

## ABSTRACT

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**RADIOLOGICAL HAZARDS ASSOCIATED WITH RADON PROGENY  
UNDER HUMID CONDITIONS.**

(Under the direction of Dr. Douglas J. Crawford-Brown)

The purpose of this project was to construct a radon exposure chamber and mimic a typical bathroom climate (relative humidity of 90%). This allowed us to compare doses delivered to the lungs from radon exposure under conditions of high humidity (ie. showers) to conditions of low humidity (relative humidity of 60%). Measurements of radon and radon progeny were performed. In addition, information on the state of attachment of progeny to aerosols was obtained for lung deposition modeling. To analyze the state of attachment of radon progeny, filter measurements analyzed by alpha spectroscopy were performed. Alpha scintillation cells were used to determine the unattached fraction. Unlike previous studies, this study simulated hot, humid shower conditions encountered in bathrooms. These measurements were used to calculate the dose equivalent delivered to the lungs of humans exposed to these conditions. These calculations utilized a mathematical model of lung deposition developed by Maher, Rudnick, and Moeller (Effective Removal of Airborne  $^{222}\text{Rn}$  Decay Products Inside Buildings; Health Physics 1987). The results indicate that the risk from emanated radon is lower under conditions of high humidity than under conditions of low humidity.

## ACKNOWLEDGEMENTS

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## INTRODUCTION

Radon, a colorless, odorless, tasteless radioactive gas has a short half life of 3.82 days. Radon decays by alpha emission to Po-218 which also has a short half life (3.05 minutes). Polonium-218 decays to lead-214 by emitting a 6.0 MeV alpha particle (See Table I, Characteristics of  $^{222}\text{Rn}$  and its "Short-Lived" Progeny). Lead-214 decays to bismuth-214, which in turn decays to Po-214, both by beta emissions with half-lives under 30 minutes. Polonium-214 is a high energy alpha emitter (7.69 MeV). Radon-222, polonium-218, and polonium-214 emit alpha particles with high energies. The alphas emitted from polonium-218 and polonium-214 contribute significantly to the lung dose after inhalation of these radon decay products (internal exposure). By contrast, the radon itself does not deposit in the lung and is exhaled. Therefore, the hazards associated with radon actually are due to short-lived radon progeny, especially Po-218 and Po-214. As seen in Table I, an atmosphere containing 100pCi/L of each of the progeny equals 1 WL (working level).

The unit for measuring the potential hazard from a given atmosphere of radon and progeny is the working level. A WL is defined as "any combination of short-lived radon daughters in air that will result in the ultimate emission of  $1.3 \times 10^5$  MeV of alpha particle energy". (Radiological Health Handbook).

In this report radon-222 will be referred to as radon or Rn. Its short lived decay products, Po-218, Pb-214, Bi-214, and Po-214, will be referred to as RaA, RaB, RaC and RaC' respectively in this report. Collectively, radon's short-lived

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Table I Characteristics of  $^{222}\text{Rn}$  and its "Short-Lived" Progeny

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| Nuclide                              | T min.  | No. atoms/<br>100 pCi | Decay<br>mode | Alpha<br>energy<br>(MeV) | Ultimate<br>decay<br>(MeV-alpha) | WL   |
|--------------------------------------|---------|-----------------------|---------------|--------------------------|----------------------------------|------|
| $^{222}\text{Rn}$                    | 5500    | (1.75 E+6)            | (alpha)       | (5.49)                   | (3.33 E+7)                       | -    |
| $^{218}\text{Po}$                    | 3.05    | 9.77 E+2              | alpha         | 6.0                      | 1.34 E+4                         | 0.10 |
| $^{214}\text{Pb}$                    | 26.8    | 8.58 E+3              | beta          | --                       | 6.60 E+4                         | 0.52 |
| $^{214}\text{Bi}$                    | 19.6    | 6.28 E+3              | beta          | --                       | 4.83 E+4                         | 0.38 |
| $^{214}\text{Po}$                    | 2.7 E-6 | 8.8 E-4               | alpha         | 7.69                     | 6.7 E-3                          | 0    |
| Total sum of "Ultimate Alpha Energy" |         |                       |               |                          | 1.28 E+5                         | 1.00 |

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Values (in parentheses) are not considered in computation of Working Level.

Table adapted from information in Evans 1969.  
(Cothorn, C. Richard and Smith, James E. Jr.1987.)

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decay products will be referred to as radon progeny, radon daughters, or radon decay products.

The contribution of radon to household air from water supplies typically is a small fraction (<5%) of the average over the household. The radon air



concentration is dominated by the ground emanation pathway into the home, with a U.S. mean ratio of air concentration to water concentration ( $C_a/C_w$ ) of  $1 \times 10^{-4}$  (Crawford-Brown, D. J. 1987; Cothorn, C. R. 1988 and Cothorn, C. Richard and Smith, James E. Jr. 1987). However, in rooms utilizing water, the radon contribution from water may be substantially higher than the average. The mean concentration of radon in ground water is about 5000pCi/L (UNSCEAR 1972) while Hess et. al. (1978) showed values up to 200,000pCi/L for granite areas in Maine (NCRP#78, 1984).

Table II depicts the radon released per day into a home, assuming 1000pCi/L in the water for four people and for various water uses. The toilet, dishwashing, laundry, and cleaning water uses are accompanied by extremely short exposure periods, therefore doses are assumed to be negligible in comparison to tub baths and showers. Drinking water yields a very low transfer rate (see Table II), therefore, it does not present a problem. Tub baths and showers do present a potential problem. The agitation and pulsation of the water exiting the faucet and shower head effectively releases a greater fraction of the radon to the air (U. S. Environmental Protection Agency; Draft Criteria Document for Radon in Water. 1987).

Preliminary studies indicate that showers transfer 62 to 100% of the radon in the water to the air (U. S. Environmental Protection Agency; Draft Criteria Document for Radon in Water. 1987 ). As a result, the concentration of radon in bathrooms may be much higher than in other rooms for short periods of time. It has been suspected that exposure to this increased level in bathrooms



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Table II Radon Released Per Day Into Home Air,  
Assuming 1000 pCi/L in the Water, For Four People

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| Use                | Daily<br>consumption<br>(L) | Transfer<br>to air<br>(%) | Radon<br>liberated<br>(pCi/L) |
|--------------------|-----------------------------|---------------------------|-------------------------------|
| Showers            | 150                         | 63                        | 94,500                        |
| Tub baths          | 150                         | 47                        | 70,500                        |
| Toilet             | 365                         | 30                        | 109,500                       |
| Laundry            | 130                         | 90                        | 117,000                       |
| Dishwasher         | 55                          | 90                        | 49,500                        |
| Drinking & kitchen | 30                          | 30                        | 9,000                         |
| Cleaning           | <u>10</u>                   | 90                        | <u>9,000</u>                  |
| Total              | 890                         |                           | 459,000                       |

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U. S. Environmental Protection Agency; Draft Criteria Document for Radon in  
Water. 1987.

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may deliver as much as 30 to 40% of the total daily dose to the lung, at least in cases where the concentration of radon in water is fairly high (personal communication, D. J. Crawford-Brown). These previous calculations have assumed, however, that the risk per unit radon concentration is the same in the general home area and the very humid bathrooms.

Past studies have focused only on a comparison between the radon air concentration in the entire household and that in a bathroom. Due to higher humidities and temperature commonly seen in the shower, it is suspected that these conditions may influence the state of attachment of radon progeny to aerosol particles. There are typically between 10,000 (Jacobi 1964) to 30,000 (Haque and Collinson 1967) aerosol particles per cubic centimeter in normal room air (NCRP #78, 1984), and it is suspected that this concentration may change under increased humidity and temperature. However this has not been studied, and the lung deposition models do not account for this possible change in the state of attachment of progeny in relation to high humidity and temperature.

The size distribution for the radon daughters attached to aerosol particles was found to be log normal (NCRP #78, 1984). Activity median aerodynamic diameters (AMAD) are found to range from 0.2 to 0.4 micrometers (NCRP #78, 1984).

The state of attachment of radon progeny to aerosol particles (condensation nuclei included) affects the percent lung deposition (NCRP #78,

1984). The percent lung deposition in the total tracheobronchial region is greatest for two distinct aerosol particle size regions;  $<0.1$  micrometers and between 1.0 and 10 micrometers. In Figure 1, it may be seen that a 0.01 micrometer particle may deposit with 30% efficiency in the tracheobronchial region of the lung for the case of light physical exertion (Cothorn, C. Richard and Smith, James E. Jr. 1987 and Crawford, D. J. 1982).

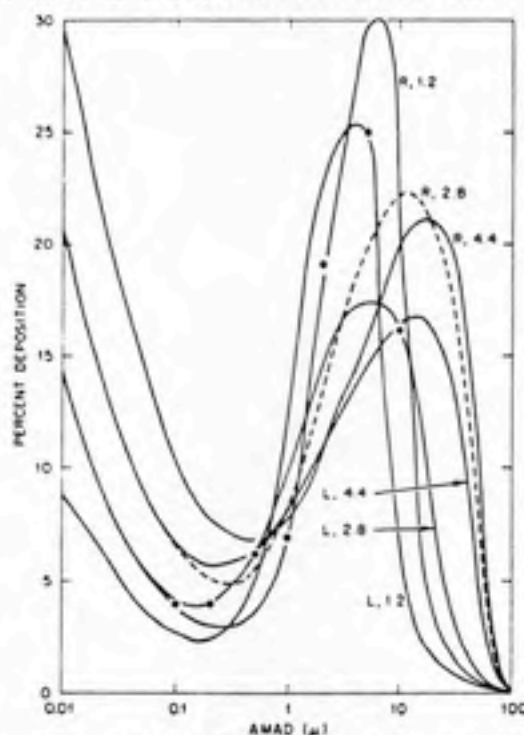


Figure 1 A comparison of model predictions and experimental results for the deposition fraction in the total TB region. Deposition fractions for both resting (R) and light physical exertion (L), and for three different values of the geometric standard deviation characterizing the distribution of particle sizes, are displayed.

Larger particles ( $>10\mu\text{m}$ ) tend to be deposited in the nose and mouth, whereas smaller particles travel deeper into the respiratory tract. There, they may become lodged in the lung. Since these lung deposited radon progeny attached to aerosol particles are radioactive, the process of decay occurs. The

alpha emissions from Po-218 (RaA) and Po-214 (RaC') are high LET (Linear Energy Transfer) radiations with energies of 6.00 and 7.69 MeV respectively and may cause significant lung damage (ie lung cancer). The dose from the unattached RaA can be 3 to 40 times that of each of the attached daughters per unit concentration in the atmosphere (NCRP #78, 1984) due to increased deposition of the unattached fraction. In normal atmospheres the unattached fractions from RaA, RaB, RaC are 0.3506, 0.0578 and 0.0771 respectively (Haque and Collinson 1967). If conditions of high humidity and temperature change the state of attachment in such a way as to increase the percent lung deposition, then the risk of lung cancer is also increased. Therefore there is a need for studies to observe the changes in the state of attachment due to high humidity and temperature as they reflect changes in the percent lung deposition and, therefore, the risk.

The dose equivalent delivered to the lung tissue by radon progeny can be determined by an equation developed by Rudnick, Maher, and Moeller (Maher, Edward F.; Rudnick, Stephan N.; Moeller, Dade W. 1987.):

$$D = (70 + 790f)C$$

Here, D is the mean bronchial lung dose equivalent in units of mSv/yr and f is the unattached fraction of radon progeny (percent of radon progeny not attached to aerosol particles). The C is the total exposure to radon progeny, with no separation of the attached and unattached fractions, in units of WLM/yr. The unattached radon progeny concentration divided by the total concentration of radon progeny, unattached and attached radon progeny inclusive (pCi/L),

equals the unattached fraction (NCRP #78, 1984). In other words,  
(unattached radon progeny concentration) / (unattached and attached radon  
progeny concentration) = unattached fraction =  $f$

One minus the unattached fraction is the attached fraction:

$$1 - f = 1 - \text{unattached fraction} = \text{attached fraction.}$$

Therefore, the total concentration is the concentration of the attached radon  
progeny divided by  $1-f$ .

$$\text{Total concentration} = \frac{\text{attached radon progeny concentration}}{1 - f}$$

The purpose of this project is to

1. Determine empirically how the state of attachment of radon is influenced by humidity and temperature.
2. Calculate the dose equivalent delivered to the lungs when radon is released in showers.
3. Compare this dose equivalent from exposure in the shower to the total dose equivalent from all sources of radon in the home.

## Materials and Methods

Measurements of relative humidity and temperature were taken in several bathrooms with running showers with Fisher Scientific's digital hygrometer/thermometer (model 11-661-7A) (see Table III). These bathrooms were chosen randomly from personnel in the the Department of Environmental Sciences and Engineering. All measurements were conducted during October 1987. The digital instrument was placed as close to the running shower as possible, without getting wet. The shower was turned on by the person living at that particular residence to their desired temperature. The digital hygrometer/thermometer was turned on to the relative humidity setting (hygrometer). It takes 5 minutes for an accurate reading. Then it was set to temperature. The temperature reading took 1 minute to complete. The results were recorded and the shower turned off. Also it was noted if the bathroom door was opened or closed and if the bathroom fan was on, off, or if there was not one. The temperature of the home immediately outside of the bathroom, usually in a hallway, was noted also. This temperature varied slightly from the temperature in the bathrooms. Higher humidities were observed under closed conditions (fan off and closed bathroom door). Under these specific conditions (fan off and closed bathroom door) the temperature and humidity readings were: 78.5 F & 93.6%, 76.2 F & 89.3%, 72.5 F & 89.5%, and 75 F & 89.5%. The average of these numbers is: 75.6 F and 90.5% relative humidity. Bathrooms 6 and 7 were not included in this calculation because they possess cathedral ceilings which are atypical size of U.S. bathrooms.



Table III Actual Shower Data, showing temperature, humidity and state of doors and fans in the bathroom during showers.

| Bathroom ID No. | Adjacent Room Temp. (Degrees F) | Bathroom Temp. | Bathroom Rel. Humidity | Door  | Fan |
|-----------------|---------------------------------|----------------|------------------------|-------|-----|
| 1               | 78.1                            | 78.5           | 93.6                   | close | off |
| 1               | 78.1                            | 78.5           | 68.3                   | close | on  |
| 1               | 78.1                            | 78.5           | 49.9                   | open  | off |
| 1               | 78.1                            | 78.4           | 48.8                   | open  | on  |
| 2               | 74.5                            | 76.2           | 89.3                   | close | -   |
| 3               | 72.6                            | 72.5           | 89.5                   | close | -   |
| 3               | 73.4                            | 73.9           | 47.7                   | open  | -   |
| 4*              | 73.2                            | 73.4           | 65.2                   | close | -   |
| 4*              | 73.2                            | 72.6           | 61.6                   | open  | -   |
| 5               | 74.9                            | 75.0           | 89.5                   | close | -   |
| 5               | 74.9                            | 74.8           | 57.4                   | open  | -   |
| 6**             | 73.7                            | 74.6           | 61.3                   | close | off |
| 6**             | 73.7                            | 73.8           | 57.7                   | close | on  |
| 6**             | 72.1                            | 73.3           | 55.7                   | open  | off |
| 6**             | 72.1                            | 73.7           | 55.0                   | open  | on  |
| 7**             | 73.6                            | 72.4           | 56.8                   | close | off |
| 7**             | 73.6                            | 72.3           | 55.9                   | close | on  |
| 7**             | 73.1                            | 72.8           | 53.4                   | open  | off |
| 7**             | 73.1                            | 73.1           | 53.2                   | open  | on  |

\* window slightly ajar

\*\* cathedral ceiling

A radon exposure chamber was built to meet the needs of the research and to mimic these average climate conditions in a bathroom having a running shower (see Table IV and Figure 2).



Table IV Radon Exposure Chamber General Characteristics

|        | Chamber          | Air Lock Chamber    |
|--------|------------------|---------------------|
| Height | 119.4 cm         | 14.9cm              |
| Length | 153.2cm          | 26.0cm              |
| Width  | 58.4cm           | 21.3cm              |
| Area   | 1 m <sup>3</sup> | 0.008m <sup>3</sup> |

$$\text{Total Area of Chamber} = 1 \text{ m}^3 - 0.008\text{m}^3 = 1 \text{ m}^3 = 37.3\text{ft}^3$$

A rectangular lucite chamber (Figure 2) with gloves and an air lock box was constructed for this research project. An air inlet, sample ports and outlet were installed. The air inlet originates at the laboratory house air valve which leads to a calibrated rotameter (Dwyer Rotameter RMC Series; 5 to 50scfh) ,and then to the inlet of the chamber. There was a shelf built to aid in the air movement and circulation, as well as minimizing short circuiting of the air flow. A small fan (Pamotor model 4600x fan) was placed on the shelf to promote this circulatory air flow. Under the air lock box, four electrical outlets were installed for all necessary electrical appliances. Sample ports were installed on the middle face of the chamber . It is necessary to point out that the chamber's air flow (ventilation rate of 0.05 per minute) was designed to mimic a typical room (personal communication, D. J. Crawford-Brown). Stale air corners are present

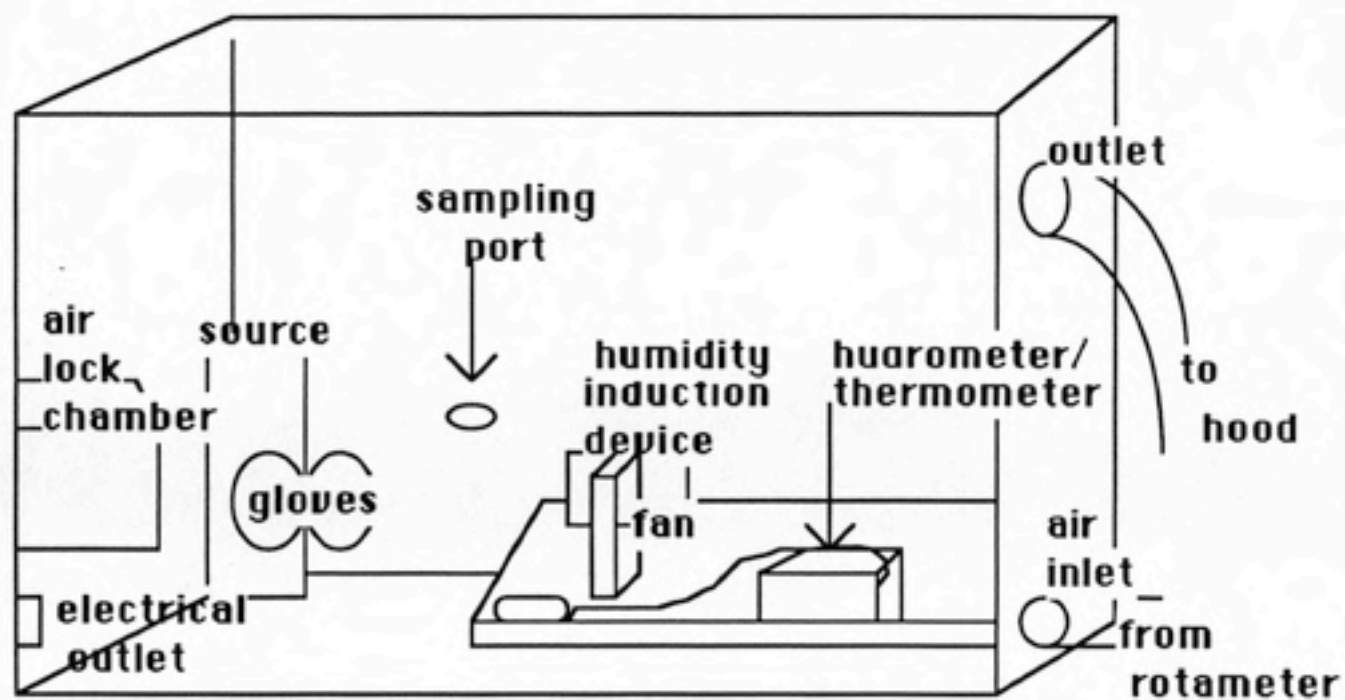


Figure 2 Radon Exposure Chamber. Air flow into the chamber was constant at 36cfh, and ventilation was 0.05 per minutes.

in the chamber, as is the case in a home. The top sample port is equipped with an extension. This extension avoids wall boundary effects.

The air outlet is located on the same side of the chamber as the inlet. However, it is located at the upper portion of the chamber. The outlet is equipped with a dryer hose which is placed inside a laboratory hood. This hood draws air at a fairly constant rate.

The rotameters were calibrated using a spirometer. A house air line was connected to the rotameter's inlet and the rotameter's outlet was connected to the spirometer. A spirometer measures the displacement of volumes of air per unit time. The spirometer readings were converted to cubic feet per hour (cfh) with the aid of the spirometer manufacturer's calibration factor. The rotameter settings were compared to the readings generated by the spirometer; hence a calibration was performed.

Special features required for this particular project were added to the chamber, such as a calibrated digital hygrometer/thermometer (Fisher Scientific) and humidity induction devices. These humidity induction devices are a child's steam vaporizer (Kaz Steam Vaporizer Safeguard 76) and a large beaker of water placed on a hot plate. With these devices high humidity and temperature were induced and measured with the digital hygrometer/thermometer.

A source of radon was obtained from the Pylon company(see Table V). The source is placed inside the chamber. By opening both valves, the radon is

able to diffuse freely from the source. There is an initial burst of radon released due to a buildup in the system (see Figure 3). At an air flow of 36cfh into the chamber, which produces a ventilation rate of 0.05 per minute, an equilibrium

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Table V General Source Characteristics

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Pylon Model Rn-1025 Flow Through Radon Gas Calibration Standard

Serial Number        A-163

Radium-226 activity 488.4kBq as of 9/20/87

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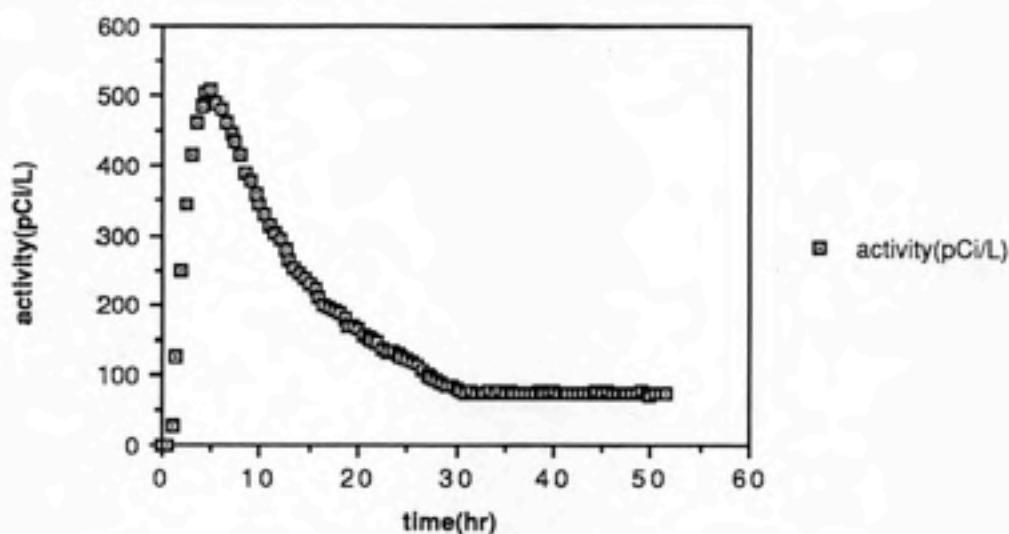


Figure 3 Pylon Continuous Monitoring Device Results illustrates the initial burst of radon immediately after opening and then reaching an equilibrium concentration of 70pCi/L (with a ventilation rate of 0.05 per minute).

radon concentration of 70 pCi/L inside the chamber can be maintained within 35 hours after the source has been opened. The radon concentration was measured with a Pylon AB5 Portable Radiation Monitor Device with a Passive Radon Detector PRD-1 Attachment for several days. The device itself contains a scintillation cell into which air diffuses at a constant rate. The device calibrated by exposure into a known concentration of radon at the USEPA laboratory in Montgomery, Alabama. The counts were converted to activity in pCi/L using a calibration factor provided by the manufacturer. All sampling and measurements reported here were collected at this steady state concentration and under conditions of high and low humidity (90%,60%). Once the source was turned off, the air flow into the chamber was increased to 80cfh. This allowed for quick removal of radon from the chamber; so that it was possible to open the chamber.

The house air line is 25 feet long leading to the rotameter, which connects to the air inlet. The aerosol particles flowing along with the air would plateout (surface deposition) in the 25 feet of tygon tubing because of particle impaction and diffusion. Therefore, there was a low particle count inside the exposure chamber when only aerosols from the house air were present. Induction of additional aerosol particles was needed. At the beginning of each sample collection, a cigarette was lit for 30 seconds to provide an adequate amount of aerosol particles. The cigarette provided a crude, but effective process for generating aerosols.

Two sample analysis techniques were used during this work; alpha

scintillation cells and alpha spectroscopy. Alpha scintillation cells (see Figure 4) were used to calculate the unattached fraction and alpha spectroscopy was used to measure the attached radon progeny concentration.

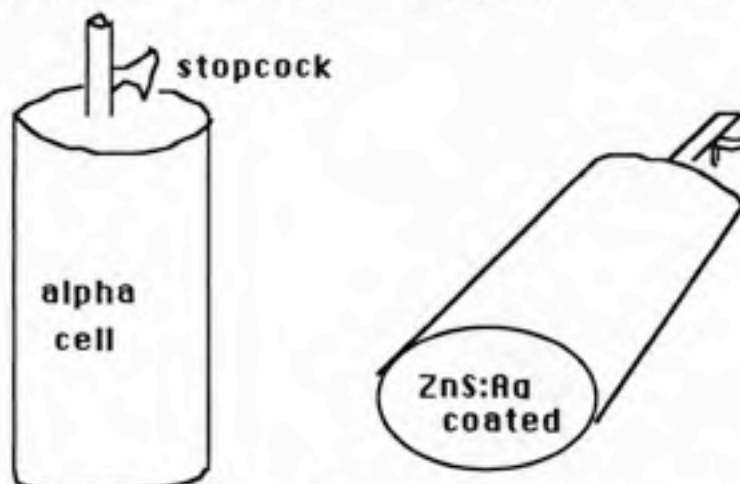


Figure 4 Alpha Scintillation Cell are evacuated chambers (0.125 Liters) with interior surfaces coated with a ZnS:Ag scintillator.

The first technique used alpha scintillation cells (Random Alpha Scintillation Cells model ASC-125), which are evacuated chambers (0.125liters) with interior surfaces coated with a ZnS:Ag scintillator. The uncoated quartz window allows scintillations produced by alpha emissions to leave the alpha cell. The resulting light pulses are collected by a photomultiplier tube and counted by a scalar (see Appendix I for a description of operating procedures). Alpha scintillation cells were used with and without a filter (Whatman 40 ashless filter paper in a Delrin Plastic In-Line Filter Holder) prior to the entrance of the alpha cell. The filter allowed only the radon gas and the unattached radon progeny to enter the alpha cell. The alpha cell without a filter at the entrance of the cell allowed for radon, attached radon progeny and unattached radon progeny to enter the cell (total concentration). By comparing the number of scintillations



with and without the filter, it was possible to calculate the unattached fraction (see Mathematical Analysis and Results Section)

#### ALPHA SCINTILLATION CELL METHOD

The electronic counting system used is depicted in figure 5. For a complete description of equipment settings and components and procedures used, see appendices I and II.

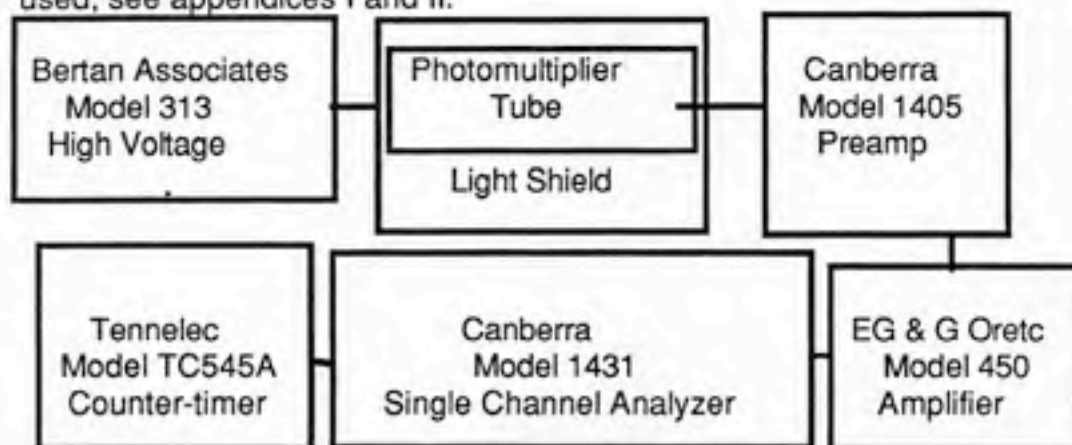


Figure 5 Alpha Scintillation Cell Electronic Apparatus. Block diagram of electronics system used for counting scintillation cells. The cell was placed inside the light shield on top of the photomultiplier tube. For a complete description of settings, see Appendix I.

Prior to any background or sample counting for the day, and at the end of counting, the consistency of the system was tested. A standard activity scintillation cell (Random Alpha Scintillation Reference model ASR-125) was used for this testing. This standard cell does not contain radon, but emits alphas of an energy similar to radon (the exact source is proprietary information by the manufacturer). This cell is placed on the photomultiplier tube in a light shield (black box). The equipment used is the same as for alpha scintillation cells (see Figure 5). Ten one minute counts were recorded and averaged. If these



averaged counts lie in between 22,000 and 24,000 cpm, then the system is said to be working correctly, since the source produces 23,000 disintegrations per minute (as specified by the manufacturer). Prior to sampling, an hour background count was obtained for each scintillation cell. Sample collection was made at the sample port as close to the radon exposure chamber as possible. The alpha scintillation cell, having been evacuated, draws in an air sample from the exposure chamber. The equipment set up is shown in Figures 6 and 7.

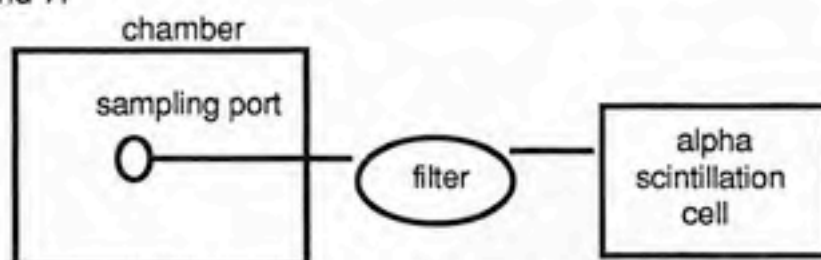


Figure 6 Alpha Scintillation Cell Sampling Apparatus With a Filter. The alpha scintillation cell was connected to a filter which was connected to the sample port of the chamber. The sample port and the cell's stopcock were opened. A sample of chamber air rushed into the evacuated scintillation cell. After 10 seconds, the sample port and the cell's stopcock were closed. All connections were made with tygon tubing. For a complete description of sampling procedures, see Appendix II.

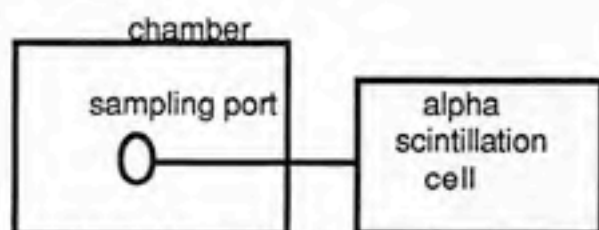


Figure 7 Alpha Scintillation Cell Sampling Apparatus Without a Filter. The alpha scintillation cell was connected directly to the sample port of the chamber. The sample port and the cell's stopcock were opened. A sample of chamber air rushed into the evacuated scintillation cell. After 10 seconds, the sample port and the cell's stopcock were closed. All connections were made with tygon tubing. For a complete description of sampling procedures, see Appendix II.

Immediately after sampling, the alpha cell was counted for 10 minutes. Then the alpha cell was set aside for 4 hours after sampling to allow the original radon progeny to decay and allow the new progeny to reach equilibrium with the radon. Then the cell was counted for 60 minutes. After the 10 minute count, a 60 minute background count of the next alpha cell was begun. There were two alpha scintillation cell measurements performed without a filter and two with a filter per day (see Table VI in the Mathematical Analysis and Results Section). The filters used were two 1 inch Whatman 40 filters and are placed inside a Delrin Plastic In-Line filter holder between the sampling port and the entrance to the alpha cell. The active side of the filter faces the chamber.

The second technique utilizes filter measurements to be analyzed by alpha spectroscopy. In this technique, a 1 inch Whatman 40 filter is placed inside the Delrin Plastic In-Line filter holder. A house vacuum line was connected to a calibrated rotameter, which in turn was connected to the filter next to the sample port of the exposure chamber (see Figure 8). Tygon tubing was used to make the connections. A 15 minute sample was obtained (at a flow rate of 4lpm) by drawing air through the filter, and the activity on the filter analyzed by alpha spectroscopy. This filter collected attached radon progeny. The sampling equipment used is depicted in Figure 8. For a complete step by step guide to the procedures see Appendix III.

### FILTER METHOD

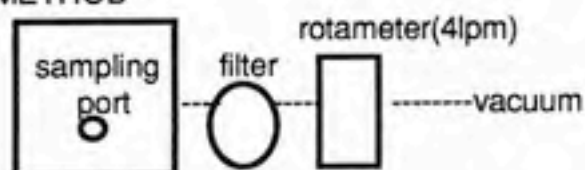


Figure 8 Filter System. A vacuum line was connected to a calibrated rotameter. This rotameter was connected to a filter holder (containing a Whatman 40 filter) which in turn was connected to the sample port of the chamber. The sample port was opened and a 15 minute sample was collected (at a vacuum flow of 4 liters per minute). For a complete description of the filter sampling procedures, see Appendix III.

### ALPHA SPECTROSCOPY

The alpha spectroscopy electronic counting system used is depicted in Figure 9. The components used are indicated. For a complete description of equipment settings used and procedures see appendices IV and V.

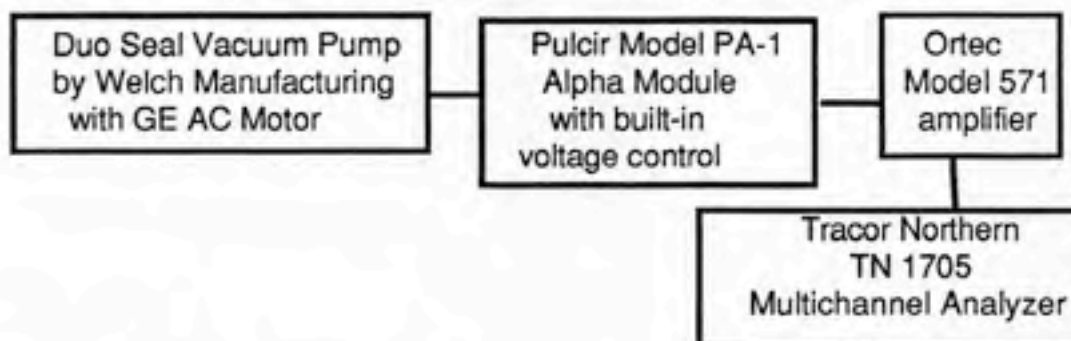


Figure 9 Alpha Spectroscopy Apparatus. Block diagram of electronics system used for counting filter samples. The filter was placed under the surface barrier detector of the alpha module. For a complete description of settings and procedures, see Appendices IV and V.

The filter was left inside the bottom part of the filter holder; thereby not to smear or disrupt the sample. The filter was placed under the surface barrier detector (alpha module detector) on the second shelf. Placing the filter on the second shelf allowed for the filter to be placed as close as possible to the

detector with a negligible gap. A vacuum was maintained during the entire sample analysis in order to minimize loss of the alpha energy. Two minutes after the 15 minute sampling from the exposure chamber, a 10 minute count was performed by alpha spectroscopy. The regions of interest were determined to correspond to the energy ranges of alphas emitted by RaA and RaC', as specified by a modified Tsivoglou computer code provided by Oak Ridge National Laboratories. This ten minute count showed a spectrum with two distinct peaks (see Figure 10). These peaks refer to the alpha emissions from RaA and RaC' (6.00 and 7.69 MeV). The counts in each specific region were recorded by integration. These regions of interest, which correspond to those of the computer code are:

Region A: 5.2 to 6.16 MeV, corresponding to channel numbers: 259 to 295. Region B: 6.16 to 6.75 MeV, corresponding to channel numbers: 295 to 318. Region C: 6.75 to 8.1 MeV, corresponding to channel numbers: 318 to 368. Region D: 8.1 to 9.5 MeV, corresponding to channel numbers: 368 to 422.

In the 10 minute count, the 2 peaks were observed in regions A and C.

Calibration was performed by locating the RaC' peak and placing it into channel 350.

Once the 10 minute count was finished, it was necessary to wait 3 minutes before initiating a 15 minute count. The counts in each region of interest then were recorded for this count. This 15 minute count showed one distinct peak (Figure 11), that of RaC' (7.69MeV). From these counts in specific

regions of interest, a radon progeny concentration on the filter (in pCi/L) can be computed with the aid of the computer code. During this 15 minute count, the next 15 minute sampling at the exposure chamber was started with identical procedures.

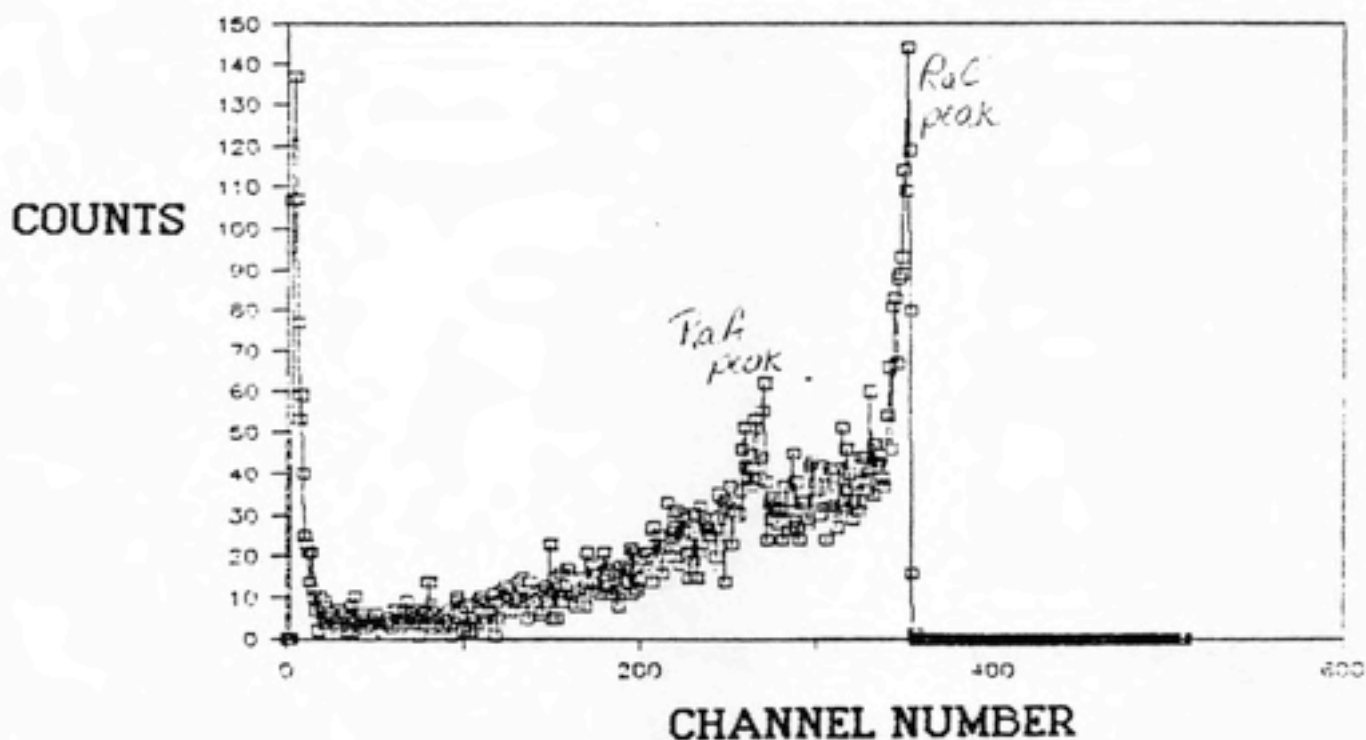


Figure 10 Ten Minute Spectrum. This graph illustrates the two peaks produced from the alpha emissions from RaA and RaC' (6.00 and 7.69 MeV) respectively.

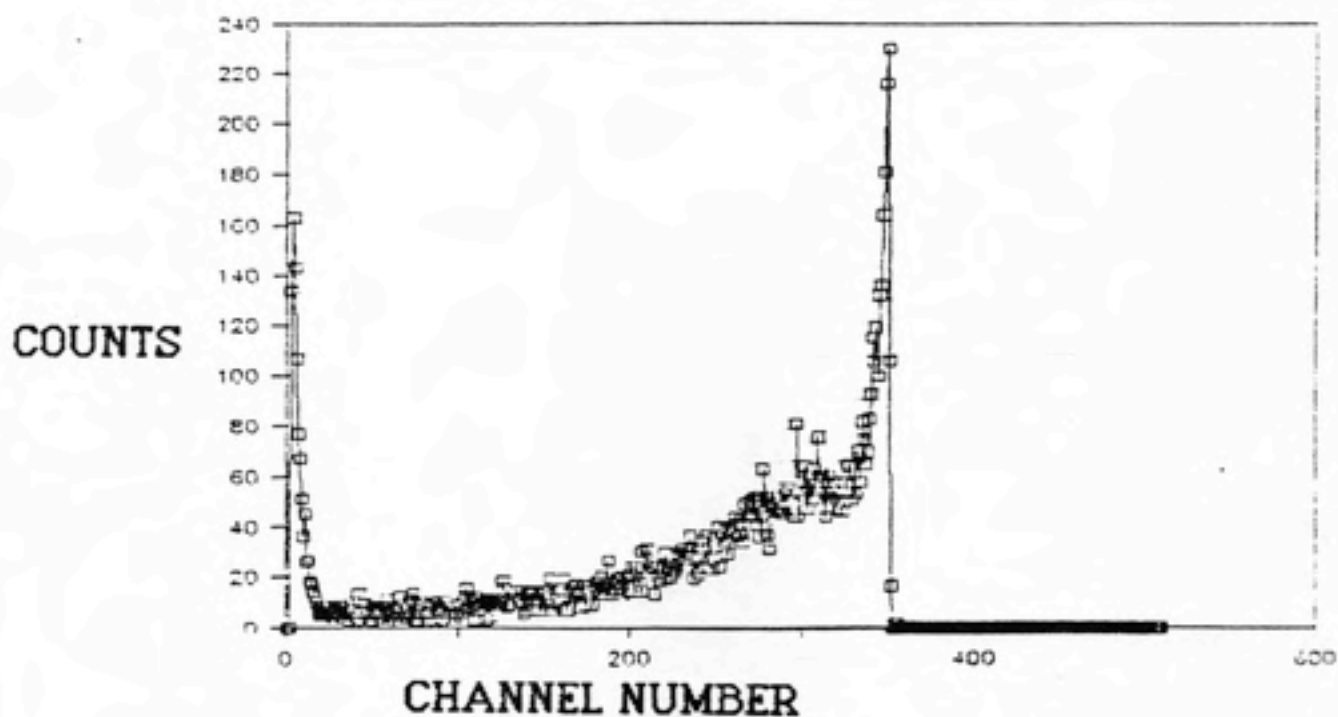


Figure 11 Fifteen Minute Spectrum. This graph illustrates the buildup of RaC'. The RaC' peak has greatly increased in comparison to the ten minute count (Figure 10).

Input into the modified Tsivoglou computer code consisted of the sample flow rate (4Lpm), length of sampling (15minutes), filter efficiency (95%), absolute efficiency of the detector (25%). The latter efficiency of the detector includes loss of counts due to placement of the particles on the filter.



## MATHEMATICAL ANALYSIS AND RESULTS

### Alpha Scintillation Data Analysis

Table VI shows the data collected from alpha scintillation cells for four days. On each day 4 alpha cells were used for sampling; two samples with filters and two without. Each of the 4 alpha cells was counted, including a background, 10 minute and 60 minute count. The background count occurred prior to sampling and continued for 60 minutes. The 10 minute count occurred immediately after sampling and continued for 10 minutes. The 60 minute count occurred 4 hours after sampling and continued for 60 minutes. The first 10 minute count was used to determine the relative concentration of attached and unattached radon progeny in the chamber air. During this count, there were three sources of alphas. These were (1) from radon drawn from the chamber, (2) from progeny which were produced in the scintillation cell by this radon and (3) from progeny drawn into the cell from the chamber. The first two sources must be separated from the third in order to determine the progeny drawn from the chamber.

The number of decays contributed to the 10 minute count by radon may be determined from the 60 minute count performed after 4 hours. After 4 hours, the progeny produced by the radon in the cell would have grown into equilibrium. As a result, the count rate at 4 hours would be three times the count rate from the radon alone. This same count rate (from the radon alone) would



Table VI     Alpha scintillation cell data. Each cell was counted for 10 minutes immediately following sampling, and then for 60 minutes 4 hours after sampling (to allow equilibrium of the progeny). The column labelled filter refers to whether a filter was or was not placed over the entrance to the cell.

| Day | Humidity | background<br>count | 10min<br>count | 60min<br>count | filter |
|-----|----------|---------------------|----------------|----------------|--------|
| 1   | 60%      | 33                  | 259            | 2190           | no     |
| 1   | 60%      | 34                  | 152            | 1777           | yes    |
| 1   | 60%      | 14                  | 192            | 1890           | yes    |
| 1   | 60%      | 14                  | 222            | 2527           | no     |
| 2   | 90%      | 26                  | 238            | 1994           | no     |
| 2   | 90%      | 35                  | 146            | 1646           | yes    |
| 2   | 90%      | 17                  | 142            | 1526           | yes    |
| 2   | 90%      | 39                  | 185            | 2087           | no     |
| 3   | 60%      | 40                  | 135            | 1649           | yes    |
| 3   | 60%      | 20                  | 210            | 1952           | yes    |
| 3   | 60%      | 23                  | 282            | 2580           | no     |
| 3   | 60%      | 26                  | 257            | 2390           | no     |
| 4   | 90%      | 21                  | 205            | 1851           | no     |
| 4   | 90%      | 27                  | 164            | 1855           | yes    |
| 4   | 90%      | 31                  | 189            | 1826           | yes    |
| 4   | 90%      | 34                  | 229            | 2079           | no     |

apply during the 10 minute count. To obtain the radon contribution to the 10 minute count, therefore, the count rate after 4 hours was divided by 3. This then

was subtracted from the count rate during the 10 minute count.

It then was necessary to determine the counts (in the 10 minute count) contributed by progeny produced by the radon after entering a cell. Only the RaA was of importance in this regard due to its short half-life. Calculations, given in detail below, indicated that approximately 0.69 decays from RaA would be produced for each decay of radon during the 10 minute count. The count rate from the radon alone, therefore, was multiplied by 0.69 to determine the contribution from ingrowth of RaA. This also was subtracted from the total count rate during the 10 minute count. The result was an estimate of the count rate due only to progeny drawn in from the chamber. This latter count rate, when obtained without a filter across the cell entrance, was proportional to the concentration of all progeny (attached plus unattached) in the chamber. The count rate obtained with a filter was proportional to the concentration of unattached (free) progeny.

#### **RaA Contribution Calculations:**

At time equal zero, assume that there is pure radon in the scintillation cell at a steady state. The decay rate from the radon alone is  $\lambda_{222}\text{N}_{222}$ . The symbol  $\lambda$  is the decay constant for radon and the N is the number of atoms of radon. This concentration was assumed constant at all times.

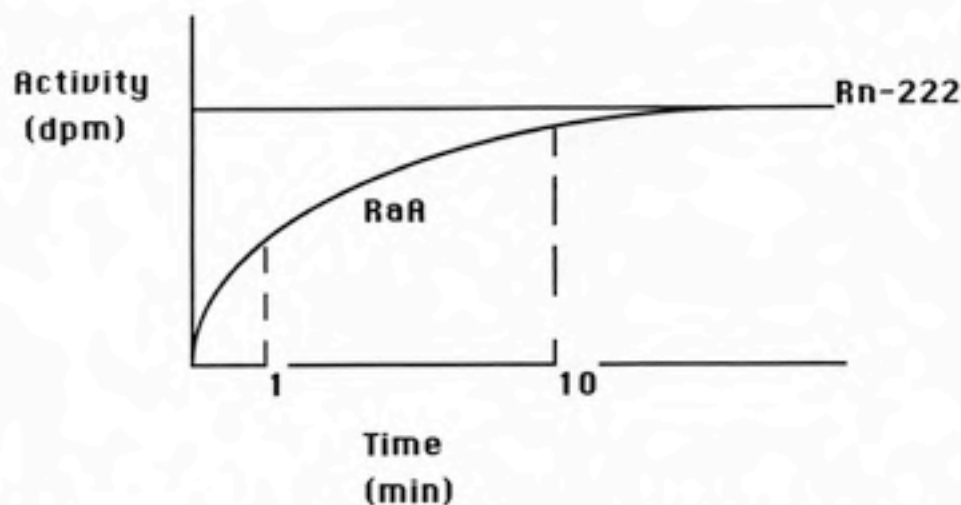


Figure 12 RaA buildup curve. This curve shows the short amount of time necessary for RaA to reach equilibrium with radon, assuming a fixed radon concentration.

At any time during the 1 to 11 minute counting interval, the activity of Rn equals

$\lambda_{222}N_{222}$  (see Figure 10) and the activity of RaA equals  $\lambda_{222}N_{222} (1 - e^{-\lambda_A t})$ .

The exponential portion of this equation denotes the decay of radon to RaA. The

$\lambda_A$  is the decay constant for RaA. Total decays from Rn in the time interval from 1 to 11 minutes is

$$\lambda_{222}N_{222} \times 10 \text{ minutes.}$$

Total decays from RaA in the time interval from 1 to 11 minutes is

$$\int_1^{11} \lambda_{222}N_{222} (1 - e^{-\lambda_A t}) dt.$$

The solution to this integral is  $\lambda_{222}N_{222} (6.85)$  which is the total decays from

RaA. Therefore the total decays of Rn and RaA is simply the sum of the two:

$$\begin{array}{r} \lambda_{222}N_{222} (10 \text{ minutes}) \\ + \lambda_{222}N_{222} (6.85) \\ \hline \lambda_{222}N_{222} (16.85). \end{array}$$

In other words, there is a 69% contribution from RaA during the 10 minute alpha scintillation cell count.

### **Unattached Fraction Calculation**

The following is an example of the determination of the unattached fraction:

Using data from day 1 and no filter (Table VI)

The net counts (during the 60 minute count) = gross counts - background  
counts = 2190 - 33 = 2157 counts per 60 minutes.

Converting the net counts to counts per 10 minutes:

$$\frac{2157 \text{ counts}}{60 \text{ minutes}} \times 10 \text{ minutes} = 360 \text{ counts per 10 minutes}$$

For each decay of radon there are three alphas emitted; one each from radon, RaA, and RaC'. To determine the number of counts from radon alone:  
(360 counts per 10 minutes) / 3 alphas emitted per each radon decay =  
120 counts per 10 minutes

Recall that there is a 69% RaA contribution; therefore adding the RaA contribution:

120 counts per 10 minutes  $\times$  1.69 = 203 counts per 10 minutes from the radon and RaA (which grew in from the radon).

The 10 minute count yielded 259 counts per 10 minutes.

During these 10 minutes, the radon (and its ingrowth of RaA) contributed 203 counts. The net counts per 10 minutes from progeny drawn into the cell from the chamber is:

$$259 - 203 = 56 \text{ counts per 10 minutes.}$$

Thus that there are 56 counts per 10 minutes contributed from the attached and unattached radon progeny drawn into the cell.

Used from day 1 and with filter (Table VI)

Total counts during the 60 minute count = gross counts - background counts =

$$1777 - 1743 \text{ counts per 60 minutes.}$$

Convert the net counts to counts per 10 minutes:

$$\frac{1777 - 1743 \text{ counts}}{60 \text{ minutes}} \times 10 \text{ minutes} = 290.5 \text{ counts per 10 minutes}$$

For each decay of radon there are three alphas emitted; one each from radon,

RaA, and PoC'. To determine the number of counts from radon alone:

$$(290.5 \text{ counts per 10 minutes}) / 3 \text{ alphas emitted per each radon decay} =$$

$$96.8 \text{ counts per 10 minutes}$$

Recall that there is a 69% RaA contribution; therefore adding the RaA

contribution:

$$96.8 \text{ counts per 10 minutes} \times 1.69 = 163.6 \text{ counts per 10 minutes from the}$$

radon plus RaA.

The net counts per 10 minutes from progeny drawn into the cell from the chamber is:

$$152 - 163.6 = -11 \text{ counts per 10 minutes.}$$

The concentration of unattached radon progeny was less than the lower limit of detection. Therefore the background count was greater than the sample count.

Repeating the same process for the two remaining cases of day 1, the results

are as follows:

| <u>No filter</u>                 | <u>Filter</u>                     |
|----------------------------------|-----------------------------------|
| 56 counts per 10 minutes         | -11.6 counts per 10 minutes       |
| <u>-14 counts per 10 minutes</u> | <u>15.7 counts per 10 minutes</u> |
| Total: 42 counts per 10 minutes  | 4 counts per 10 minutes           |

The filter attached to the alpha scintillation cell allowed for the radon gas and unattached radon progeny to enter the alpha scintillation cell. Without the filter, radon, attached and unattached radon progeny entered the alpha scintillation cell. Assuming the radon concentration in both cases was constant, the unattached radon progeny concentration divided by the attached and unattached radon progeny concentration equals the unattached fraction.  $(4/42) \times 100 = 9\%$ .

Continuing this identical process for days 2, 3, and 4, the results are in Table VII.

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Table VII Results of Alpha Scintillation Cell Measurements.  
Uncertainties have not been calculated.

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| Day | Humidity | Percent Unattached |
|-----|----------|--------------------|
| 1   | 60%      | 9.0                |
| 2   | 90%      | <1.0               |
| 3   | 60%      | 17.0               |
| 4   | 90%      | 18.0               |

---



### **Unattached Fraction**

Table VII shows the results obtained by the alpha scintillation cell measurements. These results indicate that the presence of high humidity usually decreases the percent unattached (from 9% to <1%). For example, the average percent unattached for these four studies is 13% with low humidity and 9% with high humidity. However, the last test run does not reflect this conclusion. I feel this is due to a static charge buildup on the walls of the chamber which has been discussed by other authors. I'll return to this topic in my recommendations. If however, we focus only on the results of the first 2 tests, where charge buildup was negligible, it is clear that high humidity decreased the percent unattached. The following calculations will utilize both of these approaches.

### **FILTER DATA ANALYSIS**

Table VIII shows the filter counts in each energy range of interest for the 10 minute and 15 minute counting intervals. The results from the separate days were averaged for this study. These averaged filter measurements were inputted into a modified Tsivoglou computer code at Oak Ridge National Laboratory. The results are shown in Table IX.

Table VIII Filter data

| Day | Humidity | 10 minute count |      |      |   | 15 minute count |      |      |   |
|-----|----------|-----------------|------|------|---|-----------------|------|------|---|
|     |          | A               | B    | C    | D | A               | B    | C    | D |
| 1   | 60%      | 1309            | 874  | 1825 | 0 | 1665            | 1241 | 2673 | 1 |
| 1   | 50%      | 1175            | 767  | 1520 | 0 | 1536            | 1065 | 2278 | 0 |
| 1   | 50%      | 1180            | 754  | 1774 | 0 | 1480            | 1074 | 2632 | 0 |
| 1   | 50%      | 1162            | 797  | 1560 | 0 | 1475            | 1122 | 2331 | 0 |
| 2   | 30%      | 1527            | 975  | 2682 | 0 | 1695            | 1534 | 4065 | 1 |
| 2   | 30%      | 1489            | 966  | 2649 | 0 | 1618            | 1364 | 3895 | 1 |
| 2   | 30%      | 1484            | 1000 | 2624 | 0 | 1771            | 1408 | 3631 | 1 |
| 2   | 30%      | 1494            | 1011 | 2672 | 1 | 1824            | 1459 | 3776 | 1 |

## Averages of each day

|   | Humidity | 10 minute count |     |      |      | 15 minute count |      |      |      |
|---|----------|-----------------|-----|------|------|-----------------|------|------|------|
|   |          | A               | B   | C    | D    | A               | B    | C    | D    |
| 1 | 60%      | 1207            | 798 | 1669 | 0    | 1539            | 1126 | 2479 | 0.25 |
| 2 | 90%      | 1499            | 988 | 2657 | 0.25 | 1727            | 1441 | 3842 | 1    |

Energy region A = 5.2 to 6.16 MeV    Energy region B = 6.16 to 6.75 MeV

Energy region C = 6.75 to 8.1 MeV    Energy region D = 8.1 to 9.5 MeV

These results in Table IX show an increased activity from the radon progeny on the filters for high humidity, which indicates that the induction of humidity raised the concentration of attached progeny. For example, in the filter measurements the activity of progeny attached was 55, 42 and 40 picocuries per liter for low humidity and 63, 45, and 47 picocuries per liter for high humidity. This is in agreement with the general findings of the degree of unattachment in Table VII; since Table VII indicates that the unattached fraction was highest under conditions of low humidity. We suspect a high unattached

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Table IX Results of Filter Measurements

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| Humidity | Attached Concentration |                |                |
|----------|------------------------|----------------|----------------|
|          | RaA<br>(pCi/L)         | RaB<br>(pCi/L) | RaC<br>(pCi/L) |
| 60%      | 55 $\pm$ 0.25          | 42 $\pm$ 0.25  | 40 $\pm$ 0.25  |
| 90%      | 63 $\pm$ 0.25          | 45 $\pm$ 0.25  | 47 $\pm$ 0.25  |

---

fraction increases deposition of the progeny to the walls. These results show that the radon progeny suspended in the air are more likely to be attached to aerosol particles or condensation nuclei under conditions of high humidity.

The percent errors were generated by the computer code incorporating uncertainties in volumetric flow rate, filter efficiency, geometry of the detector, and intrinsic efficiency of the detector due to placement of the particles on the filter. These uncertainties were specified by the computer code.

### Dose Equivalent Calculation

Results concerning the percent unattached (Table VII) and the concentration of the attached progeny (Table IX) under conditions of high and low humidity were placed into an equation provided by Robley D. Evans:

$$WL = (0.00103) I_a + (0.00507) I_b + (0.00373) I_c \quad (3.1)$$

WL = working level of short-lived radon progeny

$I_a$  = activity per liter of RaA, including both attached and unattached [ Recall that the total concentration is the attached progeny concentration divided by 1-f, the unattached fraction. ]

$I_b$  and  $I_c$  are the concentrations of RaB and RaC, respectively.

For example; focussing on the case of low humidity using an averaged unattached fraction of 13%:

Substituting into equation (3.1):

$$\begin{aligned} WL &= 0.00103(55/(1-.13)) + 0.00507(42/(1-.13)) + 0.00373(40/(1-.13)) \\ &= 0.48 \end{aligned}$$

It then was assumed that an individual spends 20 minutes/day in the shower. In the following calculations, the concentration in the exposure chamber (70pCi/L) was used.

Converting to Working Level Months per year (WLM/yr):

$$\begin{aligned} \text{WLM/yr} &= 0.48 \times [(20 \text{ min/day}) \times (1 \text{ hr}/60 \text{ min}) \times (365 \text{ day/yr})] / 170 \text{ hr/yr} \\ &= 0.35 \end{aligned}$$

Substituting into the following equation by Rudnick, Maher, and Moeller:

$$D = (70 + 790f)C \quad (3.2)$$

D=the mean bronchial lung dose equivalent in mSv/yr.

f=unattached fraction of radon progeny.

C=cumulative exposure to potential alpha energy of radon progeny in WLM/yr.

$$D = (70 + 790(.13)) 0.35$$

$$= 59.5 \text{ mSv/yr}$$

$$= 5.95 \text{ rems/yr}$$

This is the dose equivalent for a 20 minute shower to the bronchial region of the lung for the case of low humidity when the radon concentration was maintained at the value of 70pCi/L found in the exposure chamber. However, the concentrations of radon in home air typically will be at least an order of magnitude below this value maintained in the exposure chamber.

Case of high humidity using an averaged unattached fraction of 9%:

Substituting into equation (3.1):

$$WL = 0.00103(63/(1-.09)) + 0.00507(45/(1-.09)) + 0.00373(47/(1-.09))$$

$$= 0.52$$

Converting to Working Level Months per year (WLM/yr):

$$WLM/yr = 0.52 \times [(20 \text{ min/day}) \times (1 \text{ hr}/60 \text{ min}) \times (365 \text{ day/yr})] / 170 \text{ hr/yr}$$

$$= 0.37$$

Substituting into equation (3.2)

$$D = (70 + 790(.09)) 0.37$$

$$= 51.9 \text{ mSv/yr}$$

$$= 5.19 \text{ rems/yr}$$

This is the dose equivalent for a 20 minute shower to the bronchial region of the lung under conditions of high humidity and a radon concentration of 70pCi/L.

For the cases of high and low humidity using  $f$  values of 1% and 9% as indicated by only the first set of measurements, the dose equivalents are 2.64 and 4.65 rems/yr respectively.

### **Relationship Between Radon Air Concentration ( $C_a$ ) and Radon Water Concentration ( $C_w$ )**

Assume that a person takes 20 minute showers every day in a bathroom 6feet by 8 feet by 8feet, and assume a transfer efficiency of radon to the air is 90%. A typical average shower uses 37.5 liters (L) of water per shower (Cothorn, C. Richard and Smith, James E. Jr. Environmental Radon, 1987).

The rate of release of radon into the bathroom,  $R$ , is equal to the amount of water used divided by the time spent in the shower multiplied by the concentration of radon in the water and the transfer efficiency.

$$R = (37.5 \text{ L}/20 \text{ minutes}) \times C_w \times 0.9 = 1.69 \text{ Lpm} \times (C_w)$$

where  $C_w$  = concentration of radon in the water (pCi/L)

$R$  = rate of radon entry into the room (pCi/L/minute)

The concentration of radon in the air liberated from the shower is equal to the rate of radon into the bathroom air, divided by a removal factor and by the size of the bathroom (384 ft<sup>3</sup>) . The decay factor,  $\lambda$ , incorporates both the ventilation rate and the radiological decay as routes of elimination of radon from the air, although it was dominated by the ventilation rate dose to the long



radiological half-life of radon. For this example,  $\lambda$  equals 0.05 per minute.

$$C_a = \frac{R (1 - e^{-\lambda t})}{\lambda V} = \frac{1.69 \text{ Lpm} \times C_w \times (1 - e^{-0.05 \text{ per min} (20 \text{ min})})}{384 \text{ ft}^3 \times (28.3 \text{ L} / 1 \text{ ft}^3) \times 0.05 \text{ per minute}}$$

where  $V$  = the volume of the room

$\lambda$  = the removal factor or rate constant

In this equation,  $C_a$  is the concentration at the end of the 20 minute shower. The average concentration during this shower is approximately  $0.5 C_a$ .

Therefore the relationship between the radon concentration in the water to the air is:

$$C_a = 0.001 C_w$$

where both  $C_a$  and  $C_w$  are in units of pCi/L. Typically  $C_w$  is several thousand picocuries per liter (UNSCEAR, 1972).

### **Dose Equivalent Rate For a Typical Home**

Assuming 1pCi/L of radon in complete equilibrium with the progeny in the average home at continuous exposure, the exposure rate is:

$$(1 \text{ pCi/L}) / [(100 \text{ pCi/L}) / \text{WL}] = 0.01 \text{ WL}$$

At 50% equilibrium (NCRP #78, 1984, 1984), this exposure rate is:

$$0.01 \text{ WL} \times 0.5 = 0.005 \text{ WL}$$

Assuming 52 months per year, the cumulative exposure is:

$$0.005 \text{ WL} \times 52 \text{ months/year} = 0.26 \text{ WLM/yr}$$

Assuming 0.5rads per WLM (NCRP #77), converting from WLM/yr to rads/yr:

$$0.26 \text{ WLM/yr} \times 0.5 \text{ rads/WLM} = 0.13 \text{ rads/yr}$$

Since these alphas have a quality factor of 20 (Cember 1983), the dose equivalent is:

$$0.13\text{rads/yr} \times 20 = 2.6 \text{ rem/yr.}$$

**Determination of the radon concentration in water required to deliver 2.6 rems/yr as a result of showers**

The above calculations suggest that the concentration of radon in bathroom air is approximately 0.001 times that in the water. Previous results (see page 7), however, indicate that the dose equivalent delivered to the lung also depends upon the level of temperature and humidity. It is of interest, therefore, to determine the concentration of radon in water that will produce 2.6 rems/year, which is the average annual dose rate from other sources in the home. In the following calculations, this water concentration will be determined for both high and low humidity, using the results of the first day of measurements alone and the average of the two separate days of measurements.

The first case is for low humidity using the average of the two days. Bear in mind that this corresponded to an unattached fraction of 13% and to a dose equivalent of 5.95 rems per year (assuming exposure of 20 minutes per day). Since the radon concentration was 70pCi/L in this experiment, the first case suggests that under conditions of low humidity, bathroom exposures would yield:

$$(5.95 \text{ rems/yr}) / 70\text{pCi/L} = \frac{0.085 \text{ rems/yr}}{[\text{pCi/L}]_a}$$

where  $[\text{pCi/L}]_a$  refers to the concentration in air. Since the concentration in

water will be 1000 times that in air, bathroom exposure will yield:

$$(0.085) / 1000 = 8.5 \times 10^{-5} \frac{\text{rems/yr}}{[\text{pCi/L}]_w}$$

where  $[\text{pCi/L}]_w$  refers to the concentration in water. The water concentration needed to produce 2.6 rems/year in the bathroom under conditions of low humidity then is:

$$C_w = 2.6 / 8.5 \times 10^{-5} = 30,600 \text{ pCi/L}$$

The second case is for high humidity using the average of the two days. Bear in mind that this corresponded to an unattached fraction of 9% and to a dose equivalent of 5.19 rems per year (assuming exposure of 20 minutes per day). Since the radon concentration was 70pCi/L in this experiment, the first case suggests that under conditions of low humidity, bathroom exposures would yield:

$$(5.19 \text{ rems/yr}) / 70 \text{ pCi/L} = \frac{0.074 \text{ rems/yr}}{[\text{pCi/L}]_a}$$

where  $[\text{pCi/L}]_a$  refers to the concentration in air. Since the concentration in water will be 1000 times that in air, bathroom exposure will yield:

$$(0.074) / 1000 = 7.4 \times 10^{-5} \frac{\text{rems/yr}}{[\text{pCi/L}]_w}$$

where  $[\text{pCi/L}]_w$  refers to the concentration in water. The water concentration needed to produce 2.6 rems/year in the bathroom under conditions of low humidity is:

$$C_w = 2.6 / 7.4 \times 10^{-5} = 35,000 \text{ pCi/L}$$

The third case is for low humidity. Bear in mind that this corresponded to an unattached fraction of 9% and to a dose equivalent of 4.65 rems per year (assuming exposure of 20 minutes per day). Since the radon concentration was 70pCi/L in this experiment, the first case suggests that under conditions of low humidity, bathroom exposures would yield:

$$(4.65 \text{ rems/yr}) / 70 \text{ pCi/L} = \frac{0.066 \text{ rems/yr}}{[\text{pCi/L}]_a}$$

where  $[\text{pCi/L}]_a$  refers to the concentration in air. Since the concentration in water will be 1000 times that in air, bathroom exposure will yield:

$$(0.066) / 1000 = 6.6 \times 10^{-5} \frac{\text{rems/yr}}{[\text{pCi/L}]_w}$$

where  $[\text{pCi/L}]_w$  refers to the concentration in water. The water concentration needed to produce 2.6 rems/year in the bathroom under conditions of low humidity is:

$$C_w = 2.6 / 6.6 \times 10^{-5} = 39,000 \text{ pCi/L}$$

The last case is for high humidity. Bear in mind that this corresponded to an unattached fraction of 1% and to a dose equivalent of 2.64 rems per year (assuming exposure of 20 minutes per day). Since the radon concentration was 70pCi/L in this experiment, the first case suggests that under conditions of low humidity, bathroom exposures would yield:

$$(2.64 \text{ rems/yr}) / 70 \text{ pCi/L} = \frac{0.038 \text{ rems/yr}}{[\text{pCi/L}]_a}$$

where  $[\text{pCi/L}]_a$  refers to the concentration in air. Since the concentration in water will be 1000 times that in air, bathroom exposure will yield:

$$(0.038) / 1000 = 3.8 \times 10^{-5} \frac{\text{rems/yr}}{[\text{pCi/L}]_w}$$

where  $[\text{pCi/L}]_w$  refers to the concentration in water. The water concentration needed to produce 2.6 rems/year in the bathroom under conditions of low humidity then is:

$$C_w = 2.6 / 3.8 \times 10^{-5} = 69,000 \text{ pCi/L}$$

These results are summarized in Table X.

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Table X Summarized Results, showing the unattached fractions (f), exposures (WLM), exposure rates (WLM/yr), and annual dose equivalent (D) for the exposure chamber. This table also shows the concentration of radon in water ( $C_w$ ) needed to produce an annual dose equivalent of 2.6 rems.

---

|                | Humidity |        |        |        |
|----------------|----------|--------|--------|--------|
|                | High     | Low    | High   | Low    |
| f              | 0.09*    | 0.13*  | 0.01   | 0.09   |
| WLM            | 0.52     | 0.48   | 0.47   | 0.46   |
| WLM/yr         | 0.37     | 0.35   | 0.34   | 0.33   |
| D in rems/yr   | 5.19     | 5.95   | 2.64   | 4.65   |
| $C_w$ in pCi/L | 35,000   | 30,600 | 69,000 | 39,000 |

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\* averages of the 2 sets of measurements in the chamber  
(2 at low humidity and 2 at high humidity).

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## DISCUSSION AND RECOMMENDATIONS

The calculated annual dose equivalent to the bronchial tissue, assuming 20 minute showers per day for 365 days per year, is 26.4mSv/yr (2.64rem/yr) under conditions of high humidity and 46.5mSv/yr (4.65rem/yr) under conditions of low humidity, assuming the radon concentration is held constant at the 70 picocuries per liter which was maintained in my exposure chamber.

The typical U.S. home contains approximately 1 pCi/L of radon in air. This produces a dose equivalent of 2.6 rems per year to the tracheobronchial region of the lung. Under conditions of low humidity, water used in showers would require a concentration of 39,000 pCi/L of radon in order to produce this same dose equivalent of 2.6 rems per year. Under conditions of high humidity, the water must contain a concentration of 69,000 pCi/L.

In conclusion, the presence of high humidity typical of conditions in a bathroom containing a running shower decreases the dose equivalent delivered to the lungs as a result of a fixed concentration of radon. In addition, relatively high concentrations of radon in water are needed in order to significantly raise the dose equivalent delivered by other sources in typical U. S. homes. The reader should bear in mind that an average concentration of radon in water is approximately 5,000 pCi/L (UNSCEAR, 1972).

Under high humidity conditions, the attached progeny concentration increases; however, the unattached fraction decreases significantly. The overall result shows a decrease in the dose equivalent for a fixed radon concentration. Recommendations for future studies include:



1. Control the static build up in the exposure chamber. For example, build the chamber out of wood and not lucite. Lucite is an insulator , therefore, there is significant charged progeny plateout at a greater rate.
2. Control the concentration of aerosol particles. For example, install a corona discharge filament at the airstream inlet.
3. Measure the aerosol size distribution and the distribution of the attached progeny under high and low humidity.
4. Measure deposition onto wall surfaces in order to obtain a complete understanding of the processes controlling exposure in showers.
5. Connect small air pump (100cc/minute) to the Pylon gas flow Rn-1025 source's dessicant. This will allow for the emanation of radon in one direction, as well as, a more efficient removal of radon from the source.
6. Personal communication (Andreas George) indicated that the unattached radon progeny may also be filtered out, hence introduce some error. This matter needs further study (ie. compare collection efficiency of unattached radon progeny on millipore filters to glass fiber filters).

## APPENDIX I

### Settings for alpha scintillation cell electronics

A light shield (black box) houses the photomultiplier tube(PMT). The signal wire coming out of the PMT goes to the preamplifier, then to the amplifier, which is housed in the nimbin. Input is into the normal input. (The normal and differential inputs may be two distinct inputs, however, they are both connected together in the back of this unit). The unipolar output of the amplifier attaches to the single channel analyzer (SCA) input. Then the SCA output connects to the scalar in positive socket. NOTE: If blackout occurs, turn voltage off.

Specifics:

BERTAN ASSOCIATES MODEL 313 HIGH VOLTAGE

CANBERRA MODEL 1405 PREAMPLIFIER

ORTEC MODEL 450 AMPLIFIER

BLR is OUT

Unipolar output range of 10 volts (coincides with discriminator)

Differentiate is set to 2 and integrate is set to OUT for

the shaping time constant. They both determine the RC circuit time. The differentiate switch looks for the slope of the pulse as well as eliminating noise. Noise generates a faster rising pulse than radiation, therefore, differential cuts out noise and looks only at radiation.

Coarse gain is set to 50.

Fine gain is set to 10 (actually 1.0 due to the range of 0.5 to 1.5).

Input mode is negative on differential side.

CANBERRA MODEL 1431 SCA

Mode is on dual disc (pays attention to both Lower Limit of Detection (LLD) and Upper Limit of Detection (ULD).

LLD is set to 0.5.

ULD is set to 10 (similar to window size  $\Delta E$ ; 10 is the maximum).

TENNELEC TC 545A COUNTER-TIMER

## APPENDIX II

### Procedures for alpha scintillation cell analysis

1. Voltage is off (down).
2. Turn power on.
3. Perform a system check using a standard. The alpha scintillation cells are located on the bottom shelf above the nimbin. The one on the far right is the standard. The standard is not actually radon however it emits alphas with comparable energies as radon. The standard checks the reliability of the electronics. Place the standard on top of photomultiplier tube (PMT) in the black box (serves as a light screen) to the right of the nimbin. NOTE: Run a standard at the beginning and end of each day when this equipment is being used. NEVER open the top of the box when the voltage is on. Access to the PMT is through the sleeve cloth. Occasionally check to see if dust has accumulated on the PMT. If there is some, remove rubber ring adaptor and wipe with clean rag.
4. Replace the top of the box, turn voltage on and set to 1000 volts (positive light signifies polarity).
5. Check the display test button to see if all display channels are functioning and not burned out.
6. Count the standard 10 times for 1 minute each time. Divide by 10 to get average cpm. Check Radiation Instrumentation by Knoll for Error Propagation Case #4. If the counts are consistent (23,000) then proceed. If not, check all equipment hookups and switches; then re-do. Record all data.

#### ALPHA CELL MEASUREMENTS:

Alpha cells have very low backgrounds. Before using any alpha cell, check to see if the window is clean. Always try to use a cell which maintains a vacuum for a sufficient amount of time.

Use the vacuum nozzle in the back lab to evacuate the cell. This is done by placing the vacuum nozzle on top of the cell and turning the cell's stopcock to an upright position (open). One can actually hear it dissipate. Then close the stopcock and remove the vacuum hose. Repeat two more times prior to use.

7. Before sampling, take a background count of the cell selected to be used. (An hour was chosen to reproduce all sampling procedures).
8. To check background, set the timer to count for 1 hour. Press reset button to initiate the counting process and push count button up. It will automatically

stop. Record all results.

9. After the background count, take the alpha scintillation cell into lab 8. Light a cigarette for 30 seconds to allow attachment of progeny in the chamber. Attach the alpha scintillation cell to the hose after the filter attachment. Filter holder will contain 2 filters. Check to see that the filter side is facing the chamber and not the screen side. Open the valve to the chamber at the sampling port location. Open the cell's stopcock for 10 seconds. The pressure difference will allow the air to enter the scintillation cell. This process only takes a couple of seconds. Close the valve to the chamber and close the cell's stopcock.

10. Count the alpha cell immediately at the end of the sample for 10 minutes. To do this, press the reset button. Record all counts.

11. Set the cell aside for 4 hours after the time of sample to allow ingrowth of the daughters. The daughter products will then be in equilibrium with the radon.

12. Set the timer to count for 1 hour. Due to the low radon concentrations present in the chamber, the longer the counting time, the less statistical fluctuation present.

13. Press reset button to initiate the counting process and push count button up. It will automatically stop. Record the results.

14. Repeat steps 3 through 6.

15. Turn counter to stop.

16. Turn voltage down.

17. Turn power off on voltage and nimbin at the end of each day.

#### END OF SAMPLING:

Before placing the alpha scintillation cells back in their box, it is a proper procedure to flush out the cell with helium. This ensures low background. First, flush out the alpha scintillation cell with the vacuum hose in the back lab. Then proceed to the helium tank where all the valves are marked according to numbers. Open valve #1 (counterclockwise). The pressure gauge on the right will display the amount of helium in the tank. Open valve #2 (clockwise) until the pressure gauge on the left needle reads 10. Open valve #3 (counterclockwise). Attach the hose to the alpha scintillation cell and open the stopcock. Be careful that the hose does not slip off. Watch the pressure gauge on the left. When it returns to its original position close the stopcock. Repeat flushing with vacuum and helium; end with helium. This procedure flushes out the radon daughters. With all the valves open on the tank, close valve #1 first and bleed other valves. Close valves #2 and #3.

### APPENDIX III

#### Filter sampling procedure

##### Filter Method

1. Connect filter holder (with Whatman 40 one inch diameter filter inside) to the sampling port of the exposure chamber as close as possible with tygon tubing. Note: the active side of the filter faces the chamber.
2. Connect the filter to the rotameter with tygon tubing.
3. Connect the rotameter to the vacuum line with tygon tubing.
4. Light cigarette inside chamber and extinguish after 30 seconds.
5. Open sample port.
6. Open vacuum line with a vacuum flow of 4 liters per minute.
7. Sample for 15 minutes.
8. Close sample port and turn off vacuum line.
9. Remove filter holder.
10. Continue with Alpha Spectroscopy Procedures in appendix IV.

## APPENDIX IV

### Settings for alpha spectroscopy electronics

The pump is connected to the vacuum attachment of the alpha module by a thin orange tubing. The alpha module's output is connected to the input of the amplifier. The amplifier's bipolar output is connected to the input of the multichannel analyzer(MCA).

Specifics:

DUO-SEAL VACUUM PUMP with GE AC Motor

PULCIR PA-1

ALPHA MODULE    Voltage is set to 80 volts  
Turn to "pump"

EG&G ORTEC  
AMPLIFIER

Gain is set to 9.0  
Coarse gain is set to 50  
Shaping time is 2 microseconds  
Thresh is on  
Delay is out  
Positive is on

TRACOR NORTHERN  
TN-1705  
MCA

Gain is set to zero  
Lower limit of detection is 10  
Upper limit of detection is 120  
Offset is zero  
Conversion gain is set to 1024  
Time base is either 600 seconds(10 minutes) or  
900 seconds(15 minutes)  
Horizontal is set to one-half  
Mode is PHA  
Preset is live  
PHA is set to 100  
Vertical scale is set to 100  
Pen is set to SEL  
Amp is out  
Add is on



## APPENDIX V

### Procedures for alpha spectroscopy analysis

1. Place the filter and bottom part of the filter holder on the second shelf of the alpha module. Note : the active face of the filter should face up toward the surface barrier detector. Close the detector door.
2. Turn the voltage on the nimbin on and turn the voltage of the alpha module to 80 volts.
3. Vent the alpha module by pressing the vent switch.
4. Turn the pump on and press the pump switch on the alpha module.
5. Turn the MCA on and set the counting time to 600 seconds (10 minutes).
6. Two minutes after the end of sampling initiate the 600 second count.
7. Record the counts in the regions of interest and then erase the spectrum.
8. Set the counting time to 900 seconds.
9. Three minutes after the end of the 600 second count start a 900 second count.
10. Record the total counts in the regions of interest and then erase the spectrum.
11. Turn the MCA, alpha module , and the nimbin voltage off.
12. Turn the pump off.
13. Press the vent switch on the alpha module.
14. Remove the filter and the filter holder.
15. Since the filter contains long-lived daughter products it is classified as radioactive waste. Therefore throw out the filters into the radioactive waste.
16. Flush out the filter holder with a vacuum line.

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