United States
Environmental Protection
Agency

Research and Development

Air and Energy Engineering
Research Laboratory
Research Triangle Park, NC 27711

EPA/600/S8-91/210 Dec 1991

EPA

Project Summary

Development of Alternate Performance Standard for Radon Resistant Construction Based on Short-term/Long-term Indoor Radon Concentrations

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This report gives results of a study of short- and long-term variations in radon concentration in approximately 80 houses in Florida. The study involves year-long comparative sampling using the most common radon measurement technologies. This study, providing the most detailed database of which we are aware, addresses the time variation of indoor radon concentrations in a significant number of occupied houses having moderately elevated radon concentrations. In these study houses, the degree of variation of radon varies roughly in proportion to the long-term mean concentration, with a coefficient of variation within a calendar quarter of approximately 25% of the quarterly mean, and a coefficient of variation within a year of approximately 35% of the annual mean. This pattern of variability supports the use of multiplicative models to fit the variation and to predict intervals of confidence for long-term averages based on short-term measurements. This study indicates a distinct seasonal effect on the average radon, with quarterly averages relative to the annual average increasing in the order of spring (82%) < summer (93%) < fall (97%) < winter (123%). These models have been used to develop threshold values for the performance criteria of the proposed Building Standard for Radon-Resistant Construction for the State of Florida.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Many studies have been conducted nationwide to determine the extent of elevated indoor radon concentrations in the U.S. Most 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 complicate the relation 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 and air-conditioning equipment and usage patterns, and the use of natural or mechanical ventilation during mild weather. The physical factors affecting the entry of radon into buildings are understood, at least in principle. 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 of uncertainty due to the radon measurement devices themselves. Each major measurement technique has technical shortcomings and limitations in the

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possible sampling periods. This report gives results of a study of short- and long-term variations in radon concentration in about 80 houses in Florida. The study involves comparative sampling using the most common radon measurement technologies during the past year. To our knowledge, it is the most extensive study of its kind.

Conclusions and Recommendations

This study, providing the most detailed database of which we are aware, addresses the time variation of indoor radon concentrations in a significant number of occupied houses having moderately elevated radon concentrations. In these study houses, the degree of variation of radon varies roughly in proportion to the long-term mean concentration, with a coefficient of variation within a calendar quarter of approximately 25% of the quarterly mean, and coefficient of variation within a year of about 35% of the annual mean. This pattern of variability supports the use of multiplicative models to fit the variation and to predict intervals of confidence for long-term averages based on short-term measurements. These models have been used to develop threshold values for the performance criteria of the proposed Building Standard for Radon-Resistant Construction for the State of Florida.

This study indicates a distinct seasonal effect on the average radon, with quarterly averages relative to the annual average increasing in the order of spring (82%) < summer (93%) < fall (97%) < winter (123%). One recommendation for further study includes follow-up studies on the seasonal effect. The seasonal trends seen in these data are clearly beyond experimental uncertainty; they only reflect the trends within a single year. Follow-on studies (using only quarterly alpha track detectors) over 1 or more additional years would allow replication of the seasonal data and evaluation of the reproducibility of the trend in different years.

Background and Approach

The only known significant prior study of time variability of concentrations in Florida houses covered the period 1987-88. This study included a year-long measurement program in 37 houses in the Gainesville, FL area. Short-term average radon was measured by charcoal cannisters deployed once a month in each house, and long-term average concentrations were measured using alpha-track detectors deployed for the 1- year study. Considerable variability was noted from month to month, and there were clear suggestions of a seasonal effect, with November-March elevated, April and May depressed, and the remaining months intermediate. On a quarterly basis, these results translated into the relationship summer ≤ spring < fall ≤ winter. The data reduction methods used in this study were developed from those of the Gainesville study.

Since the goal of this project was to support a statewide building standard, the scope of this project was expanded in several ways beyond that of the Gainesville study: (1) this study was to be statewide in scope, so it included four regions expected to span the climate and geological variations in the radon-prone portions of the state; (2) the study was more comprehensive in the number of devices employed, including candidate samples not in widespread use at the time of most of the earlier studies; and (3) the study was structured to provide exploration or control for house structural and operational variables which can potentially affect radon entry.

The short-/long-term study was initiated in November 1989. Originally, the project work plan called for 40 houses to be selected for 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 two 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); and
- Natural ventilation: attempt to select about half of the houses which never use natural ventilation for cooling.

Candidate houses were screened and 10 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 20 more houses in each county. The same selection criteria were employed in identifying the additional houses for the study. All houses are single-story, single-family, slab-on-grade houses. Regional data were collected by the following investigators:

- Alachua County: C. E. Roessler, University of Florida;
- Dade County: Howard Moore, Florida International University;
- Leon County: James Cowart, Florida State University; and
- 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- and long-term sampling devices were deployed in each study house. The devices selected and their deployment periods are:

- Alpha-track detector (ATD) (deployed for 1 year);
- Alpha-track detector (deployed for 3 months each; four per house);
- Low-sensitivity Electret Passive Environmental Radon Monitor (EPL) (read on about 4-week intervals);
- High-sensitivity Electret Passive Environmental Radon Monitor (EPS) (read on about 1- and 2- week intervals);
- Seven-day Charcoal Canisters (CC7) (1 week per month per house);
- Two-day Charcoal Canisters (CC2) (one 2-day deployment per month); and
- Pylon AB-5 with Passive Radon Detector (rotated between houses about 4 weeks per house).

Results and Discussion

Sampling was conducted in the study house set between November 1989 and early March 1991. 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 pCi/l, 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 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 Department of Health and Rehabilitation Services (DHRS) standard.

It is instructive to observe the relationship between the quarterly mean radon concentrations and the standard deviation of the corresponding set of EPS measurements in that house and quarter. As is apparent from plots of these data, the standard deviation has a clear positive correlation with the mean and can be fit (r^2 = 0.59) to the linear trend: STD = mean* (0.2466) with a standard error of 0.0065 for the constant of proportionality, and the intercept not significantly different from zero. A corresponding plot using an annual averaging period gives regression parameters of $r^2 = 0.78$, slope = 0.357 ± 0.013, and intercept not significantly different from zero. The roughly linear correlation of the standard deviation with the mean is significant. This assumption is used in multiplicative models such as that of the Gainesville study and other fitting techniques that use logarithmic transformations for stabilization of variance.

Comparison of Study Devices

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% lower (for CC2 measurements) to 8% 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.

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.

In order to assess the seasonal trends in this study, quarterly average radon concentrations in each house were normalized to the annual average for that house. 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 consistent between houses, with half the houses 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 the Gainesville study 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 (eight 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 variance remains essentially constant through the four seasons in the range of 24-28% relative to the quarterly average.

Prediction of Long-term Average from Short-term Data

Several slightly different approaches to the prediction of long-term averages from short-term concentrations were investigated in the course of this study. The first, which was adapted from the Gainesville study, relies on the assumption that the *relative* variability of radon concentration is on the same order in all houses in the state (at least for houses in the 2-8 pCi/l range). This assumption is inherent in the use of radon concentrations only as normalized to the long-term concentration in the fitting process. Other conventional regression approaches were considered which incorporate long-term radon explicitly as a variable and typically use additional parameters. These models make the slightly different assumption that the *absolute* variability of radon in the houses in the 2-8 pCi/l range in this study is representative of houses in the state. Since our data lies in this range, the two assumptions are effectively indistinguishable. All approaches were found to give similar results in this case, so the simplest model was used.

In order to describe the selected approach, we will use a simplified form of the linear effects model described above. 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 concentration in each house vary about the long-term average with a standard deviation proportional to this mean. We define the quantities

$C^o_{ij} = ST_{ij}/LT_i$ and

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

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,

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

where

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

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

Thus, our model can also be written in the form used for the Gainesville study,

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

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 that

$Y_i = X_{ij} - \hat{u}$

and that the residuals are normally distributed.

This is in essence the approach used for the Gainesville study. It can also 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- and long-term average radon concentrations, the quantities $\hat{u}$, VAR($\hat{u}$), and VAR(Δ) are calculated, where X_{ij} and Y_i are defined by house for each combination of sampler and sample period, Δ_{ij} is calculated as above,

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

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

Table 1. 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 (70), Last 4 Qtrs

Device/days*	Confidence 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	2.51	2.27	1.96
eps-14	3.46	3.12	2.78	2.61	2.44	2.25	2.03	1.75
epl-14	3.75	3.34	2.95	2.75	2.55	2.33	2.08	1.77
epl-28	3.62	3.32	3.02	2.87	2.71	2.53	2.32	2.05
cc2	3.66	3.27	2.90	2.72	2.52	2.32	2.08	1.77
cc7	3.77	3.42	3.08	2.91	2.73	2.53	2.30	2.01

Closed Houses (26), Last 4 Qrtrs

Device/days*	Confidence 0.5	0.6	0.7	0.75	0.8	0.85	0.9	0.95
eps-7	3.81	3.43	3.08	2.90	2.71	2.50	2.26	1.96
eps-14	3.58	3.26	2.94	2.78	2.61	2.43	2.21	1.93
epl-14	3.67	3.29	2.92	2.74	2.55	2.34	2.11	1.80
epl-28	3.48	3.18	2.89	2.75	2.59	2.42	2.21	1.95
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	2.86	2.68	2.46	2.17

Mostly Closed Houses (39), Last 4 Qrtrs

Device/days*	Confidence 0.5	0.6	0.7	0.75	0.8	0.85	0.9	0.95
eps-7	3.81	3.46	3.13	2.95	2.77	2.58	2.35	2.05
eps-14	3.55	3.22	2.90	2.74	2.56	2.38	2.16	1.88
epl-14	3.67	3.29	2.92	2.74	2.55	2.34	2.11	1.80
epl-28	3.64	3.36	3.08	2.94	2.78	2.62	2.42	2.16
cc2	3.68	3.31	2.95	2.77	2.58	2.38	2.14	1.84
cc7	3.83	3.52	3.21	3.05	2.89	2.71	2.49	2.21

(*) crm = continuous radon monitor
eps = short-term EPerm
epl = long-term EPerm
cc2 = open face charcoal canister (2 day)
cc7 = diffusion barrier charcoal canister (7 day)

VAR(Δ) is 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

$$Z_p = [\ln(ST/LT_R) - \hat{u}]/[VAR(\hat{u})+VAR(\Delta)]^{1/2}$$

where Z_p is the p quantile of the standard normal distribution. Rearranging and redefining the probability, 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, an upper confidence limit), we compute the relation

$$ST = LT_R \exp[\hat{u} - Z_p [VAR(\hat{u})+VAR(\Delta)]^{1/2}]$$

Plots analogous to these relationships are used for the Gainesville data.

These relationships can also be applied to any homogeneous subsets of the study pool. If quarterly data are evaluated, in principle the seasonal factor would be absorbed into the bias factor û and the VAR (Δ) for the quarterly population would apply (recall that this value is smaller for our quarterly averages). These analyses are not included here, partly due to the arbitrariness in defining quarterly boundaries.

In order to compare the difference in the predictive strength of the different short-term sampling techniques used in this study, 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 of continuous radon monitor data from a subset of the houses over three different data averaging periods were computed as a comparison. The data from the non-continuous samplers were further subdivided into three sets based on house ventilation characteristics. The first analysis was performed on all 65 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 eight houses which "rarely" opened their windows (nominally < 5% of the time). Table 1 contains upper confidence limit calculations for these data sets for several probability values.

Comparison of the data 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.

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 are:

(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 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 ensure 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 are being 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 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 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. (This approach has been taken in the current recommendations.)

The code language incorporates the possibility of several combinations of device and measurement period. No provision for incorporating average seasonal variations in radon data is included, due to lack of sufficient data on the form of systematic seasonal differences.

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The complete report consists of two volumes, entitled "Development of Alternate Performance Standard for Radon Resistant Construction Based on Short-term/Long-term Indoor Radon Concentrations":
"Volume 1" (Order No. PB92-115 211/AS; Cost: $19.00, subject to change) is the technical report.
"Volume 2" (Order No. PB92-115 229/AS; Cost: $19.00, subject to change) contains the appendices.
Both volumes of this report will be available only from:
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