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A COMPARISON OF EPA SCREENING MEASUREMENTS AND ANNUAL ^{222}Rn CONCENTRATIONS IN STATEWIDE SURVEYS

D. J. Steck
Physics Department, St. John's University, Collegeville, MN 56321

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INTRODUCTION

ELEVATED ^{222}Rn concentrations have been found indoors in widely separated regions of the U.S. Surveys have indicated that some large areas of the U.S. may contain a substantial number of homes with Rn concentrations that warrant remedial action (Nazaroff and Nero 1988). In an attempt to assess both nationwide and statewide distributions of indoor Rn, the U.S. EPA has been assisting states in conducting Rn surveys during the last 2 y. These surveys sampled the 2-d-average Rn concentrations in the lowest liveable level of individual houses. Since Rn-related health risks depend on long-term exposure, it is vital to know the relationship between these short-term measurements and long-term Rn concentrations in the living spaces of those homes.

Previous research has shown significant variation between several types of short-term Rn measurements and longer-term concentrations (Hans et al. 1985; Ronca-Battista et al. 1986; Ronca-Battista and Magno 1988). Many factors may contribute to the temporal and geographic variation in Rn entry and retention in houses. These factors may differ from one region of the country to another and over time. Thus, it is important that comparisons of different measurement protocols include samples drawn from a broad range of Rn sources, housing types, climates, and lifestyles. Variations in indoor Rn make it difficult to assess an individual's long-term exposure based on sampling surveys that are quite limited in time and number. In particular, the current assumption that screening surveys that consist of a 2-d, closed-house, winter Rn measurement in a basement represent the "worst case" may not be accurate in all regions. To date, little information has been published comparing statewide screening surveys with yearly average Rn concentrations in the living spaces. The present work compares the results of short-term and long-term statewide surveys conducted in a region that contains average-strength Rn sources, energy-efficient housing, and both extremely cold and hot seasons.

MATERIALS AND METHODS

The important characteristics of the measurement protocols discussed below are summarized in Table 1.

Upper Midwest survey

Annual-average airborne Rn concentrations were measured between 1983 and 1988 in 250 houses using α-track detectors. Two hundred fifteen houses were located in Minnesota, 25 in Northern Wisconsin, and 10 in the Upper Peninsula of Michigan (see Fig. 1). Houses were clustered in town-sized areas (1 to 100 km^2), giving a sampling density of approximately 1 to 5 detectors km^{-2}. The towns were selected to represent a wide range of surface geologies, physical environments, and housing types. This survey will be called Upper Midwest survey (Steck 1987).

The α-track detectors were placed on the two lowest liveable levels of each house for periods ranging from 8 to 12 mo. Ninety-five percent of the houses had below-grade liveable spaces, usually basements. Seventy percent of those below-grade spaces were inhabited for an average of 20% of the total time spent indoors. Approximately 50 homes were monitored during the summer months (June–September) and the winter months (October–May) to estimate the summer-to-winter indoor ratio. This was done to estimate yearly average Rn in houses that were sampled only during the heating season. The Rn concentrations in houses that were sampled only in the winter have been corrected to reflect the observed seasonal variation in the levels of the average house (Steck 1986). From these seasonally adjusted annual-average Rn concentrations, an estimate of the Rn concentration in the occupied spaces of a house (henceforth called Annual Rn) was calculated in the following manner. The Annual Rn is either: (a) the average of all above-grade concentrations, or (b) if the below-grade level was used as a living space, the sum of 80% of the above-grade concentration and 20% of the below-grade concentration.

Table 1. Comparison of measurement protocols.

Survey	Sampling Time	Location	Condition	Detector	Density (detectors km^{-2})
Upper Midwest	8–12 mo	Lowest two levels	Normal	Alpha Track	2
EPAMN EPAWI	2 d	Lowest level	Closed house	Charcoal Canister	10^{-3} to 4
Joint	2 d	Lowest two levels	Normal and Closed house	Alpha Track and Canister	NA

Minnesota state survey (EPAMN)

The Minnesota Department of Health conducted an EPA-designed survey (EPAMN) of 1001 houses during the 1987–88 heating season (December–April) (Tate 1988). The survey protocol required that indoor airborne Rn concentrations be measured by charcoal canisters left in place for 2 d in the lowest level of the house. Measurements taken with this protocol will be called Screen Rn. Houses were selected randomly within regions of the state. The number of houses sampled in each county or region was selected on the basis of population and predicted geologic potential for elevated Rn sources. The sampling density ranges from 10^{-3} to 4 canisters km^{-2}.

Joint survey

In an attempt to compare the results from two different Rn measurement protocols applied in the same house, the Minnesota Department of Health surveyed 76 houses that had been previously measured in the Upper Midwest survey. These houses will be called Joint survey. The same EPA protocol was followed in contacting and measuring these houses as was used in the EPAMN survey. In an attempt to understand detailed differences between Screen Rn and Annual Rn results, five living spaces were monitored during the canister measurement with a continuous Rn monitor.* Monthly α-track measurements were made in six living spaces during the period October 1987 to October 1988.

Wisconsin state survey (EPAWI)

The Wisconsin Department of Health and Social Services surveyed 1191 houses during the 1986–87 heating

* Pylon model AB5 + PRD − 1, Pylon Electronic Development Company, Ottawa, Ontario, Canada.

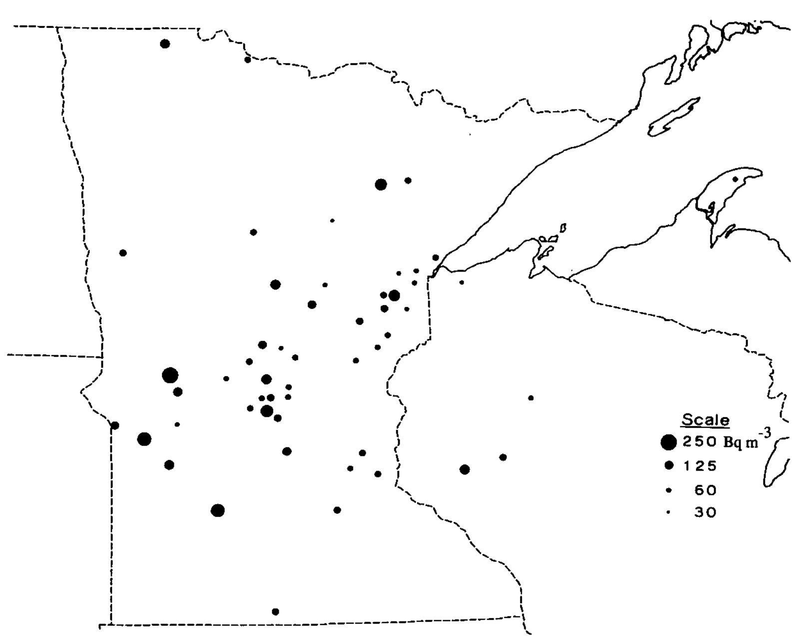

Fig. 1. Geographic distribution of Annual Rn from the Upper Midwest survey. Circle radii are scaled to the median Annual Rn concentration in each town surveyed.

season (December–April), following a protocol designed by the U.S. EPA (McDonnell 1987). Two hundred thirty-two of these houses were located in the same geographic area as the 25 Wisconsin houses in the Upper Midwest survey. These houses will be designated the EPAWI survey, and the measurements also will be called Screen Rn.

RESULTS

A statistical summary of the survey distributions is given in Table 2. All survey distributions appear to be best described by log-normal distributions. Thus, geometric averages and standard deviations will be used to compare surveys. Survey medians exceed the estimated median for the U.S. as a whole (Nazaroff and Nero 1988). See Fig. 2 for an illustration of the Upper Midwest and EPAMN survey distributions.

Upper Midwest survey

The living spaces of the average home in the area studied in this survey contained approximately three times the Rn concentration estimated to be in the average U.S. home (Steck 1987; Nazaroff and Nero 1988). The median yearly-average Rn concentration in the living spaces in our study was 100 Bq m^{-3} as compared to the estimated national median of 33 Bq m^{-3} (Nazaroff and Nero 1988). The deviation of our distribution is smaller than the deviation of the estimated national distribution and some other state-sized distributions (Nero et al. 1986). Approximately 30% of our homes had Annual Rn in excess of 150 Bq m^{-3}(4 pCi L^{-1}) as compared to an estimated 7% nationwide. The indoor Rn appears to be more uniformly distributed in the Upper Midwest than in some other regions or in the nation as a whole. Although significant geographic variation was observed between town-sized clusters (100 km^2), no significant variation was evident between randomly selected larger regions within our area (see Fig. 1). Seasonal and compartmental variations within a house differ from those in other parts of the U.S. (Fleischer and Turner 1984; Hess et al. 1985; Wilkening and Wicke 1986). In the average Minnesota home studied, the median basement Rn concentration was 140 Bq m^{-3} and was essentially constant year-round. The median value of the first floor Rn concentration was 70% of the basement concentration during the heating season (October–May) and 50% during the summer (June–September) (Steck 1986). An *a priori* estimate for the ratio expected between Annual Rn and heating season Rn measurements in the basement can be calculated from the medians of the seasonal distributions and the fraction of homes with basement living spaces. The calculated *a priori* estimate for this ratio is 0.7 $\overset{\times}{\div}$ 1.1. The monthly Rn concentrations at six sites (Table 3) suggest that, for some houses in our area, spring and fall may be the periods of highest Rn, with lower concentrations in both mid-winter and mid-summer. Figure 3 illustrates this behavior in two houses. While additional research is needed to confirm the extent of this seasonal behavior, the mid-winter suppression of Rn and the spring-fall enhancement may be related to changes in the soil's Rn emanation and transport properties. Both seasons are characterized by significant precipitation and frostline motion. Frost usually penetrates several meters deep in Minnesota.

Table 2. Comparison of survey distribution.

Survey:	Sample Size	Arithmetic Average (Bq m^{-3})	Geometric Average (Bq m^{-3})
Upper Midwest (Minnesota)	215	141	104 $\overset{\times}{\div}$ 1.1
	(185)[a]	(204)	(144 $\overset{\times}{\div}$ 1.1)
EPAMN	1001	178 [b]	126 $\overset{\times}{\div}$ 1.03
Joint			
Annual	76	148	96 $\overset{\times}{\div}$ 1.1
	(72)[a]	(203)	(137 $\overset{\times}{\div}$ 1.1)
Screen	76	192	118 $\overset{\times}{\div}$ 1.1
Upper Midwest (Wisconsin)	25	104	81 $\overset{\times}{\div}$ 1.1
	(24)[a]	(155)	(126 $\overset{\times}{\div}$ 1.2)
EPAWI	232	107 [b]	74 $\overset{\times}{\div}$ 1.1

a Statistics for the lowest livable level of houses sampled in the Upper Midwest survey are shown in parentheses.
b Population-weighted averages calculated by the EPA.

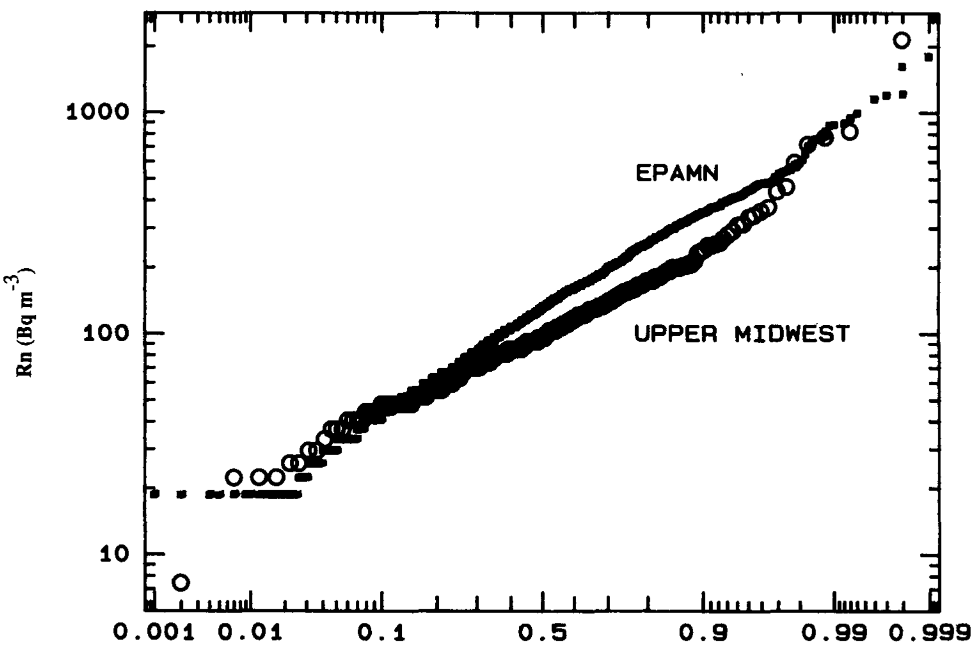

Fig. 2. Statewide survey probability distributions. Log-normal distributions would appear as straight lines on such plots. The EPAMN survey distribution is plotted as small squares. The Upper Midwest survey distribution is plotted as large circles.

Table 3. Monthly Rn concentrations.

	Site:					
Month:	111A	111B	113A	113B	344A	344B
Oct 87	85	130	93	300	1300 [b]	1900 [b]
Nov 87	185	520	130	89	1800 [c]	3000 [c]
Dec 87	220	85	19	33	1300 [c]	2200 [c]
Jan 88	180	19	<18	170	1200 [c]	2200 [c]
Feb 88	100	41	<18	22	960 [c]	190 [c]
Mar 88	89	110	26	<18	3400 [c]	6000 [c]
Apr 88	220	220	11	11	2400 [b]	2100 [b]
May 88	300	85	<18	85	360 [b]	2300 [b]
Jun 88	150	110	19	56	410 [b]	740 [b]
Jul 88	120	150	<18	<18	52 [b]	93 [b]
Aug 88	67	300	<18	37	89 [b]	260 [b]
Sep 88	180	330	81	180	370 [b]	220 [b]
Annual Ave.	160	170	36	83	2000 [d]	3700 [d]

a typical uncertainty in monthly measurements is ± 20%; lower level of detection is 18 Bq m^{-3}
b mitigation system on
c mitigation system off
d pre-mitigation (1986-1987) annual average

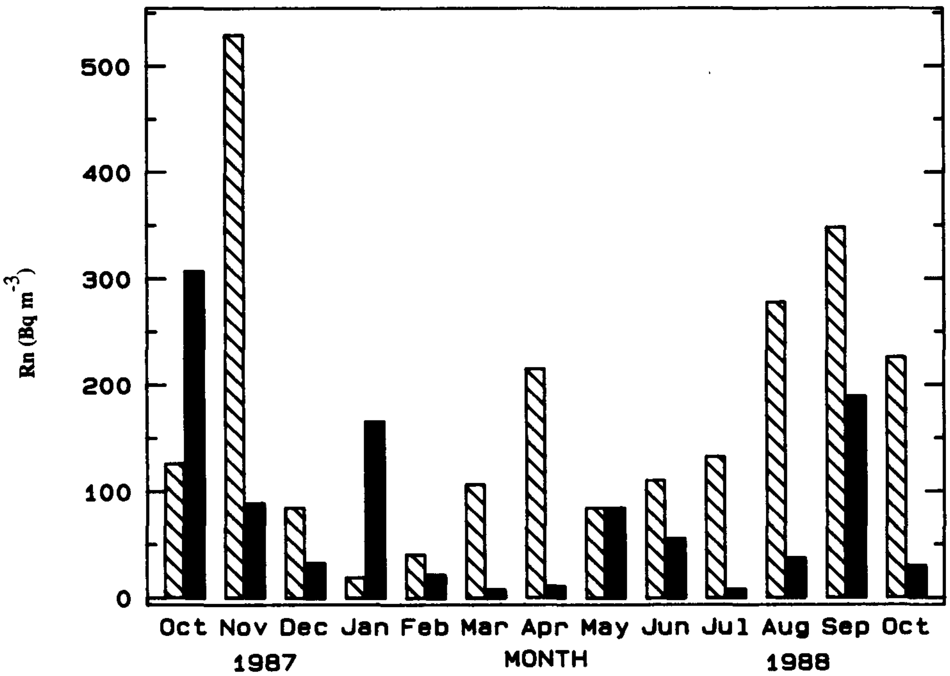

Fig. 3. Monthly Rn concentrations in two houses. The solid bars represent site 113B, and the horizontal lined bars represent site 111B. The houses are located within 1 km of each other.

EPAMN, EPAWI surveys

In Minnesota, the ratio of the geometric average Annual Rn from the Upper Midwest survey to the geometric average Screen Rn from the EPAMN survey is 0.82 $\overset{\times}{\div}$ 1.1 (see Table 2). The geometric standard deviations of the two surveys are also comparable, as Fig. 2 illustrates. In Wisconsin, the ratio of Annual Rn to Screen Rn is 1.1 $\overset{\times}{\div}$ 1.15. Thus, for both states as a whole, the Screen Rn median provides a reasonable estimate of the median Rn concentrations in the living spaces. This result is in sharp contrast with the current "conventional wisdom" that Screen Rn surveys would produce an exaggerated or "worst case" estimate for the Annual Rn (Ronca-Battista et al. 1988; McDonnell 1987; Tate 1988). The small difference between the ratios for Wisconsin and Minnesota may reflect either year-to-year variation or the poor geographical overlap and small sample size of the comparison groups in Wisconsin. The Minnesota ratio is in agreement with the *a priori* estimate based on the Upper Midwest survey.

Joint survey

The Annual Rn and Screen Rn distributions of the Joint survey have averages and deviations that are consistent with those of the Upper Midwest and EPAMN distributions, respectively. Figure 4 illustrates that the Annual Rn and Screen Rn measurements are well correlated ($p < 0.001$) in the Joint survey houses. The distribution of the ratio of the Annual Rn to Screen Rn in these houses is shown in Fig. 5. The distribution is approximately log-normal, with a geometric average of 0.82 $\overset{\times}{\div}$ 1.07 and a geometric standard deviation of 1.76. This average ratio is comparable with the ratio of the averages from the Upper Midwest and EPAMN surveys.

Concurrent Rn measurements were made at six of the Joint survey sites in order to examine the relationship between short- and long-term measurement protocols. The results, listed in Table 4, suggest that none of the short-term measurements (hourly, daily, monthly) are particularly reliable in accurately predicting the Annual Rn concentration. Monthly Rn measurements at six sites, listed in Table 3, suggest that significant temporal Rn variations of duration longer than a month may cause the failure of the short-term measures to accurately predict the yearly average Rn concentration. The consistent difference between the continuous Rn monitor and the charcoal canister measurements may result from the difference between the canisters' actual exposure conditions, i.e., lower temperatures (10° to 15°C) and relative humidities (10% to 30%) and those used to establish the canisters' calibration.[†‡]

† Ronca-Battista, M.; Gray, D. The influence of changing conditions on measurements of Rn concentrations with charcoal adsorption techniques. Presented at the Health Physics Society Meeting, July 1987, Salt Lake City, UT.

‡ Personal communication (1988). S. Windham, U.S. Environmental Protection Agency, Montgomery, AL.

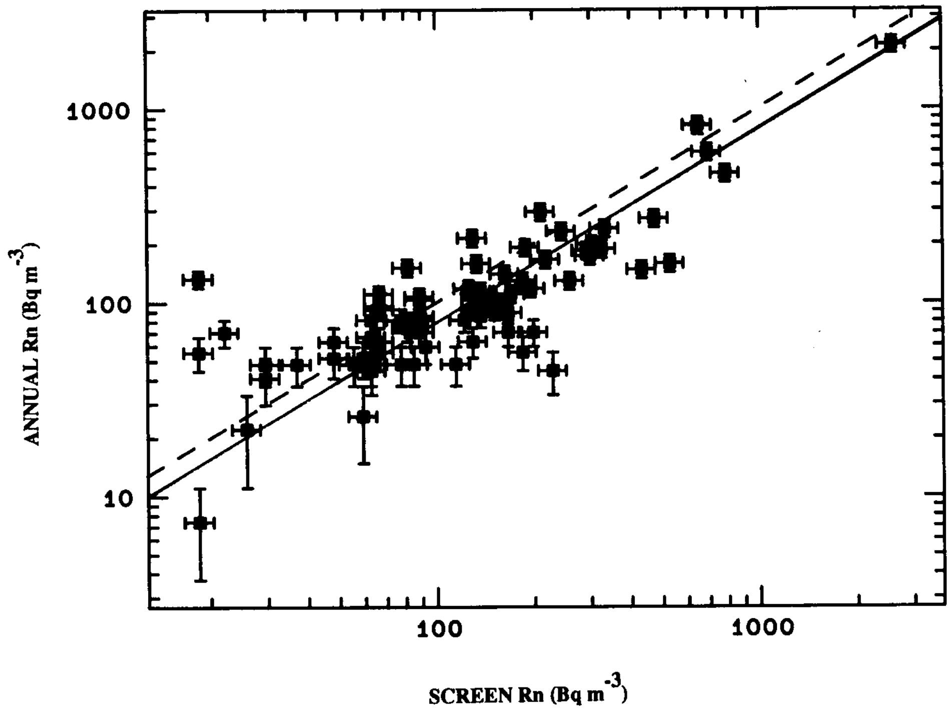

Fig. 4. A comparison of the Annual Rn measurements and Screen measurements for 76 houses included in the Joint survey. The dashed line shows equal values, while the solid line represents a linear regression fit ($p < 0.001$).

DISCUSSION

In the statewide surveys, the median Screen Rn value is representative of the median Annual Rn concentration in large and diverse samples of houses. In the EPAMN survey, 46% of the houses had Screen Rn measurements above 150 Bq m^{-3} threshold. The results of the Joint survey suggest that, in Minnesota, the probability is 0.6 that a Screen Rn measurement above the threshold represents an Annual Rn concentration above the threshold. The probability is 0.9 that a Screen Rn measurement below the threshold represents an Annual Rn concentration be-

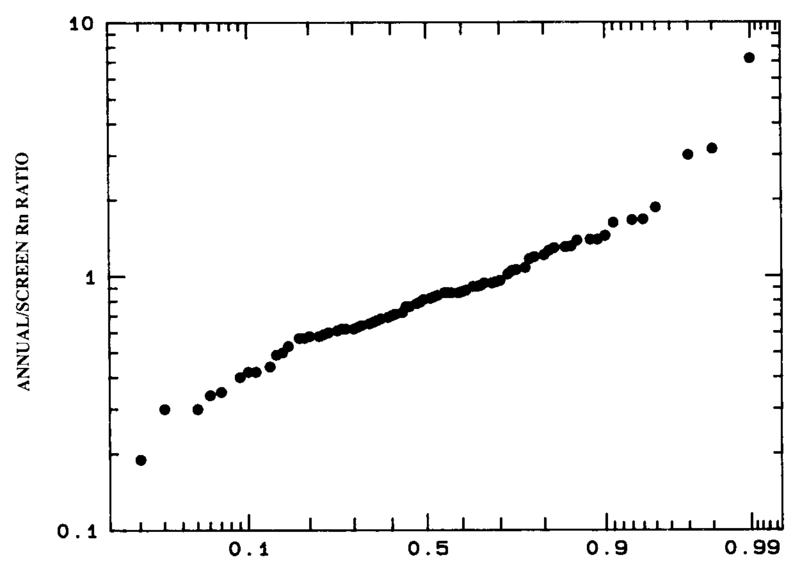

Fig. 5. The probability distribution for the ratio of Annual Rn to Screen Rn measurements in the Joint survey. The geometric mean is 0.82 $\overset{\times}{\div}$ 1.07 with a geometric standard deviation of 1.76.

Table 4. Comparison of short- and long-term measurements.

Measurement ($Bq\ m^{-3}$)	Site: 111A	111B	113B	113S	1110B	344B
Continuous Monitor 2-d average	70 ± 7	85 ± 7	18 ± 4	11 ± 4	163 ± 15	NA
Screen[a] 2 d	166	174	22	18	218	2590
Alpha-track (March–April)	89 ± 22	107 ± 22	11 ± 7	26	170 ± 30	5920 ± 740
Alpha-track (yearly average)	160 ± 22[b]	174 ± 22[b]	86 ± 11[b]	86 ± 11[b]	178 ± 22[c]	3700 ± 550[c]

[a] The EPA estimates uncertainties of 10% but reports to the nearest 4 $Bq\ m^{-3}$.
[b] 1987–1988.
[c] 1986–1987.

low the threshold. If these probabilities are applied to the EPAMN survey results, the estimate for the percentage of homes with an Annual Rn exceeding 150 $Bq\ m^{-3}$ is 32%. In the Upper Midwest survey, 30% of the houses actually had Annual Rn concentrations in excess of the threshold. Therefore, both measurement protocols produce similar distributions for statewide samples of houses.

Single Screen Rn measurements are not reliable predictors of Annual Rn concentrations in individual houses. As Fig. 5 shows, in nearly 30% of the houses Screen Rn results were different from Annual Rn results by more than a factor of 2. The 95% confidence interval for the ratio of Annual Rn to Screen Rn ranges from 0.26 to 2.5. Therefore, a Single Screen Rn measurement near the survey's median value, 126 $Bq\ m^{-3}$, indicates that the house would most likely have an Annual Rn concentration between 33 and 315 $Bq\ m^{-3}$. The 95% confidence interval in the Upper Midwest survey spans an almost identical interval, from 25 to 437 $Bq\ m^{-3}$ (Annual Rn). Thus, an average homeowner is unlikely to gain any more reliable information from a Single Screen Rn measurement than from what is already available from the Upper Midwest survey.

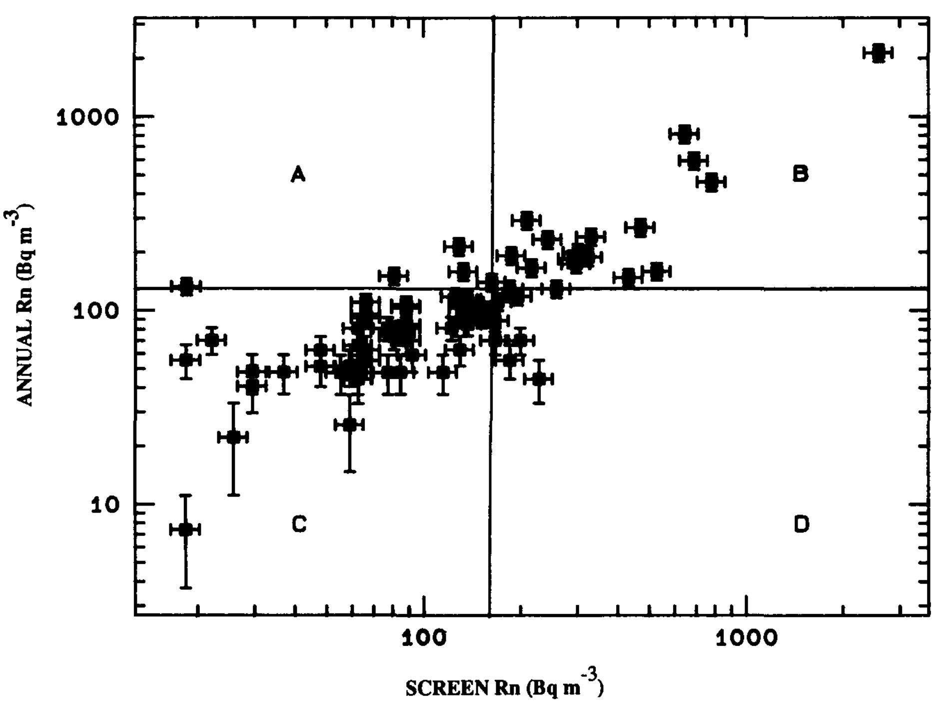

Fig. 6. The effects of applying a 150 $Bq\ m^{-3}$ threshold to interpret the screen Rn measurement. In the Joint survey, 20 homes had Annual Rn equal to or greater than 150 $Bq\ m^{-3}$ (Regions labeled A and B). Four of those houses had screen Rn results that were less than threshold (Region A: Screen-low failure zone). Twenty-eight homes had Annual Rn below 150 $Bq\ m^{-3}$ (Regions C and D). Eleven of those houses had Screen Rn measurements that were above threshold (Region D: Screen-high failure zone).

The interpretation of a Screen Rn measurement as suggested by the EPA frequently fails to accurately characterize the long-term Rn potential in individual homes (Ronca-Battista et al. 1988). As Fig. 6 shows, the application of a sharp 150 Bq m^{-3} (4 pCi L^{-1}) threshold on the Screen Rn measurement failed to detect 20% of the houses in which Annual Rn exceeded 150 Bq m^{-3} (Fig. 6: Region A, Screen-low failure). In addition, 11 of the 28 houses in which Screen Rn measurement exceeded 150 Bq m^{-3} had Annual Rn concentrations less than threshold (Fig. 6: Region D, Screen-high failure). In order to lower the Screen-low failure rate to 5%, the threshold would have to be lowered to 55 Bq m^{-3}. The Screen-high failure rate at that lowered threshold is 90%. The utility of Screen Rn measurements in identifying problem houses is dramatically decreased at this lowered threshold. Discounting the Screen Rn measurement by raising the "action" threshold is not appropriate in our area. This form of discounting, based on unofficial EPA estimates, was suggested in the Wisconsin Health Department report (McDonnell 1987). The report claimed that there was little likelihood that annual average Rn concentrations would exceed 150 Bq m^{-3} not only for screening measurements near 150 Bq m^{-3} but also for Screen Rn measurements up to 370 Bq m^{-3} and possibly up to 740 Bq m^{-3}(20 pCi L^{-1}). If those two higher thresholds are applied to the houses in the Joint survey, the Screen-low failure rate increases to 70% and 90%, respectively.

CONCLUSIONS

Short-term and long-term measurement protocols produced similar distributions for indoor Rn in statewide samples of diverse homes in the Upper Midwest. In Minnesota, the yearly-average Rn in the median home's living spaces is 80% of the median value of the statewide EPA screening survey. Thus, severe discounting of the median value of the screening results is not warranted in our area. The fraction of homes (30%) exceeding a 150 Bq m^{-3} threshold is approximately the same for both surveys if the EPAMN screening survey distribution is corrected for Screen-low and Screen-high failures.

A single EPA-protocol screening measurement has a significant chance of grossly underestimating or overestimating the yearly-average Rn concentration. Approximately 30% of the screening measurements in individual homes differed by more than a factor of 2 from the Annual Rn concentrations in the living spaces of those homes. A single short-term measurement is not likely to improve the accuracy of an assessment of the long-term Rn potential in an individual house beyond that already available from the statewide surveys. Significant temporal variations in indoor Rn concentrations in individual homes suggest that, at the present time, the only way to obtain an accurate assessment of the Rn potential in a home's living spaces is to make a measurement that spans several seasons.

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