Title

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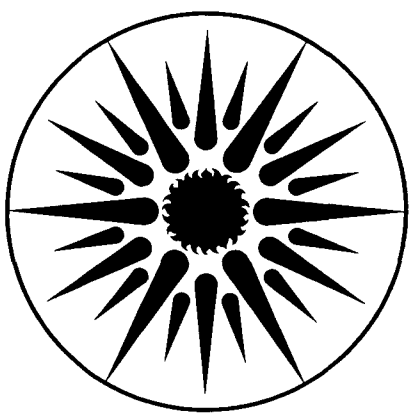

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Abstract

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. The experiments were conducted in a room-size chamber using cigarette smoke and radon injection from an external source. Of the devices 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 essentially 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. At the low particle concentrations, deposition of the unattached radon progeny on room surfaces was found to be a significant removal mechanism. Deposition rates of attached and unattached progeny have been estimated from these data, and were used to calculate the equilibrium factors for total and unattached progeny concentrations as a function of particle concentration. While particle removal reduces total airborne radon progeny concentrations, the relative alpha decay dose to the lungs appears to change very little as the particle concentration decreases due to the greater radiological importance of unattached progeny.

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 radon decay product (progeny) concentrations present in indoor air. There are a variety of air cleaning devices available, both portable, unducted units designed primarily for use in a single room, and ducted devices designed for installation in forced-air heating/cooling systems. Tests of several unducted devices published previously (Whitby, *et al.*, 1983; New Shelter, 1982) indicated a wide range in particle removal capability.

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 (NAS, 1981), and the concentration and size distribution of indoor particles are important factors in determining the total human exposure to airborne particles (ICRP, 1966).

Radon-222 and its immediate radioactive decay products are also present in indoor air, with typical annual average radon concentrations in U.S. homes ranging from 5 to 150 Bq m^{-3}, although radon concentrations in excess of 400 Bq m^{-3} have been observed (Nero, 1983). 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 polonium 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 radiological dose to the lungs from the alpha decay of radon progeny depends upon whether the progeny are attached to airborne particles. For those radon decay products not attached to particles the dose from the alpha decays is approximately 9 to 35 times larger than the dose from alpha decay of radon progeny attached to particles (James, *et al.*, 1981). Therefore the indoor particle concentration is an important factor in determining the ratio of unattached to attached progeny concentrations, and thus in estimating the health effects associated with indoor radon concentrations.

This paper presents an *in situ* evaluation of the effects of several types of unducted air cleaners on particle concentrations and size distributions, and the concomitant effects on radon progeny concentrations and behavior. A more complete discussion of the experimental and analytical methods are presented in Offermann, *et al.*, (1984) and Sextro, *et al.* (1985).

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 a 36 m^3 room within this test space, shown schematically in Figure 1. A cigarette smoking machine, the air cleaning device being examined, and instruments for measurement of aerosol mass and radon progeny concentration were all placed inside the test chamber, at locations indicated in Figure 1. Sampling points for external instrumentation are also shown in Figure 1.

Instrumentation

The instruments used in this study are part of computer-controlled data acquisition, monitoring and control systems installed at the IAQRH. Data are stored on cartridge magnetic tape for subsequent off-line analysis. 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 provided by 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 and analyzed 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. Aerosol mass concentration is monitored at fixed intervals by

measuring the frequency shift of a piezoelectric crystal; the change in frequency is proportional to the aerosol mass accumulated on the crystal during the measurement period.

Description of air cleaners studied

Ten air cleaning devices, listed in Table 1, were evaluated: four panel-filter units, two extended-surface filter units, two electrostatic precipitators, and two negative-ion generators. In addition, two oscillating fans were used to investigate the effect of simple air circulation on particle concentration. Air flow rates for each air cleaner containing a fan were measured using an orifice plate flowmeter described in Offermann, *et al.*, (1984). These flow rates and the fan speed setting used in the experiments are indicated in Table 1.

Each of the four panel-filter devices (PF1-PF4), ranging in retail price (1983) from $30 to $150, has a small fan which draws air through a thin flat panel of filter media. Charged electret filter media, which contain permanently charged fibers, are used in the PF2, PF3, and PF4 devices while a relatively porous uncharged foam filter is used in the PF1 device. The PF4 device also incorporates a pair of negative ion-generators with electrode voltages of –3.4 kV DC just upstream of the filter medium.

The two extended surface filter devices, ES1 and ES2, have higher retail prices, $295 and $395 respectively. The ES1 device uses an electret filter material and has a filter surface area to face area ratio of 3.8, while the ES2 device, a glass fiber High Efficiency Particle Air (HEPA) type filter, has a filter surface area to face area ratio of 32. The ES1 device also has a negative ion-generator with an electrode voltage of –6.1 kV DC located just behind the airstream discharge grill.

The two electrostatic precipitators, with similar retail costs of $370 and $395 for EP1 and EP2, respectively, are two-stage flat-plate electrostatic precipitators. The EP1 device operates at +6.2 kV DC on the ionization electrodes and on the deflection plates, which alternate with the collector plates at ground potential; the unit has a total collector surface of 0.98 m^2. The EP2 device is similarly constructed, operating at +6.5 kV DC, with 1.20 m^2 of collector surface.

The two ion-generators both produce negative ions. The IG1 device is a table-top ionizer with an emitting electrode voltage of –19 kV DC; this device also incorporates a +7.8 kV DC collector surface arranged as a 11-cm-long cylinder ~4 cm below the emitter surface. The IG2 device is a ceiling-hung ionizer with an electrode voltage of –32 kV DC.

The two circulating fans, CF1, are typical multi-speed desk-top oscillating fans. The fans, with a blade diameter of 0.30 m, were positioned on the floor approximately 0.6 m from the surface of the wall.

Measurement Sequence

Particles were generated in the chamber using a cigarette smoking machine with a smoking rate of two 35 cm^3 puffs per minute. Both sidestream and mainstream smoke were emitted into the test chamber. A typical six-minute cigarette burn consumed ~600 mg of tobacco and produced a peak concentration of ~1 to 2 x 10^5 particles cm^{-3}. After cigarette ignition, radon was injected into the test chamber in a single pulse 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 was typically between 18 and 22 ° C.

Results and Discussion

The effects of air cleaner operation on particle and radon progeny concentrations can be seen in Figures 2 through 5. As can be observed in Figure 2, the total particle concentration drops by almost three orders of magnitude when device ES2, containing a HEPA-type filter, is operated. The effectiveness of the device varies little with particle size, as the data in Figure 2 indicate. Radon progeny concentrations, shown in Figure 3, are also substantially reduced when the HEPA-type filter is operated. These results can be contrasted with the effects observed from operation of a small panel filter unit, shown in Figures 4 and 5. No measurable reduction in particle concentration is seen in Figure 4; similarly, radon progeny concentrations are unaffected, as shown in Figure 5. These results are typical for all the small panel filter units and one of the negative ion generators, IG1, evaluated in these experiments.

The results are summarized in Table 1 for both particles and radon progeny. The effect of air cleaner operation on particle concentration can be 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 the system efficiency is the ECR divided by the air flow rate through the device. 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 shown in Table 1 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 tobacco smoke aerosol. With no air cleaner operating, the decrease in particle number concentration due to natural removal mechanisms was $\sim$0.16 h^{-1}, corrected for the infiltration rate. This decay rate is principally due to particle deposition on room surfaces.

The measured radon progeny concentrations have been converted to potential alpha energy concentration, PAEC, using:

$$PAEC = k_1 A_1 + k_2 A_2 + k_3 A_3 \text{ , where} \qquad (1)$$

the subscripts i=1, 2, and 3 refer to ^{218}Po, ^{214}Pb, and ^{214}Bi respectively. The A_i are measured radon progeny activity concentrations, and the coefficients k_i account for the potential alpha decay energy and radioactive decay constant for each nuclide of interest. For A_i measured in Bq m^{-3} and PAEC in units of working level (WL), the coefficients are $k_1 = 2.78 \times 10^{-5}$, $k_2 = 1.38 \times 10^{-4}$, and $k_3 = 1.00 \times 10^{-5}$.

The performance of the various air cleaners for removal of radon progeny can be conveniently parameterized using the equilibrium factor, F, which is proportional to the ratio of the PAEC to the radon concentration, A_0:

$$F = \frac{3700\ PAEC}{A_0} = \frac{3700\ [k_1 A_1 + k_2 A_2 + k_3 A_3]}{A_0} . \qquad (2)$$

The equilibrium factors, based on progeny concentration measurements before air cleaner operation and at the end of the air cleaner operating period, are tabulated in Table 1. The resulting change in F, termed the reduction factor in Table 1, is the ratio of these

two equilibrium factors.

Particles

The results for the air cleaners examined are displayed in Figure 6, 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, PF1 to PF4, have low effective cleaning rates, less than 12 m^3h^{-1}, 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.

The devices with the highest system efficiencies were those units with extended surface filters, which were 86 and 100 percent efficient for cigarette smoke particles. These units had moderate to high effective cleaning rates. Both of the electrostatic precipitators tested had high ECR values, near 200 m^3h^{-1}, and system efficiencies of $\sim$57 percent. For the two negative ion generators evaluated, the unit with the low ECR value had both an emitter and a positively-charged collector surface, a design which appears to limit the range of the ion field and thus reduces the air cleaning effectiveness. The IG2 ionizer operated at a higher emitter voltage and had no built-in collector so that particles are removed by collection on room surfaces. This device had a moderate ECR value. The two oscillating fans (device CF1), used as a means of evaluating the effect of increased air circulation on particle removal, had negligible particle removal rates, based on changes in total number concentration. However, for particles larger than $\sim$0.5 μm in diameter, there appears to be a slight increase in particle deposition due to air circulation with the fans.

The time required for reduction of the particle concentration by 98 percent has been calculated based on the net removal rate observed for each device in the 36 m^3 chamber; these results are also shown in Figure 6. The time periods range from about 30 minutes for the ES2 device to more than 12 hours for any of the small panel filters or the IG1 ionizer.

Radon Progeny

As indicated in Table 1, those devices with large ECR values also produce large reduction factors; conversely, those devices with minimal particle removal capabilities, shown by small ECR values, have little effect on radon progeny equilibrium factors as well. In order to estimate the effects of particle concentration on radon progeny concentration, the results from the various particle control experiments were pooled, and the

equilibrium factors derived from the measured progeny concentrations were plotted as a function of observed particle concentration. These results are shown in Figure 7 as solid circles.

The overall reduction rate, Λ_i, of airborne radon progeny concentrations, is a combination of all the removal mechanisms (excluding radioactive decay, which is accounted for separately):

$$\Lambda_i = \lambda_V + \lambda_F + f_i\lambda_D^f + (1-f_i)(\lambda_D^a) \tag{3}$$

where the various removal terms are ventilation, λ_V, direct filtration by an air cleaning device, λ_F and deposition on room surfaces by progeny either unattached, λ_D^f, or attached, λ_D^a, to airborne particles, where f_i is the fraction of progeny not attached to airborne particles (unattached fraction). Based on the steady-state mass-balance equations derived by Jacobi (1972) and Porstendoerfer, *et al.*, (1978) for the various radon progeny removal modes, the overall progeny removal rate, Λ_i, can be also determined by direct measurement of the progeny activities, A_i:

$$\Lambda_i = \lambda_i \left[\frac{A_{i-1}}{A_i} - 1\right] . \tag{4}$$

Taken together, equations 3 and 4 provide a means of estimating the deposition rate of unattached progeny. The radioactive decay constants, λ_i, are known, while the ventilation rate can be obtained directly from the radon concentration measurements. We have assumed that the removal of radon progeny, either attached or unattached to particles, by the control device occurs at the same rate as for removal of particles. The unattached fraction, f_i, can be inferred from our data as a function of particle concentration (see Sextro, *et al.*, 1985 for further details). If we assume that the deposition rate of the attached progeny is the same as our estimate for the *average* particle deposition rate, 0.16 h^{-1}, the estimated *average* deposition rate of unattached progeny, using the pooled data, is 15 h^{-1},

Based on these measured and inferred removal rates, Λ_i can be estimated as a function of particle concentration. Combining equations 2 and 4, the equilibrium factor can be written as

$$F = \frac{\lambda_1}{\lambda_1 + \Lambda_1}\left[k_1 + \frac{\lambda_2}{\lambda_2 + \Lambda_2}\left(k_2 + k_3\,\frac{\lambda_3}{\lambda_3 + \Lambda_3}\right)\right] . \tag{5}$$

Using this equation, calculated values for the equilibrium factor as a function of particle

concentration for total radon progeny are shown as the solid line in Figure 2. The equilibrium factor for unattached progeny can also be calculated from equation 5 by first multiplying each k_i term by the respective unattached fraction, f_i. These results are shown as the dashed line in Figure 7. 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, on the other hand, increases rapidly as particle concentration increases from ~1000 to 25,000 particles cm^{-3}, a concentration range typical of indoor environments.

As noted earlier, the radioactive exposure due to radon progeny depends upon the relative concentrations of attached and unattached progeny. Using the dose model of Harley and Pasternak (1972), as applied by Jonassen (1982), the dose for different unattached progeny concentrations can be estimated relative to the dose calculated assuming no unattached progeny. The results are shown in Figure 7; both curves refer to the right hand scale (RHS). The relative dose curves are based on two different cases; the top curve is for children undergoing light activity, while the lower curve is estimated for adults at rest. As these estimates illustrate, the radiological effects associated with radon progeny concentrations do not decline significantly with decreasing particle concentration, even though the total radon progeny concentration (at constant radon concentration) decreases as particle levels decline.

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 Figure 7. 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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Table 1. Portable air cleaners and their effects on particle and radon progeny concentrations

Device characteristics				Particle results		Radon progeny results		
						Equilibrium factor		
Type	Number	Description	Flow rate[a] (m^3h^{-1})	ECR[b] (m^3h^{-1})	Efficiency[c] (%)	Before Operation	At end of Operation	Reduction Factor
Panel Filters:	PF1	foam filter	17; H	0 ± 2	0 ± 1	0.83 ± .14	0.83 ± .14	1.0 ± .24
	PF2	electret filter	49; H	5 ± 2	11 ± 1	0.92 ± .16	0.77 ± .13	1.20 ± .29
	PF3	electret filter	36; H	5 ± 2	16 ± 3	0.87 ± .15	0.65 ± .12	1.34 ± .34
	PF4	negative corona charging and electret filter	29; M	12 ± 3	39 ± 11	—	—	—
Extended Surface Filters:	ES1	electret filter and negative ion-generator	112; H	97 ± 3	86 ± 9	0.81 ± .14	0.068 ± .013	11.9 ± 3.1
	ES2	HEPA filter	267; M	306 ± 14	115 ± 17	0.86 ± .11	0.056 ± .007	15.3 ± 2.7
Electrostatic Precipitators:	EP1	two-stage flat plate positive corona	366; M	207 ± 32	57 ± 11	0.86 ± .15	0.070 ± .010	12.3 ± 2.8
	EP2	two-stage flat plate positive corona	340; M	187 ± 9	58 ± 6	0.82 ± .14	0.076 ± .013	10.8 ± 2.6
Ion-Generators:	IG1	residential model negative corona positive collector	—	2 ± 2	—	—	—	—
	IG2	commercial model negative corona no collector	—	51 ± 2	—	0.88 ± .15	0.10 ± .012	8.5 ± 1.8
Circulating Fan:	CF1	oscillating fan 2 units	3060[d]; H each	2 ± 2	0 ± 1	0.81 ± .14	0.58 ± .10	1.40 ± .34

a. Measured with an orifice plate flowmeter at the fan speed indicated; (H - high; M - medium).

b. Effective cleaning rate (ECR) calculated as the flow rate of particle free air required to produce the observed decay rate in cigarette smoke (± 90% confidence limits).

c. Efficiency calculated as the observed effective cleaning rate (ECR) divided by the measured air flow rate (± 90% confidence limits).

d. Flow rate as reported by the manufacturer.

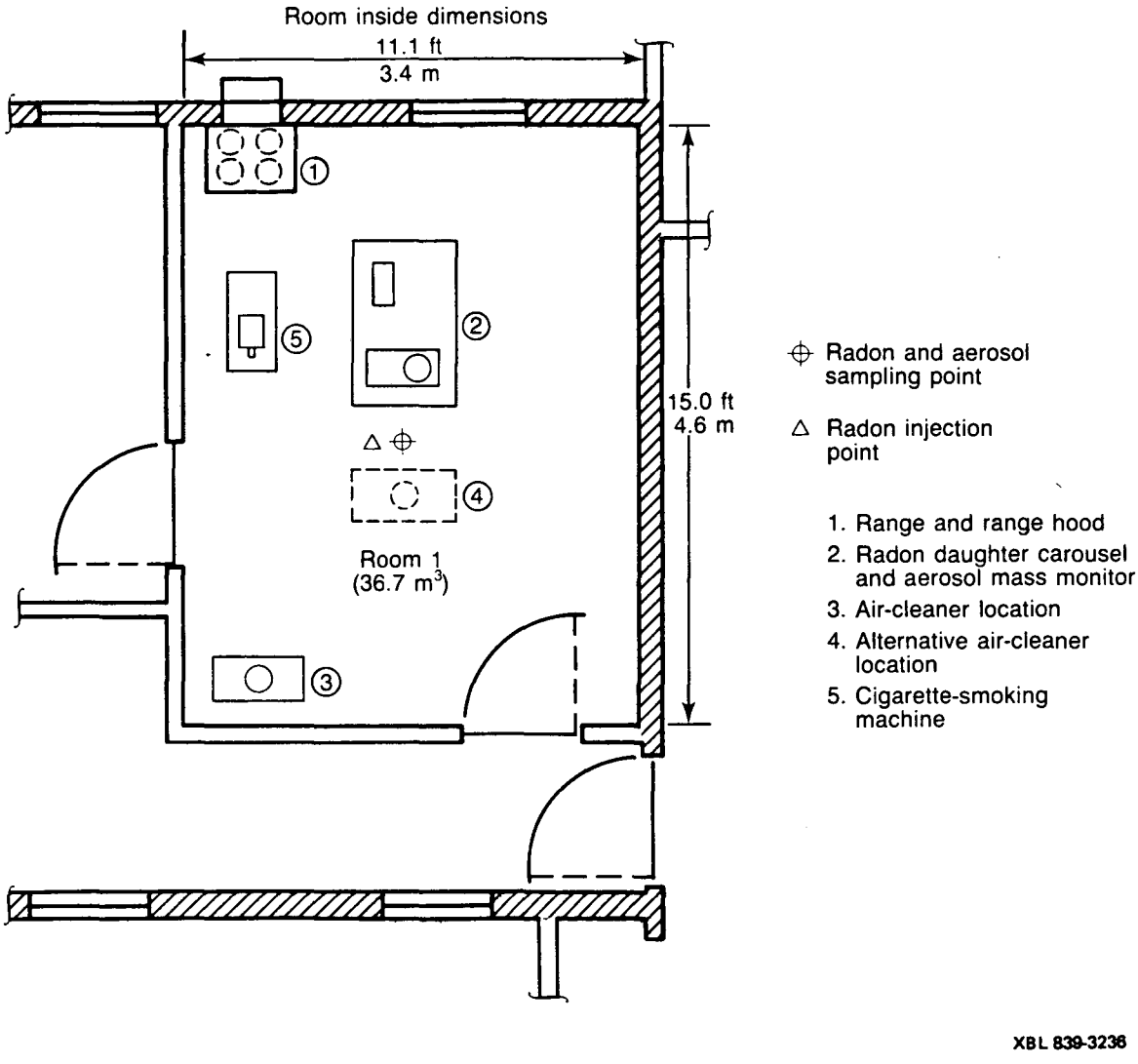

Figure 1. Floor plan for the 36 m^3 test chamber at the LBL Indoor Air Quality Research House.

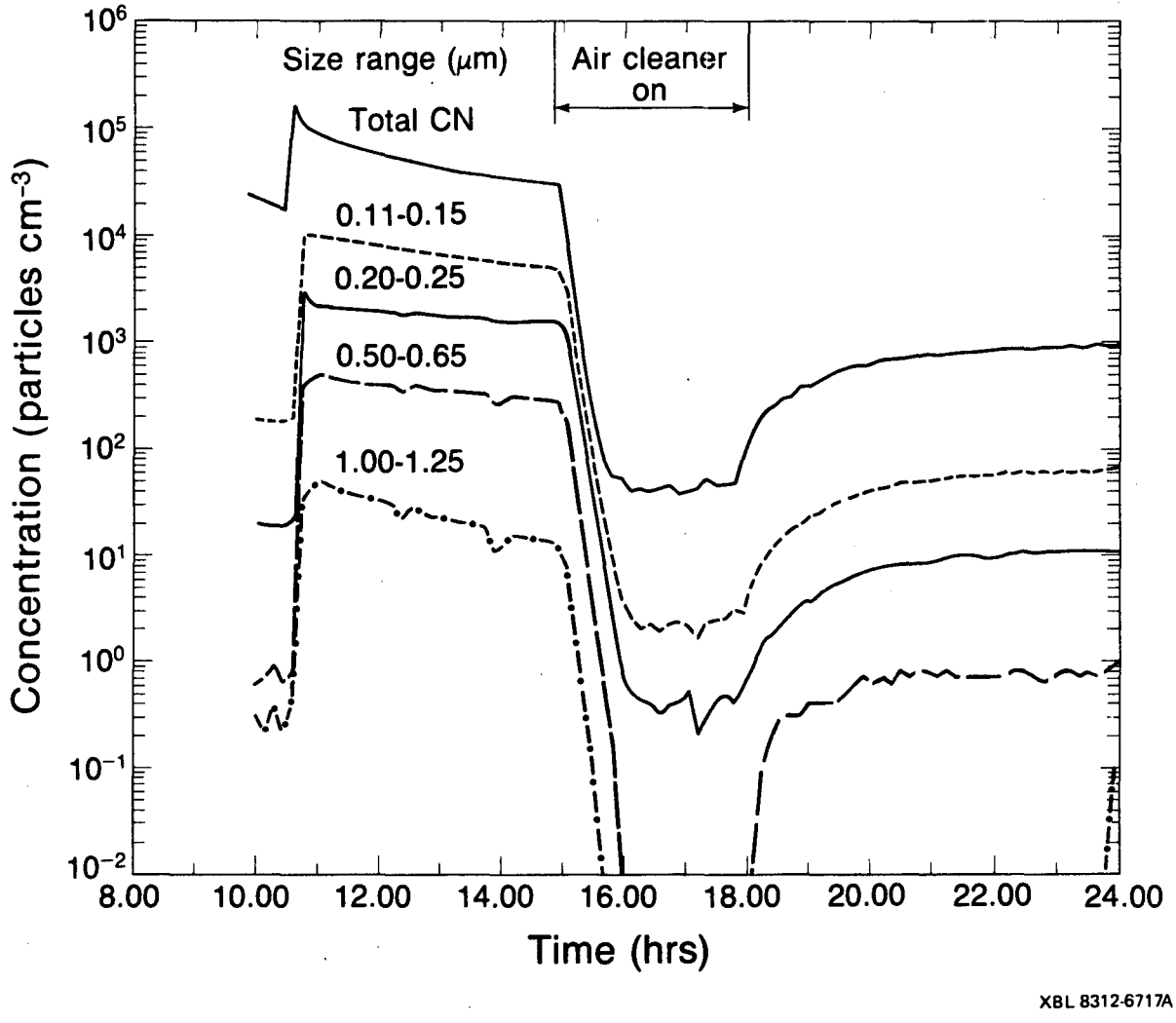

Figure 2. Particle concentration as a function of time, showing the effect of operation of a portable air cleaner utilizing a HEPA-type filter. The increase in particle concentration after device operation appears to be due to infiltration of particles in outdoor air.

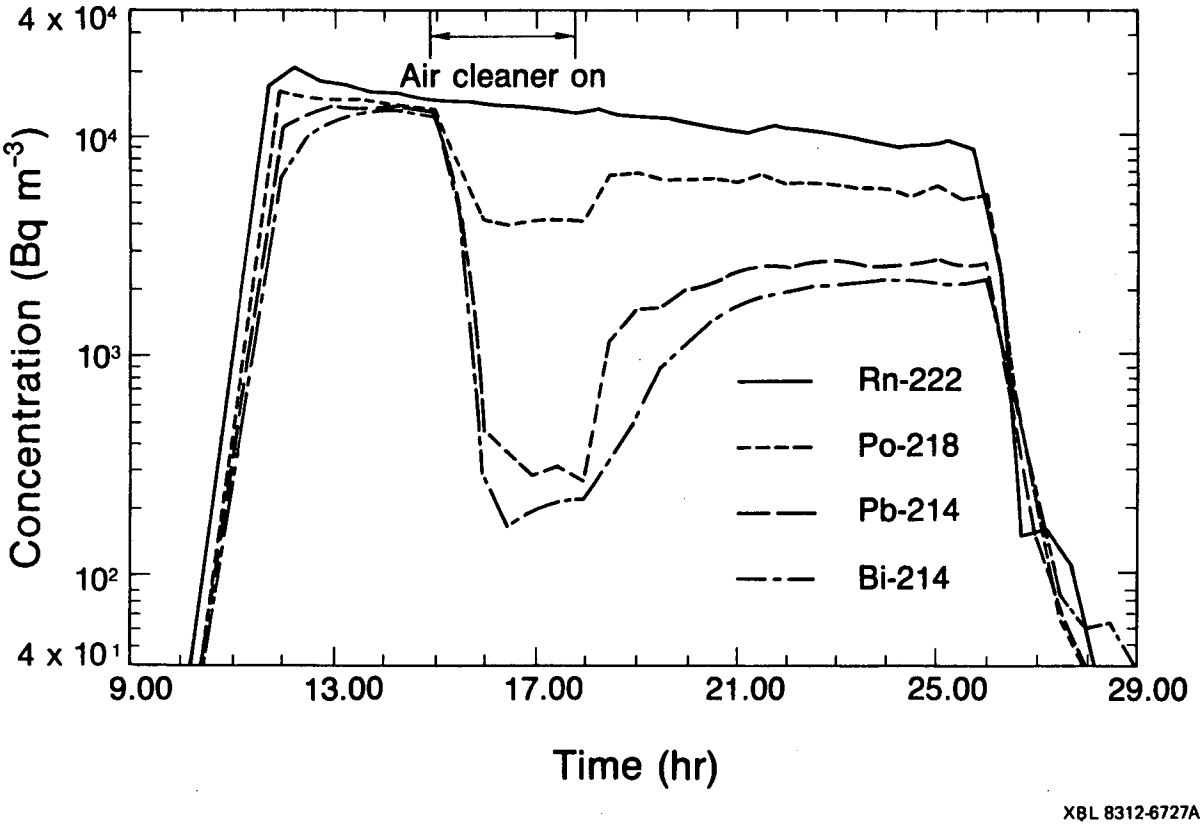

Figure 3. Radon and radon progeny concentration as a function of time. The effect of operation of the HEPA-type filter is indicated. The sharp decrease in radon and radon progeny concentrations shown in the figure is due to ventilation of the test space at the end of the experiment.

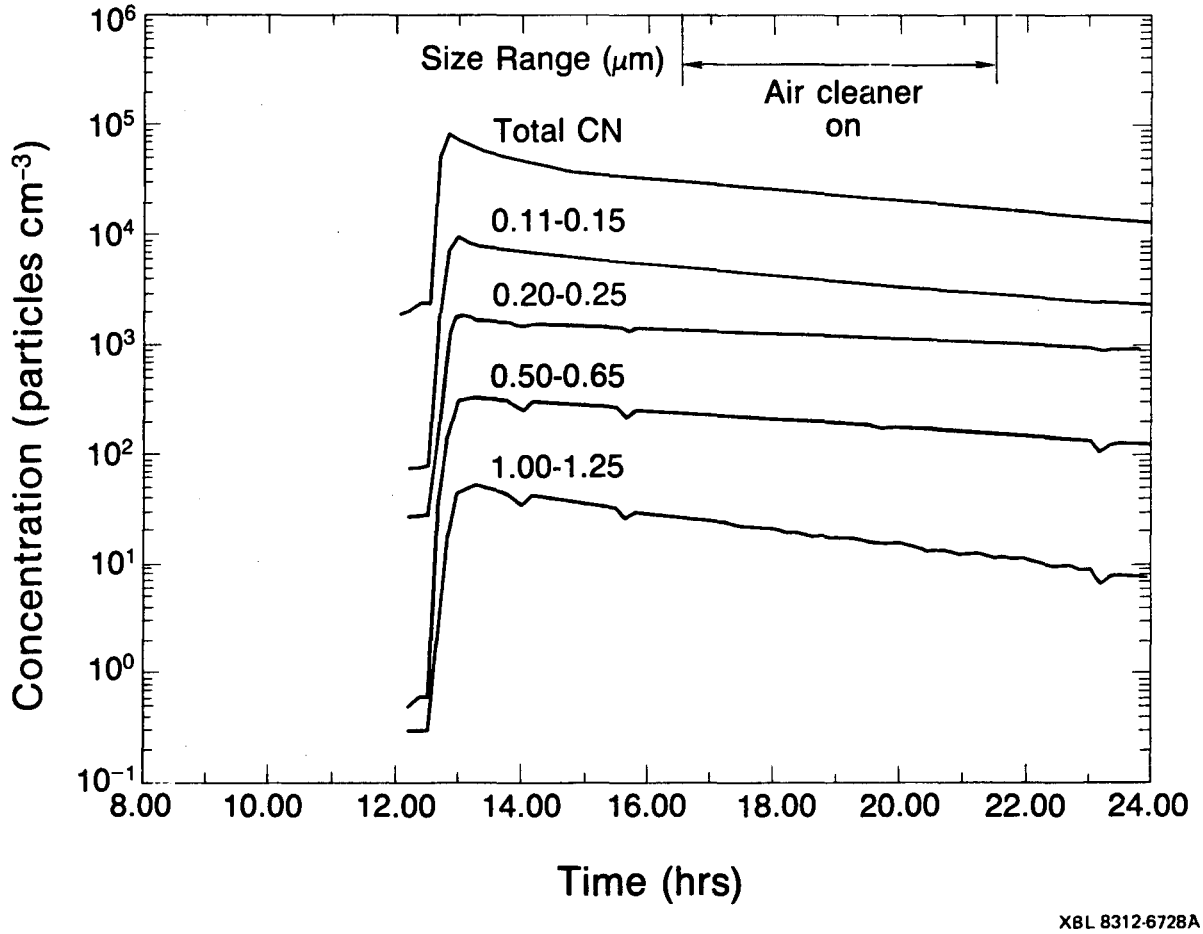

Figure 4. Similar to Figure 2, except the air cleaner used was a small panel filter device.

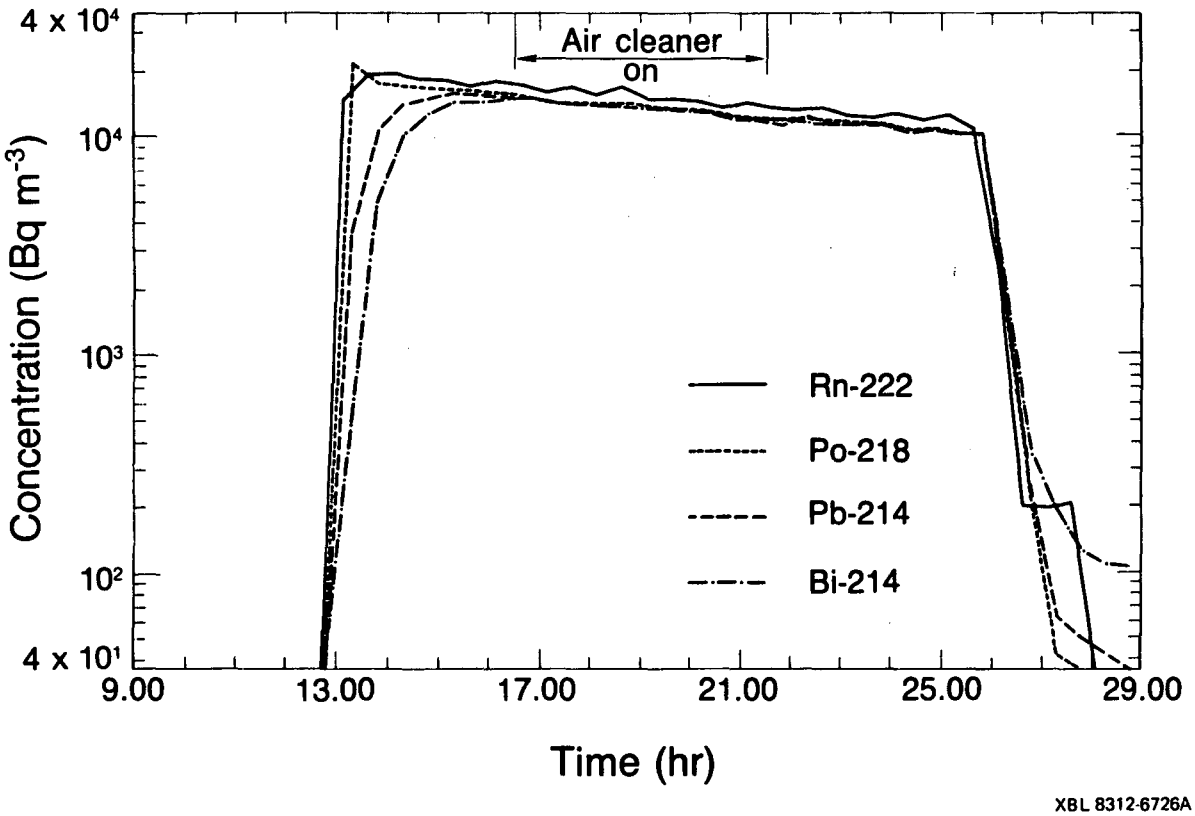

Figure 5. Similar to Figure 3, except the air cleaning device was a small panel filter.

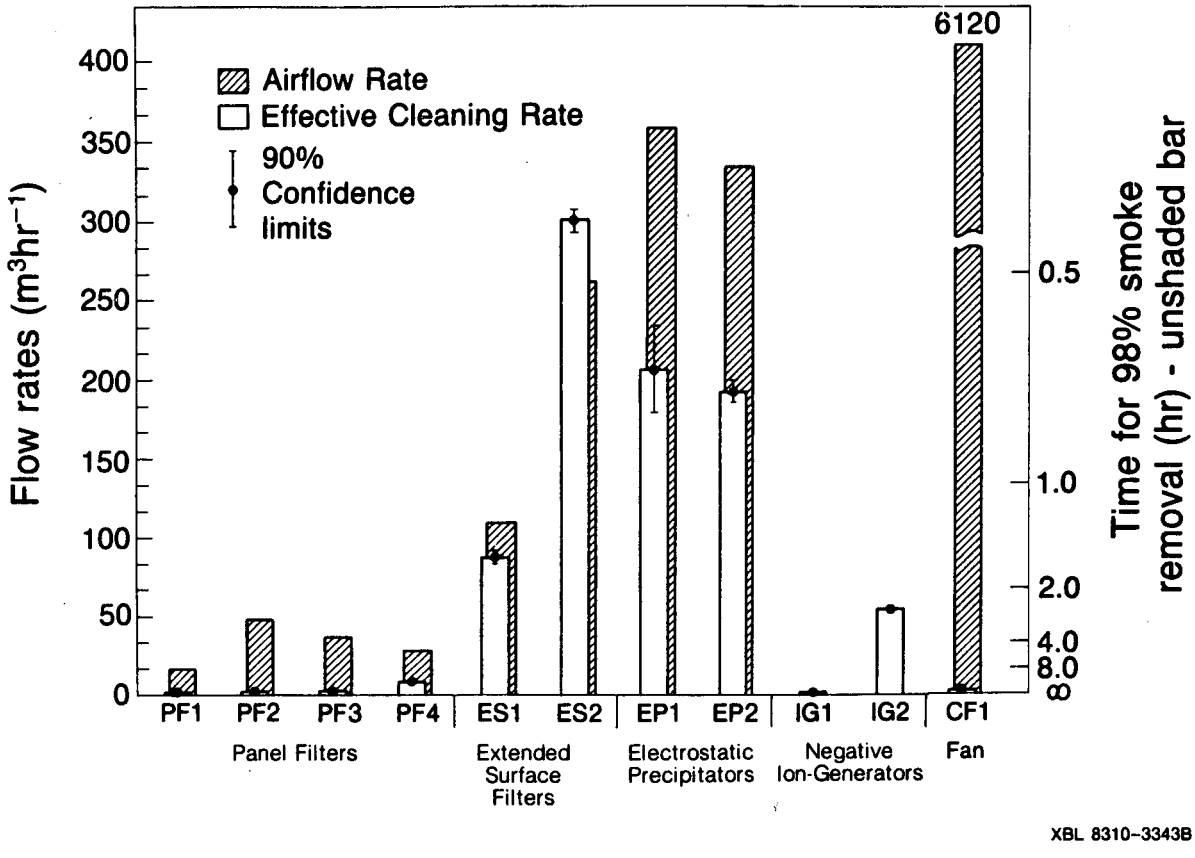

Figure 6. Effective cleaning and air flow rates for several types of air cleaning devices evaluated in this study. The right axis indicates the time required (in hours) for removal of 98 percent of the particles for each device (unshaded bar) in the 36 m^3 chamber.

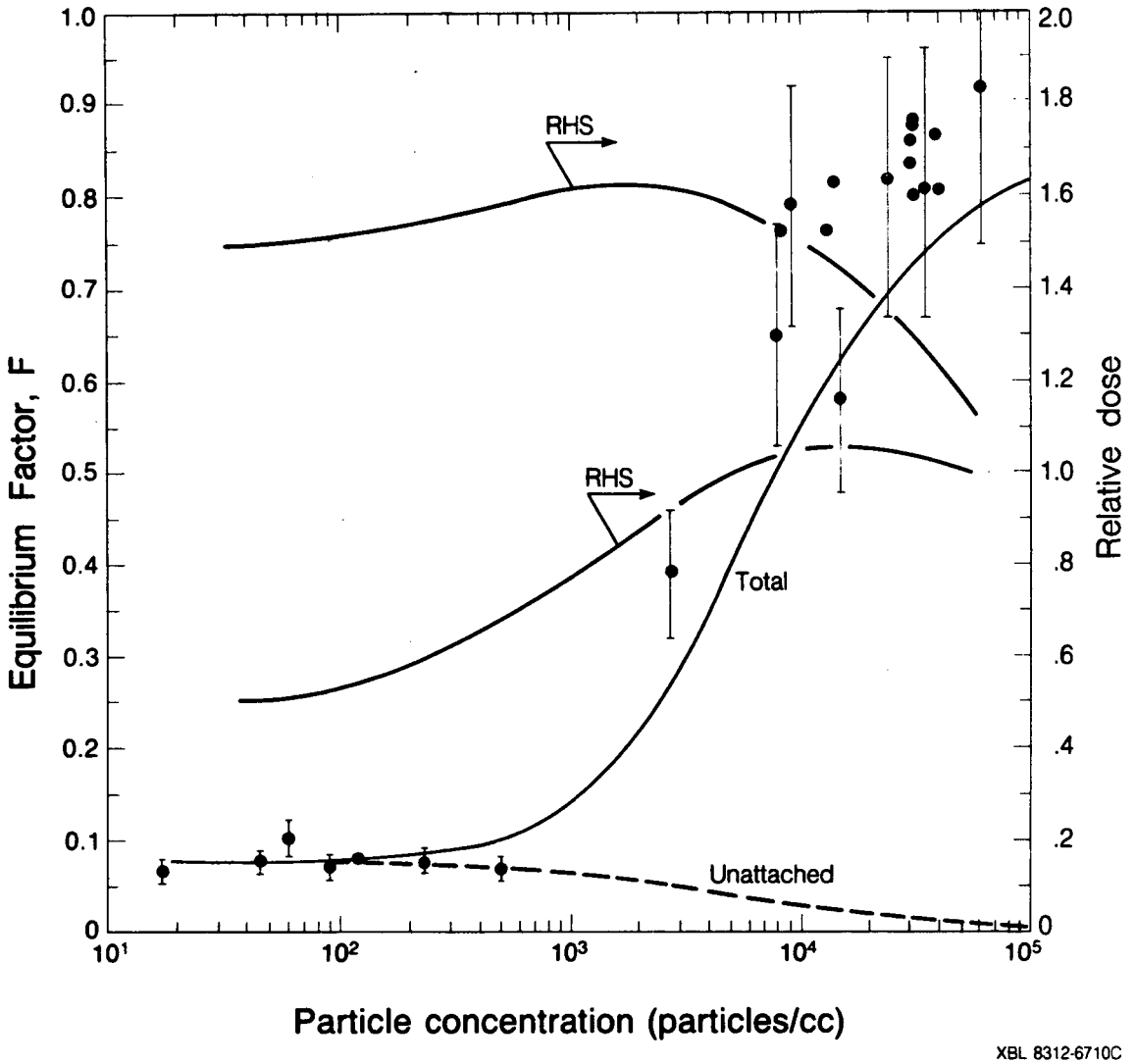

Figure 7. Equilibrium factor, F, versus particle concentration. Measured data and representative uncertainties are indicated by the solid circles and error bars. The solid line labelled Total represents calculated values of F for total airborne radon progeny concentrations while the dashed line indicates calculated F values for unattached radon progeny only (see text). The relative dose curves, which refer to the right axis (RHS), are for children undergoing light activity (upper curve) and adults at rest (lower curve). These relative dose curves should be regarded as illustrative, rather than accurate dosimetric predictions.

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