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No. 3198

Removal of Airborne Radon Decay Products

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ABSTRACT

Comparisons of various indoor air treatment methods have shown that while flow-through air-cleaning methods, such as filtration and electrostatic precipitation, were effective in reducing total potential alpha energy concentrations (PAECs), they caused a greater percentage of the radon decay products (subsequently formed through decay of the remaining radon gas) to be unattached to particles. Estimates show that this results in a substantial increase in the dose to the bronchial tissues of people breathing the treated air. The optimal form of air treatment appears to be a combination of nonuniform space charge generated by an ion generator and enhanced convection using a fan. Laboratory studies showed that this combination provided reductions in PAECs ranging up to 95%; reductions in the mean dose to the bronchial tissues ranged up to 87%. Tests of a portable fan-ion generator unit in homes in Massachusetts and Connecticut showed PAEC removals in the range of 75% to 90%.

INTRODUCTION

Indoor exposures to naturally occurring radon decay products (^{218}Po, ^{214}Po, and ^{214}Bi) inside homes are a significant public health problem. Estimates (Nero et al. 1986) suggest that as many as 1 million homes in the U.S. have indoor radon (^{222}Rn) concentrations that exceed the remedial action criterion recommended by the National Council on Radiation Protection and Measurements (NCRP 1984). These decay products are the dominant source of ionizing radiation exposure to the public (NCRP 1987), with the annual average dose equivalent to the bronchial tissue of the lungs of an average-size adult estimated to be about 30 mSv · y^{-1} (NCRP 1984). This corresponds to an effective dose equivalent of about 2 mSv · y^{-1} (ICRP 1981). In terms of public health impact, estimates indicate that these exposures cause some 10,000 to 20,000 lung cancer deaths in the U.S. each year (NAS 1988).

One method for minimizing indoor concentrations of radon decay products is to impede the entry of ^{222}Rn into the home. This can be accomplished by removing the source of the radon, diverting the ^{222}Rn before it enters the structure, or placing a barrier between the source and living space. Although these techniques are readily applicable to new construction, they are not always easy to incorporate into existing housing. For the latter situation, alternative approaches are to increase the ventilation rate or to apply some form of air treatment to remove the airborne radon decay products.

EFFECTIVENESS OF AIR-CLEANING METHODS

To test the effectiveness of various air-cleaning methods for the removal of airborne radon decay products, a series of studies was conducted in a laboratory radon chamber. The chamber had a volume of 2750 ft^3 (78 m^3) and a floor area of 235 ft^2 (22 m^2). Although the chamber was designed to simulate conditions in a home, no attempt was made to simulate the rapid and erratic transient effects that occur in houses, such as changes in the ventilation or radon intrusion rate with time. To facilitate interpretation of experimental results, all parameters were held constant, although some, such as the aerosol properties, were not easily controlled. Only steady-state data were retained for analysis. To simulate the release of radon from the soil beneath a home, ^{222}Rn was introduced into the chamber through a series of distribution pipes located on the floor. Details of the chamber have been described elsewhere (Rudnick et al. 1983).

Data obtained in a comparison of the effectiveness of a wide range of air-cleaning methods on the removal of individual airborne radon decay products, as well as the potential alpha energy concentration, are summarized in Figure 1 (Maher et al. 1987). These studies were similar to those conducted by Sextro et al. (1986), except that the studies reported here were more extensive with regard to the testing of ion generators, and they involved measurements of both the attached and unattached airborne radon decay products as well as estimates of the effects of the various air-cleaning methods on the associated dose to the bronchial tissues of the lungs. Each test was conducted at three different room ventilation rates. These rates were controlled by monitoring the rate of air leaving the chamber and were verified through sulphur hexafluoride tracer measurements. Makeup air infiltrated into

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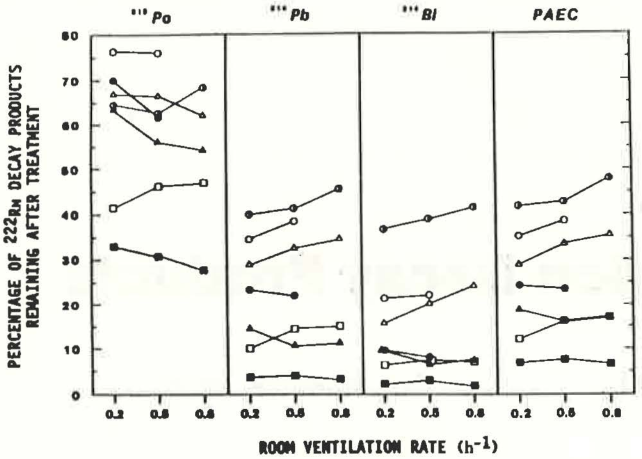

Figure 1 *Percentage of individual ²²²Rn decay products and potential alpha energy concentration (PAEC) remaining after application of various air treatment methods. Data are plotted as a function of room ventilation rate.*

Key for Symbols

- ○ *Electrostatic Precipitator*
- ◑ *Ceiling Fan*
- ● *High Efficiency Filter*
- △ *Negative Ion Generator*
- ▲ *Positive Ion Generator*
- □ *Negative Ion Generator and Ceiling Fan*
- ■ *Positive Ion Generator and Ceiling Fan*

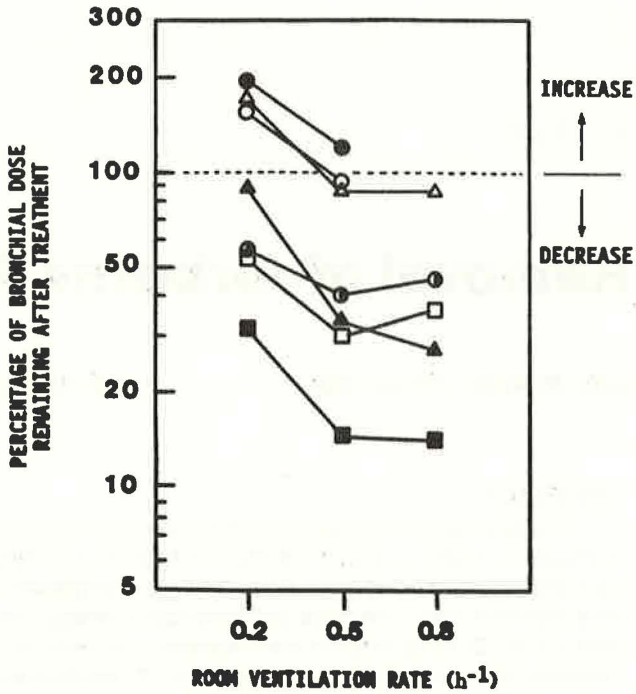

Figure 2 *Fraction of bronchial dose remaining after application of various air treatment methods. Estimates are based on calculations using the Harley-Pasternack lung models (Harley and Pasternack 1982), and are plotted as a function of the room ventilation rate.*

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the chamber from adjoining laboratories through cracks in the walls, floor, and ceiling and from leaks around door jambs and window seals.

Although not shown in Figure 1, the radon concentration was unchanged for all treatment methods. As may be noted from the data presented, the most effective treatment method, based on reductions in potential alpha energy concentrations (PAECs), was the positive ion generator and ceiling fan combination; the least effective method was the ceiling fan alone; and the positive ion generator was always more effective than the negative ion generator.

In terms of explaining the mechanisms by which these various techniques remove radon decay products, it should be noted that the highly diffusive nature of airborne particles, particularly those that are in what is called the unattached state, favors their removal by deposition onto surfaces by molecular diffusion. The turbulent flow created by a fan facilitates such deposition. Air turbulence reduces the boundary layer thickness at the surface-to-air interface throughout a room and thus reduces the distance that unattached decay products must travel by molecular diffusion before depositing onto room surfaces. The net result is a higher flux of unattached decay products plating onto the walls of a room and a corresponding reduction in their airborne concentrations. Enhanced surface deposition caused by turbulent convection becomes progressively less effective as particle size increases and is relatively unimportant for particle sizes greater than 0.1 μm.

In terms of the removals effected by ion generation, it is thought that mutual repulsion of air ions in the vicinity of a strong unipolar point source creates a spatially nonuniform distribution of airborne charge and an electric field gradient directed radially from the source. Simultaneously, by the process of diffusion charging, decay product atoms, as well as airborne particles to which the decay products are attached, become charged to the polarity of the ion generator. The force exerted by the electric field on these charged particles causes their migration toward the boundaries of the air space, and this results in their deposition onto surfaces and their removal from the air. The greater reductions in PAECs with the positive ion generator are thought to be due to the fact that ^{218}Po and ^{214}Pb atoms initially possess a positive charge following their formation. These positively charged atoms migrate more rapidly to surfaces in the presence of a positive nonuniform space charge than in a negative space charge. For a negative space charge to be effective, the decay product atoms must first be made negative by diffusion charging. Air ionization proved effective in reducing the concentrations of both the unattached and attached airborne radon decay products.

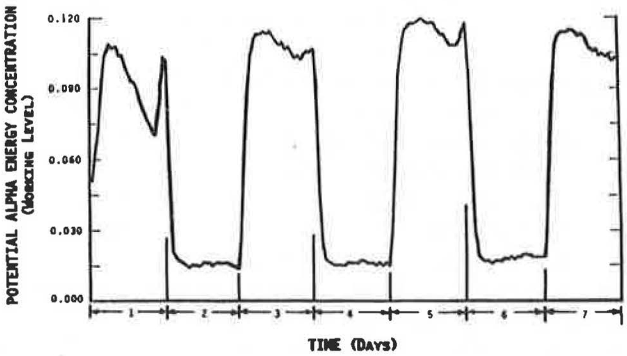

Figure 3 *Hourly potential alpha energy concentrations in the laboratory chamber.*

Key:

Day 1—Background measurement

Day 2—Fan-ion generator unit on—fan at slowest speed

Day 3—Background measurement—fan-ion generator unit off

Day 4—Fan-ion generator on—fan at intermediate speed

Day 5—Background measurement—fan-ion generator unit off

Day 6—Fan-ion generator unit on—fan at highest speed

Day 7—Background measurements—fan-ion generator unit off

Although the reduction in PAEC is informative in terms of the effectiveness of an air-cleaning method, the primary consideration is the reduction in estimates of the dose to the bronchial tissues of the lungs. Estimates of the bronchial dose that would be produced by the airborne radon decay products after the application of the various methods of air treatment, expressed as a percentage of the dose estimates prior to treatment, are shown in Figure 2 (Maher et al. 1987). Calculations of the dose to the bronchial tissues were made using the dosimetry model of Harley and Pasternack (1982) as modified by James (1984) for application to an indoor environment with a typical aerosol concentration and size distribution.

As may be noted, application of a high-efficiency filter yielded up to a doubling in estimates of the bronchial dose. The reason for this is that high-efficiency filtration removes the dust particles from the air while, at the same time, the radon gas remains. Under these circumstances, the radon decay products subsequently formed in such an atmosphere (through the continuing decay of the radon gas) have no dust particles to which to attach. Such decay products, therefore, remain in the unattached state. Since, atom for atom, an unattached radon decay product produces 30 to 40 times the dose to the lungs as does the same atom attached to a dust particle (NAS 1988), the net result is an increase in the dose to the lungs of people breathing the treated air. For purposes of estimating the doses to the bronchial tissues, the unattached fraction of the airborne radon decay products was separately measured using a diffusion battery (Maher et al. 1987).

COMBINATIONS OF AIR TREATMENT METHODOLOGIES

To determine if there would be advantages in combining several air treatment methodologies into one system, tests were conducted using a combination of a ceiling fan plus a negative ion generator and a ceiling fan plus a positive ion generator. As may be noted from Figures 1 and 2, the most effective treatment method proved to be a combination of a positive ion generator and a ceiling fan. Such a system provided reductions in PAECs up to 95% and in estimates of the bronchial dose ranging from 68% to 87%. In addition, there was an unexpected benefit of this approach. This was the fact that the combination proved to be synergistic, that is, the removal effectiveness of the two methods in combination was better than the sum of the two applied independently (Moeller et al. 1986). This synergism is thought to result from the fact that the addition of turbulent convection by the ceiling fan improves room air mixing. This, in turn, allows the radon decay products and particles to which they attach to become more rapidly charged. As previously noted, the fan also facilitates molecular diffusion to the room walls by reducing the thickness of the air boundary layer.

TESTS OF PORTABLE UNIT

On the basis of the laboratory experiments, a small portable hassock fan-ion generator unit was developed so that the feasibility of the techniques developed could be evaluated under realistic conditions (Moeller et al. 1987).

Laboratory Evaluations

Initial evaluations of the portable unit were conducted in the laboratory radon chamber previously described. For purposes of the studies, the fan-ion generator unit was placed on the floor near the center of the chamber. Measurements of the PAECs of radon decay products were made using a continuous Working Level* monitor. The resulting data were analyzed using a computer software package.

The test sequence was as follows. Over a 24-hour period, measurements were made of the background PAECs in the chamber (without treatment), followed by a similar 24-hour series of measurements with the fan-ion generator removal unit in operation. This alternating sequence was performed over a period of seven days. For each sequence of measurements, hourly readings were recorded.

Shown in Figure 3 is a graph of the hourly PAECs for each of the seven days. As may be noted, the test sequence included operation of the fan in the radon removal unit at three different speeds. These correspond to air flow rates of about 100, 200, and 400 cfm (0.05, 0.1, and 0.2 m^3 per second). Fluctuations in the PAECs during the first day of the studies were due to problems with the radon generator. Nonetheless, the graph shows that the portable fan-ion generator unit provided a significant and rapid reduction in the PAECs within the chamber. Although approximately six to eight hours were required to reach equilibrium, a major share of the reduction in PAEC occur-

* The Working Level (WL) is a unit that has been developed to express the concentration of airborne radon decay products in terms of the cumulative exposure to potential alpha energy. Assuming that the decay products are in 50% equilibrium with the radon parent, a WL of 0.005 corresponds to the concentrations of airborne radon decay products that would be produced by a radon concentration of one picocurie per liter (1 pCi/L).

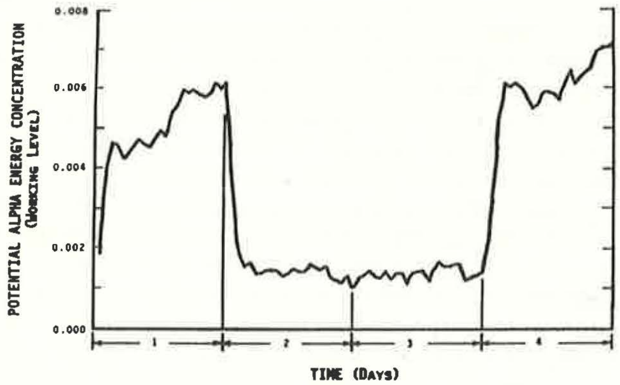

Figure 4 *Hourly potential alpha energy concentrations in home in Massachusetts.*

Key:

Day 1—Background measurement

Day 2—Fan-ion generator unit on—fan at highest speed

Day 3—Fan-ion generator unit on—fan at slowest speed

Day 4—Background measurement—fan-ion generator unit off

red within the first three to four hours after the removal unit was turned on.

In order to estimate the removal efficiency of the fan-ion generator unit, the average of the last 18 hours within each 24-hour testing period was used. The reason for selecting this time period was to ensure that the data being compared represented equilibrium conditions. On the basis of this approach, calculations show that the effectiveness of the removal unit during these tests ranged from 83% to 86%. As may be noted, the speed of the fan appeared to have no significant effect on the efficiency of the removal unit.

Field Evaluations

Field studies of the fan-ion generator unit were conducted in a home in Massachusetts having what was considered to be relatively low concentrations of radon and in a home in Connecticut considered to have relatively high concentrations of radon.

Massachusetts Studies. The studies in the home in Massachusetts were conducted in a finished recreation room located in the basement. The room contained a sofa and chairs, a rug, and a fireplace. The room was located in one corner of the basement and had a volume of about 1300 ft^3 (37 m^3) and a floor area of 195 ft^2 (18 m^2). The room was connected to the remainder of the basement by two doorways. The doors to the recreation room, as well as all windows and doors to the basement itself, were kept closed during the tests. The remainder of the basement had a volume of about 4520 ft^3 (128 m^3) and a floor area of about 580 ft^2 (54 m^2).

The sequence of the tests conducted included an initial day (24 hours) of background measurements, a second 24-hour sequence with the radon decay product removal unit operating with the fan set at the highest speed, a third 24-hour period with the fan operating at the slowest speed, followed by a final 24-hour period during which background measurements were made with the removal unit turned off. The radon removal unit was located on the floor in the center of the room. The PAEC monitor was located about 3 ft (1 m) above the floor, about 4.5 ft (1.5 m) from the removal unit, and about 4.5 ft (1.5 m) from the wall.

Shown in Figure 4 is a graph of the hourly PAECs on each of the four days covered in these tests. As may be noted, the PAECs show an increasing pattern during the first and fourth days. This was thought to be due, in part, to changing weather patterns. Shortly after the studies began on Day 1, a period of rather heavy rain was experienced. Analyses of the data show that the average PAEC of radon decay products for the final 18 hours of the initial 24-hour period (Day 1) during which background measurements were being made was 0.0054 Working Levels (WL). The average concentration during the final 18 hours of the next 24-hour period (Day 2) during which the removal unit was being operated with the fan set at the fastest speed was 0.0013 WL. Comparing these two readings, the overall efficiency of the removal unit was 76%.

During the final 18 hours of Day 3, while the fan-ion generator unit was being operated with the fan set at the slowest speed, the average PAEC of airborne radon decay products was also 0.0013 WL. During the final 18 hours of Day 4, after the removal unit had been turned off, the average background PAEC in the room was 0.0062 WL. Comparison of these two numbers shows an overall removal efficiency of 79%. As in the case of the laboratory tests, the speed of the fan appears to have had essentially no effect on the removal efficiency of the fan-ion generator unit.

Connecticut Studies. The home in Connecticut in which studies were conducted was built into the side of a hill with the back, sides, and top being essentially covered with earth. The tests described in this report were conducted in a bedroom located within the house with the fan-ion generator unit being located on the floor in the middle of the room. Except for the door through which entrance was gained, the room had no other openings. The room had a volume of approximately 920 ft^3 (26 m^3) and a floor area of 120 ft^2 (11 m^2).

During the studies, which covered a time span of three days, measurements were made simultaneously of the PAECs and the radon concentrations in the room using a second portable radiation monitor. For purposes of these measurements, which were made with and without the fan-ion generator unit in operation, the PAEC and radon monitors were located about 3 ft (1 m) above the floor, about 4.5 ft (1.5 m) from the removal unit, and about 4.5 ft (1.5 m) from the wall. Although it was realized that simultaneous measurements of the radon concentrations and the PAECs would have been useful in the laboratory studies and in the field studies in the home in Massachusetts, the radon monitor was not available at the time these latter studies were conducted.

Shown in Figure 5 is a graph of the hourly radon concentrations (pCi/L) within the room. Shown in Figure 6 is a graph of the hourly PAECs as observed over the same period of time. As may be noted, the radon concentrations were quite variable over the three-day period. Again, this was thought to be due, in part, to changing weather patterns. Because data on the radon concentrations were

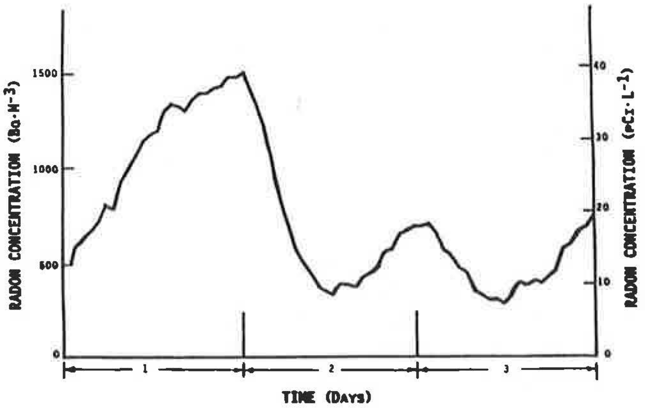

Figure 5 *Hourly radon concentrations in home in Connecticut.*

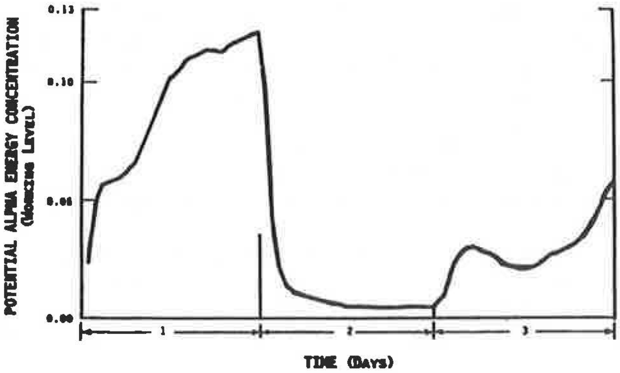

Figure 6 *Hourly potential alpha energy concentrations in home in Connecticut.*

Key:

Day 1—Background measurement

Day 2—Fan-ion generator unit on—fan at highest speed

Day 3—Background measurement—fan-ion generator unit off

available, however, it was possible to estimate the PAECs that would have been present during the second day had the removal unit not been in operation. This was accomplished by multiplying the average PAEC during Day 1 by the ratio of the average radon concentration on Day 2 to that on Day 1. The estimated value was 0.038 WL. Since the average PAEC measured on Day 2 with the removal unit in operation was 0.005 WL, the removal efficiency was estimated to be 87%. Again, for purposes of this calculation, comparison was made of the PAECs with and without treatment during the last 18 hours of each 24-hour period.

DISCUSSION AND CONCLUSIONS

The data reported in this paper show that a fan-ion generator combination is effective in reducing the airborne concentrations of radon decay products (PAECs) in the home. These data have been independently confirmed by scientists in Canada (Bigu 1983), Denmark (Jonassen and Jensen 1984), and Finland (Keskinen et al. 1987). This same combination also provides comparable reductions in estimates of the accompanying doses to the lungs of people breathing the treated air. Such a system, which is simple and relatively inexpensive, removes the airborne radon decay products, regardless of their source, and, with routine maintenance, should provide effective removal of the decay products for many years. For homes with modest radon concentrations, it will provide adequate airborne radon decay product removals; for homes with high radon concentrations, it can serve as an adjunct to other remedial measures such as building modifications.

Because other air-cleaning methods, most noticeably high-efficiency filtration and electrostatic precipitation, can cause an increase in estimates of the dose to the lungs, there are serious questions as to the appropriateness of the application of these methods. It is for this reason that the U.S. Environmental Protection Agency has stated that, until more is known, it cannot suggest the use of these two techniques for the control of airborne radon decay products inside homes (EPA 1986).

In addition to these considerations, it should be noted that scientists have shown that radon is but the tip of the indoor air pollution iceberg. There are a multitude of other contaminants in the home. These arise from sources such as cigarette smoking, natural gas stoves, heating systems, oven cleaners, furniture and floor polishes, insulation materials, insect parts, pollens, and so forth. Because a fan-ion generator combination removes dust from the air (as well as the unattached radon decay products), it is effective in helping to control a number of these other contaminants. The principles it incorporates can also serve as a basis for developing a system that will handle the full range of airborne contaminants within the home.

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