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Air Filtration and Radon Decay Product Mitigation

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Abstract

Air cleaning as a means of mitigating the risks arising from exposure to indoor radon progeny has been evaluated in a single-family house in the north eastern U.S. using an automated, semi-continuous activity-weighted size distribution measurement system. The measurements included radon concentration, condensation nuclei count, and activity-weighted size distribution of radon decay products. Measurements were made in the house with and without an operating air filtration system and with various particle sources common to normal indoor activities operating. Aerosols were generated by running water in a shower, candle burning, cigarette smoking, vacuuming, opening doors, and cooking. Using a room model, the changes in attachment rates, average attachment diameters, and deposition rates of the unattached fraction with and without the air cleaning system were calculated. In the presence of active aerosol sources, the air filtration unit typically reduced the concentration of particles within the hour following the end of particle generation. After candle burning, cigarette smoking, and vacuuming in the bedroom, the reductions of PAEC by air filtration are about 60% with the air filtration system operating in the bedroom. During cooking in the kitchen, the reductions of PAEC in the bedroom with the air filtration system were about 40%. However, for all cases the dose reductions were smaller than the particle and PAEC reductions. For those particles that were generated within the bedroom, there was a 20% to 50% reduction in dose. In the case of cooking where the door was open and particles infiltrated from the rest of the house, the dose reduction was only 5% on average and appears to be insignificant. Thus, the dose reductions were lower than the reductions in activity concentration, but there were no cases where the estimated dose actually increased.

KEY WORDS:
Air filtration system, Radon decay products, Activity-weighted size distribution, Potential alpha energy concentration, Indoor aerosols, Radiation dose reduction.

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Introduction

The inhalation and lung deposition of the radon progeny produce adverse health effects. The U.S. Environmental Protection Agency estimated 20,000 deaths annually from radon-induced lung cancer (Puskin and Nelson, 1989). A dosimetric analysis of homes and mines has recently suggested that the dose in homes is slightly less than that to active underground miners (NRC/NAS, 1991) but the radon progeny still represent a significant health risk. It is thus necessary to control exposure to the radon progeny in order to lower the risk arising from indoor radon. Controlling radon progeny in the air space of houses may be divided into three principal categories: (1) preventing radon infiltration (basement pressurization, basement sealing, sub-slab depressurization, choice of building materials); (2) diluting the radon and radon progeny within the house (air-to-air heat exchanger, ventilation); and (3) using air cleaning systems for direct removal (filtration, mixing fan, electric field methods, radon adsorption, and ion generator). The use of various methods to reduce infiltration or to lower the concentrations through increased ventilation have been under active study for several years. These systems can often be the most effective in reducing exposure, but until decisions have been made regarding the need for and nature of long-term solutions, interim measures for lowering exposure, e.g. air cleaning, are needed. Because of the studies of Rudnick et al. (1983) suggesting that air cleaning systems may increase risk in some situations, the EPA (1986) has not endorsed the use of air cleaners as a method of reducing radon decay products in indoor air.

There have been a number of previous evaluations of air cleaning systems undertaken in test chambers or in actual indoor environments, and a review of these earlier studies has recently been compiled (Hopke et al., 1990). It demonstrated that air cleaning systems can effectively remove radon decay products from indoor air, although the reduction of ^{218}Po is not as great as that of ^{214}Pb and ^{214}Bi. At the same time, the particles are removed from the air. As a result, the unattached fraction of air-

borne activity increases, especially for ^{218}Po. Since the unattached fractions of the radon progeny are considered to be more effective in depositing their radiation dose to the lung tissue, concern has been expressed regarding the efficacy of air cleaning as a means of mitigating the hazards arising from indoor radon.

The main problem in the previous studies is that the systems used to measure the radon progeny were not able to determine their full size distribution, especially in the range less than 10 nm. Estimates of the unattached fractions were made using measurement systems that provide a poorly defined size segregation (Ramamurthi and Hopke, 1989). In many cases, the progeny size measurement methods and results are not clearly stated. Therefore, further research is needed to measure the concentration and the size distribution of the radon progeny activities when air cleaning devices are employed.

In this study, the evaluations of an air filtration system were performed in a single-family house in Princeton, NJ. In a previous paper (Li and Hopke, 1991), we reported the influence of a series of particle generation processes on the exposure and dose resulting from the presence of the radon decay products. In the study reported here, the same procedures are used to evaluate the effect of an air filtration unit operating during the period when particles were actively being generated. The influence on the concentration and size distribution of radon progeny with and without the air cleaner in the presence of various active particle sources was evaluated. Using a simple room model (Jacobi, 1972; Porstendörfer et al., 1978), the changes in various parameters describing the behavior of the radon progeny were calculated for the conditions with and without the air filtration system, in the same manner as in the previous study (Li and Hopke, 1991). The dose to the cells of the bronchial epithelium were also calculated for each size distribution for two different breathing rates and for two different types of cells.

Air Filtration System

The air filtration system used in this work was called a Pureflow Air Treatment System manufactured by the Amway Corporation, Ada, Michigan. It is a multi-stage filtering system containing a total of five separate filters: (1) a flexible, foam pre-filter which traps hair, lint, and large dust particles; (2&3) two activated carbon filters that contain two pounds each of proprietary blends of a variety of specially treated activated carbons, supported uniformly in honeycomb beds, covered with white filter media and encased in a high quality aluminum frame; (4) a final carbon filter which is composed of activated carbon bonded to a non-woven substrate; and (5) a high efficiency particulate air (HEPA) filter that is designed to maximize filter efficiency, eliminate leaks and reduce the possibility of breakage. This HEPA filter contains the same filtering material used in many hospital surgical suite air filtration systems and industrial "clean rooms". The pre-filter and activated carbon filters are installed at the back of the system. A third carbon filter and the HEPA filter are placed in front of the air filtration system. The air flows from the back to the front through the filters and the fan. The system's microcomputer allows the programing of up to four different sets of ON-OFF times and fan speeds for automatic operation. There are four fan speeds, 1.13, 2.26, 3.40, and 4.25 m^3 min^{-1}. According to the manufacturer, the air filtration system gives maximum particle removal efficiency when operating at the highest speed (4.25 m^{-3} min^{-1}). This highest speed was used for all of the experiments.

Measurement System for Radon Progeny Size Measurements

The measurement system uses sampler/detector units incorporating wire screen and surface barrier detectors to determine the activity size distributions (Ramamurthi and Hopke, 1991). The use of this system for these measurements was described by Li and Hopke (1991). The PC-based analysis system allows the determination of the concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi (or ^{214}Po) that penetrate to the filter in each sampler-detector unit using α spectroscopy. Given knowledge of the penetration characteristics and the measured detection efficiency of each sampler, the activity size distributions can then be calculated from the observed activities and for the Potential Alpha Energy Concentration (PAEC) in six size intervals covering a particle size range of 0.5 to 500 nm (Ramamurthi and Hopke, 1991). The unattached fraction is defined in this study as the activity in the 0.5 to 1.6 nm region of the measured activity size distributions. These measured quantities and the uniformly mixed room model (Postendörfer et al., 1978) were used to estimate the values of parameters relating to the rate of attachment of the radon progeny to the airborne particles, the deposition rate

of that activity that remained uncombined with the particles, and the average size of the particles to which the activity had become attached. The details of these calculations are given by Porstendörfer (1984), Reineking et al. (1985), and Porstendörfer et al. (1987). The size dependent rates for the attachment for the radon progeny to particles was taken from Porstendörfer et al. (1979).

Dosimetric Calculations

The alpha radiation dose to the bronchial epithelium has been calculated using the model developed for the recent report of the National Research Council (1991). In this model, the average dose (mGy) per unit exposure to PAEC (in WL) has been calculated for both basal and secretory cells of generations 0 to 8 of the tracheobronchial tree at several breathing rates. A plot of dose conversion coefficients as a function of particle size, cell type, and breathing rate were given by Li and Hopke (1991). The lower breathing rate for each cell is 0.45 m^3hr^{-1} (B_l, S_l), while the highest likely breathing rate (B_h, S_h) is 1.5 m^3hr^{-1}.

The hourly dose rate per Bq m^{-3} radon can be estimated from these dose conversion coefficients and the measured size distributions as follows. The PAEC in each size range can be obtained from the measured total PAEC and the PAEC fractional size distribution. The PAEC in each size interval is multiplied by the dose conversion factor determined at the mid-point of every size interval, providing estimates of the dose in every size interval. Summing these doses over all six size intervals and dividing by 170 hours (a working month) and the radon concentration, the hourly dose rate per Bq m^{-3} radon can be calculated.

Results of Field Sampling in Princeton, NJ

The measurements were made in collaboration with the Center for Energy and Environmental Studies (CEES) at Princeton University. Houses have been identified and instrumented for continuous measurement of radon and physical parameters including basement, bedroom, and subslab radon concentrations, pressure differences across the basement/outside south interfaces, basement/subslab, basement/upstairs, and basement/outside east interface, temperatures in basement, upstairs, outside, and soil. House 21 was a one-story residence with a living room, a dining room, a kitchen, two bedrooms, a study, two bathrooms, and a basement. A floor plan for this house was given by Li and Hopke (1991). Activity size distributions were also measured in the living room and the master bedroom over a two-week period. A total of about 10 measurements were made in the living room and more than 100 measurements in the bedroom. The particle concentrations were measured by using a Gardner manual condensation nucleus counter. This device has an effective minimum detection limit of 1000 cm^{-3}. The concentration and size distribution of radon progeny were determined using a 75-minute total interval to maximize the number of distributions measured on the evolving aerosol.

The evaluation of the air filtration system was made by operating different types of particle generation with and without the air cleaner operating. Particles were generated by running a shower, burning a candle, allowing a cigarette to smolder in an ashtray, vacuuming (electric motor), opening the room door, and cooking. In each case, the particles were generated for a period of 20 minutes. Five minutes into the particle generation period, a 15-minute sampling interval with alpha counting was initiated so that the particle generation and the sample intervals terminated at the same time. After a 20-minute decay time, a second count of 40 minutes was obtained before starting the next sampling/counting cycle. A third sample was obtained beginning at 135 minutes after the end of the particle generation period so that the evolution of the airborne activity over time could be evaluated. Two separate experiments were performed for each particle generation activity. The activity size distributions produced by these various aerosol sources when the air cleaner was not operating and the resulting calculated bronchial dose have been represented by Li and Hopke (1991).

Background Conditions

Door Closed

The air cleaning studies were performed in the master bedroom which adjoined one of the bathrooms. The infiltration rate had been measured by CEES group to be around 0.3 hr^{-1} with the interior doors open and all the windows in the house closed. Therefore, the ventilation rate was assumed to be 0.2 hr^{-1} with the bedroom door closed. Figure 1 shows the average size distribution obtained from three activity size distributions measured for each of the radon progeny and PAEC under background

conditions of the bedroom door shut and after the air filtration system had been running for at least 2 hours. The results of the measurements, room model, and dosimetric model calculations are presented in Table 1. This table presents the measured ^{222}Rn concentration (Bq m^{-3}), C_0, the measured condensation nuclei concentration (10^3 cm^{-3}), Z, the unattached fraction of ^{218}Po, f_1, the unattached fraction of PAEC, f_p, and the equilibrium factor, F. Calculated values are the average attachment rate, X, the attachment average diameter, d, the deposition rate for the unattached progeny, $q^{(u)}$, and the dose to basal and secretory cells at low (l) and high (h) breathing rates.

With the bedroom door closed and the air filtration system off, the background conditions of the bedroom are: (1) the particle concentration was about 2,500 to 3,000 cm^{-3}; (2) the unattached fraction of ^{218}Po was between 0.5 and 0.7; (3) the unattached fraction of PAEC was between 0.2 and 0.4;

Table 1 Measurement, room, and dose model results for the closed door experiments with the air cleaner operating.

C_0 (Bq/m^3)	Z ($10^3 cm^{-3}$)	f_1	f_p	F	PAEC (mWL)	X (hr^{-1})	d (nm)	$q^{(u)}$ (hr^{-1})	Dose ($\mu Gyhr^{-1}/Bqm^{-3}$) Basal (l, h)	Secretory(l, h)
477	1.8	0.931	0.500	0.14	18.1	1.0	30	19	3.5, 10.6	7.5, 23.2
(cleaner on for 4.0 hours)										
382	1.8	0.933	0.621	0.164	16.9	1.0	30	11	3.9, 13.1	8.5, 28.6
(cleaner on for 5.5 hours)										
429	1.0	0.967	0.835	0.136	15.7	0.46	26	7.5	3.9, 13.8	8.6, 30.5
(cleaner on for 4.0 hours)										
444	1.0	0.967	0.825	0.132	15.8	0.46	26	9.99	3.7, 13.3	8.3, 29.3
(cleaner on for 6.0 hours)										
408	1.0	0.934	0.754	0.134	14.8	0.96	36	11.9	3.7, 12.7	8.0, 27.9
(cleaner on for 8.0 hours)										
777	1.0	0.933	0.681	0.163	34.2	0.97	36	7.6	4.1, 14.1	9.0, 31.0
(cleaner running for 4 hours, background)										
323	1.8	0.967	0.801	0.158	13.8	0.40	18	9.4	4.5, 15,7	9.8, 34.4
(cleaner on for 6 hours)										
300	1.8	0.967	0.777	0.164	13.3	0.40	20	8.9	4.4, 15.7	9.8, 34.5
(cleaner on for 7.5 hours)										
302	1.0	0.934	0.712	0.103	8.4	0.96	36	16.6	2.8, 9.6	6.2, 21.1
(cleaner on overnight)										
520	1.0	1.000	0.841	0.113	15.9	0.00	10	12.9	3.2,11.5	7.1, 25.4
(cleaner on for 0.4 hours)										
416	1.8	0.967	0.803	0.147	16.5	0.46	19	8.5	4.8, 15.7	10.4, 34.3
(cleaner on for 4.0 hours)										

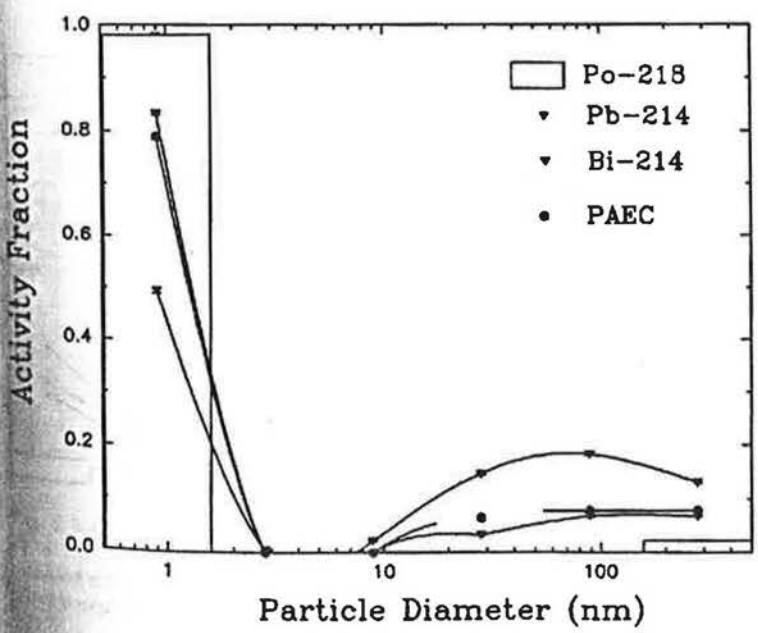


Fig. 1 Average activity size distributions measured in the bedroom with the closed door and the air filtration system operating.

(4) the equilibrium factor was in the range of 0.3 to 0.5; (5) the attachment rate was between 6 and 14 hr^{-1}; (6) the average attachment diameter was about 50 to 90 nm; and (7) the deposition rate of the unattached fraction was around 4 to 12 hr^{-1}. With the air filtration operating, more than 95% of ^{218}Po was in the 0.5 to 1.6 nm size range. The fractions of ^{214}Pb and ^{214}Bi in the 0.9 nm size range were about 80% and 50%, respectively. These results showed that the air filtration system effectively removed most of the particles in the bedroom. There was an insignificant fraction of the three distributions in the 1.6 to 16 nm size range. The values of PAEC and dose per unit radon are shown in Figure 2. The average PAEC reduction was about 60% while the reduction in dose was 31%.

Bedroom Door Open

When the bedroom door was open and the air filtration system operating, the particle concentration was reduced to 6,000–7,000 cm^{-3} from approximately 10,000 cm^{-3}. Average activity size distributions for a series of measurements are shown in Figure 3. The unattached fraction of ^{218} Po was still high (90%), but slightly lower than when the bedroom door was closed and the air filtration system operating. This result is due to the higher ventilation rate under these conditions. Particles continued to enter the bedroom as the air filtration system created additional air circulation. Thus, radon decay products became attached to particles with the bedroom door open. The unattached fraction of ^{218}Po and PAEC were between 0.87 and 0.93 and ranged from 0.58 to 0.63, respectively. The fraction of ^{214}Pb and ^{214}Bi in the 0.9 nm size range was about 25% and 18%, respectively. No ^{218}Po activity was observed in the 1.5-5 nm size range but 30% of the ^{214}Pb and ^{214}Bi was observed. The results of the measurements, room model, and dosimetric model calculations are shown in Table 2.

Since there were no active particle sources operating, it is assumed that the particles in this size range were probably the result of leakage from the oil-fired forced air furnace. The emittance of particles of a similar size had previously been observed from a leaking furnace in a house in Springfield, PA (Li, 1990). These particles were observed in a number of the measured size distributions. The variation in the particle concentration and size distributions that occurs when the door is open is presumed to be responsible for the much greater variability in the measured and inferred quantities. In summary, a bimodal size distribution was observed for all three

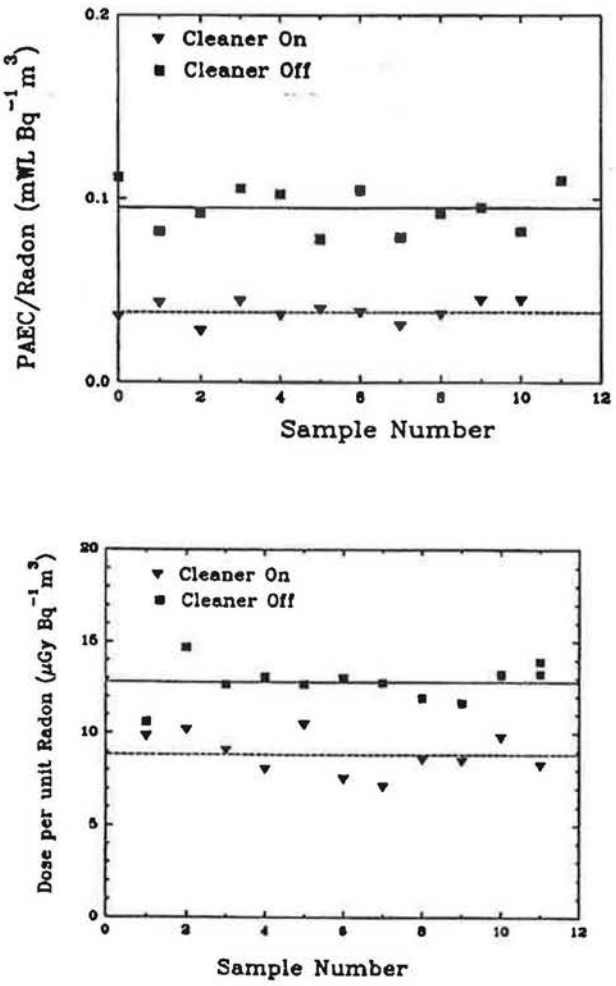


Fig. 2 Top: PAEC per unit radon for the series of samples taken in the bedroom with the door closed.
Bottom: Dose per unit radon concentration for the series of samples taken in the bedroom with the door closed.

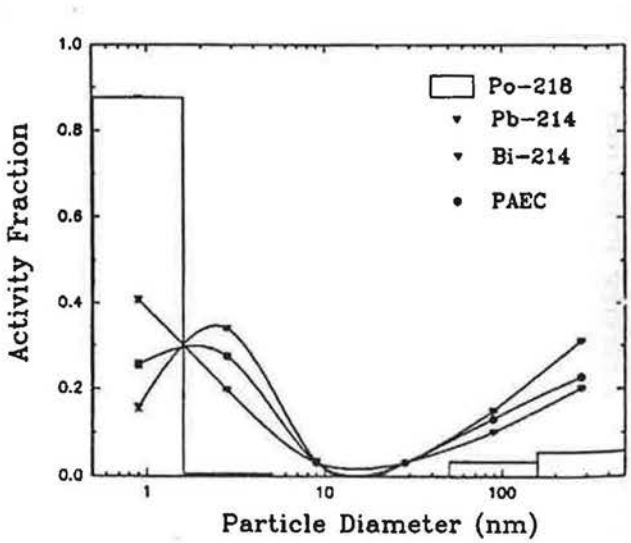


Fig. 3 Average activity size distributions measured in the bedroom with the door open and the air filtration system operating.

Table 2 Measurement, room, and dose model results for the open door experiments with the air cleaner operating.

C_0 (Bq/m^3)	Z (10^3cm^{-3})	f_i	f_p	F	PAEC (mWL)	X (hr^{-1})	d (nm)	$q^{(u)}$ (hr^{-1})	Dose (μGyhr^{-1}/Bqm^{-3}) Basal (l, h)	Secretory(l, h)
870	7.0	0.833	0.323	0.370	76.0	2.1	21	6.0	9.0, 26.2	19.7, 57.3
(cleaner on for 6.0 hours)										
1544	6.0	0.828	0.416	0.235	98.0	1.0	17	9.2	7.0, 20.5	15.2, 44.9
(cleaner on for 2.0 hours)										
994	6.0	0.897	0.415	0.227	61.0	1.5	19	7.7	7.1,20.9	15.6, 45.7
(cleaner on for 3.5 hours)										
713	6.0	0.897	0.473	0.228	44.0	1.5	19	8.8	7.0, 21.0	15.3, 46.0
(cleaner on for 7.0 hours)										
436	8.0	0.678	0.321	0.189	22.3	5.9	33	29.3	4.4, 11.6	9.3, 25.0
(cleaner on for 2.0 hours)										
472	8.0	0.722	0.331	0.216	27.6	4.8	31	19.5	5.2, 13.9	11.1, 29.9
(Cleaner on for 3.5 hours)										
513	7.5	0.707	0.309	0.201	27.9	5.3	33	28.0	4.4, 11.7	9.4, 25.2
(cleaner on for 7.0 hours)										

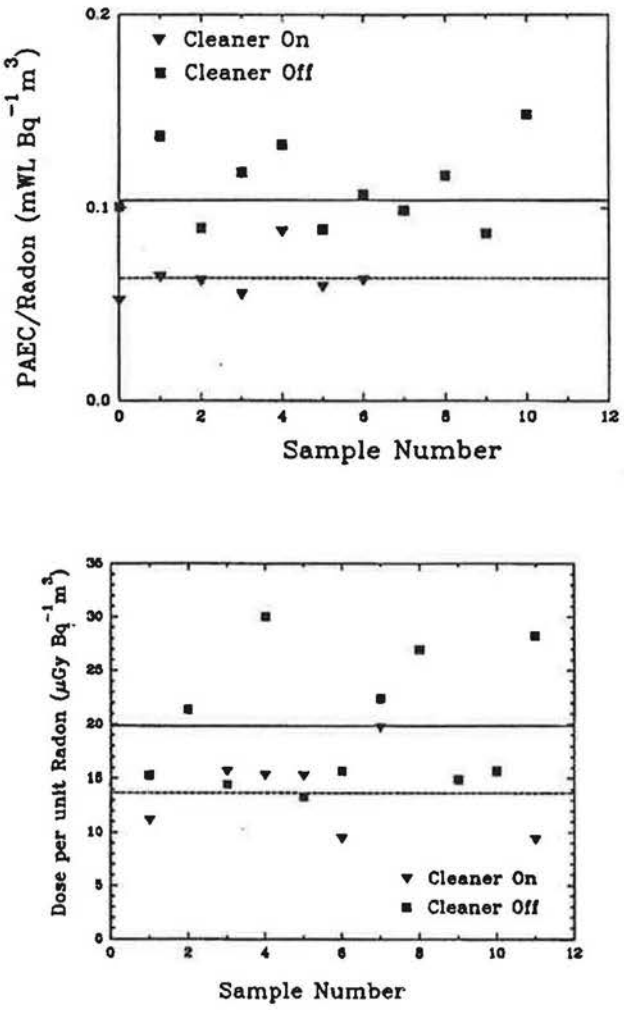
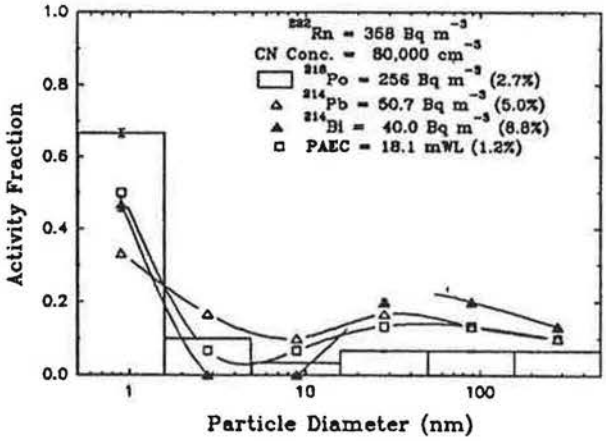


Fig. 4 Top: PAEC per unit radon for the series of samples taken in the bedroom with the door open.
Bottom: Dose per unit radon concentration for the series of samples taken in the bedroom with the door open.

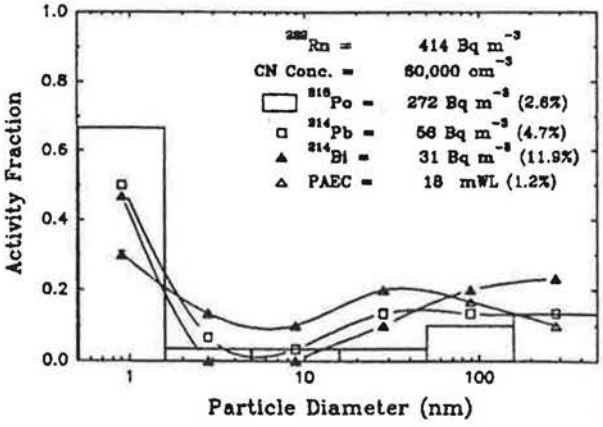
decay products with a major mode (80%) in the 0.5-5 nm size range and a minor mode (20%) in the 50-500 nm size range. The equilibrium factor decreased from 0.50 to 0.23. A decrease in the attachment rate (from 4 hr^{-1} to 2 hr^{-1}) and average attachment diameter (from 30 nm to 24 nm) was observed compared with the background conditions without the air filtration system. The deposition rate of the unattached fraction increased from 3 hr^{-1} to 7 hr^{-1}. The values of PAEC and dose per unit radon are shown in Figure 4. The reduction in PAEC per Bq m^{-3} radon was 39% and the dose reduction was 31% compared to the condition without the air filtration system.

Candle Burning

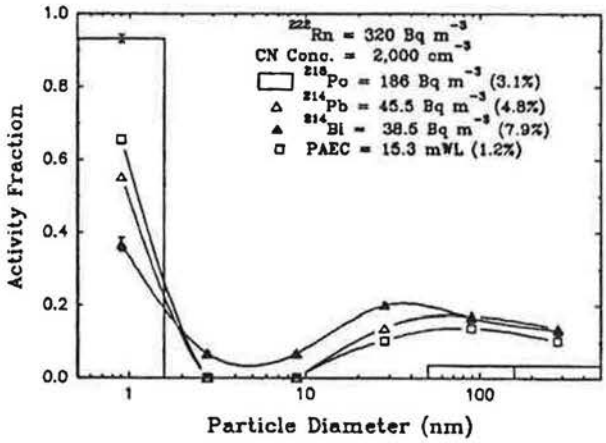
To examine the influence of an open flame on the radon progeny concentrations and size distributions as well as the effectiveness of the filtration system to remove these particles, a single candle was burned in the closed bedroom. The effect on the radon progeny behavior of the filtration unit operation during and after the candle burning is shown in Figure 5. The results of duplicate experiments are presented. These results can be compared with those measured without the air cleaner operating (Li and Hopke, 1991). The fraction of ^{218}Po changed from 95% to 65% in the 0.9 nm size range during candle burning, then back to 95% after 65 minutes. The fraction of ^{214}Pb in the 0.9 nm size range is about 70% (background, 60 minutes later, and 135 minutes later) and 50% during candle burning. During candle burning, there is a 10% fraction of ^{218}Po in the 1.5 to 5 nm size range, but an insignificant fraction in the background 60 minutes later, and 135 minutes



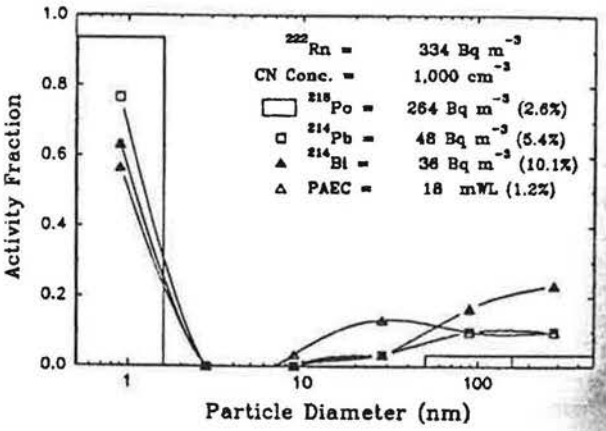
During candle burning interval (first experiment).



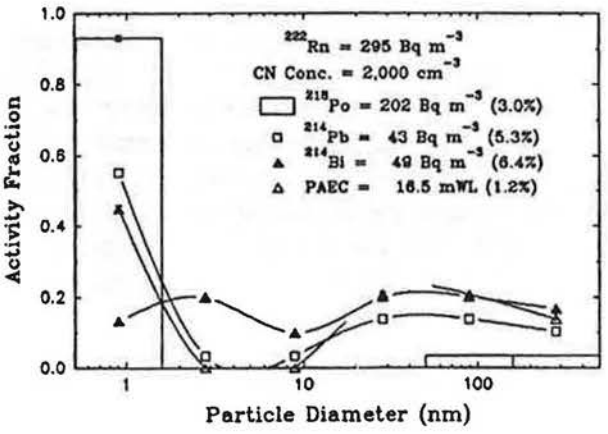
During candle burning interval (second experiment).



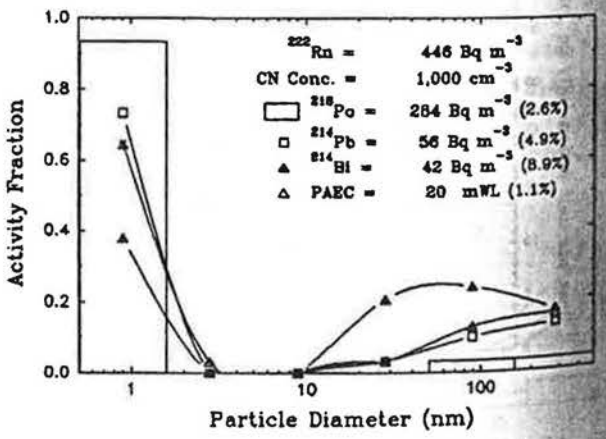
60 minutes after the burn interval.



60 minutes after the burn interval.



130 minutes after the burn interval.



130 minutes after the burn interval.

Fig. 5 Activity size distributions measured when particles were generated by a burning candle with the air filtration system operating.

Table 3 Measurement, room, and dose model results for the candle burning experiments with the air cleaner operating.

C_0 (Bq/m³)	Z (10^3cm^{-3})	f_l	f_p	F	PAEC (mWL)	X (hr^{-1})	d (nm)	$q^{(u)}$ (hr^{-1})	Dose (μGyhr^{-1}/Bqm^{-3}) Basal (l, h)	Secretory(l, h)
(1) 359	80	0.667	0.500	0.187	18.1	4	10	7	5.3, 15.6	11.5, 34.1
(during candle burning, cleaner on for 7 hours)										
320	2.0	0.931	0.655	0.177	15.3	1	26	10	4.4, 14.8	9.5, 32.4
(55 minutes after candle extinguished)										
295	2.0	0.931	0.552	0.207	16.5	1	26	7	5.4, 16.9	11.8, 36.9
(130 minutes after candle extinguished)										
316	2.0	0.933	0.633	0.190	16.2	0.9	24	7	4.9, 16.4	10.8, 35.9
(205 minutes after candle extinguished)										
(2) 414	60.0	0.667	0.507	0.165	18.4	5.82	15	9.86	4.3, 13.2	9.5, 28.8
(cleaner on for 10 hours, during candle burning)										
334	1.0	0.936	0.768	0.194	17.5	0.93	35	3.77	5.2, 18.4	11.5, 40.5
(55 minutes after candle extinguished)										
446	1.0	0.934	0.726	0.163	19.7	0.96	36	8.16	4.2, 14.8	9.3, 32.4
(130 minutes after candle extinguished)										

later. Very few of the three distributions are in the 5 to 15 nm size range. The results of the measurements, the room and dose models are given in Table 3.

With the air filtration system operating, the effect of radon decay products from candle burning are: (1) the unattached fraction of ^{218}Po and PAEC decreased from 0.93 to 0.73 and from 0.76 to 0.57; (2) the equilibrium factor increased from 0.14 to 0.18; (3) the attachment rate increased from 1 hr^{-1} to 4 hr^{-1} during candle burning (from 1,800 cm^{-3} to 60,000 cm^{-3}), to 1 hr^{-1} after 60, 135 minutes (1,500 cm^{-3}); (4) the average diameter changed from 30 nm to 13 nm during candle burning, to 30 nm after 60 minutes; and (5) the deposition rate of the unattached fraction decreased from 11 hr^{-1} to 9 hr^{-1} during candle burning. The CN counts for each of the two experiments are shown in Figure 6. The particle concentration increased during particle generation activity and then declined more rapidly than observed in the absence

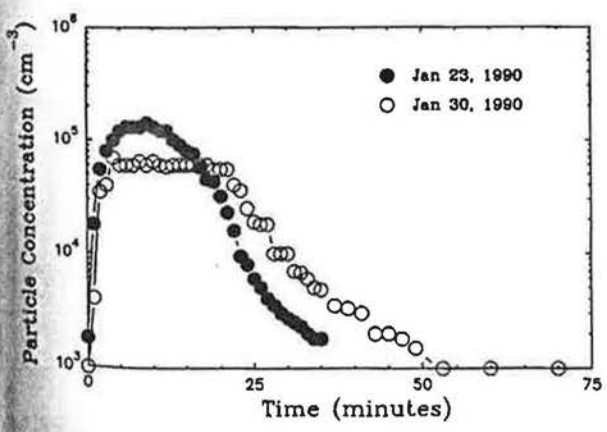
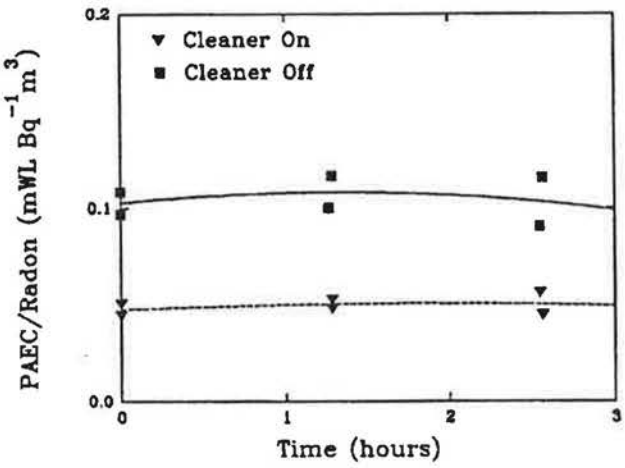


Fig. 6 CN counts as a function of time during the candle burning experiments with the air filter operating.



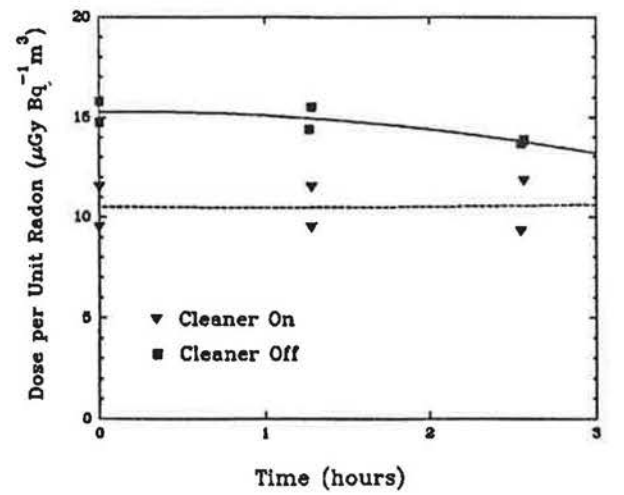
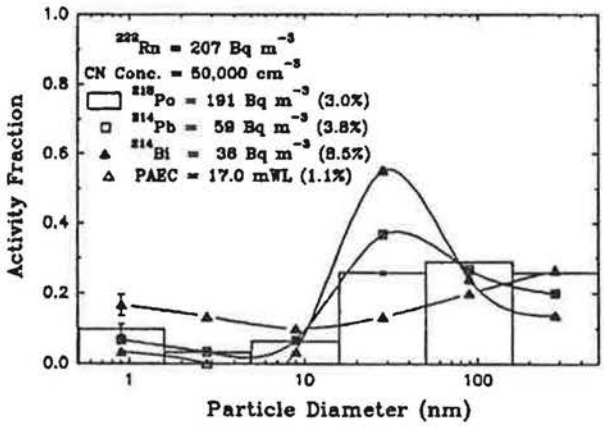
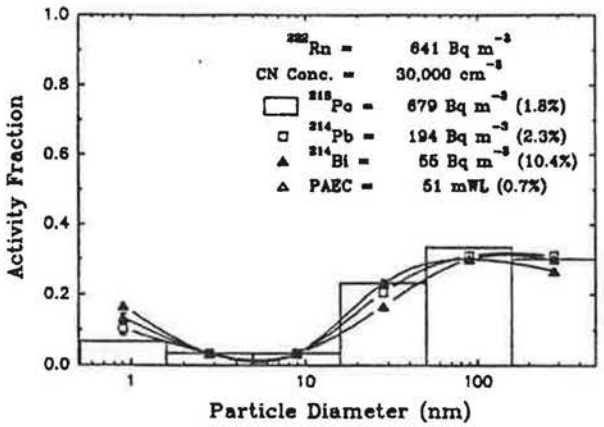


Fig. 7 Top: PAEC per unit radon concentration as a function of time from the start of the sample taken while the candle was burning.

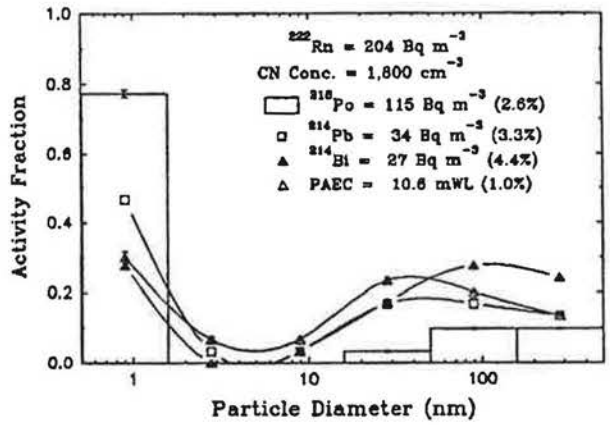
Bottom: Dose per unit radon concentration as a function of time from the start of the sample taken while the candle was burning.



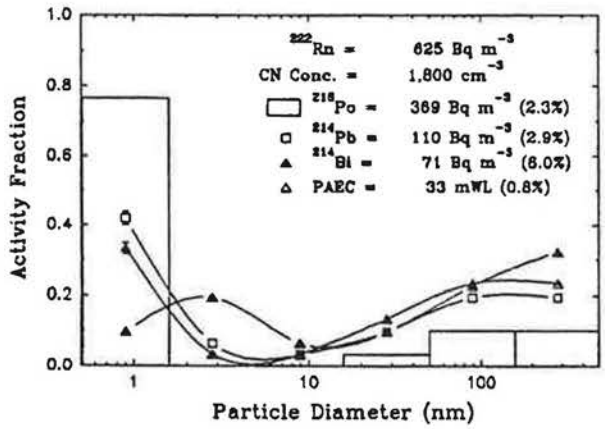
During the cigarette smoldering interval (first experiment)



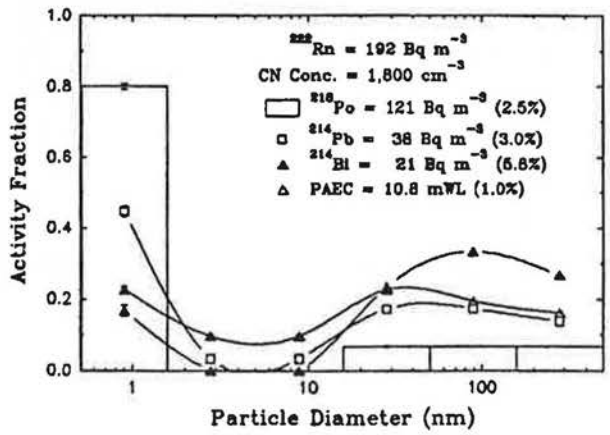
During the cigarette smoldering interval (second experiment)



60 minutes after the burn interval



60 minutes after the burn interval



135 minutes after the burn interval

Fig. 8 Activity size distributions measured when particles were generated by a cigarette smoldering with the air filtration system operating.

Table 4 Measurement, room, and dose model results for the cigarette burning experiments with the air cleaner operating.

C_0 (Bq/m^3)	Z (10^3cm^{-3})	f_1	f_p	F	PAEC (mWL)	X (hr^{-1})	d (nm)	$q^{(u)}$ (hr^{-1})	Dose (μGyhr^{-1}/Bqm^{-3}) Basal (l, h)	Secretory(l, h)
[1] 207	50	0.097	0.167	0.304	17.0	92	52	8	5.7, 11.6	11.9, 24.4
(cleaner on for 4 hours, during cigarette smoking)										
204	1.8	0.774	0.467	0.193	10.6	4	60	13	4.7, 14.0	10.1, 30.6
(after 60 minutes)										
192	1.8	0.800	0.448	0.208	10.8	3	50	10	5.0, 14.9	10.8, 32.2
(after 135 minutes)										
[2] 641	30.0	0.067	0.115	0.295	51.1	122	85	12.5	4.9, 11.0	10.3, 23.3
(cleaner on for 5.5 hours, during cigarette smoking)										
625	1.8	0.767	0.435	0.192	32.5	4.12	61	12.1	4.4, 13.4	9.6, 29.2
(after 60 minutes)										

of the operating air filter (Li and Hopke, 1991). The PAEC and dose to secretory cells at a breathing rate of 0.45 m^3 hr^{-1} per unit radon are shown in Figure 7. The lines are drawn through the points only to suggest the trends in the results. With the air filtration system, the PAEC decreased 53% from the value observed with the candle burning alone. The dose reduction averaged over the duplicate set of 3 measurements was 28%.

Cigarette Smoldering

A cigarette was allowed to burn in an ashtray producing only sidestream smoke in the closed room. For the measurements without the air cleaner (Li and Hopke, 1991), the fraction of ^{218}Po in the 0.5 to 1.6 nm size range changed from 67% to 8%. The fraction of ^{214}Pb and ^{214}Bi in this smallest size range was about 10% before the cigarette was lit and showed a significant reduction to essentially zero so that the unattached fraction of PAEC declined to 7% from an initial value of 31%. The fraction of three distributions in the 1.5 to 15 nm size range remained the same. A large increase in the 50 to 500 nm size

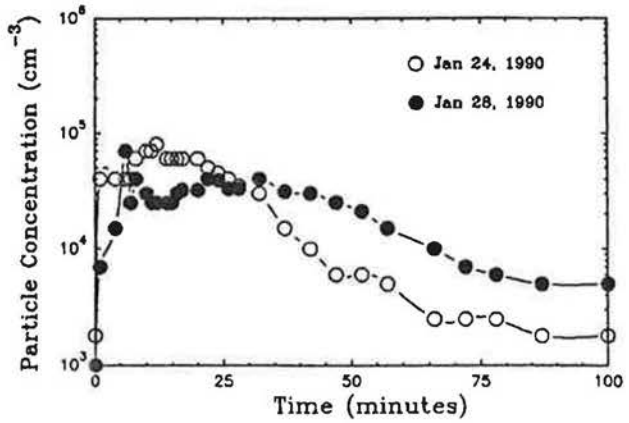
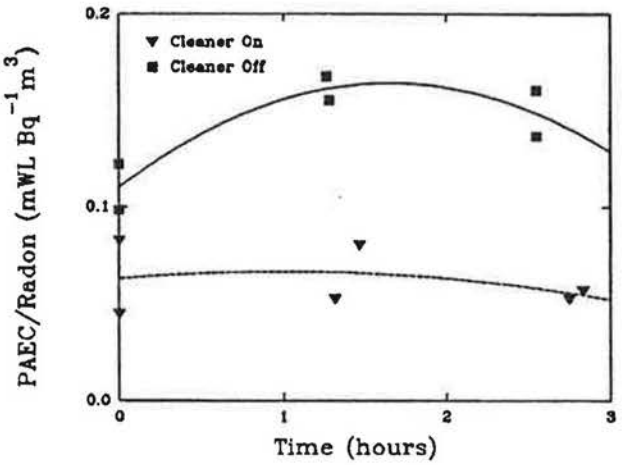


Fig. 9 CN counts as a function of time during the cigarette burning experiments with the air filter operating.



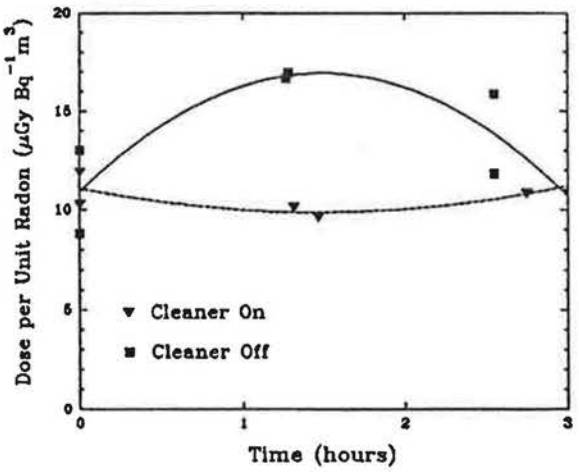


Fig. 10 Top: PAEC per unit radon concentration as a function of time from the start of the sample taken while the cigarette was smoldering.

Bottom: Dose per unit radon concentration as a function of time from the start of the sample taken while the cigarette was smoldering.

range was observed for ^{218}Po (from 40% to 80%) with only small changes for ^{214}Pb and ^{214}Bi (from 35% to 40%). Without the filtration system operating, the particle concentration increased significantly (up to 100,000 cm^{-3}) during burn interval, then declined to a steady-state concentration of around 8,000 cm^{-3}. Thus, without the air cleaner, the cigarette smoke particles remain for an extended period of time and substantially perturb the activity-weighted size distributions.

With the air cleaner operating, the size distributions measured in the cigarette smoke experiments are shown in Figure 8. The fraction of ^{218}Po changed from 95% to 10% in the smallest size range after 5 minutes, then increased back to 80% in the later distributions. The fraction of ^{214}Pb and ^{214}Bi in the 1.6 to 5.0 nm range was 8% after 5 minutes, but returned to 25% by the 60-minute measurement. Very little activity appears in the 1.6 to 15 nm size range for samples at 60 or 135 minutes, but 15% was present at 5 minutes. The results of the measurement, the room and dose models are given in Table 4.

The attached mode activity increased from 20% to 80% in the sample obtained during the particle generation interval, then returned to the background condition by the second measurement. The air filtration system thus rapidly removed the particles from the air as shown in Figure 9. The changes in PAEC and dose over time are shown in Figure 10. The average decrease in PAEC per unit radon was 56% compared to the case where the filtration unit was not functioning, but a reduction in dose per unit radon occurred only during the period beginning 60 minutes from the end of the particle generation interval, although the average reduction was 24%.

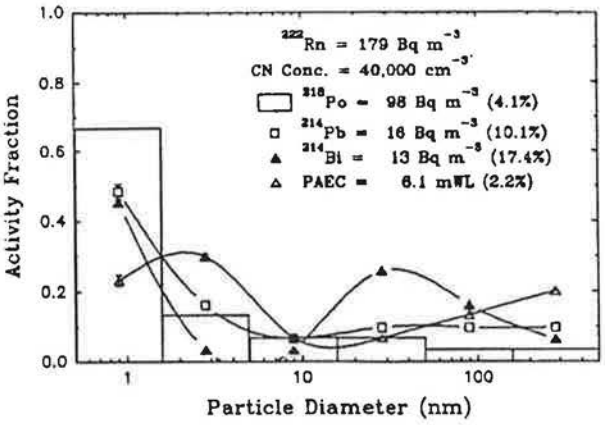
Vacuuming

With the door closed, a portion of the carpet was vacuumed for 20 minutes to produce particles smaller than 100 nm, similar to those produced from candle burning. These results were similar to those observed by Reineking and Porstendörfer (1986). They found an additional mode in the size range 20 to 80 nm formed by the particles generated from an electric motor. In the first experiment with the air cleaner off, the particle number concentration reached 90,000 cm^{-3}, then decreased to 4,000 cm^{-3} at 135 minutes after the end of vacuuming. A significant additional mode in ^{218}Po activity distribution was found in the 15 to 100 nm size range because of the attachment of ^{218}Po to the small particles produced by the motor (Li and Hopke, 1991).

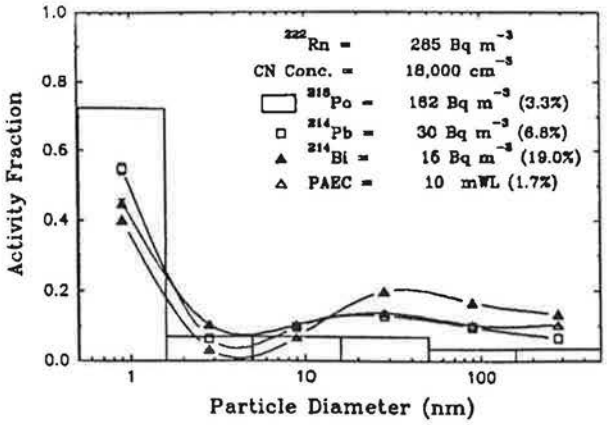
However, in the second vacuuming experiment, a significantly smaller concentration was observed (15,000 cm^{-3}) during the particle generation period. The lower concentration caused a variation in the size distribution of radon decay products. A moderate activity decrease in the 0.9 nm size range was observed for ^{218}Po (about 40%) and a smaller result for ^{214}Pb and ^{214}Bi (about 10%). The unattached fraction of ^{218}Po decreased during the particle generation to 35%, and increased back to 56% at 60 minutes after the end of vacuuming, and finally to 67% at 135 minutes after the end of vacuuming. The unattached fraction of PAEC decreased from 45% to 16% during the particle generation period, and returned to 30% in the sample taken 60 minutes after the end of vacuuming. The equilibrium factor increased from 0.24 to 0.26 (during the particle generation period), to 0.34 (60 minutes after the end of vacuuming), and to 0.28 (135 minutes after vacuuming stopped). The average attachment diameter of these small particles was smaller, and thus, a lower attachment rate was

Table 5 Measurement, room, and dose model results for the vacuuming experiments with the air cleaner operating.

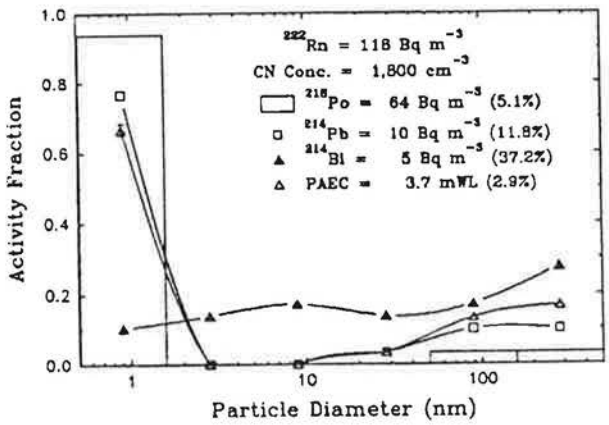
C_0 (Bq/m^3)	Z (10^3cm^{-3})	f_t	f_p	F	PAEC (mWL)	X (hr^{-1})	d (nm)	$q^{(u)}$ (hr^{-1})	Dose (μGyhr^{-1}/Bqm^{-3}) Basal (l, h)	Secretory(l, h)
[1] 179	40	0.667	0.487	0.126	6.1	3.4	12	13.7	4.1, 12.0	9.0, 26.3
(cleaner on for 9.5 hours, during the vacuuming)										
118	1.8	0.937	0.754	0.115	3.7	0.9	26	12.1	3.1, 10.9	6.8, 23.9
(after 60 minutes)										
72	1.5	0.967	0.700	0.124	2.4	0.5	22	11	3.6, 12.0	8.0, 26.4
(after 135 minutes)										
[2] 285	18	0724	0.554	0.131	10.1	3.54	17	12.7	4.0, 12.0	8.8, 26.3
(during the vacuuming)										
303	1	0.934	0.711	0.170	13.9	0.95	36	7.5	4.6, 15.7	10.2, 34.4
(after 60 minutes)										
328	1	0.967	0.735	0.160	14.2	0.46	26	7.9	4.3, 14.9	9.4, 32.7
(after 135 minutes)										



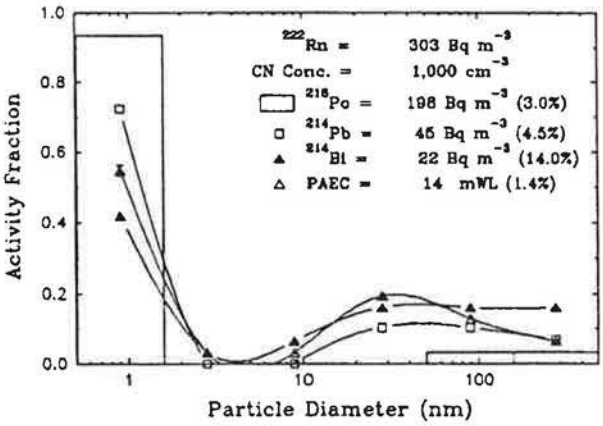
During the vacuuming period (first experiment).



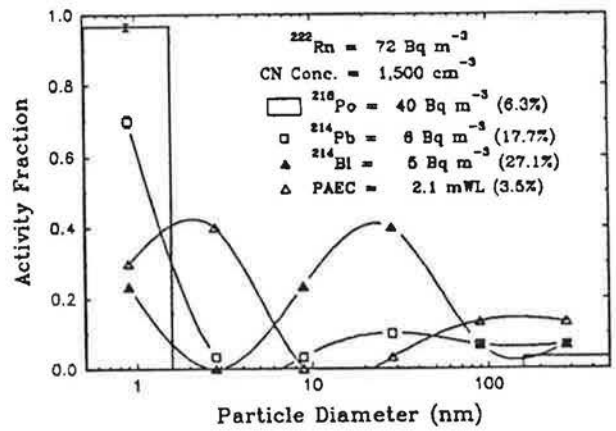
During the vacuuming period(second experiment).



60 minutes after vacuuming.



60 minutes after vacuuming.



135 minutes after vacuuming.

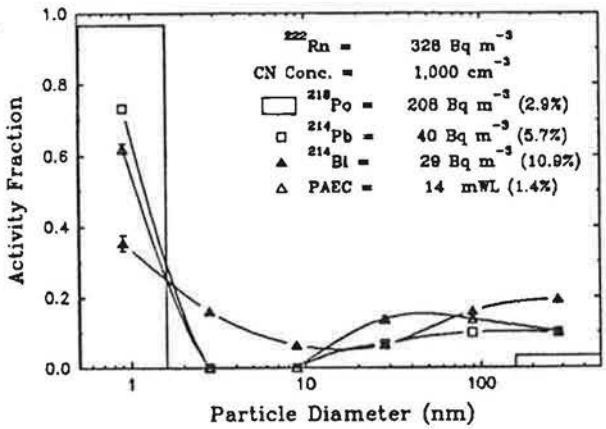


Fig. 11 Activity size distributions measured when particles were generated by vacuuming in the room with the air filtration system operating.

observed (50 hr^{-1}). The activity-weighted size distributions returned to those of the background condition gradually after vacuuming was discontinued. The deposition rate of the unattached fraction increased from 5 hr^{-1} to 30 hr^{-1}.

The results of the duplicate experiments with the air filter operating are presented in Figure 11 in the form of the activity-weighted size distributions. The of these measurements, the room, and dose e given in Table 5. The CN counts as a time are shown in Figure 12. The first pears to follow the expected pattern, experiment on January 29, the CN ch more slowly than would have reason for this discrepancy is nd dose per unit radon for without the air cleaner 13. The activity in the d to be 70% for ^{218}Po, unattached fraction The unattached 0.74 to 0.62. The isignificantly. A mod- ached fraction during the observed both with and with- system. A 25% increase in the range was observed for ^{218}Po due to nt of decay products to the small parti- rated from vacuuming. A 30% increase in to 150 nm size range was also observed for all ree size distributions. The size distributions of the 60 and 130 minute measurements were very similar to the background condition. The attachment rate increased from 1 hr^{-1} to 3.5 hr^{-1} during the active particle period, and decreased to 0.8 hr^{-1} after 60 and 135 minutes. The average diameter decreased from 30 nm to 15 nm during the active particle period, and to 26 nm after 60 and 135 minutes. The average reduction in PAEC per Bq m^{-3} radon was 60% and the average dose reduction was 49%.

Cooking

A steak was pan fried for 20 minutes using the gas stove in the kitchen. The bedroom door was open for these experiments. During the cooking experiment with the air filtration system off, the particle number concentrations were found to be 250,000 cm^{-3} in the kitchen and 30,000 cm^{-3} in the bedroom. With the air cleaner off, only 10% activity of all three size distributions was in the 0.9 nm size range. The unattached fraction of PAEC was 0.15 with the equilibrium factor of 0.50. All three size distributions in

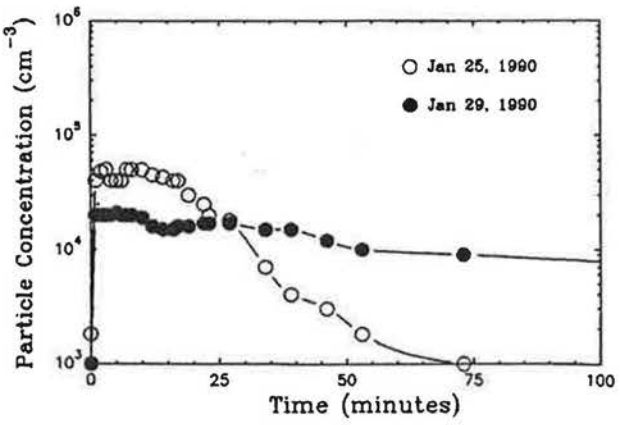


Fig. 12 CN counts as a function of time during the vacuum cleaner operation with the air filter operating.

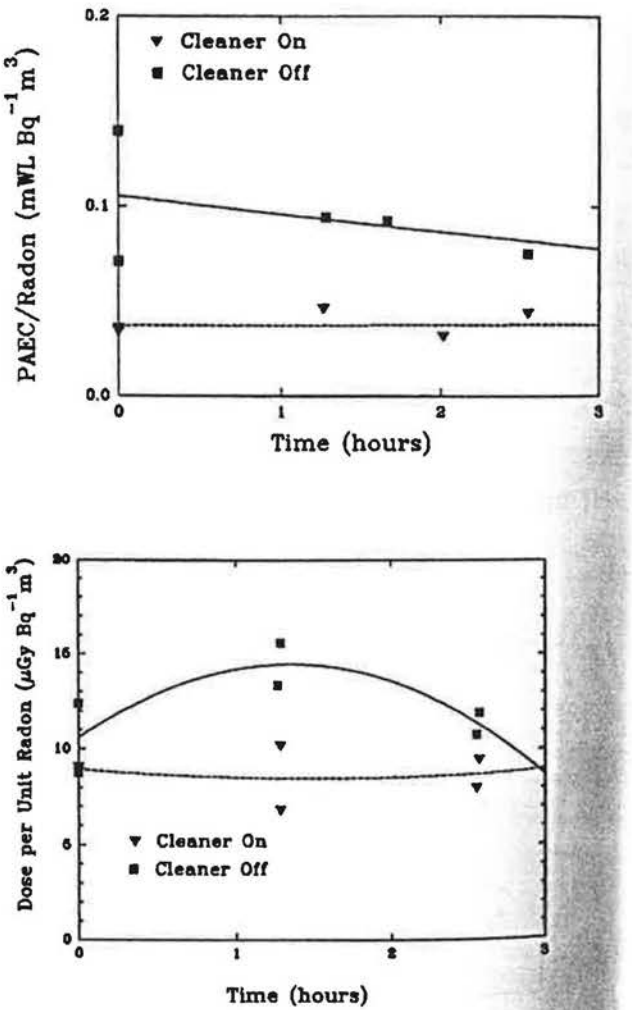


Fig. 13 Top: PAEC per unit radon concentration as a function of time from the start of the sample taken while the vacuum cleaner was operating.

Bottom: Dose per unit radon concentration as a function of time from the start of the sample taken while the vacuum cleaner was operating.

the bedroom were bimodal, with a major mode in the attached size range (80%). A significant increase in the attached fraction larger than 20 nm was observed in the bedroom. The average attachment diameter increased from 25 to 50 nm during the particle generation period, and to 80 nm at 60 and 135 minutes after the end of the cooking interval. Reineking et al. (1985) reported a 74 nm attachment diameter for particles produced from a tiled stove and cooking aerosols. Tu and Knutson (1988) measured the particle size distributions in two homes. They found that the size ranges were different for cooking soup and frying meat and eggs. The soup particles produced using a gas stove are smaller in size, with a mean diameter of 14 nm. Particles from frying food had a mean diameter of 54 nm. Tu and Knutson's results are in general agreement with the activity size distributions obtained in the bedroom after frying a steak in the kitchen.

The larger particles observed in the bedroom from cooking had higher attachment rates than the smoldering cigarette particles. The attachment rate increased from 6 hr^{-1} to 40 hr^{-1} during the particle generation period, and to 48 hr^{-1} after 60 and 135 minute samples. It appears that the particles took a moderate time moving from the kitchen to the bedroom. The size distributions of three decay products remained the same for longer periods of time.

Strong (1988) found a quite different size distribution of radon decay products because of cooking. Stong's results showed that the activity size distribution was trimodal (1.5 nm, 11 nm, 130 nm) before cooking and bimodal (11 nm, 110 nm) during cooking. During cooking, the smallest mode (1.5 nm) disappeared, and this activity became associated with the 11 nm size range. In the same house, Strong (1989) made measurements in the living room while cooking in the adjacent kitchen. A trimodal size distribution of radon decay products was observed, with the additional mode occurring at the 6 nm size range. This 6 nm mode may be due to the growth of aerosols from vapors generated during cooking. In Strong's paper, no specific information was provided regarding the cooking process or the type of food cooked.

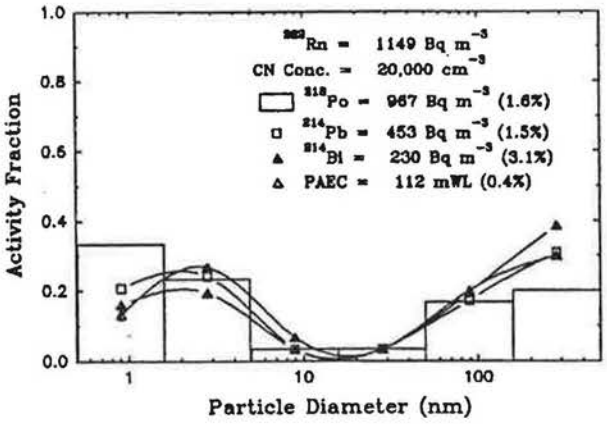
Ramamurthi and Hopke (1991) also conducted several measurements in another kitchen. They found an approximately 10 nm mode when the gas burners were operating. This small size range mode observed in the kitchen may be related to gas combustion of the gas burners.

The activity size distributions of radon decay products in the bedroom are presented in Figure 14. The activity in the 0.9 nm size range was found to be 50% for ^{218}Po and 15% for ^{214}Pb and ^{214}Bi. The unattached fraction of ^{218}Po and PAEC decreased from 0.87 to 0.45 and reduced from 0.40 to 0.20. The equilibrium factor increased from 0.23 to 0.32, respectively. The fraction of all three distributions in the 1.5 to 5 nm size range was found to be 20%. For all three radon decay products there was very little activity in the 5 to 50 nm size range for all conditions. An increase from 20% to 50% in the 50 to 500 nm size range was observed for all three distributions. As a whole, a bimodal size distribution was observed. For ^{218}Po, the major mode was in the unattached cluster size range. For ^{214}Pb and ^{214}Bi, the minor mode was in the 2.8 nm size range and the major mode was in the 280 nm size range. The size distributions of the second and third measurements did not return to the background condition as did the distributions found after candle burning, cigarette smoldering, and vacuuming. It appears that the delay caused by the transport from the kitchen to the bedroom maintained the particle concentrations whereas when the particle sources were operated within the room, the particles were at their highest level at the end of the generating period. This pattern is also observed in the CN counts presented in Figure 15. The measurements and the results of the room and dose models are summarized in Table 6.

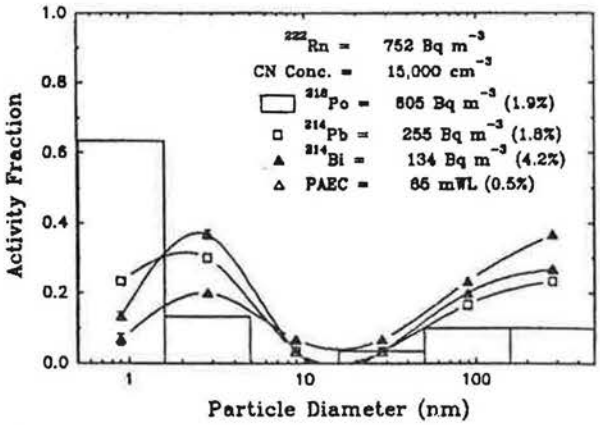
The PAEC and dose per Bq m^{-3} radon are shown in Figure 16. The reductions in the PAEC and the dose rate per Bq m^{-3} radon were quite different from the other experiments. The dose per unit radon showed a very slight average decrease of 4.6%. However, given the uncertainty in both the measured and calculated quantities, the dose was essentially the same for the experiments with and without the air cleaner operating.

Conclusions

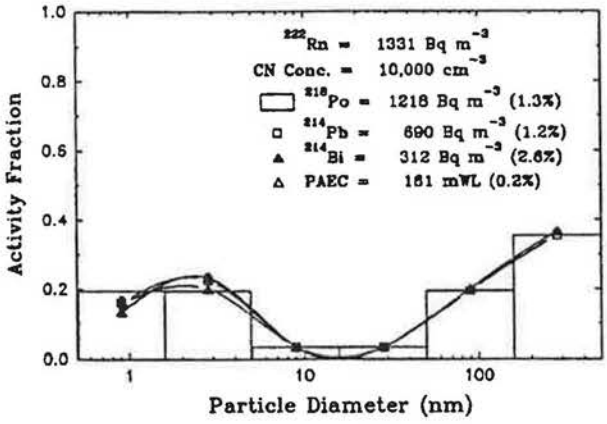
Under normal conditions in the domestic environment, the unattached fraction of PAEC can vary over a wide range (7%-40%). The equilibrium factor was between 0.13 and 0.50. However, these two quantities are strongly dependent on the situation measured in the house. Because of a large number of particles generated from normal household activities, the PAEC increased for a period of time and the unattached fraction decreased. The particles generated from cigarette smoke and cooking dramatically shifted most of the radon progeny to the attached mode.



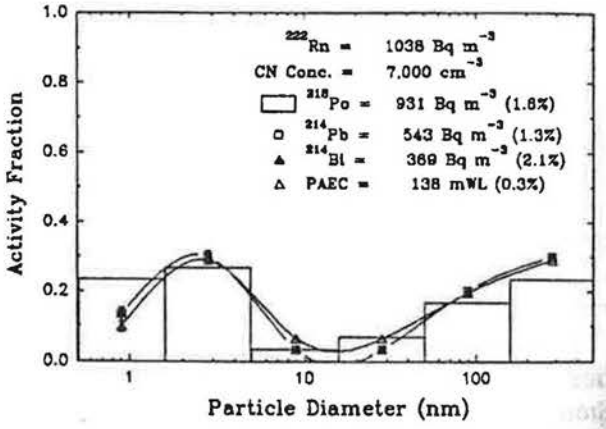
During the cooking interval (first experiment).



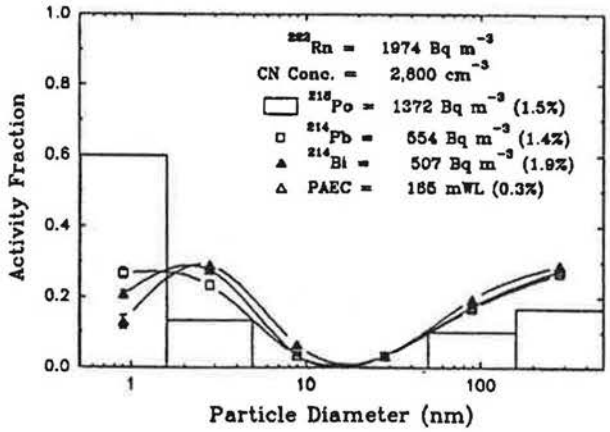
During the cooking interval (second experiment).



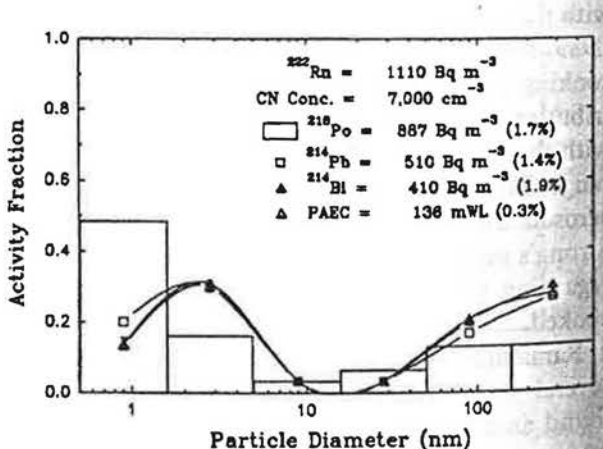
60 minutes after the cooking period.



60 minutes after the cooking period.



135 minutes after the cooking period.



135 minutes after the cooking period.

Fig. 14 Activity size distributions measured when particles were generated by cooking in the kitchen (bedroom door open) with the air filtration system.

Table 6 Measurement, room, and dose model results for the cooking experiments with the air cleaner operating.

C_0 (Bq/m³)	Z (10^3cm^{-3})	f_l	f_p	F	PAEC (mWL)	X (hr^{-1})	d (nm)	$q^{(u)}$ (hr^{-1})	Dose (μGyhr^{-1}/Bqm^{-3}) Basal (l, h)	Secretory(l, h)
[1] 1149	20	0.333	0.198	0.361	112	10	26	4.2	10.1, 26.4	22.0, 57.5
(cleaner on for 7.5 hours, during cooking period)										
1331	108	0.194	0.172	0.447	161	21	60	2.8	11.3, 29.5	24.7, 64.2
(60 minutes cooking)										
1974	2.8	0.600	0.277	0.31	165	4.9	52	7.9	9.2, 25.1	20.1, 54.9
(135 minutes after cooking)										
[2] 752	15	0.633	0.234	0.321	65.2	4.1	20	4.1	10.0, 26.5	21.8, 57.8
(during the cooking interval)										
1038	7	0.233	0.122	0.490	137	13	52	2.8	14.5, 36.0	31.5, 78.4
(60 minutes after cooking)										
1110	7	0.484	0.189	0.453	135	7.4	37	5.1	13.8, 35.8	30.1, 78.0
(135 minutes after cooking)										

These size distributions were stable for a long time after the aerosol generation. The particles produced from candle burning and vacuuming were much smaller, with the average attachment diameters being around 15 nm. These particles did decrease the unattached fraction. However, after 150 minutes, the size distributions had returned to the original background condition.

With the air filtration system operating without active aerosol sources, the unattached fraction of PAEC increased substantially to > 80%. The equilibrium factor was about 0.14. The PAEC reduction was about 60% with the bedroom door closed and only about 40% with it open. It appears that the increased circulation that occurred with the air cleaner operating and the door open substantially changed the infiltration rate of the attached activity into the room. The dose rate reduction for these two cases was essentially the same.

In the presence of active aerosol sources, the air

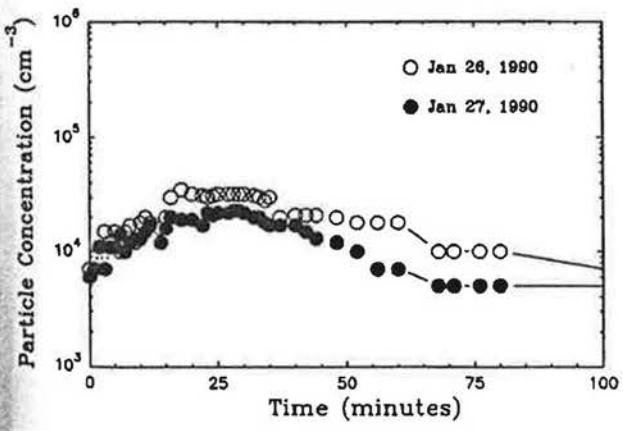
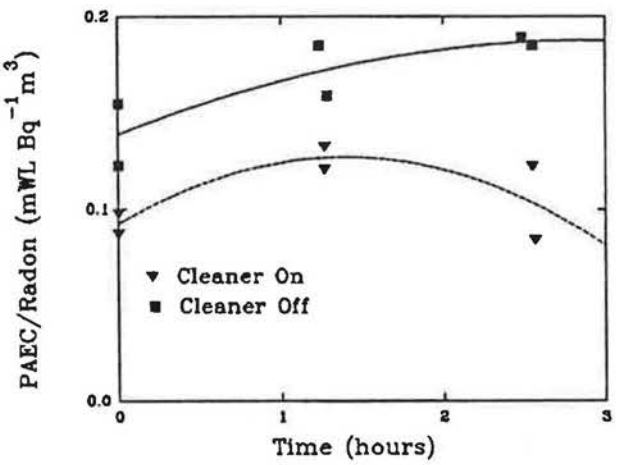


Fig. 15 CN counts as a function of time during the cooking experiments with the air filter operating.



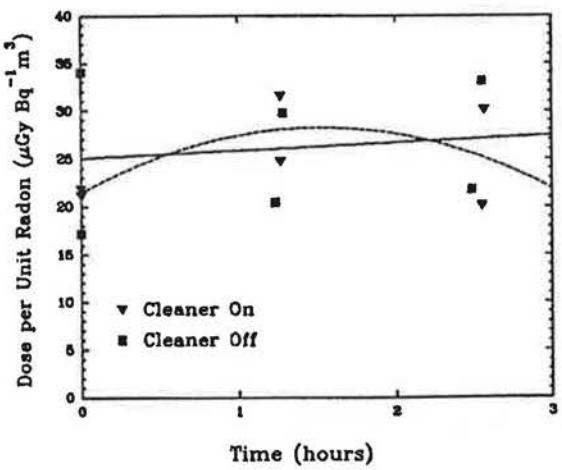


Fig. 16 Top: PAEC per unit radon concentration as a function of time from the start of the sample taken while cooking was being done in the kitchen with the door open.

Bottom: Dose per unit radon concentration as a function of time from the start of the sample taken while cooking was being done in the kitchen with the door open.

filtration unit typically reduced the concentration of particles within the hour following the end of particle generation. After candle burning, cigarette smoking, and vacuuming in the bedroom, the reductions of PAEC by air filtration are about 60% with the air filtration system operating in the bedroom. During cooking in the kitchen, the reductions of PAEC in the bedroom with the air filtration system were about 40%. However, for all cases the dose reductions were smaller than the particle and PAEC reductions. For those particles that were generated within the bedroom, there was a 20% to 50% reduction in dose. In the case of cooking, where the door was open and particles infiltrated from the rest of the house, the dose reduction was only 5% on average and appears to be insignificant. Thus, the dose reductions were lower than the reductions in activity concentration, but there were no cases where the estimated dose actually increased.

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