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CORRELATION BETWEEN SHORT- AND LONG-TERM INDOOR RADON CONCENTRATIONS IN FLORIDA HOUSES

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ABSTRACT

In support of a possible performance standard for radon-resistant construction for the State of Florida, a protocol is needed to provide post-construction indoor radon measurement. In order to relate the results of short term compliance measurements to inferred annual average concentrations, a study is in progress in four regions of Florida known to have potential for elevated indoor radon. Eighty study homes in Polk, Alachua, Dade, and Leon Counties are being simultaneously monitored using long-term (quarterly and annual alpha track and long-term electret-ion chambers) and short-term monitors (open-face and barrier charcoal canister and short term electret-ion chambers). Electrets are deployed continuously and read over 1- and 2- week intervals. A subset of the houses are monitored using Pylon AB-5 continuous radon monitors. Houses were selected to be representative of typical Florida housing construction, with indoor radon concentration in the 2-20 pCi/L range. Data have been analyzed to isolate systematic seasonal variations and to derive confidence limits for predicted long-term (annual) averages from single or multiple short-term measurements according to the candidate protocols. For relevant combinations of device and sampling period, thresholds have been determined below which a single short-term measurement can provide specified confidence that the long-term average radon does not exceed 4 pCi/L. These results have been incorporated into draft building standards.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION AND BACKGROUND

Many studies have been conducted nationwide to determine the extent of elevated indoor radon concentrations in the U.S. The majority of these studies have employed short-term screening techniques, ranging from 1 to 90 days, using either open-faced or diffusion barrier charcoal canisters or alpha track detectors according to EPA protocols. Several factors prevent the development of a direct relationship between short-term measurements and long-term indoor radon concentrations. Primarily, radon concentrations have been shown to vary considerably with time; diurnal and seasonal variations are prominent in many houses and suggestions of weekly or other periods have been made. Some of these variations clearly correlate with house construction or occupant behavior patterns, such as heating, ventilation, and air-conditioning (HVAC) equipment and usage patterns, and the use of natural or mechanical ventilation during mild periods. However, no general means of computing the effect of these factors on resulting levels of indoor radon has been demonstrated. Added to this uncertainty due to fluctuations in actual radon concentrations is a smaller measurement uncertainty due to the radon measurement devices themselves. Each possible sampling periods. This paper reports preliminary results of a study of short-term and long-term variations in radon concentration in approximately 80 houses in the state of Florida. The study involves comparative sampling using the most common radon measurement technologies, and extends over a year to date. It is probably the most extensive study of its kind.

This project was commissioned by the state of Florida, in cooperation with the U.S. Environmental Protection Agency, as one portion of the Florida Radon Research Program (FRRP) (1). The purpose of the FRRP is to provide technical support for a statewide building standard for radon-resistant construction currently in the rulemaking process. The FRRP includes several projects targeted for technical support of specific standard elements. In this case the information provides technical background for a post-construction radon test specified as a performance element of the standard. Other projects address prescriptive elements of the code such as specifications on soil and fill characteristics, barrier or sealing techniques, HVAC systems, and active subslab depressurization systems.

The philosophy of the proposed performance standard can be briefly stated as a compromise between conflicting needs in the light of measurement uncertainty. First, as described below, estimates of long-term radon exposure from single short-term radon measurements are subject to measurement uncertainty. Second, the State needs to have confidence that a building actually will conform to the long-term radon concentration standard set [currently 4 pCi/L, considered as equivalent to 0.02 Working Level (WL)] by the State's Department of Health and Rehabilitative Services (DHRS); therefore, the needs of the State are best served either by a longer testing period or multiple measurements (either of which decreases measurement uncertainty) or by a conservative performance threshold (i.e., lower than the DHRS standard). Third, builders and developers need to minimize delays between construction and occupancy; therefore, the construction industry is best served by as short a test period as is feasible. The proposed standard was written to offer options in measurement device and sampling period to address both needs.

Thus the objectives of this study were conceived to provide the specific information required for the threshold levels incorporated in the codes. A goal of the project is to provide short-term (less than 2 weeks) measurement options which would provide adequate confidence that the long-term average indoor radon concentration does not exceed a specified level (in this case, 4 pCi/L). To achieve this goal, supporting objectives include documentation of the variability of indoor radon in typical houses in the state, characterization of this variability as measured by the most probable candidate radon measurement devices, separation of seasonal trends in radon concentrations in the state, and evaluation of regional climatic or construction factors which affect radon variability.

While most studies of this type have been performed outside the state of Florida, and many reflect sampling situations inappropriate for Florida housing (e.g. basement screening measurements), the major features of other research studies are corroborated by several studies which have been conducted within the state to identify factors which contribute to the variability of radon concentrations in Florida homes (2-4). These studies suggest that both short-term and seasonal variability can cause uncertainties of a factor of 2 or more in predicting long-term averages from single short-term measurements. These studies were limited, however, in devices used, region of the state, and number of houses studied. The current project was designed to supplement these earlier findings with a more definitive database.

EXPERIMENTAL METHOD

In order to provide an adequate statistical basis for the development of code recommendations for Florida, the current project includes the monitoring of approximately 80 houses for over a year using parallel measurements with different sampling devices. The selected study homes represent a sampling from four geographical regions of the state, specifically Alachua (Gainesville), Dade (Miami), Leon (Tallahassee), and Polk (Lakeland) Counties. The houses were selected based on the characteristics identified as most common to Florida housing stock such as:

- Single family, single level, slab on grade housing with forced air heating and cooling
- Low to moderate radon level - 2 to 20 pCi/L
- Unmitigated
- Air handler characteristics: split between houses with air handler inside building shell (closet) and outside shell (garage, attic)
- Natural ventilation; attempt to select about half of the houses which never use natural ventilation for cooling.

Five radon measurement devices were employed in the study for the purpose of identifying acceptable methodologies for estimating the annual average indoor radon concentration as well as developing appropriate predictive relationships between short-term measurements and long-term (annual) average concentrations. The devices selected and their deployment periods were:

- Alpha Track Detectors (ATD; quarterly and annual deployment)
- Short-Term (EPS) and Long-Term (EPL) Electret Passive Environmental Radon Monitors (deployed continuously; EPS read on a 1-week, 1-week, 2-week cycle; EPL read biweekly or monthly)
- Seven day passive diffusion barrier (CC7) and two day open face (CC2) charcoal canisters (deployed once per month in each house)
- Pylon AB-5 Continuous Radon Monitor with a Passive Radon Detector (deployed for month-long periods in subset of houses)

Each county researcher devised a sampling schedule based on the above guidelines and homeowner schedules. The homeowners were asked to keep their homes closed during the charcoal canister deployment period, but were allowed to ventilate their houses according to their normal habits otherwise. In each county the data were gathered, checked for consistency, and entered into a regional database. The regional databases were combined at least quarterly and a quality control (QC) survey was performed on the entire database. Quarterly data analyses were performed on the combined data set.

In order to assess seasonal trends, the quarterly boundaries were chosen to isolate the peak heating and cooling seasons as defined by historical mean outdoor temperatures in the state. The study began the first week of December 1989, with 40 houses per region. After completion of the first winter quarter at the end of February 1990, the study was increased to 80 houses total. Although some houses were lost during the study, at least three quarter's data was available for 71 houses by the end of November 1990, the last fall quarter incorporated in this paper. The study was scheduled to continue another calendar quarter until the beginning of March 1991.

RESULTS AND DISCUSSION

In order to assess the radon variability displayed in the study homes, the quarterly and annual arithmetic average radon concentration, standard deviation (STD), and coefficient of variation (COV -- defined as the ratio of the STD to the mean, expressed as a percentage) were calculated for each house and device from all observations made during the period. For the electret measurements, time-weighted averages were used due to the variable sampling interval. The distribution of radon concentrations among the houses is illustrated by the short-term electret quarterly average results presented in Figure 1.

In general, the sample population can be approximated by a log normal distribution as is typical of studies in larger, randomly selected populations. The observed quarterly average radon concentrations ranged from 0.5 to greater than 20 pCi/L with almost 49% falling between 2 and 4 pCi/L. Approximately 11.4% of the quarterly averages fell outside of the study screening boundaries of 2-20 pCi/L. The median radon concentration was 3.41 pCi/L, and the geometric mean and standard deviation were 3.61 pCi/L and 2.1, respectively. The arithmetic mean and standard deviation among the study houses were 4.71 and 3.95 pCi/L, respectively.

The error structure of the quarterly average radon measurements is depicted in Figure 2. In Figure 2, the standard deviations of the 7 or 14 day electret measurements in a quarter are plotted against the quarterly time weighted mean for the house. Within a significant degree of scatter, the standard deviation tends to vary linearly with the mean. This suggests that a variance stabilizing transformation (either performing a log transformation on the data or normalizing all concentrations to the long-term mean radon) is justified prior to any regression analysis of the time variability of the data.

Figure 3 shows the pairwise comparison of the quarterly average short-term electret radon concentrations to those measured by each of the other devices. In general, the devices agree quite well with each other. Regressions for the alpha track and long-term electret, which were continuously deployed with the short-term electret, show slopes near unity and R2 of about 0.95. The 7 and 2 day charcoal canisters, which were deployed 1 week or 2 days each month, showed somewhat greater scatter (R2 of 0.93 and 0.91, respectively). A more detailed description of the results of this investigation is beyond the scope of this paper.

SEASONAL VARIATION

One key issue in the variability of radon measurements is the seasonal component of this variability. In order to compare pooled seasonal trends across the study houses, the quarterly average radon concentration data were normalized by dividing each quarterly average by a longer-term average radon concentration measured by the same device in the same house. In order to include the houses which were added in the Spring of 1990, all data were normalized to the average of the last three quarters of the study (March - November 1990). For the 40 houses which were in the study an entire year, this three-quarter average was typically less than the annual mean (by an average ratio of 95%). To simplify data presentation, this investigation will focus on the outcome of the short-term electret data, although similar plots for the other devices have been developed.

Figure 4 shows the frequency distribution of these normalized quarterly average concentrations in the study house pool. An examination of the seasonal plots reveals several clear qualitative differences. Winter, as a rule, is found to be the season with highest relative radon, as in other parts of the country. Spring, as a rule, had the lowest radon, then summer and fall.

More striking is the range of normalized quarterly averages. The fall quarter data correlates best with the long-term average, with 50% of the normalized concentrations falling within ±0.07 of the mean value (1.094). By contrast, the winter quarter distribution has a "tail" of houses with higher relative concentrations, and the inner 50% of the normalized concentrations fall over the range from 0.98 to 1.61. Thus, given nothing but quarterly average radon, the most precise estimate of the annual average in a given house appears to be 96% of the fall quarter mean. The winter quarter mean had the largest range of variation relative to the long-term average radon. While most of the houses fell within ±0.30 of the long-term average, 25% of the houses had winter concentrations over 1.5 times the mean for the rest of the year, resulting in a broad distribution ranging from 0.65 to 2.1. Since the study was continued in the full set of over 70 houses last winter, it will be of special interest to see if this behavior is repeated.

VARIABILITY OF RADON MEASUREMENTS

As noted in Figure 2, the standard deviation of short-term E-Perm measurements during a calendar year was, on the average, proportional to the quarterly mean, with a constant of proportionality of 0.26. Thus the distribution of the coefficient of variation should cluster around 26%. The data for long- term E-Perms are similar. Figure 5 illustrates the distribution of quarterly COV value in the study houses by quarter. One might expect that the measurements taken during the summer cooling season would vary less than those for the other three seasons, in which occupants are more prone to ventilate their houses. There is indeed a slight tendency toward higher mean COVs for the spring and fall as compared to the summer, but the variability among houses in each season is greater than this seasonal effect. Therefore, the short-term variability in relative radon concentrations can be assumed to be of the same magnitude in all seasons.

If the distribution of normalized radon concentration is assumed uniform for the houses in the pool, the upper or lower confidence limits can be calculated for certain distributions. Using a lognormal model similar to Roessler, et al. (3), one-sided upper confidence levels were calculated for different combinations of device and sampling period. These thresholds, shown in Table 1, were incorporated into the proposed building standard currently in the rulemaking process. The values in Table 1 represent threshold levels for the device/time combinations listed at the left of each row and the confidence level shown in the column headings. In order to predict within the specified level that the long-term average radon concentration in a house will be less than 4 pCi/L, the results of a single measurement must be lower than the corresponding threshold level in Table 1. The model from which Table 1 was generated does not include seasonal effects, but was based on the three quarters of data available at the time of the calculation. Nonetheless, the table gives a good indication of the way our observed level of uncertainty can be incorporated into a conservative building standard.

CONCLUSIONS

This study has provided the most detailed database of which we are aware of the time variation of a significant number of occupied houses with moderately elevated radon concentrations. We see clear evidence of seasonal trends in radon concentrations from four regions of the state of Florida. Winter concentrations are typically higher than for the rest of the year, although the degree of elevation varies strongly over the pool of study houses. Fall quarterly average concentrations correlate best with the annual mean concentration. The pattern of variability suggests that models with logarithmic scaling can be used to estimate expected uncertainties in long-term average radon from short-term measurements.

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TABLE 1. THRESHOLD RADON CONCENTRATIONS FOR SINGLE RADON MEASUREMENT CORRESPONDING TO SEVERAL CONFIDENCE LEVELS OF FINDING LONG-TERM AVERAGE CONCENTRATIONS UNDER 4 pCi/L.

	CONFIDENCE LEVEL							
Device/Days*	0.5	0.6	0.7	0.75	0.8	0.85	0.9	0.95
CRM-1	4.18	3.87	3.56	3.39	3.22	3.03	2.81	2.51
CRM-7	4.02	3.81	3.61	3.50	3.39	3.25	3.10	2.88
CRM-14	4.00	3.83	3.65	3.56	3.46	3.35	3.21	3.02
EPS-7	4.22	3.85	3.49	3.31	3.11	2.90	2.66	2.33
EPS-14	4.23	3.88	3.54	3.37	3.18	2.98	2.74	2.43
EPL-14	4.39	3.88	3.39	3.15	2.90	2.63	2.33	1.95
EPL-28	4.32	3.91	3.51	3.31	3.10	2.87	2.60	2.26
CC2■	4.78	4.30	3.84	3.61	3.37	3.11	2.81	2.42
CC7	4.20	3.81	3.43	3.23	3.03	2.81	2.55	2.22

*Where CRM = Continuous Radon Monitor
EPS = Short-Term (High Sensitivity) Electret-Ion Chamber
EPL = Long-Term (Low Sensitivity) Electret-Ion Chamber
CC2 = Open Face ("2 day") Charcoal Canister
CC7 = Diffusion Barrier ("7 day") Charcoal Canister

CC2 values may be overestimated due to observed bias in study sample.

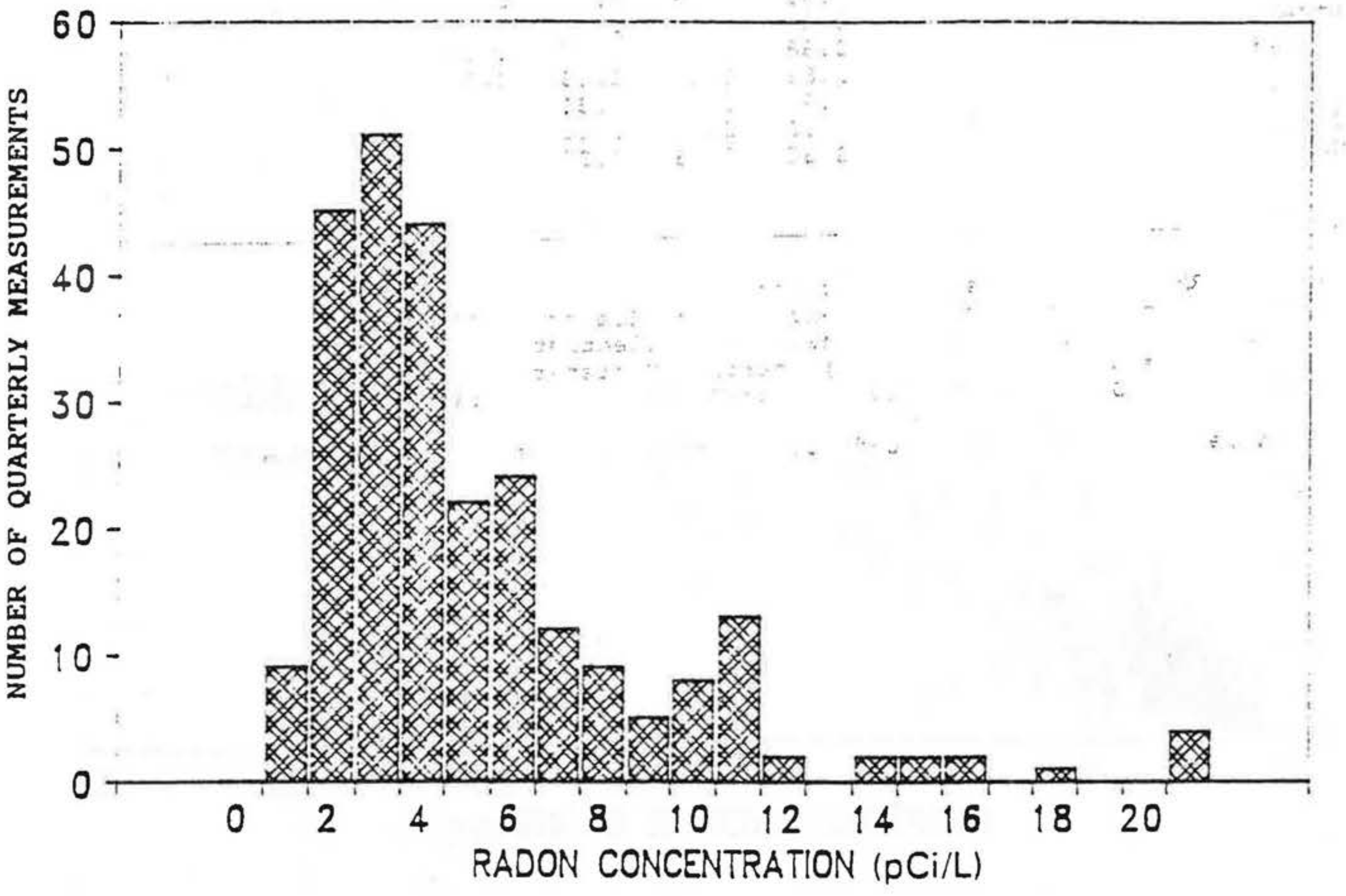

Figure 1. Distribution of quarterly average radon concentration in study houses.

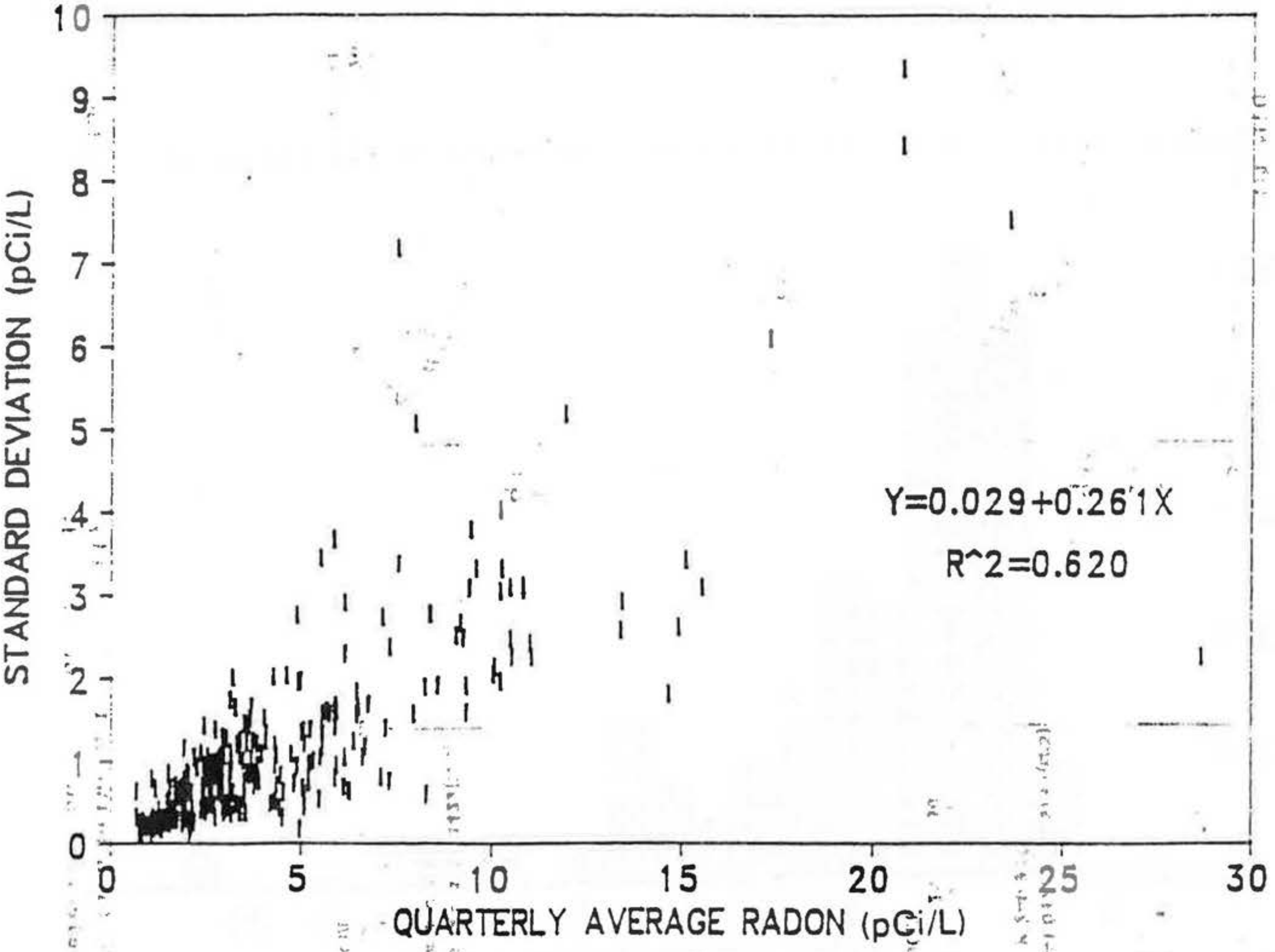

Figure 2. Standard deviation of individual short-term electret concentrations compared to quarterly mean concentration in study houses.

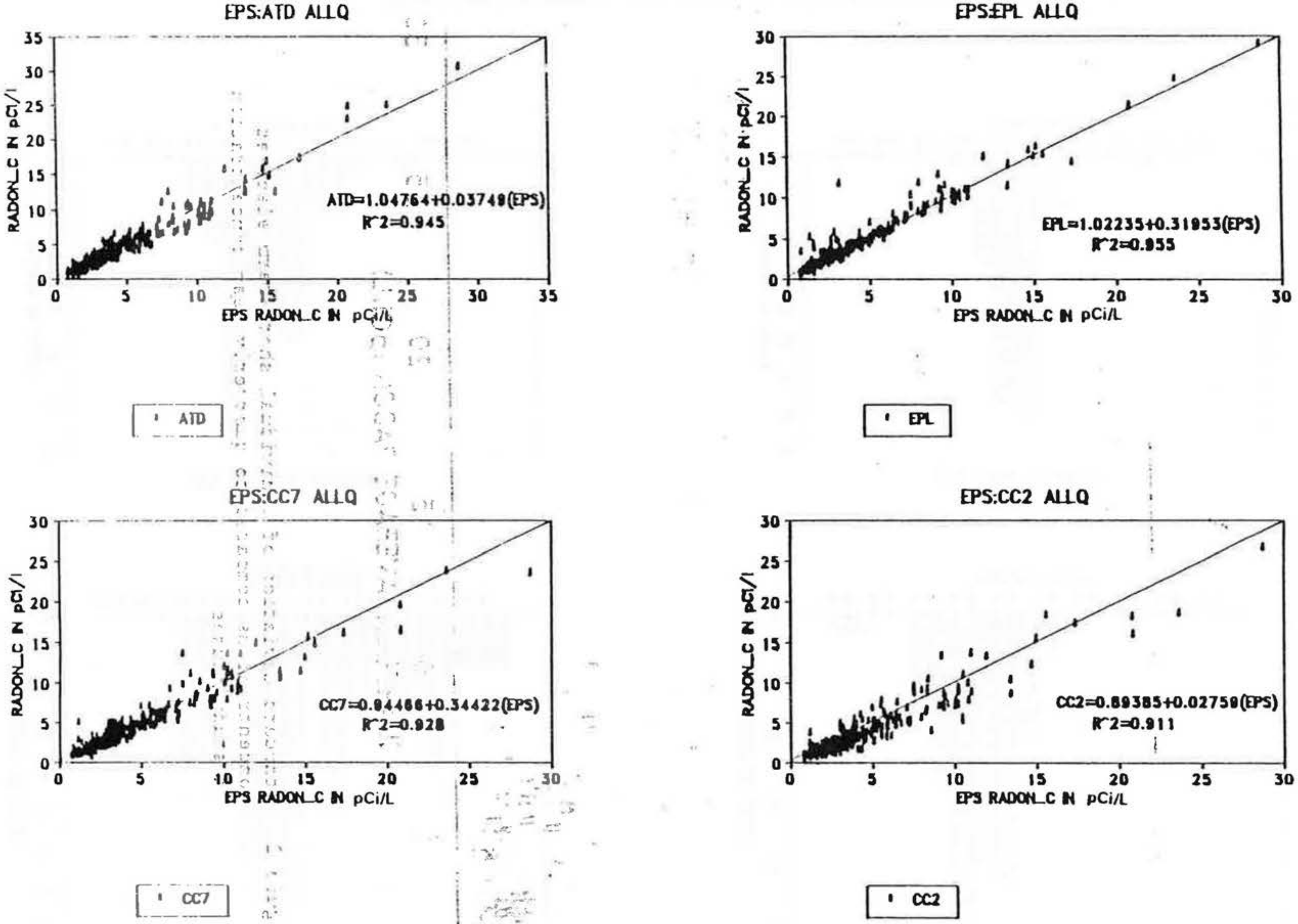

Figure 3. Linear regression between the quarterly average radon concentrations measured by short-term electret and each other device.

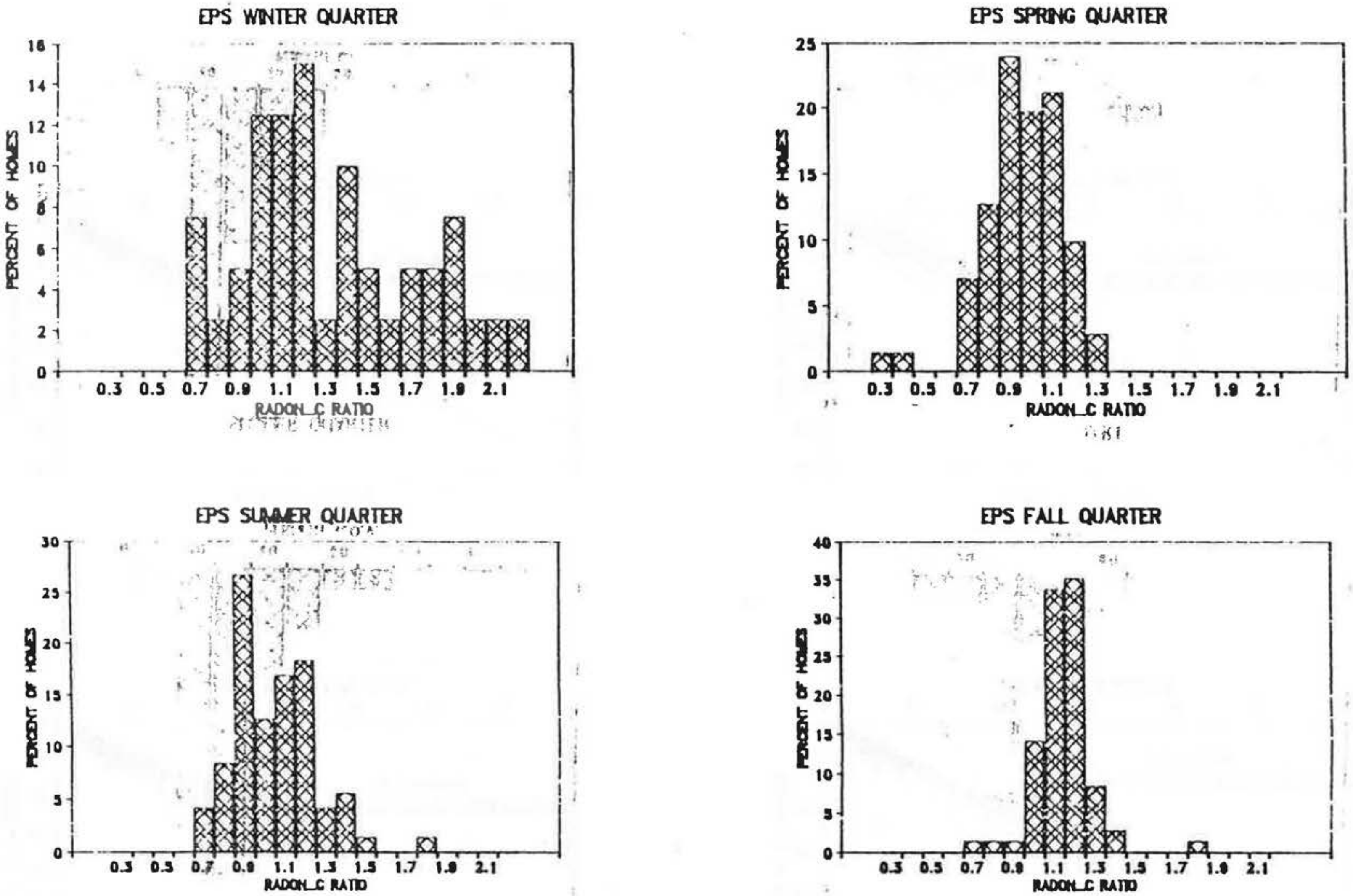

Figure 4. Relative frequency distribution of the quarterly average radon concentrations normalized to a 9-month average.

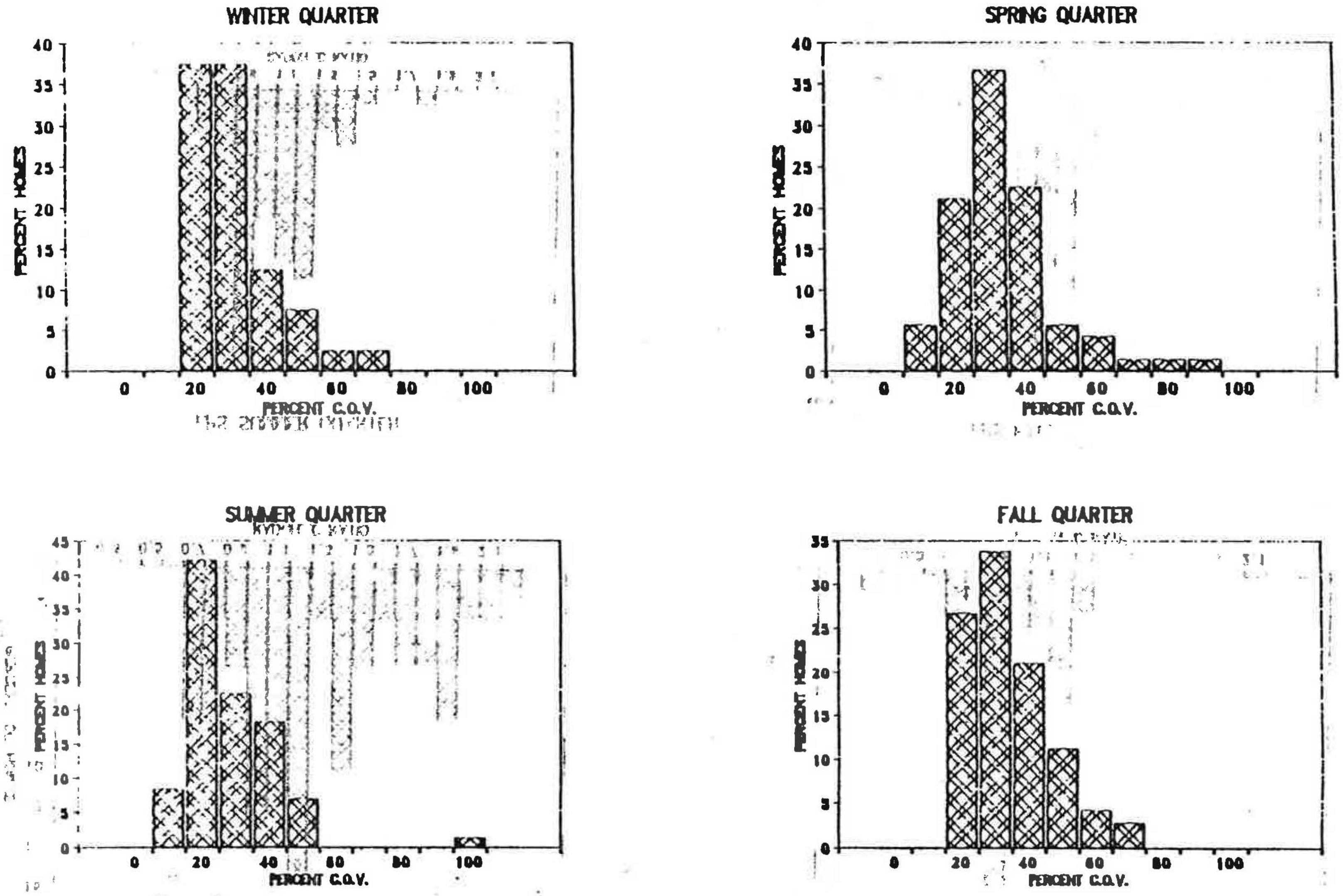

Figure 5. Distribution of quarterly coefficient of variance values from short-term electret data.