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Abstract

Eleven portable air cleaning devices have been evaluated for control of indoor concentrations of respirable particles, and their concomitant effects on radon progeny concentrations have been investigated. Of the devices we examined the electrostatic precipitators and extended surface filters had significant particle removal rates, while the particle removal rates for several small panel-filters, an ion-generator, and a pair of mixing fans were found to be negligible. The evaluation of radon progeny control produced similar results; the air cleaners which were effective in removing particles were also effective in reducing radon progeny concentrations. Furthermore, at the low particle concentrations, plateout of the unattached radon progeny was found to be a significant removal mechanism. The overall removal rates due to deposition of attached and unattached progeny have been estimated from these data, and the equilibrium factors for total and unattached progeny concentrations have been calculated as a function of particle concentration.

Introduction

As average residential ventilation rates decrease, due to weatherization measures or new construction practices, indoor pollutant concentrations may increase. Air cleaning may mitigate the resulting increases in indoor particle concentrations, although the effectiveness of air cleaners will depend upon their actual design and operating characteristics, the removal method employed, the indoor environmental conditions, and the particle characteristics. Air cleaning may also reduce the radon progeny concentrations that are present in indoor air.

There are many sources of indoor particles, among them are indoor emissions related to human activities, such as tobacco smoking, food preparation (fuel combustion, cooking emissions), and space heating (unvented gas and kerosene heaters, fireplaces, wood stoves), and infiltrating outdoor pollutants, such as atmospheric dust, combustion emissions, and plant pollens. Indoor particle concentrations can often exceed outdoor concentrations (3), and the concentration and size distribution of indoor particles are important factors in determining the human exposures to airborne particles (7).

Radon and its immediate radioactive decay products are also present in indoor air, with typical annual average radon concentrations ranging from 5 to 150 Bq m^{-3}, although radon concentrations in excess of 400 Bq m^{-3} have been observed (4). The health risk associated with radon is due to the alpha decay of two of the short-lived progeny, Po-218 and Po-214. These isotopes, along with other radon decay products, are chemically active and can attach to surfaces, such as airborne particles, walls, and lung tissue. Dosimetric modeling indicates that the alpha dose to the lungs from radon progeny not attached to particles is larger than from radon progeny attached to particles (2). Thus the indoor particle concentration is an important consideration in estimating the health effects associated with indoor radon concentrations.

This paper presents an in situ evaluation of the effects of several types of air cleaners on particle concentrations and size distributions, and the concomitant effects on radon progeny concentrations and behavior. More experimental and analytical detail are presented in Reference 5.

Experimental Procedure

These experiments were conducted at the LBL Indoor Air Quality Research House (IAQRH), a two story, wood-frame structure with a three-room test space that has been extensively weatherized to reduce the infiltration rate to ~0.05 air changes per hour. Measurements were performed in one room, which has a volume of 36 m^3. A cigarette smoking machine, the air cleaning device being examined, and instrumentation for the measurement of radon progeny were all placed inside the test chamber.

Instrumentation

The instruments used in this study are part of an automated computer-controlled data acquisition and monitoring system installed at the IAQRH. Radon concentrations in the test space are measured using three continuous-flow scintillation cell/photomultiplier tube assemblies, with data logged every 30 minutes. Real-time data for radon progeny are taken with an automated sampler, the Radon Daughter Carousel (RDC), which collects radon progeny on a filter (usually for a five-minute sampling period), then places the filter beneath a surface-barrier detector for alpha particle counting. A radon progeny sample is collected every 30 minutes. Filter grab samples are also taken periodically and analyzed using alpha spectroscopy to supplement the RDC data.

Instruments for the real-time determination of particle size and concentration are located on the second floor of the IAQRH and connected to the test chamber with a 6-m-long, 1-cm-diameter copper sampling line, through which air is continuously drawn at ~5 liters/min. Total particle concentrations are measured with a Condensation Nucleus Counter

(CNC). The CNC is also used to sample the output of an electrostatic classifier, which provides particle size and concentration data for particle diameters between 0.01 and 0.3 μm. An optical particle counter with a specially-adapted dynamic range measures particle concentrations and size distributions for particle diameters between 0.1 and 3.0 μm.

Measurement Sequence

Concentrations of particles were generated in the chamber using a cigarette smoking machine. A typical six-minute cigarette burn consumed ~600 mg of tobacco and produced a peak concentration of ~150,000 particles cm^{-3}. After cigarette ignition, radon was injected into the test chamber by passing air through a Ra-226 source that had previously been vented and then allowed to accumulate for about 24 hours. This resulted in an initial radon concentration of ~18,000 Bq m^{-3} in the chamber.

Following particle production and radon injection, the room air was allowed to mix naturally for four hours, which was sufficient time to establish a steady particle decay rate and to achieve radioactive equilibrium of the radon and radon decay products. After this period, the control device was switched on for a three-to-five hour operating period. A portable dehumidifier was operated in the chamber before each experiment to produce an initial relative humidity of 35 to 50 percent. The relative humidity slowly increased by 5 to 10 percentage points during the test sequence, while the indoor temperature varied between 18 and 22^{o} C.

Results and Discussion

Particles

The effect of air cleaner operation on particle concentration can be parameterized in two ways, the effective cleaning rate (ECR) and the system efficiency. The ECR is the difference in particle concentration decay rates observed with and without operation of the air cleaner multiplied by the test chamber volume. Thus the ECR is the effective flow of particle-free air that would produce the observed reduction in particle concentration. For those air cleaners with fans (all but the ionizers had fans), the system efficiency is the ECR divided by the air flow rate through the device; the air flow rates were measured in a separate set of experiments using an orifice plate flowmeter. The ECR for each device was determined for each particle size fraction and for the total particle concentration. Little variation in ECR as a function of particle size was observed for particle diameters between 0.09 and 1.25 μm. For comparative purposes the ECR for each air cleaner is based on the data for 0.45 μm diameter particles, which is close to the mass median diameter for tobacco smoke and thus is a reasonable index for the total mass decay rate of the aerosol. With no air cleaner operating, the decrease in particle number concentration due to natural removal mechanisms was 0.16 hr^{-1}, corrected for the infiltration rate. We attribute this decay rate to particle deposition on room surfaces.

The results for the air cleaners examined are displayed in Figure 1, where the height of the unshaded bar represents the effective cleaning rate and the shaded bar the measured air flow rates. The ratio of the height of the unshaded bar to that of the shaded bar yields the air cleaner system efficiency. The small, table-top panel filters, devices 1 through 4 in Fig. 1, have low effective cleaning rates and system efficiencies of 0, 11, 16, and 39 percent respectively. The low particle removal rates appear to be due to the low total air flow rates and the large fraction of the air flow that bypasses the filters in these devices. Similarly, negligible particle removal rates were observed using two oscillating fans as a means of evaluating the effect of increased air circulation on particle removal (device 11).

The devices with the highest system efficiencies were those with extended surface filters, which were 86 and 100 percent efficient for cigarette smoke particles, while both of the electrostatic precipitators tested had system efficiencies of ~56 percent. Two negative ion generators were evaluated. The unit with the lower ECR had both an emitter operating at -19 kV and a positively-charged collector surface, which appears to limit the range of the ion field and thus reduce the air cleaning effectiveness. The other ionizer operated at -32 kV and had no collector so that particles are removed by collection on room surfaces.

Radon Progeny

In order to estimate the effects of air cleaning, radon and radon progeny concentrations measured as part of each air cleaner experiment were tabulated as a function of observed particle concentration. These data were used to calculate the equilibrium factor, F, which can be written as:

$$F = \frac{k_1 A_1 + k_2 A_2 + k_3 A_3}{A_0}, \tag{1}$$

where the subscripts i = 0 to 3 refer to Rn-222, Po-218, Pb-214, and Bi-214, respectively. A_i are the radon or radon progeny concentrations and the coefficients k_i account for the potential alpha decay energy and the radioactive decay constant for each radon decay product. These results are shown in Figure 2 (solid circles).

Removal of airborne radon progeny can occur through several mechanisms (associated rates are shown in parentheses): deposition on surfaces by progeny either attached ($\lambda_D{}^a$) or unattached ($\lambda_D{}^f$) to airborne particles; direct filtration by an air cleaning device (λ_F); ventilation (λ_V); and radioactive decay (λ_i). The radioactive decay constants are known, while the ventilation rate can be obtained directly from the radon concentration measurements. We have assumed that the direct removal of radon progeny by the control device occurs at essentially the same rate as for particles. Based on the steady-state equations derived by Jacobi (1) and Porstendoerfer (6) for the various radon progeny removal modes, the overall progeny removal rate, Λ_i, can be found in terms of the progeny activities, A_i:

$$\Lambda_i = \lambda_i \left[\frac{A_{i-1}}{A_i} - 1\right] \quad \text{where} \tag{2}$$

Λ_i is a function of the removal processes noted above and the relative concentration of progeny not attached to particles. This latter term, referred to as the unattached fraction, f_i, can be estimated from our data as a function of particle concentration. From these results we then estimate the deposition rate of unattached progeny to be 15 hr^{-1}, which, when combined with our estimated average particle deposition rate, 0.16 hr^{-1}, provides an overall removal rate due to deposition of unattached and attached radon progeny. Combining equations 1 and 2, the equilibrium factor can then be written as

$$F = \frac{\lambda_1}{\lambda_1 + \Lambda_1} \left[k_1 + \frac{\lambda_2}{\lambda_2 + \Lambda_2} \left(k_2 + k_3 \frac{\lambda_3}{\lambda_3 + \Lambda_3}\right)\right] \tag{3}$$

Results using this equation are shown for different particle concentrations as the solid line in Figure 2. The equilibrium factor for unattached progeny can also be calculated from equation 3 by first multiplying each k_i term by the respective unattached fraction, f_i. The results are shown as the dashed line in Fig. 2. As can be observed in the figure, at particle concentrations below 500 particles cm^{-3}, the equilibrium factor is primarily associated with unattached progeny. The relative concentration of unattached progeny declines with increasing particle concentration. The total equilibrium factor (solid line) increases as particle concentration increases from ~1000 to 25,000 particles cm^{-3}, a range typical of indoor environments.

Conclusions

Air cleaning can have a significant effect on indoor particle concentrations, although the different types of devices exhibit a wide range in performance. Operation of an effective particle-control device will also remove airborne radon decay products, not only by direct filtration of unattached and attached radon progeny, but also by producing low particle concentrations where deposition of unattached progeny is the dominant removal mechanism. The relative importance of unattached progeny concentrations can be seen from Fig. 2. Depending upon the relative radiological dose assigned unattached and attached progeny, radon concentrations in indoor air with less than 10,000 particles cm^{-3} may have larger health consequences than inferred from the total progeny equilibrium factor.

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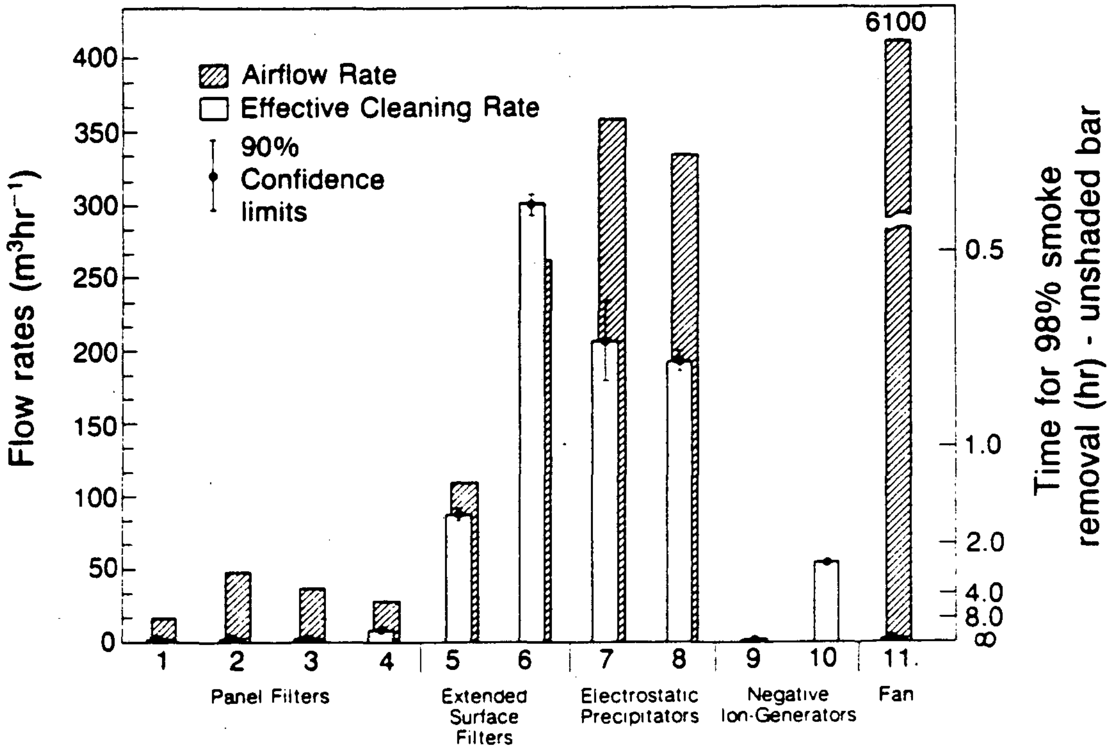

Fig. 1. Effective cleaning and air flow rates for several types of air cleaning devices evaluated in this study. The right axis indicates the time required (in hours) for removal of 98 percent of the particles for each device (unshaded bar) in the 36 m^3 chamber.

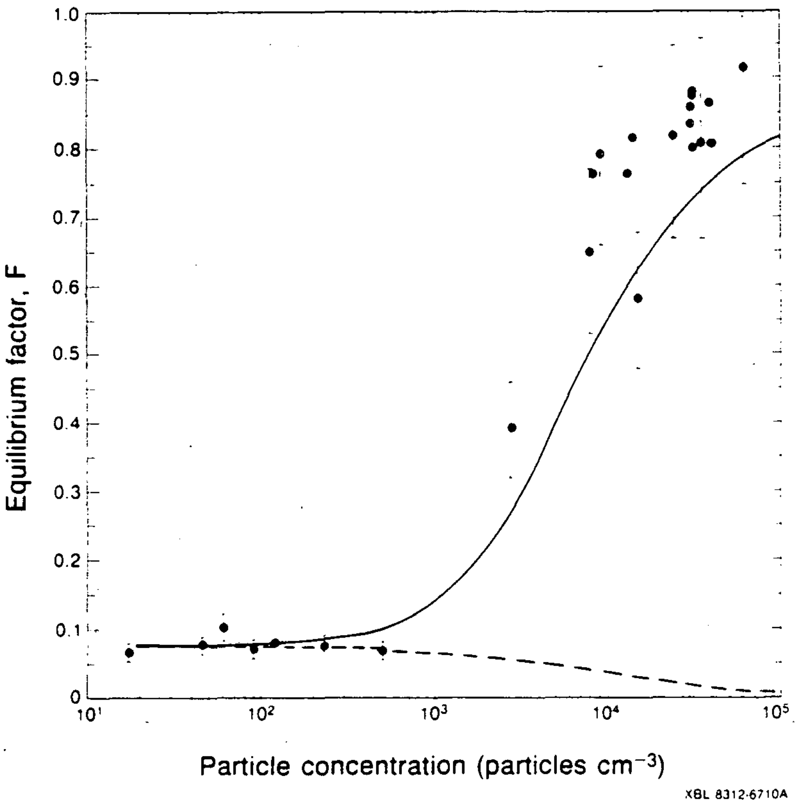

Fig. 2. Equilibrium factor, F, versus particle concentration. Measured data and representative uncertainties are indicated by the solid circles and error bars. The solid line is based on calculated values for total radon progeny while the dashed line indicates calculated values for unattached radon progeny (see text).

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