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Filtration approach to mitigate indoor thoron progeny concentration

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Abstract. This study investigates filtration of air as potential mitigation method of thoron progeny exposure. The experiments were conducted in a model room (volume 7.1 m^3) which was equipped with a pump and an HEPA (high efficiency particulate air) filter. Filtration at a rate of 0.2, 0.4, 0.5 and 0.8 h^{-1} during 88 h proved an effective practice in reducing the total indoor thoron decay product concentration. The results indicate that 0.4–0.8 h^{-1} filtration rate had almost the same filtration efficiency in decreasing the total thoron EEC (equilibrium equivalent concentration) by 97% while 80% of total thoron EEC were reduced by 0.2 h^{-1} filtration rate; meanwhile, the unattached thoron EEC rose significantly by 190, 270, 290%, respectively under 0.4–0.8 h^{-1} filtration rate, whereas 0.2 h^{-1} filtration rate increased unattached thoron EEC by 40%. The aerosol number size distribution variation reveals that filtration operation removes smaller particles faster or earlier than the larger ones. The annual effective dose calculated was reduced by 91–92% at a filtration rate of 0.4–0.8 h^{-1} while 75% reduced at 0.2 h^{-1} filtration rate after 88 h filtration process.

Key words: filtration • thoron progeny • potential alpha energy concentration (PAEC) • equilibrium equivalent concentration (EEC) • mitigation

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Introduction

Enhanced thoron (^{220}Rn) concentrations reported in Chinese traditional clay dwellings [18, 21], Japanese traditional mud houses [3, 6], Italian tuff and pozzolana buildings [16, 17] and some other potential high risk areas [19] have caused some attention. The decay products of thoron, both attached and unattached fractions, have high potential alpha energy per activity which contributes to a distinct inhalation exposure [23]. Increasing reports point out that the ratio of effective dose from thoron and its progeny to that from radon, thoron and their progeny in some cases accounts for 20% [26], 38% [18] and 55% [7]. Thereby, the exploration on controlling the thoron decay products has practical significance.

There are some existing reports about the mitigation of radon and its decay products [2, 8, 10, 14, 25], while scarce literature on the active mitigating of thoron decay products exists. For radon, there are several techniques to minimize the radon concentration, like sub-slab ventilation, foundation drain suction, crawl space ventilation, heat recovery ventilation, sump and sealing, fan-ion generator [1, 4, 9, 12], etc. On the contrary to radon and its progeny, thoron has a very short half-life (56 s), and its most important decay products have longer half-lives (10.6 h, 1 h) compared to the short-lived radon decay products. The consequence is a different activity size distribution in nucleation and accumulation mode of the thoron decay products [5]. The mitigation approach and its effectiveness might therefore differ.

First, the definitions of the PAEC and EEC are given. PAEC of any mixture of short-lived thoron daughters in air is a sum of the potential alpha energy of all thoron short-lived daughter atoms present per unit volume of air. The potential alpha energy of a thoron daughter atom in the decay chain of thoron is the total alpha energy emitted during the decay of this atom to stable nuclide ^{208}Pb. PAEC of any thoron daughter mixture in air can also be expressed in terms of EEC of their mother nuclide thoron. The SI unit for PAEC and EEC is J/m^3 and Bq/m^3, respectively. Both are related as follows: PAEC (J/m^3) = EEC (Bq/m^3) × 75.6 nJ/Bq.

In an attempt to reduce the thoron decay products concentration in terms of PAEC in an effective, practical and long term way, thus, to minimize the inhalation exposure, an alternative method of filtration was adopted and investigated in a thoron model room at Helmholtz Zentrum München. We deployed a pump and an HEPA filter under various air flow rates. PAEC, aerosol particle number concentration and number size distribution were measured simultaneously to evaluate the filtration efficiency. Furthermore, for detailed dose evaluation, attached and unattached thoron progenies were recorded and analyzed during the filtration process. The initial results suggest pump equipping with the HEPA filter at an appropriate air flow rate has high efficiency in control of the exposure and committed dose from thoron decay products.

Materials and methods

To investigate the detailed behaviour of thoron and its decay products under controlled conditions in high thoron area in China, a model room was constructed by simulation, see Fig. 1. A comparison study shows that it is a successful simulation of the original house in Gansu, China [22]. When windows and door closed, the PAEC was about 1–3 μJ·m^{-3} in good agreement with result measured in original house in China. The model room is 2.8 m long, 1.5 m wide and 1.8 m high with curved roof, has a net volume of 7.1m^3 and is built from adobe bricks which were plastered with 4.5 cm thick clay layer homogeneously enriched with powdered granite. The model room represents at the scale 1:2.2 of an above ground cave dwelling in China which was intensely investigated in a field test [23].

HEPA filters are glass or quartz fibrous filters which are designed to filter suspended particles from air with high efficiency. HEPA filter in this study is a kind of cylindrical glove box filter (DKB model, glass fibre) which was manufactured by GEA Delbag Luftfilter GmbH, Germany. It was used to filter the air from the model room under the filtration rate of 0.2, 0.4, 0.5, 0.8 h^{-1}, respectively. Starting conditions were always at high thoron decay products concentration to examine the effectiveness of filtration. Therefore, before each filtration period, the door and two windows of the model room were closed for around four days to let the thoron progenies reach equilibrium, which could be detected by working level monitors, and then the pump was started to filter for 88 h. After stopping filtration, the door and windows were opened completely for 4 h in order to exchange the air with ambient environment, and then they were closed again to wait for new equilibrium for the next filtration.

A time-resolved working level monitor (Tracerlab GmbH, Germany) along with a modified working level monitor were placed on a table inside the model room,

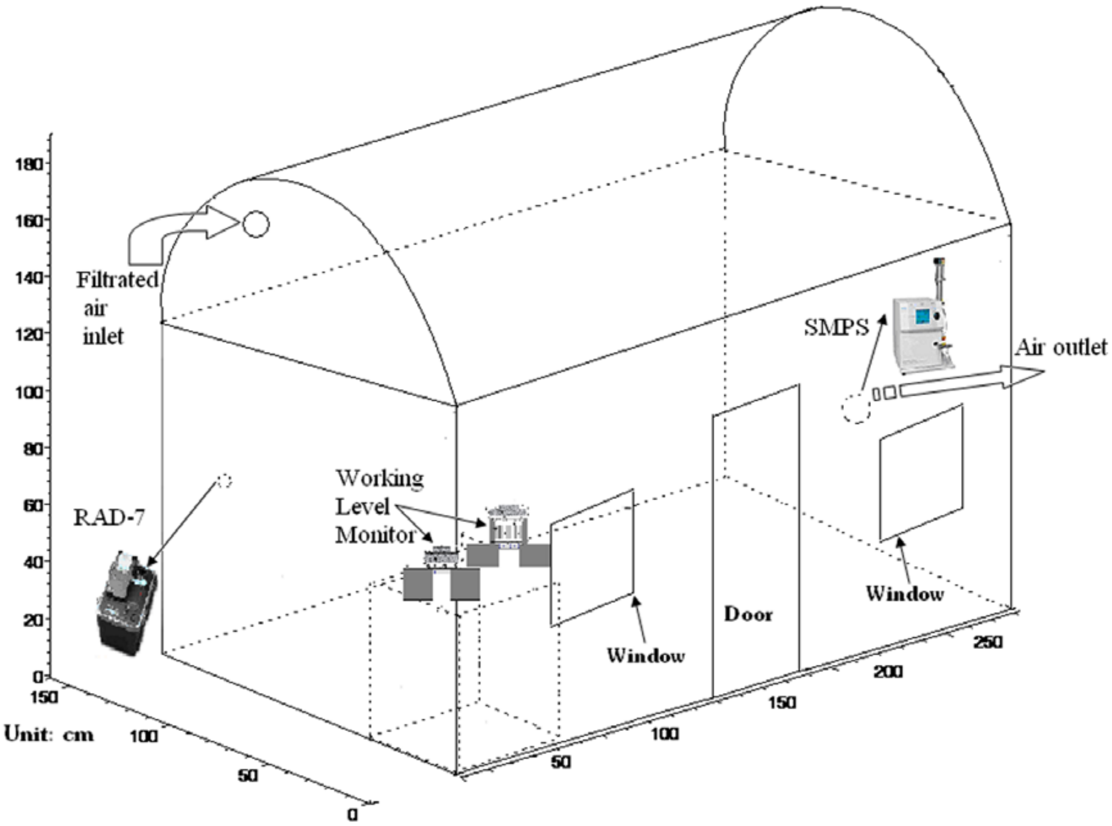

Fig. 1. Schematic display of the experimental design.

working continuously to observe the PAEC of total (attached and unattached thoron progeny) and unattached progeny, respectively. The working principle of these two monitors was illustrated comprehensively by Meisenberg and Tschiersch [15, 21].

Particle size and number concentration were measured by SMPS 3080 (scanning mobility particle sizer, TSI GmbH, Aachen, Germany) with impactor type 0.0508 cm, DMA Model 3081 and CPC 3025A, within the particle size range from 7 to 294 nm. The resolution of the DMA is 64 channels per decade, and the CPC has 50% detection sensitivity at 3 nm and 90% at 5 nm. Sheath flow rate and aerosol flow rate were set to be 10 litres per min (lpm) and 0.3 lpm, respectively. Other relevant parameters: voltage range 10–9647 V, scan time 135 s (up 120 s, retrace 15 s), each sample was scanned 4 times and lasted for 10 min.

Results and discussion

Reduction in total thoron progeny concentration and influence on unattached fraction

The filtration has a strong impact on scavenging the total fraction of thoron progeny. As shown in Fig. 2, 0.4–0.8 h^{-1} filtration rates have almost the same filtration efficiency in decreasing the total thoron EEC by about 94% in 48 h and by 97% in 88 h (the average measurement uncertainty is 8%). For the lower 0.2 h^{-1} filtration rate, filtration brings down the total thoron EEC by 68% in 48 h and by 80% in 88 h (the average measurement uncertainty is 7%). The dynamic evolution of aerosol number concentration (Fig. 3) illustrates its mechanism. Aerosol level declined dramatically by 97, 99 and 100% under varied filtration rate of 0.4, 0.5 and 0.8 h^{-1} respectively after 6 h, removing the airborne particles rapidly to which thoron progeny would attach. This is attributed to HEPA filters' high efficiency of removing particles from the gas stream. In general, HEPA filters can remove at least 99.97% of airborne particles of 0.3 μm in diameter. Particles that are larger or smaller are filtered with even higher efficiency [20]. However, the lower 0.2 h^{-1} filtration rate removing the aerosol particles slowly in spite of equipping with high efficiency filters, which implies that there might exist a minimum air flow rate range to run the HEPA filters with high performance. Furthermore, as shown in Figs. 4 and 5 aerosol particle number size

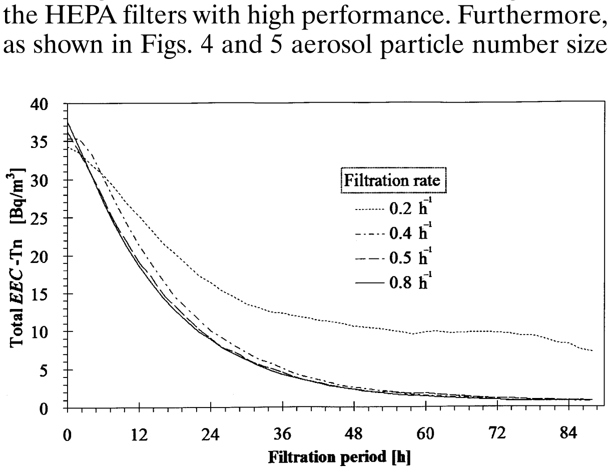

Fig. 2. Graphical illustration of total thoron EEC reduction indicating the effectiveness of filtration.

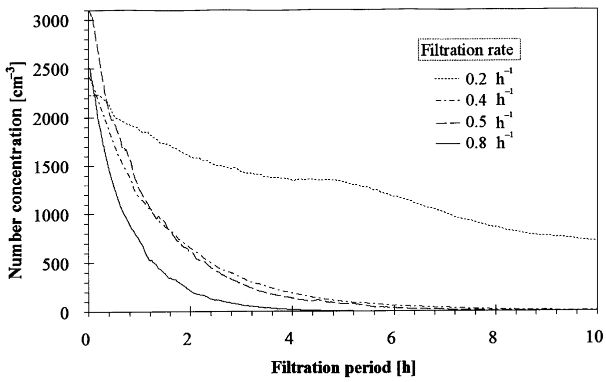

Fig. 3. Aerosol concentration variation with duration of filtration.

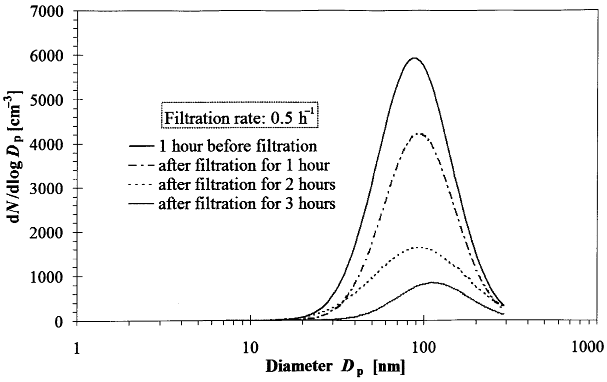

Fig. 4. Aerosol number size distribution ($dN/d\log D_p$) variation with duration of filtration – stage I.

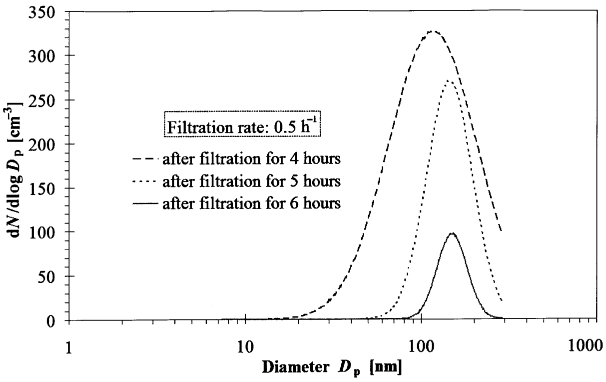

Fig. 5. Aerosol number size distribution ($dN/d\log D_p$) variation with duration of filtration – stage II.

distribution (median diameter and geometric standard deviation (σ_g) are listed in Table 1) in the model room shows that peak diameter shifts from around 88 nm to about 150 nm at a much narrow distribution width after 6 h filtration, which suggests HEPA filtration remove the finer particles faster or earlier than the larger ones.

Consequently, as proved in Figs. 6 and 7 unattached thoron EEC and fraction f_p increase as a result of aerosol removal with the average measurement uncertainty 10 and 16%, respectively. The average unattached fraction f_p of thoron decay products is 0.02, 0.16, 0.14 and 0.16, respectively in 0.2, 0.4, 0.5 and 0.8 h^{-1} filtration rate operation. As displayed in Table 2, the value of unattached fraction of thoron progeny (f_p^{Tn}) is low compared to 0.52 and 0.68 (f_p^{Rn}) in the field test performed by Kranrod *et al.* [11] and Yasuoka *et al.* [24] for radon progeny. The difference may be caused by a large filtration rate

Table 1. Time behavior of median diameter and geometric standard deviation (σ_g) of aerosol number size distribution with continuing filtration at 0.5 h^{-1} filtration rate

Item	1 h before filtration	After filtration					
		for 1 h	for 2 h	for 3 h	for 4 h	for 5 h	for 6 h
Median diameter (nm)	88	94	94	113	116	145	150
σ_g	1.64	1.6	1.84	1.62	1.78	1.35	1.22

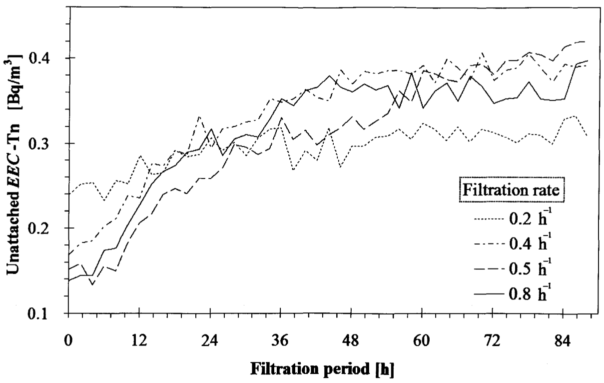

Fig. 6. Unattached thoron EEC went up and finally leveled in the duration of filtration.

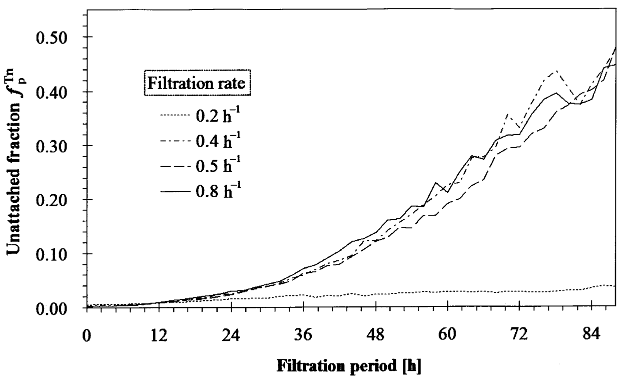

Fig. 7. Unattached fraction of thoron progeny (f_p^{Tn}) rose with duration of filtration.

disparity: 5.4 and 4 h^{-1} were adopted in their filtration process. Our study also indicates that except the 0.2 h^{-1} filtration rate, the other three different filtration rates have no significant difference in enhancing the unattached fraction of thoron decay products within the uncertainty range.

Estimation of effective dose

Owing to the fact that filtration process increases the unattached thoron progeny, which contributes larger to dose per activity than the attached fraction, the simultaneous calculation and assessment of effective doses from attached and unattached thoron progeny during filtration operation are important. The effective dose to the lung and respiratory tract is calculated by the following equation:

$$(1) \qquad E = \alpha \cdot t \cdot \sum_{i=\text{nuclide}} \mathrm{DC}_i \cdot \mathrm{PAEC}_i$$

where E refers to the effective dose; α is the breathing rate; t is the duration of exposure; DC_i is the dose coefficient for unattached or attached nuclide i and PAEC_i is the potential alpha energy concentration of nuclide i.

In the present calculation, only ^{212}Pb and ^{212}Bi were taken into account due to their significance to inhalation dose contribution, while the thoron itself and its progenies ^{216}Po, ^{212}Po and ^{208}Tl were not included because of their negligible contribution to the PAEC. Hence, the above equation is specified as:

$$(2) \quad E = \alpha \cdot t \cdot (\mathrm{DC}^{att}_{^{212}\mathrm{Pb}} \cdot \mathrm{PAEC}^{att}_{^{212}\mathrm{Pb}} + \mathrm{DC}^{una}_{^{212}\mathrm{Pb}} \cdot \mathrm{PAEC}^{una}_{^{212}\mathrm{Pb}} + \mathrm{DC}^{att}_{^{212}\mathrm{Bi}} \cdot \mathrm{PAEC}^{att}_{^{212}\mathrm{Bi}} + \mathrm{DC}^{una}_{^{212}\mathrm{Bi}} \cdot \mathrm{PAEC}^{una}_{^{212}\mathrm{Bi}})$$
$$\approx \alpha \cdot t \cdot \begin{bmatrix} {}^{P}W_{^{212}\mathrm{Pb}} (\mathrm{DC}^{att}_{^{212}\mathrm{Pb}} \cdot \mathrm{PAEC}^{att}_{tot} + \mathrm{DC}^{una}_{^{212}\mathrm{Pb}} \cdot \mathrm{PAEC}^{una}_{tot}) \\ + {}^{P}W_{^{212}\mathrm{Bi}} (\mathrm{DC}^{att}_{^{212}\mathrm{Bi}} \cdot \mathrm{PAEC}^{att}_{tot} + \mathrm{DC}^{una}_{^{212}\mathrm{Bi}} \cdot \mathrm{PAEC}^{una}_{tot}) \end{bmatrix}$$

where ${}^{P}W_{212_{Pb}}$ and ${}^{P}W_{212_{Bi}}$ are the weighting factor of contribution to PAEC for ^{212}Pb and ^{212}Bi (their values are 0.913 and 0.087, respectively); $\mathrm{DC}^{att}_{212_{Pb}}$ and $\mathrm{DC}^{una}_{212_{Pb}}$ are the dose coefficients of attached and unattached ^{212}Pb; $\mathrm{PAEC}^{att}_{tot}$ and $\mathrm{PAEC}^{una}_{tot}$ are the total attached progeny and total unattached progeny of potential alpha energy concentration measured, respectively; $\mathrm{DC}^{att}_{212_{Bi}}$ and $\mathrm{DC}^{una}_{212_{Bi}}$ are the dose coefficients of attached and unattached ^{212}Bi.

Based on the modeling by Li [13], the dose coefficient of unattached ^{212}Pb is 10 Sv/J, attached ^{212}Pb

Table 2. Comparison of the dose reduction by thoron progeny filtration (this study) with radon progeny mitigation; f_p^{Rn} refers to the unattached fraction of radon progeny, for this study f_p^{Tn} (the unattached fraction of thoron progeny) is given

Type	Room volume (m^3)	Flow rate (m^3/h)	Device and material	Filtration period (h)	f_p^{Rn} (f_p^{Tn} only this study)	Filtration rate (h^{-1})	Dose mitigation (%)
Yasuoka *et al.* [23]	30	120	air cleaner + HEPA filter	22	0.68	4.0	31
Kranrod *et al.* [11]	72	390	air cleaner + HEPA filter + carbon filter	24	0.52	5.4	50
This study	7.1	1.5	pump + HEPA filter	88	0.02	0.2	75
		2.8			0.16	0.4	91
		3.6			0.14	0.5	91
		5.8			0.16	0.8	92

1.3 Sv/J and unattached ^{212}Bi 26 Sv/J, attached ^{212}Bi 3.3 Sv/J, which assumes the activity median thermodynamic diameter (AMTD) of unattached ^{212}Pb and ^{212}Bi to be 1.5 nm, activity median aerodynamic diameter (AMAD) of 300 nm for attached ^{212}Pb and ^{212}Bi; here we suppose 8 h per day spent in such building, then $t = 8\text{ h} \times 365 = 2920\text{ h}$, taking average breathing rate 0.78 m^3/h into account, then the effective dose computed were listed in Table 3 with distinguished calculation of attached, unattached and total annual effective dose.

As seen in the table, the dose from unattached thoron progeny increases by a factor of 3.5 (from 0.2 to 0.7 mSv), while the dose from attached thoron progeny significantly decreases by a factor of 90 (from around 9 to 0.1 mSv) for 0.4–0.8 h^{-1} filtration rate in 88 h. For the lower filtration rate 0.2 h^{-1}, the dose from unattached thoron progeny increases by a factor of 1.25 compared to that from attached fraction decreasing by a factor of 4.8. From the table we could also easily calculate the mitigation of total annual effective dose: 65% reduced in 48 h and 75% reduced in 88 h by 0.2 h^{-1} filtration rate, 87–89% reduced in 48 h and 91–92% reduced in 88 h by 0.4–0.8h^{-1} filtration rate.

Table 3. Annual effective dose mitigation by different filtration rate. E_{att}, E_{una}, E_{tot} stand for annual effective dose of attached, unattached and total thoron progeny, respectively

Filtration length (h)	0.2 h^{-1}			0.4 h^{-1}			0.5 h^{-1}			0.8 h^{-1}		
	E_{att} (mSv)	E_{una} (mSv)	E_{tot} (mSv)	E_{att} (mSv)	E_{una} (mSv)	E_{tot} (mSv)	E_{att} (mSv)	E_{una} (mSv)	E_{tot} (mSv)	E_{att} (mSv)	E_{una} (mSv)	E_{tot} (mSv)
0	8.6	0.4	9.0	8.9	0.2	9.2	9.2	0.2	9.4	9.5	0.2	9.7
2	8.4	0.4	8.8	8.9	0.3	9.2	8.5	0.2	8.7	8.6	0.2	8.8
4	8.0	0.4	8.4	8.4	0.3	8.7	7.7	0.2	7.9	7.7	0.2	7.9
6	7.7	0.4	8.1	7.6	0.3	7.9	7.0	0.2	7.2	6.9	0.2	7.1
8	7.3	0.4	7.7	6.8	0.3	7.2	6.2	0.2	6.3	6.0	0.2	6.3
10	6.8	0.4	7.2	6.1	0.4	6.5	5.5	0.3	5.8	5.3	0.3	5.6
12	6.3	0.5	6.8	5.4	0.4	5.7	4.8	0.3	5.1	4.7	0.3	5.0
14	5.9	0.4	6.3	4.7	0.4	5.2	4.3	0.3	4.6	4.1	0.4	4.5
16	5.4	0.4	5.8	4.2	0.4	4.6	3.7	0.4	4.1	3.6	0.4	4.0
18	5.1	0.5	5.5	3.6	0.5	4.1	3.3	0.4	3.7	3.2	0.4	3.6
20	4.7	0.5	5.2	3.2	0.5	3.7	2.9	0.4	3.3	2.8	0.5	3.3
22	4.3	0.5	4.8	2.8	0.6	3.4	2.5	0.4	2.9	2.4	0.5	2.9
24	4.1	0.5	4.6	2.5	0.5	3.0	2.2	0.4	2.6	2.2	0.5	2.7
26	3.8	0.5	4.3	2.2	0.5	2.7	1.9	0.4	2.4	1.9	0.5	2.4
28	3.6	0.5	4.1	2.0	0.5	2.5	1.8	0.5	2.2	1.7	0.5	2.2
30	3.4	0.5	3.8	1.7	0.5	2.3	1.5	0.5	2.0	1.5	0.5	2.0
32	3.3	0.5	3.8	1.5	0.5	2.1	1.4	0.5	1.8	1.3	0.5	1.8
34	3.1	0.5	3.6	1.4	0.6	2.0	1.2	0.5	1.7	1.1	0.5	1.7
36	3.1	0.5	3.6	1.2	0.6	1.8	1.1	0.6	1.6	1.0	0.6	1.6
38	3.0	0.4	3.4	1.0	0.6	1.6	0.9	0.5	1.4	0.9	0.6	1.5
40	2.9	0.5	3.4	0.9	0.6	1.5	0.8	0.5	1.3	0.8	0.6	1.4
42	2.8	0.5	3.3	0.8	0.6	1.4	0.7	0.5	1.2	0.7	0.6	1.3
44	2.8	0.5	3.3	0.7	0.6	1.3	0.6	0.5	1.2	0.6	0.6	1.3
46	2.7	0.4	3.1	0.6	0.7	1.3	0.6	0.5	1.1	0.6	0.6	1.2
48	2.6	0.5	3.1	0.6	0.6	1.2	0.5	0.6	1.1	0.5	0.6	1.1
50	2.6	0.5	3.1	0.5	0.7	1.2	0.5	0.5	1.0	0.4	0.6	1.1
52	2.5	0.5	3.0	0.5	0.7	1.1	0.4	0.5	1.0	0.4	0.6	1.0
54	2.5	0.5	3.0	0.4	0.7	1.1	0.4	0.6	1.0	0.4	0.6	1.0
56	2.4	0.5	2.9	0.4	0.7	1.0	0.4	0.6	1.0	0.3	0.6	0.9
58	2.3	0.5	2.8	0.3	0.7	1.0	0.4	0.6	1.0	0.3	0.7	0.9
60	2.4	0.5	3.0	0.3	0.7	1.0	0.4	0.7	1.0	0.3	0.6	0.9
62	2.4	0.5	3.0	0.3	0.6	0.9	0.3	0.7	1.0	0.2	0.6	0.9
64	2.4	0.5	2.9	0.2	0.7	0.9	0.3	0.6	0.9	0.2	0.6	0.8
66	2.4	0.5	2.9	0.2	0.7	0.9	0.3	0.6	0.9	0.2	0.6	0.8
68	2.4	0.5	2.9	0.2	0.6	0.8	0.2	0.7	0.9	0.2	0.6	0.8
70	2.4	0.5	3.0	0.2	0.7	0.9	0.2	0.7	0.9	0.2	0.6	0.8
72	2.4	0.5	2.9	0.2	0.6	0.8	0.2	0.6	0.8	0.2	0.6	0.7
74	2.4	0.5	2.9	0.1	0.7	0.8	0.2	0.7	0.9	0.1	0.6	0.7
76	2.3	0.5	2.8	0.1	0.7	0.8	0.2	0.7	0.9	0.1	0.6	0.7
78	2.3	0.5	2.8	0.1	0.7	0.8	0.2	0.7	0.9	0.1	0.6	0.8
80	2.2	0.5	2.7	0.1	0.7	0.8	0.2	0.7	0.8	0.1	0.6	0.7
82	2.1	0.5	2.6	0.1	0.6	0.8	0.1	0.7	0.8	0.1	0.6	0.7
84	2.0	0.5	2.6	0.1	0.7	0.8	0.1	0.7	0.9	0.1	0.6	0.7
86	1.8	0.6	2.4	0.1	0.7	0.8	0.1	0.7	0.9	0.1	0.7	0.8
88	1.8	0.5	2.3	0.1	0.7	0.8	0.1	0.7	0.8	0.1	0.7	0.8

Conclusion

Cleaning the indoor air by pumping it through the HEPA filter proved successful to mitigate the effective dose of indoor thoron progeny. All investigated different filtration efficiencies have a promising effect on reducing the total thoron EEC and annual committed effective dose. However, on one hand, in the filtration rate range of 0.4–0.8 h^{-1}, there is no significant difference in decreasing the total thoron EEC (all around by 97%) and committed dose (all in the range 91–92%), while 0.2 h^{-1} filtration rate gets rid of 80% total thoron EEC and 75% committed dose despite removing aerosol concentration slowly. Additionally, aerosol number size distribution makes it clear that the pump with the HEPA filter captures small size particles faster or earlier than the larger ones. On the other hand, filtration process generally increases the unattached fraction, that is, higher unattached fraction results from higher filtration rate. Nevertheless, the dose from increased unattached thoron progeny is small compared to the dose mitigation of attached thoron progeny and total thoron progeny. Therefore, it indicates that equal or larger than 0.4 h^{-1} is the minimum and reasonable filtration rate towards mitigating the indoor thoron progeny concentration as well as the inhalation exposure and related dose.

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