ALTERNATE PERFORMANCE STANDARD PROJECT - INTERPRETING THE POST-CONSTRUCTION TEST

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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 was conducted 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 one- and two-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 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.

PROJECT APPROACH

This paper describes the results of a project 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) (Sanchez, et al., 1990) 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 code elements. In this case the information provides technical background for a post-construction radon test specified as a performance element of the code. 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 (currently 4pCi/l, considered as equivalent to 0.02 WL) set by the 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 two 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, 4pCi/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 factors 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 consistent with the few studies within Florida to identify factors which contribute to the variability of radon concentrations in Florida homes (Nagda, et al. 1987; Roessler, et al. 1983, 1990). 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.

The short-term/long-term study was initiated in November 1989. Originally, the project work plan called for forty houses to be selected for inclusion in the project. The houses were selected based on the characteristics identified as 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 levels (2 to 20 pCi/l)
- Unmitigated (although 2 previously mitigated houses were selected for comparison in Polk County)
- 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 houses which never use natural ventilation for cooling

Candidate houses were screened and ten study houses selected in each of four regions in the state, including, Alachua, Dade, Leon and Polk Counties. In February 1990 the project increased in scope to include up to twenty more houses in each County. The same selection criteria were employed in identifying the additional houses for inclusion in the study. All houses are single story, single family homes, which are slab-on-grade.

Regional data collection was performed by the following coinvestigators:

- Alachua County: Professor C. E. Roessler-University of Florida
- Dade County: Professor Howard Moore-Florida International University
- Leon County: Professor James Cowart-Florida State University
- Polk County: Susan McDonough-Southern Research Institute

In order to develop a predictive relationship between short-term measurements and long-term (annual) average concentrations, a variety of short-term and long-term sampling devices were deployed in each study house. The devices selected and their deployment periods are summarized as follows:

- Alpha-track detector (ATD deployed for one year)
- Alpha-track detector (deployed for one quarter each; four per house)
- Low sensitivity "long term" Electret Passive Environmental Radon Monitor (EPL-read on approximately twenty-eight day intervals)
- High sensitivity "short term" Electret Passive Environmental Radon Monitor (EPS read on approximately seven- and fourteen-day intervals)
- Seven-day Charcoal Canisters (CC7-one week per month per house)
- Two-day Charcoal Canisters (CC2-a single two-day deployment per month)
- Pylon AB-5 with Passive Radon Detector (rotated between houses approximately four weeks per house)

Sampling was conducted in the study house set during the period from November 1989 through early March, 1991. The range of radon measurements is indicated by the frequency histogram in Figure 1. The population represented in the histogram consists of quarterly average concentrations in each study house as measured by one of the devices in the study. The median quarterly radon concentration in the study houses is 3.7 pCi/l, with 35% between 2 and 4 pCi/l, 19% between 4 and 6, and 26% above 6 pCi/l. This distribution is desirable for the goals of the study in several ways. First, by minimizing the number of measurements below 2 pCi/l (about 19% here) all devices were generally able to operate above their detection limits and avoid the

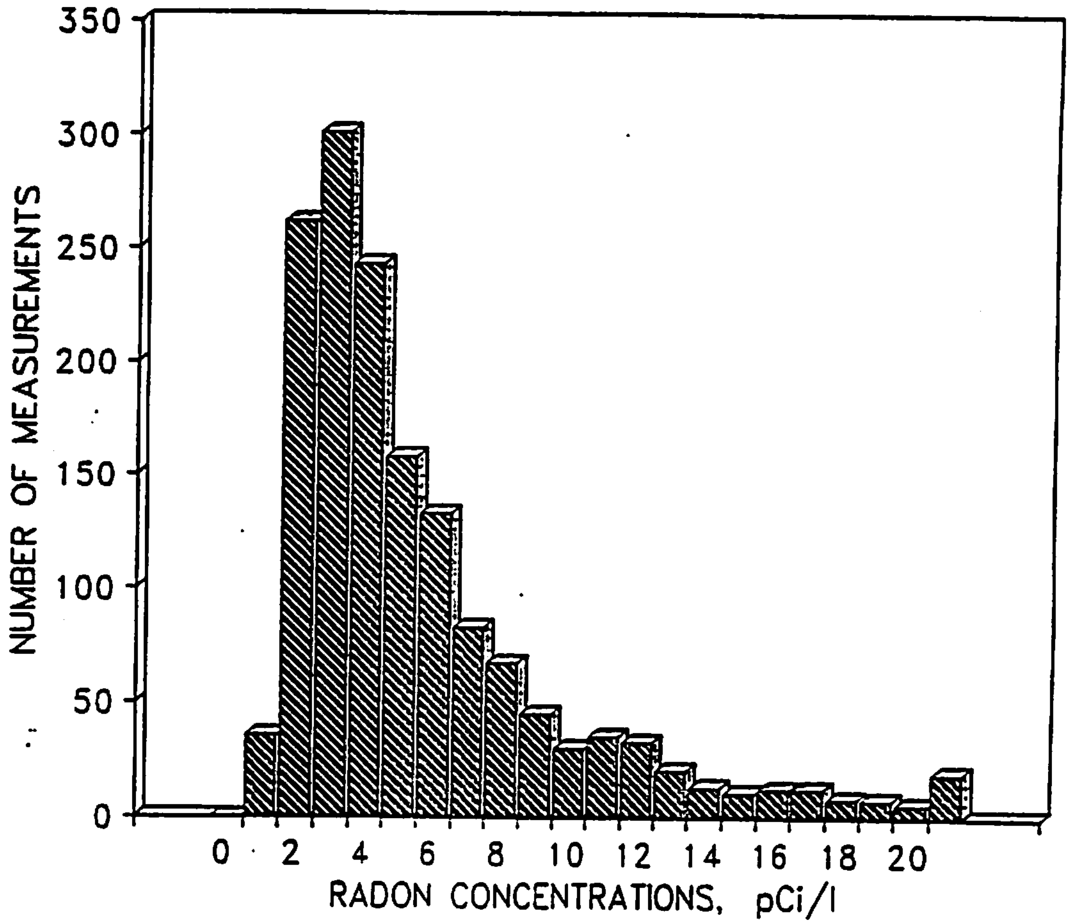

Figure 1. Distribution of indoor radon concentrations in the study houses.

complications of censored data. More significantly, most of the houses fall in the zone near 4 pCi/l in which greatest uncertainty exists in predicting from a short-term measurement whether the long-term average radon will be above or below the 4 pCi/l DHRS standard.

COMPARISON OF STUDY DEVICES

Figure 2 presents the annual average radon in each house as measured by the short term E-PERM (EPS) as compared to the alpha track detectors (ATD). Plots for other devices are similar. As might be expected, the correlations between the data from different devices in the same house are high. Simple linear regressions for each pair of data sets were performed. Standard linear regressions show r^2 values above 0.95, intercepts not significantly different from zero, and constants of proportionality ranging from 7 percent lower (for CC2 measurements) to 8 percent higher (ATD measurements) than the EPS averages. Thus, while some degree of scatter remains, the comparability of different devices is high and well within the accuracy objectives for each device individually.

TABLE 1. REGRESSION PARAMETERS FOR FITS TO ANNUAL AVERAGE RADON COMPARISONS (INDEPENDENT VARIABLE - EPS)

Models: (1) $Y = Co + C_1 * EPS$
(2) $Y = C_1 * EPS$

Dependent Variable		r^2	Co	Std. Error (Co)	C_1	Std. Error (C_1)
ATD	(1)	0.981	0.050	0.573	1.077	0.018
	(2)	0.981	---	---	1.083	0.011
EPL	(1)	0.982	0.262	0.575	1.042	0.017
	(2)	0.980	---	---	1.076	0.011
CC2	(1)	0.959	-0.047	0.741	0.933	0.023
	(2)	0.959	---	---	0.927	0.014
CC7	(1)	0.970	0.247	0.642	0.952	0.020
	(2)	0.969	---	---	0.983	0.013

SEASONAL TRENDS

A key issue in the variability of radon measurements is the seasonal component of this variability. To the extent that radon in a structure varies with a short period (hours, days, or weeks), multiple short period measurements (multi-day) or single medium period measurements (weeks) can average the fluctuations and give good predictions of the long term average. However, to the extent that a systematic seasonal trend is present, increasing the number or duration of short term measurements can reach a point of diminishing returns unless the general form of the seasonal effect can be predicted by other means. Without such a priori knowledge of the seasonal trend, this trend defines a minimum level of uncertainty for estimates of the annual average by any short term measurement strategy.

Seasonal effects have been the object of many of the past studies referenced in this report and most studies reveal a typical trend for the parts of the U.S. where heating is required in winter, and ventilation supplements or replaces air conditioning as the dominant form of summer cooling. In these studies, radon concentration generally exhibits a winter maximum, often a summer minimum, and intermediate values during other seasons. The only previous detailed study of seasonal trends in Florida is the work of Roessler, et. al. (1990) on 35 homes in the Alachua County area. Their study showed a significant fall-winter maximum and a spring-summer minimum with monthly means variable on the level of -20% to +50% of the annual mean.

In order to assess the seasonal trends in our study, quarterly average radon concentrations in each house were normalized to the annual average for that house. Results for the short term E-PERMS are plotted as frequency distributions in Figures 3a-d. For each quarter, the mean of the distributions relative to 1.0 indicates the degree to which the radon concentration in the average house is elevated or depressed during the quarter. The width of the distribution gives an indication of house to house variability in the seasonal effect. The spring quarter radon is lower in essentially all houses, with a mean quarterly concentration of 82% of the annual average. The effect is fairly consistant between houses, with half the homes showing quarterly ratios between 65% and 90% of the annual. On the other hand, winter quarter radon was elevated in most houses (mean concentration 1.28 times the annual average), but the degree of this effect varied considerably between houses (for winter the central half of the population extended from 1.06 to 1.45 times the annual mean). Both the elevated radon and greater house-to-house variability are evident in two winter seasons a year apart. The seasonal trends in radon concentration seen in these data are qualitatively in accord with the results of Roessler, et al. (1990) with the same Winter/Fall elevation and Spring/Summer minimum. The only difference in these results is the reversal of the Spring/Summer trend in the present study.

Some of the features of the seasonal variation can be noted by inspection of the seasonal variability in individual houses. While the average radon trend follows the pattern spring < summer < fall < winter, most individual houses do not. Of 65 houses with complete data for four full quarters only 18 fall into a class which has a winter maximum and spring minimum. The most common class (25 members) shows the winter maximum and summer minimum which is typical of other regions of the country (ironically, this pattern is dominant in Dade County). The third most abundant pattern (8 houses) shows a summer maximum and spring minimum. The remaining houses do not appear to fall into groups of any significance. Somewhat surprisingly, the average coefficient of variation of the short-term samples remains essentially constant through the four seasons in the range of 24-28 percent relative to the quarterly average.

PREDICTION OF LONG-TERM AVERAGE FROM SHORT-TERM DATA

The major approach to the prediction of long-term from short-term concentrations were was adapted from the methods of Roessler, et al. (1990) First, we assume that we can apply a log-normal effects model; that is, that all effects are multiplicative and that short-term measurements of radon

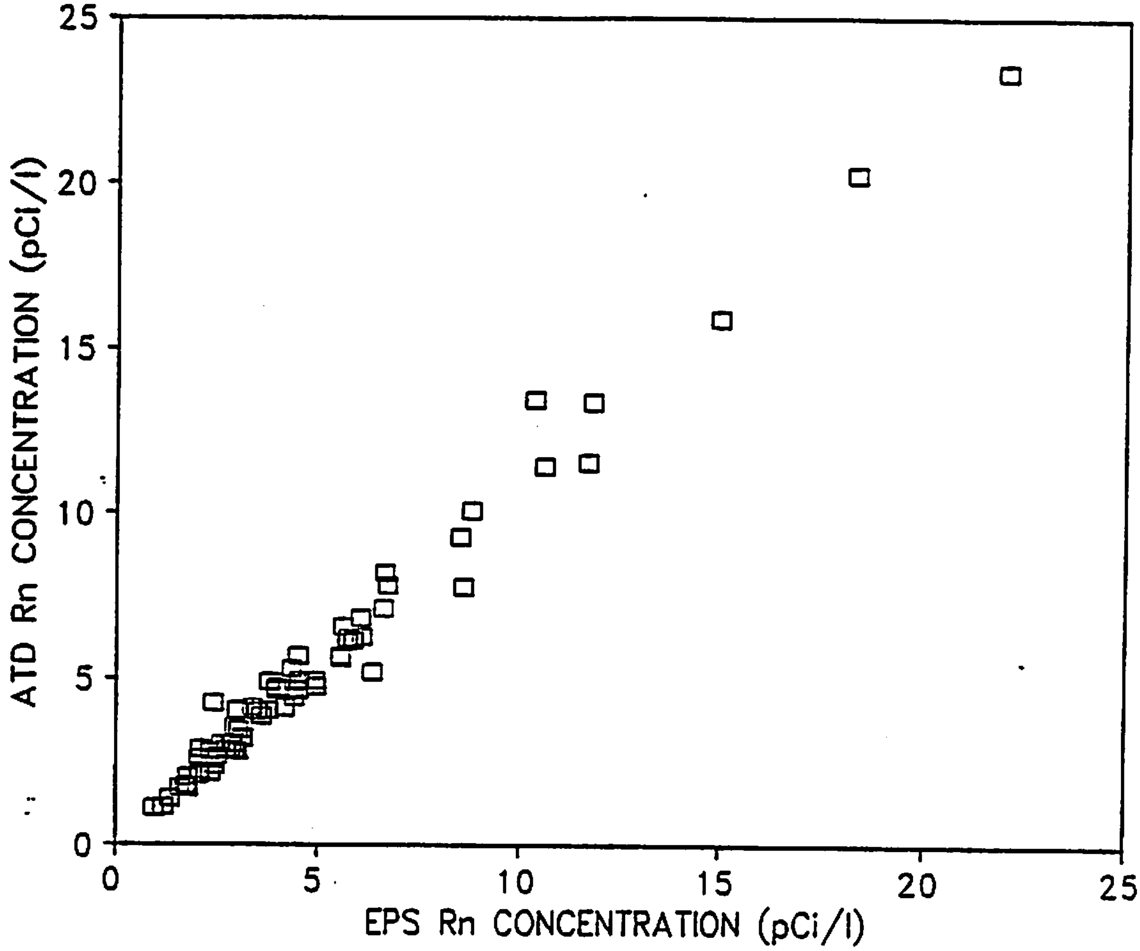

Figure 2. Annual average radon concentration in study houses as measured by alpha track detector compared to short-term Electret-ion chamber.

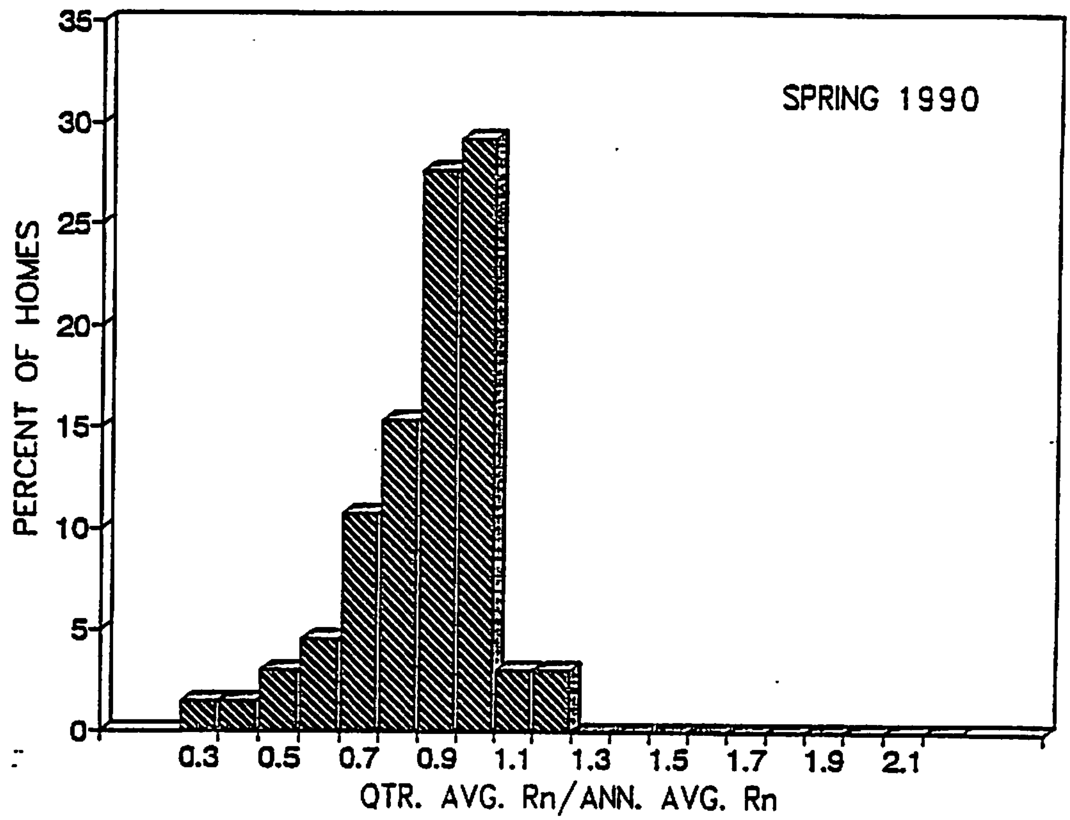

Figure 3a. Relative frequency distribution of spring quarter average radon concentrations normalized to annual average (as measured by EPS).

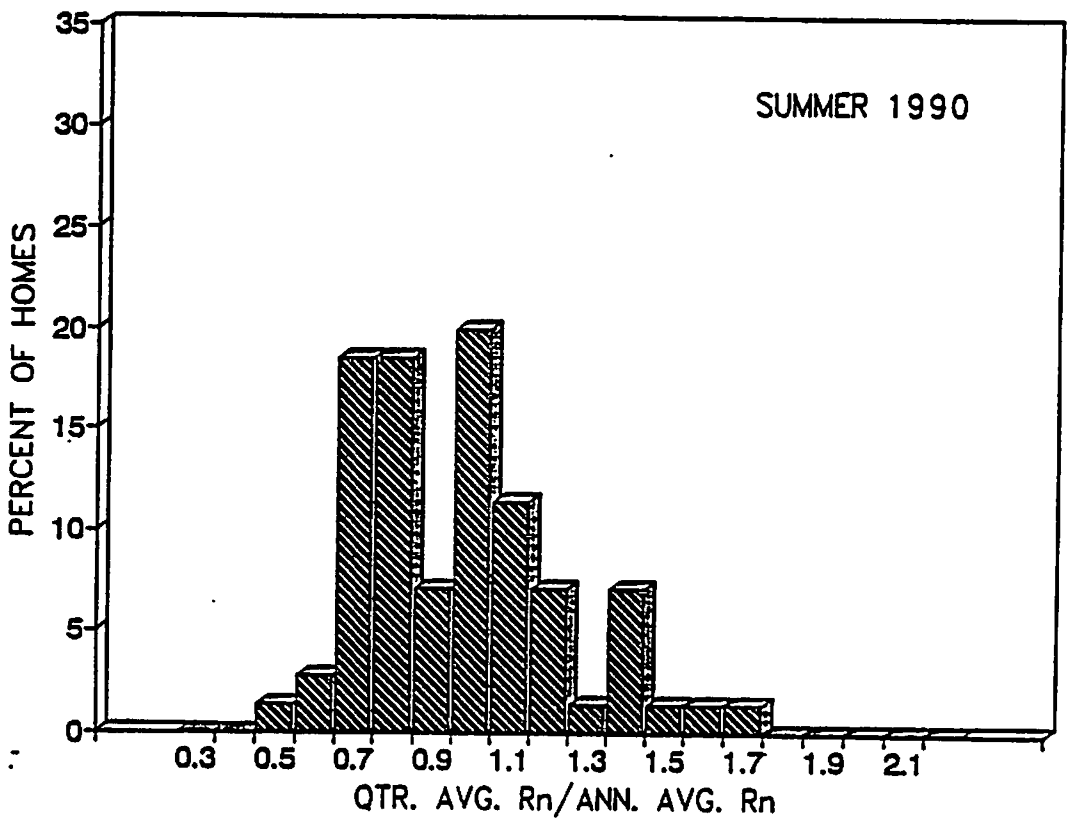

Figure 3b. Relative frequency distribution of summer quarter average radon concentrations normalized to annual average (as measured by EPS).

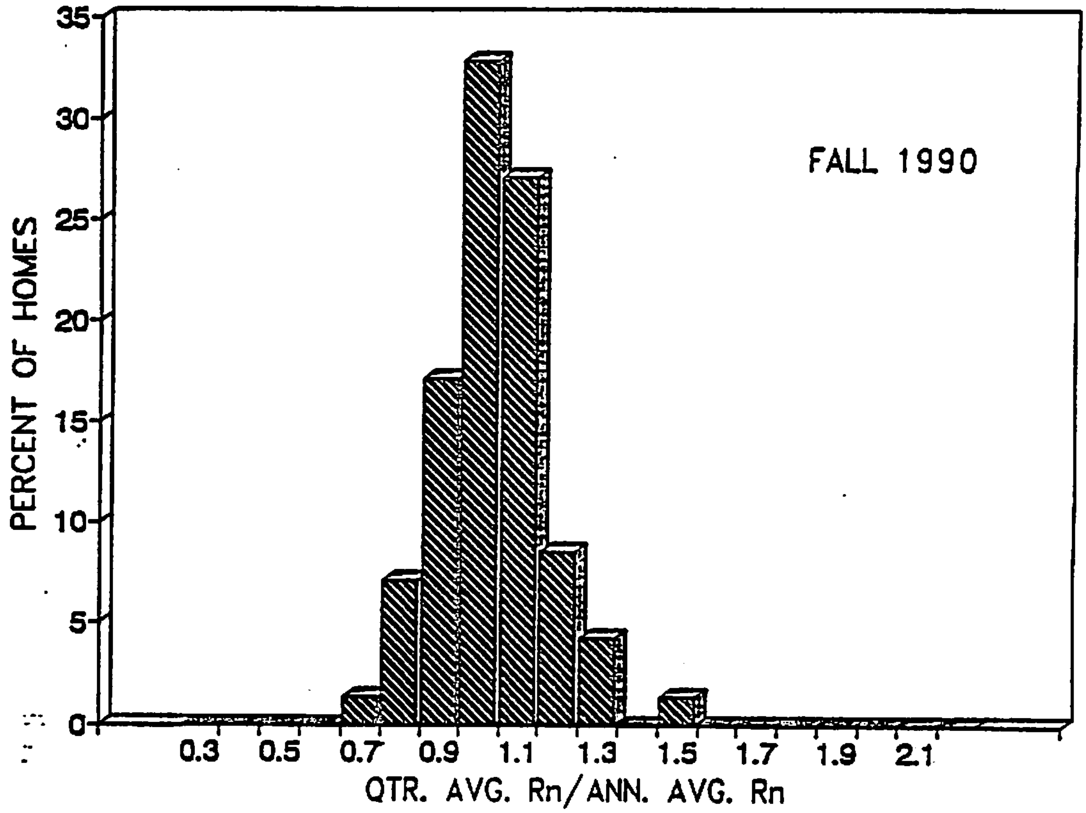

Figure 3c. Relative frequency distribution of fall quarter average radon concentrations normalized to annual average (as measured by EPS).

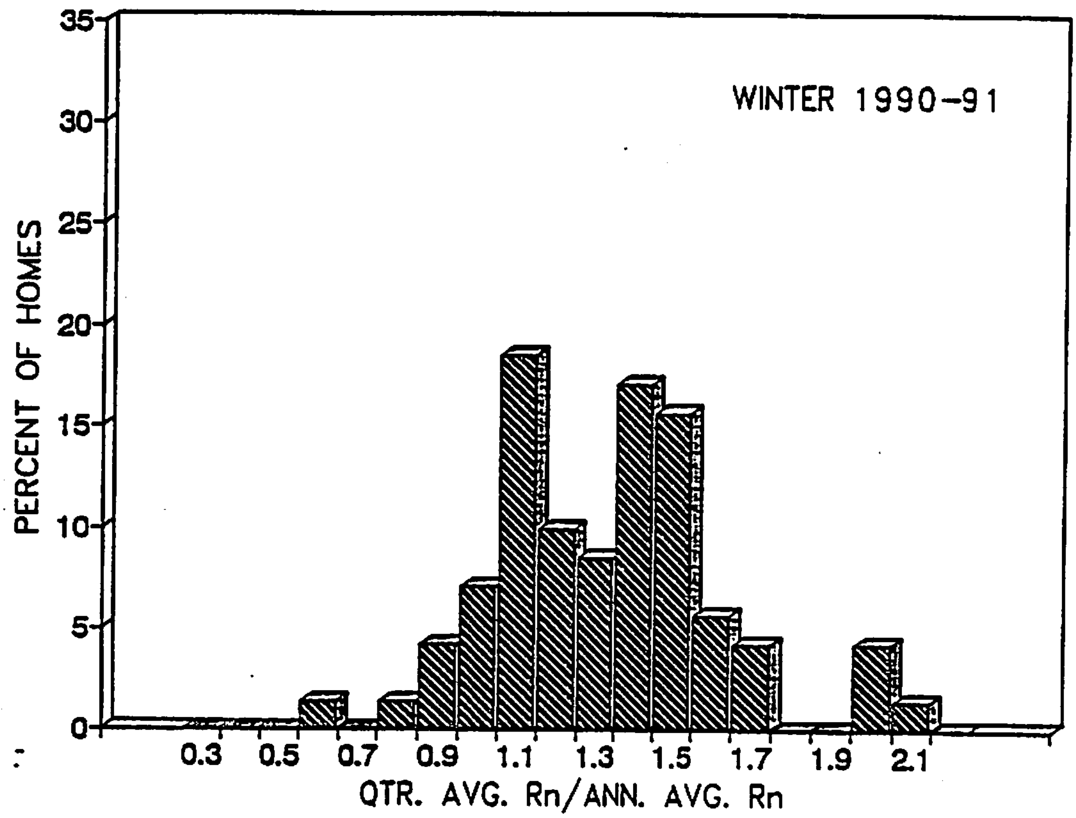

Figure 3d. Relative frequency distribution of final winter quarter average radon concentrations normalized to annual average (as measured by EPS).

concentration in each house vary about the long-term average with a standard deviation proportional to this mean. We define the quantities

$C^0_{ij} = ST_{ij}/LT_i$

and

$\Delta_{ij} = \ln (C^0_{ij})$, where in effect C^0 becomes a dimensionless relative radon concentration and Δ is its logorithm.

Our model becomes

$$\Delta_{ij} = u + a_i + e_{ij}$$

where u = an overall mean of Δ_{ij}

a_i = a group mean of effect of any subgroups found to be significant

and e_{ij} = random error (assumed normally distributed in the log-transformed variable system).

In terms of measured variables,

$\Delta_{ij} = Z_{ij} - Y_i$, where

$Z_{ij} = \ln(ST_{ij})$, and

$Y_i = \ln(LT_i)$, as described previously.

Thus, our model can also be written in the form used by Roessler, et al. (1990).

$$Z_{ij} - Y_i = u + a_i + e_{ij}$$

In the event that other groupings are not treated as significant (which seems justified except for the possibility of seasonal corrections) the a_i term disappears. The simplest predictive assumption is to assume that

$$\hat{Y}_i = Z_{ij} - \hat{u}$$

and that the residuals are normally distributed. This can be viewed as a very simple regressional approach where only the intercept is fit.

Using the methodology described above, the data in the present study were used for estimation of probability ranges for long term average radon given single short term radon measurements. For a given pool of data of short-term and long-term average radon concentrations, the quantities $\hat{u}$, VAR($\hat{u}$), and VAR(Δ) are calculated, where Z_{ij} and Y_i are defined by house for each combination of sampler and sample period,

$\Delta_{ij} = Z_{ij} - Y_i$,

$\hat{u}$ = the mean of the quantity (Δ_{ij}) over all measurements (i and j),

VAR($\hat{u}$) = the standard error of $\hat{u}$, given by the variance (s^2) of the sample Δ_{ij} divided by the number of samples N,

$VAR(\Delta)$ = the within house sample variance of Δ_{ij} as determined from standard ANOVA methods.

These quantities were then used in a predictive sense as follows. For any postulated long term reference value LT_R, the probability p that the long term average radon will exceed LT_R will fit the relationship

$$Z(p) = [\ln(ST/LT_R) - \hat{u}]/[VAR(\hat{u}) + VAR(\Delta)]^{½}$$

where Z(p) = is a normal probability distribution. Rearranging and redefining the probablility, if we wish to find the short-term average corresponding to a given probability that the long term average will not exceed a given reference long term average (that is, a upper confidence limit), we compute the relation

$$ST = LT_R \exp\left[\hat{u} - Z(p)\ [VAR(\hat{u}) + VAR(\Delta)]^{½}\right]$$

These calculations were applied to the data for all short term samplers. The EPS data were further subdivided, since these samplers were operated over different time periods. Likewise, averages over three different sampling periods of continuous radon monitor data from a subset of the houses were computed as a comparison. The data were further subdivided into three sets based on house ventilation characteristics. The first analysis was performed on all unmitigated houses which had complete data over the period from February 1990 to February 1991. A second calculation was run on the subset of 26 houses which never use natural ventilation (open windows) for cooling. A third calculation was performed with the closed houses and the 8 houses which "rarely" opened their windows (nominally < 5 percent of the time). Table 2 contains upper confidence limit calculations for these data sets for several probability values.

Comparison of the tables shows very little difference between the three groups of houses. This suggests that the variability due to the use of natural ventilation status is relatively minor compared to the variability from other causes. If this is generally true, these results may be generally applicable to houses with a wide range of ventilation practices.

DEVELOPMENT OF THE RECOMMENDED STANDARD

The data collected and analyzed to date in the FRRP Alternate Performance Standard project have been incorporated into thresholds in the recommended code currently in the rule making process. In summary, the assumptions and philosophy that have been used to develop the standard can be summarized as follows:

(1) The goal of a building standard is to reduce the long-term average (annual or longer) radon concentration in the building to be occupied.

(2) Short-term measurements in the building will have uncertainty due to (a) measurement accuracy of the device used and (b) variability of the indoor radon concentration with time. Uncertainty due to the second effect can be reduced by increasing the measurement time.

(3) A performance test must be completed and the results known prior to occupancy for practical enforcement of a construction performance

TABLE 2. THRESHOLD SHORT/TERM RADON CONCENTRATIONS (in pCi/l) CORRESPONDING TO DIFFERING LEVELS OF CONFIDENCE THAT LONG-TERM AVERAGE DOES NOT EXCEED 4 pCi/l.

ALL HOUSES (65), LAST 4 QTRS

CONFIDENCE

Device/Days	0.5	0.6	0.7	0.75	0.8	0.85	0.9	0.95
crm-1	3.82	3.54	3.25	3.10	2.95	2.77	2.57	2.30
crm-7	3.98	3.79	3.58	3.48	3.36	3.23	3.07	2.86
crm-14	4.00	3.83	3.66	3.57	3.46	3.35	3.21	3.02
eps-7	3.81	3.44	3.08	2.90	2.71	2.50	2.27	1.96
eps-14	3.46	3.12	2.78	2.61	2.44	2.25	2.03	1.75
epl-28	3.60	3.28	2.98	2.82	2.65	2.48	2.26	1.99
cc2	3.66	3.27	2.90	2.72	2.52	2.31	2.08	1.77
cc7	3.77	3.42	3.08	2.90	2.72	2.52	2.29	2.00

CLOSED HOUSES (26), LAST 4 QTRS

CONFIDENCE

Device/Days	0.5	0.6	0.7	0.75	0.8	0.85	0.9	0.95
eps-7	3.82	3.47	3.12	2.95	2.76	2.56	2.33	2.03
eps-14	3.58	3.26	2.94	2.78	2.61	2.43	2.21	1.93
epl-28	3.50	3.19	2.89	2.74	2.58	2.41	2.20	1.94
cc2	3.67	3.30	2.95	2.77	2.58	2.38	2.15	1.85
cc7	3.84	3.52	3.20	3.04	2.87	2.68	2.46	2.17

MOSTLY CLOSED HOUSES (34), LAST 4 QTRS

CONFIDENCE

Device/Days	0.5	0.6	0.7	0.75	0.8	0.85	0.9	0.95
eps-7	3.80	3.45	3.10	2.93	2.74	2.54	2.31	2.01
eps-14	3.55	3.22	2.90	2.74	2.57	2.38	2.17	1.89
epl-28	3.60	3.31	3.02	2.87	2.71	2.54	2.34	2.07
cc2	3.67	3.30	2.95	2.77	2.58	2.38	2.15	1.85
cc7	3.84	3.52	3.22	3.06	2.89	2.71	2.49	2.21

Note: crm - continuous radon monitor
eps - short-term EPerm
epl - long-term Eperm
cc2 - open face charcoal cannister (2 day)
cc7 - diffusion barrier charcoal cannister (7 day)

standard. In view of the time pressures on the construction industry, the measurement period in a workable performance standard will probably be a compromise between the schedule needs of the builder and the uncertainty of the radon measurement.

(4) The radon standard set by DHRS is assumed to remain at 4 pCi/l.

(5) The threshold for passing a short-term performance test should be conservative; i.e. low enough to assure that (within a confidence level to be determined by the State) the building will not have a long-term average radon concentration in excess of the HRS standard if a short-term performance test gives results less than the threshold.

(6) Thresholds of this type have been developed for several device/ measurement period combinations, so that the builder may elect to use a shorter-duration test with a lower pass-fail threshold in order to achieve the same confidence of that the building will comply with the standard.

(7) Similarly, the project data have been analyzed to allow the State to choose thresholds based on different levels of confidence according to its regulatory priorities and according to the standard ultimately to be set by HRS.

(8) If the effects of the time of year on indoor radon concentration can be quantified, an algorithm to account for seasonal effects can be built into the threshold criteria. If such an algorithm cannot be developed, the variability due to season must be included in the total variability of radon measurements in determining the thresholds for all times of the year.

The code language incorporates the possibility of several combinations of device and measurement period. No provision for incorporating "average" seasonal variations in radon data are included at this time.

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