FINAL REPORT -- USDOE Grant DE-FG-02-87ER60547

Project Period: 1993 -1997

DOE/ER/60547--T1

Title: Radon Source Apportionment in the Home, Dosimetry and Risk Modeling

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August 4, 1998

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Radon Source Apportionment in the home, Dosimetry and Risk Modeling

This research covered 3 topics in 4 years.

- A. The source apportionment of ^{222}Rn in the home
- B. The internal bronchial dosimetry of inhaled ^{222}Rn decay products
- C. The lung cancer risk from inhalation of the short lived decay products of ^{222}Rn

A 4th year of support was appended to this grant with a switch in research effort to determine a method for long term measurement the particle size distribution of the short lived decay products in homes.

- D. Measurement of long term average aerosol particle size distribution

A. Source Apportionment

A.1. The source apportionment of ^{222}Rn in the home

This research resulted in the only rigorous model to describe the way ^{222}Rn concentration in a home varies, and the major parameters. It comprises the largest existing data base of ^{222}Rn measurements in homes and outdoors, covering hourly measurements for about 8 years.

Two research homes in northern New Jersey, separated geographically by 100 km and under the same air mass, were studied for about 8 years. Radon is measured hourly along with several meteorological variables. One home is a highly energy-efficient home, 5 years old, and the other an 80 year old frame house. The average ^{222}Rn concentration in the 2 homes over 4 years is $126 \pm 24 \text{ Bq m}^{-3}$ in the basement of the energy efficient home, 94 ± 14 on the second floor, and 32 ± 5 in the basement of the old frame home. The primary factor controlling the indoor concentration is the indoor/outdoor temperature difference, with peaks from barometric pressure drops a secondary factor. Indoor/outdoor temperature difference accounts for 50% of the variability, with 25% of the contribution to indoor ^{222}Rn coming from excursions due to barometric pressure drops. All other factors such as wind speed and rainfall are minor contributors to the annual average.

Because the 2 homes are under the same air mass the ^{222}Rn concentration track exactly but at higher and lower average values. Once the baseline home condition is

set, i.e., no indoor outdoor temperature difference and stable barometric pressure, this establishes C_0 , and variations about this value can be modeled almost exactly.

Hourly ^{222}Rn measurements are made using continuous ^{222}Rn monitors in the basement, on the second floor and, at the old frame house, outdoors (Chittaporn et al 1981). Additional measurements are made of the pressure difference across the basement slab, indoor/outdoor temperature, barometric pressure, wind speed, rainfall, spot soil gas measurements. Grab samples of indoor ^{222}Rn are taken frequently to assure the quality of the data. The grab samples are collected and counted using the same system as for our participation in the USDOE Environmental Measurements Laboratory (EML) ^{222}Rn Intercomparison exercises. Our Intercomparison results over 19 exercises fall within $\pm 10\%$ of the true value reported by EML.

The model that fits the data best is,

$$\text{Ln (Rn conc.)} = C_0 + C_1 (\text{Outdoor Temp}) + C_2 (3 \text{ Hour Baro Press. Difference})$$

Our model has since been validated in a Swedish home by Hubbard et al. (1996).

Figure 1 shows a measurement interval (October 30 to November 17, 1993) selected for an abundance of barometric pressure drops and a distinct temperature change to illustrate the model for the energy efficient home. The equation above was used for the model. The R^2 is good (72%) and over any interval selected varies from about 50% to 90%.

Figure 2 shows the older frame house during winter 1991. Hourly outdoor ^{222}Rn was also measured at this home.

Figure 3 shows the correlation of the logarithm of the 4 year weekly average indoor concentration and outdoor temperature. Either indoor/outdoor temperature difference may be used as the independent variable or simply the outdoor temperature. The correlation is the same (52%). The logarithm always provides a better correlation as the direct relationship is curved and asymptotic (the ^{222}Rn concentration has upper and lower bounds).

Both the temperature and the barometric pressure differences in the energy efficient home must be lagged by 3 hours, i.e., the ^{222}Rn is regressed with the temperature or pressure difference occurring 3 hours prior. This is necessary as these variables do not immediately influence the average indoor concentration. In the old frame home, no lagging of the variables is necessary as the ^{222}Rn entry from soil is rapid.

Other variables such as the wind speed and rainfall improve the regression

correlation slightly but are not a major factor in these research homes. In other areas of the U.S. where there is scant tree cover or negligible or excessive rainfall these other factors may play a greater role.

It is clear from Figures 1, that barometric pressure drops are a significant surge source of the indoor ^{222}Rn . An examination of the data in a cumulative frequency plot shows two distinct regions. There is a sharp break in the cumulative frequency plot where the barometric pressure peaks produce high indoor concentrations. From these plots it can be estimated that the upper 25% of the hourly concentration measurements fall within barometric pressure excursions. If these peaks were not present, the average indoor ^{222}Rn would be 30% lower in each of the 2 research homes.

Our experiments with sub floor fans, blowing in first one direction and then reversed (from under the floor to outside and then from outside to under the floor) support the theory that fans blowing into the floor effectively reduce the barometric pressure excursions, but do not alter the annual average concentration significantly.

The annual average in the energy efficient home was not constant over the study interval. This home varied from 86 to 150 (where the full year's measurements were available), or almost by a factor of 2. The correlation of the annual average ^{222}Rn concentration with annual average temperature in Figure 3, suggests a trend with temperature but other factors are operative but not as significant.

The model applied to the data, gives a good fit and can be used to predict the home concentration once the coefficients are established. We have previously reported on a logarithmic model using other parameters such as wind speed, rainfall and sub-slab pressure difference, but the additional factors do little to improve the correlation.

A. 2. ^{222}Rn in Water

Radon in water is of major importance because it is not a guideline but regulated by EPA in accordance with the clean water act. Our data was used in the National Research Council background document describing the risk from airborne ^{222}Rn released by water use.

The ^{222}Rn released during showering contributes more to homes than ^{222}Rn from other types of water use. The ^{222}Rn release from showering was measured in an energy efficient home by averaging 7 months of hourly measurement data by hour of the day, and observing the peak during the shower interval. The measurement coincided with the use of a sub basement floor ventilation fan to provide the lowest normal indoor ^{222}Rn concentration. In this way the ^{222}Rn peak from showering could be seen clearly. The integrated ^{222}Rn exposure from showering was 20 Bq h. m^{-3} and a clear shift in the

time of the shower ^{222}Rn peak could be distinguished between weekdays and weekends. This integrated exposure corresponds to the addition of 0.9 Bq m^{-3} to the normal home concentration of 60 Bq m^{-3} during the measurement interval. The additional bronchial alpha dose from showering is about 2% of that from the normal soil ^{222}Rn source.

Radon released from ground water during its use can be a significant indoor source. In a typical home, it is difficult to determine the long term contribution to indoor ^{222}Rn from water use unless its ^{222}Rn concentration is high. Short term measurements, for example, made in the vicinity of the shower, provide data to estimate the contribution but do not provide data long term exposure.

We have made continuous hourly ^{222}Rn measurements in two locations in an energy efficient home with a private well, for over 4 years. The average ^{222}Rn concentration in this home is 100 Bq m^{-3} . By averaging the data over each hour of the day, the water use peak is usually evident, and is most obvious during morning showering. The estimate of ^{222}Rn released from water during showering at a normal home concentration of 100 Bq m^{-3} is reported elsewhere (Harley and Chittaporn 1994).

In May 1993 a $4.2 \text{ m}^3 \text{ m}^{-1}$ (150 cfm) fan was added to the sub floor venting network to study its effect on indoor ^{222}Rn . This lowered the average indoor ^{222}Rn concentration by a factor of 2, and the water use peak could be easily identified. The integration under the water use peak provides an accurate estimate of the additional exposure due to this source.

The home is in northern New Jersey, and was constructed in 1989 to be highly energy efficient. The natural air infiltration rate is very low (ventilation $t_{1/2} = 6 \text{ hrs}$), and the air movement in the home is dictated by a user controlled setting the air to air heat exchanger. The ventilation half times are measured frequently by using the ^{222}Rn removal half time following a ^{222}Rn excursion due to a sharp barometric pressure drop. The mean ventilation half time is 4.1 ± 0.6 hours measured over 5 events from October 1993 to April 1994.

A family of 2 adults and 3 children occupy the home and during the weekday their showering schedule begins at 5 A.M. On weekends, the showering schedule is relaxed. Measurement of the ^{222}Rn concentration in the hot and cold water was made in September 1993 and April 1994. The average ^{222}Rn concentration was 52 and 68 Bq L^{-1} in the hot and cold water respectively. The ^{222}Rn in water coming from the shower head under conditions of normal use is 30 Bq L^{-1} . During showering a booster fan draws air into the bathroom ventilator to prevent buildup of moisture in the house.

The subfloor ^{222}Rn reduction fan was cycled between on and off during this measurement period as necessary for the development of our indoor ^{222}Rn model. The

hourly ^{222}Rn measurements made over the interval from October 1993 to June 1994 were averaged while the subfloor fan was on (6 months on, 3 months off). Radon measurements were made in the basement and on the second floor using 2 continuous monitors designed by us (Chittaporn et al 1981).

Periodic grab samples of ^{222}Rn are also collected and measured to assure the quality of the continuous measurements. The grab samples are also used in the USDOE ^{222}Rn intercomparison exercises held at the Environmental Measurements Laboratory semi-annually. Our results are within $\pm 10\%$ from their stated true concentration. Passive alpha track detectors of our design are located at each continuous monitor, also for quality assurance, and are changed each season. All ^{222}Rn measurements agree within 10%.

A.3. Integrated Exposure in the Home from Showering

The average ^{222}Rn concentration at each hour of the day was calculated separately for weekdays and weekends. The measurements for the 2nd floor (near the bathroom) is shown in Figure 4. The integrated ^{222}Rn exposure (about 20 Bq h. m^{-3}) from the peak areas are shown in Table 1. Also shown in Table 1 are the ^{222}Rn concentration for the hot and cold tap water, and in the water as it comes from the shower head at showering temperature.

It can be seen from Table 1., that showering adds an average of 0.9 Bq m^{-3} to the daily indoor ^{222}Rn concentration. The average ^{222}Rn concentration in this home during this measurement interval was 60 Bq m^{-3} and thus the release from water during showering, which is the major release, added about 2% to the normal concentration.

Activity Balance

It is of interest to attempt an activity balance in the home for the estimated ^{222}Rn release from the well water. From Table 1, a mix of hot and cold raw water contains 60 Bq L^{-1} , and in water coming directly from the shower head, 30 Bq L^{-1} . Therefore, approximately 30 Bq are released to the air for each liter of water used in showering.

This family of 5 shower for about 90 minutes per day. The flow rate from the shower head was measured at 5 LPM. Thus, $30 \times 5 \times 90 = 13,500 \text{ Bq}$ are released from shower water each morning. From the ventilation half time for this house (4.1 h.) and the house volume (600 m^3), an integrated exposure of $13,500 / 600 \times 4.1 / \ln(2) = 130 \text{ Bq h. m}^{-3}$ is expected. As only about 20 Bq h. m^{-3} (15%) was observed in the measured data, corresponding to an input of 2000 Bq, it is assumed that the balance was exhausted through the bath ventilator.

To determine whether this assumption was correct, a measurement of the air flow rate into the bath ventilator and at the air exit from the house was made. The flow from the bath ventilator was $0.7 \text{ m}^3 \text{ min}^{-1}$ or a removal rate from the 2 m^3 shower of about 0.35 min^{-1} . An estimate of the activity released to the house volume during a shower is then $30 \text{ Bq L}^{-1} \times 5 \text{ L min}^{-1} / 0.35 = 400 \text{ Bq per shower} \times 5 \text{ showers} = 2000 \text{ Bq}$. This agrees well with the measured integrated house exposure of 2000 Bq.

Bronchial Dose from ^{222}Rn Released by Water Use

The bronchial dose from inhaled ^{222}Rn decay products is reported as 7 mGy/WLM (Harley et al. 1994). This dose is the alpha dose to basal cell nuclei in the epithelial lining of the airways. The dose to secretory cell nuclei is about 25% higher. The additional exposure and dose from the 1 Bq m^{-3} ($0.006 \text{ WLM per year}$) added to the home from the morning showers is thus, 0.04 mGy yr^{-1} . This can be compared to the average exposure and dose in the home during the measurement period of 40 Bq m^{-3} (0.25 WLM yr^{-1}) or about 2 mGy yr^{-1} . These alpha dose estimates depend upon home occupancy and so represent the potential for exposure and dose.

A maximum credible dose during the shower itself can be estimated if it is assumed that ^{218}Po is in steady state with the ^{222}Rn released and that the ^{218}Po is in the unattached form. The dose conversion factor for unattached ^{218}Po , breathing at a rate of 10 LPM is 40 mGy WLM^{-1} .

The exposure from ^{218}Po during a 15 minute shower each day, or 91 hours per year for these conditions would be $0.003 \text{ WLM per year}$, yielding a bronchial dose of $0.003 \times 40 \text{ mGy WLM}^{-1} = 0.12 \text{ mGy yr}^{-1}$. As the conditions during a shower are undoubtedly optimized in this calculation to give the highest dose, the actual bronchial alpha dose is somewhat lower.

Table 1. The Concentration of ^{222}Rn in Tap Water and Water from the Shower Head in an Energy Efficient Home and the integrated ^{222}Rn Exposure from Showering is Shown for Weekdays and Weekends.

Sample	Bq L ⁻¹	Basement (Bq m ⁻³ h)		2 nd Floor (Bq m ⁻³ h)		daily avg. addition from water use (Bq m ⁻³)
		Weekday	Weekend	Weekday	Weekend	
Water contribution to Indoor air		20	24	22	18	0.9
Tap water (hot)	52					
Tap water (cold)	68					
Water from Shower head	30					
ratio air/water						1/60,000

A. 4. The Bronchial Dose from ^{222}Rn Released from Water During Showering

The exposure characteristics during showering have not been well documented. In one study in an energy efficient home with a private well, a passive ^{222}Rn monitor was placed in the ventilator duct directly above the shower, and another for background in an adjacent room. The purpose was to measure the average concentration of ^{222}Rn in the shower itself. The ventilator fan runs during all showers to remove moisture from the home, and so the measured ^{222}Rn concentration in the ventilator is a reasonable equivalent to the shower concentration.

This home is occupied by 5 persons, 2 adults and 3 children, and the annual home concentration has been measured as 80 Bq m⁻³. The duration for morning showers was measured as 60 minutes daily. The ^{222}Rn concentration measured at the bathroom cold water tap, and water at showering temperature collected from the

shower head but near the tub surface to determine ^{222}Rn loss, is shown in Figure 5. The mean concentration in cold tap water is 60 Bq m^{-3} , and on average 6 Bq m^{-3} remains in the water as it is sprayed from this shower head, i.e., 90% loss.

The shower head used by the family delivers 5.3 lpm of water with a mean concentration of 60 Bq l^{-3} . The average amount lost (Table 1) from the water to the air as the water cascades to the tub base is 60 to 6 Bq m^{-3} or 90%. Thus, on average the shower releases 290 Bq min^{-1} to the air in this home.

Table 2 shows the measured ^{222}Rn concentration in the ventilator duct. The concentration varies somewhat due to different habits and conditions in the shower. The average air concentration while showering is 4000 Bq m^{-3} .

Bronchial Dose During Showering

There are events during which exposure to ^{222}Rn result in either enhanced or reduced bronchial dose, i.e., the dose per unit exposure increases/decreases over the typical indoor value. One situation with potentially enhanced dose rate occurs most likely during the short interval while showering. This is because ^{222}Rn released from the hot spray is resident in the shower for short periods of time, permitting mainly the build up of the first decay product (3.05 minute ^{218}Po), and most likely maintaining a larger unattached fraction.

It is necessary to provide the decay product activity size distribution as a function of time, during and subsequent to showering. There have been three recent studies of the increment of exposure and dose that arises from showering with radon-laden water (Hopke et al 1995, Bernhardt and Hess 1996, Scarpitta, 1998).

In the Fitzgerald *et al.* (1997) study, a home was found which was supplied with water from a drilled well; the water contained 518,000 to $555,000 \text{ Bq m}^{-3}$ of radon. The home is a one story wooden house of a type common in northern New York State. Measurements of the ^{222}Rn concentrations were made using both a passive scintillation cell and an active cell. The particle size measurements were made with a Scanning Electrical Mobility Spectrometer. From the number-weighted size distributions, activity weighted distributions were calculated using the attachment coefficients of Porstendörfer *et al.* (1979).

The air concentrations of ^{222}Rn at the midpoint of showering was 1000 Bq m^{-3} and 1500 Bq m^{-3} at the end of showering, and 1700 Bq m^{-3} 5 minutes after showering. The results of the particle size distribution showed the distribution was the same as in other normally occupied rooms of the home.

The equilibrium factor (decay product to ^{222}Rn ratio), however, was 0.03 at the

midpoint of a 15 minute shower and 0.06 at the end of the shower and 0.11 at 5 minutes after the shower, rather than a typical values of 0.40 for normal room conditions. This small value for the decay product equilibrium is not unexpected because of the short build up time of the decay products as ^{222}Rn gas is released during showering. For the dose calculation a value of 0.05 is estimated as the average equilibrium factor.

The very small size particles of about 1 nm diameter (f_{pot} , the unattached fraction) constituted 0.3 of the total potential alpha activity concentration (PAEC) initially, 0.08 during the shower and a typical value of 0.05 immediately after the shower. A conservative estimate of the unattached fraction during showering is $f_{\text{pot}} = 0.2$.

The easiest method of comparing bronchial dose for the different conditions of normal room occupancy versus showering is to estimate the equivalent equilibrium concentration (EEC) of ^{222}Rn . The central value of dose rate per unit exposure, 100 to 200 nm median particle diameter and f_{pot} of 0.05 is 7 nGy hr⁻¹ per Bq m⁻³, ^{222}Rn (EEC)¹. Using a value of f_{pot} equal to 0.21 for the unattached fraction of ^{218}Po , rather than a typical value of 0.05, the dose per unit exposure more than doubles to a value of 17 nGy hr⁻¹ per Bq m⁻³, ^{222}Rn (EEC) (Harley et al, 1996).

The dose for the two situations (4000 Bq m⁻³ shower versus 80 Bq m⁻³ in the home) in the research house studied is then,

Showering =

$$4000 \text{ Bq m}^{-3} \times 0.05 = 200 \text{ Bq m}^{-3} \text{ (EEC)} \times 17 \text{ nGy hr}^{-1} \text{ per Bq m}^{-3} = 3400 \text{ nGy hr}^{-1}$$

Normal Occupancy =

$$80 \text{ Bq m}^{-3} \times 0.4 = 32 \text{ Bq m}^{-3} \text{ (EEC)} \times 7 \text{ nGy hr}^{-1} \text{ per Bq m}^{-3} = 220 \text{ nGy hr}^{-1}$$

The total time in the bathroom (15 minute shower plus 5 minute) with elevated dose is 20 minutes. The number of hours spent in each location annually, assuming 70% home occupancy, is 122 hours in the bath while showering versus 6047 hours in the home. The annual dose in each location is,

$$\text{Shower} = 3400 \text{ nGy hr}^{-1} \times 122 \text{ hours} = 0.41 \text{ mGy/year}$$

$$\text{Normal Occupancy} = 220 \text{ nGy hr}^{-1} \times 6047 \text{ hours} = 1.87 \text{ mGy/year}$$

The annual bronchial dose from showering in this home is therefore about 30% of the total annual dose. The use of well water is a special condition and reflects an unusually high fraction of the annual dose. The use of surface water essentially eliminates this dosimetric component.

¹ EEC. Equilibrium Equivalent Concentration. The activity concentration of radon, in equilibrium with its short lived decay products that would have the same potential alpha energy concentration as the as the existing non-equilibrium mixture.

A. 5. A Seven Year Data Base of Outdoor Radon

Outdoor ²²²Rn is of importance because it is a defacto guideline against which indoor air is to be regulated by the EPA multimedia risk reduction approach when water is the source. Only few long term studies have been performed and our study is the longest.

Outdoor ²²²Rn hourly was measured at a home in northern New Jersey to determine its contribution to indoor concentration and to study trends in a long term data set. In addition to the ²²²Rn, several meteorological variables were measured, barometric pressure, temperature, and rainfall. Outdoor radon in this data base is not constant either over a diurnal cycle, an annual cycle, or the 7 year cycle studied. The average over 7 years is 8 Bq m⁻³, with changes of about 100 percent daily and 50 % by month.

Measurements

Beginning in 1990, the outdoor data were measured hourly using a ²²²Rn detector based on the design of Chittaporn et al (1981). This is one of the few instrument designs that permit the measurement without interference from the decay products. The measurements are made at a home in northern New Jersey, where hourly indoor ²²²Rn has been measured up to the present for the purpose of modeling indoor concentration (Harley Chittaporn, 1994).

The detector output is recorded using an ADC¹ input to a PC data file. The data are analyzed using the statistical package Minitab². Temperature and barometric pressure are also recorded on the data file, and individual rainfall collections measured since 1993 using a tipping bucket rain gauge.

Considerable quality control must be exercised in establishing a long term data base, to assure the reliability of the results. The quality control exercised in this research consists of multiple passive alpha track detectors of our design placed in close proximity to the real time detector (Litt et al 1991, Harley et al 1991).

One passive alpha track detectors remain in place over each season and one over each one year interval. This assures that no loss of signal occurs over extended time periods in the outdoor environment in these detectors. Each passive monitor contains duplicate alpha track films. The continuous monitor data agrees well with the passive monitor results (Table 3).

The passive monitors used for the QC measurements participate in the U.S. Dept. Of Energy, Environmental Measurements Laboratory (EML) Passive Monitor Intercomparison Program in every exercise. The reported results are always within 3% of the EML measured "true" mean concentration.

Results

The ^{222}Rn measurements over the entire 7 year interval are summarized in (Figures 6). Figures 7 separates the data by hour of the day and month of the year.

The factors responsible for the observed trends can be inferred from an analysis of the ^{222}Rn and meteorological data.

The diurnal cycle occurs because of the buildup of ^{222}Rn at ground level during the typical nighttime temperature inversion, followed by a decrease during solar heating which breaks up the inversion, permitting the characteristic mixing of the outdoor air to higher altitude during the day. The minimum to maximum ratio over the daily cycle is indicative of the dilution factor and is a crude measure of the height to which ground level pollutants are mixed.

The longer hours of darkness during the colder months provide a longer time period for the nighttime inversion with concurrent higher ^{222}Rn to take place as well. Also, in colder months, it is well known that the nighttime inversions are more pronounced because of generally lower windspeed. Thus, there is less turbulent mixing of the atmosphere and the temperature inversion can be well established.

It is not known whether the soil ^{222}Rn flux is relatively constant over an annual cycle. Because the ^{222}Rn gas solubility in soil water is less with higher temperature (Henry's Law) there should be about 30% more ^{222}Rn available for release from soil during the warmer months. This would moderate the summer/winter trends observed in the data.

The higher concentration in the colder months, however, is most likely due to the more pronounced effect of nighttime inversions.

Some subtle trends are probably seen in the 7 year interval, and may probably be explained by the annual changes in rainfall. It is well known that the moisture

content of the upper soil layers controls the availability of ^{222}Rn for release to the atmosphere (Tanner 1964, 1980).

In another long term study of outdoor ^{222}Rn , Fisenne measured outdoor ^{222}Rn , at the USDOE remote location in Chester NJ, for a period of nine years and in New York City for 4 years (NCRP 1987). The cyclic variations were similar except monthly variation was much larger at the remote Chester site, i.e., about a factor of 3, and less in New York City, about 20 percent change. The annual average at Chester was 8 Bq m^{-3} , and in New York City, 5 Bq m^{-3} .

Conclusions

Seven years of hourly outdoor ^{222}Rn measurements are summarized. The monthly average concentration over the period 1990 through 1996 shows two marked trends. One, that higher concentration is present in the colder months (fall) of the year than spring, (9 versus 6 Bq m^{-3}), and two, that the diurnal cycle accounts for almost a factor of 2 variation (5 to 9 Bq m^{-3} over one day).

The explanation for the seasonal trend, i.e., the higher concentration in colder months, is mainly due to higher nighttime concentrations during the more pronounced cold season inversions, but also the reduced dilution during the day because of less convective turbulence from a shorter solar heating day.

Outdoor ^{222}Rn concentration provides an interesting and useful tracer for global scale phenomena, such as the mixing height of pollutants in the atmosphere, and is underutilized as such.

Table 2. Results of the quality control measurements for the 7 year data base of outdoor ²²²Rn in northern New Jersey (1990 - 1996)

Date	Number of Days	Passive Monitor	Continuous Monitor
Seasonal			
12/91 to 3/92	91	7.4	7.4
3/92 to 6/92	98	6.3	6.7
6/92 to 9/92	91	8.5	7.0
9/92 to 12/92	84	10.4	7.8
12/92 to 3/93	91	6.3	7.4
3/93 to 6/93	91	7.0	6.7
6/93 to 9/93	91	10.7	7.0
9/93 to 12/93	104	7.4	7.4
12/93 to 3/94	85	7.8	5.9
3/94 to 6/94	84	10.4	5.6
6/94 to 9/94	98		5.2
9/94 to 12/94	91	11.1	10.1
Annual			
9/91 to 9/92	363	7.4	7.4
12/91 to 12/92	364	6.7	7.0
12/92 to 12/93	377	5.6	7.0
12/93 to 12/94	358	8.1	5.6
12/94 to 12/95	358	7.0	10.0
12/95 to 12/96	367	6.3	7.3

A. 6. Indoor/outdoor Radon and Gamma-ray Background

We have measured indoor and outdoor ^{222}Rn hourly at a research home over a five year interval in northern New Jersey, to be able to model indoor ^{222}Rn using the major factors that control concentrations. In addition to the ^{222}Rn , several meteorological variables are measured, including temperature, barometric pressure, and rainfall. Beginning in 1993, we initiated measurements of the gamma-ray background using a Reuter/Stokes pressurized ionization chamber.

The gamma-ray background is composed of 3 fractions, the cosmic ray component, ^{40}K in the soil and ^{222}Rn decay products in the soil, with minor contribution from decay products in air. The cosmic ray and ^{40}K components are constant at any one location. The ^{222}Rn decay product gamma-ray component is of interest in that it can be used to infer the kinetics of ^{222}Rn movement in the surface soil and in this way can be useful in the modeling of indoor ^{222}Rn concentrations.

Measurements

Beginning in 1990, up to the present, the ^{222}Rn data are measured hourly using a detector based on the design of Chittaporn et al (1981). This is one of the few instrument designs that permit the measurement without interference from the decay products. The measurements are made at a research home in northern New Jersey, where hourly indoor ^{222}Rn has been measured over the same time interval (Harley and Chittaporn, 1993, 1994).

The detector output is recorded using an ADC³ input to a PC data file. The data are analyzed using the statistical package Minitab⁴. Temperature and barometric pressure are also recorded on the data file, and individual rainfall collections measured since 1993 using a tipping bucket rain gauge.

The gamma-ray measurements are made using a Reuter-Stokes pressurized ionization chamber. The ionization chamber is 1 meter from the ground surface. The average hourly ion chamber signal is also on the PC data file.

The hourly data have been aggregated in three ways to show the weekly average data, the average by month, and by hour of the day for the time interval from 1993 to

June 1995

Considerable quality control must be exercised in establishing a long term data base, to assure the reliability of the results. The quality control exercised in this research consists of replicate thermoluminescent detectors (TLD, either $_{CAF}$ or Al_2O_3) nearby to the pressurized ionization chamber. The TLD monitors determine the integrated average exposure over 3 or 6 month periods. The QC TLD was performed throughout 1993, no TLD measurements were made in 1994 and TLD measurements were resumed in 1995. The exposure rates for the 2 types of measurement agree within 10%. A 5.0×10^4 Bq ^{137}Cs NIST point check source is used every month to assure that the chamber calibration is constant.

The weekly average measurements are shown in Figure 8. There is a pattern of exposure rate with the colder season having higher exposure rate. The hourly and monthly averages are shown in Figure 9.

In Figure 9 the patterns from averaging the 2 ½ years of data can be seen clearly. The average hourly gamma-ray dose rate is 102 nGy hr^{-1} and this varies by 1 nGy hr^{-1} over the diurnal cycle. The monthly average varies about the mean by 5 nGy hr^{-1} over an annual cycle with the coldest months having the highest exposure rate.

Two transient weather conditions affect the gamma-ray air dose, rainfall and barometric pressure changes.

Three major factors contribute to the observations.

1. With increasing temperature, the solubility of ^{222}Rn gas in the soil water is much decreased (Henry's law), and therefore more ^{222}Rn is available for emanation from the soil surface. This factor accounts for the larger diurnal cycle during the warmer months (larger temperature cycle) and for the reduced gamma-ray dose rate in warmer months (increased emanation rate).

In one extraordinarily high temperature event on July 15, 1995 with temperature reaching $40^\circ C$, the gamma-ray dose rate was reduced to as low as 70 nGy hr^{-1} .

2. A decrease in the barometric pressure induces a pressure driven flow of ^{222}Rn from depth increasing the concentration in soil gas near the soil surface. The decay products attain near steady state if the pressure drop persists over many hours.

3. A transient increase occurs due to washout of the decay products during rainfall.

The measured gamma-ray exposure from the decay products actually consists of two ^{222}Rn decay product components, the airborne decay products and those in soil.

The average air concentration of ^{222}Rn at this site is 6.8 Bq m^{-3} and the decay products for this concentration should support a gamma-ray exposure of about 1 nGy hr^{-1} (Beck 1974). The diurnal ^{222}Rn variation, averaged over a 5 year interval, due to changes in atmospheric stability at this site, is 40% (Chittaporn and Harley, 1995). Thus, the contribution from airborne decay products is small and does not completely explain the diurnal variability observed in our data.

Conclusions

Two and one half years of hourly gamma-ray background with simultaneous indoor/outdoor ^{222}Rn measurements were made at a research home in northern New Jersey. The weekly average gamma-ray background was not constant over this interval and the hourly data aggregated by hour of the day or by month show clear trends.

The maximum and minimum average monthly air dose rates are in June and October and the diurnal cycle has maxima and minima at 0700 and 1900 hours respectively. The diurnal cycle is more pronounced in warmer months, varying by 5 nGy hr^{-1} versus 1 nGy hr^{-1} in cold months.

Assuming that the cosmic ray and potassium-40 components of gamma-ray background are constant, the main variation over the diurnal cycle is due to changes in the soil based decay products resulting from variations in ^{222}Rn emanation.

We propose that the temperature cycle over the day is a major driving force. The daytime high temperature induces a higher soil ^{222}Rn flux because the ^{222}Rn gas solubility in soil water is less with higher temperature (Henry's Law).

In accordance with the greater ^{222}Rn release rate from soil in warmer months, the gamma-ray background is lower in summer and the diurnal cycle is more pronounced.

In addition to the main relationship with temperature, two additional features cause the gamma-ray background to vary on a transient basis. The first is the washout of ^{222}Rn decay products to the ground surface during rainfall and the second, the increase in dose rate during barometric pressure decreases. The latter is due to the pressure driven flow of soil air from depth to the surface. The longer the time interval for the pressure drop the higher the gamma-ray dose rate observed.

This increase in gamma-ray dose rate is correlated with the ^{222}Rn surges seen in the basement of the research home during barometric pressure drops.

No correlation of the gamma-ray dose rate and outdoor ^{222}Rn was observed and the overall correlation with indoor ^{222}Rn concentration at the research home was marginal.

B. Bronchial Dosimetry

B.1. The variability of the Bronchial Dose factor.

Considerable effort was spent to assemble all of the data in the Radon Research program that is input to the bronchial dose modeling. Indoor particle size distributions, target cell morphometry in the bronchia airways, the deposition fractions measured in hollow casts of the human lung etc.

The full model is reported in Harley et al. 1996. Figure 10 shows the results of the calculations. This model will be in the forthcoming year 2000 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report. This report is the most comprehensive compilation of radiation data that exists. It is updated every 5 years.

C. Lung Cancer Risk

C.1. a Model for Lung Cancer Based on Measurements of Cycling Cells in Bronchial Epithelium

This was a collaborative effort with Dr. Edith Robbins in the Dept. Of Cell Biology. She has the largest existing data base of morphometric measurements of bronchia cells. She developed a PCNA staining technique to identify a surrogate for the stem cell population in airways. The model then can calculate the actual number of hits by alpha particles for a given exposure. The model fit the observed lung cancers in the Colorado underground uranium mining cohort well.

The manuscript is published in Harley et al. 1996b.

C.2. The location of lung tumors in uranium miners

This is a joint publication with Dr. Geno Saccomanno who performed the histology on the Colorado uranium miners. The location of the tumors was compared with the location in non miners and found to be different. The location of miner tumors was more proximal. The full publication is in Saccomanno et al

C. 3. Pooling of epidemiological studies

This was a joint effort with Dr. John Neuberger at the University of Kansas. The publication is in Neuberger et al. 1995. Pooling will not substantially improve the data on domestic exposure.

D. Particle Measurements

D. 1. Long Term Measurement of Indoor Outdoor ^{222}Rn , Decay Products, and Aerosol Size.

Measurements of ^{214}Pb indoors and outdoors at a single family home in northern NJ and a basement laboratory in New York City were made as part of a study of the indoor outdoor ultrafine particle size. The measurements were performed using a modified Thomas method to determine whether such data were worthwhile. The air concentrations were too low to provide useful data for either ^{218}Po or ^{210}Bi , but the ^{214}Pb measurements proved useful with about 30% error. The data are consistent with the indoor ^{222}Rn measurements and the preliminary particle size data show that a significant fraction of the atmospheric particulates are in the ultrafine region.

Introduction

We measured the long-term integrated ultrafine particulates in indoor and outdoor air and at urban New York City and a suburban site. Two samples of filtered air, one to determine total particulates and another analyzed using the NYU ultrafine particle size distribution sampler, have been collected at 3 locations for about 1 year. Both samplers have a Millipore filter to capture either the total sample or the exit particulates from the size sampler. Although the ultimate measurement will be $^{210}\text{Pb}/^{210}\text{Po}$ for the size distribution, we investigated the ability to measure the short lived ^{222}Rn decay products as the filter material was removed for replacement.

Methods and Materials

The NYU ultrafine particle size sampler was developed initially to study the size distribution of radon decay product aerosol. The pilot version of the particle size sampler utilized fine mesh screens and/or sintered porous metal disks as filter elements. Duplicate alpha track detectors were located in the walls of the sampler following each filtration stage. A low flow pump (4-6 LPM) drew ambient air through the sample, and the sampling time was about 2-3 weeks. This instrument provided size distribution data for the short lived decay products, and proof of principle was established (Heikkinen, 1997).

However, the fractional wall deposition is low, and the decay of ^{222}Rn during its pass through the unit results in unnecessary background on the nuclear track film. A modified version of the particle size sampler uses fine mesh screens and a Millipore filter that captures any exiting particulates. The screens and Millipore are then

measured directly using nuclear track detectors.

The screens and backup filter are first stored for several weeks to permit the build up of ^{210}Po from the ^{210}Pb deposited on these filtration elements. To determine whether it is worthwhile to measure the short lived ^{222}Rn decay products when the filters are replaced, about 1 year of data was accumulated. The Millipore filter was alpha counted in low background (3-5 counts per day) scintillation counters (Hallden, Harley 1957) using a modified Thomas method, i.e., long sampling time, to estimate the ^{218}Pb , ^{214}Pb , ^{214}Bi decay products. The capture of particulates on fine mesh screens is predictable and has been studied theoretically and experimentally for many years (Cheng et al. 1985)

Results

The measurements were made both indoors and outdoors at a single family home in northern New Jersey, and in a basement laboratory at New York University Medical School.

The results of the ^{218}Po and ^{214}Bi were of little value because the alpha activity was low ($< 15 \text{ Bq m}^{-3}$), and the error term large, so that the activity could not be statistically measured as different from zero.

The ^{214}Pb measurement however, provided useful information. The outdoor data are shown in Figure 11 and the standard deviation of each weeks measurement is about 30%. The average ^{214}Pb concentration over about 1 year was 7 Bq m^{-3} . The average outdoor ^{222}Rn concentration over this interval was 8 Bq m^{-3} . Figure 11 also shows that the average concentration on the Millipore backup filter in the particle size sampler was 6 Bq m^{-3} .

Examination of the penetration fraction for the 5 screens used in this version of the particle size sampler (90 mesh and four 500 mesh) indicates qualitatively that about 25% of the particulates are 30 nm diameter. It is of interest that a relatively large fraction of the particulates are in the ultrafine size range.

Figure 12 shows the same measurement protocol for the basement of this home. The average ^{214}Pb for the basement total and particulate sampler was 24 and 13 Bq m^{-3} respectively. This indicates that over 50% of the particulates are 30 nm diameter. This home has an oil fired heating system in the basement, and so the large ultrafine particulate fraction was not surprising.

Figure 13 shows about 6 months of data in 1997 measured on the second floor of this home. The results are similar to the basement but lower concentration, with averages of 14 and 12 Bq m^{-3} for the total and particle size sampler ^{214}Pb concentrations

The basement and outdoor ^{222}Rn concentrations in an 80 year old, single-family, wood frame suburban home have been measured hourly for over 6 years using continuous low background monitors of our design. The quality of the data is monitored full time using passive alpha track detectors of our own design. The ^{212}Pb supplement these data and provide insight into the atmospheric particle size distribution.

Methods and Materials

The NYU ultrafine particle size sampler was developed initially to study the size distribution of radon decay product aerosol. The pilot version of the particle size sampler utilized fine mesh screens and/or sintered porous metal disks as filter elements. Duplicate alpha track detectors were located in the walls of the sampler following each filtration stage. A low flow pump (4-6 LPM) drew ambient air through the sample, and the sampling time was about 2-3 weeks. This instrument provided size distribution data for the short lived decay products , and proof of principle was established (Heikkinen, 1997).

However, the fractional wall deposition is low, and the decay of ^{222}Rn during its pass through the unit results in unnecessary background on the nuclear track film. A modified version of the particle size sampler now in use utilizes several fine mesh screens as capture elements, and a Millipore filter that seizes any exiting particulates. The screens and Millipore are then to be measured directly using nuclear track detectors.

The screens and backup filter are first stored for several weeks to permit the build up of ^{210}Po from the ^{210}Pb deposited on these filtration elements. To determine whether ^{212}Pb could be measured accurately when the filters are replaced, about 1 year of data were accumulated. The Millipore filter was alpha counted in low background (3 counts per day) scintillation counters (Hallden, Harley 1957). The capture of particulates on fine mesh screens is predictable and has been studied theoretically and experimentally for many years (Cheng et al. 1985). The NYU size sampler (NYUSS) sampler presently utilizes 5 screens (90, four 500 mesh).

Alpha counting is commenced about 4 hours post sampling to insure the decay of short lived ^{222}Rn decay products and any airborne ^{212}Po collected on the filter. Samples are counted for several days. In this way, only airborne ^{212}Pb is measured via its ^{212}Po decay product.

Results

Figure 14 shows the outdoor concentration of ^{212}Pb in weekly samples for almost 2 years. This is the largest data base in existence. The average air concentration of total

particulates over this interval is 0.1 Bq m^{-3} . A seasonal trend can be identified with summer about a factor of 2 higher than winter concentrations.

Figure 15 shows the basement concentration of ^{212}Pb , averaging 0.4 Bq m^{-3} over the 2 years, in the single family home. The size/total ratio infers that a significant fraction of the particulate is in the 30 nm range. The basement houses an oil fired heating system and the small particle size is expected.

A seasonal trend is also seen in the basement. The summer concentrations are about a factor of 2 higher than winter.

Figure 16 shows the ^{212}Pb concentration on the second floor of the home. The average concentration of ^{212}Pb is slightly less than the basement (0.2 and 0.17 Bq m^{-3} for the total and size sampler respectively).

Summary

The ^{212}Pb measurements in the basement of a single family home show a seasonal trend of about a factor of two both in the basement and outdoors. The summertime high averages about 200 and 50 mBq m^{-3} in the basement and outdoors respectively. About 25% of the basement ^{212}Pb aerosol had a median diameter less than 50 nm, and outdoors essentially the same fractional ultrafine ^{212}Pb concentration.

The dose factor for ^{222}Rn decay products has a central value of 6 mGy/WLM and that for ^{220}Rn decay products 2 mGy/WLM . The low activities measured in this study (maximum 0.4 Bq m^{-3}) would result in an exposure of 0.06 WLM per year, and thus a bronchial dose of 0.12 mGy per year. This can be compared with the dose from ^{222}Rn decay products which is about a factor of 50 times greater. A bronchial dose of about 2% of that for ^{222}Rn decay products is in general agreement with other published estimates (Pan, 1996).

D.3. ^{222}Rn Decay Products as Tracers of Indoor/outdoor Aerosol Particle Size*

Measurements of ^{210}Pb indoors and outdoors at a suburban single family home in northern NJ, and a basement laboratory in New York City were made as part of this study of indoor/outdoor ultrafine particle size, using the NYUMS particle size sampler. The long lived ^{222}Rn decay product ^{210}Pb presents a unique and highly sensitive tracer to study atmospheric aerosol particles. The aerosol particle size sampler integrates particulates deposited over 3-4 weeks. It consists of a very low flow rate sampling tube with 5 fine mesh screens as filter elements, and a Millipore backup filter. The measurement of ^{210}Pb on the screens and filter was performed using very low background scintillation counters (3-5 counts/day), and long count times (5000 minutes). Deconvolution of the count data using an extreme value estimation provides

an accurate evaluation of the outdoor particle size distribution. The particle size data show that a significant fraction (20-60%) of the atmospheric particulates are in the ultrafine region.

The long-term integrated ultrafine particulates in indoor and outdoor air at urban New York City and a suburban site are being measured. Two samples of filtered air, one to determine the ^{210}Pb concentration in the total particulate sample, and another analyzed using the NYU ultrafine particle size sampler, have been collected at 3 locations for about 1 year. Both samplers utilize a Millipore filter to capture the total sample on the exit particulates from the size sampler. The basement, 2nd floor and outdoor ^{210}Pb data at the suburban site are presented here, with particle size calculated for outdoor ^{210}Pb .

The fine particulates (<2500 nm) are associated with significant respiratory health effects. The ultrafine particulates are poorly documented, yet are the significant carrier of pollutants into the lung because of their large numbers, large surface area, and low mass. Their small diameter makes lung airway deposition efficient. The small mass associated with the ultrafine fraction makes these particulates difficult to measure by conventional means.

The basement and outdoor ^{222}Rn concentrations in an 80 year old, single-family, wood frame suburban home have been measured hourly for over 6 years using continuous low background monitors of our design. The quality of the data is monitored full time using passive alpha track detectors of our own design. The ^{210}Pb supplement these data to provide insight into the fraction of outdoor aerosol particles that enter the home.

Methods and Materials

The NYU ultrafine particle size sampler was developed initially to study the size distribution of radon decay product aerosol. The pilot version of the particle size sampler utilized fine mesh screens and/or sintered porous metal disks as filter elements. Duplicate alpha track detectors were located in the walls of the sampler following each filtration stage. A low flow pump (4-6 LPM) drew ambient air through the sample, and the sampling time was about 2-3 weeks. This instrument provided size distribution data for the short lived decay products, and proof of principle was established (Heikkinen, 1997).

However, the fractional wall deposition is low, and the decay of ^{222}Rn during its pass through the unit results in unnecessary background on the nuclear track film. A modified version of the particle size sampler now in use utilizes 5 fine mesh screens as capture elements, and a Millipore filter that seizes any exiting particulates. The screens and Millipore are then measured directly using very low background (3-5

counts per day) alpha scintillation detectors (Hallden and Harley 1957).

A total particulate sample is always collected simultaneously on 0.8 μm Millipore filter media, and subsequently counted. The Millipore filters were counted immediately to measure short lived ^{222}Rn decay products, after 3 hours to measure ^{212}Pb concentrations, and after several months to determine ^{210}Pb concentrations. The ^{222}Rn decay product and ^{212}Pb were presented separately (Chittaporn, Harley 1997, Harley Chittaporn 1997).

The screens and backup filter are first stored for several months to permit the build up of ^{210}Po from the ^{210}Pb deposited on these filtration elements. To determine whether ^{210}Pb could be measured accurately by direct counting of the filters, about 1 year of data were accumulated and measured by alpha counting and radiochemically (Fisenne, Perry, Keller 199X).

The capture of particulates on fine mesh screens is predictable and has been studied theoretically and experimentally for many years (Cheng et al. 1985). The NYU Medical School size sampler (NYUMS) sampler presently utilizes 5 screens (1) 90 mesh, and (4) 500 mesh.

Results

Figure 17 shows the total collector measurements of the outdoor concentration of ^{210}Pb in weekly samples for 1.5 years. The average outdoor air concentration of total particulates over this interval is $520 \mu\text{Bq m}^{-3}$. No particular seasonal trend can be identified with season which is unusual, for example, as compared with our long term ^{222}Rn data base.

Figure 18 shows the total collector measurement of basement ^{210}Pb concentration averaging $460 \mu\text{Bq m}^{-3}$ over the 1.5 years, in the single family home.

Figure 19 shows the ^{210}Pb concentration on the second floor of the home. The average concentration of ^{210}Pb is slightly less than the basement, $420 \mu\text{Bq m}^{-3}$ for the total collector sample.

Figure 20 shows a plot of the basement total sample versus the outdoor concentration of ^{210}Pb , but corrected for the additional alpha activity due to the decay of short lived decay products on the filter, and subsequent build up of ^{210}Pb . The slope of the regression is 0.65 and should represent the fraction of the outdoor aerosol in this size range that enters the home and is found airborne. The ventilation half-time in this home was measured as 1.9 hours and so there should not be a measurable concentration of ^{210}Pb in air from the direct decay of short-lived products.

The particle size distribution for the outdoor measurements is determined from the measured alpha activity on the screens. All screens and the exit filter were counted for 5000 minutes in the low background alpha scintillation detectors. The data were then analyzed using the deconvolution program based on an extreme value estimation (EVE) and is the only program to yield confidence intervals for the size spectrum.

Figure 21 to 24 shows the particle size spectrum from ^{210}Pb measurements of the screens from outdoor samples at this suburban site in northern NJ.

The fraction of ultrafine particles is also significant, with from 17 to 65% of the activity associated with the ultrafine particulates. The unattached fraction of the aerosol particles is barely perceptible in these measurements, and should reflect the unattached fraction of ^{214}Pb present initially that have decayed to ^{210}Pb . The unattached fraction has a median diameter typically of 1-5 nm. This mode is present at small concentrations in each size spectrum, but because of the small number of short lived ^{222}Rn decay product atoms present initially as unattached ^{214}Pb and ^{214}Po , the contribution to the alpha activity when decay to ^{210}Pb occurs, is small. The number of atoms of unattached ^{218}Po present initially on the screens would be too few to be able to detect when decay to ^{210}Pb occurs. This may be one of the more sensitive detection methods available to measure unattached $^{214}\text{Pb}/^{214}\text{Po}$ over long time periods.

One of the spectra, with the smallest fraction of ultrafine particles (17%) does show a significant initial unattached fraction of $^{214}\text{Pb}/^{214}\text{Po}$ that has decayed to ^{210}Pb .

Summary

The ^{210}Pb measurements in the basement, 2nd floor and outdoors at a single family home do not show a seasonal trend. The regression of indoor and outdoor ^{210}Pb corrected for the contribution of ^{210}Pb from the initial deposit of short lived decay products of ^{222}Rn implies that 65% of the outdoor aerosol is found airborne indoors. The outdoor ^{210}Pb aerosol has a median diameter of about 80 nm. The fractional ultrafine ^{210}Pb concentration also does not vary with season. The unattached fraction of $^{214}\text{Pb}/^{214}\text{Po}$ initially present on the screens that decay to ^{210}Pb is present in all samples.

The dose factor for short lived ^{222}Rn decay products has a central value of 6 mGy/WLM for the typical median size spectrum reported in the literature of 100-150 nm. If a fraction of the size spectrum does in fact have another mode in the ultrafine region, it increases the dose conversion factor by about 30%.

E. Report Summary

We believe that the 4 years of DOE supported research have been productive and have provided the most comprehensive and largest data base in existence. This includes indoor and outdoor ^{222}Rn , the decay products ^{214}Pb , ^{212}Pb , ^{210}Pb , water, and gamma ray data . The research produced 18 publications.

This support is gratefully acknowledged.

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Radon Model - Oct 31 - Nov 17, 1993

Energy Efficient Home, Northern NJ

Fig 1

Radon Measurement vs. Model

Home - Northern NJ - Winter 1991

FIG 2

Weekly Average Radon versus Weekly Average Temperature 1990-1994

Energy Efficient Home, Northern NJ - Basement

FIG 3

Energy Efficient Home, Northern NJ 1993-1994

Average of Hourly Data - 2nd Floor - Fan On

Fig 4

²²²Rn Release from Well Water During Showering Northern NJ Home

FIG 5

Outdoor Radon Northern NJ

Weekly Average 1990 - 1995

FIG 6

Outdoor Radon Northern NJ 1990-1994

Average by Month and Hour of Day

FIG 7

Gamma-Ray Exposure - Northern NJ

Weekly Average 1993 - June 1995

FIG 8

Gamma - Ray Exposure 1993 - June 1995 Avg. by Month and Hour of Day

Fig 9

Bronchial Dose Factors as a Function of Particle Diameter

Sigma $g = 2$ for size distributions

214 Pb - Outdoors Single Family Home Northern NJ

1996 - 1997

Fig 11

214 Pb - Basement Single Family Home Northern NJ

1996 - 1997

1996 1997

214 Pb - 2 nd Floor Single Family Home Northern NJ

1996 - 1997

1996 1997

212Pb Outdoors - Single Family Home

Northern NJ 1995 - 1997

FIG 14

212Pb Basement - Single Family Home

Northern NJ 1995 - 1997

212Pb 2nd Floor - Single Family Home

Northern NJ 1995 - 1997

FIG 16

Outdoor ^{210}Pb Weekly Measurements

Suburban Northern NJ

Basement 210Pb Weekly Measurements

Suburban Northern NJ

2nd Floor 210Pb Weekly Measurements

Suburban Northern NJ

Net Basement 210Pb as a function of Outdoor 210Pb

Suburban Northern NJ 1996-1997

Fig 20

Outdoor Aerosol Particle Size Distribution

^{210}Pb Measurements 3 - 24 May 1997

Suburban Northern NJ

Outdoor Aerosol Particle Size Distribution

^{210}Pb Measurements 9 Aug - 6 Sept 1997

Suburban Northern NJ

Outdoor Aerosol Particle Size Distribution

^{210}Pb Measurements 1 - 29 Nov 1997

Suburban Northern NJ

Outdoor Aerosol Particle Size Distribution

²¹⁰Pb Measurements 27 Dec 97 - 24 Jan 1998

Suburban Northern NJ