SEASONAL VARIABILITY AND BILEVEL DISTRIBUTION OF RADON AND RADON PROGENY CONCENTRATIONS IN 200 NEW JERSEY HOMES

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ABSTRACT

To provide data necessary to perform a health risk assessment of the radon problem in New Jersey, concurrent radon and radon progeny measurements were made in 200 homes on two lowest floors in two different seasons. The homes were divided into categories based on their substructure, heat distribution system, and the degree of air flow between the basement and first floor levels. Specific conversion factors (equilibrium coefficients, inter-floor radon ratios, inter-season radon ratios) were determined for each house type. Basement equilibrium coefficients were generally lower in the winter than in the non-winter season. First floor equilibrium coefficients were higher than basement values. First floor to basement radon ratios were higher for forced air houses than for houses with hot water or electric heat distribution systems and the ratios for both types of houses were higher in the winter than in the non-heating season. The winter to non-winter ratio for first floors is lower than for basements. While the winter to non-winter ratios seem high, ranging from 0.3 to 0.97, the results are consistent with other studies.

INTRODUCTION

As awareness of the indoor radon issue grew and radon sampling activities within New Jersey expanded, it became evident that occurrences of elevated indoor radon were more widespread than originally suspected. In the fall of 1986, the New Jersey Department of Environmental Protection (NJDEP) initiated a comprehensive project to characterize the nature and extent of the radon problem within the State of New Jersey. This project, the Statewide Scientific Study of Radon, was conducted by Camp, Dresser & McKee, Inc. (CDM) under the auspices of the Bureau of Environmental Radiation within the NJDEP.

A major component of this study was the radon sampling of over 6,000 residences and approximately 170 institutional facilities throughout the state. Samples were taken on regular grids to ensure uniform geographic coverage. Different sampling densities were used based on the radon potential of the geologic provinces, with the majority of the state sampled at least once per square mile. The actual sampling locations and final densities are shown in Figure 1. Results of this mass sampling indicate that the statewide spatial average radon concentration in New Jersey is 3.4 pCi/l. Approximately one-third of the houses sampled showed levels greater than 4 pCi/l. The Highlands Province had the highest average indoor radon concentration, 8.6 pCi/l and two other geologic provinces showed averages above 4 pCi/l, the Valley and Ridge at 7.6 pCi/l and the Southern Piedmont at 4.9 pCi/l. The average radon for the Inner Coastal Plain was 2.4 pCi/l, and the Northern Piedmont and the Outer Coastal Plain showed low radon levels of 1.7 and 1.4 pCi/l, respectively.

To evaluate the health risks that the observed radon levels presented to New Jersey residents, a method was needed to translate the 6,000 lowest level radon screening results in pCi/l into annual average working levels of radon progeny for all levels of a house. It is exposure to radon progeny, measured in working level concentrations, rather than radon itself that offers the most significant health risk. Radon and radon progeny concentrations have been reported to vary with season, floor of sample, substructure type, and heating system. Therefore, inter-floor radon ratios, equilibrium coefficients, and inter-season radon ratios were needed.

To obtain this data, a supplemental sampling phase (Level II) was initiated in the fall of 1987 (one year after the Level I mass screening) at a subset of approximately 200 homes which had been included in the Level I mass sampling program. Integrated radon and radon progeny measurements were made on the lowest two floors of each home in two seasons.

METHODS

SAMPLING DESIGN

In selecting the pool of potential participants for the Level II study, one criteria applied was that the Level I measurement be at least 8 pCi/l. It was felt that lowest level concentrations should be significantly elevated to assure that first floor sample concentrations would remain detectable through a non-heating season. Another consideration was that the homes selected be representative of New Jersey housing stock, particularly with respect to substructure and heat distribution type. An effort was also made to preclude homes that had instituted remediation. A final goal was to achieve a geographical sampling distribution similar to that used in the Level I sampling.

Figure 2 shows the Level II sampling distribution and initial Level I results. It can be seen that the sampling distribution among provinces is reasonably consistent with the Level I sampling strategy, with the exception that no samples were obtained from the Northern Piedmont. The preponderance of participant houses are situated in the three provinces with high radon levels; Highlands, Valley and Ridge, and Southern Piedmont. Table 1 shows the sampling distribution by house type and province.

Two rounds of Level II sampling were conducted to allow an estimation of seasonal variation in radon concentrations. The first round of Level II sampling was conducted from September 30, 1987 to March 13, 1988. The second round of sampling was not initiated until January 13, 1988 and was completed on July 16, 1988. Sampling proceeded in roughly the same order for each round so that houses sampled early in round 1 experienced "non-heating season" conditions for the first round and "heating season" conditions for the second round. The opposite was true for houses sampled at the end of round 1 (January to March 1988) who had their "non-heating season" sampling at the end of round 2, in May, June or July 1988. Although the rounds did not correspond to calendar seasons, results from two "seasons" were obtained for all houses.

SAMPLING METHODS

Integrated 4-day radon measurements were performed using charcoal canisters as in the mass screening sampling. Integrated radon progeny measurements were obtained using the radon progeny integrated sampling unit (RPISU) developed by R.A.D. Services of Ontario, Canada. This unit is a small air pump which collects radon progeny on a filter. An alpha track detector chip of polycarbonate CR39 is exposed to the alpha particles deposited on the filter. The detector chips are removed from the pumps and sent to the laboratory where the alpha tracks are manually counted.

Homeowners were mailed sampling kits and were provided with detailed instructions as to where and how to place the sampling devices. A "hot line", toll-free telephone number was instituted to give advice to homeowners during the sampling. Homeowners were reminded by phone and through the mail to return the sampling devices when the sampling period had ended.

DATA AGGREGATION METHODS

As discussed earlier, indoor radon and working level concentrations will tend to systematically vary depending on season and house characteristics. Therefore, to aid in the interpretation of the Level II results, methodologies were developed for both house- and season-specific stratifications as described in the following sections.

House Typology

A simplified house typology was established whose purpose was to group the sample set of Level II houses into types which were different with respect to features expected to significantly affect either inter-floor ratios, seasonal differences, or equilibrium coefficients.

Based on the analysis of the Level I data set, a 16 category typology was initially established which consisted of stratifications by substructure (4 types) and heat distribution system (4 types). Substructure types included basement, basement and crawlspace, crawlspace-only, and slab-on-grade homes. Heat distribution types consisted of forced-air, hot water/steam, electric, and "other". These 16 categories were simplified based on two conceptual considerations suggested by the previous data analyses--the presence or absence of either a basement or a forced air heat distribution system.

Analysis of the Level I data had suggested that basement homes with attached crawlspaces acted similarly to basement homes without crawlspaces, thus a single basement house category was established. Also, due to the small number of non-basement homes in the Level II data base, both crawlspace-only and slab-on-grade homes were also collapsed into a single category. The result was a typology with two substructure categories--basement and non-basement.

Conceptual considerations and previous data analyses had also suggested that forced air systems differed from other heat distribution types in their ability to promote more complete inter-floor mixing during the heating season. There was no strong reason to expect hot water/steam and electric distribution systems to differ significantly in their ability to promote inter-floor mixing or to impact working level equilibrium coefficients; so they were combined in the final typology.

Since analysis of the Level I data had indicated that the existence of an open passageway to the upstairs from the basement acted much like forced air distribution in promoting inter-floor mixing, homes with hot water/steam or electric systems in which the passageway to the upstairs was open (no door or the door was kept open) were added into the forced air house grouping. Finally, the "other" heat distribution category was retained as a separate category primarily because it contained a spectrum of largely unknown distribution types that could distort the results if they were collapsed into another distribution type category.

The basic house typology, then, consists of 6 categories, three heat distribution types for each of the two substructure types.

Designation of Seasons

Based on the previous experience of CDM and the work of other researchers, it was expected that indoor radon concentrations, inter-floor concentration ratios and equilibrium coefficients would show a systematic variability with season. Radon concentrations tend to be higher in winter presumably due to stronger depressurization effects, and perhaps also lower ventilation rates (1,2).

Since rounds 1 and 2 of Level II spanned calendar seasons, it was decided to develop a functional definition of seasons in terms of radon dynamics, rather than simply use a calendar date definition. Conceptual analysis suggested that the average air temperature during the sampling period (obtained from one of 19 regional meteorological stations) could provide a reasonable basis for separating heating from non-heating seasons to more generally designate "functional" seasons. The results of the Level I analysis also lent support to this approach since there was a significant drop in indoor radon when the average air temperatures for the sampling period rose above 45-50°F, approximately coincident with the temperature interval at which the heating system is shut down. Therefore, a two season scheme was adopted, consisting of a heating and non-heating season.

A suitable air temperature was needed as a break point for separating heating and non-heating seasons. The annual average temperature for northern New Jersey is 54 °F. However, since the Level II sampling did not begin until the end of September, there were not enough "warm" samples if 54° was used as the break point. In addition, the heating season is normally considered to begin when the average temperature drops below 50°F. The average of the individual non-heating season/heating season indoor radon ratios for all Level II houses was plotted against temperature break points from 44° to 56°F as shown in figure 3. As can be seen, this ratio varies from above 1 (non-winter radon is higher than winter radon on the average) to about 0.8. There appears to be a general flattening of the trend line in the range 46° to 52°F, suggesting this to be a natural break point for partitioning "seasons". For these reasons, a break point value of 48°F for separating heating and non-heating seasons was adopted.

RESULTS

Table 2 presents the average radon and radon progeny results for the 200 Level II houses stratified by house type and round. Since both rounds spanned heating and non-heating seasons, the average results for each round are very similar. Average equilibrium coefficients (100 x VL/Radon) and inter-floor radon ratios (upper level/lower level) were computed for each building type and the results are presented in table 3. These coefficients represent the average of the individual house ratios and not merely the ratios of the average results presented on table 2.

The inter-floor radon ratio is significantly higher for forced air/basement houses (0.49) than for hot water and electric/basement houses (0.32), as expected. In addition, the inter-floor radon ratio tends to be higher for non-basement houses, than for basement houses, reflecting the ease of air movement between floors within the "upstairs" area. The data suggests that forced air systems achieve almost complete mixing between upstairs floors for non-basement homes (the inter-floor radon ratio approaches 1.0); however, the data set is too small for conclusions to be definitive.

Equilibrium ratios tend to be larger on the first floor than the basement, consistent with previous studies (3). This pattern probably reflects the longer residence time of the upstairs air. The data also suggests that first floor equilibriums for a particular heat distribution system are similar for basement and non-basement homes. For the hot water/electric distribution system group, first floor equilibriums were comparable for basement (0.42) and non-basement (0.39) homes.

To develop the final conversion parameters that could be used to translate lowest level radon screening measurements to annual average working level concentrations, the Level II data was segregated by house type and season. Average seasonal equilibrium coefficients, inter-season radon ratios, and seasonal inter-floor radon ratios were then obtained. For certain groupings of non-basement homes there were no Level II samples, therefore appropriate equilibrium coefficients and inter-season ratios had to be inferred from available data. The final seasonal coefficients (and their standard deviations) developed from the Level II data base are listed in table 4.

For basement houses, the inter-floor radon ratio is consistently higher in the winter than in the non-winter. This could be due to the increase in air movement from the basement to the first floor caused by the operation of a forced-air heating system (the highest inter-floor ratio occurs in the winter in forced air houses) or simply due to an increased stack effect.

The equilibrium coefficients are 10-20% lower in the winter than in the non-winter for all but the "other" heat distribution houses. This effect has been seen by other studies (4,1). Also, the equilibrium ratios are in a range consistent with most other studies (5).

As seen from the standard deviations shown on Table 4, the coefficient of variation (S.D./mean) for both inter-floor radon ratios and equilibrium coefficients is on the average about 0.5, with the exception of the inter-floor ratio for hot water/electric basement homes. This indicates that inter-floor air flow may differ between hot water and electric houses and that they probably should not have been combined for this situation.

The coefficient of variation for the inter-season ratios is also around 0.5 for hot water/electric homes but is very high (0.9 to 1.2) for forced air homes. Since the other forced air coefficients are less variable, it does not appear that the variability is due to poor house classification. It is possible, however, that the large differences in inter-season ratios for these homes is due to the fact that many forced air homes have central air conditioning in the warmer months. While generally radon concentrations are seen to be lower in non-heating seasons, homes with central air conditioning have been noted to have the same radon concentrations in the summer as in the winter. It is hypothesized that if the central air system is located in the basement it could serve to depressurize the basement causing radon influx similar to that seen from furnace depressurization in winter months. Since information concerning central air conditioning was not obtained for any of the houses, it was not possible to stratify by this additional factor.

The inter-season radon ratios are higher than those found in previous studies, ranging from 0.3 to 0.97. However, upon examining many of these studies, it was determined that they calculated their ratios by first averaging the winter results and the non-winter results and then taking the ratio of these two averages. This method has produced non-winter to winter ratios of 0.57 (6), 0.45 (7) and 0.436 (2), for example. The ratios calculated in this study were actually the averages of ratios for individual houses. This method does not give an unequal weight to houses with higher concentrations as does the "ratio of averages" method used by other studies. To lessen the effect of high concentrations, a larger sample set is sometimes used. The three studies listed above all had sample sets of less than 100. However, Cohen (8) has reported seasonal ratios for sample sets of over 100 that range from 0.83 to 0.41, the higher side of which is consistent with this study's results. Other studies have, like this study, looked at averages of individual ratios, but the variability in these measurements has been quite large, sometimes over 100 percent (9,10). This has led some researchers to report that there is no consistent variation of radon with season (3). However, the variability in each ratio in this study is usually less than 100% and the variability for hot water/electric homes (which make up over 50% of New Jersey homes) is less than 50%. Thus, although the seasonal ratios developed in this study are larger than might be expected, the variability obtained was actually less than in other studies, which can be seen as a success of stratifying by house type.

The inter-season ratio in basement houses is consistently lower on the first floor than on the basement, and the first floor non-winter to winter ratio for a similar non-basement house is smaller still. In fact, the ratios for the non-basement houses (0.45-0.54) are similar to the summer to winter ratio of 0.54 found in nine, primarily non-basement houses in New Mexico (7). This increased seasonal effect for first floors in basement homes could be because the increase in ventilation rates during the summer months primarily affects the first floor. This would also explain the greater seasonal effect for non-basement homes--for the same source term, the summer concentration on the first floor of non-basement homes should be even lower, because the radon concentration is being reduced on the floor where it enters the house.

CONCLUSION

The Level II data set served to provide credible average inter-floor ratios and equilibrium coefficients that could be used to estimate average working level concentrations from lowest level screening measurements. Less confidence can be placed on the inter-seasonal coefficients. However, the relatively low variability for the average inter-seasonal coefficients for hot water/electric homes would indicate that these coefficients may also be reasonable. A major benefit of this study was that the variability among the individual house-specific coefficients was quantified. The coefficients vary considerably between houses. No general seasonal trend could be found, particularly with forced air houses. Further research in this area is definitely warranted.

The coefficients on Table 4 must be considered specific to this study for they have been developed using real data obtained during the Statewide Scientific Study of Radon, with all its limitations. If additional non-heating season samples had been obtained or more non-basement homes had been sampled, the respective coefficients might be different. The coefficients were primarily developed as an attempt to organize and interpret the data collected during the Level II sampling phase so that annual working level exposures could be extrapolated from the 6,000 home data set. Without this effort the risk assessment performed on the Level mass screening would have been extremely unrealistic and the impact of the radon problem in New Jersey may have been undermined.

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REFERENCES

1. Israeli, Miron. 1985. Deposition Rates of Rn Progeny in Houses. Health Physics. 49:1069-1083.

2. Nero, A.V., M.B. Schwehr, W.W. Nazaroff, and K.L. Revzan. 1986. Distribution of Airborne Radon-222 Concentrations in U.S. Homes. Science. 234:992-997.

3. George, A.C., and A.J. Breslin. 1978. The Distribution of Ambient Radon and Radon Daughters in Residential Buildings in the New Jersey - New York Area. In: Natural Radiation Environment III, volume 2:1272-1292. Technical Information Center/U.S. Department of Energy.

4. Toohey, R., M.A. Essling, and J. Rundo. 1987. Some Measurements of the Equilibrium Factor for ^{222}Rn Daughters in Houses. Health Physics. 53(1):89-91.

5. Swedjemark, Gun Astri. 1983. The Equilibrium Factor F. Health Physics. 45(2):453-462.

6. Abu-Jarad, Falah, and J.H. Fremlin. 1984. Seasonal Variation of Radon Concentration in Dwellings. Health Physics. 46(5):1126-1129.

7. Wilkening, Marvin, and Andreas Wicke. 1986. Seasonal Variation of Indoor Rn at a Location in the Southwestern United States. Health Physics. 51(4):427-436.

8. Cohen, Bernard L., and Nickifor Gromicko. 1988. Variation of Radon Levels in U.S. Homes with Various Factors. JAPCA. 38(2):129-134.

9. Fleischer, R.L. and L.G. Turner. 1984. Indoor Radon Measurements in the New York Capital District. Health Physics. 46(5):999-1011.

10. Toohey, R., M. Essling, F. Morkun, and J. Rundo. 1985. Radon Levels in Single-Family Houses. In: Environmental Radiation. Laramie, WY: Health Physics Society.

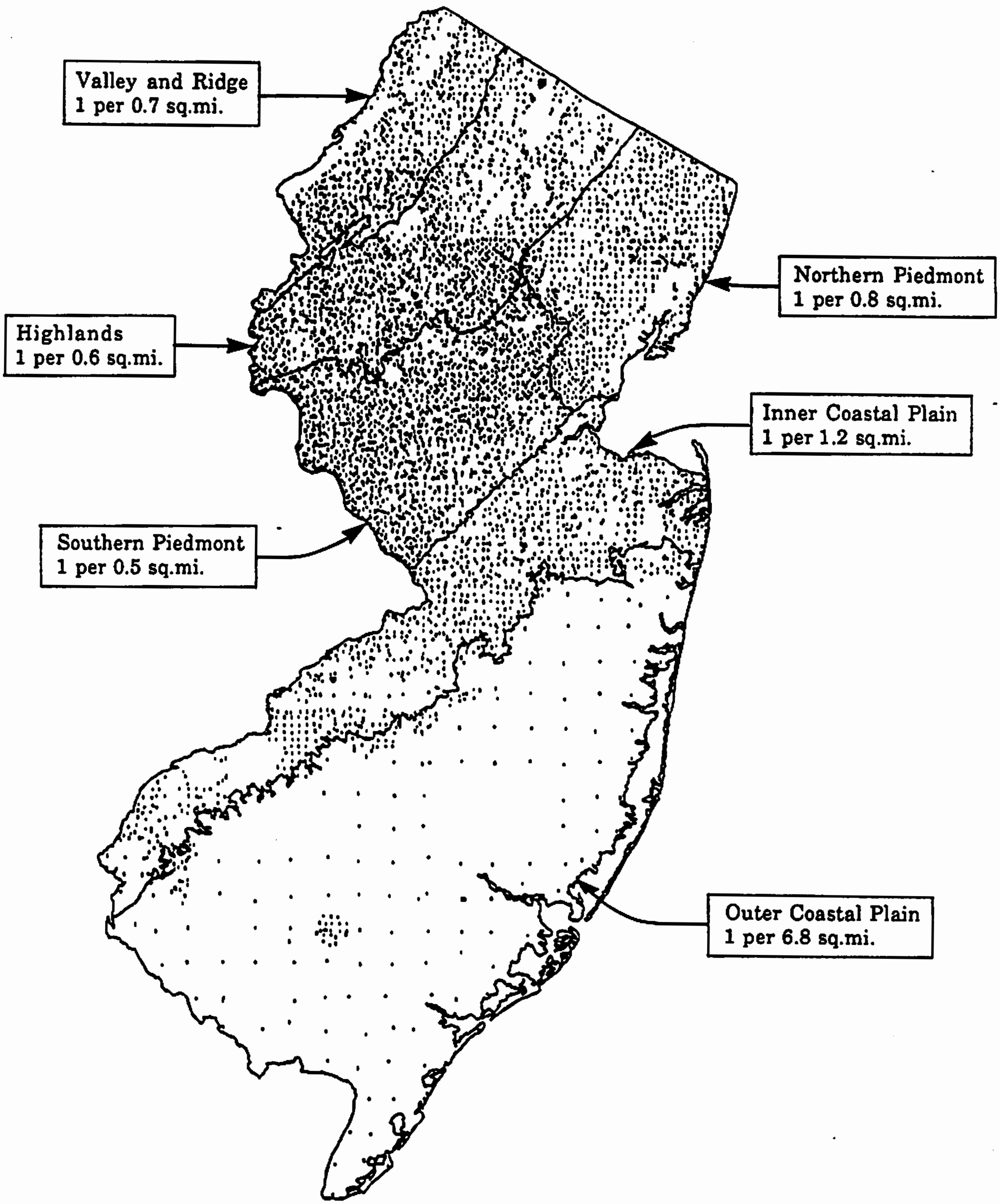

Figure 1 Sampling density within New Jersey geologic provinces.

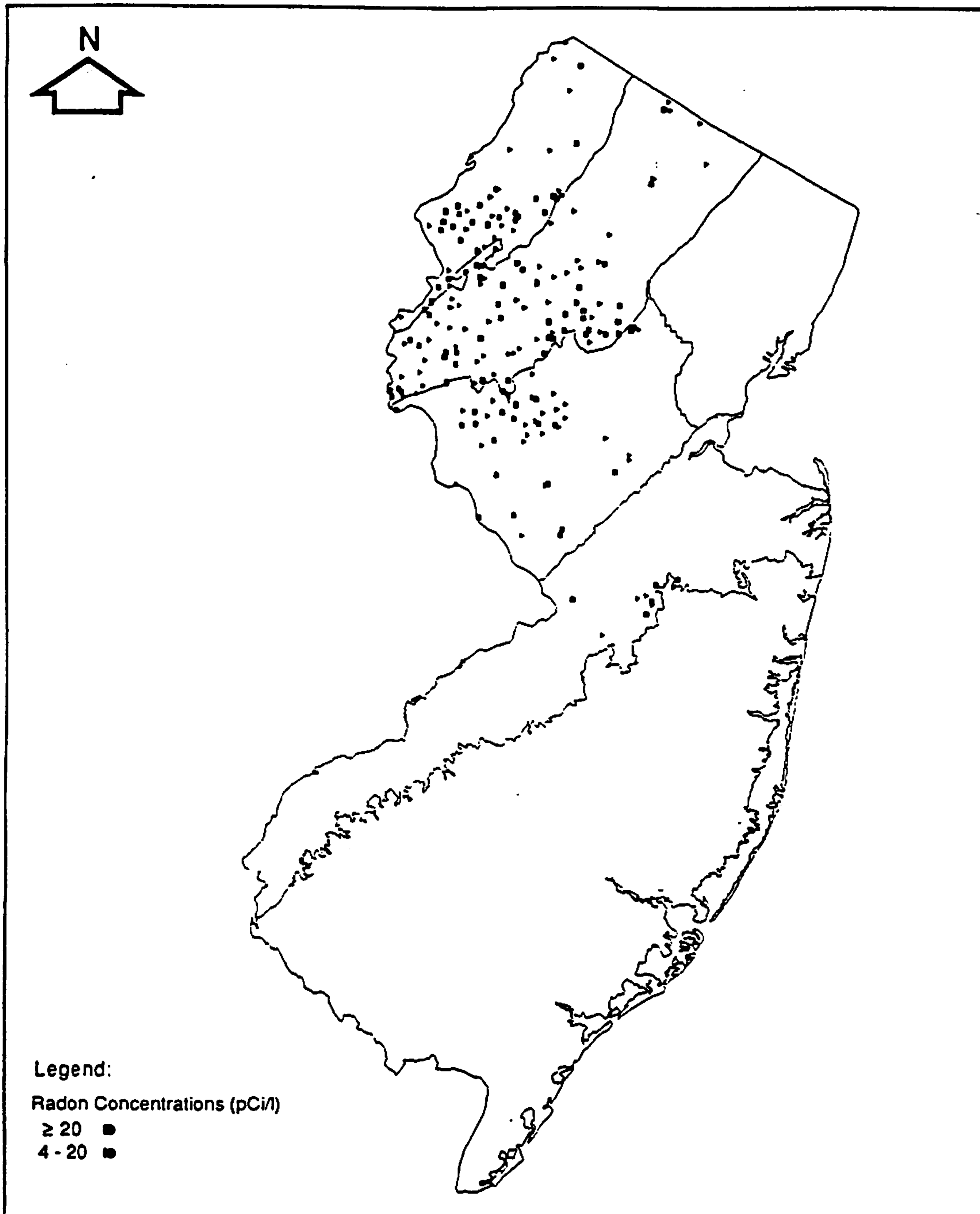

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Figure 2

Location of Level II Homes Selected for Radon/Progeny Sampling

Statewide Scientific Study of Radon

LEVEL II SEASONAL ANALYSIS
AVERAGE RADON RATIO VS TEMPERATURE BREAK

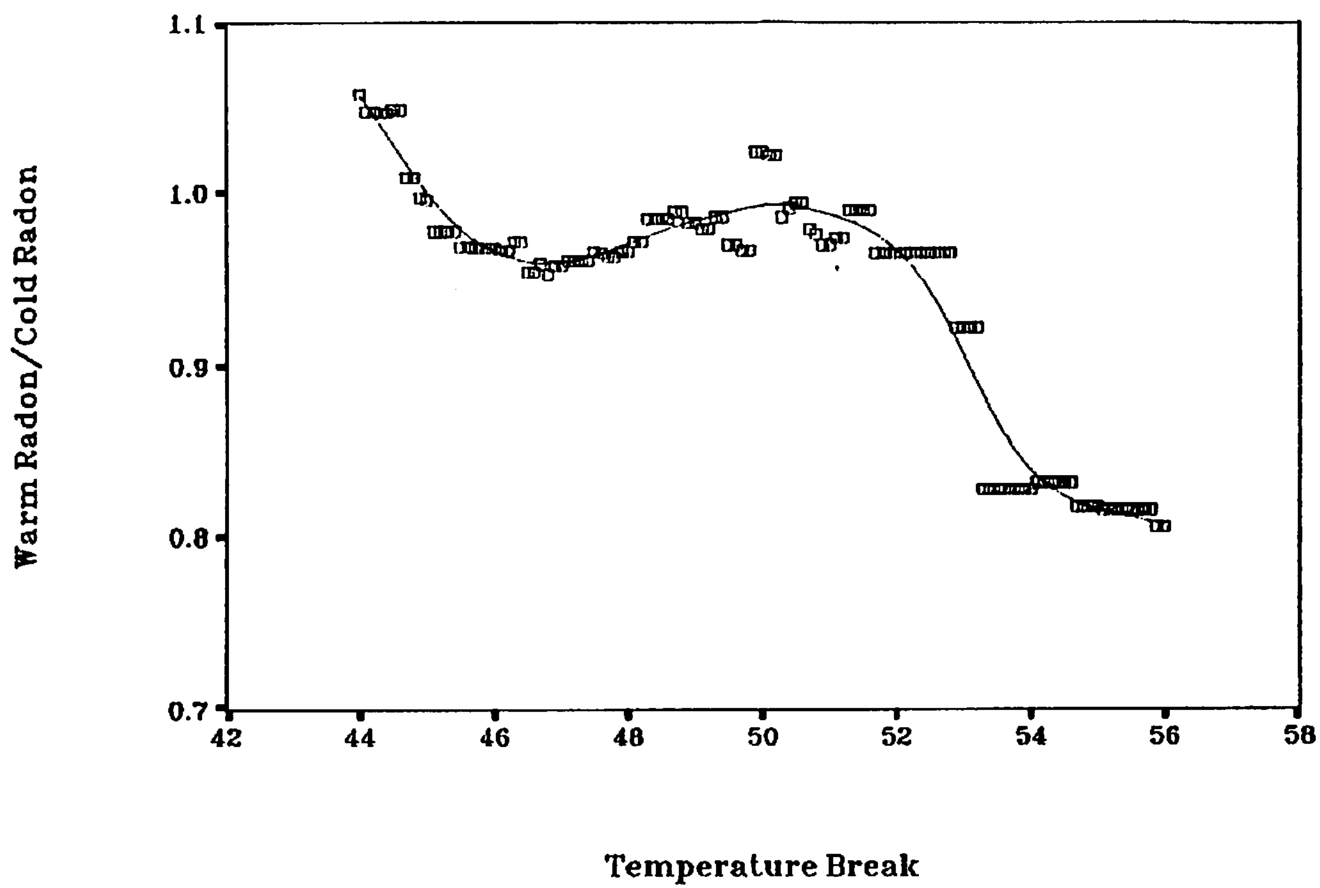

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Figure 3. Seasonal Break Temperature

TABLE 1. LEVEL II SAMPLING DISTRIBUTION BY PROVINCE AND HOUSE TYPE

PROVINCE	SUBSTRUCTURE: BASEMENT, NO CRAWLSPACE — HEAT DISTRIBUTION: FORCED AIR (CASES)	HOT WATER (CASES)	ELECTRIC (CASES)	OTHER (CASES)	SUBSTRUCTURE: CRAWLSPACE, NO BASEMENT — HEAT DISTRIBUTION: FORCED AIR (CASES)	OTHER (CASES)
HIGHLANDS	12	43	9	1		1
VALLEY AND RIDGE	5	18	5	1	1	
SOUTHERN PIEDMONT	12	18	3			
INNER COASTAL PLAIN	3	3	1			
OUTER COASTAL PLAIN		1				
Total	32	83	18	2	1	1

PROVINCE	SUBSTRUCTURE: COMBINATION BASEMENT AND CRAWLSPACE — HEAT DISTRIBUTION: FORCED AIR (CASES)	HOT WATER (CASES)	ELECTRIC (CASES)	OTHER (CASES)	SUBSTRUCTURE: FULL SLAB — HEAT: HOT WATER (CASES)
HIGHLANDS	7	19	1	3	
VALLEY AND RIDGE	1	11	3		1
SOUTHERN PIEDMONT	2	8	1		
INNER COASTAL PLAIN		1			
OUTER COASTAL PLAIN					
Total	10	39	5	3	1

PROVINCE	SUBSTRUCTURE: SEMI-BASEMENT — HEAT DISTRIBUTION: HOT WATER (CASES)	ELECTRIC (CASES)	OTHER (CASES)	TOTAL CASES
HIGHLANDS		1	1	98
VALLEY AND RIDGE	2	1		49
SOUTHERN PIEDMONT				44
INNER COASTAL PLAIN				8
OUTER COASTAL PLAIN				1
Total	2	2	1	200

Table 2
Average Radon and Working Level Results[a]
LEVEL II Sampling

		Round 2				Round 3			
		Lowest Level		Second Lowest Level		Lowest Level		Second Lowest Level	
		Radon (pCi/l)	Working Level (WL)	Radon (pCi/l)	Working Level (WL)	Radon (pCi/l)	Working Level (WL)	Radon (pCi/l)	Working Level (WL)
Basement	Forced Air or Door Upst. Open	22.8 (72)	0.077 (62)	10.4 (73)	0.041 (59)	19.7 (56)	0.069 (49)	7.6 (56)	0.025 (42)
	Hot water/steam or Electric	24.9 (115)	0.086 (99)	7.4 (114)	0.024 (106)	23.0 (95)	0.084 (87)	5.8 (96)	0.022 (81)
	Other	16.9 (4)	0.053 (4)	5.2 (4)	0.023 (4)	28.3 (2)	0.129 (2)	6.0 (2)	0.029 (2)
	Total	23.9 (191)	0.082 (165)	8.5 (191)	0.030 (169)	21.9 (153)	0.079 (138)	6.5 (154)	0.023 (125)
Non-Basement	Forced Air or Door Upst. Open	11.0 (1)	———	11.1 (1)	0.038 (1)	13.0 (1)	0.030 (1)	11.8 (1)	
	Hot water/steam or Electric	14.1 (5)	0.070 (5)	6.2 (5)	0.018 (4)	22.3 (4)	0.064 (4)	7.0 (4)	0.037 (3)
	Other	14.1 (2)	0.053 (2)	9.4 (2)	0.043 (2)	19.6 (2)	0.084 (2)	18.2 (2)	0.085 (2)
	Total	13.7 (8)	0.065 (7)	7.6 (8)	0.028 (7)	20.2 (7)	0.065(7)	10.9 (7)	0.056 (5)
									(340)

[a] Values in parentheses are the number of samples.

TABLE 3
INTER-FLOOR RADON RATIOS AND EQUILBRIUMS
FOR HOUSE TYPOLOGY GROUPINGS

House Type	Working Level/Radon Equilibrium Ratios*			Inter-Floor Radon Ratios*
	Basement	1st Floor	2nd Floor	Second level/lowest level
Basement House: Forced Air (or Door Open)	0.36 (108)	0.41 (98)		0.49 (126)
Basement House: Hot Water/Steam or Electric	0.37 (184)	0.42 (185)		0.32 (209)
Basement House: Other	0.38 (6)	0.46 (6)		0.39 (6)
Slab,Crawl,Semi-Base House Forced Air or Door Open		0.23 (1)	0.34 (1)	0.96 (2)
Slab,Crawl,Semi-Base House Hot Water/Steam or Electric		0.39 (9)	0.43 (7)	0.54 (8)
Slab,Crawl,Semi-Base House Other		0.49 (4)	0.54 (4)	0.82 (4)

* Values in parentheses are the number of samples.

TABLE 4

LEVEL II COEFFICIENTS FOR BASIC HOUSE TYPOLOGY[a,b]

HOUSE TYPE		NON-WINTER			WINTER			NON-WINTER:WINTER RADON	
SUBSTRUCTURE	HEATING SYSTEM	1ST FL:BASE RADON	BASEMENT EQUILIBRIUM[d]	1ST FLOOR EQUILIBRIUM[d]	1ST FL:BASE RADON	BASEMENT EQUILIBRIUM[d]	1ST FLOOR EQUILIBRIUM[d]	BASEMENT	1ST FLOOR
Basement	Forced air	0.45 ± 0.28 (31)	0.46 ± 0.24 (27)	0.48 ± 0.27 (20)	0.51 ± 0.27 (69)	0.34 ± 0.12 (57)	0.41 ± 0.18 (57)	0.97 ± 0.82 (30)	0.80 ± 0.98 (31)
	Hot water/ electric	0.27 ± 0.22 (55)	0.40 ± 0.15 (51)	0.50 ± 0.20 (48)	0.33 ± 0.24 (102)	0.37 ± 0.23 (87)	0.38 ± 0.17 (87)	0.89 ± 0.43 (48)	0.75 ± 0.54 (48)
	Other	0.11 (1)	0.32 (1)	0.71 (1)	0.45 ± 0.34 (4)	0.39 ± 0.14 (4)	0.42 ± 0.08 (4)	0.82 (1)	0.63 (1)
Slab-on grade/ crawlspace/ semi-basement	Forced air	——	——	0.32 (c)[c]	——	——	0.23 (1)	——	0.54 (c)[c]
	Hot water/ electric	——	——	0.42 (c)[c]	——	——	0.30 ± 0.12 (5)	——	0.49 (1)
	Other	——	——	0.36 (c)[c]	——	——	0.44 ± 0.34 (2)	——	0.45 (c)[c]

Notes: [a] Errors given are plus or minus one standard deviation
[b] Numbers in parenthesis indicate sample size
[c] (c) indicates number calculated from other ratios
[d] Equilibrium = 100 x WL / Radon