etching. However, there are no data on the sensitivity of this detector to alpha particles emitted by ^{220}Rn and its short-lived progeny.

The sensitivity of the LR115 detector to the ^{222}Rn and ^{220}Rn chains are calculated in the present paper. A previously developed computer program is used for these calculations (Nikezić and Baixeras 1995), so it will not be described in detail here. The program uses the Monte Carlo method to simulate the propagation of alpha particles, and the Bethe-Bloch expression to calculate the stopping power of alpha particles in air and cellulose nitrate. The program incorporates a visibility criterion for the tracks. The program was described in detail by Nikezić and Baixeras (1995). The track density is not constant over the detector, and the average value is

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calculated and presented. The results for a uniform concentration in air of each nuclide obtained from the calculations are presented in Table 1. The calculations were performed for a removed layer of 6.54 μm, which corresponds to the etching conditions of 2.5 N water solution of NaOH, with a temperature of 60°C and etching duration of 120 min.‡

By simple inspection of the data in Table 1, it can be seen that the sensitivities for ^{222}Rn and its progeny are similar to each other. The differences exceed the statistical error of calculations, which correspond to 10^4 "detected particles" in the simulation, and is about 1%. The sensitivities are lower for nuclides with larger alpha energies, which is due to the LR115 upper detection threshold of 4.1 to 4.6 MeV. This energy threshold depends on the thickness of removed layer during etching (Nikezić and Baixeras 1996).

The total sensitivity of the bare LR115 detector to the ^{222}Rn chain is equal to

$$\epsilon_{tot} = \epsilon_0 + F_1\epsilon_1 + F_3\epsilon_4, \qquad (1)$$

where values of ϵ_i are given in Table 1, $F_1 = C_1/C_0$ the ratio between concentrations of ^{218}Po and ^{222}Rn, $F_3 = C_1/C_0$ the ratio between concentrations of ^{214}Bi and ^{222}Rn. Because ^{214}Po is in equilibrium with ^{214}Bi due to its short half life, $F_3\epsilon_4$ is used in eqn (1). It is clear that the total sensitivity depends on the ratios between ^{222}Rn and its progeny.

The variation in sensitivity of the LR115 detector with progeny ratio was calculated by varying the values of F_1, F_2, and F_3 in steps of 0.1 while keeping the condition $F_1 > F_2 > F_3$ fulfilled, e.g., by fixing $F_1 = 0.7$ and varying F_2 between 0 and 0.6 in steps of 0.1. The results are presented in Fig. 1, with data points corresponding to combinations of F_i (i = 1, 2, 3). The solid line in Fig. 1 is obtained by linear regression of all data points, and can be written as

$$\epsilon_{tot} = (0.4 + 0.415 \times F)10^{-2}, \qquad (2)$$

where F is the equilibrium factor. The equilibrium factor F is defined as the ratio of the total potential alpha energy for the actual progeny concentrations in air (C_p) to the total potential alpha energy of the progeny, which would

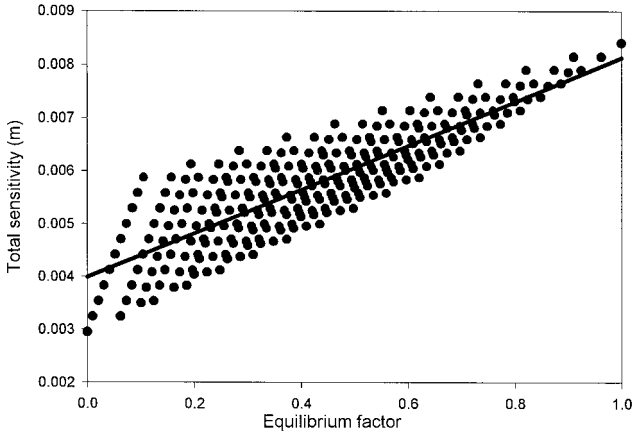

Fig. 1. Total sensitivity of the LR115 detector to the ^{222}Rn chain as a function of the equilibrium factor. The solid line represents the best fit to all data points from linear regression. Calculations were performed for a thickness of 6.45 μm for the removed layer of the detector. Calculations were performed with arbitrary variation of F_i in eqn (1).

be found if the progeny were in equilibrium with the parent gas (with concentration Rn), and can be calculated by $F = 3.7 \times C_p/\text{Rn}$, if C_p and Rn are in units of mWL and Bq m^{-3}, respectively. In general, eqn (2) can be represented by $\epsilon_{tot} = a + bF$, where parameters a and b depend on the thickness of the removed layer.

This simple approach to determine the relationship between sensitivity and equilibrium factor can be criticized on the basis that concentrations of short-lived ^{222}Rn progeny are not independent of each other. The relationships between ^{222}Rn progeny concentrations depend on a few parameters, among them the ventilation rate and the deposition rate are the most important. The behavior of short-lived ^{222}Rn progeny in rooms can be described by the predictive Jacobi's model (Jacobi 1972), which consists of a set of linear equations relating the indoor concentrations of different ^{222}Rn progeny species in air. The model employs a few parameters such as ventilation rate and deposition rate, which depend on room conditions and have typical ranges of values. In this paper, Jacobi's model is applied to calculate the sensitivity of the bare LR115 detector on the ^{222}Rn chain under typical room conditions.

The following typical values are adopted for the parameters in Jacobi's model: deposition rate of unattached progeny = 20 h^{-1}; deposition rate of attached progeny = 0.2 h^{-1}; recoil factor after alpha decay = 0.83; and ventilation rate = 0.55 h^{-1}. The following values are obtained: equilibrium factor $F = 0.372$; ratio $F_1 = 0.723$; and ratio $F_3 = 0.271$.

In addition, the range of ventilation rates in Jacobi's model is from 0.1 to very large values. The results are shown in Fig. 2. Compared to the results shown in Fig. 1, the relationship is non-linear at very low equilibrium factors, i.e., $F < 0.1$. However, this is not very important

‡ Nikezić, D.; Janićijević, A.; Kostić, D. Some characteristics of a LR115 detector and its applicability in retrospective radon measurements. (Unpublished data).

Table 1. Partial sensitivities of the bare LR115 detector for ^{222}Rn and ^{220}Rn chains.

Radionuclide	Energy (MeV)	Sensitivity (10^{-2} m)
^{222}Rn	5.49	$\epsilon_0 = 0.295$
^{218}Po	6.0	$\epsilon_1 = 0.294$
^{214}Po	7.69	$\epsilon_4 = 0.254$
^{220}Rn	6.29	$\epsilon_0' = 0.269$
^{216}Po	6.78	$\epsilon_1' = 0.253$
^{212}Bi	6.05	$\epsilon_{2a}' = 0.288$
	6.09	$\epsilon_{2b}' = 0.285$
^{212}Po	8.78	$\epsilon_3' = 0.252$

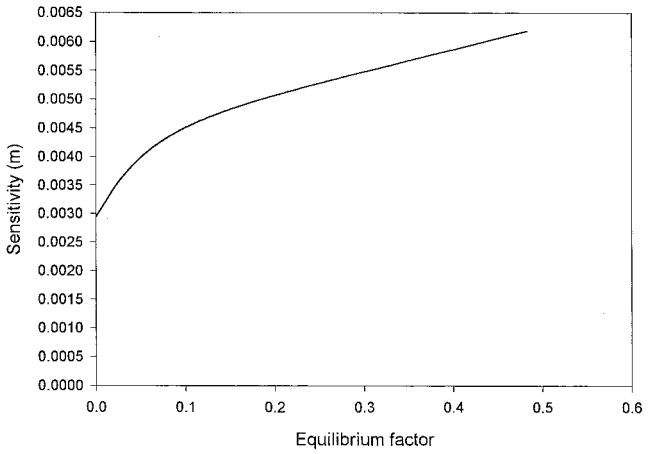

Fig. 2. Sensitivity of bare LR115 detector to the ^{222}Rn chain as a function of the equilibrium factor. Calculations were performed by using Jacobi's model and eqn (1).

since it is almost impossible to obtain such small equilibrium factors. The model also shows that large equilibrium factors, e.g., $F > 0.5$, are difficult to realize in practice. Even when $\lambda_v = 0\ h^{-1}$, which is for hermetically closed spaces, the equilibrium factor is still only slightly above 0.5. The removal rate of short-lived ^{222}Rn progeny by deposition on surfaces prevents higher F values. The equation for the linear part of the curve between $F = 0.1$ to 0.5 in Fig. 2 has been obtained by linear regression as $\epsilon_{tot} = (0.42 + 0.43 \times F)\ 10^{-2}$, and is very similar to eqn (2).

If values F_1 and F_3 obtained from Jacobi's model and those values of ϵ_i shown in Table 1 are employed for eqn (1), the total sensitivity ϵ_{tot} is found as $\epsilon_{tot} = 0.575\times10^{-2}$ m. When using eqn (2) and the value $F = 0.372$ obtained from Jacobi's model, we have $\epsilon_{tot} = 0.554\times10^{-2}$ m. It is apparent that the difference for the two approaches is relatively small. The second approach, namely, using Jacobi's model and typical values of parameters, also has a weakness: the rate constants λ_i in some rooms do not have typical values. Therefore, the linear fit represented by the line in Fig. 1 can be taken as the dependence of the sensitivity of the bare LR115 detector on the equilibrium factor for $F > 0.1$. For $F < 0.1$, there are significant deviations from the linear dependence (Fig. 2).

In reality, however, the bare detector will also register alpha particles emitted by ^{220}Rn and its short-lived progeny. The sensitivities of the LR115 detector to the ^{220}Rn chain are also given in Table 1. These sensitivities are smaller than those to ^{222}Rn because the alpha energies of the ^{220}Rn chain are larger. The total sensitivity to the ^{220}Rn chain is given by

$$\epsilon'_{tot} = \epsilon'_0 + F'_1\epsilon'_1 + F'_2(0.251 \times \epsilon'_{2a} + 0.0977 \times \epsilon'_{2b}) + F'_3 \times 0.6407\epsilon'_3, \quad (3)$$

where values of ϵ'_i are given in Table 1, and F'_i is the ratio between the concentration of the i-th ^{220}Rn progeny and that of ^{220}Rn. The first progeny ^{216}Po can be taken to be in equilibrium with ^{220}Rn. The second progeny ^{212}Pb has a "long" half life of 10.64 h. By applying Jacobi's model to the ^{220}Rn chain, with the parameters same as above, we have obtained $F'_1 = {}^{216}\text{Po}/{}^{220}\text{Rn} = 0.998$, $F'_2 = {}^{212}\text{Pb}/{}^{220}\text{Rn} = 0.057$, and $F'_3 = {}^{212}\text{Bi}/{}^{220}\text{Rn} = 0.027$. ^{212}Pb cannot attain large concentrations in air due to its long half life. From these values of F'_i and eqn (3), the total sensitivity of the LR115 detector to the ^{220}Rn chain is $\epsilon'_{tot}=0.531\times10^{-2}$ m. The slightly lower sensitivity to ^{220}Rn compared to that of ^{222}Rn is mainly due to the larger alpha energies in the ^{220}Rn chain.

Overestimation of ^{222}Rn measurements by bare LR115 detectors due to ^{220}Rn

We denote ^{222}Rn and ^{220}Rn concentrations in air as C_0 and C', respectively. All the tracks on the LR115 detector are attributed to ^{222}Rn, and so ^{222}Rn concentration can be overestimated. The "overestimated" ^{222}Rn concentration obtained from the LR115 detector is denoted as C*. The track density due to ^{222}Rn and ^{220}Rn chain, denoted as $N_{\text{Rn-222}}$, and $N_{\text{Rn-220}}$ respectively, are

$$N_{\text{Rn}-222} = \epsilon_{tot}C_0t; \quad N_{\text{Rn}-220} = \epsilon'_{tot}C't \quad (4)$$

where t is the time of detector exposure. The total track density N_{tot} is the sum of these two, i.e., $N_{\text{tot}} = N_{\text{Rn-222}}+N_{\text{Rn-220}}$. Since all the tracks are attributed to ^{222}Rn, its overestimated concentration is equal to

$$C^* = \frac{N_{tot}}{\epsilon_{tot}t} = \frac{N_{\text{Rn}-222} + N_{\text{Rn-220}}}{\epsilon_{tot}t} = \frac{(\epsilon_{tot}C_0 + \epsilon'_{tot}C')t}{\epsilon_{tot}t} = C_0 + \frac{\epsilon'_{tot}}{\epsilon_{tot}}C' \quad (5)$$

The relative error is obtained as

$$\frac{\Delta C}{C_0} = k = \frac{C^* - C_0}{C_0} = \frac{C'\epsilon'_{\text{tot}}}{C_0\epsilon_{tot}} \quad (6)$$

The real ^{222}Rn concentration can be obtained as $C_0 = C^*/(k + 1)$.

In normal indoor environments, ^{220}Rn can go up to 10% or $C'/C_0 = 0.1$. The ratio of the sensitivities $\epsilon'_{tot}/\epsilon_{tot} = 0.531/0.56\approx0.95$. It follows that the relative error in normal indoor environments can go up to 10%. However, cases of high indoor ^{220}Rn concentrations have been reported (Yu et al. 1999). In addition, if the ^{220}Rn source is the building material of the wall, the ^{220}Rn concentration decreases exponentially with the distance from the wall (Katase et al. 1988). Under such circumstances, ^{222}Rn measurements performed at different distances from the wall will give different values. Therefore, ^{220}Rn in air leads to confusion in ^{222}Rn measurements with the bare LR115 detector.

LR115 DETECTOR ENCLOSED IN DIFFUSION CHAMBER

Normal practices using the LR115 detector are based on the understanding that the bare detector registers alpha particles emitted by ^{222}Rn as well as its short-lived progeny. Therefore, if ^{222}Rn measurements are aimed for, the progeny are causing a complication. On the other hand, if the detector is used to measure PAEC, ^{222}Rn is causing a complication. The bare detector offers information about the concentrations of ^{222}Rn and its progeny in air, while the enclosed detector has information about ^{222}Rn only.

In order to minimize the influence of the unknown ratio between ^{222}Rn and its short-lived progeny on ^{222}Rn measurements, the detector in a diffusion chamber or a cup (referred to as the enclosed detector) is often used instead of the bare detector. The method of enclosed detector is also widely applied and well described in literature (Frank and Benton 1981; Khan et al. 1993; Durrani and Ilic 1997). It is assumed that only the ^{222}Rn gas can pass through the filter covering the chamber, and all the short-lived ^{222}Rn progeny are stopped by the filter. ^{220}Rn gas can enter the chamber, but the nuclides in the ^{220}Rn chain are stopped by the filter.

The sensitivity of the enclosed LR115 detector to ^{222}Rn and its short-lived progeny has been calculated by Nikezić and Baixeras (1995) where the results for partial sensitivities to the ^{222}Rn chain are given.

^{222}Rn chain

Only the total sensitivity to ^{222}Rn chain is given here. Short-lived ^{222}Rn progeny are deposited onto inner chamber surfaces, so the irradiation geometry and thus the detector sensitivity are changed. Since ^{214}Bi has a long half life, it is taken to be completely deposited. However, ^{218}Po has a short half life and will not be fully deposited. The effects of the non-deposited fraction of ^{218}Po has been studied and the results are shown in Fig. 3. Calculations were performed for cylindrical chambers with radii r of 2 and 3 cm and heights between 2 and 6 cm. The total sensitivity is given as a function of the non-deposited fraction of ^{218}Po inside the chamber. A linearly increasing function is obtained in all cases; each line is denoted by a pair of numbers (r, H), with the first number as the radius and the second as the height.

The sensitivity of the chamber with $r = 2$ cm and $H = 2$ cm is independent of the deposited fraction of ^{218}Po (horizontal line in Fig. 3). However, the total sensitivity in such a small chamber is much lower than in bigger ones. Therefore, small chambers are only recommended for ^{222}Rn measurements at places where high ^{222}Rn concentrations are expected, e.g., mines, or for cases that allow long exposure time.

^{220}Rn chain

The sensitivity for the ^{220}Rn and short-lived progeny was calculated using the same method as Nikezić and Baixeras (1995). Figs. 4 and 5 give the partial sensitivities for the radionuclides in the ^{220}Rn chain in the chambers with radii r of 2 and 3 cm as functions of the chamber height. It is taken that ^{216}Po completely decays in the volume of the chamber due to its short half life value. The second and the third ^{220}Rn progeny are completely deposited inside the chamber because the half life of ^{212}Po is relatively large (10.64 h). On increasing the height of the chamber, the sensitivities to ^{220}Rn and ^{216}Po increase and achieve saturation. It is observed that the saturation level is larger for chambers with $r = 3$ cm.

It is interesting to note that ^{212}Po is not recorded for chambers lower than 4 cm because its alpha particles are too energetic (8.78 MeV). They must be de-energized in air between the point of emission and the detector to fall below the upper energy threshold of LR115 detector to be detected.

There is no uncertainty in the ^{220}Rn chain detection due to unknown deposition fractions of its progeny. In

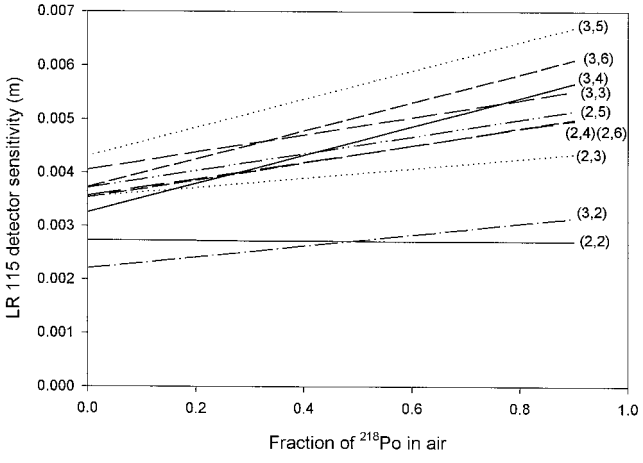

Fig. 3. Sensitivity of the LR115 detector in diffusion chamber as a function of the fraction of ^{218}Po in air. Calculations were performed for the chambers with radii $r = 2$ and $r = 3$ cm and heights $H = 2$ to 6 cm.

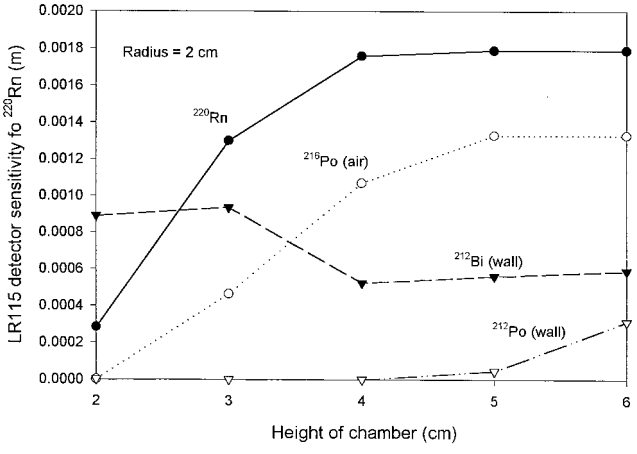

Fig. 4. The partial sensitivity of the LR115 detector to ^{220}Rn and its short-lived progeny as a function of the chamber height. The chamber radius is $r = 2$ cm.

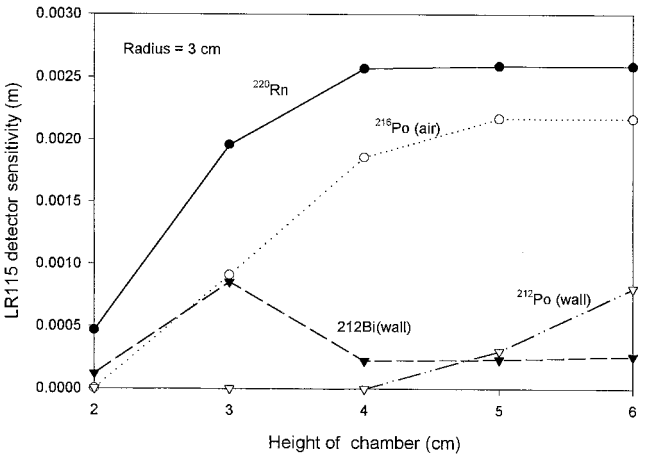

Fig. 5. The partial sensitivity of the LR115 detector to ^{220}Rn and its short-lived progeny as a function of the chamber height. The chamber radius is $r = 3$ cm.

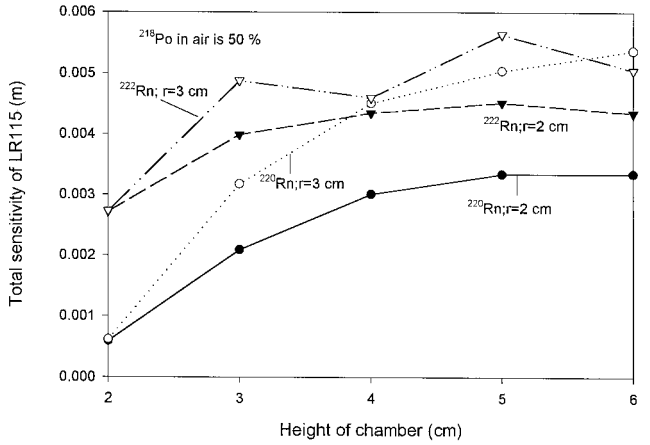

Fig. 6. Total sensitivity of the LR115 detector to ^{222}Rn and ^{220}Rn as a function of the chamber height, with the chamber radius as a parameter. Data for ^{222}Rn are related to the fraction of non-deposited ^{218}Po (F_1=0.5).

addition, there is no significant difference in the behavior of the partial sensitivity of the chambers ($r = 2$ and $r = 3$ cm) with the variation of the height.

Fig. 6 gives the total sensitivity to the ^{222}Rn and ^{220}Rn chains for the chambers with $r = 2$ and $r = 3$ cm. It is observed that the total sensitivities increase with the height. Calculations for the ^{222}Rn chain were performed for the deposition fraction of 50% for ^{218}Po. The increase in sensitivities with height for the ^{220}Rn chain is more profound than that for the ^{222}Rn chain since the enlargement of the chamber enables the detection of more energetic alpha particles emitted in the ^{220}Rn chain.

Unlike ^{222}Rn, the sensitivity for ^{220}Rn is not determined by the chamber geometry alone. The concentration of ^{220}Rn in a chamber will be much lower than in the ambient air unless the diffusion time through the filter is less than 1 min. Although the detector records the activity from the ^{220}Rn chain nuclides in the chamber, a correction that depends on filter design and material must be applied to estimate ^{220}Rn concentrations in the ambient air. The practical result is that for small chambers and "thick" filters the ^{220}Rn interference is negligible.

Overestimation of ^{222}Rn measurements by LR115 detectors enclosed in diffusion chambers due to ^{220}Rn

The presence of ^{220}Rn in the chamber increases the track density and thus affects the ^{222}Rn measurements. Since all the tracks are attributed to ^{222}Rn, the ^{222}Rn concentrations are overestimated. This error can be analyzed in a way similar to that for the bare detector (eqn 6). Figs. 7 and 8 show the magnitude of overestimation as a function of the ^{220}Rn/^{222}Rn ratio for chambers with $r = 2$ and $r = 3$ cm. The height of the chamber is given as a parameter. The overestimation depends on the chamber dimensions and increases with the chamber height and radius because the sensitivity to ^{220}Rn increases more than that to ^{222}Rn. The overestimation can reach 20% if the ^{220}Rn concentration inside the chambers is high and large chambers are used.

Equilibrium factor and ratio of track densities on bare and enclosed detectors. In the past, methods for estimation of the equilibrium factor between ^{222}Rn and its short-lived progeny were developed (Planinić and Faj 1990) based on the ratio between tracks on the bare and the enclosed detectors (hereafter referred to as the track-density ratio). For simplicity, we first consider the case where only ^{222}Rn is present in air (i.e., ^{220}Rn is absent). Furthermore, we only consider the chamber with $r = 2$ cm and $H = 2$ cm [denoted hereafter as the (2,2)-chamber] because its response is independent of the behavior of ^{218}Po inside it.

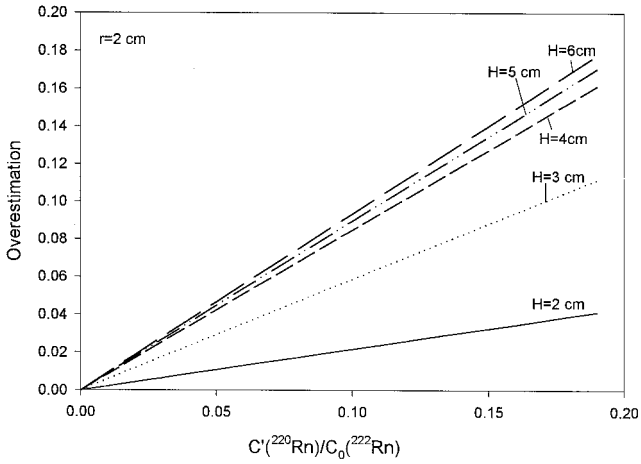

Fig. 7. Overestimation in ^{222}Rn measurements due to the presence of ^{220}Rn inside the chamber as a function of the ratio ^{222}Rn/^{220}Rn with the chamber height as a parameter. Calculations were performed for the chambers with a radius $r = 2$ cm.

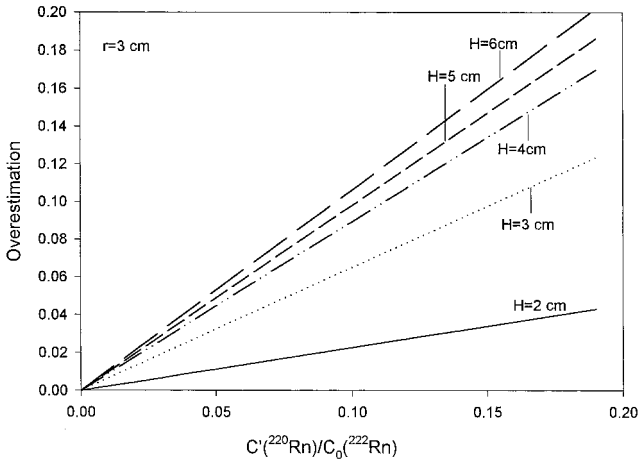

Fig. 8. Overestimation in ^{222}Rn measurements due to the presence of ^{220}Rn inside the chamber as a function of the ratio ^{222}Rn/^{220}Rn with the chamber height as a parameter. Calculations were performed for the chambers with a radius $r = 3$ cm.

The dependence of the bare detector sensitivity on the equilibrium factor F for $F > 0.1$ is given by the eqn (2) as

$$\epsilon_{tot}^{bare} = (0.4 + 0.415 \times F)10^{-2}. \qquad (2')$$

The sensitivity of the (2,2)-chamber to ^{222}Rn is determined as $\epsilon_{tot}^{c} = 0.273\times10^{-2}$ m. The track-density ratio in the (2,2)-chamber is given by the ratio of their sensitivities as

$$c = \frac{\epsilon_{tot}^{bare}}{\epsilon_{tot}^{c}} = \frac{0.4 + 0.415F}{0.273}. \qquad (7)$$

From this equation, we have $c = 1.62$ for $F = 0.1$ and $c = 2.985$ for $F = 1$, so the ratio c should be in the range from 1.62 to 2.985. Ranges of c also exist for other chambers but are different. In bigger chambers, the sensitivity is larger, which changes only the denominator in eqn (7). However, in these chambers, the unknown behavior of ^{218}Po would introduce an additional uncertainty in the consideration. Eqn (7) can be rewritten in more generalized form as

$$c = \frac{\epsilon_{tot}^{bare}}{\epsilon_{tot}^{c}} = \frac{a + bF}{\epsilon_{tot}^{c}}, \qquad (7')$$

from which the equilibrium factor F can be easily found as

$$F = \frac{c}{b}\epsilon_{tot}^{c} - \frac{a}{b}. \qquad (8)$$

For the (2,2)-chamber and a removed layer of 6.54 μm, we have

$$F = 0.65c - 0.964. \qquad (9)$$

In a case where 10% ^{220}Rn and its short-lived progeny are present, they will cause 10% additional tracks on the bare detector and <2% on the (2,2) chamber (Fig. 8), so the ratio c will be 8% larger and the estimated equilibrium factor will also be larger. A large amount of ^{220}Rn in air will impair the method; for example, indicated values with $F > 0.7$ can be found. If the track-density ratio c is found to fall outside the predicted range, this can be a signal that alpha emitters other than the ^{222}Rn progeny are present in the air.

CONCLUSIONS

The influence of ^{220}Rn on ^{222}Rn measurements with the LR115 detector is investigated in the present work. It has been found that the overestimation due to ^{220}Rn in air can reach 10% in normal environmental conditions. The determination of the equilibrium factor from the track-density ratio is also investigated here. The application of eqn (8) to determine the equilibrium factor requires a good quality calibration of the chamber as well as experimental determination of the parameters a and b for the given etching and readout conditions.

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