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Indoor ^{222}Rn in Tennessee Valley Houses: Seasonal, Building, and Geological Factors

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Abstract

A two-season survey of indoor ^{222}Rn concentrations was conducted in 226 occupied houses in Roane County, TN, during 1985 and 1986. A similar survey of 86 houses in Madison County, AL, was conducted in 1988 and 1989. Alpha track detectors were placed in each of the houses for three or more months during the winter heating season. Detectors were placed at the same sampling sites during the following cooling season. In this study, comparisons were made between winter and summer sampling times and between building types. For the data from Madison County, additional comparisons were made among regions of the county that differed in geological characteristics, especially the thickness of overburden above the Chattanooga Shale layer, a geological stratum that has high concentrations of ^{226}Ra and is widely found in the southeastern United States. The geometric means of summer and winter measurements in Roane County were 33 and 54 Bq m^{-3}, respectively. For Madison County, the summer and winter geometric means were 121 and 88 Bq m^{-3}, respectively. The winter ^{222}Rn concentrations for houses in Roane County exceeded summer ^{222}Rn concentrations, as is generally the case for houses in the U.S. For houses in Madison County, we found the opposite and atypical situation of higher ^{222}Rn concentrations in the summertime. ^{222}Rn concentrations differed significantly among groups of houses in distinguishable regions of Madison County. Substructure and other building factors had no observable effect on indoor ^{222}Rn concentrations found in this study.

KEY WORDS:
Indoor, Radon, Summer, Winter, Chattanooga Shale, Karst, Tennessee Valley.

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Introduction

During the past several years, houses have been discovered with indoor concentrations of ^{222}Rn and its short-lived progeny in excess of federally mandated occupational exposure limits. The discovery of homes with markedly elevated ^{222}Rn concentrations has resulted in increased awareness of the need for surveys of ^{222}Rn concentrations in typical American homes. Nero et al. (1986) have estimated that about one million American homes have indoor concentrations in excess of 300 Bq m^{-3}.[1]

Pressure-driven ingress of soil gas is the dominant means of ^{222}Rn entry (Nero and Nazaroff 1984). In many areas of the United States, higher indoor than outdoor temperatures can lead to substantial pressure differences across basement (or other substructural) walls. This phenomenon is referred to as the thermal stack effect. Its effect on indoor ^{222}Rn concentration was amply illustrated (see Figure 1) in a study of seven New Jersey houses (Hubbard et al., 1988; Dudney et al., 1989). Currently, many Americans are testing their homes for the presence of ^{222}Rn gas. In most cases, they are being encouraged to conduct the tests in the winter. In a widely distributed pamphlet that is currently undergoing revision, the U.S. Environmental Protection Agency and the Centers for Disease Control recommend "that you [i.e., homeowners] make short-term ^{222}Rn measurements during the cool months of the year" (EPA/CDC, 1986). However, Dudney et al. (1990a) have reported the occurrence of houses near Birmingham, AL, in which wintertime ^{222}Rn concentrations were found to be less than those occurring during the summer. In central Alabama, closed-house conditions in air-conditioned homes are more likely to occur in summer than in winter and, as noted by Ronca-Battista et al. (1988), closed-house conditions cause an increase in indoor ^{222}Rn concentrations.

In addition to closed-house conditions, other factors may affect seasonal patterns of ^{222}Rn entry into

[1] One pCi L^{-1} equals 37 Bq m^{-3}.

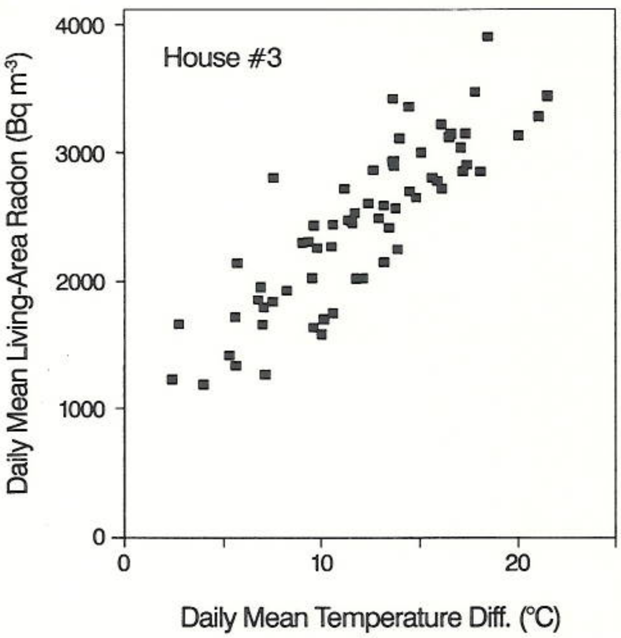

Fig. 1 Comparison of indoor radon concentration and indoor:outdoor temperature difference using 24-hour averaged data from a house in New Jersey (Dudney et al., 1989).

occupied dwellings. Occupant activities and some geological processes are likely to increase seasonal differences, whereas the presence of radium in significant amounts in building materials will contribute equally in all seasons to ^{222}Rn entry processes. Occupant activities affecting ventilation or indoor heating can strongly affect indoor ^{222}Rn concentrations. As a consequence of operation of heating and air-conditioning systems in two unoccupied houses, Matthews et al. (1990) have observed three-fold increases in transport rates from crawlspace to living area of gaseous tracers. Daily setback of the heating system thermostat correlated well with changes in indoor ^{222}Rn concentration in a New Jersey home studied by Dudney et al. (1989). Nazaroff et al. (1985) have shown that fireplace operation can lead to house depressurization and increased ^{222}Rn entry but the effect can be masked by geological factors affecting the availability of ^{222}Rn in the near-surface soil. Other examples of geological phenomena affecting indoor ^{222}Rn have also been described. Rose et al. (1988) and Wilson et al. (1991) have described occurrences of elevated ^{222}Rn concentrations in the soil in the summer. This could contribute to elevated indoor summertime ^{222}Rn concentrations.

For several reasons, including the examination of seasonal variations in indoor ^{222}Rn concentrations, an indoor air quality study of 300 houses in Roane County, TN, was conducted in 1986 and 1987 (Hawthorne et al., 1988; Hawthorne et al., 1989) during both the heating and cooling seasons. The results can now be compared to another indoor ^{222}Rn study that was conducted in Madison County, AL, during the heating and cooling seasons of 1988-89. The results of both surveys are presented here, using comparisons among data grouped by seasonal, geological, and building factors.

Study Design and Experimental Methods

In Roane County, the houses for this study were selected as part of the Harvard Six Cities Study (Ferris et al., 1979). The study population was selected in the spring of 1984 from students in the Kingston and Harriman schools. Solicitation letters were sent

Table 1 Summary of results from geological study groups in Madison County.

Study group	Surface rock layer	Depth to Chattanooga Shale (m)	Winter radon concentration			Summer radon concentration			Summer-to-winter radon concentration ratio		
			N*	GM** (Bq m^{-3})	GSD***	N	GM (Bq m^{-3})	GSD	N	GM	GSD
1	St. Genevieve Limestone	100	28	100	2.1	27	120	2.0	26	1.0	1.9
2	Chattanooga Shale	0	19	34	2.1	13	85	1.3	12	2.7	1.6
3	Tuscumbia Limestone	100	21	95	1.9	20	110	2.3	20	1.1	2.1
4	Ft. Payne Chert	15	28	140	2.2	28	160	2.0	28	1.2	2.5

*N = Number of measurements.
**GM = Geometric mean.
***GSD = Geometric standard deviation.

home to students in the second, third, and fourth grades. From among those houses participating in the larger study, 241 houses were monitored for indoor ^{222}Rn in the winter, 285 houses in the summer, and 226 houses were monitored during both seasons. Laboratory personnel placed and retrieved cup-sized, alpha track monitors in the houses. The monitors were typically placed on top of the kitchen refrigerator and exposed for three to five months.

In Madison County, four groups of houses were identified for the study according to the characteristics shown in Table 1. The geological characteristics of regions of the county were determined from U.S. Geological Survey maps. The houses for study groups 1, 3, and 4 were selected from among those homeowners who had responded to requests for participation in an earlier study of ^{222}Rn mitigation measures (Dudney et al., 1990b). Additional participants for study group 2 were obtained by door-to-door solicitation in the northern portion of the county in which the geological conditions matched the study objectives. For the winter measurements, laboratory personnel placed the monitors, and after about three months, letters were sent to the homeowners requesting them to seal and return the monitors. At the start of the summer monitoring period, letters and monitors were sent to the homeowners. They were instructed to open the monitors and place them in the same location used the previous winter. At the end of the summer monitoring period, letters were sent to the homeowners requesting them to return the monitors to us. Winter measurements were made in 96 houses and summer measurements were made in 88 houses. In 86 houses, both summer and winter measurements were made.

Integrating, alpha track detectors (ATDs) were used in both studies. The ATDs used in Roane County were about 95 mm high and 75 mm in diameter. Smaller ATDs, about 35 mm in diameter and 22 mm high, were used in Madison County. The monitors were obtained commercially[1] and are functionally similar to those described by Alter and Fleischer (1981).

Some (i.e., 8%) of the ATDs were used for quality assurance purposes. The precision of the measurements under field conditions was evaluated by the placement of replicate (i.e., collocated) monitoring devices at some of the sites. In 16 houses during the winter of 1985-86 and in 16 houses during the summer of 1986, paired monitors were deployed. Using analysis-of-variance techniques (Snedecor and Cochran, 1967), the mean standard errors of these measurements were 81 Bq m^{-3} and 42 Bq m^{-3}, respectively, in the winter and summer. The coefficient of variation of the replicate measurements was about 18%, independent of mean response between 40 and 400 Bq m^{-3}. The mean response of 24 field blanks (i.e., unexposed ATDs) was 6.7 ± 3.3 Bq m^{-3}. The mean response of the unexposed ATDs is not significantly larger than zero ($t=2.0$, $P>0.05$). To ensure that all errors relating to the laboratory analysis of the detectors were randomly distributed among the measurements, detectors were returned to the vendor without labels that might indicate to the laboratory personnel the location or duration of exposure.

One of our sponsors' goals was to characterize ^{222}Rn levels in a large number of occupied houses, and this affected the design of these surveys. This study was conducted using commercially available ^{222}Rn detectors that do not require electric power in the field. Insufficient resources were available to allow the use of continuous detectors which are much more sensitive with limits of detection approaching 4 Bq m^{-3}. The detectors we did use are one of the more common types of measurement devices that can be used in surveys of residential ^{222}Rn concentrations. In contrast, the ongoing national residential ^{222}Rn survey by EPA (White et al., 1989) has used 48-h exposures of charcoal canisters to assess ^{222}Rn concentrations in the lowest habitable locations of many occupied homes. The three-month (or longer) exposures used in this study provide a better measure of the indoor environment to which occupants are being exposed because these measurements are not as likely to be perturbed by short-term variations such as those associated with rainstorms.

Information about building characteristics was collected by means of questionnaires administered to the homeowners/occupants by project personnel. In Roane County, a very extensive questionnaire (Hawthorne et al., 1989) was administered as part of the Harvard Six Cities study. The information from those questionnaires pertaining to substructural characteristics and numbers of stories above the substructure were used in the data analyses reported here. Of the 241 houses where winter measurements were made, 202 owners provided information on structural characteristics. Structural information was

[1] Terradex Corporation, 3 Science Road, Glenwood, IL, 60425-1579.

available for 226 of the 285 houses where summer measurements were made and for 183 houses there was structural information along with both summer and winter ^{222}Rn data. In Madison County, houses were classified into four categories: rancher, two story, split foyer, and split level. Owners of all houses where ^{222}Rn measurements were made provided structural information.

Statistical calculations reported here were made on a personal computer running programs written by SAS (1987) or by Englund and Sparks (1988).

Results

Seasonal Comparisons

Measurements of indoor ^{222}Rn concentrations were made in the living area of Roane County houses during the winter of 1985/86 and during the following summer. Figure 2 shows the distribution of results from houses where data were collected in both phases of the study. Figure 3 shows the distribution of data collected in houses in Madison County during the winter of 1988/89 and the following summer. In Roane County, the geometric mean and standard deviation of all winter measurements were 54 Bq m^{-3} and 2.5, respectively. The geometric mean and standard deviation of the summer measurements were 33 Bq m^{-3} and 2.3, respectively. Considering only those homes in which both summer and winter measurements were made, the geometric means of the summer and winter measurements were 33 Bq m^{-3} and 53 Bq m^{-3}, respectively. In Madison County, the geometric mean and standard deviation of all winter measurements were 88 Bq m^{-3} and 2.4, respectively. The geometric mean and standard deviation of the summer measurements were 121 Bq m^{-3} and 2.0, respectively. Considering only those homes in which both summer and winter measurements were made, the geometric means of the summer and winter measurements were 120 Bq m^{-3} and 96 Bq m^{-3}, respectively.

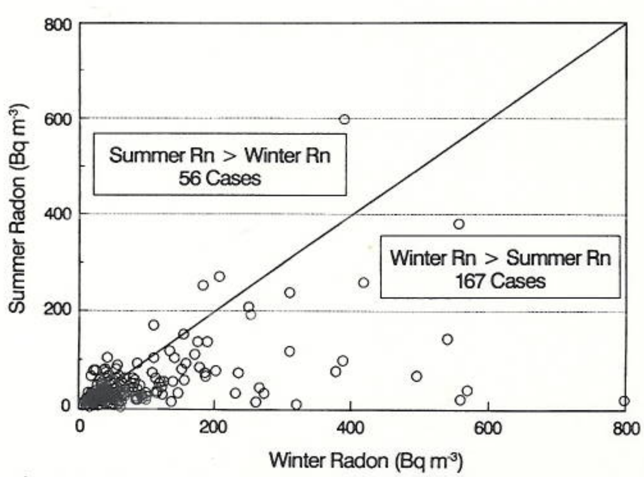

Fig. 2 Distribution of radon results from Roane County houses. The line indicates the division between cases when wintertime or summertime elevation of indoor radon was observed.

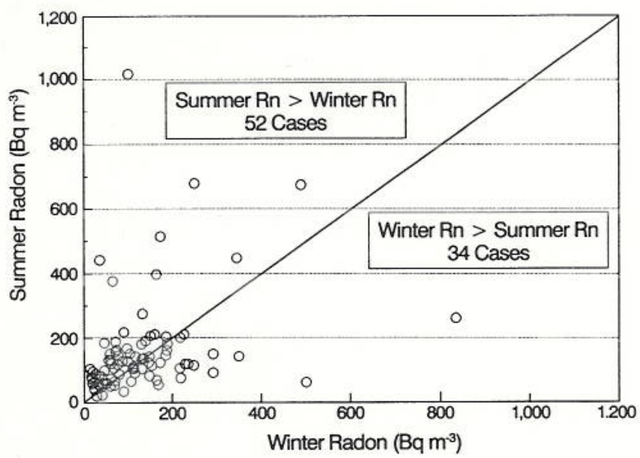

Fig. 3 Distribution of radon results from Madison County houses. The line indicates the division between cases when wintertime or summertime elevation of indoor radon was observed.

The data for both counties and for both seasons show skewed distributions. Using the Shapiro-Wilke goodness-of-fit test (SAS, 1987), the data were found to be lognormally distributed ($P > 0.10$ in all cases) and not normally distributed ($P < 0.01$ in all cases). Because of the distribution of the data, all other statistical tests of the data were performed using logarithmically transformed values.

The most striking feature of the data is the difference in the seasonal pattern between the two counties. In Roane County, winter results were higher than summer results in 74% of the houses, whereas, in Madison County, winter results were higher than summer results in only 40% of the houses. Because of the study design used, the data were compared pairwise. The ratio of summer ^{222}Rn concentration to winter ^{222}Rn concentration was calculated for each house. The distributions of summer-to-winter ratios in both Roane County and Madison County were found to be lognormal, not normal. In Roane County, the geometric mean and standard deviation of the ratios were 0.58 and 2.2, respectively. The geometric mean is significantly less than unity ($t = -9.4$, $P << 0.01$). In Madison County, the distribution of ratios was also found to be lognormal. The geometric mean and standard deviation of the ratios were 1.26 and 2.2, respectively. In this case, the geometric mean is significantly greater than unity ($t = 2.6$, $P < 0.01$).

Geostatistical Analyses and Geological Factors

For the data from Madison County, the effects of geological factors were evaluated by analysis of variance (Snedecor and Cochran, 1967) in logarithmically transformed values of data from houses classified by study group (see Table 1). The variance in the data indicates that there are significant differences among the study groups for: winter ^{222}Rn ($F=15$, $P<<0.01$), summer ^{222}Rn ($F=3.0$, $P=0.034$), and summer-to-winter ratio ($F=4.8$, $P<0.01$). For each of the geological study groups, Table 1 summarizes the geometric means and standard deviations for winter and summer ^{222}Rn concentrations, as well as the ratios of paired summer and winter measurements made at identical sites. Results from study group 2 should be noted since Chattanooga Shale is enriched for ^{226}Ra compared to soil and other strata (Dudney et al., 1990a).

Because we had successfully identified differences between the geologically defined study groups in Madison County, we undertook a geostatistical analysis of the data from both counties. The location of each house in the study (except Group 2 in Madison County) was recorded on topographical maps of the area and digitized for analysis of the spatial correlation of indoor ^{222}Rn levels. Figure 4 is a schematic map of the central portion of Roane County showing the house locations indicated according to whether winter indoor ^{222}Rn levels were above or below 150 Bq m^{-3}. Figure 5 is a similar map of the study area in Madison County showing the house locations (for study groups 1, 3, and 4) indicated according to whether summer indoor ^{222}Rn levels were above or below 150 Bq m^{-3}. Using software developed by Englund and Sparks (1988) for geostatistical analyses, semivariograms (Clark, 1979) were computed for summer and winter data from the houses in Roane County. Neither the summer nor the winter semivariogram provided any evidence of

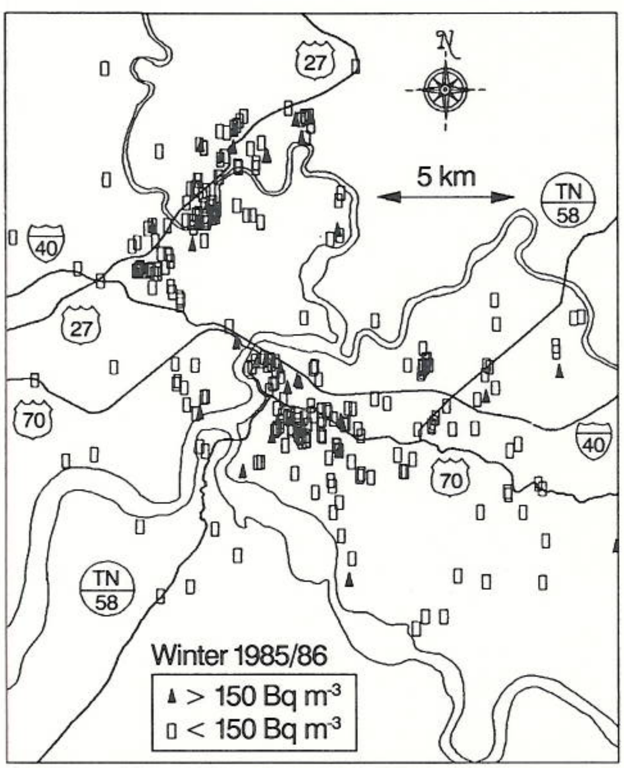

Fig. 4 Schematic map of Roane County. House locations are indicated according to whether the winter radon concentration was found to be above or below 150 Bq m^{-3}.

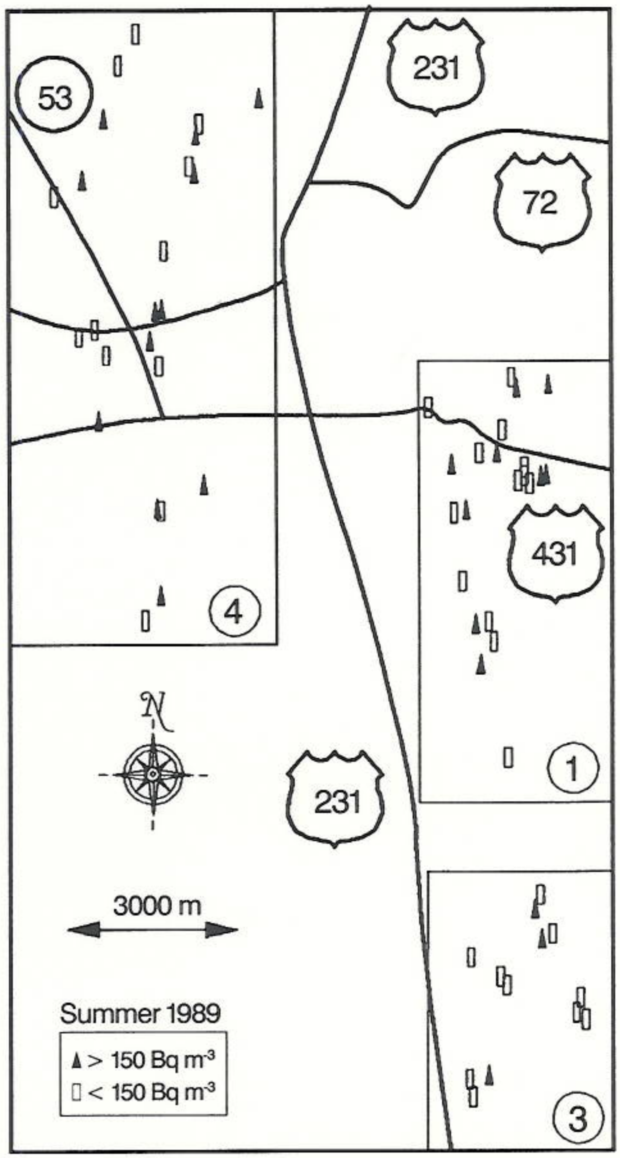

Fig. 5 Schematic map of Madison County. House locations are indicated according to whether the summer radon concentration was found to be above or below 150 Bq m^{-3}.

Table 2 Distribution of study houses among structural and substructural groups.

Roane County		
Type of substructure	Number of stories above substructure:	
	One	Two
Full basement	92	13
Partial basement	16	9
Crawlspace	44	15
Slab on grade	44	12

Madison County				
Type of substructure	Style of house:			
	Two story	Ranch	Split foyer	Split level
Basement	2	13	4	0
Crawlspace	6	38	0	0
Slab on grade	1	5	0	0
Crawl/slab	0	1	0	0
Crawl/bsmt	2	11	5	8

increased correlation of ^{222}Rn levels in close (< 0.5 km) house pairs compared to distant (> 3 km) house pairs. Similar results were obtained when the calculations were made with data only from houses with full basements or data only from houses with crawlspaces. Similar negative results were obtained from the data collected in Madison County.

Building Factors

An analysis of variance was performed using the logarithmically transformed values of the ^{222}Rn concentration data and grouping the houses by building factors. Table 2 shows the numbers of houses in the study classified according to county and structural and substructural features. A two-way analysis of variance in the ^{222}Rn concentration data from Roane County revealed no evidence of a systematic effect attributable to number of stories ($F=0.12$, $P=0.73$) or to type of substructure ($F=0.33$, $P=0.80$). For the data from Madison County, there was no evidence of a systematic effect attributable to type of substructure ($F=0.59$, $P=0.67$) or to style of structure ($F=0.15$, $P=0.93$). There is little evidence of any significant effect due to these building factors in these data.

Discussion

To date, most federal public health officials have recommended that homeowners who are concerned about the ^{222}Rn concentrations in their homes, test their homes when driving forces causing ^{222}Rn ingress are strongest and indoor ^{222}Rn concentrations are highest (EPA/CDC, 1986; Ronca-Battista et al., 1988). For most of the U.S. housing stock, the time of highest concentrations is thought to be the winter heating season when the thermal stack effect is strongest. However, Dudney et al. (1990a) reported on 70 houses in the Tennessee Valley area, in which it was seen that in 30 houses near Birmingham, AL, the summer-to-winter ratios of ^{222}Rn concentrations were significantly greater than unity. This paper reports another area containing a population of houses in which the summer-to-winter ratios are greater than unity. The geographical range in which summertime elevation of indoor ^{222}Rn concentrations occurs may not be large because the seasonal distribution of data from Roane County is more or less what is expected for typical houses in the U.S. in which the dominant factor controlling the winter ^{222}Rn concentration is the thermal stack effect.

At this time it is not entirely clear what causes the summertime elevation of indoor ^{222}Rn in houses near Birmingham and in Madison County. Two possible explanations include: (1) occupant control of the heating and air-conditioning system and window openings, and (2) strong seasonal variation in ^{222}Rn potential in the soil. In colder climates such as Roane County (this study) or eastern Pennsylvania (Sachs et al., 1982), relatively few houses exhibit summertime elevation of indoor ^{222}Rn. In those cases in colder climates in which summertime elevation occurs, we suspect that unusual occupant preferences may account for the occurrences. Ronca-Battista et al. (1988) have pointed out the probability that closed-house conditions may lead to elevation of indoor ^{222}Rn concentrations. Earlier guidance by the federal government in the "Citizen's Guide to Radon" (EPA/CDC, 1986) suggested that homeowners would have an increased likelihood of discovering elevated ^{222}Rn concentrations in their homes if they sampled in the cool weather seasons of the year.

Because ^{222}Rn in soil gas is the dominant source of indoor ^{222}Rn (Nero and Nazaroff, 1984), seasonal phenomena in the soil may account for summertime elevation of indoor ^{222}Rn in houses. Rose et al. (1988) have observed that soil gas ^{222}Rn concentrations are higher in the summer than in the winter for several study sites in central Pennsylvania. For a study site in Madison County (AL), Wilson et al. (1991) have recently reported that gas in near-surface soil channels is enriched in ^{222}Rn in the summer compared to the winter. In addition, they observed that indoor ^{222}Rn levels in four nearby houses declined in concert with the decline of ^{222}Rn in the channels. It remains to be determined which has greater impact on indoor ^{222}Rn levels: occupant activities or near-surface geological factors.

The other important finding in this paper is the observation of significant differences between study populations selected in Madison County based on geological differences. Generally lower indoor ^{222}Rn concentrations were found in houses from a region (i.e., study group 2) in which the Chattanooga Shale outcrops frequently. In addition, houses from this same area exhibited greater summer-to-winter ratios. The black shale in this area has more ^{226}Ra than the surface soil or any stratum above it (Dudney et al., 1990a). Because the limestone layers above the Chattanooga Shale in Madison County are frequently penetrated by small (10 cm) fissures, we suspect that complex and poorly understood phenomena are operating in the soil and near-surface strata in Madison County. Peake (1988) has found that regions underlain by carbonate (i.e., limestones and dolomites) can pose a "moderate or even high risk" of elevated indoor ^{222}Rn concentrations. He points out that Terra Rosa soils (clayey soils with iron rich hydroxides) may scavenge available radium and uranium, enriching the soil relative to the parent rock from which it derived. Clay soils are very common in the Tennessee Valley. Peake (1988) also points out that channels in limestone areas may serve to transport ^{222}Rn from caves, which are frequently rich in ^{222}Rn, into nearby houses.

Geostatistical analyses of data from two counties failed to reveal any evidence of spatial correlation of indoor ^{222}Rn concentrations. Two possible factors may cause this finding. Building factors affecting ^{222}Rn entry processes may vary greatly between houses. If this were the case, one might expect enhanced spatial correlation if geostatistical analyses were performed on data taken from houses with similar substructural features. This was not the case. In regions of karst terrain such as exists in both Roane and Madison Counties, an alternative explanation may be the occurrence of small ($<<10$ m) geological features capable of transporting large quantities of ^{222}Rn into near-house regions. If such small "hot spots" of ^{222}Rn potential were randomly distributed in an area, little spatial correlation would be observable. We have observed the ^{222}Rn concentrations in near surface channels in Madison County to reach 300 000 Bq m^{-3} (Wilson et al., 1991). By measuring both flow velocity and ^{222}Rn concentration, we have observed source strengths in a single 10-cm channel as high as 30 Bq s^{-1}. These observations will be reported separately.

In summary, this study has shown that summertime elevation of indoor ^{222}Rn can occur in a large population of Alabama houses. It was also seen that there is significant variation in indoor ^{222}Rn among houses from geologically distinct regions of Madison County. These findings may imply the occurrence of important subsurface ^{222}Rn transport processes in karst terrain.

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