

Equilibrium factor determination using SSNTDs

K.N. Yu^{a,*}, S.Y.Y. Leung^a, D. Nikezic^a, J.K.C. Leung^b

^aDepartment of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon Tong, Hong Kong

^bDepartment of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong

Abstract

The proxy equilibrium factor F_p was recently proposed by Nikezic et al. [2004. Theoretical basis for long-term measurements of equilibrium factor using LR 115 detector. *Appl. Radiat. Isot.* 61, 1431–1435] and Yu et al. [2005. Long-term measurements of radon progeny concentrations with solid state nuclear track detectors. *Radiat. Meas.* 40, 560–568] for long-term passive monitoring of the equilibrium factor F for short-lived ^{222}Rn progeny. In the present paper, we further look into the details for the F_p method and study the potential factors affecting the measurements of F using this technique. These factors include (1) the removed active layer of the LR 115 detector, (2) the presence of ^{220}Rn in the ambient environment, and (3) the deposition of dust particles on the LR 115 detector. The corresponding results are: (1) the removed active layer thickness of the LR 115 detector is a very critical parameter in determining F_p and hence F ; (2) the presence of thoron in the ambient environment will affect the track densities on the bare LR 115 detector but can be corrected for using the partial sensitivities to thoron; and (3) deposition of dust particles on the bare LR 115 detectors normally will not have significant effects. In addition, a mini-survey of radon and thoron gas concentration and the radon equilibrium factor in different indoor environments has been carried out in different seasons. The conclusion is that the use of an assumed constant F value can result in inaccurate determinations of the effective dose; therefore, actual (long-term) measurements of the F values should be made.

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1. Introduction

It is well established that the absorbed radon dose in the lung is mainly due to radon progeny, but not the radon gas itself. Therefore, long-term measurements of the concentrations of radon progeny or the equilibrium factor F and a measurement or an estimation of the aerosol size distribution are needed to accurately assess the health hazards contribution from radon progeny.

Nowadays, in general practice, the radon gas concentration is first determined and an assumed F between radon and its progeny, typically from 0.4 to 0.5, is then applied. The exposure to radon progeny can be expressed in the traditional unit *working level month (WLM)* and then multiplied with the dose conversion coefficient (DCC) by assuming a given aerosol size distribution to give the effective dose.

However, in reality, the concentrations of radon and its progeny vary significantly with time and place. Therefore, an assumed F cannot reflect the actual conditions. This problem cannot be solved through active measurements based on air filtering, since they only give short-term measurements. Many researchers have proposed different long-term methods for measuring radon progeny concentrations. Recent reviews of the methods have been given by Amgarou et al. (2003), Nikezic and Yu (2004) and Yu et al. (2005). Unfortunately, many of these proposed methods suffer from some kinds of problems. Recently, Amgarou et al. (2003) and Nikezic et al. (2004) proposed measurements of the equilibrium factor through the so-called “reduced equilibrium factor” and “proxy equilibrium factor”, respectively, which are feasible methods for long-term measurements of F . The “proxy equilibrium factor” method has also been applied in passive monitoring of the equilibrium factor inside a radon exposure chamber (Leung et al., 2006).

In the present paper, we further look into the details for the proxy equilibrium factor F_p and study the potential factors

* Corresponding author. Tel.: +852 2788 7812; fax: +852 2788 7830.
E-mail address: peter.yu@cityu.edu.hk (K.N. Yu).

affecting the measurements of F using this technique. These factors include (1) the removed active layer of the LR 115 detector, (2) the presence of ^{220}Rn in the ambient environment, and (3) the deposition of dust particles on the LR 115 detector. In addition, a mini-survey of radon and thoron gas concentration and F in different indoor environments has been carried out in different seasons.

2. Proxy-equilibrium factor (F_p) method

Nikezic et al. (2004) and Yu et al. (2005) proposed the use of bare LR 115 detector for determining the airborne $^{218}\text{Po}+^{214}\text{Po}$ concentration and showed that this concentration can be employed to give good estimates of F for the radon progeny in an environment. The LR 115 detector has an upper energy threshold for track formation, which is well below the energy of alpha particles emitted by the radon progeny plate out on the detector, i.e., plate-out progeny are not detected by LR 115.

The responses of the bare LR 115 detector to ^{222}Rn , ^{218}Po , and ^{214}Po are expressed by the partial sensitivities ρ_i of the detector to these species (i.e., the number of tracks per unit area per unit exposure, i.e., the unit of $(\text{m}^{-2})/(\text{Bq m}^{-3}\text{s})$ or just (m)). The partial sensitivities, ρ_i , were found to be the same for ^{222}Rn , ^{218}Po , and ^{214}Po . A simplified explanation is given as follows (neglecting some minor details such as the critical angle for track formation). The probability P of an alpha particle emitted at the point $A(r, \theta, \phi)$ hitting a point-like detector at the origin of the coordinate system with a surface area S is given as $S \cos \theta / (4\pi r^2)$; therefore, the average detection efficiency is proportional to

$$\int P dV = \iiint \frac{S \cos \theta}{4\pi r^2} r^2 dr \sin \theta d\theta d\phi$$

$$\propto \int_{R_{\min}}^{R_{\max}} dr \propto (R_{\max} - R_{\min}) \quad (1)$$

where R_{\min} and R_{\max} are the minimum and maximum distances, respectively, of the alpha emitters from which the alpha-particle energies will fall within the energy window of the LR 115 detector. It is apparent that the $(R_{\max} - R_{\min})$ values are the same for ^{222}Rn , ^{218}Po , and ^{214}Po , since the $(R_{\max} - R_{\min})$ value is in fact controlled by the energy window of the LR 115 detector. Therefore, $\rho_i = \rho_{^{222}\text{Rn}} = \rho_{^{218}\text{Po}} = \rho_{^{214}\text{Po}}$. It is remarked here that the equality of partial sensitivities arises because of the presence of the upper energy threshold for recording alpha-particle tracks in LR 115; therefore, the lower limit of integration in Eq. (1) is R_{\min} . For other detectors without the upper energy threshold, e.g., CR-39, the lower limit of integration in Eq. (1) becomes 0; therefore, $\int P dV$ will be proportional to R_{\max} instead of $(R_{\max} - R_{\min})$, and the partial sensitivities will not be the same. The difference $(R_{\max} - R_{\min})$ does not depend on the alpha-particle emitter because the energy–distance curves are parallel to one another for different emitted alpha-particle energies (see Nikezic et al., 2004), while R_{\max} depends on the alpha-particle emitter.

Now that the partial sensitivities are equal, the total track density ρ (in track m^{-2}) on the detector is given by

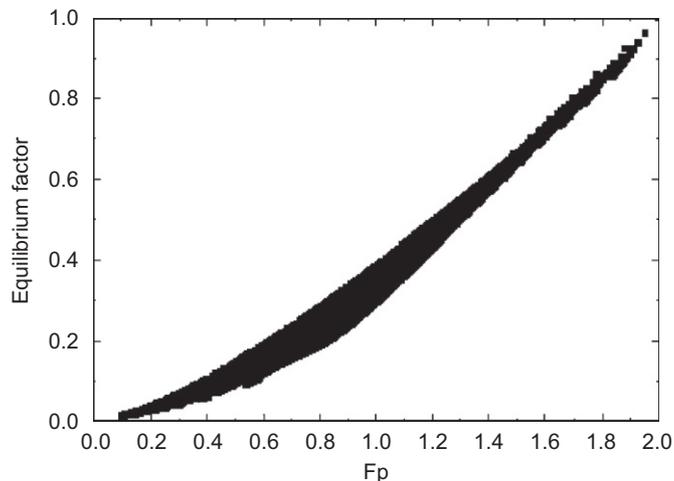


Fig. 1. The relationship between the equilibrium factor F and the proxy-equilibrium factor $F_p (=f_1 + f_3)$ (from Yu et al., 2005).

$\rho = \rho_i (C_0 + C_1 + C_3) \cdot t$, where C_0 , C_1 , and C_3 are the concentrations of ^{222}Rn , ^{218}Po , and ^{214}Po in air, respectively and t is the exposure time. The proxy-equilibrium factor F_p is defined as (Nikezic et al., 2004; Yu et al., 2005)

$$F_p = f_1 + f_3 = \frac{C_1}{C_0} + \frac{C_3}{C_0} = \frac{\rho}{\rho_i \cdot t \cdot C_0} - 1 \quad (2)$$

Yu et al. (2005) calculated F through the Jacobi (1972) room model by systematically varying all parameters that influence the concentrations of radon and its progeny and plotted them with F_p ; the results are shown in Fig. 1. The proxy-equilibrium factor F_p was found to be well correlated with F .

In Sections 4–6 below, the factors affecting the partial sensitivities of the bare LR 115 detector to ^{222}Rn , ^{218}Po , and ^{214}Po are investigated. We first describe the experimental techniques involved in handling the LR 115 detectors in Section 3.

3. Experimental techniques for LR 115 detectors

The LR 115 detectors (Type 2, non-strippable) were purchased from DOSIRAD, France. The LR 115 detector consists of a $12 \mu\text{m}$ red cellulose nitrate active layer and $100 \mu\text{m}$ clear polyester base substrate as declared by the manufacturer. After the exposure process, the SSNTDs were etched in 10% aqueous NaOH at 60°C for approximately 1 h. The temperature was kept constant with an accuracy of $\pm 1^\circ\text{C}$. The detectors were etched using a magnetic stirrer (Model no. SP72220-26, Barnstead/Thermolyne, Iowa, USA) so as to provide faster etching (Yip et al., 2003a). After etching, the detectors were taken out of the etchant, rinsed with de-ionized water and then dried.

As will be discussed in Section 4, the sensitivity of the LR 115 detectors critically depends on the removed active layer thickness. Therefore, measurements of the removed active layer thickness after chemical etching are required. Different methods have been used to measure the active layer thickness of LR 115 detectors, e.g., surface profilometry (Nikezic and Janicijevic, 2002; Yip et al., 2003a), absorption of X-ray

fluorescence photons (Yip et al., 2003b), infrared absorption (Ng et al., 2004) and gray level determination (Yu and Ng, 2004).

The infrared absorption method (Ng et al., 2004) is adopted in the present study to measure the active layer thickness of LR 115 detectors. The active layer thickness of the detector was obtained through the infrared absorption determined using a Perkin–Elmer Fourier transform infrared (FTIR) spectroscopy system (Model 16 PC FT-IR) for 10 cycles. The scanned diameter was 9 mm, and therefore the scanned area was 0.64 cm^2 . The exponential decay relationship between the infrared transmittance at the wave number at 1598 cm^{-1} corresponding to the O–NO₂ bond and the thickness of the active layer (Ng et al., 2004) was used for the present study. For each detector, the IR transmittance values were measured at six different locations to give the average values.

Finally, the alpha-particle tracks registered by the detector were then counted manually under an optical microscope with $200\times$ magnification and only those completely perforated the active layers of the LR 115 SSNTDs were counted. Completely perforated tracks were easier to identify due to the different colors at the bottom of the track when compared to the non-perforated tracks. This visibility criterion was introduced in order to minimize the level of subjectivity.

4. Removed active layer of the LR 115 detector during chemical etching

4.1. Methodology

For this part of the studies, the LR 115 detectors are exposed to ²²²Rn and its progeny inside an exposure chamber (Leung et al., 1994). The exposure chamber was filled with radon generated from the 22.9 kBq radium (²²⁶Ra) source. The reference value of the radon gas concentration was monitored by the continuous radiation monitor AB-5 (PYLON, Canada). The aerosols were generated by an aerosol generator and injected regularly into the exposure chamber so as to maintain the equilibrium equivalent concentration (EEC) of the radon progeny concentration. The radon progeny concentration was measured by collecting them on a 47 mm diameter membrane filter. The alpha emissions from the collected progeny were read by a ZnS scintillator connected to a photomultiplier tube. Finally, the PAEC, EEC, and the equilibrium factor of the progeny were calculated by the 3-count method.

4.2. Results and discussion

The experimental relationship between the partial sensitivity and the removed active layer thickness of the bare LR 115 detector obtained from experiments performed in our exposure chamber is shown in Fig. 2. We have performed two sets of exposures. The radon gas concentration RC and the equilibrium factor F in sets 1 and 2 were found to be $(1010 \pm 40 \text{ Bq m}^{-3}$ and 0.148 ± 0.022) and $(1100 \pm 40 \text{ Bq m}^{-3}$ and 0.109 ± 0.012), respectively, with the uncertainties representing one standard

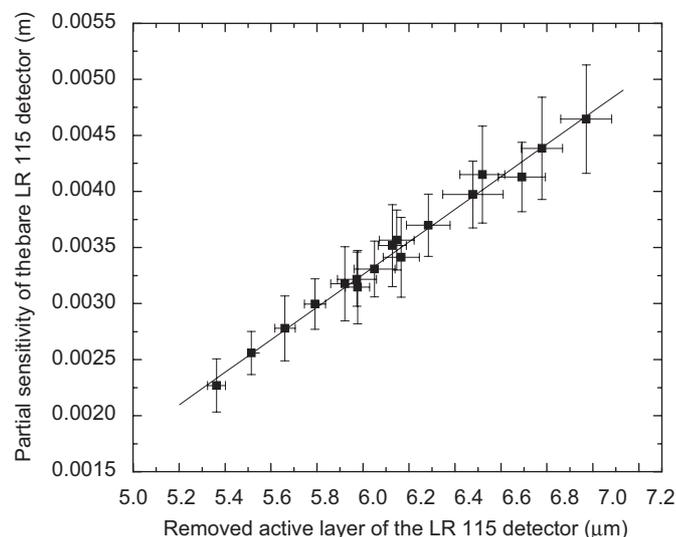


Fig. 2. The relationship between the partial sensitivity ρ_i (m) of the bare LR 115 detector and the removed active layer thickness x (μm). The solid line is the best-fit line represented by $\rho_i = -0.00547 + 0.00145x$, with an R^2 of 0.9950.

deviation. The corresponding F_p value can be read from Fig. 1. For the mid-point value of 0.148 and 0.109, F_p are determined to be from 0.47 to 0.71 with the mid-point 0.59, and from 0.38 to 0.60 with the mid-point 0.49, respectively. The equilibrium factor interval from $(0.148 - 0.022)$ to $(0.148 + 0.022)$ then corresponds to an F_p interval from 0.42 to 0.77, and the equilibrium factor interval from $(0.109 - 0.012)$ to $(0.109 + 0.012)$ corresponds to an F_p interval from 0.35 to 0.62. Such F_p intervals are used in determining the relationship between the partial sensitivity and the removed active layer thickness as shown in Fig. 2.

By fitting the linear relationship $\rho_i = A + Bx$ to the present experimental data, where x (μm) is the removed active layer thickness of the LR 115 detector, we obtain $A = -0.0055 \pm 0.0010$ and $B = 0.0015 \pm 0.0002$, with $R^2 = 0.9950$. The fit is observed to be valid within the entire range of the present data set, which is from the removed active layer thickness 5.4–7.0 μm . It is interesting to note that the data collected from the two separate exposures closely follow the same trend.

It is remarked here that the linear relationship agrees, within experimental uncertainties, very well with a similar relationship obtained previously by exposing LR 115 detectors in a walk-in exposure chamber at the HPA (Leung et al., 2007a). As reported by Leung et al. (2007a), the partial sensitivities for different removed active layer thicknesses can be used to derive the V function for the LR 115 SSNTD. For example, if we use the form of the Durrani–Green’s function, i.e., $V = 1 + (a_1 e^{-a_2 R} + a_3 e^{-a_4 R})(1 - e^{-a_5 R})$, the best-fitted constants for the present data are $a_1 = 15$, $a_2 = 0.54$, $a_3 = 5.1$, and $a_4 = 0.061$ ($a_5 = 1$), which are very close to the values obtained by Leung et al. (2006b) using the data obtained at the HPA as $a_1 = 14$, $a_2 = 0.48$, $a_3 = 5.9$, and $a_4 = 0.077$ ($a_5 = 1$).

It is also noted that the removed active layer thickness of the detector is a very critical parameter in determining the proxy-equilibrium factor F_p and hence the equilibrium factor F .

Therefore, the removed layer thickness of the detector should be monitored carefully; otherwise errors will occur.

5. Presence of ^{220}Rn in the ambient environment

Thoron (^{220}Rn) and its progeny are also present in the ambient environment, which can affect the track densities on the bare LR 115 detector. Depending on the thoron gas concentration, thoron can contribute a significant amount of alpha tracks to the bare LR 115 detector. These extra alpha tracks will lead to erroneous estimate of F_p and hence F . In particular, enhancement of the track densities, ρ , on the bare LR 115 detector will overestimate F_p or even lead to out-of-range values (i.e., $F_p > 2$). Corrections should be performed to account for the number of tracks due to thoron on the bare detector.

5.1. Methodology

To assess the possible effects of thoron, experimental calibration of the bare LR 115 detector to thoron inside the exposure chamber (Leung et al., 1994) was performed. Bare LR 115 detectors were placed inside the chamber with known thoron concentrations recorded by RAD-7 (DurrIDGE Company Inc., MA). After chemical etching and determination of the removed active layer thickness, the alpha-particle tracks registered by the LR 115 detector were counted under an optical microscope with $200\times$ magnification. Knowing the time of exposure and the thoron gas concentration given by RAD-7, the partial sensitivities of bare LR 115 detector due to thoron corresponding to different removed active layer thicknesses were determined. The actual number of alpha tracks due to a measured ^{220}Rn concentration can be subtracted in real-life measurements.

5.2. Results and discussion

In order to assess the possible effects of thoron on the bare LR 115 detector, the experimental relationship between the partial sensitivity to thoron of the bare LR 115 detector, γ , and the removed active layer thickness has been determined and is shown in Fig. 3. By fitting the linear relationship $\gamma = A + Bx$ to the experimental data, where x (μm) is the removed active layer thickness of the LR 115 detector and γ (m) is the partial sensitivity to thoron of the bare LR 115 detector, we have obtained $A = -0.00887 \pm 0.00174$ and $B = 0.00319 \pm 0.00030$, with $R^2 = 0.9622$. The fit is observed to be valid for the entire range of the present data set, in which the removed active layer thickness ranges from 5.3 to 6.5 μm .

The actual number of alpha tracks due to thoron, N_{Tn} , on the bare LR 115 detector can be calculated by

$$N_{\text{Tn}} = c(\text{Tn}) \times t \times \gamma \times (\text{area of the bare LR 115 detector}) \quad (3)$$

where $c(\text{Tn})$ is the thoron gas concentration with the unit (Bq m^{-3}), t is the exposure time with the unit (s), and γ is the

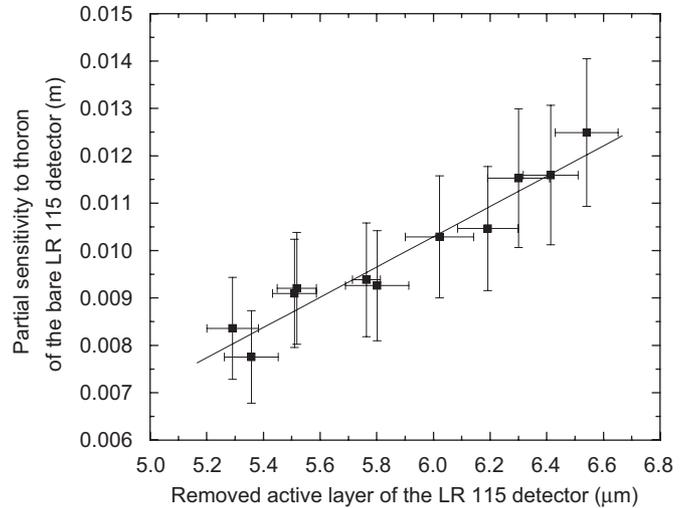


Fig. 3. The relationship between the partial sensitivity to thoron γ (m) of the bare LR 115 detector and the removed active layer thickness x (μm). The solid line is the best-fit line represented by $\gamma = -0.00887 + 0.00319x$, with an R^2 of 0.9622.

partial sensitivity to thoron of the bare LR 115 detector with the unit (m).

6. Deposition of dust particles on the bare LR 115 detector

6.1. Methodology

In order to study the possible effects of dust particles deposited on the surface of the bare LR 115 detector, experiments have been performed to examine the track densities on (A) detectors placed in an indoor environment facing upwards so that dust particles can be deposited onto the detector and (B) detectors same as (A) but cleaned with a brush everyday. The experiments were carried out at a site (no. 4) with a normal equilibrium factor (~ 0.35) and a site (no. 7) with a relatively high equilibrium factor (~ 0.6). The detectors were exposed for about 1 month and then sent back to laboratory for chemical etching and track analysis as described in Section 3. The track densities can then be obtained for comparison.

6.2. Results and discussion

The numbers of alpha-particle tracks registered by the bare LR 115 SSNTD, the track densities and the measured removed active layer thickness are summarized in Table 1. However, one should be cautious about of the variation in the removed active layer thickness of the detector. In order to eliminate the effects from this variation, we used a ratio R for this purpose, which is defined as

$$R = (F_p + 1) \times (C_0 \times t) = \frac{\rho}{\rho_i} \quad (4)$$

In each exposure, F_p , C_0 , and t , and thus also R , are independent of the removed active layer thickness of the detector.

Table 1

Comparisons of the number of tracks counted on the bare LR 115 SSNTDs and the corresponding track densities for (A) detectors facing upwards so that dust particles can be deposited on the detector and (B) detectors same as (A) but cleaned with a brush everyday

Exposure	Detector	Number of alpha tracks counted	Track density (10^5 m^{-2})	Removed active layer thickness (μm)	R (10^8 track/m^3)
1 (site 4)	A	560 ± 40	5.95 ± 0.42	6.05 ± 0.14	1.81 ± 0.19
	B	564 ± 40	5.90 ± 0.41	6.16 ± 0.08	1.70 ± 0.19
2 (site 7)	A	745 ± 53	7.91 ± 0.55	6.43 ± 0.10	2.05 ± 0.22
	B	759 ± 54	8.07 ± 0.56	6.52 ± 0.11	2.03 ± 0.22

The removed active layers of the LR 115 SSNTDs are measured by FTIR and the ratios R are given for identification of effects of dust particles on the bare detector.

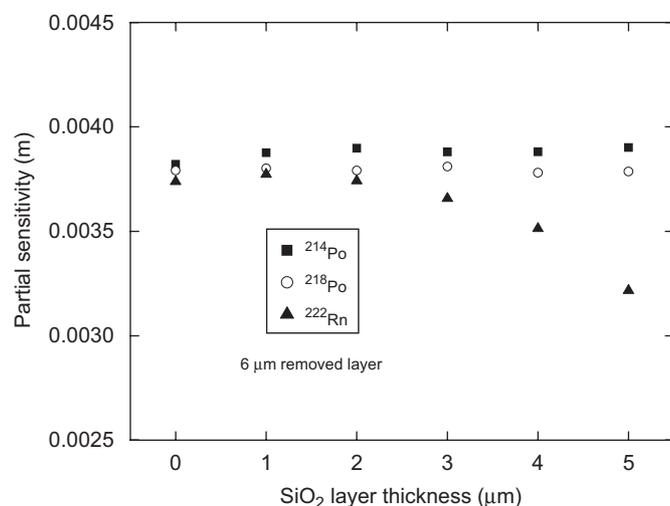


Fig. 4. Computer simulation results on the partial sensitivities to the airborne ^{222}Rn , ^{218}Po , and ^{214}Po for the LR 115 detector covered with a layer of SiO_2 with different thicknesses, for a nominal removed layer of $6 \mu\text{m}$ during the chemical etching of the exposed LR 115 detector.

From Table 1, it can be seen that from exposures at both sites, the two detectors show similar R values. It can thus be concluded that the deposition of dust particles on the bare LR 115 detector will not contribute significant effects. Based on these experimental results, we can therefore ignore the deposition of dust particles on the bare LR 115 detector in the determination of the equilibrium factor F . This finding is particularly important for the success of the proxy equilibrium factor method because it will be otherwise too inconvenient to apply the method.

6.3. Theoretical considerations

To understand why the deposition of dust particles on the bare LR 115 detector will not affect the track densities recorded on the LR 115 detector, we have performed computer simulations on the partial sensitivities to the airborne ^{222}Rn , ^{218}Po , and ^{214}Po for the LR 115 detector covered with a layer of SiO_2 with different thicknesses, for a nominal removed layer of $6 \mu\text{m}$ during the chemical etching of the exposed LR 115 detector. The SiO_2 layer is used to simulate the dust layer. Of course, this serves to illustrate the extreme case, since the majority

of the indoor dust particles are much lighter than SiO_2 and the dust particles have different shapes and will never be fully packed as a layer on top of the LR 115 detector. The simulation results are shown in Fig. 4. From Fig. 4, we can see that even for the heavy SiO_2 layer, the partial sensitivities are equal to one another for a thickness of $2\text{--}3 \mu\text{m}$. Therefore, unless the indoor environment is extremely dusty or consistently has heavy aerosols, the deposition of dust particles on the bare LR 115 detector will not affect the track densities recorded on the LR 115 detector.

7. Mini-survey of long-term measurements of RC, TC, and F in dwellings

In this mini-survey, a total of 11 sites were surveyed using the “twins diffusion chamber” method and the “proxy-equilibrium factor” method. The diffusion chambers employed for the present study were conical, with the inner base radius of 2.35 cm , top radius of 3.35 cm and height of 4.8 cm . In order to differentiate between the contributions from radon and thoron, two diffusion chambers are used, one for mainly recording the signal of radon while the other for (radon+thoron). The difference between the signals recorded by the SSNTDs inside these two diffusion chambers can give the radon and thoron gas concentrations. This technique is known as the “twin diffusion chamber” method (Virk and Sharma, 2000; Barooah et al., 2003; Sreenath Reddy et al., 2004; Leung et al. 2007b, c). At each site, two diffusion chambers were set up: one covered with a filter paper and the other with an optimal thickness of polyethylene (PE) membranes to measure the radon and thoron gas concentrations (Leung et al., 2007c). Polyethylene membrane has been found to be a very appropriate anti-thoron filter (Hafez and Somogyi, 1986) and has been used widely. An LR 115 SSNTD with a size of $3 \times 3 \text{ cm}^2$ was attached to the center of the inner bottom of each diffusion chamber. In addition, one bare mode LR 115 detector, also with a size of $3 \times 3 \text{ cm}^2$, was attached on the outside of the top lid of the diffusion chambers to determine F_p .

We performed two rounds of measurements in the same dwellings but in different seasons. The periods were from mid-September to October 2005 (summer/spring seasons) and from February to mid-March 2006 (winter/autumn seasons). After the desired exposure period (about 1 month in the present study), the diffusion chambers were collected from the

Table 2
The results of the radon and thoron gas concentrations obtained by the “twins diffusion chamber” method and the equilibrium factor F obtained by the “proxy-equilibrium factor” method in round 1 site measurements (from mid-September to October, 2005)

Site	Radon gas concentration (Bq m ⁻³)	Thoron gas concentration (Bq m ⁻³)	F_p	F
1	34.5 ± 3.8	0.00 ± 0.04	0.63	0.13–0.22
2	27.7 ± 3.1	5.12 ± 0.58	1.06	0.32–0.43
3	32.8 ± 3.6	0.59 ± 0.07	1.07	0.33–0.44
4	33.5 ± 3.7	0.09 ± 0.01	1.02	0.30–0.41
5	34.4 ± 3.8	10.5 ± 1.2	1.10	0.35–0.45
6	52.7 ± 5.7	4.13 ± 0.44	1.36	0.51–0.60
7	43.8 ± 4.8	4.15 ± 0.45	1.41	0.55–0.63
8	44.8 ± 4.8	6.05 ± 0.65	1.44	0.57–0.65
9	26.4 ± 3.0	0.00 ± 0.02	1.63	0.72–0.76
10	29.9 ± 3.4	6.91 ± 0.76	1.77	0.83–0.85
11	65.9 ± 7.1	0.26 ± 0.03	1.81	0.86–0.88
Average	38.8	3.44	1.30	0.47–0.56

Table 3
The results of the radon and thoron gas concentrations obtained by the “twins diffusion chamber” method and the equilibrium factor F obtained by the “proxy-equilibrium factor” method in round 2 site measurements (from February to mid-March 2006)

Site	Radon gas concentration (Bq m ⁻³)	Thoron gas concentration (Bq m ⁻³)	F_p	F
1	47.6 ± 5.1	0.00 ± 1.04	0.78	0.19–0.29
2	51.9 ± 5.5	0.00 ± 0.81	1.57	0.67–0.73
3	27.7 ± 3.2	0.47 ± 0.05	1.42	0.55–0.63
4	35.7 ± 4.0	0.00 ± 0.33	0.97	0.27–0.38
5	34.3 ± 3.8	5.27 ± 0.58	1.72	0.78–0.82
6	35.2 ± 3.9	8.97 ± 0.98	0.76	0.18–0.28
7	35.9 ± 4.0	0.90 ± 0.10	1.01	0.30–0.40
8	54.3 ± 5.8	4.02 ± 0.43	1.48	0.60–0.67
9	34.8 ± 3.9	0.00 ± 0.15	1.77	0.83–0.85
10	37.3 ± 4.1	10.2 ± 1.1	1.73	0.80–0.83
11	55.9 ± 6.1	6.50 ± 0.70	1.83	0.89–0.90
Average	41.0	3.30	1.37	0.52–0.60

dwellings and sent back to laboratory for chemical etching and track analysis. The radon and thoron gas concentrations and the equilibrium factor can then be obtained.

Tables 2 and 3 summarize the results of radon (RC) and thoron (TC) gas concentrations obtained using the “twins diffusion chambers” method (closed mode) and the equilibrium factor (F) obtained using the “proxy-equilibrium factor” method (open mode) for round 1 and 2 site measurements, respectively. For round 1 measurements (see Table 2), the radon and thoron gas concentrations were found to range from 26.4 to 65.9 Bq m⁻³ and from 0 to 10.5 Bq m⁻³, respectively. The corresponding average radon and thoron gas concentrations were found to be 38.8 and 3.4 Bq m⁻³, respectively. On the other hand, for round 2 measurements (see Table 3), the radon and thoron gas concentrations were found to range from 27.7 to 55.9 Bq m⁻³ and from 0 to 10.2 Bq m⁻³, respectively. The corresponding average radon and thoron gas concentrations were found to be 41.0 and 3.3 Bq m⁻³, respectively. It can be seen that both the average values of RC and TC for the two rounds of measurements are very close.

The average F values for round 1 and 2 measurements were found to be 0.47–0.56 (see Table 2) and 0.52–0.60 (see Table 3),

respectively. It can be seen that the average equilibrium factor is a little bit higher for round 2 measurements that were made in the winter/autumn seasons. In this season, the weather was drier and the airborne aerosol concentrations were larger, which explained why the average F value was also higher.

The global average radon gas concentration has been found to be 46 Bq m⁻³ (UNSCEAR, 2000). On the other hand, the mean value of indoor radon concentration in Hong Kong was found to be ~ 45 Bq m⁻³ (Yu et al., 1992). This latter value is close to the average value, ~ 40 Bq m⁻³, obtained in the current study. The average thoron gas concentration was found to be 3.4 Bq m⁻³ and the average Tn/Rn value was found to be ~ 8.5%. However, an exceptional case with a ratio of about 25% was also found (see site 10). The average F values for the two rounds of measurements lie in the range of 0.49–0.58, with the mean $F = 0.54$.

In order to estimate the effective dose from radon progeny, the methodology usually adopted in practice is to determine the radon gas concentration and to assume an equilibrium factor between radon and its progeny, typically from 0.4 to 0.5. It is interesting to note that the average F values found in the present survey are commensurate with those assumed by different

Table 4
Summary of the equilibrium factor, average values, and the ranges, reported for different countries (adopted from Ramachandran and Subba Ramu, 1994)

Name of the country	Equilibrium factor F	
	Average value	Range
Germany	0.27	0.25–0.65
Sweden	0.44	0.10–0.80
Canada	0.47	0.30–0.63
Finland	0.50	0.30–0.80
India	0.52	0.19–0.67
Norway	0.52	0.26–0.76
USA	0.54	0.15–0.97

researchers. For example, Oufni et al. (2005) used the assumed value of 0.4 while Marenny et al. (1996) and Mansour et al. (2005) used $F = 0.5$. The need to assume nominal F values is unavoidable if no actual measurements of F can be made.

However, due to the spatial and temporal fluctuations of environmental parameters, such as ventilation, aerosol concentrations, surface deposition, etc., the concentrations of radon and its progeny will vary; therefore, an assumed constant F cannot reflect the actual conditions for many realistic situations. Our experimental data show large variations in F in dwellings, which ranges from 0.18 to 0.89. For a comparison, the F values measured in dwellings in different countries and summarized by Ramachandran and Subba Ramu (1994) are reproduced in Table 4. Large variations in the F values are observed, ranging from 0.10 to 0.97.

From the variations in the F values reported in the literature and in the present study, there is no doubt that the use of an assumed constant F to calculate the effective dose does present a problem. Therefore, the equilibrium factor should be measured at each site, and long-term measurements of F using the proxy-equilibrium factor are suitable for this purpose. To obtain an even more accurate estimation of the effective dose, aerosol-related parameters as well as subject-related parameters are also needed.

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