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^{222}RN PROGENY SURFACE DEPOSITION AND RESUSPENSION - RESIDENTIAL MATERIALS

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ABSTRACT

The radiological hazard of radon gas to occupants in residential environments is from the particulate progeny ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po, rather than ^{222}Rn itself. Attachment to aerosols, plateout and resuspension impacts on the actual progeny airborne concentrations. Plateout rate factors are measured for different air change (ventilation) rates, ACH, in a 0.28 m^3 test chamber for interior residential materials. Wallboard, hardwood (varnished), carpet, drapery, glass, ceiling tile, and concrete were used for plateout measurements. A NIST-calibrated ^{226}Ra source was used to assure constant source emanation rates (within ± 1% S.D.). ACH varied from 0 to 1.0 h^{-1} in a total of 32 plateout measurements. All measurements were made in a continuous air conditioned interior environment maintaining temperature at 22.2 ± 1.1° C and relative humidity of 30% ± 10%. The ACH was controlled to ± 1.0% S.D. The overall accuracy of the plateout rate values is estimated to be ± 15% S.D. For the different materials, the plateout rates for ^{218}Po progeny varied by nearly a factor of six. Drapery was found to provide the largest plateout rates. Computations were made of equivalent plateout rates and equilibrium fractions for a standard 5m x 5m x 3m high room to provide values to compare with other work. Resuspension rate factors, R, are measured and reported for five interior residential materials (carpet, drapery, glass, wallboard and hardwood). A new time-dependent measurement method was used to identify a small difference in buildup rate of ^{214}Po to equilibrium from the presence of resuspension and a fit was performed on the data to determine the value of R that provided the best fit. Values for R obtained for carpet, drapery, glass, wallboard and hardwood were 0.55, 0.44, 0.36, 0.29 and 0.31, respectively (± 30% S.D.).

INTRODUCTION

In evaluating the hazards from indoor ^{222}Rn, it is imperative that the behavior of the four short-lived particulate progeny are fully understood since they are the radioisotopes that deliver most of the radiobiological damage to occupants. One known characteristic of these radon progeny is that they deposit (plateout) onto macroscopic surfaces with which they come in contact. Some of these plated-out atoms become resuspended when they disintegrate and decay to the next progeny. Both of these mechanisms, plateout and resuspension, affect the airborne population of the individual daughters and their impact on the radiation energy delivered to the human respiratory system. There are two specific and separate areas of concern. One is that monitoring ^{222}Rn levels alone, such as with charcoal canisters, is obviously not sufficient to determine the radiation dose, since the daughters are never in absolute equilibrium with ^{222}Rn. Further, from an internal dose standpoint, the "unattached" fraction (free ions) of the daughters are believed, by virtue of their deeper tissue depositions in the tracheo-bronchial tract, to deliver the greatest dose in the body.

In this paper, we present experimental data of plateout rates in an indoor "closed-house" summertime environment for seven different residential interior materials. These are carpet, drapery, wallboard, hardwood (varnished), ceiling tile, concrete, and glass surfaces. We also provide results of measurement of resuspension factors. All measurements were made in July and August with continuous air conditioning controlling the temperature to 22.2°C ± 1.1°C (72°F ± 1°F) and relative humidity to 30% ± 10%. The method for the plateout measurements involved the determination of equilibrium levels of each of the radioisotopes' concentrations in a special, small, test chamber with dimensions 0.609m x 0.762m x 0.609m high (0.283 m^3 volume). The equilibrium concentrations were used to compute plateout rates. Computations were made of equivalent plateout rates and equilibrium fractions for a standard 5m x 5m x 3m high room to provide values to compare with residential measurements by others.

Currently, there are virtually no data on the measurements of both plateout rates and resuspension factors for specific individual residential material surfaces in typical enclosed ("closed-house"), seasonal (winter and/or summer), interior environments. Here we present experimental data providing specific values for resuspension factors in an indoor summertime environment for five of the seven residential interior materials (drapery, glass, hardwood, wallboard and carpet) that were also examined for plateout. The method used to obtain the resuspension factors involved the measurements of the time-dependent buildup to equilibrium for ^{222}Rn, ^{218}Po and ^{214}Po.

THEORY, MATERIALS AND METHODS

Theory

For consistency, we shall use the formulation of Leonard (1993) to provide both stationary, equilibrium relations for the plateout measurements and also time-dependent buildup relations for the resuspension measurements. The equilibrium relations have been treated by many others but are given again here for continuity and reference. We use the subscripts 1, 2, 3 and 4 referring to ^{222}Rn, ^{218}Po, and ^{214}Pb and ^{214}Bi-Po, respectively. Leonard's eqns (1), (2), (3) and (4) are generalized to account for plateout and resuspension as well as radioactive decay and air change as losses, by letting λ_i = total removal constant, i = 1. . .4, and thus

$$\lambda_1 = \lambda_{1r} + ACH \tag{1}$$
$$\lambda_2 = \lambda_{2r} + ACH + P_2. \tag{2}$$
$$\lambda_3 = \lambda_{3r} + ACH + P_3. \tag{3}$$
and
$$\lambda_4 = \lambda_{4r} + ACH + P_4. \tag{4}$$

where λ_{ir} = radioactive decay constant, ACH is the volummetric air change rate, and P_2, P_3, and P_4 are removal rates from the plateout of the airborne particulates of ^{218}Po, ^{214}Pb and ^{214}Bi-Po respectively by attachment to non-airborne surfaces, all in units of h^{-1}.

Furthermore, we define resuspension factors, R_2 and R_3 as the fractions of plated out atoms of ^{218}Po and ^{214}Pb respectively, which, upon radioactive decay to the next progeny ^{218}Po $\rightarrow$ ^{214}Pb, ^{214}Pb $\rightarrow$ ^{214}Bi-Po become resuspended. The value of R_2, for example, is the quotient of the number of atoms resuspended as ^{214}Pb and the number of atoms plated out as ^{218}Po. For the atom concentrations, C_i, in units of atoms m^{-3},

$$C_1(t) = - [\lambda_{1r} + ACH] \times C_1(t) + S_1 \tag{5}$$
$$C_2(t) = - [\lambda_{2r} + ACH + P_2] \times C_2(t) + \lambda_{1r} C_1(t) \tag{6}$$
$$C_3(t) = - [\lambda_{3r} + ACH + P_3] \times C_3(t) + [\lambda_{2r} + R_2 P_2] C_2(t) \tag{7}$$
$$C_4(t) = - [\lambda_{4r} + ACH + P_4] \times C4(t) + [\lambda_{3r} + R_3 P_3] \times C_3(t) \tag{8}$$

We examine the equilibrium case as t $\rightarrow$ ∞ where $C_1 (\infty) = C_2 (\infty) = C_3 (\infty) = C_4 (\infty) = 0$ and we obtain the steady state equations for the atom concentrations. If we let $\lambda_{ir} C_i (\infty) = A_i (\infty)$, for i = 1, 2, 3 and 4, where $A_i (\infty)$ are the equilibrium activities per unit volume in units of Bq m^{-3} we obtain simplified equations for plateout, i.e.

$$P_2 = [A_1 (\infty) / A_2 (\infty) - 1] \lambda_{2r} - ACH \tag{9}$$
$$P_3 = [(1 + R_2 P_2 / \lambda_{2r}) \cdot (A_2 (\infty) / A_3 (\infty)) - 1] \lambda_{3r} - ACH \tag{10}$$
$$P_4 = [(1 + R_3 P_3 / \lambda_{3r}) \cdot (A_3 (\infty) / A_4 (\infty)) - 1] \lambda_{4r} - ACH \tag{11}$$

To determine the resuspension factor, R_2, we will show that it was necessary by this method to measure the time-dependent buildup similar to the method of earlier work (Leonard 1993). Referring to eqns (5), (6), (7) and (8), the time-dependent buildup solutions for the airborne concentrations modified for plateout and resuspension are as follows

$$C_k(t) = \sum_{n=1}^{k} [S_n / \lambda_k] \cdot [\prod_{i=n}^{k-1} (\lambda_i / \lambda_i)] \cdot$$

$$[1 - \sum_{\beta=n}^{k} h_{n/k,\beta} \cdot \exp(-\lambda_\beta t)]$$

(12)

where $h_{n/k,\beta} = [\lambda_n / (\lambda_n - \lambda_\beta)] \cdot [\lambda_{n+1} / (\lambda_{n+1} - \lambda_\beta)] \ldots [\lambda_k / (\lambda_k - \lambda_\beta)]$

and

$$C_k(\infty) = \sum_{n=1}^{k} [S_n / \lambda_k] \cdot [\prod_{i=n}^{k-1} (\lambda_i / \lambda_i)] \cdot$$

(13)

where $\lambda_i = \lambda_{ir} + R_i P_i$ and the λ's are as given in eqns (1), (2), (3) and (4).

In a similar fashion, Leonard's (1993) solutions for the activities on a filter are modified to provide rigorous solutions which include plateout and resuspension by simply replacing all the ratios, $\prod \lambda_{ir} / \lambda_i$, with $\prod \lambda_i / \lambda_i$ in Leonard's (1993) eqns (14), (15), (17) and (18).

Plateout

From eqns (9), (10) and (11) herein, we see that by determining the concentration activities of ^{222}Rn and each of the decay products, P_2 may be determined explicitly and a relation between P_3 and the corresponding resuspension factor, R_2, may be found. To accomplish this, a series of measurements were made in a small test chamber (0.283 m^3) using an NIST-calibrated ^{226}Ra source as a constant supply of ^{222}Rn. The measurements were made with different carefully controlled, constant air change rates imposed on the chamber. Temperature and relative humidity were monitored with an electronic thermo-hydro meter.[1] The flow rates out of the chamber were continually monitored with a rotometer and routinely verified with a primary flow rate standard,[2] providing an accuracy in flow rate and thus air change rate to within ± 1% S.D. The chamber was constructed of aluminum and was electrically grounded. A small 1/8 inch port was provided to allow removal of the air with a 1/10 horsepower air pump.[3] The chamber was sealed during the measurements, with all the make-up air passing through the one inlet. A Victoreen, Inc.[4] Alpha CAM Model 758 filter airborne radioactivity detector was located inside the chamber and this instrument monitored the airborne radioactivity of the alpha-emitting daughters ^{218}Po and ^{214}Bi-Po, using a newly developed Victoreen Radon Data Acquisition System (DAS) designed especially for the Alpha CAM for radon monitoring. The air was pulled through the Alpha CAM with the air pump and then passed through a compensated ionization chamber[5] located outside the test chamber to also enable continuous determination of ^{222}Rn concentrations in the test chamber at the same time. The flow rates ranged from 0 to 3.8 liters per minute (during the time equilibrium was approached) providing a range of air change rates from 0 to 1 h^{-1}. To determine the equilibrium particulate daughter concentrations, a least squares fit of the 124 minute time-dependent decay data from one minute extracted air samples was performed using Raabe and Wrenn's (1969) method. By this method, the particulate progeny filter sample was extracted and ^{222}Rn concentrations were measured simultaneously. The ion chamber concentration response was recorded on a strip recorder and also a Data Acquisition System[6] with a PC computer (providing digital values of relative ^{222}Rn concentrations). The Triton recorder and ADC Data Acquisition System responses to ^{222}Rn gas were calibrated by de-emanating a 14 kBq ^{226}Ra source calibrated by NIST into the chamber and also by intercalibration

[1]Fisher Scientific No. 96290, Fisher Scientific, 711 Forbes Avenue, Pittsburgh, PA 15219.
[2]Buck Calibrator, Model M-30, A.D. Buck, Inc., 3139 Orange Avenue, Orlando, FL 32806.
[3]BGI, Inc., 58 Guinan Street, Waltham, MA 02154.
[4]Alpha CAM Model 758, Victoreen, Inc., 6000 Cochran Road, Cleveland, OH 44139.
[5]Triton MOdel 955B Monitor, Becton Dickinson Co., 7 Loviton Circle, Sparks, MD 21552.
[6]Model DAS 20, ADC, Keithly Instruments, Inc., 313 West Liberty Street, Lancaster, PA 17603.

of ^{222}Rn with another laboratory[7] by intercomparison of charcoal canister activities. By using the Alpha CAM detector inside the chamber, it was not necessary to open the chamber for counting, as has been the usual case for other investigators. The data acquisition system was designed to automatically synchronize the counts with the air sample pump for the one-minute, sample extraction and immediately begin counting of the decay of activity obtained on the filter at one minute intervals, at the end of the electronically controlled 60-second sample extraction period.

A total of 31 different measurements are reported. The materials were cut into six separate panel sections, one for each side, top and bottom, to snugly fit inside the chamber. All corner cracks were sealed with strips of duct tape to prevent the chamber air (and thus the Rn and daughters) from circulating behind the panels. Monitoring of the time-dependent buildup of ^{222}Rn (with the Triton monitor) and the ^{218}Po and ^{214}Bi-Po daughters (with the Alpha CAM) was performed from beginning of buildup to chamber equilibrium to verify the buildup and that equilibrium was indeed achieved. The DAS also recorded complete alpha particle energy spectra at preset times during the buildup stage to verify that the spectrum had not shifted from voltage or amplifier gain fluctuations. At the end of the buildup period, the DAS was reset to accumulate count data from the Alpha CAM at one-minute intervals to acquire the one-minute sample extraction and 124 minute decay data to determine the progeny concentrations by the least squares method of Raabe and Wrenn (1969). The air pump was set to Hi-Volume flow of 59 lpm and the automatic timer was set to one minute for Hi-Volume flow. With everything synchronized, the one-minute Hi-Volume sample was obtained and the DAS automatically recorded the Alpha CAM one-minute counts for 124 minutes to obtain the decay data of ^{218}Po and ^{214}Bi-Po on the filter. Also, during the decay period, progeny alpha spectra were recorded automatically with the DAS.

Resuspension

For a pre-determined ratio of activity concentrations of ^{218}Po and ^{214}Pb there is a range of combinations of P_3 values possible dependent upon the value of the resuspension factor, R_2, as given by the one-to-one linear relationship in eqn (10). To this author's knowledge, no one has explicitly measured the value of the resuspension factor, R_2, for the decay of ^{218}Po and resuspension of the daughter ^{214}Pb by recoil in residential environments. This is true for R_3, also. Investigators have speculated that the resuspension factor, R_3, for the recoil of ^{214}Bi-Po after the beta decay of ^{214}Pb is essentially zero, since the recoil from the beta decay is small ($\leq$ 5eV, average = 2.7eV). Since the molecular potential energy of a molecule attached to a surface is only about 1 eV, recoil is however technically feasible. Bigu (1991) has examined beta decay recoil for ^{220}Rn progeny both in vacuum and at atmospheric pressure and found desorption of ^{220}Rn progeny under vacuum conditions to be significant but, at normal pressure, to be approximately 10^{-3} or less under his experimental conditions. We let $R_3 = 0.001$ in the theoretical equations for the calculations herein.

The true value of P_3 is monotonically and linearly related to the variation of R_2 for fixed ACH and fixed experimentally determined ratio of $A_2 (\infty) : A_3 (\infty)$ and thus the values of P_3 and R_2 cannot be uniquely determined solely by this ratio. However, the rate in which the measurable progeny concentrations for ^{214}Pb and ^{214}Bi-Po build-up will depend slightly on the relative degree of plateout, P_3, and resuspension, R_2. This is because, the larger the resuspension of ^{214}Pb from decay of ^{218}Po, then the more quickly ^{214}Pb and ^{214}Bi-Po will reach final equilibrium levels with ^{218}Po. Mathematically, this effect is simply because the λ_{β} coefficients in the time-dependent exponential functions of the solution, i.e., eqn (12) herein, contain the plateout rates (P's), which if larger due to resuspension, cause the concentrations to achieve equilibrium more quickly. The final values of $A_2 (\infty) : A_3 (\infty)$ will be the same in either case, but there will be a slight difference in the rates at which ^{214}Pb and ^{214}Bi-Po build up and approach equilibrium.

Using the theoretical equations for time-dependent buildup on a filter, we can examine this. Fig. 1 provides graphs of the calculated time-dependent buildup of ^{218}Po and ^{214}Bi-Po alpha activities on a filter for ACH = 0.268 h^{-1} (for Run 90 for glass) for the two cases of R = 0.0 and 0.5. The measured equilibrium concentration activities, obtained by the method described above, were $A_2 = 1158$ and $A_3 = 510$ Bq m^{-3}, so we obtain from eqn (15), $P_3 =$

1.70 h^{-1} if R$_2$ = 0 or P$_3$ = 8.57 h^{-1} if R$_2$ = 0.5. Fig. 1 shows the slight difference in ^{214}Bi-Po buildup with time for the two sets of P$_3$ and R$_2$ with ^{214}Bi-Po building up slightly more rapidly for R$_2$ = 0.5. The normalized buildup of ^{218}Po is the same in Fig. 1 for both sets of R$_2$ and P$_3$, since the concentration of ^{218}Po is not affected by resuspension when ^{218}Po decays to ^{214}Pb. This difference in accumulated ^{214}Bi-Po occurs primarily in the first several hours after buildup begins. One can compute what we refer to as the Accumulated Standard Deviation (A.S.D.) - "square root of sample variance" (Evans 1982) - of this difference beginning from time t = 0, for these two curves.

Leonard (1993) has found in his method to measure ACH that Integral experimental buildup data provides a much greater degree of statistical accuracy since the total accumulated counts for each data point are much larger than Count Rate values acquired over smaller intervals of time. Therefore, integral data are reported here. In summary, we have shown that the theory indicates that it should be possible to obtain a measure of resuspension factors, R$_2$'s, from the slight variation of the experimentally measured time-dependent buildup on a filter of ^{214}Bi-Po to equilibrium from that which would be the case without resuspension. This method is applied herein. The method used to measure the time-dependent buildup of ^{218}Po and ^{214}Po alpha activities using the Alpha CAM continuous air monitor is fully described in the earlier paper presenting the measurements to determine air change (ACH) rates (Leonard 1993).

RESULTS

Plateout

Fig. 2 provides graphical presentations of the data for plateout of ^{218}Po, P$_2$, for varnished hardwood, wallboard, drapery and carpet with single values for glass, concrete and ceiling tile. Fig 3 provides a bar graph comparing plateout rates for all seven materials at ACH = 0.35 h^{-1}. As would be expected, the plateout data reflect a large plateout effect from the surfaces in the test chamber as compared to values reported by others for actual residential measurements. The chamber configuration provided a SF/V ratio of about 10 as compared to a typical residential room that would have a SF/V of about 1.5. This larger value of SF/V enabled excellent, statistically significant, data to be obtained on the effects of plateout. Figs. 2 and 3 indicate a very large plateout of ^{218}Po for the drapery material. This may primarily be due to the fact that the drapery was lined and wallboard was provided as the back surface to the chamber such that there existed considerably greater surface when the two layers of fabric and the wall are all considered. One would expect a high plateout rate in a "life-sized room" with a large amount of drapery material. The ceiling tile had a coarse surface, which may explain the high value for ^{218}Po plateout. It would be expected that carpet would exhibit a greater plateout than the smoother surfaced materials such as wallboard, hardwood and glass. All the graphs of plateout rate vs. ACH show a decrease in plateout in the middle range for values of ACH between 0.1 and 0.7 h^{-1}. The data that extend to 1.0 h^{-1} show a flatness or even perhaps a small increase in plateout rate.

Since a considerable amount of measurements of radon progeny effects have been made recently by others in residences, we have also computed equivalent plateout rates in units of h^{-1} for what we refer to as a "standard" room with dimensions 5m x 5m x 3m high. This room therefore has a surface area, SF, of 110m^2, a volume, V, of 75m^3 and thus a surface to volume ratio, SF/V, of 1.47 m^{-1}. The values of plateout rates for each run given in Table 1 were used to compute the equivalent plateout rates for this standard room. These are given in Table 1. In most residential measurements by others, values are computed for the equilibrium fraction, F = Σ β_i F$_i$, where β_i = 0.105, 0.516 and 0.379, respectively for ^{218}Po, ^{214}Pb, and ^{214}Bi-Po, and F$_i$ = C$_i$/C$_1$ where C$_i$ are the individual progeny concentrations and C$_1$ is the ^{222}Rn concentration in the space. These computed equivalent equilibrium fraction values, F, for the standard room, are given in the last column of Table 1. In Table 1 we also provide arithmetic mean values for each material as well as the individual values for each ACH run. The values of F are also provided in graphical form in Fig. 4 for comparison with other work.

Resuspension

During the time that buildup to equilibrium was being achieved for the plateout rate measurements, the DAS was used to measure the time-dependent buildup in the test chamber of ^{218}Po and ^{214}Bi-Po on the Alpha CAM detector/filter. The time-dependent buildup variational method used to determine resuspension factors for the residential materials was that proposed in the previous section. Realizing that experimental accuracy to within just

a few percent was necessary to detect the 5% to 10% variation in the buildup of ^{214}Bi-Po expected from any resuspension, we here report the analysis for resuspension effects of only a few sets of data preferentially selected from the plateout measurement runs that demonstrated a very stable buildup period. A minimization of the variance between experimental to theoretical buildup data (including plateout and resuspension) was performed by computing A.S.D. for a range of sets of values of P_3 and corresponding R_2 to ascertain the best fit of sets of P_3 and R_2 to the buildup data by an iterative process based on minimization of the computed A.S.D. to obtain a "best fit," and the resulting best values of the resuspension factor, R_2, and the corresponding plateout rate, P_3. Technically, we may refer to this process as a method of least square roots of the variances.

By this method, we have examined the time-dependent buildup regions for fixed ACH for carpet, drapery, glass, wallboard and hardwood. To illustrate the nature of the experimental data, we show in Fig. 1 the buildup region, again for Run 90 experimental data for glass material and an ACH = 0.268 h^{-1}, for normalized Integral Count data. The markers on the curves indicate experimental data points. The count interval was five minutes per count. Shown also are the theoretical curves for buildup of both ^{218}Po and ^{214}Bi-Po using the appropriate values for ACH, P_2, P_3, and P_4 with the equations for values of the resuspension factor, R, equal to 0 and 0.5. As expected, the theoretical buildup for ^{218}Po are very nearly identical and independent of the value of R. This provides a check to insure that the experimental data was properly normalized. The theoretical curves for R = 0.5 for ^{214}Bi-Po is shown to fit well to the experimental curves in Fig. 1. Analysis finds for Run 90 that P_3 = 8.03 and R_2 = 0.475 ± 0.15 provides the most accurate theoretical match to the experimental buildup curve.

The iterative process to determine the minimum Accumulated Standard Deviation (A.S.D.), that provides a least square root best fit of experimental buildup data, was applied to the four materials (wallboard, hardwood, carpet and drapery) other than glass. The procedure was identical to that for glass with values of A.S.D. being obtained for R_2 = 0.125, 0.250, 0.375, 0.500, 0.625, and 0.750. Values of R_2 that provided the best fit to the experimental data were 0.55, 0.44, 0.36, 0.29 and 0.31 for carpet, drapery, glass, wallboard and hardwood, respectively (± 30% S.D.).

DISCUSSION

Plateout

Several investigators have theoretically studied the effects of various parameters on plateout rate and equilibrium fractions. Bruno (1983) has shown in generalized terms that plateout rate would be expected to decrease with increased air change rate (with aerosol concentrations remaining constant) for the range of ACH from 0.5 to 1.25 h^{-1}. This is the general trend found in Fig. 2. Porstendörfer et al (1978) shows an increase in disequilibrium fraction for attached progeny for ^{218}Po, ^{214}Pb and ^{214}Bi-Po for increasing ACH which would result in a corresponding increase in airborne attached progeny and thus a decrease in plateout rate for a constant emanation rate and attachment rate. This also supports the same trend in Fig. 2. On a qualitative basis, one can expect that there is a limited time period after an ionized ^{218}Po atom is produced by decay of ^{222}Rn in which plateout (or attachment to an aerosol particle) occurs. Air change competes with this process and as the ACH increases, plateout can be caused to decrease by this competition with ACH. A point may be reached, however, where due to the much greater air motion at larger ACH's, plateout may be caused to increase from the air motion effects seen by Rudnick and Maher (1986) and Vanmarcke et al (1991). Therefore, it is possible that the plateout could decline and then show an increase above ACH = 1.0 h^{-1}, as some data indicate.

We can examine some of the large number of residential measurements of F. We look at the specific works of Toohey et al (1985) (309 measurements of F), Keller (1984) (133), Israeli (1985),(20) and Martz (1990) (only four, but for one week periods). If we weigh the reported mean values of F by the number of measurements in each group, we obtain a composite mean value of 0.296 (we used only the low aerosol case for Israeli) for all of these data. Thus, the F values obtained here for the flat surfaced materials, i.e., hardwood, wallboard, glass and concrete, are high compared to this mean of 0.296 and the fabric materials, carpet and drapery, give low values. It is important to note in comparing these data that all the residential measurements were cases with normal household furnishings present, whereas the test chamber measurements here contained just the subject materials. From the large plateout

and low equilibrium fractions for the fabric materials, carpet and drapery, one would expect a large effect in a bedroom from furnishings such as a large bed with bedspread in addition to carpet and drapery. In a living room, there would be a large effect from upholstered furniture such as sofas and chairs. In a dining room, there would be the effect of a large dining room tablecloth.

The precision of the plateout measurements is estimated to be about ± 10% S.D. The overall accuracy of the determination of the plateout rates is conservatively estimated to ± 15% S.D. and is primarily due to 1) the counting statistics related to the radioactive fluctuations, 2) the least squares fit of the decay data (~ ± 2.5% S.D.), 3) the determination of ACH values (~ ± 5.0% S.D.), and 4) the uncertainty of the collection efficiency for primarily the ^{218}Po unattached atoms (± 5% S.D.).

Resuspension

There are very little other works to compare with these results for R_2. Most investigators in computing plateout rates from experimental data or for theoretical consideration neglect resuspension from flat surfaces. Mercer (1976) has proposed a value for detachment of ^{214}Pb from aerosol particles of 0.83 and most investigators have accepted this value. Porstendörfer et al (1976) considered aerosol detachment but neglected resuspension in their work. Bruno (1983) has reasoned that R_2 should be at most 0.25 due to 50% of the resuspended atoms "drifting" back onto the flat surface, since their recoil range off the surface is so small. For this reason, he set R_2 = 0 in his theoretical work. For experimental measurements to compute working level ratios (WLR) or equilibrium factors (F), it is legitimate to ignore resuspension since the ratio of concentrations, as measured, are only relevant in performing the calculations. Rudnick and Maher (1986) recognized the possibility of R_2 being as large as 0.5. Jonassen and McLaughlin (1976) have looked at the ^{214}Pb recoil loss from filter surfaces during air sampling and counting and have found that under vacuum filter counting conditions as many as 50% of ^{214}Pb atoms, produced from decay of ^{218}Po on the filter, are lost. They further found that the degree of recoil loss is found to be dependent on the nature of the surface upon which the parent isotope is deposited. Bigu (1991) also saw a dependence on type of surface material in the desorption (resuspension) of ^{220}Rn progeny from metal and filter surfaces in a vacuum.

In Jonassen and McLaughlin's (1976) measurements of resuspension from filter surfaces, they found that there was a well-defined relation between filter pore size and resuspension with the smallest pore sized, filter type VC, of 0.1μm providing the greatest recoil loss (93.3% of those recoiling away from the filter). This demonstrates that resuspension could be related to surface texture with the greater the coarseness of the surface the greater the possibility of recoil escape. It was of interest that the resuspension factors for carpet and drapery that were obtained during these measurements were the largest (about 0.5), which would be assumed to be the maximum value from geometrical considerations for a perfectly flat surface. In examining the texture of the carpet, it was seen to consist of very small diameter fibers. For the case of the drapery, the fabric consisted of threads of material which with careful examination by unwinding was found to also consist of small diameter fibers. The fibers were viewed under a microscope and measured, with a reticle used for measurement of dimensions of asbestos fibers, to have an optically measured diameter of 1.3 and 0.75 μm for drapery and carpet, respectively. Mercer (1976) provides an equation for the resuspension of recoil atoms for a spherical particle given by $r = 0.5$ $(1 + R/D)$, where r is the probability of escape of a recoiling atom with range, R, in the material and the particle having a diameter of D. If we consider the fibers in the drapery and carpet as small, very long cylinders that are compared to their diameters then the probability of escape would be given by $r = 0.5$ $[1 + 2R/\pi D]$ = 0.5 $[1 + 0.637 R/D]$.

Since the fibers are polyester, we chose a density of unity and use Mercer's R = 0.14 μm for the range of ^{218}Po recoil atoms. Thus, the expected resuspension factor, R_2, for drapery and carpet would be 0.57 and 0.62, respectively, assuming that the recoiling atom does not collide with another fiber on its recoil path while escaping. Jonassen and McLaughlin (1976) have seen large differences in resuspension rates from filter material with different surface textures. Therefore, we suggest that it is not impossible to find values equal to or slightly greater than R_2 = 0.5, as in the case here for drapery and carpet. It is estimated that the overall accuracy of the resuspension factors obtained herein are to ± 30% S.D. or about ± 0.15 absolute for R_2 values of about 0.5.

CONCLUSIONS

Plateout

We here have provided experimental determination of plateout rates and computed equivalent equilibrium fractions for seven different interior residential materials, carpet, drapery, hardwood, wallboard, concrete, glass and ceiling tile. A number of measurements were made at different ACH for each material. The plateout rate for each material seemed to be fairly independent of ACH except at very low values of ACH. Values are comparable with those determined by others for actual residential measurements. Accuracy is estimated to be ± 15% S.D.

Resuspension

We here have also provided the results of the measurement of time-dependent buildup towards equilibrium of ^{222}Rn and its radon progeny concentrations. The measurements were for the study of resuspension of ^{214}Pb by the radioactive alpha decay of ^{218}Po for five different residential materials, carpet, drapery, varnished hardwood, wallboard and glass in a small test chamber. Temperature and relative humidity were carefully controlled to 22.2° C ± 1.1° C and 30% ± 10%, respectively. This data enabled computation of some values for resuspension factors. This work involved developing a special method to measure resuspension rates for the five materials by measuring the time-dependent buildup of the ^{222}Rn and progeny and examining the deviation of this buildup from what is predicted without resuspension. The resuspension factors, R_2, for ^{214}Pb recoil ranged from 0.29 to 0.55 with the largest values for carpet and drapery. These large values are reconciled due to the very small diameter fibers making up the fabric material.

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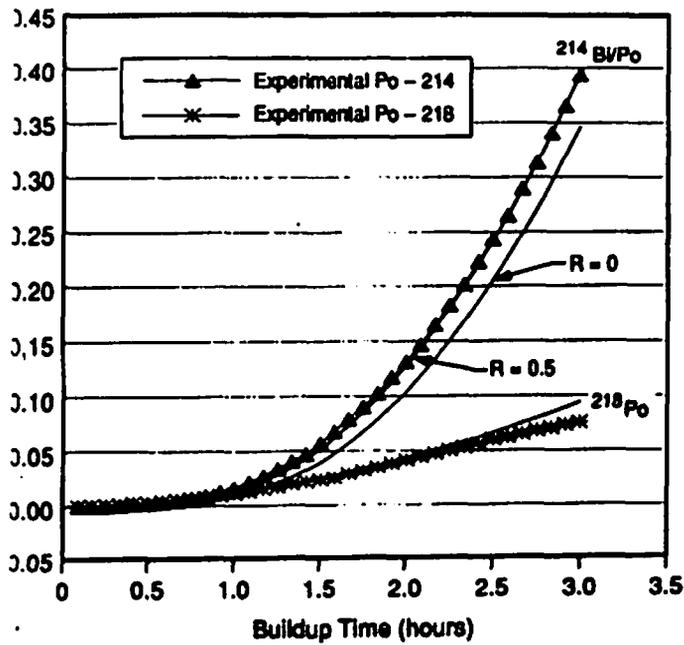
Fig. 1 - Normalized Integral count experimental data for buildup of ^{218}Po and ^{214}Bi-Po activity on filter for Run 90 ACH = 0.268 h^{-1}. Data points at 5-min. intervals. Comparison made with theoretical normalized integral counts for resuspension factor R, = 0.0 and 0.5.
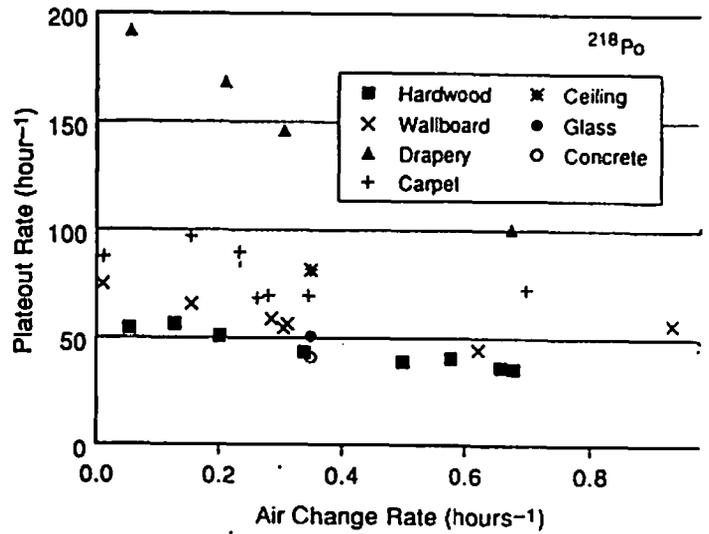

Fig. 2 - Plateout rates (h^{-1}) for ^{218}Po vs air change rates (h^{-1} for residential material surfaces in 0.283 m^3 test chamber.
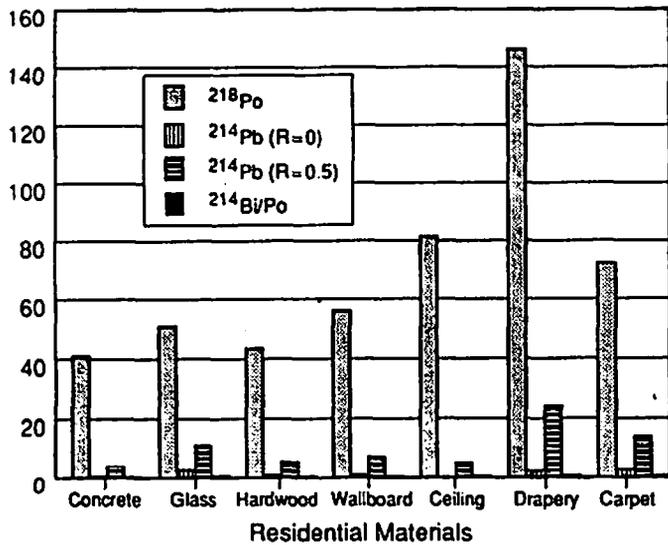

Fig. 3 - Plateout rates (h^{-1}) for ^{218}Po, ^{214}Pb (R$_2$ = 0), ^{214}Pb (R = 0.5), and ^{214}Bi-Po (R$_3$ = 0.001) for air change rates (ACH) = 0.35 (h^{-1}) of residential materials as indicated.
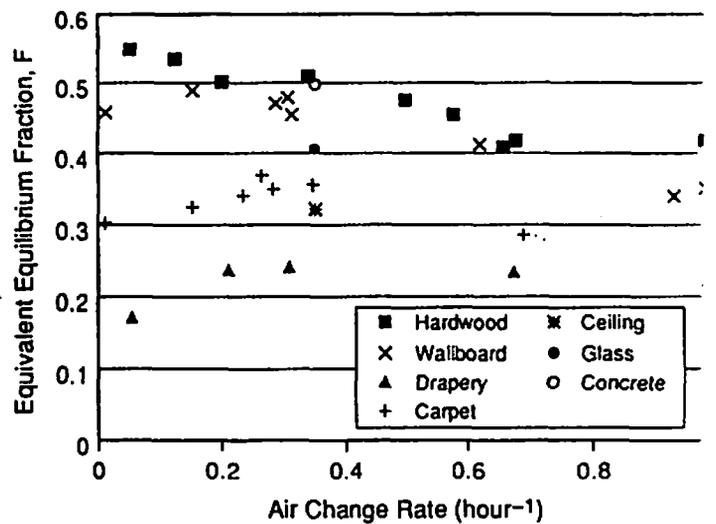

Fig. 4 - Computed values of equivalent equilibrium factors, for residential materials and air change rates (ACH as indicated for a hypothetical standard room of the materials given with dimensions 5m x 5m x 3m high

Table 1.   Computed values of equivalent plateout rates (h⁻¹) and equivalent equilibrium fractions, F, for a hypothetical standard room with dimensions 5m x 5m x 3m high with wall surfaces and ACH as indicated.

ACH R₂	EQUIVALENT PLATEOUT RATES (h⁻¹) - RADON PROGENY				EQUIVALENT EQUILIBRIUM FRACTION
	^{218}Po	^{214}Pb R₂ = 0	^{214}Pb R₂ = 0.5	^{214}Bi-Po	
HARDWOOD Average = 7.635		0.136	0.877	0.054	0.465
0.053	8.846	0.097	0.798	0.046	0.549
0.127	9.703	0.014	0.628	0.005	0.526
0.201	8.736	0.102	0.852	0.071	0.494
0.340	7.495	0.141	0.889	0.084	0.470
0.499	6.774	0.121	0.804	0.059	0.449
0.576	7.054	0.254	1.198	0.046	0.405
0.657	6.291	0.186	0.949	0.041	0.414
0.678	6.180	0.169	0.901	0.081	0.412
WALLBOARD Average	9.072	0.107	0.983	0.044	0.430
0.012	11.864	0.137	1.195	0.076	0.486
0.155	10.381	0.082	0.923	0.045	0.482
0.287	9.295	0.078	0.869	0.035	0.464
0.307	8.623	0.073	0.803	0.037	0.472
0.313	9.902	0.155	1.086	0.053	0.448
0.620	7.075	0.167	1.008	0.059	0.408
0.930	8.926	0.082	1.061	0.000	0.335
0.982	7.507	0.084	0.924	0.047	0.347
DRAPERY Average	24.870	0.516	5.262	0.228	0.217
0.056	33.634	1.073	10.923	0.383	0.169
0.211	29.476	0.301	4.110	0.130	0.233
0.309	25.631	0.354	4.055	0.130	0.237
0.674	17.633	0.514	3.923	0.332	0.232
0.983	17.945	0.335	3.297	0.167	0.217
CARPET Average	13.521	0.515	2.986	0.141	0.329
0.012	14.942	0.914	4.825	0.374	0.300
0.154	16.562	0.486	3.313	0.080	0.320
0.234	15.299	0.364	2.595	0.066	0.336
0.265	11.709	0.429	2.324	0.113	0.364
0.283	11.891	0.514	2.675	0.145	0.346
0.347	11.868	0.400	2.279	0.093	0.351
0.698	12.378	0.500	2.894	0.114	0.282
CE 0.351	13.121	0.029	0.850	0.075	0.322
GL 0.351	8.288	0.474	1.822	0.116	0.407
CO 0.351	6.692	0.103	0.625	0.060	0.499