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FILTRATION FOR CONTROL OF EXPOSURE TO RADON PROGENY: THEORY AND EXPERIMENTAL RESULTS

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ABSTRACT

The theoretical optimization of the characteristics of a recirculating filter system that minimize an individual's dose from the inhalation of radon progeny is described. The computer simulation presented combines models for a well-mixed room, lung deposition, and lung dose equivalent. A modified form of the Porstendorfer-Jacobi room model and the Jacobi-Eisfeld lung dosimetry model are used for the simulation. The goal is to determine optimal filter characteristics for reducing the lung dose equivalent under specified room conditions. The parameters of the filter that are optimized include the filter solidity, filter thickness, and fiber diameter. The resulting optimal design is a thin filter of low solidity composed of relatively coarse fibers. This analysis indicates that a significant reduction in the dose-equivalent rate can be achieved through the use of a properly designed recirculating filter system. Data from laboratory tests using three different filter designs are presented. Although the data do not appear to support the theoretical predictions, the preliminary nature of the experiments do not justify drawing any conclusions at this time.

INTRODUCTION

During the past several years there has been increased interest in the presence of radon in homes, mostly due to the realization that radon concentrations in homes can be thousands of times higher than previously suspected. This interest has resulted in an increased level of research into how to reduce the dose equivalent to people breathing the contaminated air. To date, the majority of this research has been directed toward the prevention of the entry of radon gas into the breathing zone. The present research focuses on the filtration of room air to remove radon decay products. The objective is the evaluation of the practicality of using a recirculating filter system as a mitigation device.

MODELING

The well-mixed room model in Figure 1 illustrates the relationships among particle concentration, ventilation, surface deposition, filtration, and source terms. In this model, steady state conditions require that the production terms equal the loss terms for particles within the room. Under these conditions, with no filter operating, the source term is equal to the rate of loss through exchange with outdoor air (accounting for the outdoor dust brought indoors), and the loss due to deposition on room surfaces.

The air exchange rate is defined as the ratio of the air flow into and out of the room divided by the volume of the room. The surface deposition rate for a specific particle size (or the "plateout rate") is defined as the rate at which one room volume of air is cleared of particles of that size. This is defined as the deposition velocity of the particles times the surface area of the room divided by the room volume. In this model, particles are assumed not to be resuspended once deposited on a surface. Based on measurements performed under laboratory conditions, the deposition velocity of unattached radon-222 decay products has been estimated to be in the range of 2 to 10 mm/s. For this model, 2.3 mm/s is used for the deposition velocity and 5 mm^2/s for the diffusion coefficient.(1)

The filter efficiency is a function of the characteristics of the filter, including the thickness of the fibrous mat, the filter solidity (i.e., the ratio of the volume of the fibers to the total volume of the filter), and the diameters of the fibers. For a given fiber diameter, a "single fiber efficiency" which is a function of the velocity past the fiber and diameter of the particle can be calculated. The relationship of the single fiber efficiency to the overall efficiency is determined by integrating over the thickness of the filter and the distribution of particle sizes. Although most filters are made up of fibers with a range of diameters, this model uses a single fiber diameter. The three filter parameters that are adjusted for purposes of optimization are the solidity, the filter thickness, and the fiber diameter.

The filtration rate is defined as the flow through the filter divided by the volume of the room. At a specified particle size the clean air delivery rate is defined as the filtration rate times the filter removal efficiency for that particle size. Although the clean air delivery rate is the important parameter for maximizing particle removal in a room, it is not the parameter of primary interest for radon. What is important in evaluating filter performance is the "filter effectiveness"; the steady-state ratio of the dose-equivalent rate from the airborne decay products before and after treatment.

The other variable of interest is the filter face area. For purposes of these calculations, the filter area was set equal to 1 m^2. Using these variables, and weighting the single fiber efficiency at each particle size by the particle size distribution, the filter model is applied over the entire range of particle sizes. This weighting factor is also applied to the processes of deposition, air exchange, and the source term.

Practical considerations in the design of filters include limitations on the filter characteristics, the aerodynamic noise produced by the fan, the pressure drop, and the velocity of the air through the filter. Limitations were placed on the allowed variation of the filter design parameters to restrict these parameters to practical values. Following this approach, the filter solidity was allowed to vary from 0.5% to 35%; the filter thickness from 0.1 to 100 millimeters; and the fiber diameter from 0.1 to 100 micrometers. Another limitation placed on the filter design was that the filter velocity not exceed 5 m/s (980 fpm, 11 mph), as this was regarded as the highest acceptable breeze from the fan.

From the fan law for aerodynamic noise, this noise is related to the pressure drop as an exponential function of the difference between the operating sound power level and a reference sound power level. For most vane-axial and centrifugal fans the reference sound power level varies from 45 to 55 dB (defined as "the sound power level of a homologous fan when producing a fan flow rate of unity [1 cfm] at a fan total pressure of unity [1 in. H_2O] at the same point of rating") (2). For this analysis the operating fan noise was restricted to no more than 15 dB higher than the reference sound power level. Holding the fan noise constant allows for the comparison of a wide range of different filter and fan combinations.

To simulate radon decay products in the room, the Porstendorfer-Jacobi room model was used (3). This model was modified by adding an expression for removal by the filter to it, and includes the interactions between radon decay products, particles in the air, and various sources and sinks as illustrated in Figure 2. The steady-state conditions describing the concentrations of radon and its decay products in room air were written in terms of the activity of the various nuclides inside and outside the room. These concentrations depend upon the efficiency of the filter, radioactive decay, exchange with outside air, deposition of particles on room surfaces, attachment of free decay products onto airborne particles, recoil of decay products from particles, and filtration.

The model used to calculate the dose-equivalent rate delivered to the lung tissue by the decay products was developed by Jacobi and Eisfeld (J-E) (4). The steady-state equations describing the activity retained in each generation were written as functions of the free and attached decay product activities breathed into the lungs, radioactive decay, deposition of the particles onto the lung surfaces, desorption of decay products from particle surfaces, movement of the decay products by muco-ciliary clearance, and diffusional transfer to the blood. For the purposes of optimization, the full J-E lung dose-equivalent model was used. However, to determine the filter effectiveness under laboratory conditions a simpler (linear) approximation (4) is used to calculate the mean dose-equivalent rate delivered to the basal cell layer of the Tracheo-Bronchial (T-B) region of the lungs:

$$\overline{DE}_{TB} = \frac{(0.006 + 0.042f)PAEC}{170} \qquad (1)$$

where $\overline{DE}_{TB}$ = Mean Lung Dose Equivalent Rate, Sv/hr
PAEC = Integrated Potential Alpha Energy Concentration, WLM
f = Unattached Fraction of PAEC
170 = Number of hours in a WLM

OPTIMIZATION METHODOLOGY

The objective of the optimization of filter design is to reduce the lung dose-equivalent rate to a minimum. This can be achieved by defining the function to be minimized as the ratio of the lung dose-equivalent rates from breathing room air with a filter operating compared to breathing room air without a filter operating. The filter design that produces the minimum value for this ratio is the optimum design.

Multi-parameter optimization was performed using the Modified Simplex Method (MSM) of Nelder and Mead (5). This procedure permits a simultaneous optimization of filter thickness, solidity, and fiber diameter using an adaptive, iterative, sequential search of the response surface, defined in this application as the ratio of the dose-equivalent rates from filtered and unfiltered room air. The MSM has been shown to be quite robust in finding true optima without calculating derivatives (6).

Using the approach applied in these studies, unimodality is not assured. To ensure that the technique has found the true global optimum, random starting points were chosen and repeated full optimizations performed. At least 100 such optimizations were run to assess the location of the optimal parameter set. In each case, a strict convergence criterion was set to avoid finding of "false minima" in regions of slow response change.

For optimization, certain initial conditions were specified for the calculation of the conditions within the room. The indoor ^{222}Rn concentration was set at the EPA remedial action level of 148 Bq/m^3 (4 pCi/L). The outdoor ^{222}Rn concentration was set at 5 Bq/m^3 (7). The ratio of decay product concentrations outdoors to the ^{222}Rn concentration was set at 1 : 0.8 : 0.65

(for ^{218}Po : ^{214}Pb : ^{214}Bi) (8). The surface to volume ratio of the room was set to 1.45 m^{-1}, with a room volume of 80 m^3. The exchange rate between the room and outdoor air was set at one air change per hour (1 ach). The aerosol was assumed to have a concentration of 20,000 particles/ cm^3 (of unit density), and to be lognormally distributed with a count median diameter of 0.06 micrometer and a geometric standard deviation of 2.0. (9)

Without the filter in operation, estimates of radon decay product concentrations in the room air were calculated to be 122 Bq/m^3 for ^{218}Po, 65 Bq/m^3 for ^{214}Pb, and 43 Bq/m^3 for ^{214}Bi, with 4.6% of the decay products in the free state. This corresponds to a Potential Alpha Energy Concentration (PAEC) of 0.02 Working Level (WL), and an equilibrium factor of 0.42. The mean dose-equivalent rate to the basal cells of the T-B region was calculated to be 10 μSv/hr.

Based on the results of the analytical routine, the optimum filter design was found to be a thin filter (less than 0.7 mm), with low solidity (less than 1%), and coarse fibers (greater than 30 μm). (The optimization of a filter in reducing the lung dose-equivalent rate in room air was more fully discussed in an earlier paper (10).) Concentrations of radon decay products in the treated room air were estimated to be 39 Bq/m^3 for ^{218}Po, 9.7 Bq/m^3 for ^{214}Pb, and 7.2 Bq/m^3 for ^{214}Bi, with 6% of the decay products in the free state. This corresponds to 0.003 WL, and an equilibrium factor of 0.08. The mean dose-equivalent rate to the basal cells of the T-B region was calculated to be 2.2 μSv/hr or 22% of the estimate for the unfiltered rate.

EXPERIMENTAL RESULTS

Three different filter designs were tested in a preliminary phase of experimentation: a High Efficiency Particulate Air (HEPA) filter; a very light, coarse filter (the "furnace filter"); and a filter with intermediate solidity, fiber diameter, and efficiency (the "pre-filter"). These filters were tested at comparable aerodynamic fan noise levels, as discussed above. On the basis of these dat it appears that the greatest reduction in PAEC was achieved by the HEPA filter, with the furnace filter providing lesser reductions and the prefilter providing the least. The HEPA filter also appeared to provide the greatest reduction in the T-B dose-equivalent rate. Please note, however, that these data are preliminary and subject to confirmation. Several factors, such as an using a screen sample to determine the unattached fraction and the possibility of unstable conditions in the chamber, may have perturbed the data unacceptably. Until such time as these and other questions have been answered, no conclusions can be made on the basis of this data.

CONCLUSION

From theory, it should be possible to design a filter that reduces the dose-equivalent rate delivered to the lungs from airborne radon decay products. This appears to be optimized at thin filter thicknesses (less than 0.7 mm), low filter solidities (less than 1%), and coarse fiber diameters (greater than 30 μm). However, preliminary testing of three different filter designs matched for fan noise did not support this theoretical conclusion. Further research is required, using well characterized filters across a range of designs, including as close to the theoretical optimum as is practical to manufacture, to fully prove or disprove the theoretical conclusion.

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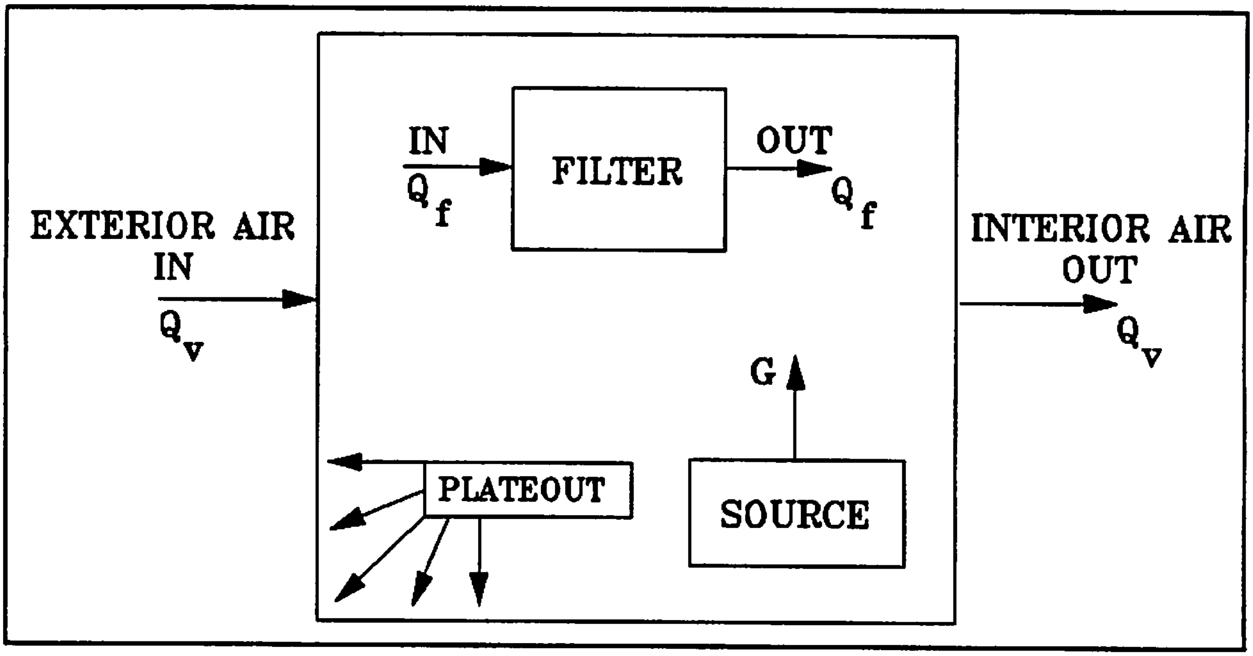

FIGURE 1. Compartmental model of particle interactions in a room.

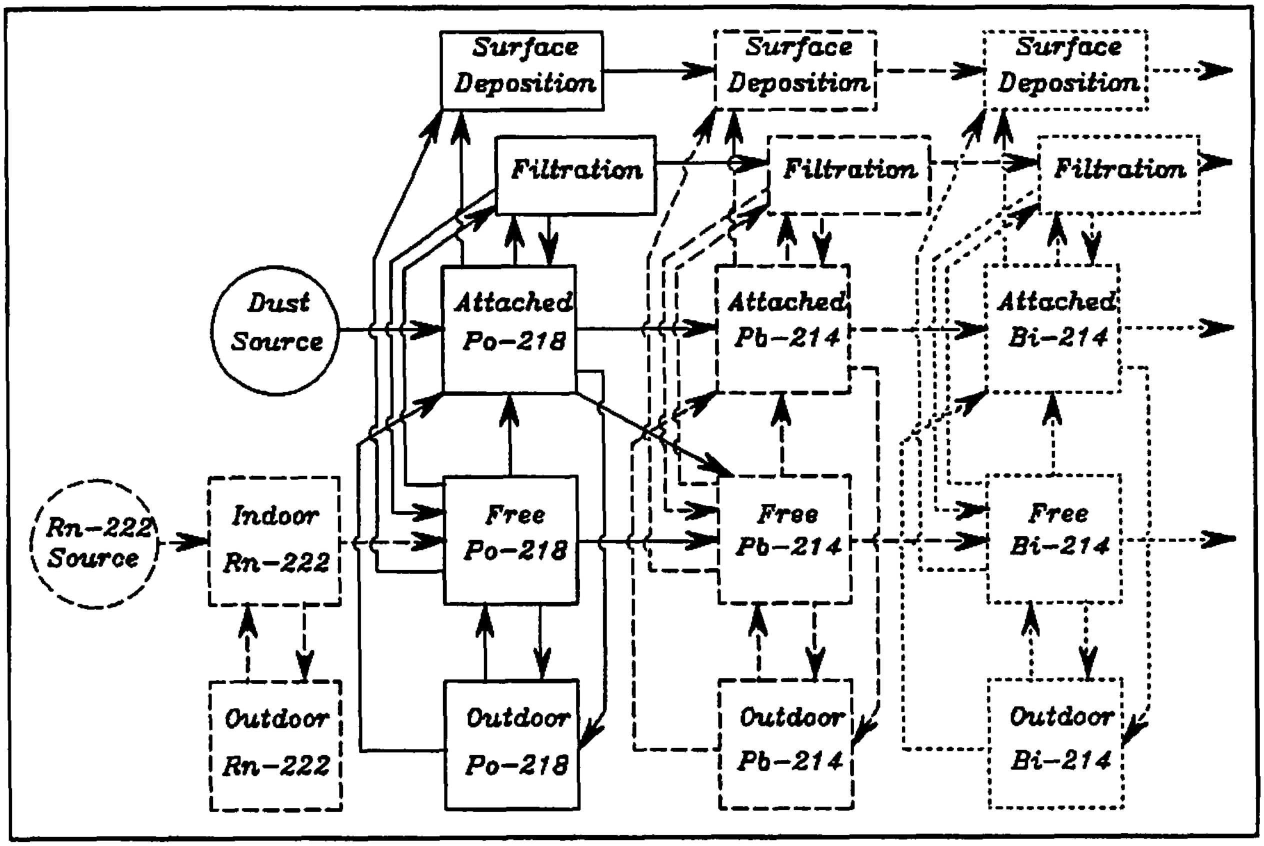

FIGURE 2. Radon decay product interactions in room air.

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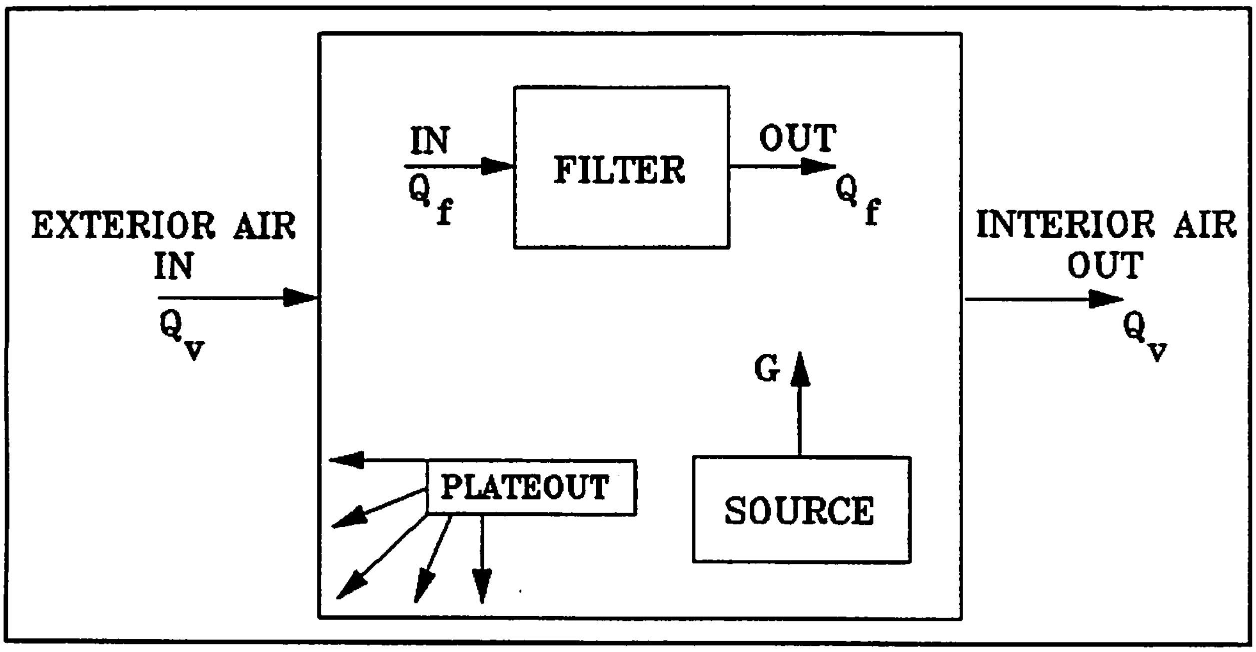

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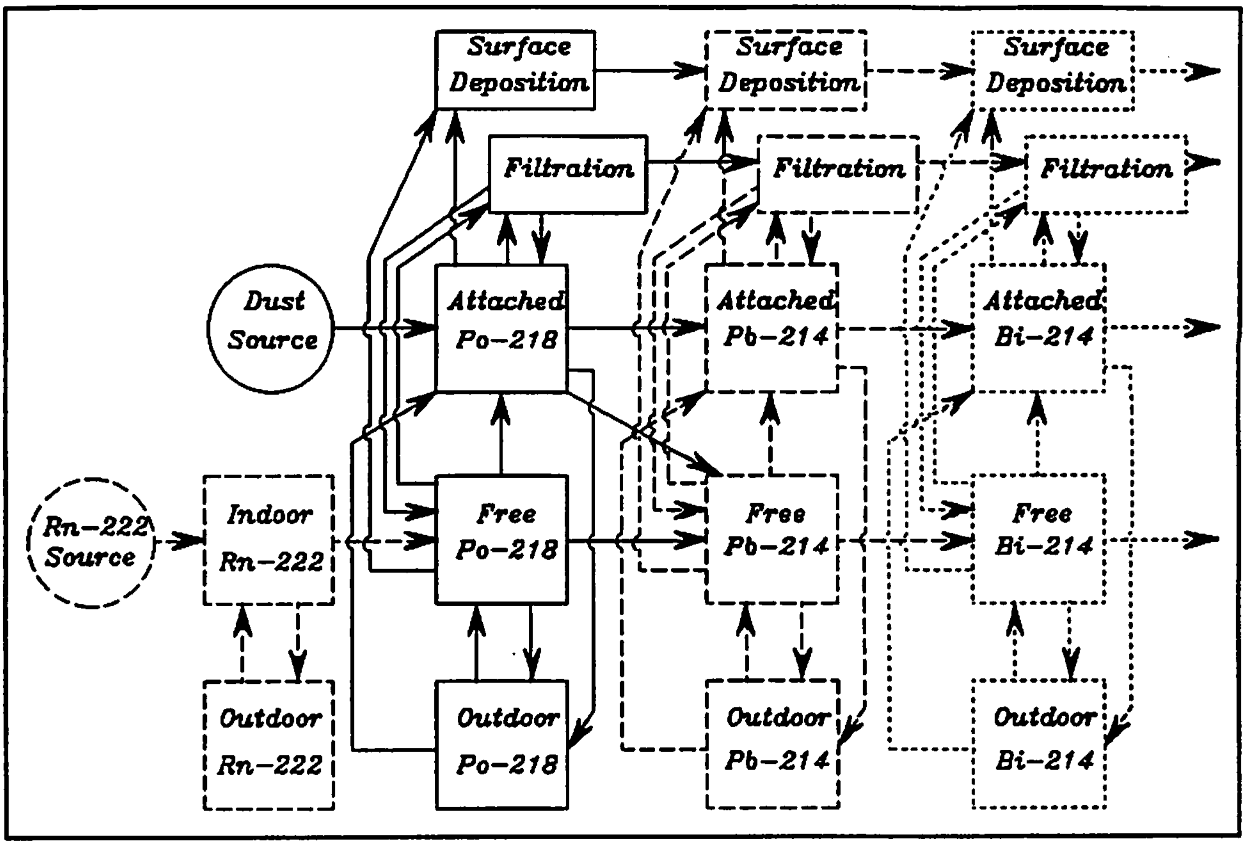

FIGURE 2. Radon decay product interactions in room air.