United States
Environmental Protection
Agency

Air an[illegible]gy Environmental
Resea[illegible]ch Laboratory
Research Triangle Park NC 27711

April 1991

Research and Development

EPA

The 1991 International Symposium on Radon and Radon Reduction Technology: Volume 2. Preprints

Session III: Measurement Methods

Session IV: Radon Reduction Methods

April 2-5, 1991
Adam's Mark Hotel
Philadelphia, Pennsylvania

The 1991 International Symposium on Radon and Radon Reduction Technology

"A New Decade of Progress"

April 2-5, 1991
Adam's Mark Hotel
Philadelphia, Pennsylvania

Sponsored by:

U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory

and

U. S. Environmental Protection Agency
Office of Radiation Programs

and

Conference of Radiation Control Program Directors, Inc.
(CRCPD)

Printed on Recycled Paper

The 1991 International Symposium on Radon and Radon Reduction Technology

Opening Session

The 1991 International Symposium on Radon and Radon Reduction Technology

Table of Contents

Session I: Government Programs and Policies Relating to Radon

Session I Posters

Session II: Radon-Related Health Studies

Session II Panel: Risk Communication

Session III Panel: Detection of Radon Measurement Tampering

Session III Panel: Short-Term/Long-Term Measurement

Session III Posters

Session IV: Radon Reduction Methods

Section IV Posters

Session V: Radon Entry Dynamics

Session V Posters

Session VI: Radon Surveys

Session VIII: Radon Prevention in New Construction

Session VIII Posters

Session X Posters

Session III:

Measurement Methods

TITLE: Quality Assurance of Radon and Radon Decay Product Measurements During Controlled Exposures

AUTHOR: Douglas J. Van Cleef, EPA - Office of Radiation Programs

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

In 1987, the Environmental Protection Agency assumed responsibility for the exposure of radon and radon decay product measurment devices submitted as part of the National Radon Measurements Proficiency Program. Since that time, thousands of devices for hundreds of federal, state, and private organizations have been exposed to various levels of radon and its decay products in EPA's environmental chambers. This paper discusses the extensive effort undertaken to insure that reported values for given exposure periods are as close to "true" values as is possible with existing sampling and analysis technology.

CURRENT STATUS OF GLASS AS A RETROSPECTIVE RADON MONITOR

by: Richard Lively, Minnesota Geological Survey, 2642 University Ave., St. Paul, MN 55114, and Daniel Steck, Dept. of Physics, St. John's University, Collegeville, MN 56321

ABSTRACT

Measurement of alpha activity on household glass surfaces has developed from an interesting idea into an attractive technique for (1) indoor radon screening and (2) improving estimates of long-term radon exposures for epidemiological studies. Early glass samples, which spanned a narrow range of radon exposures, displayed a positive correlation between exposure and surface activity. However, the age and exposure history of these early samples is uncertain. We now have calibration data from 33 pieces of glass with known exposures between 0 to 2000 kBq yrs m^{-3} and surface alpha activities as high as 2000 Bq m^{-2}. Glass has been exposed in four independent radon chambers, including the EPA Las Vegas laboratory. We also have samples from four houses, two from Minnesota, one from New York, and one from New Jersey.

There is a strong positive correlation between the exposure and surface activity, with a best-fit coefficient of variation (COV) of 70%. The calibration curve fits the house samples with a COV of 80%—somewhat larger owing to indeterminate exposure of the glass. Because indoor radon can have large spatial and temporal variability (COVs from 80% to 150% in Minnesota), we suggest that surface alpha activity is currently the best technique to acquire long-term averages of indoor radon.

Activity on glass can be measured rapidly using semiconductor or pulse ionization spectroscopy and inexpensively by track-registration detectors. These measurements provide reproducible techniques to screen homes for radon because they are insensitive to short-term radon fluctuations that confound present screening techniques. Glass surface activity is an ideal monitor for use in epidemiological studies since it can integrate radon daughter activity over decades. The method can properly average short-term radon fluctuations and radon changes due to structural alterations, and it has the ability to track exposures on glass that has been in more than one radon environment.

INTRODUCTION

A recurring dilemma for agencies that provide guidance on acceptable levels of indoor radon, and for epidemiologists trying to assess the effects of exposure to radon and radon daughter products, is that current measurement techniques collect data for periods of less than one year (1), and often for not more than two days (2). Current radon screening procedures produce relatively poor long-term radon estimates since they are subject to relatively large errors due to natural or induced variations within the home environment. These variations occur on the same time scales as the measurement protocols (3) and can be significantly greater than a factor of two (4). Additional error is introduced by assuming a fixed relationship between the measured radon and the radon daughter product concentrations. As a result, short-term screening measurements are not sufficiently accurate to assess the possible health impact of indoor radon exposure (5). Year-long measurements, although better, are still subject to long-term variability, can take a year to acquire, and may not accurately reflect lifetime exposures. The above mentioned problems illustrate the limited potential of the data to be used for epidemiological studies. Current measurement protocols also do not take into account possible exposure in the workplace or changes in housing environments over a life-time.

In 1987 Lively and Ney (6), reporting on a study of surface alpha radioactivity from radon daughter products, proposed that surfaces such as glass could be used to estimate an integrated ^{222}Rn concentration within a room. Samuelsson (7), citing the technique as a retrospective radon exposure meter, measured the activity on six pieces of household glass and reported a good correlation between surface alpha activity and radon exposure (0.5 to 9 kBq yrs m^{-3}). We report here on the correlation and reproducibility of glass surface activity with samples that were exposed in radon chambers for between 0.5 to 2,000 kBq yrs m^{-3}. We also compare these results with measurements from glass in several homes.

Surfaces can be used as radon monitors because they are passive collectors of radon daughter products. The long-lived radon decay product ^{210}Pb ($t_{1/2}$ = 22 y), which is followed by an alpha emitting isotope, ^{210}Po ($t_{1/2}$ = 138 d), will therefore display a relationship to the concentration of the radon source. In this paper we are attempting to understand and define the relationship between activity and exposure for simple environments in radon chambers with known radon concentrations and low aerosol contents. If the relationship is determinate for simple situations, it will then be possible to extend the monitoring to more complex environments, such as those in most homes, with some hope of understanding the results.

Glass is an appropriate surface for retrospective radon analysis because it is readily available, it can be recovered from a variety of environments and exposure histories, it tends to have a low intrinsic background, and it is nonporous and impermeable. The latter characteristics are important to accurate measurement of the alpha spectra. On porous, aged surfaces, such as gypsum board or plaster, a significant fraction of ^{210}Pb has diffused off the surface or beyond the range of alpha particle emission from ^{210}Po (6). In glass, however, ^{210}Pb has a very short diffusion length, estimated at 1 micron in twenty years (8). The tailing and FWHM of ^{210}Po alpha spectra from a piece of glass exposed for two weeks was the same as the spectra from a piece of glass exposed for more than thirty years.

Surfaces collect radon daughters at all stages in the decay chain between ^{222}Rn and ^{210}Pb. Some of the daughters are attached to aerosol particles and some exist as "unattached ions" or "ultrafine particles." Recoil of a parent atom by emission of an alpha particle can embed the daughter atom in the glass. Depths of recoil implantation, based upon studies of 100 keV ions, are estimated to be 0.04 ± 0.007 microns (9). Vanmarcke (10) presented a model for determining the fraction of daughters that embedded in a surface. He observed that the fraction embedded is in part controlled by the geometry of the decay/recoil couple and by the aerosol content of the room, which affects the attached-to-unattached ratio. We found early in our studies that if the glass was very dirty, up to half of the surface activity could be removed by washing. Analysis of glass from "clean" environments indicates that the removable fraction can be less than 10%.

METHODOLOGY

The calibration data in Figure 1 was obtained by exposing new pieces of glass in both static and dynamic radon atmospheres for known intervals. Multiple exposures from a single type of environment reduces the uncertainty associated with aerosols and exposure history. We used three of our own radon chambers: two were Radium Ore Revigators with internal volumes of about 5 liters and equilibrium radon activities between 3,700 to 9,000 kBq m^{-3}; the third was a large volume radon chamber (1 m^3) with higher humidity and air velocities. Several pieces of glass were also sent to the EPA Las Vegas radon laboratory for exposure in the radon chamber. The integrated exposure times from these chambers ranged from a few days to several months, simulating decades of exposure at lower radon levels.

The surface alpha activity was measured with surface-barrier alpha detectors and 10 cm^2 pieces of glass cut from 160 cm^2 exposed samples. The detectors have a high signal-to-noise ratio and good resolution and sensitivity for ^{210}Po. Count times range from three to twelve days. All of the measurements were on washed surfaces after the short-lived daughters had decayed. The detectors were calibrated, and counting efficiencies were determined using NBS traceable ^{210}Po and ^{241}Am solid sources.

Low levels of surface alpha activity mean that background activities may become very important and should be evaluated. Uranium in the glass can result in ^{210}Po activity that is unrelated to the surface deposition of radon daughter products, and there is the possibility that glass may be exposed to radon prior to emplacement in the environment of interest. Our measurements to date, over an energy range of 4-8 MeV, have detected no activity other than that related to ^{210}Po. We also tested for ^{210}Po in the glass by remeasuring several low ^{210}Po activity samples after etching the surface with hydrofluoric acid. Polonium-210 count rates from these samples were indistinguishable from the detector background, indicating that there was no supported ^{210}Po activity in the glass. A nonexposed piece of glass from the group used for several low activity exposures was measured both with and without etching. The glass background activities did not differ from each other or from the detector background, indicating that there was no measurable preexposure activity on that surface. Although these results may not apply to all glass, they do indicate that for the samples tested, all of the measured alpha activity on the glass surface can be attributed to deposited ^{210}Po.

RESULTS AND DISCUSSION

We have measured the surface alpha activity from 37 pieces of glass that were exposed in four different radon chambers and four homes. The results have been corrected for disequilibrium between ^{210}Po and ^{210}Pb and for the decay of ^{210}Pb since the beginning of the exposure. The correction for ^{210}Pb decay is dominant for glass more than five to six years old. Activities were measured to better than 10% counting statistics; however, nonsystematic variations of activity on different areas of the same glass average 25%. Exposure times for the chamber samples were known, but the concentrations of radon in the chambers have a measurement error due to unsampled temporal variations. Exposure errors for the houses combined the best estimates of radon levels based on short-term radon measurements and the length of time the glass was in place.

The results (Figure 1 and Table 1) expand the range of exposures and measured activities to cover four orders of magnitude (up to 2,000 Bq m^{-2} activity and 2,000 kBq y m^{-3} exposure). We have presented the data in Figure 1 as a log/log plot to display the complete range of data.

Linear regression analysis (ordinary least squares—OLS) shows a strong positive linear correlation between exposure and surface activity: $R=0.97$, $p<0.001$. However, because we have estimates of uncertainties associated with both exposure and surface activity, the best fit line shown in Figure 1 was calculated by using a weighted least squares fit (WLS) that more accurately reflects the influence of x-y errors at low activities and exposures. Although the scatter in the data exceeds our uncertainty estimates, the best WLS fit has a COV of 70%. This COV is similar in size to COVs for short-term Rn screening measurements and long-term Rn variations in houses(4).

That we can fit two different curves to data below exposures of 50 Bq m^{-2} results from glass samples within two environments, one static and one dynamic. Nine pieces of glass in Figure 1 were exposed for up to 15 kBq yr m^{-3} in a chamber where air velocities approach 2 m s^{-1} (clearly much breezier than the inside of most homes). In this environment, the slope of the best WLS calibration line is three times smaller than that obtained from the glass samples exposed in static air. The lower slope indicates that under dynamic air flow up to three times more radon daughter products were deposited on the surface during similar exposure intervals. In most homes, we expect that the daughter product deposition velocity would would be between static and dynamic conditions. A simple adjustment can therefore be made to the WLS calibration curve to account for indoor air flow estimates or measurements.

When the calibration equation is applied to the four different household glass samples, a COV of 80% is obtained, which is very similar to the glass calibration COV of 70%. This implies that aerosols and cleaning histories may not significantly affect the relationship between glass surface activity and exposure. When collecting data from homes, the primary limitation on the effectiveness of the technique is the uncertain surface exposure time, and that uncertainty is the major contributor to the COV.

Because of the large spatial and temporal variability of indoor radon (COVs from 80% to 150% in Minnesota), long-term estimates of radon and radon daughter concentrations based on short-term measurements are inadequate. Deposition of daughter products on surfaces represents an integrated measurement that can provide useful data over exposure intervals of approximately seventy years and a very wide range of radon concentrations. Our calibration data indicate that air flow does influence the deposition velocity of the daughter products. To obtain the most accurate long-term estimate of radon from the best-fit calibration, an evaluation of air movement during an exposure interval should be attempted.

Radioactivity on glass can be measured over a few hours or days using semiconductor (this paper) or pulse ionization (7) spectroscopy. In addition, inexpensive track-registration detectors can be used to measure the glass surface activity over a period of one year while at the same time measuring the radon concentration in the adjacent room. These types of measurements provide rapid, reproducible analyses that can be used to screen homes for radon because they are insensitive to short-term radon fluctuations and tampering that can confound present screening techniques. Alpha activity on glass surfaces is an ideal monitor for use in epidemiology since it can integrate radon daughter activity over decades, and the variations from a best-fit line over a wide range of calibration data are less than a factor of two. The method properly averages short-term radon fluctuations, radon changes due to structural alterations, and it has the ability to track exposures on glass that has been in more than one radon environment. As a result, we believe that surface alpha activity is an attractive and probably the best available technique to assess the long-term indoor radon environment.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

REFERENCES

1. Borak, T.B., and Johnson, J.A. Estimating the risk of lung cancer from inhalation of radon daughters indoors: review and evaluation. EPA 600/6-88/008, National Technical Information Service, Springfield, Va., 1988.

2. U.S. Environmental Protection Agency: A citizens guide to radon. U.S. Dept. of Health and Human Services, Public Health Service, 1986.

3. Nero, A.V. Radon and its decay products in indoor air: an overview. In: W.W. Nazaroff and A.V. Nero (eds.), Radon and its decay products in indoor air. New York, N.Y., 1988. p. 1.

4. Steck, D.J., Lively, R.S., and Ney, E.P. Epidemiological implications of spatial and temporal radon variations. In: Proceedings of the Twenty-ninth Hanford Symposium on Health and the Environment, Indoor Radon and Lung Cancer: Reality or Myth. Hanford, Wash., October 15-19, 1990.

5. Steck, D.J. A comparison of EPA screening measurements and annual ^{222}Rn concentrations in statewide surveys. Health Physics. 58: 523, 1990.

6. Lively, R.S., and Ney, E.P. Surface radioactivity resulting from the deposition of ^{222}Rn daughter products. Health Physics. 52: 411, 1987.

7. Samuelsson, C. Retrospective determination of radon in houses. Nature. 334: 338, 1988.

8. Kittel, C. Introduction to solid state physics, 5th ed. New York, N.Y., 1976. p. 542.

9. Ryssel, H. and Ruge, I. Ion implantation [English translation of German edition]. Chichester, Great Britain, 1986. p. 459.

10. Vanmarcke, H. The decay products of radon in the indoor environment. Paper presented at the Technical Exchange Meeting on Assessing Indoor Radon Health Risks, Grand Junction, Colo. September 18-19, 1989.

TABLE 1. LINEAR REGRESSION ESTIMATES FOR SLOPE AND INTERCEPT

Method	Intercept estimate	Slope estimate
Ordinary least squares*	38 ± 12	1.4 ± 0.1
Weighted least squares*	-2.5 ± 0.3	1.7 ± 0.2
WLS — Static chambers†	-3.0 ± 0.1	1.9 ± 0.2
WLS — Dynamic chamber†	-0.1 ± 0.1	0.6 ± 0.2

*Full range of calibration activities.
†Activity range 0 — 50 Bq m^{-2}.

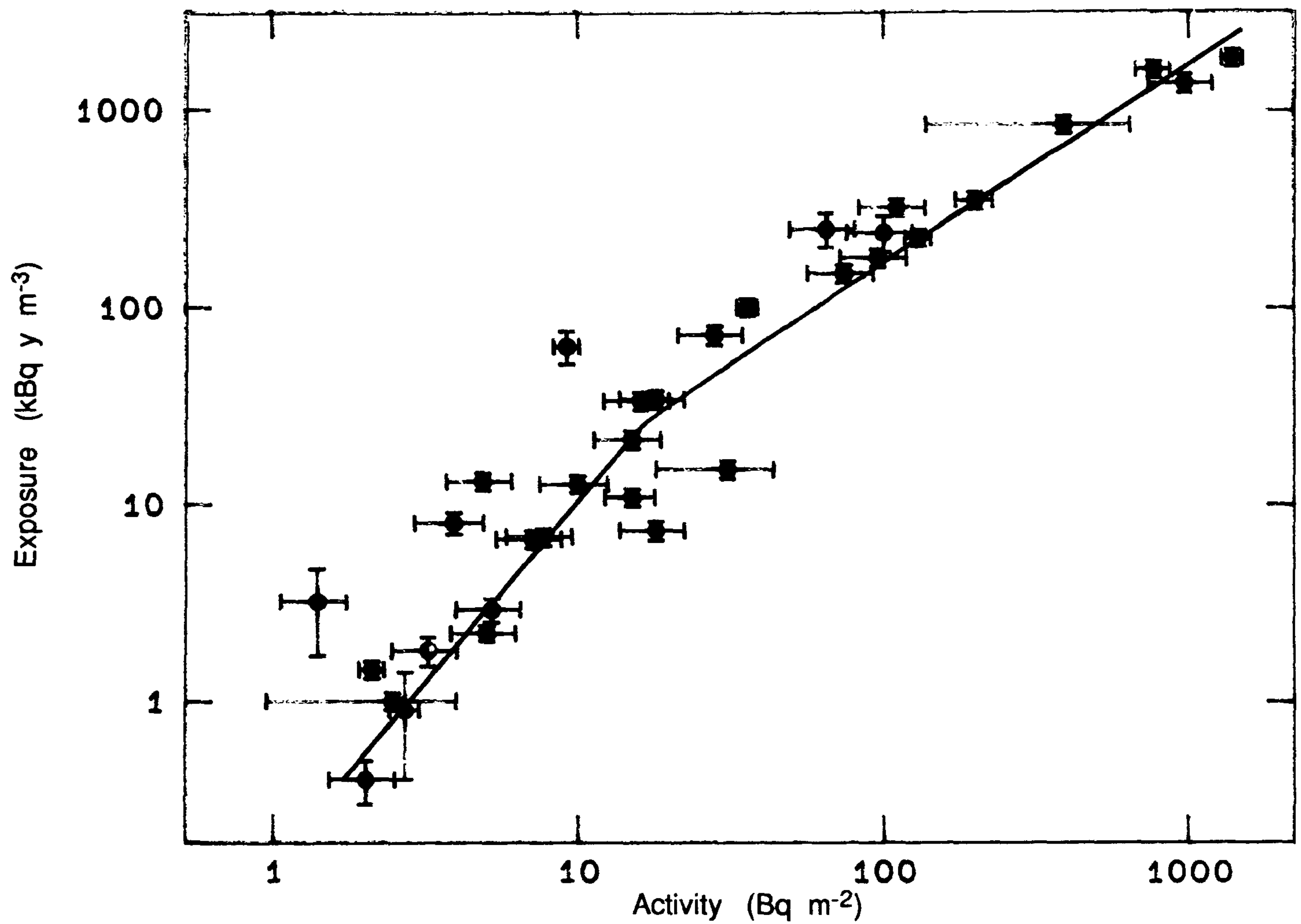


Figure 1. Log/log plot of exposure versus activity on calibration glass surfaces. The curve is obtained from the weighted least squares equation in Table 1.

SOIL GAS MEASUREMENT TECHNOLOGIES

by: Harry E. Rector
GEOMET Technologies, Inc.
20251 Century Boulevard
Germantown, MD 20874

ABSTRACT

A wide range of methods for characterizing the radon potential of land areas have evolved over the last decade through research programs in this country and abroad. Ideally, methods would provide information on radon production in the soil, as well as diffusion and permeability. This can be accomplished through various combinations of direct measurements and theoretical assumptions. Basic technologies concentrate on measuring: (1) radon in soil gas, (2) radon flux from the surface, or (3) radium content of the soil. Approaches may also include attendant measures of soil characteristics and other factors to support predefined indexes of radon potential.

Basic measurement approaches for radon potential are reviewed in terms of the following technical issues: measurement parameters, field/laboratory methodologies, quality assurance, and model concepts applied to data to estimate radon potential. Theoretical aspects of these factors are also considered. Radium-based measurements, for example, have the distinct advantage of being suited to testing water-saturated soils, but may require weeks to deliver results. Soil gas and flux measurements, on the other hand, generally fail to obtain samples from saturated soils because the gas volume is nearly zero, but approaches exist to deliver prompt results on site. If time is of the essence, then, recognition factors to avoid generally saturated conditions are necessary to ensure sample validity.

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

Soil gas entry is generally regarded as a major source of indoor radon. Consequently, attention has been directed to developing the means to evaluate radon potential based on soil factors. National- and regional-scale maps consolidating radiometric, geologic, and soil information were developed to display broad trends (Wilson 1984; Duval et al. 1989). Studies to establish site-specific methods geared to finer detail through direct measurement have also been underway.

Early efforts in Sweden to devise site-specific methods recognized the importance of air permeability of the soil and moisture conditions in determining radon concentrations in soil gas and pressure-driven transport into buildings, leading to development of a series of in-situ measurements to complement exhalation tests in the laboratory (Akerblom et al. 1984; Lindmark and Rosen, 1985). Based on model assumptions, a regional classification could be considered to define class intervals of radon potential based on air permeability of the soil and soil gas (Swedjemark 1986).

It also became clear that the building itself exerts perhaps the strongest influence on radon entry by (1) creating the pressure forces to drive radon entry and (2) presenting the cracks, joints, and service penetrations that form radon entry pathways. Consequently, soil-based measurements for indoor potential must encompass two levels of analysis: one to evaluate radon production and mobility in the soil, a second to evaluate transport into the building. Most indexes of radon potential, such as the various permutations of the Radon Index Number (RIN) and the Radon Availability Number (RAN), are formulated to define the radon that is available for transport, but do not explicitly consider radon entry into the building. Additional considerations would be required to account for differing entry routes and building pressures that occur with slab-on-grade, crawl space, and basement configurations.

Continuing work by Nazaroff and Sextro (1989) is headed in this direction. They have derived a generalizable framework that integrates soil factors with building factors. Although this latter approach requires specification of radon entry pathways, it provides a quantitative means to judge the radon potential of land areas in terms of the total effect. In the State of Florida, numerical modeling is being employed in this context (Rogers and Nielsen 1990).

This paper presents a general overview of the basic technologies applied to estimating radon potential, concentrating on measurement strategies for radium content, soil gas radon, and radon flux.

MEASUREMENT STRATEGIES

Quantitative estimates of radon potential are predicated from (1) a soil volume in flow communication to the building, (2) a supply of radon to the pore spaces of the soil, and (3) transport mechanisms to convey radon into the building. The situation is complicated by a number of factors arising from soil characteristics and environmental influences in addition to the effects of the building. Measurement strategies hinge on detecting radioactivity and other characteristics of a known sample volume (or mass) whose history has been controlled to represent one or more processes germane to the production and migration of radon in the soil.

As summarized in Figure 1, radium content is measured by isolating a defined volume of soil to retain the emanating fraction. At radioactive equilibrium, the activity concentration of radon and radon progeny is equated with the radium concentration. Soil gas measurements, on the other hand, seek to isolate radon in the pore spaces without affecting emanation or transport. Flux-based measurements rely on natural or induced transport through the soil column to deliver the radon to a sampling volume defined over a specified area of the soil.

Measurement strategies may involve in situ techniques wherein the sampling volume and detection volume coincide in the soil environment as well as extraction techniques wherein the sample is removed from the soil matrix for analysis. Procedures exist to provide point-in-time as well as time averaged and continuous measurements.

Analysis of soil-derived samples makes use of the same detectors that are commonly applied to air and water samples. The decay series from radon, through its short-lived decay products, releases three alphas (Rn-222, Po-218, Po-214) and two gammas (Pb-214, Bi-214). For samples that can be delivered to the detector in the gas phase, alpha detection is generally preferred. Samples that immobilize radon in a solid matrix (e.g., bulk soil samples, radon adsorbed onto activated carbon) are generally analyzed using gamma spectrometry.

As a rule, additional steps are required to estimate other factors such as permeability. These additional steps, however, do not necessarily entail new measurements. In developing county-scale maps of radon potential, Gundersen et al. (1988) and Otton et al. (1988) utilized water permeability data compiled by the Soil Conservation Service as a means to define classes of gas permeability. Yokel (1989) presents a detailed summary of theoretical and empirical relationships that can be used to estimate gas permeability from soil characteristics and water permeability.

In a similar vein, soil moisture could be characterized from climatological principles (Rose et al. 1990; Thornthwaite and Mather 1955). While such estimators are unlikely to approach the accuracy of standard determinations of soil moisture (e.g., ASTM D-2216), accuracy may be acceptable because underlying models are still required to extrapolate measurements to other conditions representative of seasonal or annual levels. Similarly, Rogers and Nielson (1990) cite ongoing work to estimate gas permeability and radon diffusion coefficients from standard data sources.

RADIUM CONTENT

Basic approaches for measuring the radium content of soils are summarized in Table 1. Conventional measurements of radium content involve sealing a dried soil sample in a leakproof container, storing the sealed sample for a long enough period of time to establish radioactive equilibrium, and analyzing for radionuclides of interest using gamma spectroscopy. Protocols frequently accommodate concurrent analysis of moisture content, laboratory estimates of radon emanation, and other analyses by subdividing field samples. This is the basic procedure adopted by the Florida Radon Research Program (Williamson and Finkel 1990) and utilized in other large-scale radon studies (e.g., Kunz 1989), as well as standardized radiological surveys (Myrick et al. 1983).

The general laboratory procedure is geared to a single analysis at radioactive equilibrium. An intermediate count is sometimes included a few hours after sealing the dried sample to measure the level of nonemanating radon in order to estimate the emanation fraction under standard conditions.

The prompt bismuth technique of Stief et al. (1987) features repeated analyses over shorter timeframes to evaluate the secular equilibrium between radium and radon. In this approach, the sample is sealed under field conditions and count-rate measurements are initiated very soon thereafter to establish the basis for extrapolating subsequent measurements back to the time of collection. The prompt bismuth method is directed primarily at evaluating soil gas radon; adaptations could be considered to estimate radium concentrations in timeframes of 24 hours or less. While the prompt bismuth method has shown promising results based on developmental tests and early applications, it has not entered widespread use, and warrants comparative testing against standard techniques to establish general reliability.

SOIL GAS MEASUREMENTS

Basic technologies for measuring radon concentrations in soil gas have evolved along three complementary pathways: (1) gas extraction from depth using hollow tubes, (2) analysis of bulk soil samples, and (3) in situ detectors.

Soil Gas Extraction

A number of field investigations have utilized soil gas extraction techniques to evaluate radon concentrations in soil gas. Leading approaches are summarized in Table 2. In many cases procedures incorporate measurement of permeability using an approach originally suggested by Scott (DSMA 1983). The basic approach involves driving a hollow probe to the desired depth, connecting the upper end of the probe to a vacuum source, and monitoring pressure and flow rate through the probe. Permeability is calculated from the ratio of flow to pressure with adjustments for a probe-specific calibration factor.

The reconnaissance probe described by Reimer (1990) is a relatively simple system consisting of a small-diameter (6- to 9-mm) thick-walled carbon-steel tube that is driven to sampling depth (75 cm, nominal) using a slide hammer. The relatively small probe volume (3 cm^3) allows for purging and sample collection using a hypodermic syringe for subsequent analysis using alpha scintillation. This method has been applied through a number of field surveys (Schumann and Owen 1988; Gundersen et al. 1990), and has an operating history that dates from the mid-1970s.

The permeameter probe described by Nielson et al. (1989) is also a small-diameter (13-mm) probe that is driven to sampling depth by hand. This system, however, is further equipped for controlled flow extraction to allow for estimates of soil permeability from pressure/flow relationships as well as radon concentration by alpha scintillation. This method constitutes basic procedures adopted by the Florida Radon Research Program (Williamson and Finkel 1990), and similar systems have been used in major field studies (e.g., Kunz 1989; Liu et al. 1990). A plastic foam whose permeability is verified through independent measurement serves as a test medium to establish the calibration constant (Nielson et al. 1989). This probe is also compatible with the developmental work reported by Nazaroff and Sextro (1989).

The packer probe described by Tanner (1988a, 1988b) is a more complex apparatus that also provides simultaneous measures of radon and per- meability. This system features inflatable packers to create a "waste space" in the augered hole between the packers and a "sample space" below the lower packer. The system is devised so that the waste pump draws at a slightly greater suction on the waste space than on the sample space, intercepting any surface air so that the sample fully represents the subsoil environment.

Design elements of the packer probe originate from the invention of Hassler (1940). The inflatable packers provide the means to more firmly shape the collection geometry for drawing air from the soil pores. Preliminary experiments, however, have indicated that the sample flow is little affected by the flow level from the waste space, reinforcing the concept that permeability is greater in the horizontal than in the vertical (Tanner 1988a, 1988b). It would seem, therefore, that the main benefits of the inflatable packers is to guarantee sealing against the augered hole, and the soil ultimately shapes the transport field.

Analysis of Bulk Samples

Basic approaches for determining soil gas concentrations from bulk samples of soil generally involve sealing the sample under known conditions and measuring the evolution of radon in the sample with time. As shown in Table 3, three basic patterns can be recognized: (1) emanation, a variation of the standard laboratory test for radium that infers pore gas radon from time-related changes in a sample that has been baked to controlled dryness; (2) prompt bismuth, a second variation of the radium test that monitors time evolution of a sample that is sealed under field conditions; and (3) exhalation, involving analysis of radon escaping from the sample to a headspace.

Both the emanation technique and the prompt bismuth technique monitor the ingrowth of radon in the soil sample, producing data that readily estimate the undepleted soil gas concentration. The exhalation technique, on the other hand, is used primarily to determine the time rate of release of radon from the sample (hence the term exhalation), and requires additional information to estimate the undepleted soil gas concentration of the sample.

Exhalation tests in the laboratory involve placing a soil sample in a sealed container and monitoring the ingrowth of radon in the headspace. The radon concentration in the headspace is related to the exhalation rate through a simple mass-balance model. Colle et al. (1981) observed that, while many investigations of radon exhalation have followed the same broad principles, great differences occurred with regard to the size and composition of containers and the length of time allowed for radon to build up. Nonetheless, tests of this type have provided valuable insight with regard to the role of moisture (Stranden et al. 1984; Stranden 1983).

Back-diffusion into the sample is a concern in exhalation tests because the buildup of radon is secondarily affected, masking interpretation of the free or unattenuated exhalation rate (Jonasson 1983). Based on theoretical considerations, Samuelsson (1990) suggests that the outer volume should be at least 10 times larger than the pore volume of the sample.

In Situ Detection

Direct burial of detectors to estimate radon concentrations in the soil has been in use for some time. The main avenue of development entails forming a suitable detection volume in the soil and detecting alpha activity from radon diffusing into the cavity and subsequent decays of the short-lived progeny. As shown in Table 4, two basic techniques are evident: (1) passive detection and (2) active detection.

Passive in situ detection is probably the most widely used approach. The alpha track detector, originally developed to support uranium exploration (Fleischer at al. 1980), was soon adapted to support studies of radon in buildings (Akerblom et al. 1984). While the alpha track detector is still the system most closely identified with in situ passive measurements in the soil, the basis can be extended to other technologies. Although definitive studies remain to be done, the feasibility of the passive electret technology has been demonstrated for measuring soil gas (Kotrappa et al. 1987; Dempsey and Kotrappa 1989). Burial of activated carbon canisters to collect radon in the subsoil has been used as well (Akerblom et al. 1984). Both the alpha track technology and the electret technology require a permeable membrane to prevent thoron entry into the detection volume. Thoron does not significantly interfere with the activated carbon canister approach.

The second approach, involving placement of an active detection system (Warren 1977), presents an opportunity to study short-term effects. This latter approach has not entered widespread use. Cotter and Thomas (1989) have used this technique for continuous in situ detection of soil gas in Hawaii.

RADON FLUX

Measurement systems for radon flux seek to determine the net transfer from the soil to the atmosphere. General summaries of measurement technologies appear in publications by Colle et al. (1981), Freeman and Hartley (1986), and NCRP (1988). Basic approaches have focused on capturing radon using (1) closed accumulators, (2) flow-through accumulators, and (3) adsorption. Each of these approaches, summarized in Table 5, involves isolating an area of soil and measuring the amount of radon captured over a defined period of time.

Each of these basic methods is predicated on using the naturally prevailing convective/diffusive transport to deliver radon to the measurement system. It is logical, then, to conceive a fourth category, induced flux, to transport radon under controlled conditions. Additional methods that are frequently mentioned include the vertical profile method, which utilizes patterns of atmospheric radon and meteorology to estimate flux over large areas, and the soil concentration gradient method, which involves model estimates of surface flux from soil gas concentration data. Neither of these methods has entered widespread use.

Closed Accumulation

This approach involves direct accumulation of radon into a volume defined by the soil surface and a vessel whose open face is affixed to the soil. The radon concentration in the accumulator begins to increase as soon as the vessel is emplaced because dispersion to the atmosphere is negated. Initially, the concentration grows rapidly in direct proportion to flux. Soon, however, the rate of growth in the accumulator slows due to back-diffusion into the soil. Consequently, methodologies generally focus on acquiring grab samples during the very early stages of accumulation where linear relationships apply. Currently, grab sampling is generally accomplished by direct transfer to evacuated scintillation cells (Freeman and Hartley 1986). Of course, samples can also be drawn using intermediary containers (e.g., syringes, Tedlar bags) for subsequent transfer to scintillation cells.

Flow-through Accumulation

In an effort to more closely simulate natural conditions in the collection volume, the radon can be swept out of the accumulator and replaced with ambient air. If radon concentrations in the accumulator are maintained low enough to suppress back-diffusion, radon flux into the accumulator is proportional to the radon content of the exiting air stream. Early implementations of this method employed a closed-flow loop with a charcoal trap (chilled with dry ice) to collect radon for analysis (Pearson and Jones 1965). Subsequent designs directed the air stream to a continuous monitoring system with flow compensation drawn from ambient air (Scherry et al. 1984; Freeman and Hartley 1986). The flow-through accumulation method permits the use of larger collection areas and longer measurement periods.

Adsorption

Current applications of the adsorption method are generally drawn from the work of Countess (1976, 1977). The basic method involves placing a charcoal canister in contact with the surface for a period that may range from a few hours to a few days. Radon adsorbed on the charcoal is determined by measuring the gamma activity of the radon decay products in equilibrium with the adsorbed radon. The size and construction of charcoal canisters range from prepackaged cartridges designed for respirators to large-diameter (25 cm) canisters especially designed for flux measurements (Freeman and Hartley 1986).

Induced Flux

Principal references discussing the traditional flux measurement technologies dwell, to varying degrees, on short-term and long-term fluctuations caused by meteorological conditions, and soil state, and how these factors can influence the estimation of representative flux rates from limited duration data. This treatment is analogous to concerns for interpreting soil gas data that are unsupported by information on porosity.

Alternative approaches, then, could be considered wherein the natural transport is simply overpowered. Hassler (1940), in the patent that inspired the packer soil gas probe discussed earlier, presented the basis for a flow hood to provide for controlled transport of soil gas from the surface. Basic components involve an annular guard (to discourage re-entrainment of surface air) and an inner hood to capture soil gases.

TECHNICAL CONSIDERATIONS

Currently, there are no hard and fast criteria to provide an unambiguous reference for judging the performance of measurement technologies for radon potential. While there is little doubt that site-specific measure- ments can be used to determine the radon potential of land areas, interpretations are driven by empirical correlations and theoretical considerations. A broad consensus, however, highlights the importance of examining (1) the abundance of radon in the soil, (2) its propensity to migrate in the soil, and (3) explicit building effects.

Technologies geared to measuring (1) radium concentrations in bulk soil samples or (2) soil gas concentrations are readily applied to the problem of estimating the undepleted radon concentration in soil gas. Measurements of unattenuated flux provide estimates of diffusive transport which, in turn, could be used to estimate soil gas concentrations at depth. The induced flux method, although untested, may provide the means to directly simulate radon entry for slab-on-grade and crawl space construction. Laboratory measurements of exhalation, on the other hand, while not readily extrapolated to the soil environment, may provide clues to the relative strength of radon sources through comparative tests.

Radium-based measurements have the distinct advantage of being suited to testing water-saturated soils. Soil-gas-based measurements (extraction probes, in situ detection, flux), on the other hand, generally fail to obtain samples from saturated soils because the gas volume is nearly zero. Recognition factors to avoid generally saturated conditions can be built into protocols, as can rules to invalidate samples attempted from saturated layers encountered at depth.

Material that is permanently saturated in the native state but likely to reach varying degrees of dryness after construction, therefore, is best characterized through radium-based measurements. These circumstances are likely to occur with fill material and may occur in areas with a shallow water table that could recede as property development alters drainage patterns.

Quality assurance is a vexing question for soil gas measurements. Although analytical proficiency can be deemed acceptable, there is little information at hand to evaluate system-level performance because relatively few studies have explicitly compared technologies. A number of studies have included more than one soil measurement technique, but additional analysis would be required to formally compare methods.

PRACTICAL CONSIDERATIONS

Practical decisions are likely to be guided by two absolutes: (1) avoidance of clearly inappropriate technologies, and (2) meeting the schedule demands of the situation. For the radium-based measurements, the all-weather capability must be judged against the lengthy time period necessary to achieve radioactive equilibrium. Delays could be shortened by taking more counts during the ingrowth period to extrapolate data to equilibrium levels. For soils with a low emanation fraction, a number of days may need to elapse to resolve the trend, but turnaround time could, in concept, be reduced to a matter of days. Further, initial count data offer information to provide a rough estimate without extended waits.

While the soil gas extraction techniques are not suited to testing under saturated conditions, the simplicity of equipment and field operations for the hand-driven probes can deliver prompt results, making the reconnaissance probe and the permeameter probe likely candidates for widespread use. The packer probe is a bit more complex and requires an augered hole, but delivers data in a short timeframe.

In situ detectors offer possibly the least expensive approach. Emplacing detectors at a satisfactory depth (1 m) and retrieving them may present a problem. The main disadvantages, however, could arise from the need to sample for relatively long periods of time and from unreliable results in the presence of high moisture levels.

As noted earlier, measurements of unattenuated flux can be converted to estimates of soil gas radon at depth. This conversion, however, is predicated on model assumptions that may go unverified in the field. Similarly, laboratory exhalation cannot be readily extrapolated to quan- tatative estimators of radon potential. The induced flux technique may prove to be a useful test apparatus for soils receiving slab-on-grade or crawl space construction. At the present time, however, it is an untested technology.

CONCLUSIONS

At the present time, the principal means to confirm indoor radon levels involves testing buildings, not land. Although this is likely to continue to be the main verification, soil-based measurements can help to identify land areas warranting special attention for risk communication programs as well as site-specific decisions for varying degrees of radon-resistant construction.

Each of the technologies summarized here is capable of providing useful information to evaluate radon potential. With the exception of the induced flux technique, all of the measurement techniques discussed here are supported by documented field experience and, in many cases, by published protocols. However, the means to estimate radon potential from field data is still evolving. How this evolution affects the definition of consensus protocols remains to be seen.

ACKNOWLEDGEMENTS

The work leading to this paper was funded by the Department of Community Affairs of the State of Florida and the United States Environmental Protection Agency (through EPA Contract No. 68-D9-0166).

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.

REFERENCES

Akerblom, G., P. Andersson, and B. Clavensjo. Soil Gas Radon--A Source for Indoor Radon Daughters. Radiation Protection Dosimetry, vol. 7, pp. 49-54, 1984.

Colle, R., R.J. Rubin, L.I. Knab, and J.M.R. Hutchinson. Radon Transport Through and Exhalation From Building Materials. Report No. 1139, National Bureau of Standards, Gaithersburg, MD, 1981.

Cotter, J., and D.M. Thomas. Ground Gas Radon Response to Meteorological Perturbations [Abstract]. EOS, American Geophysical Union Transactions, vol. 70, No. 15, pp. 497, 1989.

Countess, R.J. Rn-222 Flux Measurements With a Charcoal Canister. Health Physics, vol. 31, pp. 456-457, 1976.

Countess, R.J. Measurement of Radon Flux With Charcoal Canisters, pp. 139-154. IN: Atomic Industrial Forum Workshop on Methods of Measuring Radon in and Around Uranium Mills, 1977.

Dempsey, J.C., and P. Kotrappa. Subsoil Radioactive Gas Measuring System. U.S. Patent No. 4,814,608, 1989.

DSMA Atcon, Ltd. Review of Existing Instruments and Evaluation of Possibilities for Research and Development of Instrumentation to Determine Future Levels of Radon at a Proposed Building Site. Report No. INFO-0096, Atomic Energy Control Board, Ottawa, Canada, 1983.

Duval, J.S., W.J. Jones, F.R. Riggle, and J.A. Pitkin. Equivalent Uranium Map of the Conterminous United States. U.S. Geological Survey, Open-File Report No. 89-478, 1989.

Fleischer, R.L., W.R. Giard, A. Mogro-Campero, L.G. Turner, H.W. Alter, and J.E. Gingrich. Dosimetry of Environmental Radon: Methods and Theory of Low-Dose, Integrated Measurements. Health Physics, vol. 39, pp. 957-962, 1980.

Freeman, H.D., and J.N. Hartley. Radon Flux Measurement Technology, pp. 167-181. IN: Indoor Radon, SP-54, Air Pollution Control Association, Pittsburgh, PA, 1986.

Gundersen L.C.S., G.M. Reimer, C.R. Wiggs, and C.A. Rice. Map Showing Radon Potential of Rocks and Soils in Montgomery County, MD. U.S. Geological Survey Map MF-2043, 1988.

Gundersen, L.C.S., T.R. Peake, G.D. Latzke, L.M. Hauser, and C.R. Wiggs. A Statistical Summary of Uranium and Radon in Soils From the Coastal Plain of Texas, Alabama, and New Jersey. Presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 19-23, 1990.

Hassler, G.L. Soil Gas Sampling Device and Method. U.S. Patent No. 2,210,546, 1940.

Jonasson, N. The Determination of Radon Exhalation Rates. Health Physics, vol. 45, No. 2, pp. 369-376, 1983.

Kotrappa, P., J.C. Dempsey, and J.R. Hickey. Development of an Electret Passive Environmental Radon Monitor. Report No. 86-13, New York State Energy Research and Development Administration, Albany, NY, 1987.

Kunz, C. Influence of Surficial Soil and Bedrock on Indoor Radon in New York State Homes. Report No. 89-14, New York State Energy Research and Development Administration, Albany, NY, 1989.

Liu, K., S. B. Hayward, J. R. Girman, B. A. Moed, and F. Huang. Survey of Residential Indoor and Outdoor Radon Concentrations in California. Report No. CA/DOH/AIHL/SP-53, California Air Resources Board, Sacramento, CA, 1990.

Lindmark, A., and B. Rosen. Radon in Soil Gas-Exhalation Tests and In Situ Measurements. The Science of the Total Environment, vol. 45, pp. 397-404, 1985.

Myrick, T.E., B.A. Bervin, and F.F. Haywood. Determination of Concentrations of Selected Radionuclides in Surface Soil in the U.S. Health Physics, vol. 45, pp. 631-642, 1983.

Nazaroff, W.W., and R.G. Sextro. Technique for Measuring the Indoor Rn-222 Source Potential of Soil. Environmental Science and Technology, vol. 23, No. 4, pp. 451-458, 1989.

NCRP. Measurement of Radon and Radon Daughters in Air. Report No. 97, National Council on Radiation Protection and Measurements, Bethesda, MD, 1988.

Nielson, K.K., M.K. Bollenbacher, V.C. Rogers, and G. Woodruff. Users Guide for the MK-II Radon/Permeability Sampler. Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, DC, 1989.

Otton, J.K., R.R. Schumann, D.E. Owen, N. Thurman, and J.S. Duval. Map Showing Radon Potential of Rocks and Soils in Fairfax County, VA. U.S. Geological Survey Map MF-2047, 1988.

Pearson, J.E., and G.E. Jones. Emanation of Radon-222 From Soils and Its Use as a Tracer. Journal of Geophysical Research, vol. 70, pp. 5279-5289, 1965.

Reimer, G.M. Reconnaissance Techniques for Determining Soil-Gas Radon Concentrations: An Example from Prince Georges County, MD. Geophysical Research Letters, vol. 17, No. 6, pp. 809-812, 1990.

Rogers, V.C., and K.K. Nielson. Benchmark and Application of the RAETRAD Model. Presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 19-23, 1990.

Rose, A.W., E.J. Ciolkosz, and J.W. Washington. Effects of Regional and Seasonal Variations in Soil Moisture and Temperature on Soil Gas Radon, Presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 19-23, 1990.

Samuelsson, C., The Closed-Can Exhalation Method for Measuring Radon. Journal of Research of the National Institute of Standards and Technology. vol. 95, pp. 167-169, 1990.

Scherry, S.D, D.H. Gaeddert, and M.H. Wilkening. Factors Affecting Exhalation of Radon From a Gravelly Sandy Loam. Journal of Geophysical Research, vol. 89, pp. 7299-7309, 1984.

Schumann, R.R., and D.E. Owen. Relationships Between Geology, Equivalent Uranium Concentration, and Radon in Soil Gas, Fairfax County, VA. Open-File Report No. 88-18, U.S. Geological Survey, 1988.

Stieff, L.R., C.B. Stieff, and R.A. Nelson. Field Measurements of In Situ Rn-222 Concentrations in Soil Based on the Prompt Decay of the Bi-214 Counting Rate. Nuclear Geophysics, vol. 1, pp. 183-195, 1987.

Stranden, E. Assessment of the Radiological Impact of Using Fly Ash in Cement. Health Physics, vol. 44, pp. 145-153, 1983.

Stranden, E., A.K. Kolstad, and B. Lind. Radon Exhalation: Moisture Dependence. Health Physics, vol. 47, pp. 480-484, 1984.

Swedjemark, G.A. Swedish Limitation Schemes to Decrease Rn Daughters in Indoor Air. Health Physics, vol. 51, pp. 569-578, 1986.

Tanner, A.B. A Tentative Protocol for Measurement of Radon Availability From the Ground. Radiation Protection Dosimetry, vol. 24, pp. 79-83, 1988a.

Tanner, A.B. Measurement of Radon Availability from Soil. In: Geologic Cause of Natural Radionuclide Anomalies (M.S. Marikos and R.H. Hansman, eds.) Survey Special Publication No. 4, pp. 139-146, Missouri Department of Natural Resources, Rolla, MO, 1988b.

Thornthwaite, C.W., and J.R. Mather. The Water Budget and Its Use in Irrigation, pp. 346-361. IN: The Yearbook of Agriculture 1955: Water, U.S. Government Printing Office, Washington, DC., 1955.

Warren, R.K. Recent Developments in Uranium Exploration With Electronic Alpha Cups. Geophysics, vol. 42, pp. 982-989, 1977.

Wilkening, M.H., W.E. Clements, and D. Stanley. Radon-222 Flux Measurements in Widely Separated Regions, pp 717-730. IN: The Natural Radiation Environment II (J.A.S. Adams, T.F. Gesell, and W.M. Lowder, eds.), CONF-720805-P2, U.S. Atomic Energy Commission, Washington, DC, 1972.

Williamson, A.D., and J.M. Finkel. Standard Measurement Protocols. Report No. SRI-ENV-90-070-6411. Prepared for the Department of Community Affairs, State of Florida, Tallahassee, FL, 1990.

Wilson, C. Mapping the Radon Risk of Our Environment, pp. 85-92. IN: Indoor Air (Volume 2) Radon, Passive Smoking, Particulates and Housing Epidemiology Indoor Air, Swedish Council for Building Research, Stockholm, Sweden, 1984.

Yokel, F.Y. Site Characterization for Radon Source Potential. Report No. NISTR 89-4106, National Institute of Standards and Technology, Gaithersburg, MD, 1989.

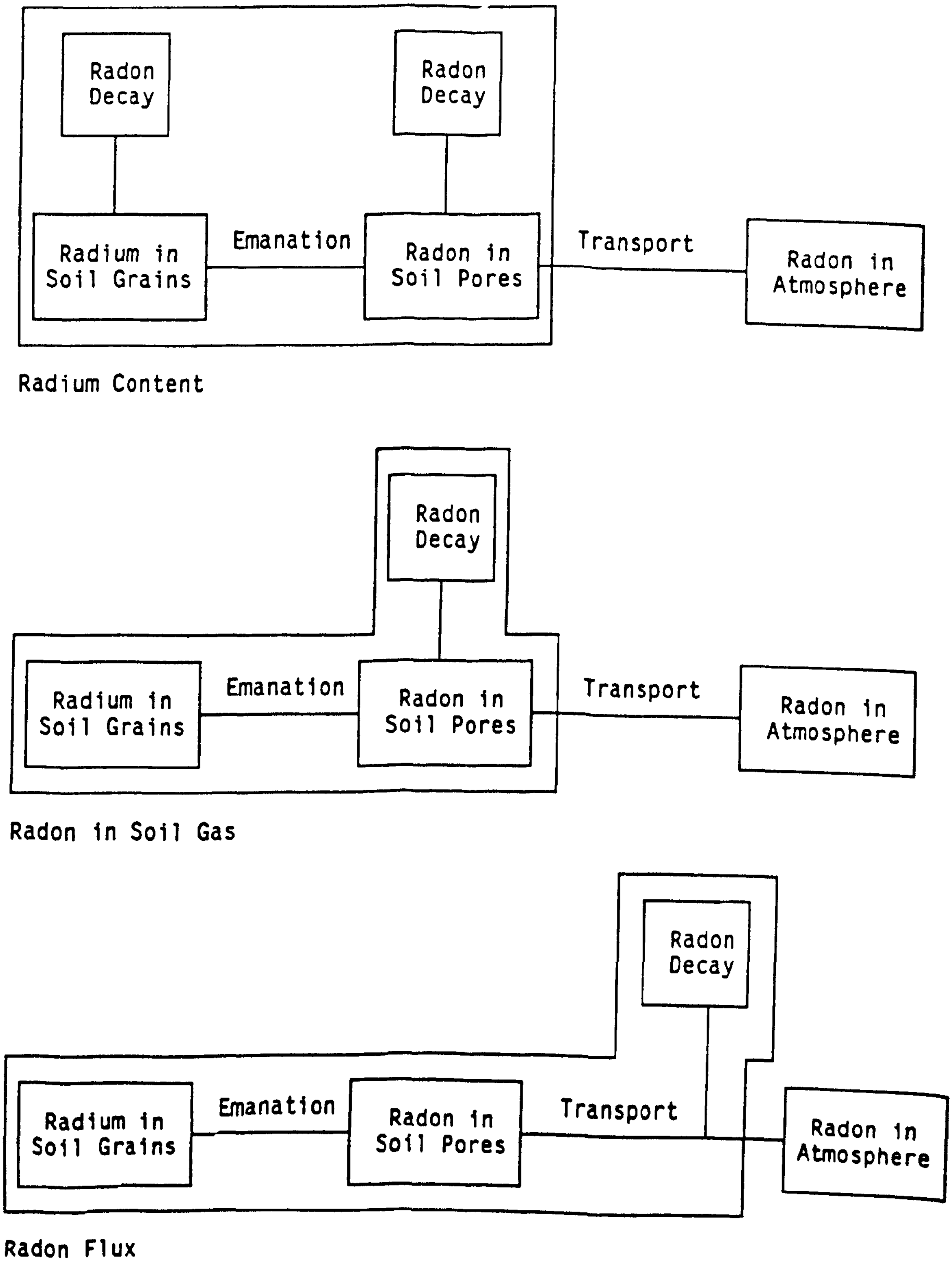


Figure 1. Sampling strategies for radon in the soil.

TABLE 1. SUMMARY OF APPROACHES TO MEASURING RADIUM CONTENT OF SOILS

Approach	Procedures/Equipment	References
Laboratory Analysis	Weigh sample, heat to dryness, store in sealed container to achieve radioactive equilibrium, analyze by gamma spectroscopy.	Williamson and Finkel (1990)
Prompt Bismuth	Seal sample and weigh at time of collection, analyze by gamma spectroscopy within 2 hours after collection, repeat analysis at 4 to 12 hours and at radioactive equilibrium.	Stieff et al. (1987)

TABLE 2. SUMMARY OF APPROACHES FOR MEASURING RADON IN SOIL GASES WITH GAS EXTRACTION PROBES

Approach	Procedures/Equipment	References
Reconnaissance Probe	Small-diameter (9-mm) probe is driven to 75-cm depth, gas sample is extracted by syringe, analysis is by scintillation.	Reimer (1990)
Permeameter Probe	Small-diameter (13-mm) probe is driven to depths of 46, 61, 76, and 122 cm; pressure/flow relationships are used to estimate permeability; soil gas samples are drawn from the 122 cm depth to flow-through scintillation cells for subsequent analysis.	Nielsen et al. (1989)
Packer Probe	Moderate diameter (27-mm) probe is inserted into 3.5-cm diameter hole to augered depth of 1 m; inflatable packers isolate sample space, and sample air is drawn to flow-through scintillation cell for analysis; permeability is estimated from pressure/flow relationships.	Tanner (1988a,b) Hassler (1940)

TABLE 3. SUMMARY Of APPROACHES FOR MEASURING RADON IN SOIL GAS FROM BULK SAMPLES

Approach	Procedures/Equipment	References
Emanation	Weigh sample, heat to dryness, reweigh, store in sealed container; analyze by gamma spectroscopy within 4 to 36 hours of sealing and again after radioactive equilibrium is achieved.	Williamson and Finkel (1990)
Prompt Bismuth	Seal and weigh sample at time of collection, analyze by gamma spectroscopy within 2 hours after collection; reanalyze at 4 to 12 hours, and at radioactive equilibrium.	Stieff at al. (1987)
Exhalation	Place soil sample in sealed container, measure outgassed radon in headspace.	Jonasson (1983) Samuelsson (1990)

TABLE 4. SUMMARY OF APPROACHES FOR IN SITU DETECTION OF RADON IN SOIL GAS

Approach	Procedures/Equipment	References
Passive Dosimeter	Passive dosimeter is buried in soil; decays of radon diffusing into detection volume and subsequently formed radon progeny are registered.	Fleischer et al. (1980)
Active	Electronic detector is buried in soil; decays of radon diffusing into detection volume and subsequently formed radon progeny are recorded by the detector.	Warren (1977)

TABLE 5. BASIC APPROACHES FOR MEASURING SOIL FLUX

Approach	Procedures/Equipment	References
Closed Accumulation	An open-ended vessel is sealed to the surface; ingrowth of radon is measured over time.	Wilkening et al. (1972)
Flow-through Accumulation	An open-ended vessel is sealed to the surface; radon entering the vessel is swept to a collector or monitor for measurement.	Freeman and Hartley (1986)
Adsorption	Exhaled radon is adsorbed onto granular charcoal; the charcoal bed is removed to laboratory for analysis.	Countess (1976, 1977)
Induced Flux	A hood is attached to the surface and radon is transported under controlled evacuation.	Hassler (1940)

RESULTS FROM A PILOT STUDY TO COMPARE RESIDENTIAL RADON CONCENTRATIONS WITH OCCUPANT EXPOSURES USING PERSONAL MONITORING

by: B. R. Litt
New Jersey Dept. of Environmental Protection
Division of Science and Research, CN-409
Trenton, New Jersey 08625

J. M. Waldman
Dept. of Environmental and Community Medicine
Robert Wood Johnson Medical School, UMDNJ
675 Hoes Lane
Piscataway, New Jersey 08854

N. H. Harley and P. Chittaporn
Dept. of Environmental Medicine
New York University Medical Center
550 1st Ave.
New York, New York 10016

ABSTRACT

Radon concentrations in indoor air are usually measured for a few days to months in one or two locations in a home. This approach can lead to errors when estimating occupant exposures. We investigated whether occupant exposures to radon could be better determined by person-based measurements than by stationary home measurements.

A pilot study was conducted in 6 homes with elevated radon levels. Occupants wore personal radon monitors (PRMs), developed for use in this research. Using room occupancy and activity diaries, personal exposures were compared with measurements from stationary monitors. Stationary measurements included identical PRMs placed in many rooms of the home, as well as the occupant's workplace; continuous radon measurements in the principal activity room; and continuous progeny measurements in at least two locations per house. Studies were conducted for one-week periods in winter, with 2 homes also studied in summer. PRM validation and pilot study results are presented.

INTRODUCTION

Since 1985, many measurements of radon-222 concentrations in indoor air have been made throughout the USA. Many have been made by private citizens, to determine whether they should remediate their homes. Others have been made by government agencies, to assess the magnitude and distribution of the public health threat posed by radon (1). Measurements are usually made with integrating detectors over several days to months in one or two locations in a home. A simple, yet widely accepted, model is that such measurements accurately estimate inhabitant exposures. Until the present study, however, this model had not been tested using actual measurements of person-based exposures. Accurate exposure estimates are necessary to understand better the health risks associated with measured concentrations of radon.

Indoor radon concentrations can exhibit major spatial and temporal variability. The temporal variations occur both on long (seasonal) and short (hours or days) timescales (2). In different zones of a single house, concentrations differing by factors of 2-3 are routinely seen, and factors of 10 can be encountered (3). In addition, people are mobile both in space and time, within and outside their homes. For these reasons, it is likely that an inhabitant's exposure may differ significantly from exposure to a time-integrating detector placed in a single location.

This pilot-scale study investigates personal exposures to radon in the home using fixed and portable (person-based) monitors. A personal radon monitor used in this work is validated. The relationship between stationary radon and radon progeny measurements and occupant exposures to radon gas has been studied. Simple models for personal radon exposure are tested. The project has provided data needed to assess the utility of personal radon monitoring in a residential setting.

EXPERIMENTAL DESIGN

Homes studied were known to have elevated radon levels (i.e., greater than 300 Bq/m^3 (8 pCi/L) in living areas as determined by New Jersey Department of Environmental Protection's (NJDEP) Radon Confirmatory Monitoring Program 3-day charcoal canister measurement). Elevated levels were desirable to ensure that there was measurable radon exposure without requiring long measurement periods. In addition, homes had at least two occupants willing to wear the personal monitors. While study participants were not statistically selected, an attempt was made to include people of different lifestyles. It turned out that all homes studied had basements, none of which were regularly occupied as living space.

Studies were conducted for one-week periods. In winter of 1989 to 1990, six homes (Houses A through F) were studied, with a total of 13 occupants. Of the six, four households dropped out of the study after the winter measurements, to seek radon mitigation. Houses B and F were revisited the following summer, with a total of three occupants restudied. House A has been excluded from this data analysis because an earlier version of the PRM was used, which did not have sufficient precision for the relatively low exposures to be measured in this study. Before studying Houses B-F, modifications were made to the PRM which substantially improved precision.

Study participants wore PRMs everywhere throughout the study, except into the shower or in bed, where they placed the PRMs nearby. Coincidental stationary radon and radon progeny measurements were made in various zones of the home and the occupant's workplace. The type, duration and location of the measurements are shown for a prototypical house in Fig. 1.

Participants completed activity diaries each day, recalling where they went and what they did over the past 24 hours. In addition to location, the activity diary chronicled heating and ventilation, appliance use, smoking (active and passive) and the presence of guests in the home. The activity diary also asked whether the person had forgotten to wear the PRM that day, and if so, when, where, and for how long.

The stationary and person-based PRMs were exposed for 2-day periods and then exchanged for fresh PRMs. This was done for a total of three exposure periods. In this way, the measurements were repeated several times for each house. In House A unequal periods of 1, 2, and 4 days were used, because the optimum period was not known. Subsequent homes used repeated 2-day exposures. The exposure periods usually began in the evening, because that was most convenient for participants. The middle exposure period ran from Friday evening to Sunday evening, representing weekend behavior for participants who had normal work schedules. The other two periods represented the weekday routine.

The study participants were sent the results of the stationary measurements made in their homes. In addition, they were sent a follow-up questionnaire to evaluate many aspects of the study. In general, people found study participation interesting and not too intrusive. However, people were unanimous in wanting a smaller, less obtrusive PRM.

METHODS

The sensitive, passive, integrating personal radon monitor (PRM) has been developed specifically for use in this project (4)[1]. Radon diffuses into the monitor through a conducting foam barrier which keeps out the progeny. The radon detector is CR-39[2], a solid state nuclear track film. Gamma ray exposure data are obtained from CaF_2 thermoluminescent chips[3] (TLD) placed beneath the CR-39. The CR-39 and CaF_2 TLD are covered with thin aluminized Mylar which nullifies any charge artifacts. Each monitor has provision for triplicate CR-39 film and TLD exposures. Duplicate films and TLDs were used for this project. Only the radon measurements are discussed in this paper. Made of lightweight conducting plastic, the version of the PRM housing used in this research is a cylinder, 7.5 cm in diameter and 3.0 cm in height. It is designed to be worn on a belt. The PRM is shown in Fig. 2. Extensive chamber studies and calibrations have been performed on the PRM. As a quality control measure, in addition to the internal duplicates, all PRM measurements in this pilot study were also made in duplicate. Occasionally larger numbers of replicate exposures were done. Results of the PRM performance assessment work are presented below.

Trip blanks accompanied the PRMs and any exposure gained during transit was subtracted. This was necessary because the PRMs were active from the time they left the laboratory to the time they returned. For the periods used in this study, the trip blanks had an average of 8 tracks, compared with 4 tracks for the laboratory blanks.

To minimize transit/storage exposures, PRMs were sent to and from the laboratory using overnight mail. If short term storage was necessary, PRMs were kept in a "low radon area" (a car trunk). The transit/storage exposure subtraction was especially important for low radon exposures (such as those obtained in a subject's workplace) and for the gamma ray exposure measurements. Because the study was done in homes with elevated radon levels, the transit/storage exposures were typically a small fraction of the overall exposures. The exposures reported here are those received by the subjects or by stationary PRMs in their locations of interest.

A variety of techniques were used to make the stationary measurements. PRMs were used in a stationary mode to make 2-day integrating measurements. Continuous (hourly average) radon measurements were made with Pylon Model AB-5 radiation monitors equipped with passive radon detectors. Continuous progeny measurements were made with Eberline continuous working level monitors. In addition to PRMs, charcoal canisters were used to make integrated radon measurements, due to their widespread use for this application. Charcoal canisters were placed at least one meter from PRMs and other passive radon

---

[1]Patent application filed.

[2]Obtained from TechOps/Landauer in batch quantities pre-cut for this detector.

[3]Obtained from Harshaw/Filtrol Partnership, Cleveland, OH.

RESULTS

EXPOSURE RESULTS

The person-based exposure measurements (E_{mp}) are compared with stationary measurements in several ways. First, the measured exposures, in Bq m^{-3} h, are compared with the exposures an occupant spending all the time in the basement, or in the living area would receive. The average basement exposure (E_{m0}) is understood to be a gross approximation to exposure, but is nevertheless used by some policymakers and homeowners to estimate occupant exposures. The average living area exposure (E_{m1}) or the average sleeping area exposure (E_{m2}) would be expected to better approximate occupant exposures. The measured exposures for each participant are also compared with exposures calculated according to the model (E_{cp}),

$$E_{cp}=\sum_i Rn_i T_i + Rn_w T_w + Rn_b T_{out}$$

where Rn_i is the average radon concentration in the ith zone of the home, Rn_w is the average radon concentration at work, $T_{i,w}$ is the time spent in a zone or at work, Rn_b is the background, or outdoor radon, and T_{out} is the time spent not in a monitored area (for example, outdoors, in transit, or shopping). The value of Rn_b is determined from the difference in trip and laboratory blanks and is typically 7 Bq m^{-3} (0.2 pCi L^{-1}). For all the winter and most summer measurements, this last term is negligible compared with the other exposure terms.

The comparisons of E_{mp} with the various exposure estimates are shown in Figures 4-7. The lines in these figures are linear regression lines, without intercepts. The slopes and coefficients of determination are given in the figure captions. Fits were significantly better without intercepts than with them.

TABLE 1. AVERAGE RATIOS OF MEASURED PERSONAL EXPOSURES TO BASEMENT, LIVING AREA, BEDROOM AND CALCULATED PERSONAL EXPOSURES

Season	N	$E_{mp}:E_{m0}$	$E_{mp}:E_{m1}$	$E_{mp}:E_{m2}$	$E_{mp}:E_{cp}$
Winter	33	0.30±0.04[a]	0.80±0.10[a]	0.72±0.10[a]	1.17±0.18[a]
Summer	9	0.42±0.17	0.74±0.30	1.05±0.44	1.30±0.62
Combined	42	0.33±0.05	0.78±0.10	0.80±0.12	1.20±0.20
Combined[b]	42	0.19±0.02	0.60±0.10	0.59±0.08	1.03±0.16
Combined[c]	42	0.26±0.05	0.86±0.18	0.70±0.08	1.18±0.13

[a] 95% confidence limit.
[b] Numbers given are weighted averages.
[c] Numbers given are unweighted linear regression coefficients with E_{mp} the dependent variable.

The average ratios of E_{mp} to these parameters are summarized in Table 1. Weighted averages were also calculated (the weighting was derived by propagating the counting errors for each datum). This was done to investigate whether the few higher exposures would unduly influence the conclusions. The weighting does make a difference, albeit not a large one, in the ratios. From Table 1, we conclude that a typical study participant received 60% of the radon exposure that a stationary monitor placed in the living space received. As indicated by the good correspondence of E_{mp} to E_{cp}, people who spent less time at home, or less time in high radon areas of the home, received less exposure. Winter and summer results appear to have differences, but measurement equipment. A hygrothermograph placed in the basement recorded the temperature and humidity throughout the study period.

Integrating 6-day radon measurements were made in the workplaces of participants employed outside the home. A pair of stationary PRMs was sent to work on the first day of the study, and brought home on the last day.

PRM CHARACTERISTICS AND VALIDATION

CHARACTERISTICS

As part of the development of the PRM, extensive studies were done in the radon chamber of the USDOE's Environmental Measurements Laboratory (4). Calibrations verified that the response of the detector is linear in the exposure range of interest. The calibration factor obtained was 2.6 tracks (kBq m^{-3} $h)^{-1}$, or 2.3 tracks (pCi L^{-1} $d)^{-1}$. Subsequently, the PRM was entered in the 1990 USDOE radon intercomparison. The result, based on the average of 4 monitors, was $98 \pm 3\%$ of the "true" value.

Two other PRM properties that were characterized are the diffusion time of radon into the PRM chamber and the effect of a moving air stream on the calibration factor. The diffusion of radon into the PRM chamber was studied. The half-time for radon diffusion was determined to be approximately 4 minutes. This is a desirable diffusion time, as it is short enough to allow exposures due to relatively short times spent in high radon areas to be registered, but it is not so short as to allow for significant signal from any thoron gas that might be present.

The moving air stream effect was studied by placing PRMs in the radon chamber in front of a fan. At a face velocity of 3.7 km h^{-1} the calibration factor doubled. This velocity might be attained by brisk walkers. The moving air stream effect was not expected to make a significant contribution to the exposure measurements. The exposure data were examined for the presence of systematic errors that could arise from this moving air stream effect. Any such errors that might have been present were not detectable.

FIELD VALIDATION

The comparisons of stationary PRM exposures with co-located continuous radon measurements and charcoal canister measurements are shown in Fig. 3. The dashed line is a guide to the eye, of slope 1, through the origin. The agreement is quite good in the lower exposure range. Discrepancies in the higher exposure range can be explained by experimental errors, specifically in the calibration factors, especially since the continuous measurements are consistently higher than the PRM and the charcoal canisters are consistently lower.

We expected the precision of the PRM measurements to be governed by counting error in the relatively low exposure region encountered in this study. To investigate this hypothesis, the relative standard deviations of the stationary and person-based replicate measurements versus radon exposure (in units of mean tracks) have been studied. Analysis indicates that the distribution of observed relative standard deviations is consistent with what is expected due to counting error. We thus conclude that, in the exposure range of interest, the PRM precision is limited by counting error.

To directly verify the accuracy of the person-based PRM measurements it would be ideal to have people wear PRMs for a known time in a known radon environment, such as a chamber. Such tests have not been done in this work, for practical and ethical reasons. Instead, the person-based exposure measurements (E_{mp}) were compared with the expected exposures (E_{cp}). The expected exposures were calculated from the stationary measurements and from the occupancy data reported in the activity diaries. This analysis and its results are discussed in detail in the next section. From this analysis we conclude that if a bias is present (due to the moving air stream effect, or from other sources) it is small.

the small sample size and low summer exposures obscure the causes, if any, of these differences. One obvious source of winter/summer differences is participants leaving their monitors at home, as reported.

CONTINUOUS MONITORING RESULTS

The continuous radon and radon progeny data are being examined both qualitatively and quantitatively. The data have been examined qualitatively in two ways. First, effects that could be correlated with human activities were sought. For the radon data, occupant's records of ventilation were compared with the occurrence of any radon peaks or troughs. For the progeny data, the coincidence of changes in the equilibrium ratio with occupant activities (for example, ventilation, cleaning, and smoking) was investigated. Second, any major time-variations in radon concentration taking place in the presence of occupants were noted. The quantitative analysis applies standard statistical methods to obtain information on the time-variation of radon and radon progeny in the study houses. Results are not ready to report at this time, but may be available by April.

DISCUSSION AND CONCLUSIONS

The sample size in this pilot study is far too small to draw conclusions that are representative of the general housing stock, or of the general population. Nevertheless, some patterns are clear here, and probably can be generalized. This is particularly true when these patterns confirm what is expected from "common sense".

One important pattern is the good agreement of measured occupant exposures with expected exposures. This tends to confirm that 1) the exposure model commonly used is correct, 2) the PRMs and study participants performed well and 3) the most significant source of indoor radon exposure is the home. Another pattern is that measurments made in basements that are not regularly occupied consistently overestimate occupant exposures. The degree of this overestimation is dependent on the distribution of radon within the house and how much time is spent at home. Measurements made in sleeping areas and living areas correlate better with and overestimate by less occupant exposures than the comparable basement measurements.

There are a number of directions in which future research using the PRMs could be directed. First, it would be desirable to have a smaller version of the PRM, so that it could be worn for longer periods without distraction or discomfort. It should be possible to make a much smaller version without sacrificing sensitivity.

Once this is accomplished, the PRM could be used in a much larger, simpler population-based exposure assessment. This could simply compare person-based exposures to stationary exposures. Activity diaries and continuous measurements could be done in a subset of homes for quality assurance purposes. Because the PRM could be worn for a longer time, it would not be necessary to study occupants of homes with elevated radon levels. Data gathered in such a study could contribute to the ongoing efforts of epidemiologists to better understand the health threat posed by indoor radon.

Another area in which the PRM may be of use is in characterizing the nature of occupant exposure to radon arising from sources other than soil gas. In the U. S., this would mainly be domestic well water. Occupants of homes with elevated radon in water, in which soil gas is not a significant radon source could be studied. In combination with other monitoring techniques, actual human exposure could be determined, as distinct from the average contribution of radon in water concentrations to radon in air concentrations.

ACKNOWLEDGEMENTS

The contributions of many individuals and organizations to this work are gratefully acknowledged: the New Jersey families who participated, NJDEP's Division of Science and Research, NJDEP's Radon Section, Princeton University's Center for Energy and Environmental Studies USDOE's Environmental Measurements Laboratory, S. C. Scarpitta, N. Freeman, and E. Wong. Major funding for this work was provided by the New Jersey State Commission on Cancer Research, grant #88-602-CCR-00 and NJDEP DSR contract #P50587.

The work described in this paper was not funded by the U.S Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

REFERENCES

1. For example: Camp Dresser & McKee. Statewide scientific study of radon summary report. New Jersey Department of Environmental Protection, Trenton, NJ, 1989.; and Dzuiban, J. A. et al. Residential radon survey of 25 states. Paper presented at the 1990 Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 19-23, 1990.

2. For example: Gessell, T. F. Background atmospheric radon-222 concentrations outdoors and indoors: a review. Health Physics. 45: 289, 1983.; and

3. Camp Dresser & McKee. Statewide scientific study of radon task 5 final report. New Jersey Department of Environmental Protection, Trenton, NJ, 1989.

4. Harley, N. H. et al. Study of the influence of time-activity patterns and lifestyle on human exposure to radon in air, part I: Developement of a personal radon monitor; draft report. New Jersey Department of Environmental Protection, Trenton, NJ, 1990.

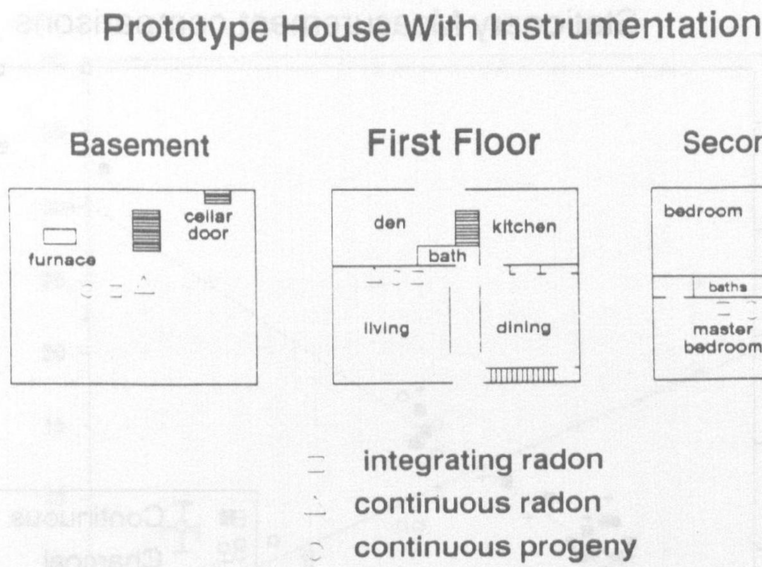


Figure 1. Prototypical study home, showing locations of stationary radon and radon progeny measurements.

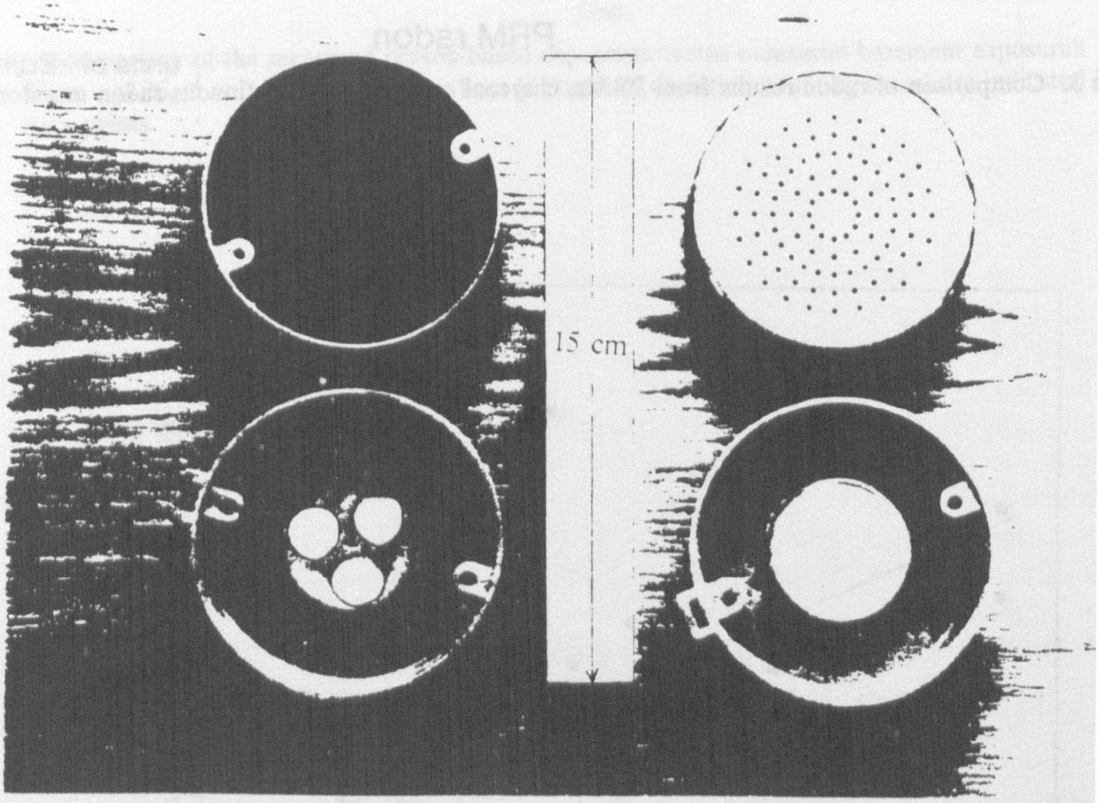


Figure 2. Photograph of the Personal Radon Monitor (PRM). Top left: inside of the PRM top, with conducting foam. Bottom left: PRM bottom, with three wells that hold the round TLD chips and square CR-39 films. Top right: outside of PRM top. Bottom right: aluminized Mylar covering the detectors.

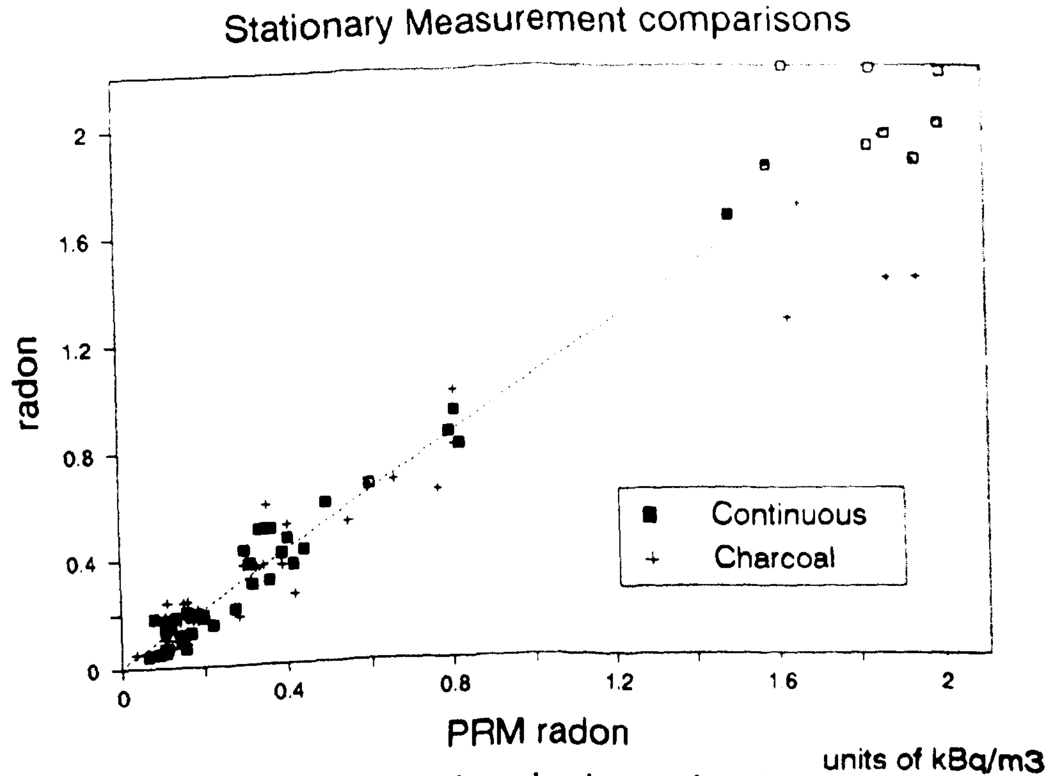


Figure 3. Comparison of radon results from PRMs, charcoal canisters, and continuous radon monitors.

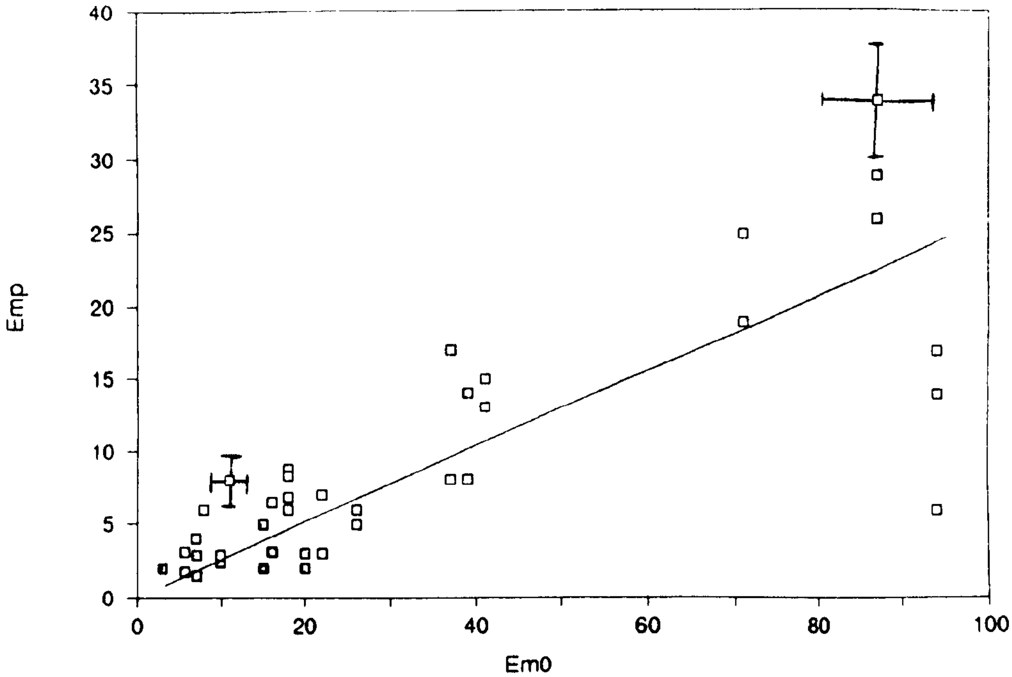


Figure 4. Comparison of the measured person-based exposures versus measured basement exposures. Slope = 0.26, r^2 = 0.65. Sample error bars (1 standard deviation counting error) are indicated for two data points.

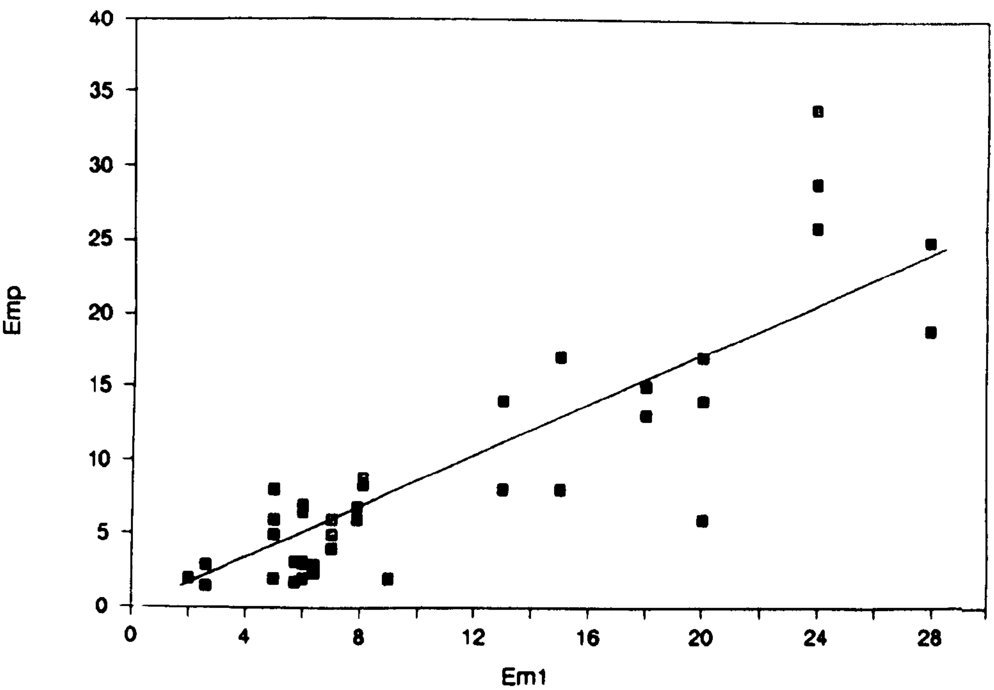


Figure 5. Comparison of the measured person-based exposures versus measured living area exposures. Slope = 0.86, r^2 = 0.77.

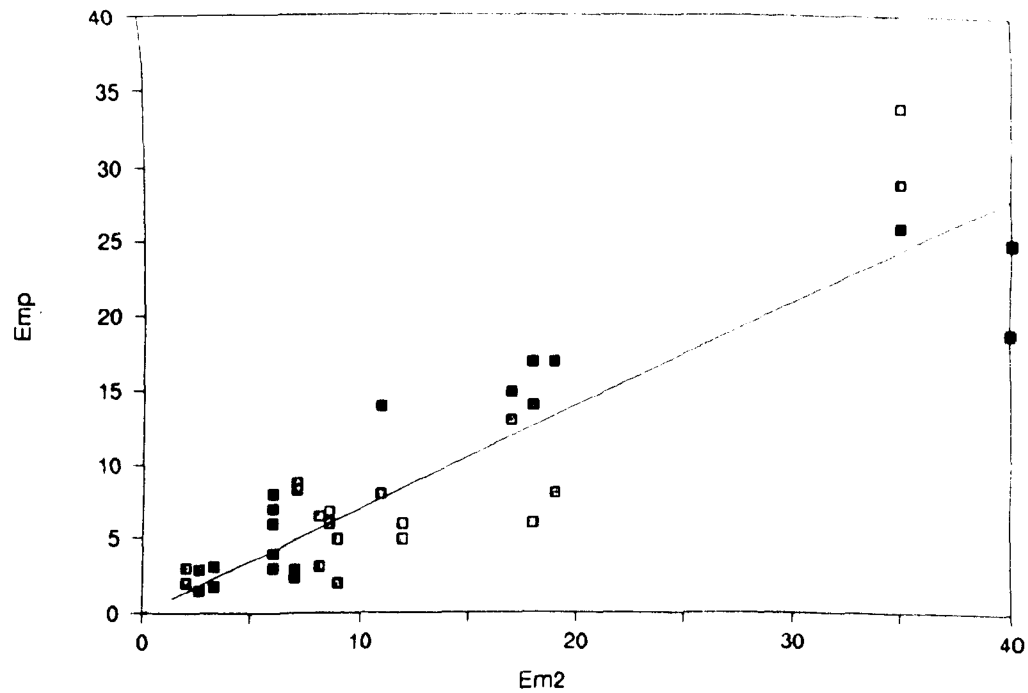


Figure 6. Comparison of the measured person-based exposures versus measured bedroom exposures. Slope = 0.70, r^2 = 0.84.

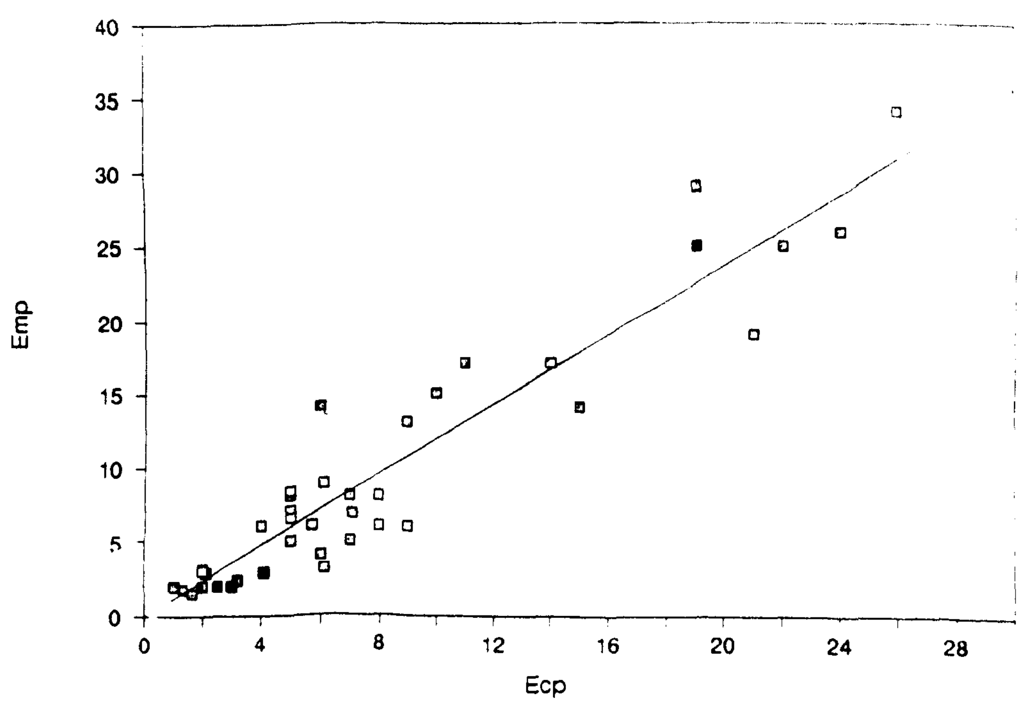


Figure 7. Comparison of the measured versus calculated person-based exposures. Slope = 1.18, r^2 = 0.90.

RAPID DETERMINATION OF THE RADON PROFILE IN A STRUCTURE BY MEASURING IONS IN THE AMBIENT ATMOSPHERE

W.G. Buckman and H.B. Steen III
Western Kentucky University
Bowling Green, KY 42101
(502) 745-4357

ABSTRACT

Normal background radiation produces about five (5) ion pairs per cubic centimeter per second with an average lifetime of about five minutes and an average concentration of about 1,600 ions per cubic centimeter. Elevated radon in the air also increases the ion concentration in the air. A simple and inexpensive electrostatic measuring device** using a charged metal sphere and an electrostatic charge detector enables one to detect low ion concentrations in the air. Assuming that the increased ion concentrations are due to radon, radon mitigators may rapidly determine the relative ion concentrations in different parts of a structure and therefore pinpoint the radon entry points at the location of highest ion concentration. A mathematical model of the ion concentration in air as a function of radon concentration will be presented. Actual measured ion concentrations in structures will also be presented.

**Patent disclosure document filed

INTRODUCTION

This paper describes an economical, reliable, and sensitive apparatus and method to measure air ions. Since radon produces air ions and, if the air ions are principally produced by radon, then this apparatus enables an individual to indirectly infer the radon concentration. A radon mitigator using the proposed ion collecting apparatus within various locations of a structure and controlling the atmosphere such that most ions are produced by radon, the profile of ions in the structure enables the high ion concentrations to be located and facilitates one to locate the entry of radon into the structure.

The ion collector consists of a metal sphere attached to a cylindrical container by using glue and Teflon. The electrical charge on the sphere is determined, or read, by placing the sphere next to a charged surface which is connected to a sensitive electronic reader.

Sources of air ions may also be produced naturally by background radiation, lightning discharges, high energy ultraviolet radiation, and the friction effects of wind, rain, snow, and hail. Man made sources of air ions consist of air ion generators, high voltage direct current transmission lines, electrostatic precipitators, and friction of the air as it moves over metal surfaces such as in heat ducts. One may easily eliminate the major sources of air ions in a structure with the exception of background radiation and radon by turning the air handling system off.

AIR ION CONCENTRATIONS PRODUCED BY RADIATION

Background radiation of 9 microroentgens per hour (79 mR/year) produces about 5 ion-pairs per cubic centimeters per second in air. The mean life of the ion-pairs is 300 seconds and in ordinary air at sea level there are about 1.6 x 10^3 ion-pairs per cubic centimeter produced by background radiation.(1)

Let us now calculate the expected number of ion-pairs per cubic centimeter for four picocuries per liter (4 pCi L^{-1}) of radon existing under secular equilibrium conditions. With the disintegration of each radon-222 nucleus, three alpha particles are emitted in the radon series with a total energy of 19.17 MeV. Since it requires about 34 electron volts to produce an ion pair in air, we have

$$19.17\times10^{6}\frac{eV}{dis}\times\frac{i.p.}{34eV}=5.6\times10^{5}\frac{i.p.}{dis} \qquad \textbf{Eq. 1}$$

For a radon concentration of 4 pCi L^{-1}, we may then determine the average number of ions produced per cubic centimeter per second as follows:

$$4\ pCi\ L^{-1}\ x\ 3.7x10^{-2}\frac{dis}{sec}\frac{1}{pCi}\ x\ 5.6x10^{5}\frac{i.p.}{dis}x\frac{1\ L}{1000cm^{3}}$$

$$= 82.8\ i.p.\ cm^{-3}sec^{-1} \qquad \textbf{Eq. 2}$$

For alpha particle columnar ionization, many of the ion pairs will readily recombine. Even if one-half of the ion-pairs readily recombine, a concentration of 4 pCi L^{-1} of radon will have a production rate of air ions(41 i.p. cm^{-3} sec^{-1}) which is about 8 times that of the normal background level(about 5 i.p. cm^{-3} sec^{-1}). Kanne and Bearden(2) published an article concerning the collection of ions produced by Columnar Ionization in which they found over 50% of the ions produced by alpha particles were collected even in low electric fields (8 volts/cm).

Let us consider a gas containing N_1 and N_2 positive and negative ions per cm^3 respectively, then we define the recombination coefficient β by the relation

$$\frac{-dN_1}{dt}=\frac{-dN_2}{dt}= \beta N_1N_2 \qquad \textbf{Eq. 3}$$

and since for our case we assume the positive and negative ions in air are equal, then

$$\frac{-dN}{dt}= \beta N^2 \qquad \textbf{Eq. 4}$$

-dN/dt is the rate at which ions recombine and values of the recombination coefficient(3) have been measured and β is of the order of 2 x 10^{-6} cm^3 ion^{-1} sec^{-1} in air.

At equilibrium, the production rate (p) is equal to the recombination rate; therefore,

$$\frac{dN}{dt}= p-\beta N^2= 0 \qquad \textbf{Eq. 5}$$

or

$$N=\sqrt{\frac{p}{\beta}} \qquad \textbf{Eq. 6}$$

Assuming that ß is a constant and equal to 2 x 10^{-6} cm^3 ion^{-1} sec^{-1}, we obtain the number of ions per cubic centimeters at equilibrium for different production rates and the values appear in Table 1 and are plotted in Figure 1. Note that under these assumptions that a production rate increase over the original production rate of four times yields double the original equilibrium concentration of ions. It is then obvious, as the radon concentration increases, the equilibrium ion concentrations also increases even through ß may change and increase significantly as the ion concentration increases.

TABLE 1
Number of Equilibrium Ions Versus Production Rate of Ions(p)

Radon (pCi L^{-1})	p * (ions $cm^{-3}sec^{-1}$)	N (ions cm^{-3})
0	5	1600
4.3	50	5000
47.8	500	15811
482.6	5000	50000

*Assume one-half of the ions produced by radon readily recombine and have only included one-half of the produced ions under p.

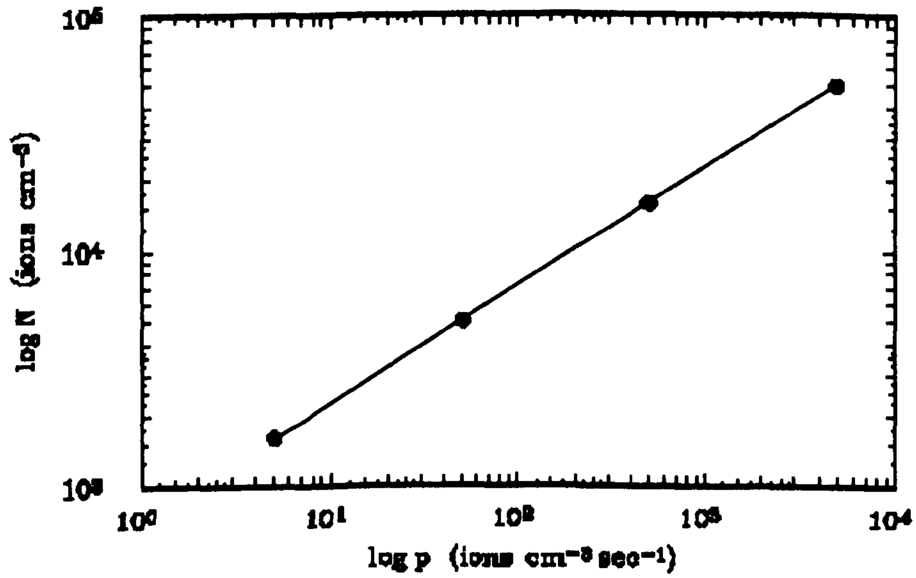


Figure 1. The logarithm of the equilibrium concentration of ions versus the logarithm of the production rate, assuming the recombination coefficient ß is constant and equal to 2×10^{-6} cm^3 ion^{-1} sec^{-1}.

The Spherical Ion Collector (SIC) was designed to contain sufficient charge so that its magnitude was easily measured, yet the quantity of charge was such that it was sensitive to a change in charge for a small number of ions collected. It is also necessary to maintain the electric field near its surface so that the electric field is below the magnitude which produces avalanche ionization. In order to enclose the spherical ionization collector (SIC), the metal ball was glued onto a 1/16" thick piece of PTFE Teflon[1] and the Teflon was then glued to the bottom of a 30 mL cylindrical container. The container could be closed by placing a conducting top on the cylindrical can. The SIC ion collector is illustrated in Figure 2.

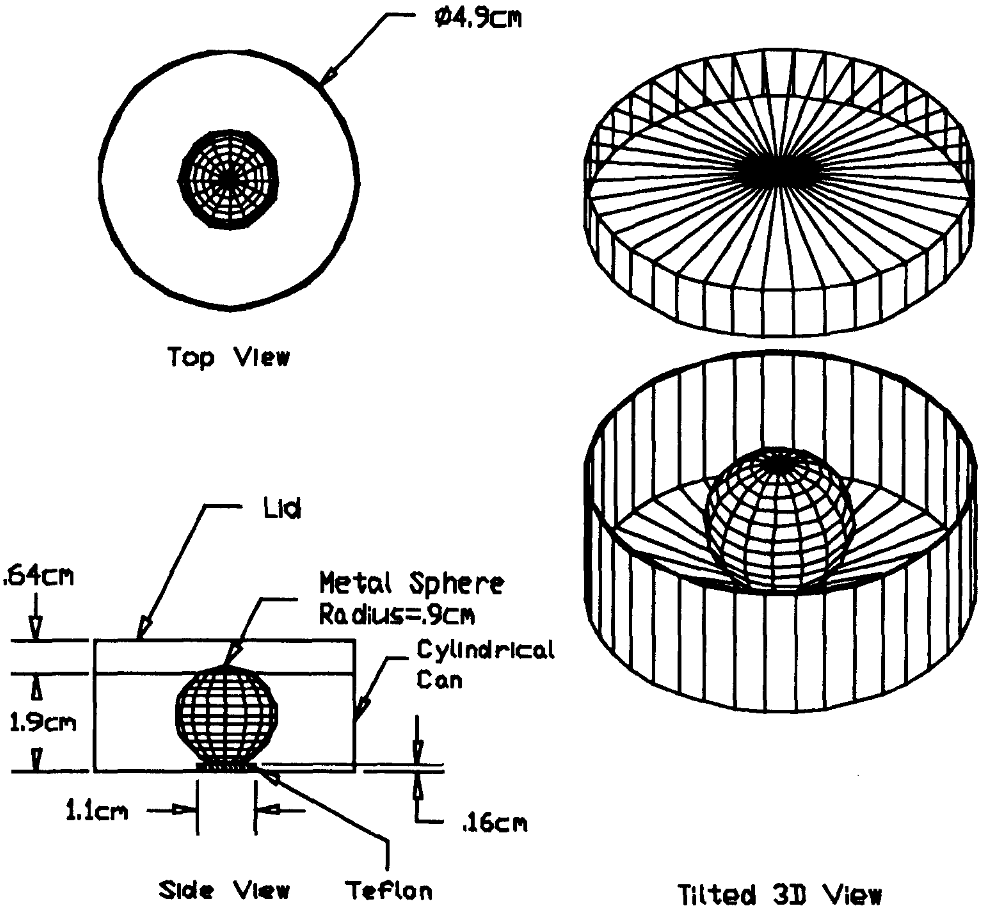


Figure 2. Illustration of the Spherical Ion Collector

[1] Teflon^{R}PTFE fluorocarbon, manufactured by E.I. duPont De Nemours and Co.Inc., Wilmington, DE 19898

To charge the sphere, a high voltage power supply potential of +400 volts was applied to the sphere and the ground was connected to the outer cylindrical can. The sphere may also be charged by using the method of induction. That is, a negatively charged object is brought near the sphere, the sphere is touched for an instant to allow part of the negative charge to leave the sphere, then the charged object is removed and the sphere is now positively charged. This produced a charge on the sphere of about 1.2×10^{-10} coulombs. The electric field at the surface of the sphere is given by using Gauss's law to yield

$$E = 9x10^{9}\frac{N\ m^{2}}{C^{2}}\ x\ \frac{1.2x10^{-10}C}{(0.009m)^{2}} = 13333\frac{volts}{meter} \qquad \textbf{Eq. 7}$$

A method known as the shutter method(4), also called the capacitive probe method, was used to measure the surface potential, and therefore the charge on the sphere. A homemade inexpensive meter as well as an electret reader produced and sold by RAD ELECT INC.(5) were used to measure the charge on the spherical ion collector. The cylindrical can is positioned where electrets are usually placed on the reader to determine their charge (or voltage). In this instrument, a metallic shutter shields the electrostatic field of the charged sphere while the meter is "zeroed." When the shutter is opened, a charge is induced on a conducting plate connected to a high impedance Op-Amp circuit and the read out is displayed on an LCD meter. The reproducibility of this reading was within one volt over the range of voltages used for the SICs.

After closing the SIC container with negligible radon in the container, a discharge rate of 7.5 volts per day was observed because of background radiation producing ion pairs in the 27 cm^3 (30 cm^3-sphere volume) of air. The background radiation was about 10 microroentgens per hour and the total negative charge (Δq) produced in the 27 cm^3 air volume was about

$$\Delta q = 10\times10^{-6}\frac{R}{h}\times24h\times\frac{2.08\times10^{3}(i.p.\ cm^{-3})}{1\times10^{-6}R}\times\frac{1\ e^{-}}{i.p.}\times\frac{1.6\times10^{-19}C}{e^{-}}\times27\,cm^{3}$$

$$= 2.2\times10^{-12}C \qquad \textbf{Eq. 8}$$

Since the change in voltage per day produced by background radiation was 7.5 volts, we obtain the charge per volt constant(k) for the SIC to be

$$K = \frac{2.2\times10^{-12}C}{7.5volts} = 2.9\times10^{-13}\frac{C}{V} \qquad \textbf{Eq. 9}$$

For curious individuals who use short term electrets to make radon measurements, the short term electrets have a constant of about $9.5x10^{-12}$C/V. Therefore, the SIC is about 30 times as sensitive as the short term electret.

EVALUATION OF THE SPHERICAL ION COLLECTOR

CHARGE STABILITY

The stability of charge on the spherical ion collector depended upon the background radiation, radon in the cylinder containing the sphere, and leakage due to moisture. Background radiation alone caused the voltage to decrease about 7.5 volts per day. By using reasonable care not to expose the ion collector and Teflon to overly humid environments, no difficulty with leakage currents were encountered. The closed detectors were placed in an open pan where rain actually wetted the tops of the relatively closed containers and after one day the voltage on these detectors had decreased about 10 volts, which is slightly more than the voltage decrease caused by background radiation.

CALIBRATION OF THE SPHERICAL ION COLLECTOR

The air handling system was turned off in a house for thirty minutes before making any radon measurements. Four charged SIC detectors were placed with open tops on a table for six minutes. The detectors discharged from 400 volts to about 304 volts over a period of six minutes. During the exposure of the SICs, an open container was allowed to come to equilibrium with the air in the center of the table and E-PERMS placed in this container for 24 hours indicated a radon concentration of 17.5 pCi L^{-1}. One day later, three SICs detectors were exposed to a radon concentration of nine pCi L^{-1} and the average voltage on these detectors during a 6 minute exposure decreased from 400 volts to 332 volts or a decrease of 68 volts. This indicates a total negative charge collection of

$$68\ volts \times 2.9\times10^{-13}\frac{C}{V} = 1.97\times10^{-11}C \qquad \textbf{Eq. 10}$$

MEASUREMENTS IN A STRUCTURE

The SICs have been used to measure the ions in various structures. The ion concentration and the radon concentration were studied in a structure. The air handling system was turned off thirty minutes prior to initiating measurements and three fans located upstairs were turned on for thirty minutes to increase the radon concentration in the structure. After turning off the fans, the SICs were charged to 400 volts, read on a reader, and then placed in the appropriate room. The top was removed to allow each SIC to be exposed for ten minutes. A Lucas Cell and the associated apparatus were used to determine the radon concentration. Table 2 contains the change in voltage of the SICs and the radon concentration at each location.

TABLE 2
Changes in voltages of the SICs and the Radon Concentrations

Location	Mean Change in Voltage (volts)	Radon Concentration (pCi L^{-1})
1. Basement (Radon Room)	131	22.5
2. Radon Room (At Peak Level)	161	28.5
3. Adjacent to Radon Room	85	10.0
4. Opposite Side of Basement from Radon Room	73	8.4
5. Upstairs	73	3.8
6. Outside Air	7	less than 1.0

Typical fractional standard deviations for three SICs used at each location were about ten percent. Note that in Table 2, as the radon concentration increased the mean of the change in voltage also increased. These measurements obviously provide a good correlation between the magnitude of the radon concentration and the change in voltage of the open SICs. Note that for the fifth measurement, the radon concentration was only 3.8 pCi L^{-1} but the change in voltage was 73 volts. A fire was burning in the fireplace near this location. The ions produced by the fire probably provided the elevated ion concentration.

For other measurements, significant exceptions were found. Using the open SICs, the detector is vulnerable to environmental effects such as charged objects or ions produced by other means. One structure had high radon concentrations, about 20 pCi L^{-1}, but a very low ion concentration. Many objects, such as plastics, are electrically charged and when located near the SICs, they compete with the SICs for the ions. This,of course, can cause false readings.

CONCLUSIONS

Spherical ion collectors used with charge readers to detect air ion concentrations are economical, reliable and sensitive. By directly exposing the SICs to the environment, one must be careful to eliminate other sources or sinks of ions in order to obtain accurate results. By placing the SICs in one or two liter containers, sufficient sensitivity should still exist for the SICs to provide rapid radon measurements and also eliminate many of the competing environmental factors. These measurements are in progress.

Two significant advantages for using the spherical ion collectors over electrets for air ion collection are the relative ease with which one can recharge the spheres and the sensitivity of the spherical ion collector. One may utilize a charged object to readily recharge the sphere.

The work described in the paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

REFERENCES

1. Korff, S.A., Electron and Nuclear Counters, D. Van Nostrand Company Inc., New York, 1955. p. 40.

2. Kanne, W.R. and J.A. Bearden, Columnar Ionization. Physical Review 50, 935 (1936).

3. Korff, S.A., Electron and Nuclear Counters, D. Van Nostrand Company, Inc., New York, 1955. p. 41.

4. Sessler, G.M. (ed.), Electrets, Topics in Applied Physics 33 (Berlin, Heidelberg, New York: Springer-Verlag). 1987. p. 40.

5. Kotrappa, P., Dempsey, J.C., Hickey, J.R., and Stieff, L.R., An Electret Passive Environmental ^{222}Rn Monitor Based on Ionization Measurement. Health Physics 54, No. 1, p. 47, 1988.

INTERCOMPARISON OF ACTIVITY SIZE DISTRIBUTION MEASUREMENTS WITH MANUAL AND AUTOMATED DIFFUSION BATTERIES - FIELD TEST

Hopke P.K., Wasiolek P.
Department of Chemistry, Clarkson University,
Potsdam NY, 13699

Knutson E.O., Tu K.W., Gogolak C.
Environmental Measurements Laboratory, U.S. DOE,
376 Hudson St., New York, NY 10014

Cavallo A., Gadsby K.
Center for Energy and Environmental Studies, Princeton University
Princeton, NJ 08540

Van Cleef D.
U.S. EPA, National Air and Radiation Environmental Laboratory
1504 Avenue A, Montgomery, AL 36115-2601

ABSTRACT

To compare the performance of the Graded Screen Array (GSA) technique for measurement of radon decay product activity size distributions in a real house environment, a series of experiments were performed in a single family house in Princeton NJ. The present study was designed as a field test following to the laboratory intercomparison measurements carried out previously in a radon-aerosol chamber.
Two different systems were used:

1) Disk-type Diffusion Battery from the Environmental Measurements Laboratory.
2) Automated, Semi-Continuous System (ASC-GSA) from Clarkson University.

Several sets of parallel measurements of radon gas concentration, particle concentration and activity size distributions were performed with and without additional aerosol sources. The conditions of the experiments were as follow: radon gas concentration varied from about 2500 Bq m^{-3} to 3500 Bq m^{-3}, and the particle concentration from 8,000 cm^{-3} to 140,000 cm^{-3}. The results of the measurements generally have shown a very good agreement between two instruments. However, the Clarkson University ASC-GSA yielded activity values from 1% up to 20% higher than the diffusion battery from EML. Despite this minor discrepancy, the tests performed proved the viability of the GSA systems for activity weighted size distribution measurements.

INTRODUCTION

Exposure to radon (^{222}Rn) and radon decay products inside homes is now recognized as the main source of radiation doses to the general public and in some situations may present a significant health risk. Two approaches to the estimation of the health risk coefficient from indoor radon have been used. The epidemiological approach derives the risk factor from studies of the incidence of desease in an exposed population (1,2). Alternatively, the dosimetric approach is based on the calculations of radiation doses from physical and biological models and from that dose develops the risk factor (3,4,5,6,7). The second approach requires detail knowledge of the physico-chemical properties of radon and its progeny. Two parameters in early lung dosimetry models used to estimate radiation doses from inhaled radon decay products (3,4,5,6), were the activity median diameter of the "attached" radioactive aerosol and the "unattached" fraction of ^{218}Po. Traditionally defined, the "unattached" fraction constitutes free molecular daughter atoms or ions possibly clustered with other molecules such as H_2O, typically within the size range of 0.5 to 3-5 nm, as distinct from daughter atoms "attached" to particles in the pre-existing ambient aerosol.

Recently, James modeled the relationship between monodisperse size of radon decay products and dose per unit exposure (7), instead of dose conversion factor or the "attached" or "unattached" fractions only. The resulting dose conversion factors per unit exposure from monodisperse activity are presented in Figure 1.

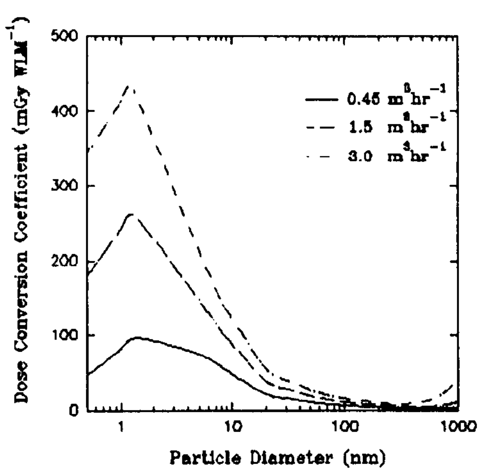


Figure 1. Dose to bronchial secretory-cell nuclei as a function of radon decay products for an adult male (7).

This development stressed the importance of measurements of the radioactive aerosol size distribution spectrum, especially in the range 0.5 nm up to 1000 nm.

The measurements of the "unattached" fraction of ^{218}Po and of the potential alpha energy concentration (PAEC) or in more general terms the size distribution of the particles carrying ^{218}Po, ^{214}Pb or ^{214}Bi has been the subject of extensive research. A critical review of such measurements was provided by Hopke (8). The majority of the techniques utilized to obtain the size distributions are based on the diffusional properties of radon progeny and use of the diffusion battery-type systems or the multiple wire-screens systems.

To assure the quality of the size distribution measurements, intercomaprison exercises have been conducted involving different laboratories (9). The reported tests were carried out in laboratory settings. In August 1990 two systems, one from the Environmental Measurements Laboratory (EML) and the second from Clarkson University (CU) were intercompared during series of tests in an unoccupied house in Princeton, NJ. It was, to the best knowledge of the authors, the first intercomparison done in the real house environment.

ACTIVITY-WEIGHTED SIZE DISTRIBUTION

A major consideration in evaluating the radiological health risk from indoor radon is the size spectrum of particles carrying the radon decay products, described by the term "activity-weighted size distribution".

The size distribution of particles may vary slightly for each decay product due to coagulation or size-dependent loss of the aerosol between the time of attachment and the time of decay. Therefore, for direct measurement of the activity-weighted size distribution, the sampling system should be able to segregate particles according to size, so that the activity of each size fraction can be determined separately.

Several factors make this a difficult task, especially in the domestic environment: the activities, usually low, become lower yet when segregating the particles into several groups; the activities are short-lived, dictating short sampling times. Owing to these difficulties, the direct measurement of the activity-weighted size distribution is a relatively recent development.

Two methods for size segregations of particles according to size are generally used: diffusion batteries (DB), and graded screen arrays (GSA). Two methods are also commonly utilized for estimation activity concentrations of radon decay products : gross-alpha counting and alpha-spectroscopy.

The diffusion battery generally consists of number of channels, typically of cylindrical shape. The deposition of aerosols in the channels of the diffusion battery is determined by its dimensions, the sampling flow rate, and the diffusion coefficient of the diffusing species. The theorey for diffusional deposition in circular tubes is presented in several papers (10-12). Diffusion batteries have been widely employed for aerosol size distribution measurements. The theoretical and operational aspects of deposition in different types of diffusion bateries have been investigated by many workers (13, 14).

The use of the wire screens to segregate particles in radon research was developed by James et al. (15), Thomas and Hinchliffe (16) and George (17). The degree of penetration, P = (1 - fractional deposition), through wire screen is dependent upon the particle size, wire screen parameters and sampling face velocity. For D_p <100 nm, the dominant wire screen collection mechanism is Brownian diffusion. For larger particle size (D_p> 500 nm), collection by interception and inertial impaction becomes predominant. The theory describing particle penetration through a wire screen was developed by Cheng and Yeh (18) and Cheng et al. (19).

The Graded Screen Array (GSA) technique is a development of more recent years (20). GSA systems consist of varying mesh number, single/multiple wire screen stages operated either in series or in parallel, with a choice of a wide range of wire screen parameters and sampling flow rates. The parameter that is used to describe a GSA stage is the particle diameter that leads to 50% penetration through the stage, $D_p(50\%)$. A GSA system may consist of two distinctly different configurations of individual wire screens that may be defined as "serial" or "parallel" (21). The "serial" system consists of a number of individual wire screens operated sequentially, thus yielding as many stages as wire screens. In contrast, the "parallel" configuration GSA system consists of a number of individual GSA stages operated in parallel, in which each stage containing a specific set of wire screens.

To measure the activity concentration, gross-alpha counting and alpha spectrometry techniques are used. Gross alpha counting is based on counting of all of the alpha particles coming from the source (usually a filter) in several different time intervals. A minimum of three count periods are required (22) to solve the set of equations yielding concentration of ^{218}Po, ^{214}Pb and ^{214}Bi. Raabe and Wrenn (23) proposed a technique in which more count intervals than unknowns are used. A least-squares fit to the count rate versus time provides activities of radon decay products.

Alpha-spectroscopy method was first reported by Martz et al. (24). The counts from the radon decay products distinguished on the basis of their energy with a multichannel analyzer are accumulated in two time intervals. Tremblay et al. (25) optimized the count-interval timing for the case in which the counting and sampling intervals overlap. The counting while sampling technique greatly improved the measurement precision especially with regards to ^{218}Po with its half life of only 3.1 min.

These methods of sizing of the active aerosols and alpha counting were used in the intercompared systems.

HOUSE CHARACTERISTICS

The intercomparison measurements were performed in a basement of a one-story residence with a living room, dining room, kitchen, study, two bedrooms and two bathrooms on ground floor. The outer basement dimensions were as follow: 11.3 m x 10.5 m x 2.5 m and the volume about 250 m^{-3}. The schematic plan of the basement with location of the measuring devices is presented in Figure 2. The house was instrumented by the Center for Energy and Environmental Studies, Princeton University for continuous measurements of the radon concentration, temperature, humidity and differential pressure. The house is equipped with sub-slab ventilation system which was turned off during the measurements. The radon concentration in the basement during tests varied between 2600 Bq m^{-3} (70 pCi L^{-1}) and 3700 Bq m^{-3} (100 pCi L^{-1}). The particle concentration without additional sources was about 8000 cm^{-3} as measured with a Rich 100 condensation nuclei counter, and up to 140,000 cm^{-3} with additional sources (cigarette smoke, a 1320 watt electric space heater and handyman's propane torch).

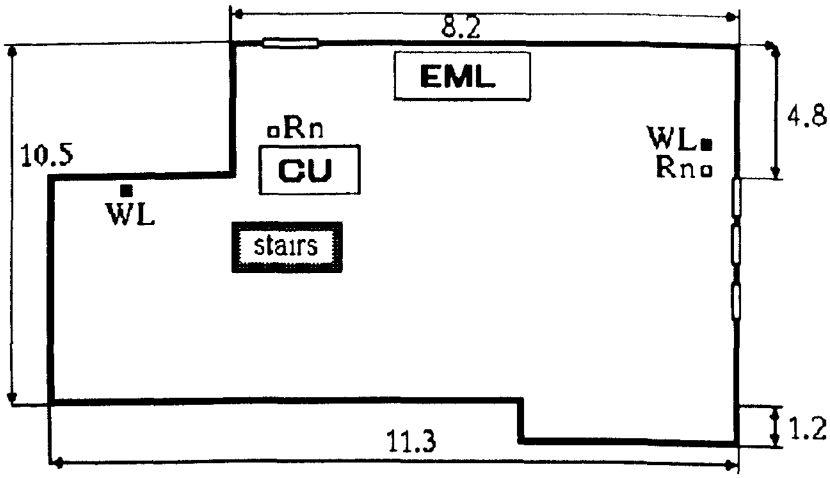


Figure 2. Plan of the Princeton house basement with localization of the measuring systems (all dimension in meters).

APPARATUS AND PROCEDURE

The measurements of the size distribution of particles carrying radon decay products were performed with two systems: EML Disk-type Diffusion Battery (DDB) and Clarkson University Graded Screen Array

(ASC-GSA). Activity-weighted size distribution measurements were complemented with continues radon gas concentration measurements (EBERLINE, Radon Gas Monitor RGM-3), continues PAEC measurements (EBERLINE, WL-meter) and the aerosol concentrations (Rich 100 CNC).

EML Disk-Type Diffusion Battery

The EML Disk-type Diffusion Battery (DDB) has a 19 year history of use, thereby providing a link between past and current measurements. The apparatus consists of one open face filter and four filters preceded by diffusion elements (26). Each element consists of a number of perforated stainless steel discs (27) arranged in a series in a tube. Each disc contains 14,500 collimated holes (tubes), 0.0228 cm in diameter. The characteristics of the four batteries are listed in Table 1.

TABLE 1. CHARACTERISTICS OF DIFFUSION BATTERIES

Battery	Number of Sections	Actual Total Lenght of Sections [cm]	Effective Lenght of Battery [cm]	Dp_{50} [nm]
1	1	0.34	5.0×10^3	11
2	2	0.95	1.37×10^4	21
3	5	8.08	1.17×10^5	83
4	10	25.75	3.73×10^5	212

A sampling time of 10 minutes, and a flow of 3.0 Lpm through each of the four sections of DDB, and through an open face filter is sufficient to achieve good counting statistics. These values were used during tests. Millipore Type AA membrane filters were used (Glass fiber filters may have been more appropriate; see discussion below). After sampling the filters were manually transfered to five identical drawer-type counters (EML Type TH-29 B (28)). The counts were accumulated in a pair of CTM-05 five-channel scalers (Metrabyte Corp., Taunton, MA) plugged into backplane slots of a portable personal computer. A Pascal program was used to supervise counting and to record data in one minute increments. Normally, 40 minutes of count data were collected in each experiment. The one-minute count data were analyzed using the weighted least squares procedure by Raabe and Wrenn (23) yielding the activity concentration of the ^{218}Po, ^{214}Pb and ^{214}Bi on each filter.

Once the EML data has been assembled, it became obvious that many of the ^{218}Po results obtained from counting the filters were not reliable. This problem was easy to determine because the amount of activity found on the five DDB filters were sometimes badly out of sequence. (They should be in a monotonic decreasing sequence). The probable reason for these erratic results was plateout of ^{218}Po onto the

Millipore filters during transfer from the filter holders to the counters. Glass fiber filters, or other media not subject to substantial electrostatic charging, should be used when radon concentrations are as high as they were in these experiments.

To ensure that the data reported here are reliable, the following data acceptance criteria were adopted for the EML data:

1) the ^{218}Po data were used only as an indicator of data quality;
2) ^{214}Pb, ^{214}Bi and PAEC were accepted only for those tests for which the ^{218}Po were in reasonable sequence.

To "unfold" the data, yielding activity-weighted size distributions the Expectation-Maximization (EM) algorithm (29) was used. EML used 16 midpoint values for "unfolded" activity-weighted size distributions: 1.00 nm, 1.58 nm, 2.51 nm, 3.98 nm, 6.31 nm, 10.00 nm, 15.85 nm, 25.12 nm, 39.81 nm, 63.10 nm, 100.00 nm, 158.49 nm, 251.19 nm, 398.11 nm, 630.96 nm and 1000.00 nm. The EML DDB system is meant for research, so experienced operators are required to collect and interpret the data.

Clarkson University Graded Screen Array

The ASC-GSA system used by the Clarkson University group involves the use of 6 compact sampler-detector units operated in parallel (30, 31). Each sampler-detector unit couple wire screen penetration, filter collection and activity detection in a way as to minimize depositional losses while being sufficiently rugged for field operations. The system samples air of the rate of about 15 Lpm, simultaneously in all of the units through the sampler slit between the alpha surface barrier detector (ORTEC Model DIAD II, 450 mm^2) and filter (25 mm Millipore 0.8 m, Type AA) section in each unit. One of the sampler-detector units is operated with an uncovered sampler slit, thus providing information on the total ambient radon decay products concentrations. The sampler slits on the remaining units are covered with single or multiple wire screens of differing wire mesh number. The operating parameters of the system are presented in Table 2.

TABLE 2. THE PARAMETERS OF THE SIX SAMPLERS OF THE ASC-GSA SYSTEM

Unit	Sampler Slit Width [cm]	Sampler Diameter [cm]	Screen Mesh	Dp_{50} [nm]
1	0.5	5.3	-	-
2	0.5	5.3	145	1.0
3	0.5	5.3	145x3	3.5
4	0.5	5.3	400x12	13.5
5	1.0	12.5	635x7	40.0
6	1.0	12.5	635x20	98.0

The signals from alpha detectors are connected through amplifiers into an 8-segment multiplexer and routed to a personal computer-based multichannel analyzer. The computer controls acquisition of the alpha spectra, operation of the sampling pump, sample time sequencing and data analysis as well. The sequence of sampling counting and analysis permits automated, semi-continuous operation of the system with a frequency of between 1.5 to 3 hours. The alpha counts from ^{218}Po and ^{214}Po detected by each alpha detector in the two counting intervals are used to calculate of the radon decay product concentrations penetrating into each unit (25). The observed concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi are used to reconstruct the corresponding activity-weighted size distributions using the Expectation-Maximization (29) algorithm. The Clarkson University program is design to use six optimized size range bins: 0.5-1.58 nm, 1.58-5.00 nm, 5.00-15.81 nm, 15.81-50.00 nm, 50.00-158.11 nm, 158.11-500.00 nm (32).
The ASC-GSA system was design for field measurements and involves very little attention during operation (31).

RESULTS

There were four sets of measurements taken simultaneously with EML and CU systems. Table 3 gives the test conditions for the four test runs.

TABLE 3. TEST CONDITIONS FOR THE SIZE DISTRIBUTION INTERCOMPARISON

Run no.	Type of aerosol	Particle concentration [particle.cm^{-3}]	Radon concentration [Bq m^{-3}]
1	background	8000	3110
2	background	8000	3108
3	cig. smoke	24000	3290
4	heater+torch	35000	3220

To compare the results, both sets of data were brought to a common basis. The EML analyses yield the $dA/d(\log D_p)$ in terms of activities, expressed in Bq m^{-3}, whereas the CU analyses yield the results in form of the activity fractions. The CU results were therefore converted to activities ($dA/d\log D_p$) and these values were used for direct comparison. Because both devices are equipped with an open face filter for total airborne activity measurements, it was possible to compare the performance of both systems for direct radon decay product concentrations and PAEC measurements. The obtained values are presented in Table 4 a), b), c).

TABLE 4. COMPARISON OF ACTIVITIES OF ^{214}Pb (a), ^{214}Bi (b) and PAEC (c) MEASURED DURING INTERCOMPARISON BETWEEN THE ENVIRONMENTAL MEASUREMENTS LABORATORY (EML) AND THE CLARKSON UNIVERSITY (CU).

a)

Run no.	^{214}Pb Concentration [Bq m^{-3}] EML	CU	CU/EML Ratio
1	1309 ± 20	1478 ± 8	1.13
2	1243 ± 18	1418 ± 8	1.12
3	1738 ± 18	2063 ±18	1.17
4	1680 ± 30	2002 ±29	1.19

b)

Run no.	^{214}Bi Concentration [Bq m^{-3}] EML	CU	CU/EML Ratio
1	1088 ± 34	1248 ± 14	1.15
2	1012 ± 26	1023 ± 5	1.01
3	1380 ± 31	1298 ± 6	0.94
4	1274 ± 50	1343 ± 4	1.05

c)

Run no.	PAEC [nJ m^{-3}] EML	CU	CU/EML Ratio
1	7351 ± 48	8004 ± 41	1.09
2	6883 ± 36	7402 ± 40	1.08
3	9214 ± 44	9983 ± 71	1.08
4	9038 ± 76	9842 ± 68	1.09

The right column in Table 4 a), b), c) shows the ratio of values obtained by the Clarkson University group and the EML group. In nearly all cases (except one) the CU values were higher then EML, but the maximum difference was not larger then 20%, and in case of PAEC less then 10%.

The main purpose of the tests was however, to measure the activity-weighted size distributions. The results of four runs presented in Figures 3, 4, 5, and 6 are the size distributions of PAEC, ^{214}Pb and ^{214}Bi measured by EML and CU. Figures 3 and 4 present the results of measurements performed in low aerosol concentration conditions (no additional sources) and Figures 5 and 6 present the high aerosol concentration samples. For the low (background) aerosol case (Runs 1 and 2) the EML spectra generally showed a mode near 100 nm, whereas the CU spectra generally showed the mode in the largest size class. This difference is fairly minor, and reflects the differing

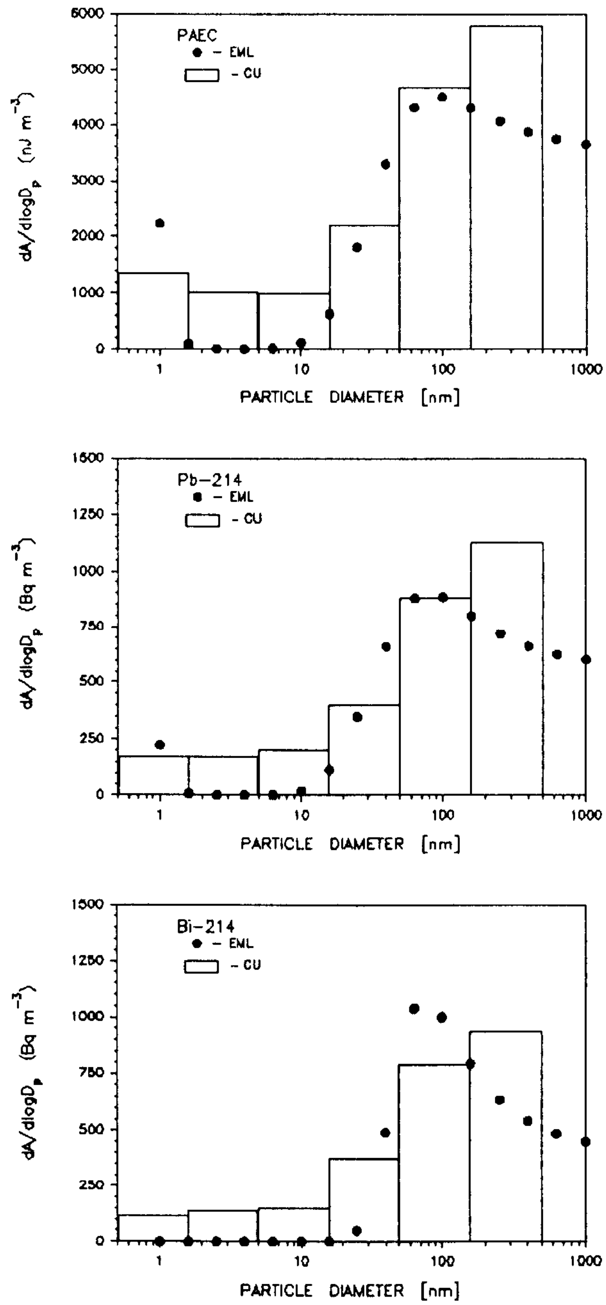


Figure 3. Comparison of the Clarkson University and the Environmental Measurements Laboratory results of the activity weighted size distribution measurements in a real house environment: Run no. 1 (09-22-90, 11:00)

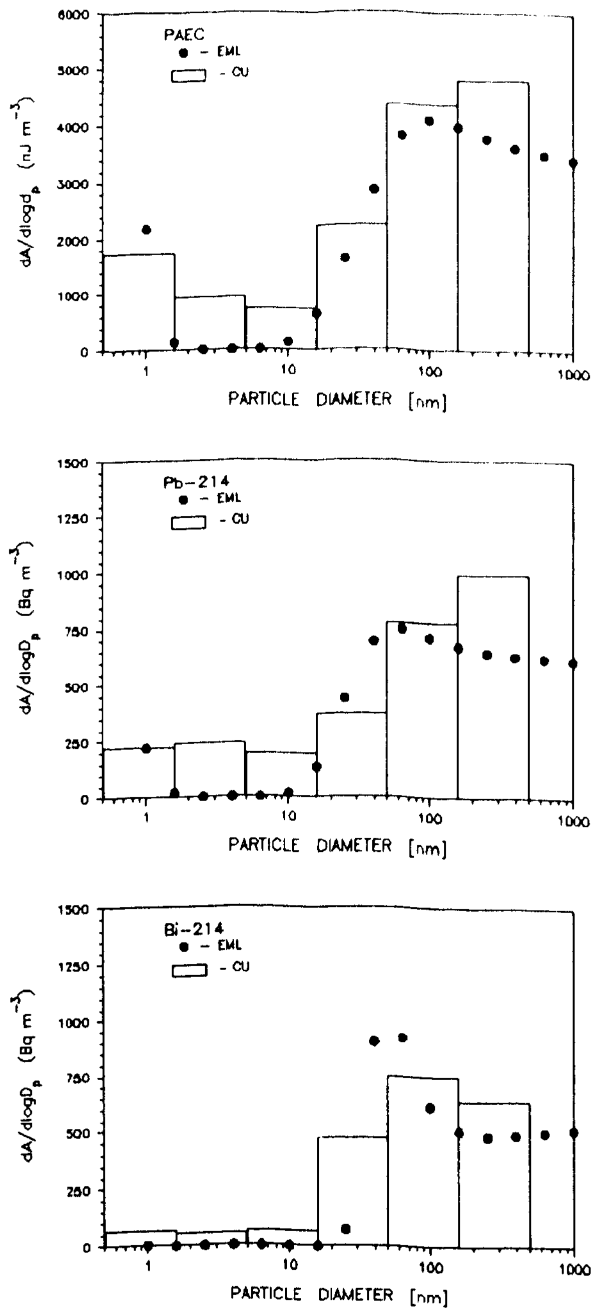


Figure 4. Comparison of the Clarkson University and the Environmental Measurements Laboratory results of the activity weighted size distribution measurements in a real house environment: Run no. 2 (09-22-90, 12:00)

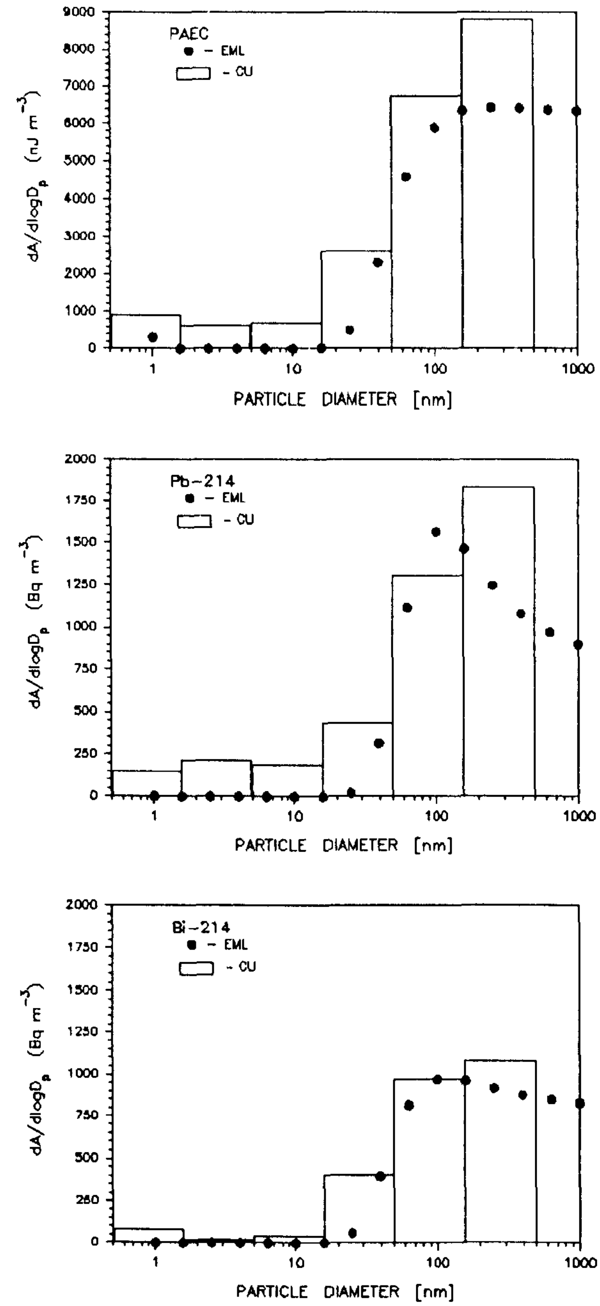


Figure 5. Comparison of the Clarkson University and the Environmental Measurements Laboratory results of the activity weighted size distribution measurements in a real house environment: Run no. 3 (09-22-90, 16:00). Aerosol: smoke from two cigarettes, aged 45 minutes.

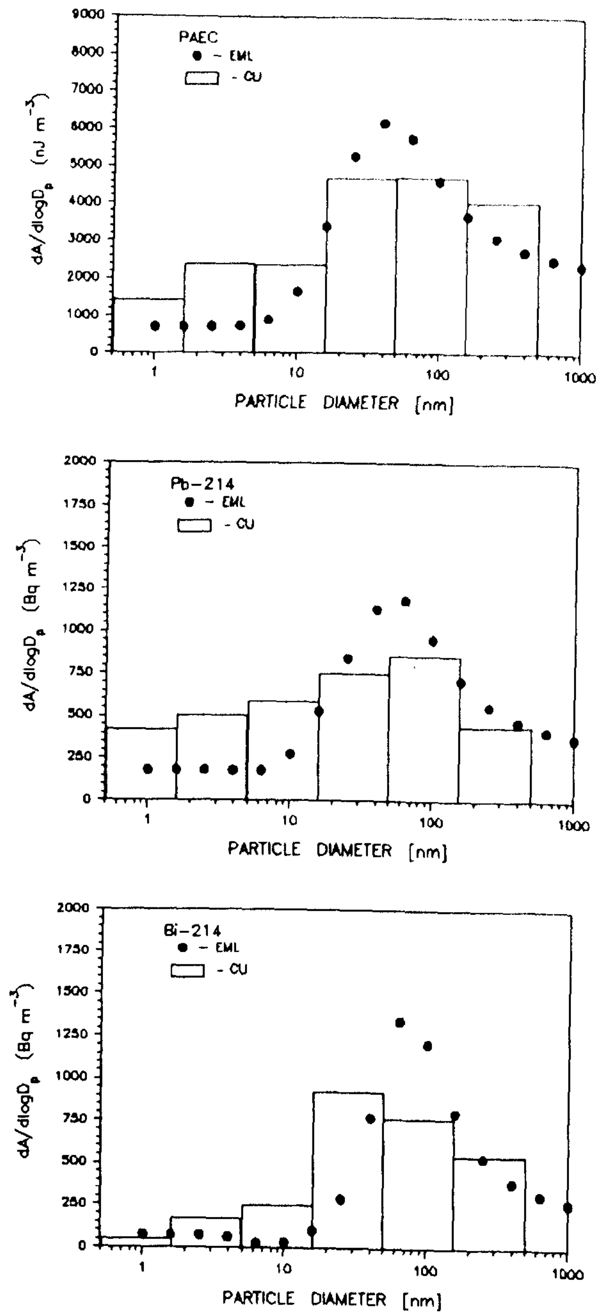


Figure 6. Comparison of the Clarkson University and the Environmental Measurements Laboratory results of the activity weighted size distribution measurements in a real house environment: Run no. 4 (09-23-90, 10:00) Aerosol: fumes from a 1320 watt electric space heater plus a handyman's propane torch, aged 45 minutes

capabilities of the two devices at the large end of the size spectrum. A similar behavior was observed for the cigarette smoke aerosol (Run 3). For the torch+heater aerosol (Run 4), the two methods agreed very well as to location of the peak near 50 nm. However, there is a substantial difference between the two methods regarding the amount of activity in the 2 to 10 nm range. Most EML curves show virtually zero activity in this range, while the CU results show a small but finite amount. In addition, the EML results generally show a sharper upturn at the small-particle end of the size range, than do the CU results. The EML results correspond to the classical idea of a well defined, uniformly sized, "unattached" fraction. The difference discussed above could result in part from a difference of assumptions concerning the smallest possible particle size. The bottom class in the EML calculation is 0.79 to 1.25 nm, compared to 0.5 to 1.58 nm for the CU calculation. This subject is a matter of further study.

As a practical, single number index of differences between EML and CU results, the dose to bronchial secretory-cells nuclei per unit exposure for adult male was calculated, based on recent James model (7). The results are presented in Table 5.

TABLE 5. DOSE TO SECRETORY-CELL NUCLEI FOR ADULT MALE ($B = 3\ m^{-3}\ hr^{-1}$) CALCULATED FOR PAEC SIZE DISTRIBUTIONS OBTAINED BY THE EML AND THE CU.

Run no.	Secretory Cell Dose [$Gy/J\ m^{-3}\ h$] EML	CU	CU/EML Ratio
1	13.39	21.65	1.62
2	14.02	24.93	1.78
3	6.27	13.60	2.17
4	15.75	28.41	1.80

The dose estimates by using data from both systems did not agree very well. This difference was probably due to the much sharper peak at about 1 nm in the EML system and no activity in the 2 to 10 nm range. Since the peaks in the dose per unit exposure curves shown in Figure 1 occur around 1.5 nm, small difference in the amount of activity in this size range can make significant difference in the estimated dose.

However, the overall performance of both systems was good and the observed differences were within the expected variability of two different techniques that have their own internal errors in addition to the statistical counting errors.

CONCLUSION

The performed test in a real house environment proved that the reliable measurements of the activity-weighted size distributions of radon decay products could be made. The results obtained with two systems, which utilize different particle segregation and alpha counting methods, have shown very good agreement. The agreement between the manual diffusion battery and the automated graded screen array system indicates that the GSA does provide useful activity size information with simplicity in its use. Automated systems of this type could be a good source of reliable information of sizes of active aerosols. That are important for proper dose estimates from inhalation of radon decay products.

ACKNOWLEDGEMENT:

The work at Clarkson University was funded in part by the New Jersey Department of Environmental Protection under contract No. P32108 and the U.S. Department of Energy under Grant No. DE-FG02-90ER61029.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the agency and no official endorsement should be inferred.

REFERENCES

1. ICRP. Lung Cancer Risk from Environmental Exposures to Radon Daughters. Report of a Task Group. International Commission on Radiological Protection, ICRP Publication 50, ICRP, Annals of ICRP 17 (1), 1987.

2. BEIR IV. Health Risk of Radon and Other Internally Deposited Alpha-Emitters. Committee on the Biological Effects of Ionizing Radiations, Board on Radiation Effects, Research Commission on Life Sciences, National Research Council, National Academy Press, Washington, D.C., 1980.

3. Harley, N.H. and Pasternack, B.S. Environmental Radon Daughter Alpha Dose Factors in a Five-Lobed Human Lung. Health Phys. 42: 771, 1972.

4. Jacobi, W. and Eisfeld, K. Dose to Tissue and Effective Dose Equivalent by Inhalation of ^{222}Rn, ^{220}Rn and Their Short-lived Daughters. GSF Report S-626, GSU, Munich-Neuherberg, 1980. 51 pp.

5. James, A.C., Greenhalgh J.R. and Birchall, A. A Dosimetric Model for Tissues of the Human Respiratory Tract at Risk from Inhaled Radon and Thoron Daughters. In: Radiation Protection. A Systematic Approach to Safety. Vol 2. Pergamon Press, Oxford, 1980. 1045 pp.

6. James, A.C., Strong, J.C., Cliff, K.D. and Stranden, E. The Significance of Equilibrium and Attachement in Radon Daughter Dosimetry. Radiat. Prot. Dosim. 24: 451, 1988.

7. James A.C. Dosimetry of Radon Exposure: What Does It Imply for Risk and Measurement of Indoor Exposure? Paper presented at the Twenty-Ninth Hanford Symposium on Health and the Environment, Richland, WA, October 15-19, 1990.

8. Hopke, P.K. A Critical Review of Measurements of the "Unattached" Fraction of Radon Decay Products. Technical Report Series DOE/ER-0451P, U.S. DOE, 1990.

9. Knutson, E.O., Tu, K.W., Solomon, S.B. and Strong, J. Intercomparison of Three Diffusion Batteries for the Measurements of Radon Decay Product Particle Size Distributions. Radiat. Prot. Dosim. 24: 261, 1988.

10. Gormley, P. and Kennedy, M. Diffusion for a Stream Flowing through a Cylindrical Tube. Proc. R. Irish Acad. 52A: 163, 1949.

11. Fuchs, N.A. The Mechanics of Aerosols. MacMillan Press, New York, 1964.

12. Ingham, D.B. Diffusion of Aerosols for a Stream Flowing Through a Cylindrical Tube. J. Aerosol Sci. 6: 125, 1975.

13. Sinclair, D., George, A., and Knutson, E.O. Application of Diffusion Batteries to Measurements of Submicron Radiactive Aerosols. In: Proc. Amer. Nucl. Soc. Series on Assessment of Airborne Radioactivity, 1978, p. 103.

14. Brown, K.E, Beyer, J., and Gentry, J.W. Calibration and Design of Diffusion Batteries for Ultrafine Aerosols. J. Aerosol Sci. 15: 133, 1984.

15. James, A.C., Bradford, G.F., and Howell, D.M. Collection of Unattached RaA Atoms Using Wire Gauze. J. Aerosol Sci. 3: 243, 1972.

16. Thomas, J.W., and Hinchliffe, L.E. Filtration of 0.001 μm Particles with Wire Screens. J. Aerosol Sci. 3: 387, 1972.

17. George, A.C. Measurements of the Uncombined Fraction of Radon Daughters with Wire Screens. Health Phys. 23: 390, 1972.

18. Cheng, Y.S. and Yeh, H.C. Theory of Screen Type Diffusion Battery. J. Aerosol Sci. 11: 313, 1980.

19. Cheng, Y.S., Keating, J.A. and Kanapilly, G.M. Theory and Calibration of a Screen-Type Diffusion Battery. J. Aerosol Sci. 11: 549, 1980.

20. Strong, J.C. The Size of Attached and Unattached Radon Daughters in Room Air. J. Aerosol Sci. 19: 1327, 1988.

21. Ramamurthi, M. and Hopke, P.K. On Improving the Validity of Wire Screen "Unattached" Fraction Radon Daughter Measurements. Health Phys. 56: 189, 1989.

22. Tsivoglu, E.C., Ayer, H.E., and Holaday, D.A. Occurrence of Nonequilibrium Atmospheric Mixtures of Radon and Its Daughters. Nucleonics. 11: 40, 1953.

23. Raabe, O.G. and Wrenn, M.E. Analysis of the Activity of Radon Daughter Samples by Weighted Least Squares. Health Phys. 17: 593, 1969.

24. Martz, D.E., Holleman, D.F, McCurdy, D.E., and Schiager, K.J. Analysis of Atmospheric Concentrations of RaA, RaB, and RaC by Alpha Spectroscopy. Health Phys. 17: 131, 1969.

25. Tremblay, R.J., Leclerc, A., Townsend, M.G., Mathieu, C., and Pepin, R. Measurements of Radon Progeny Concentration in Air by Alpha-Particle Spectroscopic Counting During and After Air Sampling. Health Phys. 36: 401, 1979.

26. George, A.C., Hinchliffe, L., and Sladowski, R. Size Distribution of Radon Daughter Particles in Uranium Mine Atmospheres. Am. Ind. Hyg.Assoc. J. 36: 484, 1975.

27. Sinclair, D. A Portable Diffusion Battery: Its Application to Measuring Aerosol Size Characteristics. Amer. Ind. Hyg. Assoc. J. 33: 729, 1972.

28. EML Procedures Manual, 27th Edition. US Department of Energy Report (in Press), Chapter 2.

29. Maher, E.F. and Laird, N.M. EM Algorithm Reconstruction of Particle Size Distribution from Diffusion Battery Data. J. Aerosol Sci. 7: 127, 1986.

30. Ramamurthi, M. The Detection and Measurement of the Activity Size Distributions (d_p> 0.5 nm) Associated with Radon Decay Products in Indoor Air. Ph.D. Thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 1989.

31. Ramamurthi, M., and Hopke P.K. An Automated, Semi-Continuous System for Measuring Indoor Radon Progeny Activity-Weighted Size Distributions, d^p:0.5-500 nm. Aerosol Sci. Technol. 14: 82, 1991.

32. Ramamurthi, M. and Hopke, P.K. Simulations Studies of Reconstruction Algorithms for the Determination of Optimum Operating Parameters and Resolution of GSA Systems (non-conventional diffusion batteries). Aerosol Sci. Technol. 12: 700, 1990.

TITLE: Influence of Radon Concentrations on the Relationship Among Radon Measurements Within Dwellings

AUTHOR: Judith B. Klotz, NJ State Department of Health

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

Measurements of radon were made in a sample of New Jersey residences as part of a retrospective epidemiological study of lung cancer in women. Data on 983 dwellings from the first and second study phases have been analyzed.

Both the short term and long term test results were distributed lognormally. Radon gas concentrations were also compared to each other within residences with respect to floor of dwelling, type of detector, and length of measurement. In particular, measurements designed to yield "worst case" concentrations for screening purposes were compared to those designed to yield estimates of average annual exposures; the ratios of these two measurements become more extreme as the measured radon concentrations increased.

Although the sample from which these data were drawn is not necessarily representative of either state or national housing stock, these observations, if verified, may have important implications for procedures and decision strategies intended to reduce individual and population exposures to radon.

THE USE OF INDOOR RADON MEASUREMENTS AND GEOLOGICAL DATA IN ASSESSING THE RADON RISK OF SOIL AND ROCK IN CONSTRUCTION SITES IN TAMPERE

by: Anne Voutilainen and Ilona Mäkeläinen
Finnish Centre for Radiation and Nuclear Safety
P.O.Box 268, SF-00101 Helsinki, Finland

ABSTRACT

We have developed a model which allows us to use indoor radon measurements in assessing the radon availability of soil and rock in construction sites. The effect of the geological nature of the construction site on indoor radon is distinguished from the construction effects of the house. The purpose is to divide the investigated area into more or less homogeneous subareas and calculate the percentages of houses exceeding 200 and 800 Bq/m^3 in future homes where no precautions have been taken against radon.

In this study we used 867 indoor radon measurements from the city of Tampere (population 171,000). They were two-month-average concentrations measured in winter. The soil and rock type for each house was determined on the basis of geological maps, the structure of the buildings according to questionnaire responses.

A radon prognosis was made for four different construction sites. For each group of contruction sites, Tampere was divided into 1-2 different subareas. Within each subarea, the assessments were also made for different foundation and rock types.

INTRODUCTION

In Finland, most indoor radon measurements are performed by the Finnish Centre for Radiation and Nuclear Safety (STUK). We keep the local authorities up to date and help them find affected areas. The means offered by the STUK are an alfa track measurement service, measurement plans and prognosis maps. We also collect information about houses where the radon level has been measured. To date we have collected a database of more than 23,000 indoor radon measurements in houses with known coordinates. Figure 1 shows the geographical distribution of indoor radon concentration in Finland.

We have constructed a model which allows us to use these measurements in assessing the radon availability of soil and rock in the contruction site. So far we have used this model for six regions. Tampere is an example of a location with wide range of indoor radon levels in a rather small area. The study area is shown in Figure 1.

MATERIALS

Since 1983 we have measured indoor radon concentrations in Tampere. Most of the measurements were made according to STUK's measurement plan. For this study we used data pertaining to 867 houses. All the measurements were performed in the lowest residential story of houses during a two-month period in winter. The measured radon concentrations were corrected to annual means (1).

Because the main purpose of our measurements was to determine which areas were affected most of the measurements were made in areas where we expected a high risk of radon. The most radon-critical areas in Finland are ususally eskers. They are long and narrow, steep-sided ridges formed by glacial rivers. Their composition of stratified sand and gravel makes them permeable to water and air. The esker running through the center of tampere has thus been investigated almost completely. We have made fewer measurements in other parts of Tampere, but we think that the findings represent the population distribution and different construction sites fairly well.

Data concerning the building stucture were collected from questionnaires filled out by the residents. The soil and rock types of the construction site were determined from maps of gravel and sand resources on a scale 1:20,000 and from other geological maps on a scale 1:100,000. Information about whether or not the house was built on rock was collected from the questionnaires. 14% of the houses were built on rock, 8% on moraine, 17% on clay and silt, 53% on eskers, and 8% on other sand and gravel formations.

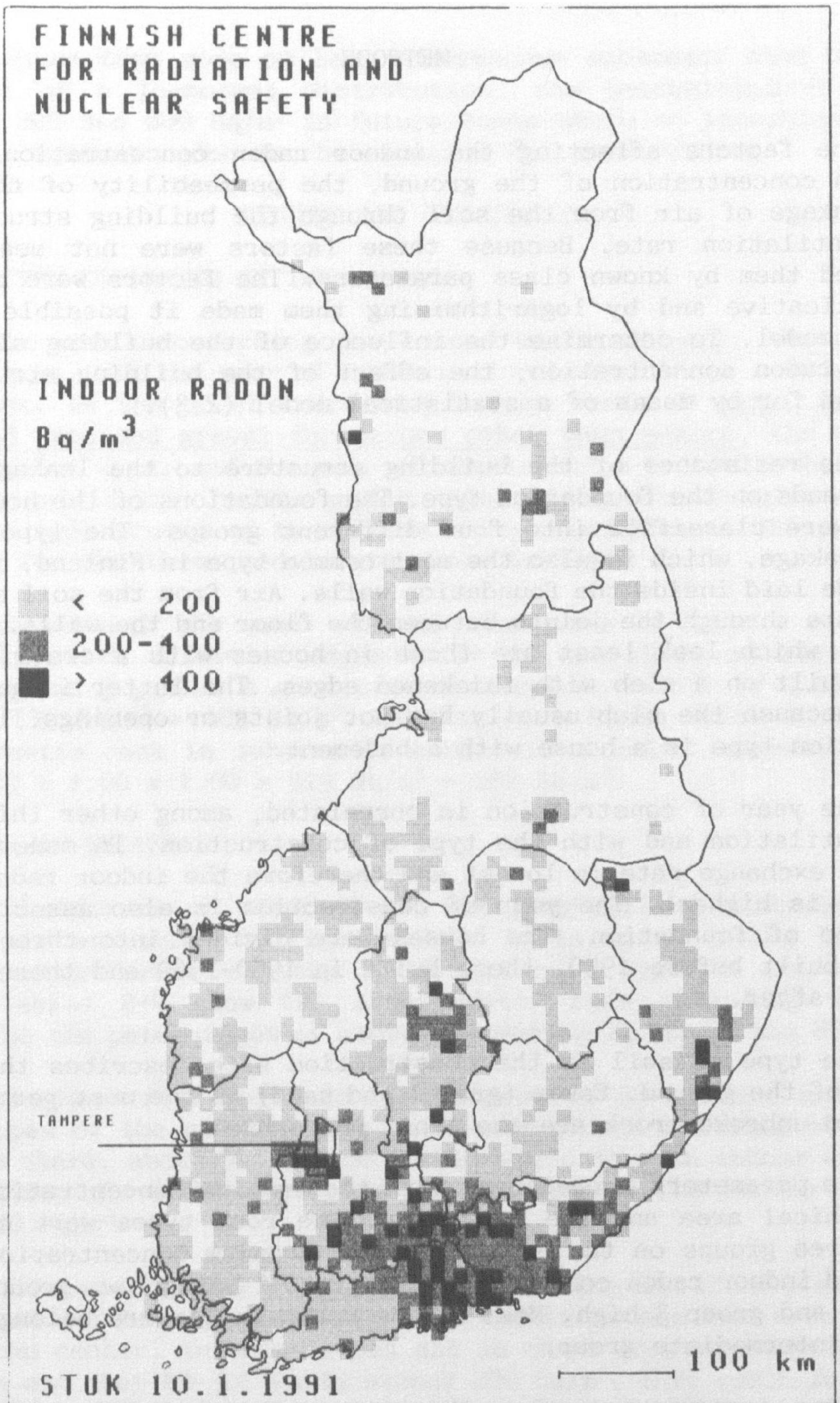


Figure 1. The indoor radon concentration has been measured in 23,000 dwellings in Finland. The square (10 x 10 km) on the map shows the arithmetic mean of the annual concentrations. The minimum is two measurements per square.

METHODS

The factors affecting the indoor radon concentration are: the uranium concentration of the ground, the permeability of the ground, the leakage of air from the soil through the building structure, and the ventilation rate. Because these factors were not measured, we replaced them by known class parameters. The factors were considered multiplicative and by logarithmizing them made it possible to use a linear model. To determine the influence of the building site on the indoor radon consentration, the effect of the building structure was adjusted for by means of a statistical model (2,3).

The resistance of the building structure to the leakage of soil air depends on the foundation type. The foundations of the houses under study were classified into four different groups. The type with the most leakage, which is also the most common type in Finland, is a slab-on-grade laid inside the foundation walls. Air from the soil can easily penetrate through the joints between the floor and the walls. The foundations which leak least are those in houses with a crawl space and those built on a slab with thickened edges. The latter is quite radon safe, because the slab usually has not joints or openings. The fourth foundation type is a house with a basement.

The year of construction is correlated, among other things, with the ventilation and with the type of construction. In modern houses, the air exchange rate is lowest and therefore the indoor radon concentration is highest. The year of construction is also associated with the type of foundation. The houses were divided into three classes: houses built before 1950, those built in 1950-1969 and those built in 1970 or after.

The type of soil at the construction site describes the permeability of the ground. Esker (gravel and sand) is the most permeable and clay and unbroken rock are the least permeable.

The parameters correlating with the uranium concentration are the geographical area and the rock type. The rock types were classified into three groups on the basis of their uranium concentration and the measured indoor radon concentrations, group 1 being low, group 2 intermediate and group 3 high. Most of the rocks in Tampere belong to group 2, the intermediate group.

After testing several combinations of parameters, we found it practical to make three different models concerning houses built on rocks, eskers, and other soil types. To draw the boundaries of the subareas, the model was used to assess the construction factors. The adjusted concentrations were drawn on a map, and they were used to divide Tampere into more or less homogeneous subareas. When using an assumption of a lognormal distribution, the percentages of houses exceeding 200 and 800 Bq/m^3 in future homes where no precautions have been taken against radon can be assessed for each subarea.

RESULTS AND DISCUSSION

THE PARAMETER ESTIMATES OF THE MODELS

In the model concerning the houses built on rock, the subarea, the rock type, and the year of construction proved to be statistically significant. In the model concerning houses built on clay, silt, moraine, and sand and gravel formations other than eskers, the subarea, the foundation type, and the year of construction proved to be statistically significant. In the esker model, only the subarea and the foundation type proved to be statistically significant. The parameter estimates for the three models are shown in Table 1.

Application of the model and the parameters of Table 1 to a house with a slab with thickened edges built in the 1980s on clay in the lowest subarea 3 yields a geometric mean concentration of 1.26 x 1.00 x 0.62 x 139 Bq/m^3 = 109 Bq/m^3. Similarly, a house built in 1950s on aplite granite rock in subarea 2 results in a radon concentration of about 0.59 x 1.00 x 1.00 x 319 Bq/m^3 = 188 Bq/m^3.

RADON RISK OF SUBAREAS

The boundaries of subareas and the geographical distribution of measurements are shown in figures 2-5. It is worth noting that each subarea number indicates only a certain soil type in the area involved. Tables 2-4 show the assessments, made according to these models, for the percentages of houses exceeding 200 Bq/m^3 and 800 Bq/m^3.

The highest risk for radon in Tampere is on the top and on the upper slopes of the esker ridges. If conventional building structures were used there, about 90% of the houses would have an indoor air radon concentration above 200 Bq/m^3 and in over 50% of the houses it would exceed 800 Bq/m^3.

The lowest risk for radon occurs in houses built on rock in the central and northern parts of Tampere and in houses built on clay or silt in the center. In these areas and on these construction sites the estimates are that 10-30% would exceed 200 Bq/m^3, that radon levels exceeding 800 Bq/m^3 would be very rare (less than 0.1%).

The eskers in Tampere are perhaps the most radon-critical eskers in Finland. On the other hand, the radon risk on other construction sites in Tampere is only slightly higher than the average in Finland.

TABLE 1. PARAMETER ESTIMATES AND THEIR 95% CONFIDENCE LIMITS, THE MULTIPLE CORRELATION COEFFICIENT (R^2) AND THE GEOMETRIC DEVIATIONS (σ_g) FOR THREE DIFFERENT MODELS. MODEL 1 CONCERNS HOUSES BUILT ON ROCK, MODEL 2 HOUSES ON CLAY, SILT, MORAINE AND OTHER SAND FORMATIONS NOT ESKERS, AND MODEL 3 HOUSES ON ESKERS (GRAVEL AND SAND)

FACTOR	MODEL 1	MODEL 2	MODEL 3
R^2	0.37	0.34	0.29
σ_g	1.81	1.95	3.34
Constant (Bq/m^3)			
	319 (228,447)	139 (108,177)	183 (141,237)
Subareas:			
1	0.64 (0.50,0.83)		
2	1.00 -		
3		0.62 (0.49,0.78)	
4		0.97 (0.80,1.16)	
5		1.00 -	
6			4.77 (3.73,6.10)
7			1.00 -
Foundation types:			
A		1.64 (1.28,2.11)	
AB			1.00 (0.76,1.30)
B		1.26 (0.96,1.66)	
C		0.89 (0.52,1.51)	0.64 (0.45,0.92)
D		1.00 -	1.00 -
Rock groups:			
1	0.50 (0.30,0.82)		
2	0.61 (0.43,0.86)		
3	1.00 -		
Year of construction::			
<1950	0.62 (0.44,0.86)	0.85 (0.63,1.16)	
1950-1969	0.59 (0.44,0.80)	0.51 (0.40,0.64)	
>1969	1.00 -	1.00 -	

A = Slab-on-grade laid inside foundation walls
B = Slab with thickened edges
C = Crawl space
D = Basement
Rock group 1 = peridotite, amphibolite, tuffite, graywacke, uralite porphyrite and conglomerite.
Rock group 2 = granodiorite, granite, gabbro and veined mica gneiss.
Rock group 3 = phyllite, micaschist, acid tuffite, quartz-feldspar schist and aplite granite.

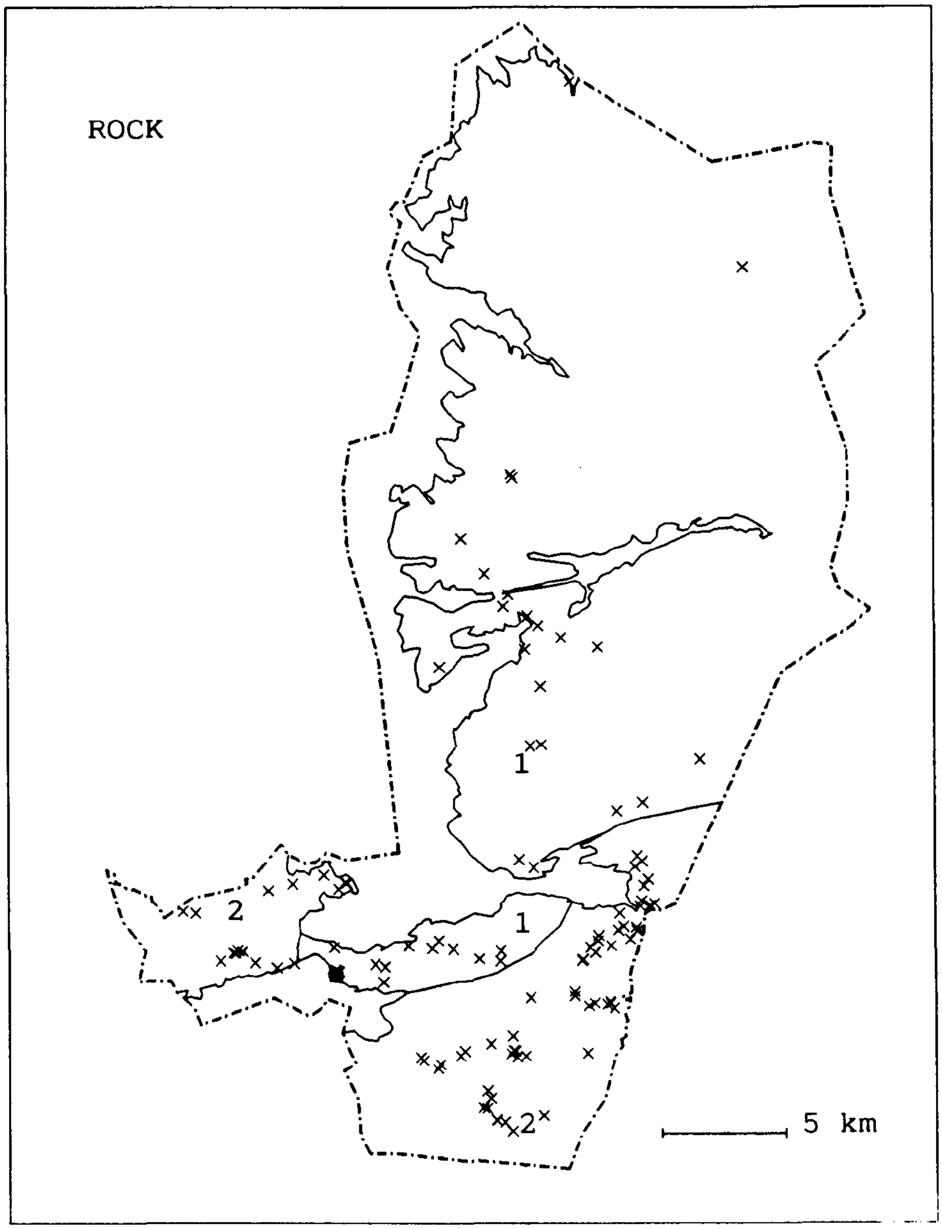


Figure 2: The boundaries of subareas 1 and 2 and the distribution of measurements made in houses built on rock.

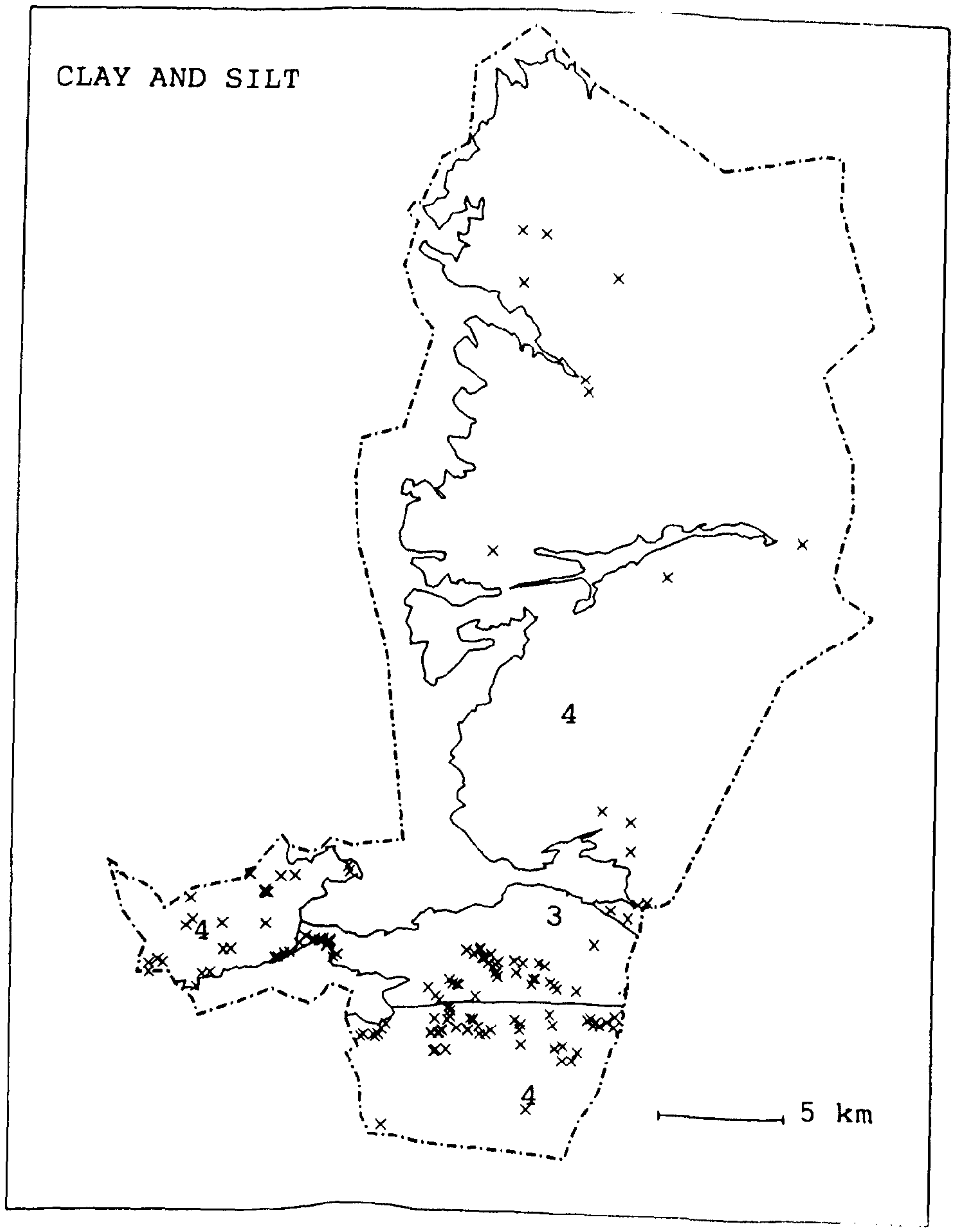


Figure 3: The boundaries of subareas 3 and 4 and the distribution of measurement made in houses built on clay or silt.

Figure 4: The subarea 5 and the distribution of measurements made in houses built on moraine or sand formations other than eskers.

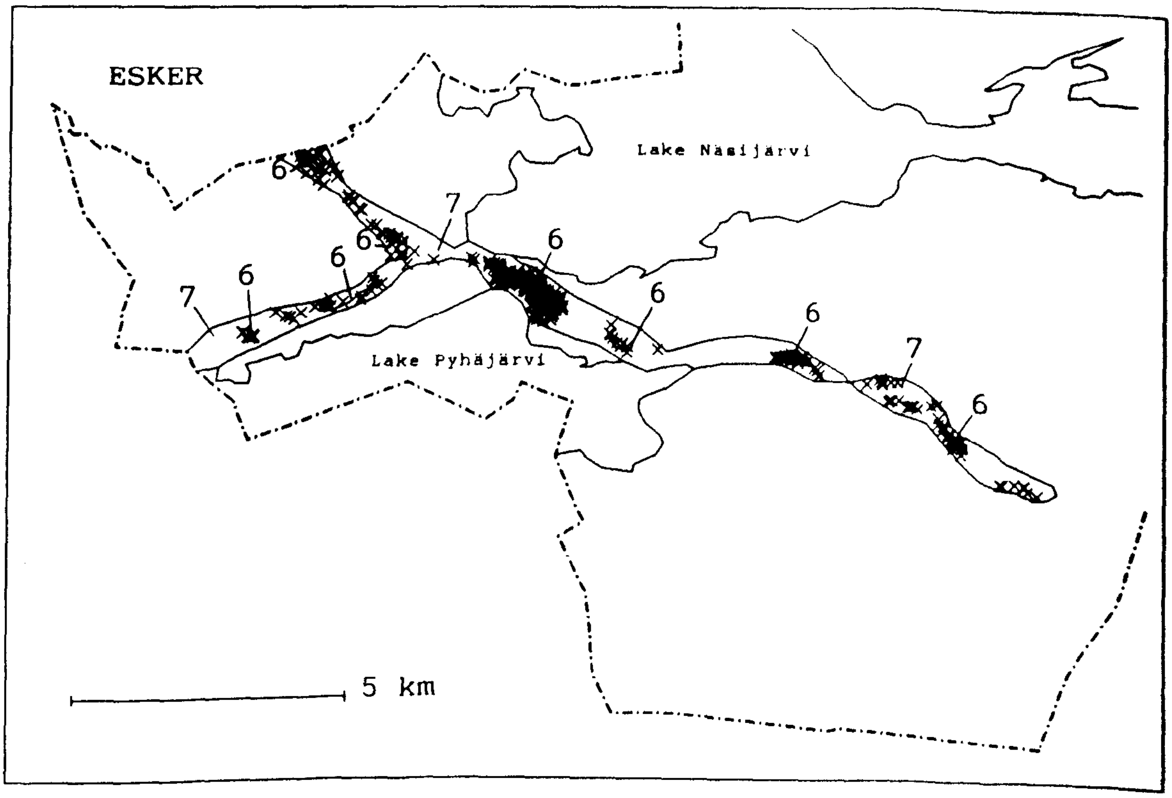


Figure 5: The boundaries of subareas 6 and 7 and the distribution of measurements made in houses built on gravel and sand in esker formations.

TABLE 2: THE RADON PROGNOSIS FOR HOUSES TO BE BUILT ON ROCK.

Construction site	Subarea	Rock type	>200 Bq/m^3 %	>800 Bq/m^3 %
Rock	1	1	13	0.03
	1	2	22	0.09
	1	3	55	1.4
	2	1	35	0.3
	2	2	48	0.9
	2	3	79	6.1

Rock type 1 = peridotite, amphibolite, tuffite, graywacke, uralite porphyrite and conglomerite.
Rock type 2 = granodiorite, granite, gabbro and veined mica gneiss.
Rock type 3 = phyllite, micaschist, acid tuffite, quartz-feldspar schist and aplite granite.

TABLE 3: THE RADON PROGNOSIS FOR HOUSES TO BE BUILT ON CLAY, SILT, MORAINE AND OTHER SAND AND GRAVEL FORMATIONS NOT ESKERS.

Construction site	Subarea	Foundation type	>200 Bq/m^3 %	>800 Bq/m^3 %
Clay and silt	3	A	30	0.5
	3	B	18	0.1
	3	D	10	0.04
	4	A	56	2.7
	4	B	40	1.0
	4	D	27	0.4
Moraine and other sand formations not eskers	5	A	58	3.0
	5	B	42	1.2
	5	D	29	0.4

A = Slab-on-grade laid inside foundation walls
B = Slab with thickened edges
D = Basement
Houses with a crawl space (only 7) are omitted.

TABLE 4: THE RADON PROGNOSIS FOR HOUSES TO BE BUILT ON ESKERS.

Construction site	Subarea	Foundation type	>200 Bq/m^3 %	>800 Bq/m^3 %
Esker	6	A,B,D	89	53
	6	C	80	38
	7	A,B,D	47	11
	7	C	33	5.6

A = Slab-on-grade laid inside foundation walls
B = Slab with thickened edges
C = Crawl space
D = Basement

THE PRACTICE IN TAMPERE

The health authorities in Tampere received STUK's report a year ago (4). In addition to the radon prognosis, the report also included the boundaries of the affected areas and a plan for additional indoor radon measurements.

The only areas where the health and building authorities have required radon-safe constructions are the top and upper slopes of the eskers (subarea 6). Elsewhere they have notified individual builders, building companies and geotechnical planning companies of the radon risk of different subareas and construction sites. The authorities do not know whether or not precautions have been taken against radon in these areas. The health authorities are still considering whether they should require radon-safe constructions in some other subareas, too. In any case, the prognosis report, which contains a summary of all previous measurements, has proved useful.

COST-EFFECTIVENESS

The estimates of the radon availability of soil and rock in construction sites can be based on field measurements or previous indoor radon measurements. Although it may be easy to make accurate field measurements, the prediction of future indoor radon concentrations is uncertain.

Some 500-1,000 measurements are needed for the radon prognosis, which is based on indoor radon concentrations. The total cost, including compilation of the report and making all the measurements needed, is FIM 20,000-30,000 (USD 5,000-7,500). The cost of the field investigations for only one planning area may be as high. It would make good sence to compile radon prognosis reports for areas consisting of several municipalities.

CONCLUSIONS

The radon prognosis report is an easy way of getting information about the radon risk of future construction areas. The report is most reliable when it concerns construction near or within an existing settlement. The problem is that there is no general practice concerning which kind of radon-safe structures should be required in areas differing as to radon risk.

REFERENCES

1. Arvela H and Winqvist K. A model for indoor radon variations. Environment International. 15: 239, 1989.

2. Mäkeläinen I, Voutilainen A and Castrén O. Estimation of indoor radon concentration in houses based on location and construction. Paper presented at the 8th regular meeting, Nordic Society for Radiation Protection, Mariehamn, Finland. August 26-28, 1987. (in Swedish)

3. Mäkeläinen I, Voutilainen A and Castrén O. Prediction of indoor radon concentration based on residence location and construction. Paper presented at The Conference of the 29th Hanford Symbosium on Health and the Environment, "Indoor Radon and Lung Cancer: Reality or Myth?" Richland, Washington, USA. October 16-19, 1990.

4. Voutilainen A and Mäkeläinen I. The indoor radon prognosis for Tampere. Research report 3.11.1989. Finnish Centre for Radiation and Nuclear Safety. Not published (in Finnish).

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Session III:

Measurement Methods -- PANEL

“Detection of Radon Measurement Tampering”

TITLE: Policy and Technical Considerations for the Development of EPA Guidance on Radon and Real Estate

AUTHOR: Lawrence Pratt, EPA - Office of Radiation Programs

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

Abstract

Real estate transactions have become a key force driving radon risk reduction. The EPA is currently developing guidance to assist consumers in handling radon risk reduction at the time of real estate transactions. There are many technical and policy considerations to be taken into account in developing guidance which effects so many industries, State programs, and consumers. This paper will examine several of the more significant issues, including: measurement devices, testing strategy, tamper prevention, conformity to existing State laws.

State Property Transfer Laws Now Include Radon Gas Disclosure

by: Michael A. Nardi
The Nardi Group
Carmel, IN 46032

ABSTRACT

During the past eight years many states have enacted comprehensive environmental laws and regulations imposing liabilities on property owners for the costs of cleaning up hazardous waste. More recently, several states have enacted laws that require environmental disclosure forms be prepared to ensure that the parties involved in certain real estate transactions are aware of environmental liabilities that may come with the transfer of property. In March, 1990, the State of Indiana enacted legislation that would require the disclosure of the presence of radon gas on many commercial real estate transactions.

INTRODUCTION

The model for state legislation and regulations concerning real estate transfer liabilities is the New Jersey Environmental Cleanup Responsibility Act (ECRA). Since its enactment in late 1983, ECRA has generated intense interest throughout the nation. This law imposes preconditions on the sale, transfer or closure of "industrial establishments" involved with hazardous substances. A number of other states such as Connecticut, Oregon, Delaware, Michigan, and New York have enacted or are now considering ECRA-style laws.

Since 1988, several states such as California, Illinois, Indiana, and Iowa have enacted legislation requiring that the seller prepare a disclosure document before property transfer to provide notice to the buyer of any hazardous substances on the property. In Illinois, the Responsible Property Transfer Act (RPTA), requires the seller of certain properties to provide a disclosure document to the buyer, lender, county recorder, and state Environmental Protection Agency. The document must disclose the past use and environmental status of the property.

THE INDIANA RESPONSIBLE PROPERTY TRANSFER LAW

The Indiana Responsible Property Transfer Law (IRPTL), signed into law on May 2, 1989 originally was very similar to the Illinois RPTA. However, this law was amended during the 1990 session of the Indiana General Assembly and signed into law by Governor Bayh on March 20, 1990. The purpose of these amendments was to address some of the shortcomings of the original law.

The original act required that sellers involved in certain commercial real estate transactions complete and file an environmental disclosure form. One reason that the IRPTL was amended was to ensure that significant environmental problems are reported even when the problem is not identified by category on the disclosure document. These amendments require the reporting of any "environmental defect" not required by a reporting category. In addition to reporting the environmental defect, the reporter must describe the defect.

To prevent a buyer or lender from abusing the IRPTL by frivolously claiming an environmental defect, the amendment includes its definition. This definition states that "environmental defect" means an environmentally related commission, ommission, activity, or condition that:

1. constitutes a material violation of an environmental statute, regulation, or ordinance;

2. would require remedial activity under an environmental statute, regulation, or ordinance;

3. presents a substantial endangerment to:
   A. the public health;
   B. **the public welfare; or**
   C. the environment;

4. would have a material, adverse effect on the market value of the property or of an abutting property; or

5. would prevent or materially interfere with another party's ability to obtain a permit or license that is required under an environmental statute, regulation, or ordinance to operate the property or a facility or process on the property.

According to this definition, radon gas would be considered an environmental defect, since it presents a substantial endangerment to the public health and because it could have a material, adverse effect on the market value of the property.

These amendments also permit a buyer or lender to cancel the sale if the disclosure document reveals one or more environmental defects in the property that were previously unknown to him. Therefore, a radon gas test should be performed for all property transfers in Indiana that are subject to this act.

CONCLUSION

With the trend that more states will be introducing property transfer legislation during future legislative sessions, it would be wise to monitor this type of legislation very closely, as it may decide the future of federal radon policy.

The work described in this paper was not funded by the U. S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

TITLE: Update on AARST Real Estate Testing Guidelines

AUTHOR: William P. Brodhead, WPB Enterprises

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

AARST has recently approved a volunteer guideline to be used by its membership when radon testing a dwelling involved in a Real Estate Transfer. It is critical that Real Estate testing be done differently than a homeowner testing his own home because of the time constraints and opportunity for test tampering. This report includes a copy of those guidelines. The important points about that document will be presented at the Symposium.

TITLE: Real Estate Transaction Radon Testing Interference

AUTHOR: Dean Ritter, ABE Testing

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

The author has been carefully installing interference indicators and controls during the past three years during professional radon testing of over a 1000 residential dwellings involved in real estate transfers. This paper includes a description of how the interference indicators were installed and how changes to the indicators were reported. The paper will present the results of the survey of the data which shows that interference in the required conditions of the test took place in 35% of all the testing done. The quantity of each type of interference and the percentage of interference with different types of dwelling conditions will also be reported.

The final portion of the paper will review the practicality of using these low cost and easily installed non-interference indicators and controls and the necessity to include such devices and technics as the owners of a dwellings become more knowledgeable about radon testing and how to influence the test results.

How to Determine if Radon Measurement Firms are Providing Accurate Readings

by: Herbert C. Roy, Ph.D.
and
Mohammed Rahman, Ph.D.

N.J. Dept. of Environmental Protection
Radon Section
Trenton, NJ 08625

ABSTRACT

The State of New Jersey is about to implement a mandatory radon certification program charging the Department of Environmental Protection (DEP) with certifying radon measurement and mitigation firms. When a radon testing firm submits monthly results how can the DEP insure that accurate readings were obtained?

This paper describes a method to determine the accuracy of radon firm measurements through statistical analysis of the difference between DEP and FIRM results (test difference curve) obtained from communities throughout New Jersey. The analysis consists of comparing the test difference with a standard difference curve derived by using DEP and FIRM data obtained from the same building.

STATISTICS

If one plots the frequency distribution curve for a large number of measurements of a quantity which ultimately conforms to the normal distribution, the result is the familiar bell-shaped curve. If independent radon measurements are obtained at the same location the observed variations can similarly be assumed to show a normal distribution[1]. The statement that independent radon test measurements show a normal distribution is supported by the following quote (1):

> The basic properties of the normal distribution can be easily seen in the case of errors in measurement... When the number of objects in a given space are simply counted (as in the case when cells that are tightly packed on a microscope slide are counted), the results obtained by different observers may vary. This variation among observations can be thought of as being random since it cannot be predicted beforehand. Such random variation arising when many independent measurements are taken of the same quantity is often accurately described by the normal distribution.

[1]It should be noted that the frequency distribution of actual radon readings describes a "lognormal pattern" (2).

The State of New Jersey is about to implement a mandatory radon certification program which charges the Department of Environmental Protection (DEP) with monitoring radon measurements. When a testing firm submits monthly results how can the DEP insure that accurate readings were obtained? The technique described in this paper determines the accuracy of radon firm measurements through statistical analysis of the difference between DEP and FIRM results within a given community.

At the start, let us assume that radon test results obtained by the DEP are accurate[1]. Now, it is hoped that radon measurements obtained from the same location in the same home tested by both the DEP and certified testing firms would be just as accurate. Thus, in the ideal case, if we looked at the difference between DEP and radon measurement firm results we would expect to observe no difference.

It should be noted that radon measurements obtained throughout New Jersey and even within the same municipality show variability[2]. This implies that care must be taken to insure that test results from Washington Township in Warren County are not compared with the results from Margate in Atlantic County. In addition, to minimize intra-municipality variability, comparisons should be performed using readings less than or equal to 20 pCi/L. This means that the differences between the DEP and test firm results would range from -20 pCi/L up to 20 pCi/L.

The DEP maintains a number of databases with confirmatory test results obtained at the same location as the measurement firm readings. These databases contain the initial testing firm results as well as the DEP's confirmatory test results. The monthly submission of firm measurement data would obviously not be correlated with a DEP reading--having a concurrent DEP reading for each firm reading would be cost prohibitive.

Therefore, given the natural variability of radon, how can the DEP be assured of the accuracy of measurement firm test results? There are two sets of confirmatory test results on the Radon Section Computer system: 1) one set containing 4302 sample points representing confirmatory data for initial test results greater than 4 pCi/L and 2) another set of 1308 sample points to confirm initial test results greater than 8 pCi/L. Each set stores the initial radon test results along with the DEP confirmatory results.

First we establish a baseline by randomly comparing firm and DEP readings from both confirmatory databases for each tested municipality throughout New Jersey. If the firm results are subtracted from the DEP test results we will obtain a frequency distribution of this difference --call this curve the **master curve** (C_m). In addition, we can calculate the sample mean and standard deviation for this difference.

As an example, suppose we look at confirmatory results for initial readings greater than 8 pCi/L (readings from the same municipality):

	DEP Data (in pCi/L)	FIRM Data
Sample # 1	8.4	9.2
Sample # 2	10.7	11.1

---

[1]The accuracy of canister radon concentration analysis by the DEP labs are confirmed by: 1) Lab participation in the Radon Measurement Proficiency Program (RMPP) 2) Use of duplicate canisters and 3) Use of blanks at least once a day.

[2]In fact radon readings obtained from the same location within a building demonstrate a natural variability over a day. This variability could be significant if readings are not obtained from the same location at the same time, i.e. weeks or months apart.

Next, we randomly match the above data. The match is random because when test firm results are initially examined for accuracy, matching DEP readings from the same location would be absent.

DEP Data	FIRM Data	DEP - FIRM
10.7	9.2	1.5
8.4	11.1	-2.7

This procedure would be followed for every tested municipality throughout New Jersey.

When we obtain the monthly firm results they can be randomly correlated with DEP readings for each municipality throughout New Jersey (again only readings less than 20 pCi/L are used to minimize large variations), their differences can be calculated and the frequency distribution of this difference obtained--this is the **test curve** (C_t)[1]. If the shape of C_t and C_m are not significantly different (meaning that the shape of C_t is not much different than the shape of C_m) then the monthly firm results are acceptable. Otherwise, further statistical testing is warranted.

If further testing is indicated, the mean and standard deviation for this difference are calculated and the paired sample T-test is applied to the data. In this T-test we consider two possible hypotheses: 1) the so-called null hypothesis (H_0)--that the population means of the C_m and C_t data are the same and 2) the alternate hypothesis (H_a)--that the population means of the C_m and C_t data are **NOT** the same.

At this time it should be pointed out that some texts (3) indicate that the T-test is usually applied when **at least** one sample population size is less than thirty. If this restriction is not applicable (i.e. both sample sizes are greater than thirty) then a similar Z-statistic (obtained from a normal distribution table) is used. Currently, tables for the T-test exists for sample sizes up to 1000--thus in practice there is no real hinderance to use the T-test for large sample sizes.

DATA ANALYSIS SECTION

As stated earlier, the DEP maintains two confirmatory database systems. One system stores confirmatory test results on firm readings greater than 4 pCi/L--DEP results are in the DEP1 database while firm results are in the FIRM1 database. The other confirmatory system stores confirmatory test results on firm readings greater than 8 pCi/L--DEP results in the DEPDATA database while firm results are in the FIRMDATA database. Test results in either system are identified by a number unique to a particular home.

The reader should keep in mind that initially data in the DEP radon concentration database would be relatively higher than testing firm data. The DEP readings having been derived for the purpose of confirming elevated radon readings (at least greater than 4 pCi/L). However, readings below 4 pCi/L also exist in New Jersey. This is a persuasive argument for adding readings obtained from testing firm inspections to the DEP database.

---

[1]It should be noted that both the **master curve** (C_m) and the **test curve** (C_t) are generated by comparing firm results with DEP results from the confirmatory databases. Initially the comparison would be made with DEP tests performed to confirm testing firm results greater than 4 pCi/L. However, if the DEP begins to verify test firm results less than 4 pCi/L this lower limit would be dropped.

The accuracy of a particular radon measurement firms' results will be determined through a random comparison with DEP data for each tested municipality throughout New Jersey. Thus, to obtain the previously defined **master curve** (C_m) DEP test data must be compared randomly with FIRM test data (for readings greater than 0 pCi/L and less than or equal to 20 pCi/L). When this was done and the randomly matched DEP and firm readings were subtracted, **figure** 1 was obtained (based on 5139 points[1]).

These 5139 points form a sample--e.g. data which is representative of the population as a whole. In this case the whole population would be the difference between statewide radon readings obtained by the DEP and testing firms.

We can appraise this sample by calculating two quantities: 1) sample mean, $\overline{X}$, (the average value of the data) and 2) sample standard deviation, s, (a measure of the variation of the sample under study)

$$s = \sqrt{\frac{\sum (X - \overline{X})^2}{n - 1}}$$

where n is the number of sample data points.

Calculating these quantities for points in the **master curve** we obtain the following:

$$\overline{X} = -0.87 \quad \text{and} \quad s = 5.76$$

which means that the average value for the difference between DEP and firm radon readings within each tested municipality throughout New Jersey is -0.87 pCi/L and that 67% of the readings would be within ± 5.76 pCi/L.

Now, we will compare the **master curve** (C_m) data with data from specific testing firms. First we will look at radon measurements from Firm A (>= 4 pCi/L) from the voluntary database system. If Firm A's results are subtracted from DEP results randomly matched for each tested municipality throughout New Jersey we obtain the test curve (C_t) marked **figure 2**. For this data, $\overline{X}$ is -0.46 while s = 5.38.

How can we statistically tell if (C_m) is different from (C_t)? One way is to look at a two sample paired test of means--Student's t-statistics. In this test, the test statistic is defined as

$$t = \frac{\overline{X_1} - \overline{X_2}}{s\sqrt{1/n_1 + 1/n_2}} \qquad \text{(eq. 1)}$$

where $\overline{X_1}$ is the mean of sample 1

$\overline{X_2}$ is the mean of sample 2

n_1 is the size of sample 1

n_2 is the size of sample 2

---

[1]These 5139 points are obtained by randomly matching, by municipality, the combined DEP and test firm readings from the two confirmatory databases (matched from the same household) as long as both readings are less or equal to 20 pCi/L.

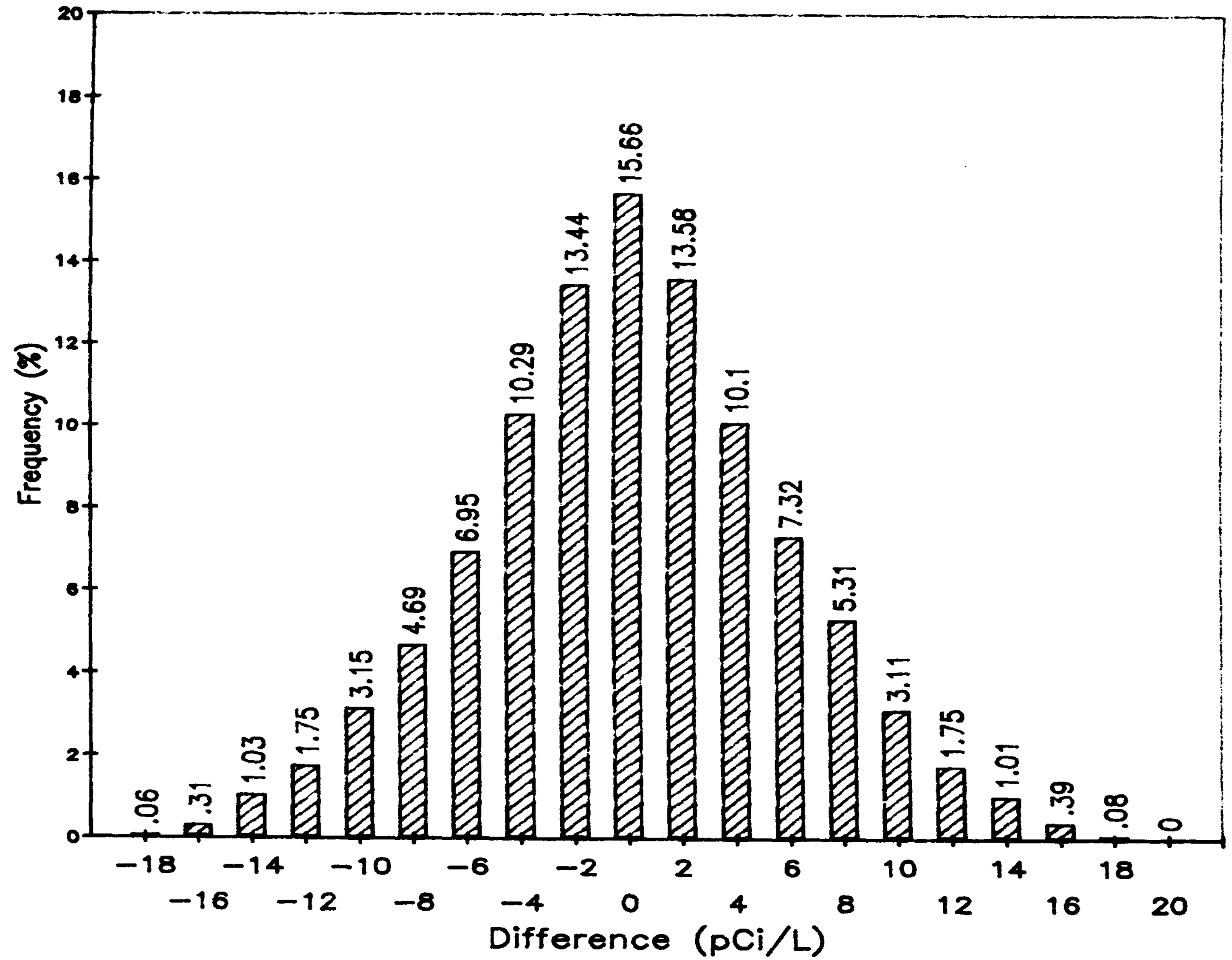


Figure 1. DEP Data Minus FIRM Data

5139 Municipality Matched Data Points

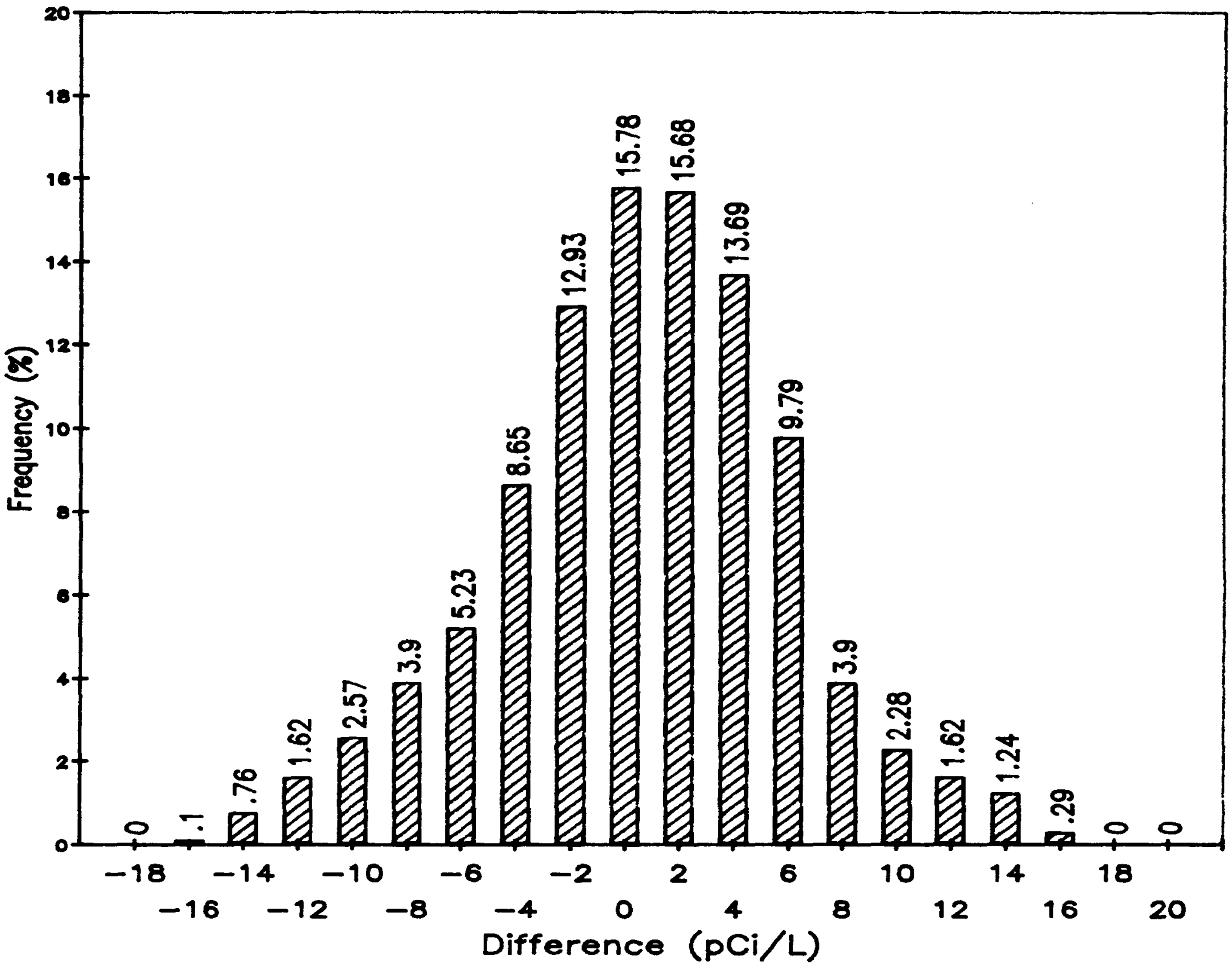


Figure 2. DEP Data Minus FIRM A's Voluntary Radon Test Data (LORAD >= 4 pCi/L) Based on 1052 Points

and s, the estimate of the common population standard deviation is defined as

$$s = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 - n_2 - 2}}$$

Inserting data from **figure 1** and **figure 2** in equation 1 we calculate t = -2.13.

What does the t-statistic mean? Recall that we are trying to test the two possible hypotheses (described on page 3) that the populations means of the C_m and the C_t data are either the same or not the same (one data sample is significantly less than or greater than the other).

Suppose we wanted to be 95% sure of which hypothesis is correct. That is to say we want to be 95% certain that the populations of the two curves, C_m and C_t, are either the same or significantly lower or higher. The Student's t distribution provides the so-called critical values (essentially the area to the left of the critical value--see figure 3 [5]) needed for the t test, for various degrees of freedom[1]--based on the number of samples (in this case $n_1 + n_2 - 2$) and the level of significance.

The <u>area</u> (critical value) represents the region of certainty. We want to be 95% certain--this criteria is often referred to as a 5% level of significance. Since our hypothesis is not one-sided (such a test would entail testing that one population mean is greater than or less than the other) but two-sided (tests that one population mean is either greater than or equal to the other). This means that we would look under a level of significance of 0.05/2 or 0.025. We want to be 95% certain that we are not either too high or low--thus the 95% would be sandwiched between two tails which total 5%.

Now we are comparing the curves in **figure 1** and **figure 2**. The number of degrees of freedom is 5139 + 1052 - 2 or 6189. From the t-statistic tables, (6) the critical value at the 0.025 level of significance is 1.96 (taking the number of degrees of freedom as infinity). Since this is a two-sided test, we would accept the null hypothesis (H_0) that the sample means of the **master curve** and the **test curve** are the same if the test statistic is between -1.96 and +1.96. Our test statistic was -2.13.

$$-2.13 < -1.96 \text{ (the critical value)}$$

The test statistic is less than the critical value, thus we **reject** H_0 and accept the alternate hypothesis (H_a)--the two population means are indeed significantly different.

There is another comparison of two samples--the F-test (one-way analysis of variance). The F-test is used when samples are independent, normally distributed and possess equal standard deviations. The test statistic is defined as:

$$F = \frac{S_B^2}{S_W^2}$$

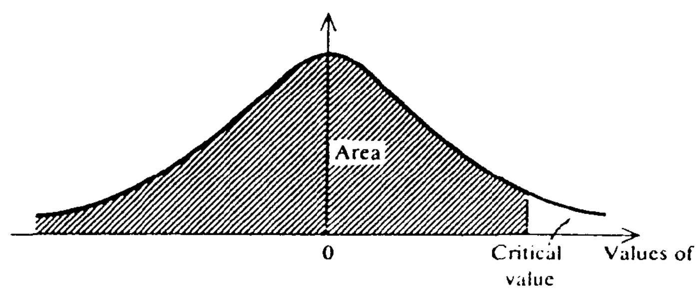
[1]The term degrees of freedom "...is the number of independent measurements available for estimating (the sample standard deviation)..." If one adds the difference X - $\overline{X}$ (referred to as a residual) for each value of X the result is zero. If we know the sum of n - 1 residuals the other residual can be determined. Thus, "...there would be only n - 1 "independent" values use to compute the sample standard deviation (4).

Student's t distribution

The table gives the critical values of *t* needed for the *t* test, for various degrees of freedom and levels of significance.

Example 1. Suppose the test is one-sided and rejects for large values of *t*, with level of significance .05. Then the critical value is in the column headed .95, on the row corresponding to the appropriate degrees of freedom.

Example 2. Suppose the test is two-sided, and has level of significance .01. Then the critical values are in the columns headed .005 and .995, on the row corresponding to the appropriate degrees of freedom. If there are 10 degrees of freedom, the test would reject if the observed value of *t* is less than −3.17 or greater than 3.17.



Degrees of freedom	*Area to the left of the critical value*			
	.005	.01	.025	.05
1	−63.66	−31.82	−12.71	−6.31
2	− 9.92	− 6.96	− 4.30	−2.92
3	− 5.84	− 4.54	− 3.18	−2.35
4	− 4.60	− 3.75	− 2.78	−2.13
5	− 4.03	− 3.36	− 2.57	−2.02
6	− 3.71	− 3.14	− 2.45	−1.94
7	− 3.50	− 3.00	− 2.36	−1.90
8	− 3.36	− 2.90	− 2.31	−1.86
9	− 3.25	− 2.82	− 2.26	−1.83
10	− 3.17	− 2.76	− 2.23	−1.81
11	− 3.11	− 2.72	− 2.20	−1.80
12	− 3.06	− 2.68	− 2.18	−1.78
13	− 3.01	− 2.65	− 2.16	−1.77
14	− 2.98	− 2.62	− 2.14	−1.76
15	− 2.95	− 2.60	− 2.13	−1.75
16	− 2.92	− 2.58	− 2.12	−1.75
17	− 2.90	− 2.57	− 2.11	−1.74
18	− 2.88	− 2.55	− 2.10	−1.73
19	− 2.86	− 2.54	− 2.09	−1.73
20	− 2.84	− 2.53	− 2.09	−1.72
21	− 2.83	− 2.52	− 2.08	−1.72
22	− 2.82	− 2.51	− 2.07	−1.72
23	− 2.81	− 2.50	− 2.07	−1.71
24	− 2.80	− 2.49	− 2.06	−1.71
25	− 2.79	− 2.48	− 2.06	−1.71
26	− 2.78	− 2.48	− 2.06	−1.71
27	− 2.77	− 2.47	− 2.05	−1.70
28	− 2.76	− 2.47	− 2.05	−1.70
29	− 2.76	− 2.46	− 2.04	−1.70
30	− 2.75	− 2.46	− 2.04	−1.70
40	− 2.70	− 2.42	− 2.02	−1.68
50	− 2.68	− 2.40	− 2.01	−1.68
60	− 2.66	− 2.39	− 2.00	−1.67
80	− 2.64	− 2.37	− 1.99	−1.66
100	− 2.63	− 2.36	− 1.98	−1.66

Figure 3. Student's t Distribution
(from Reference [1] pages 356-357)

where

$$S_W^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}$$

and

$$S_B^2 = n_1(\overline{X}_1 - \overline{\overline{X}})^2 + n_2(\overline{X}_2 - \overline{\overline{X}})^2$$

where

$$\overline{\overline{X}} = \frac{n_1\overline{X_1} + n_2\overline{X_2}}{n_1 + n_2}$$

there would two degree of freedom parameters:

1. $\nu_1 = 1$
2. $\nu_2 = n_1 + n_2 - 2$

For this example, the F-statistic is 4.52, with $\nu_1 = 1$ and $\nu_2 = 6189$. From the f-statistic tables, (7) the critical value is 5.02.

$$4.52 < 5.02 \text{ (the critical value)}$$

The F-statistic is less than the critical value, therefore, the population means are not significantly different.

In summary, the T-statistics led to a rejection of the null hypothesis (H_o) while the F-statistic leads to an acceptance of the null hypothesis (H_o). Thus radon measurements from Firm A would be deemed a borderline case.

Figure 4 is the test curve (C_t) for Firm B's radon measurements obtained from the confirmatory database (greater than 4 pCi/L). The arithmetic mean is -0.52 and the standard deviation is 6.07. Therefore, the t-statistic is -1.116--the critical value for this two-sided paired Student's t-test would be 1.96, leading to acceptance of H_o if the t-statistic is between -1.96 and +1.96.

$$-1.116 > -1.96 \text{ (the critical value)}$$

thus we accept the hypothesis that the population means are equal.

The f-statistic is 1.25--the critical value is 5.02

$$1.25 < 5.02$$

thus, confirming the hypothesis that the population means are equal. Here both statistics confirm the null hypothesis (H_o) and this firm would be designated as providing the DEP with accurate results.

Figure 5 is the test curve (C_t) derived from the voluntary radon test database for Firm C's measurements. The arithmetic mean is -0.64 and the standard deviation is 5.86. Therefore, the t-statistic is -1.55 (note that we will accept the null hypothesis if the t-statistic is between -1.96 and +1.96).

$$-1.55 > -1.96 \text{ (the critical value)}$$

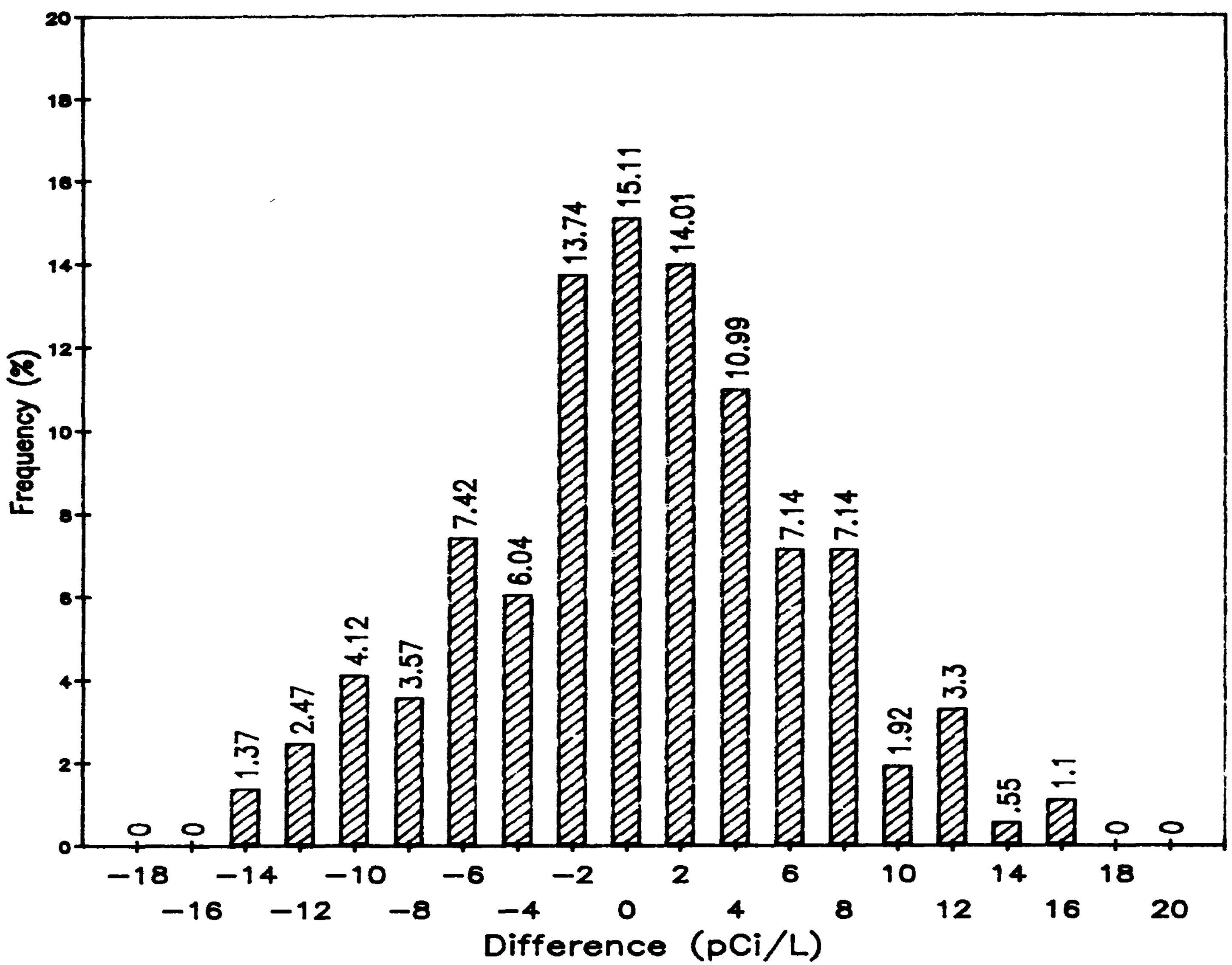


Figure 4. DEP Data Minus FIRM B's Radon Test Data

Based on 364 Points

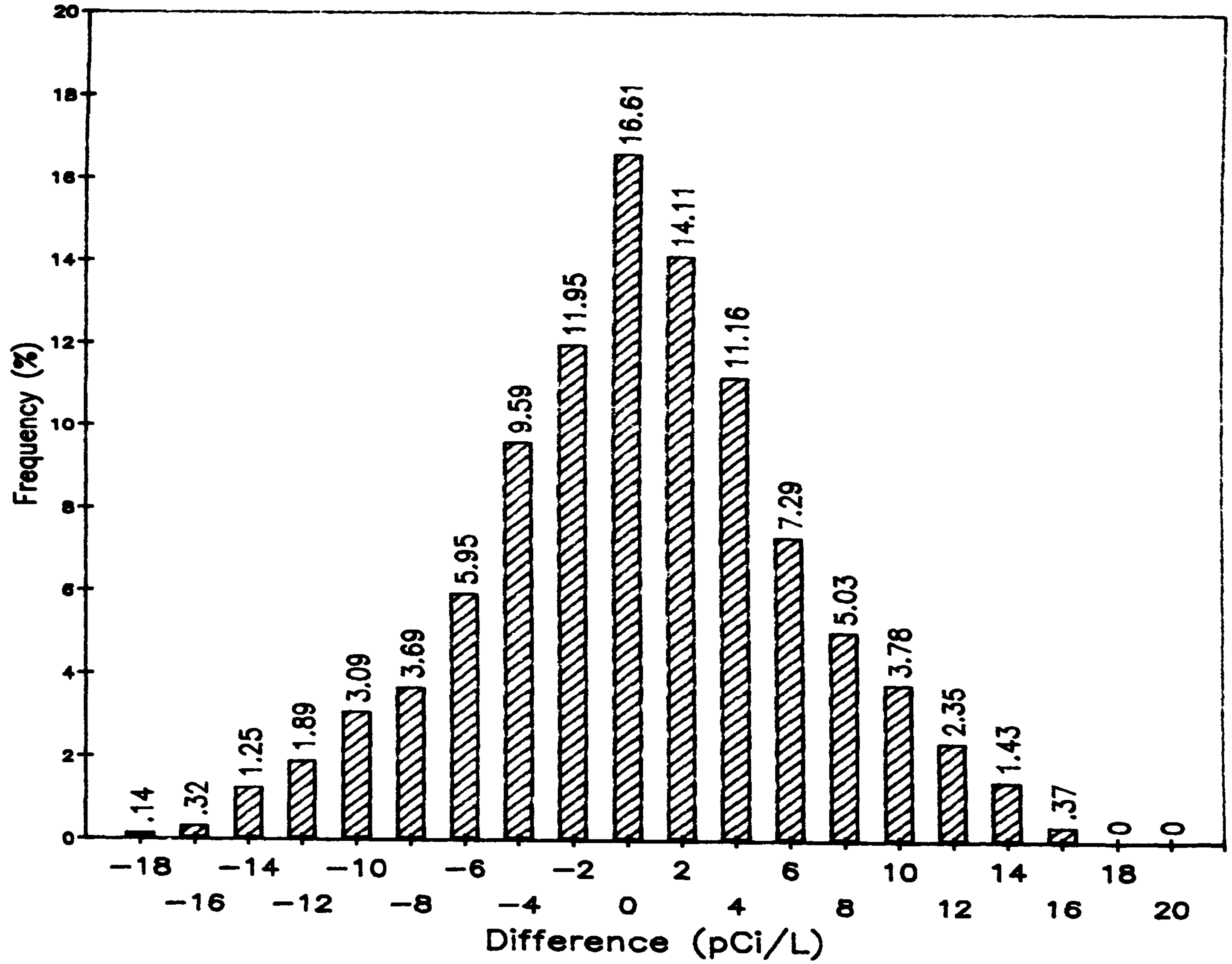


Figure 5. DEP Data Minus FIRM C's Voluntary Radon Test Data

(LORAD >= 4 pCi/L) Based on 2168 Points

thus we accept the hypothesis that the population means are equal.

The f-statistic is 2.41--the critical value is 5.02

therefore, confirming the hypothesis that the population means are statistically equal. This means that the testing firm's readings are acceptable.

Figure 6 is derived from 241 data points each arbitrarily assigned a radon level of 16 pCi/L (this represents a spiked elevated radon sample). The arithmetic mean is -8.2 and the standard deviation is 4.27. Therefore, the t-statistic is 19.51

$$19.51 > 1.96 \text{ (the critical value)}$$

thus we reject the hypothesis that the population means are equal (the hypothesis would be accepted if the t-statistic is between -1.96 and +1.96).

The f-statistic is 380.45--the critical value is 5.02

confirming the hypothesis that the population means are not statistically equal. This means that this testing firm's readings would not be acceptable.

If both the T-statistic and the F-statistic lead to a rejection of the null hypothesis (H_0) then the DEP would conduct a canister test at the same time as the testing firm to confirm the firm's results for several months.

The acceptance criteria for testing firm results can be summarized as follows:

	T-Statistic	F-Statistic	Decision
1.	Reject	Reject	DEP must conduct side by side-by-side canister tests with firm for several months
2.	Reject Accept	Accept Reject	Borderline case. If firm is borderline for three (3) consecutive months, perform side-by-side testing.
3.	Accept	Accept	Testing firms results are deemed accurate

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

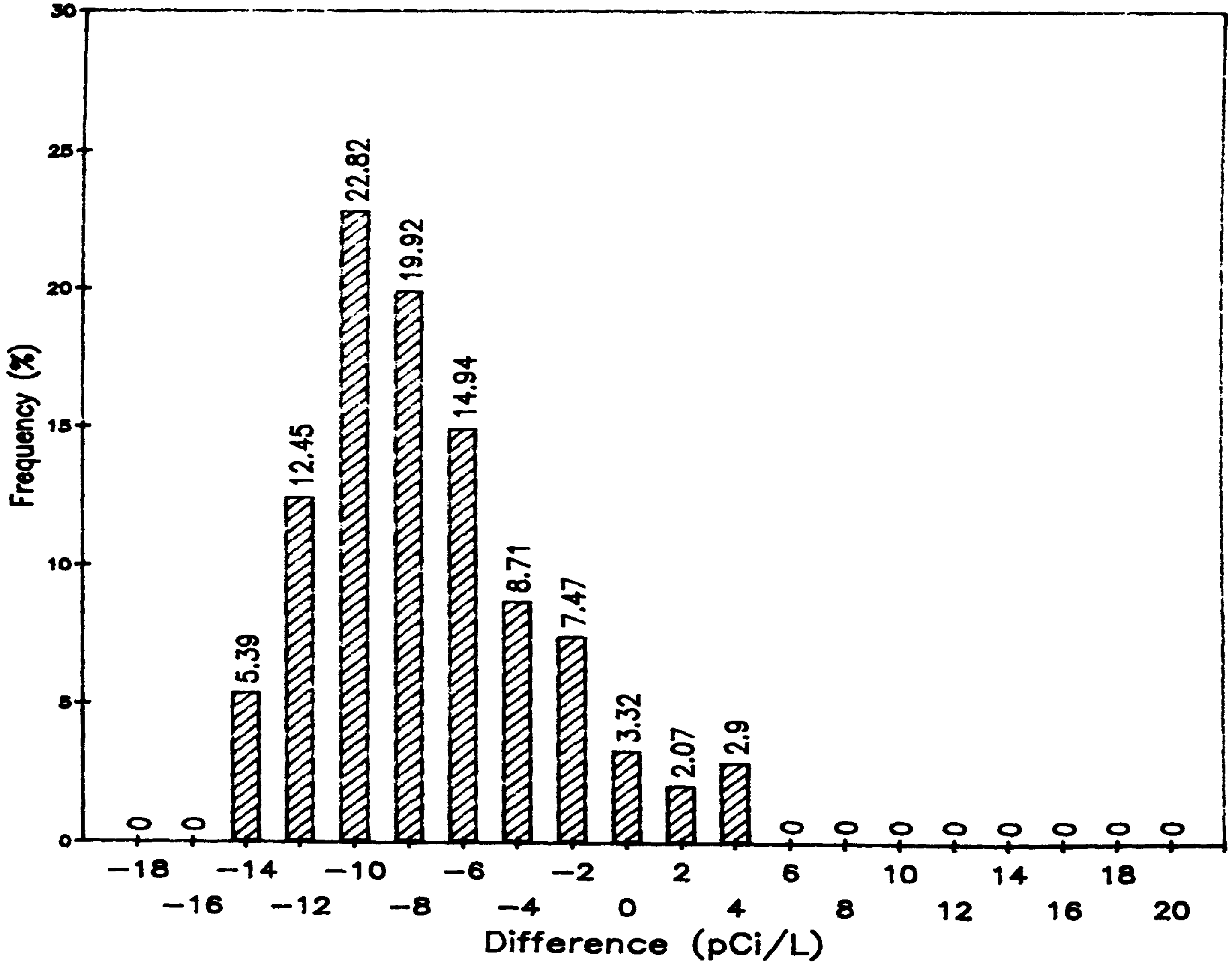


Figure 6. DEP Data Minus High Bogus Firm Data

Based on 241 Points

REFERENCES

1. Orkin, M. and Drogin, R., Vital Statistics, McGraw-Hill Book Company, c. 1975, p. 65-66.
2. CDM (Camp Dresser & McKee, Inc.), Summary Report: Scientific Study of Radon, April 1989, p. 204.
3. Orkin, M. and Drogin, R., Op. Cit., p. 146.
4. Ingelfinger, J. A., et. al., Biostatistics in Clinical Medicine, MacMillian Publishing Company, Inc., 1st edition, p. 103.
5. Orkin, M. and Drogin, R., Op. Cit., pp. 356-357.
6. Zar, J. L., Biostatistical Analysis, Prentice-Hall, c. 1974, table D.10.
7. Zar, J. L., Op. Cit., table D.11.

TITLE: Grab Sampling as a Method of Discovering Test Interference

AUTHOR: Marvin Goldstein, Building Inspection Service, Inc.

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

The Abstract is on the following pages.

WHAT HAPPENS WHEN YOU DO FOUR-HUNDRED AND SEVENTY-SEVEN (477) RADON INSPECTIONS PRECEEDED BY GRAB SAMPLES?

by: Marvin 'D' Goldstein
President-Elect
Pennsylvania AARST
Co-Chairman,
National AARST Legislative Committee
Southampton, PA 18966

ABSTRACT

After compiling the data obtained from conducting 477 radon inspections, over a four-year period, it can be concluded that performing a one-hour working level monitor test is useful in determining that two to seven day E-Perm or charcoal canister tests have not been tampered with. Duplicate readings increase the confidence that the readings are accurate.

Of the 477 tests conducted from October, 1987 through June 1990, 107 tests had high readings (above .02 WL or 4pCi/l). Of those 107, 15 one hour Thomson Nielson Monitor Tests revealed levels above .02 WL when the longer term test had provided readings below 4 pCi/l.

These figures indicate that tampering occured approximately fifteen percent (15%) of the time when I found high readings.

The working level monitor tests served as an indicator of possible tampering when compared to the E-Perm or charcoal reading.

Attached to this report is a complete list of all 477 readings.

Six of the fifteen discrepancies were followed up after settlement and, in every case, the one hour working level monitor result, was confirmed indicating elevated radon levels.

The following examples illustrate tampering that occured with multi day tests entrusted to sellers or their agents.

An expensive new house, upon first inspection, had a 1 hour working level monitor reading of .65. This high reading made the buyers suspicious and on two occassions they observed all of the windows were open in the house during the 2 day test period. The E-Perm reading was 3.0 pCi/l from this test in the basement.

After the buyers moved in, a follow-up test revealed between 80 and 90 pCi/l in the home.

At an attorney's house, the realtor tried to talk me out of conducting a radon test. I insisted that I was hired to do the testing. The buyer also said that he wouldn't buy without a radon test. The realtor allowed the testing.

The home measured .08 WL with a one hour working level monitor. The 2 day test showed between 2 and 2.5 pCi/l. After a $2000.00 escrow account was set up at settlement, a retest showed a reading of 20 pCi/l.

In another case, I asked the realtor if the home had ever been inspected before. The realtor said the house had been tested and the result was a low radon reading.

My first 1 hour working level monitor reading was .05 WL. The E-Perm test showed 3.5 pCi/l.

When the seller was asked if the house had been inspected previously, he responded that the basement and the first floor had been tested. The readings showed 6.0 pCi/l in the basement and 2.0 pCi/l on the first floor.

My retest showed a basement reading of 6.5 pCi/l and a first floor reading of 3.5 pCi/l.

In these examples we can see how grab sampling served effectively as an early warning system to help detect tampering.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

EXPLORING SOFTWARE DEVICE MANAGEMENT ROUTINES THAT ENSURE THE OVERALL QUALITY OF CONTINUOUS WORKING LEVEL AND CONTINUOUS RADON MONITOR PERFORMANCE IN A FIELD ENVIRONMENT

by: Richard Tucker
Gemini Research
Cockeysville, MD 21030

Rick Holland
Radonics, Inc.
McLean, VA 22102

ABSTRACT

Various software modules will be discussed that demonstrate how field measurement problems can be identified for quality assurance purposes prior to reporting results from actual measurements. Items such as device performance, measurement to measurement variances, equipment failure history, and other measurement device software tools will be examined.

SOFTWARE MANAGEMENT ROUTINES

It is not difficult to argue that the advent of the micro-processor has had a profound impact on American business. Computers have changed our lives. A single micro-computer now allows one person to do what five people did manually only a few years ago. The efficient and error-free accumulation, sorting, and processing of massive amounts of data allows American business to review that data in ways that were once not thought possible. This, of course, is accomplished using computer software routines.

In the field of radon measurements, automation provides a very powerful operating advantage. Well-designed software routines are a critical component of this advantage. In any high volume transaction environment, heavy reliance on computers is the only practical way to ensure that jobs are handled timely and efficiently and not confused with other jobs. This is all the more true in the radon industry. Automation minimizes human error. Automation of any part of the process associated with performing a radon test (order taking, scheduling, testing, quality assurance, and reporting) eliminates errors in that part of the process.

Automating the interface between any two of these independent processes reduces the possibility of errors even further. Completely automating all of these processes, as well as the interface between each, reduces possible errors to their absolute lowest levels: human intervention in the entire process is virtually non-existent. In this scenario, a completely integrated system exists. This provides an even greater advantage; a synergistic advantage. Because the entire process, from order taking to reporting, is automated (including the smallest component of each process) the entire system lends itself to detailed computer analysis.

Practically speaking, software routines are a brilliant means for analyzing data. In a completely automated system, software allows for the highest levels of quality assurance. Well written programs can easily spot problems that would not otherwise be obvious. This ensures a test is valid. Such assurance is nothing less than <u>critical</u> in a real estate-related radon test where real-time (immediate) quality assurance reviews are absolutely necessary before results are reported.

Considering that the outcome of a legally binding contract is dependent on the results of the radon test, errors in the accuracy or validity of that test which are discovered after results are reported are completely unsatisfactory.

RADON MEASUREMENT EQUIPMENT AND AUTOMATION

Software routines are not possible without an instrument that generates information in sufficient quantity and detail to allow a computer to analyze that information. Additionally, software routines are not possible if the instrument does not have a means for transferring that information into "machine readable" form (a computer file) for such analysis.

In any continuous based monitor this information may include raw data representing (1) radon progeny levels, (2) radon gas levels, (3) pump flow rate, (4) filter pressure, (5) motor voltage, (6) motor current, (7) reference voltage, (8) monitor status, (9) indoor ambient air temperature, (10) barometric pressure, etc., as well as the exact time and date the information was recorded and the length of each measurement period subset (15 minutes, 30 minutes, 1 hour, etc.).

If an instrument is capable of accurately measuring and recording the above information, and it is available as a computer file, it may be analyzed via software programs in two basic ways. First, computer programs can be written to **determine the extent to which the monitor making the measurement performed its intended functions.** In essence, these "internal monitor performance" routines are a software analysis of how well the machine worked. Second, computer programs can be written to **present measurement data and other information in such a way that it allows a human being to more easily determine whether or not a test is valid.** In essence, these "quality assurance" routines are a software analysis of what happened during the measurement period.

Internal monitor performance routines analyze measurement and internal monitor data to validate monitor performance. These routines flag abnormal monitor performance and performance outside nominal ranges as well as excessive radon variances and other indications of possible error which may impact the validity of the test. The **quality assurance routines** enhance the ease with which quality assurance personnel review all job data (monitor-generated data as well as other relevant job data) before validating and releasing radon test results.

It is important to understand that the software routines used to analyze a monitor's measurement and performance data or enhance quality assurance reviews are not designed to form conclusions or take action. They are only designed to provide warnings to the people reviewing the results of these routines and to prompt action by these people based on the warnings. The technician in the field and the quality assurance personnel in the office must decide, based on these software "red flags", whether or not problems have occurred and whether they require further investigation or action.

Aside from very small corrections in machine performance, software routines must be designed to tell people of potential problems. Computer programs cannot decide if a test is valid; they can only flag possible test problems. Actual decisions must be made by people. As wonderful as computers are, they do not have the ability to reason. Reliance should not be placed on computer programs that attempt to validate a measurement. Artificial intelligence is still in its infancy and these programs cannot "think." They should only assist the quality assurance personnel responsible for validating a test and signing off on the results.

Obviously then, software routines are only as good as the individuals reviewing the results of those routines. Proper action by these people prior to releasing results is what is important. That is the reason quality assurance personnel must be independent of any phase of the test. Scheduling, test installation, and test pick-up should not be performed by persons having quality assurance responsibility for reviewing the data or reporting the results from that test.

SOFTWARE ROUTINES FOR VALIDATING INTERNAL MONITOR PERFORMANCE

Software routines that analyze data for a particular measurement must be designed to determine the extent to which the monitor performed its intended functions for that test. Because the health threat associated with radon is great, and particularly because a legally binding contract rests on the outcome of the test, it is imperative that the quality assurance process be real-time (immediate) and that it identify equipment reliability problems before results are reported. This is done with software in two ways: preventive routines and detective routines.

Preventive Software Routines

Preventive routines are designed to prevent unanticipated problems before the measurement begins by preventing or highlighting problems before a monitor is installed in a house. For example, software routines can be written to ensure that measurement data from one test is not confused with measurement data from another test or another house.

This is accomplished in a fully integrated system by programming the computer to designate a specific job number for each data set; a job number unique to that data set. When office and field functions are automated and completely integrated, there is no need for anyone to manually enter or re-enter job numbers or property addresses in the field after the order is originally entered into the system. As a result, the computer ensures that job numbers are not duplicated.

These programs can also ensure that the detailed measurement data, as well as a separately created job information file (grab samples, technician notes at installation and pick-up, sketch of property tested, answers to questions about property tested, etc.) associated with a particular test on a particular house, are not confused with other tests on that house or with other tests of other houses.

Other preventive routines can be programmed into the monitor at instrument power-up in the form of monitor self-checks. For example, a monitor has three primary areas that must be carefully reviewed at power-up to ensure a "working" machine is placed in the house: (1) filter integrity, (2) flow, and (3) detector efficiency. Simply put, the filter cannot leak or the test is rendered invalid. Even a pin hole leak not visible to the naked eye can cause large measurement errors and result in reporting false negatives. In addition, air flow and detector efficiency must be exactly known in order to perform an accurate working level (WL) calculation. WL measurement errors are directly proportional to flow errors and detector efficiency errors.

One preventive software routine needed at monitor power-up is to check filter pressure drop to determine whether or not the filter has a leak. If it does, the software can warn the install technician to replace the monitor's filter. The software can then record when such replacement occurred.

Another preventive routine at power-up is a detector check. The software can be written to request the equipment operator insert a radioactive source into the filter holder in place of the filter. A two minute count can then perform to measure the activity of the source. The known activity of this source and the number of counts measured in the two minute period can be compared against similar data taken when the monitor was calibrated, which can be stored in internal monitor calibration tables. The software can ensure that the activity ratio compares favorably with the reference source at the time of calibration. If it does not, the software can warn the technician that the detector is experiencing problems or operating outside its tolerance, etc. and that the monitor must not be installed in the house.

Finally, the flow rate must be precisely known. This is typically tested with either a bubble tube device or with a mass flow meter during calibration. Care must be taken with a mass flow meter to correct for the altitude, barometric pressure and temperature effects on the mass flow meter. If the equipment includes a mass flow sensor, absolute pressure sensor and temperature sensor, the absolute pressure sensor can measure the cumulative effect of the altitude and barometric pressure.

These sensors allow software routines to make accurate volumetric flow measurements. The results of the flow measurements can be stored with the raw measurement data for each 15 minute period. If internal flow measurement capability is not available, then flow measurements should be made both before and after the test and frequent checks should be performed to demonstrate that the flow for the device is stable and does not "wander" during tests.

Other preventive software routines can be written to track the performance history of monitors in the field. This can ensure that monitors with excessive recent problems are pulled from service before a failure occurs. A computer program can compress, sort, and analyze all measurements made by each machine for the last ten weeks. Tests performed the previous week can be examined especially closely by the software.

For example, impending pump failure caused by slow bearing deterioration may be easy to spot. A monitor with a malfunctioning pump bearing will show motor current increasing slowly over a period of several weeks. This monitor can be pulled from service, before the pump actually fails, for pump repair or replacement. Another good example is monitor detector failure. A monitor showing increasing detector background noise over a period of recent tests could also be pulled from service before failure occurs with well written software analysis routines.

In essence, any machine experiencing difficulty, exhibiting deterioration of some parameter, or showing sub-par performance can be identified by computer programs designed to review all monitor measurement and internal performance data. The software can automatically print this information on a computer-generated report with a specific request for action by a specific date for follow-up by quality assurance personnel.

Detective Software Routines

Detective software routines are designed to discover the existence, presence, or occurrence of monitor malfunction, error, or substandard performance during a measurement. Detective routines flag problems that occurred during the test in the quality assurance process prior to reporting measurement results.

Examples of these software quality assurance routines would be to verify that instrument internal motor voltages, filter pressures, flow rates, detector efficiencies, calibration factors, and a variety of other internal parameters are operating within their prescribed limits. The quality assurance personnel reviewing this information are able to repeat a test if the instrument has malfunctioned during the measurement period.

Software routines can also be designed to verify that the date and time of the test are correct by comparing the actual measurement dates and times with scheduled dates and times. If for some reason the computer had no record of the scheduled date and time, a comparison with other known dates would be valid. For example, the dates the measurement was conducted should occur after the date it was ordered. Similarly, measurement dates should be less than the current date, etc.

SOFTWARE ROUTINES FOR VALIDATING QUALITY ASSURANCE

Prior to performing a detailed review of a particular test, quality assurance personnel should have the ability to review previous tests conducted on the property. Software routines can query the data base for previous tests at the property address tested to identify prior tests and to allow for the detailed review of those tests. Similarly, if multiple machines were used to measure a particular property, either because of the size of the structure or characteristics of it requiring more than one machine, these measurements should be identified and located in the data base and be available for review. Their results can be analyzed by special software routines that compare their performance. Well-written software allows for all of this.

All of the software routines described in the previous section that validate internal monitor performance are designed to flag quality assurance personnel concerning possible problems with a particular measurement. Preventive software routines are often designed more for the technician in the field to prevent him from installing a monitor that has a problem. These routines are also useful to quality assurance personnel because of the ongoing record of each machine's performance history. However, they are somewhat less useful after the fact. Detective routines on the other hand, which have limited application for field personnel, are enormously valuable for quality assurance personnel and are directed more to assist them. Because these routines are used to generally used to review a job after the fact, they are designed more to help determine whether or not a test is valid and whether or not that test should be repeated.

In addition to the preventive and detective routines that can be performed on a monitor's measurement and internal performance data, there are other software routines designed for quality assurance. These routines enhance the ease with which quality assurance personnel are able to review all of the data from a particular measurement. Perhaps the easiest way to explain the benefit of this software would be to refer directly to a graph of that data (see Figure 1). Rather than looking at page after page of endless rows and columns of number after number of raw data (see Figure 2), this picture paints a thousand words. Figure 1 is a graphical depiction of the raw data in Figure 2. In reality this "picture" represents many hundreds of individual 15 minute data sets.

The graph in Figure 1 shows clearly radon progeny levels, radon gas levels, temperature, barometric pressure, as well as changes in each over the course of the measurement period. In addition, this graph also shows information concerning the presence of individuals in the vicinity of the instrument during the measurement period as well as information showing if and when the monitor was moved. In combination this information has real meaning particularly when graphed.

Moreover, by depicting reams of measurement data in an easy to understand graph, the analysis of that data by quality assurance personnel is significantly simplified. Changes in radon progeny or radon gas levels, changes in indoor air temperature, barometric pressure, and the location of the monitor, or the presence of persons in the vicinity of the monitor are all very easy to identify. In addition, abnormalities or tampering with measurement conditions is often very easy to identify as well.

For purposes of distinction, it is worth mentioning that the greater an instrument's level of sensitivity, the greater that instrument's ability to identify changes in radon levels due to tampering versus the diurnal variation of radon. A typical graph with an instrument having great sensitivity shows changes in radon levels very sharply and dramatically (see Figure 3) whereas devices having less sensitivity show sharp changes in radon levels only gradually, leaving a question as to whether or not tampering occurred at all.

With the benefit of software routines analyzing data to flag potential problems, quality assurance personnel are also able to correlate other relevant data accumulated during the measurement to help determine whether or not a test is valid. For example, elevated grab samples at test initiation or test completion may indicate failure of the monitor, or even tampering, if they do not corroborate data provided by the continuous based monitor.

Also, closed-house conditions, which are explained when a measurement is scheduled, that are not observed when a technician arrives at the house to initiate the test, gives good reason for quality assurance personnel to scrutinize measurement data more carefully. Reluctance or failure of a seller responsible for closed-house conditions to sign a property owner agreement, which identifies the conditions necessary for a valid test, may also mean reason for greater scrutiny of the test data.

CONCLUSION

In summary, well designed software routines offer a tremendous operating advantage. In any high volume environment, they are critical to ensure quality.

To the extent that a company's radon measurement equipment is not able to generate internal information concerning its own performance or transfer that information into "machine readable" form (a computer file), that company is severely limited in its ability to know whether or not its instruments performed properly on a test. And to the extent that a radon measurement system is not fully integrated (automated) from order taking to reporting, that system suffers a significantly reduced ability to preserve quality.

Simply put, computers and well written software routines run circles around human beings trying to perform the same tasks.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

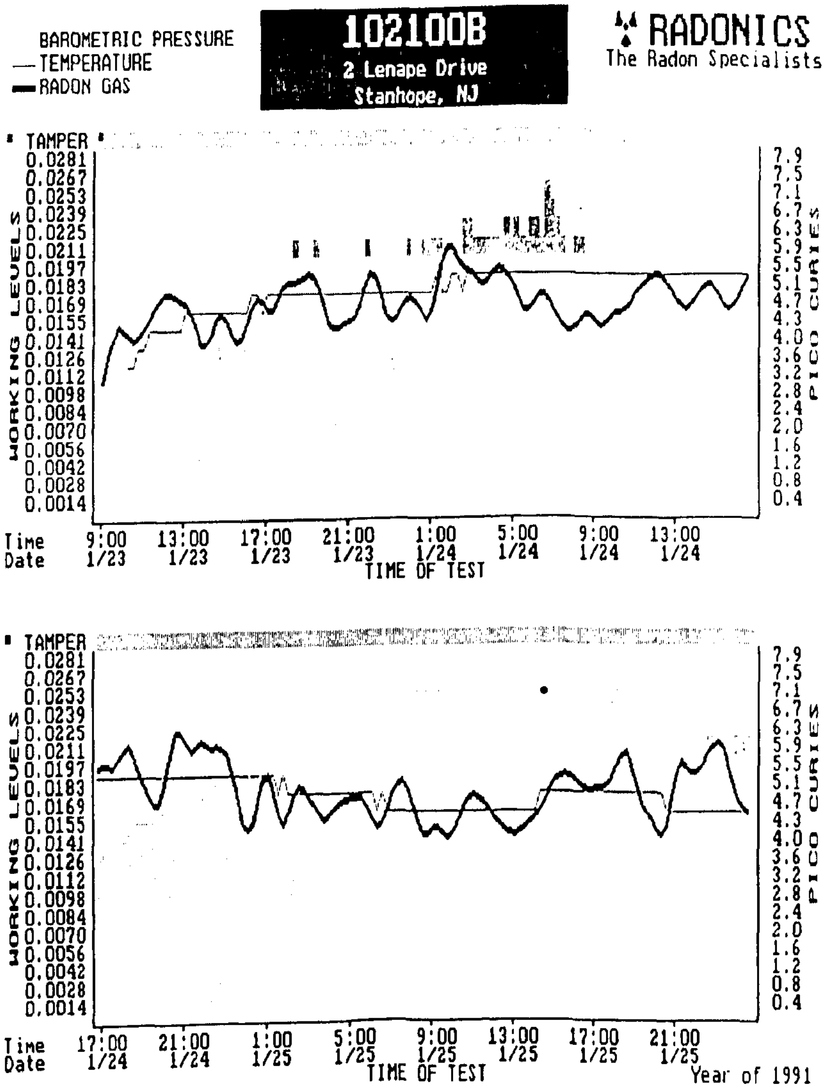


Figure 1. Graphical depiction of measurement data.

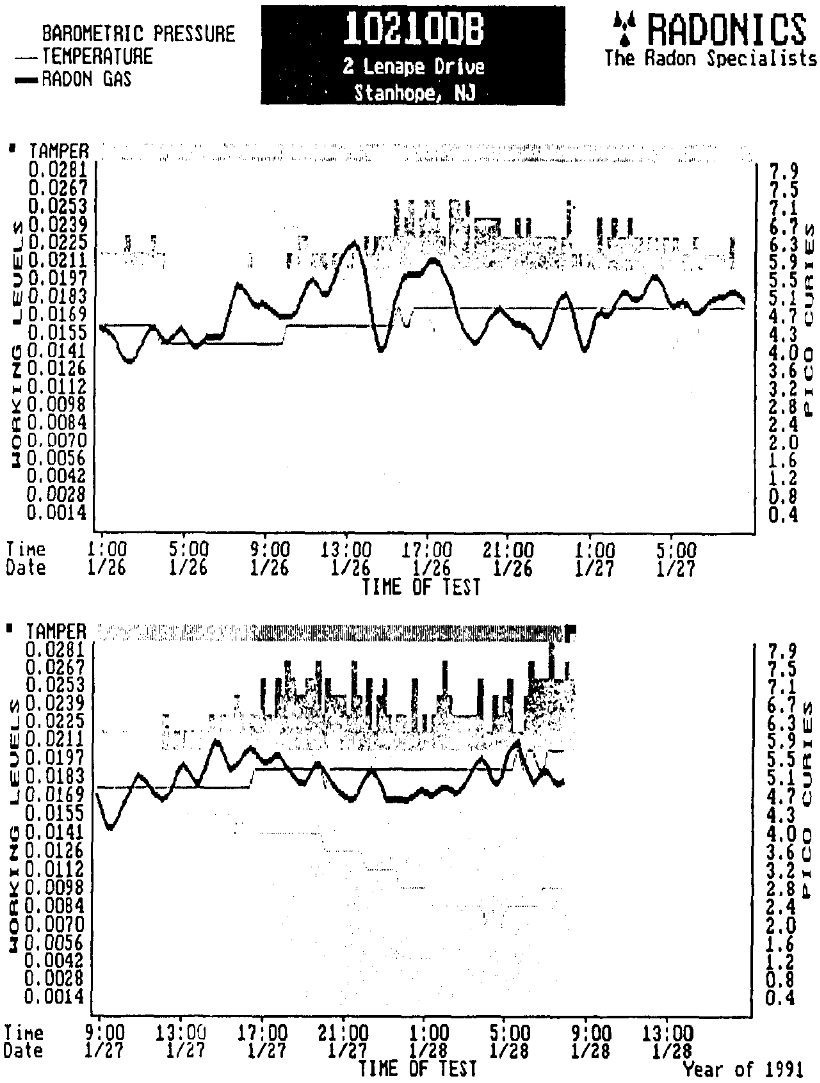


Figure 1 (continued).

Time	Cnt1	Cnt2	Flo	Bar	FP	MV	MI	Ref	Status		Flow		Temp	I	S
09:12:03	30	15	161	199	43	86	100	51	0000	0000	SDS	205	255	8	2
09:27:03	59	20	161	192	42	86	91	51	0000	0000	SDS	205	241	0	0
09:42:03	90	12	165	188	41	86	86	51	0000	0000	DDS	302	227	0	0
09:57:03	139	38	163	185	40	84	82	51	0000	0000	DDI	210	217	0	0
10:12:03	148	28	161	183	40	82	78	51	0000	0000	SSI	025	210	0	0
10:27:03	166	26	160	181	39	82	76	51	0000	0000	SSI	025	206	0	0
10:42:03	186	21	160	180	40	82	75	51	0000	0000	SSI	025	203	0	0
10:57:03	217	27	160	180	39	82	74	51	0000	0000	SSI	025	201	0	0
11:12:03	240	26	160	179	39	82	73	51	0000	0000	SSI	025	199	0	0
11:27:03	244	24	160	178	39	82	74	51	0000	0000	SSI	025	198	0	0
11:42:03	278	28	159	178	40	82	73	51	0000	0000	ISI	032	197	0	0
11:57:03	268	31	161	178	40	84	74	51	0000	0000	SSI	015	197	0	0
12:12:03	262	33	161	177	40	84	74	51	0000	0000	SSI	015	196	0	0
12:27:03	276	26	161	177	40	84	74	51	0000	0000	SSI	015	195	0	0
12:42:03	277	39	161	177	40	84	74	51	0000	0000	SSI	015	196	0	0
12:57:03	310	31	161	176	40	84	74	51	0000	0000	SSI	015	195	0	0
13:12:03	267	26	161	176	40	84	74	51	0000	0000	SSI	015	195	0	0
13:27:03	294	31	159	176	40	84	73	51	0000	0000	ISI	022	194	0	0
13:42:03	315	35	159	176	40	84	74	51	0000	0000	ISI	022	194	0	0
13:57:03	302	26	159	175	40	84	74	51	0000	0000	ISI	022	194	0	0
14:12:03	319	22	159	175	40	84	73	51	0000	0000	ISI	022	194	0	0
14:27:03	319	16	159	175	40	84	74	51	0000	0000	ISI	022	193	0	0
14:42:03	340	32	159	175	40	84	74	51	0000	0000	ISI	022	193	0	0
14:57:03	320	25	159	175	40	84	73	51	0000	0000	ISI	022	193	0	0
15:12:03	294	33	159	174	40	84	73	51	0000	0000	ISI	022	193	0	0
15:27:03	296	31	159	174	40	84	73	51	0000	0000	ISI	022	192	0	0
15:42:03	307	21	159	174	40	84	73	51	0000	0000	ISI	022	192	0	0
15:57:03	339	24	159	175	40	84	74	51	0000	0000	ISI	022	192	0	0
16:12:03	324	20	159	175	40	84	73	51	0000	0000	ISI	022	192	0	0
16:27:03	322	33	159	174	40	84	73	51	0000	0000	ISI	022	192	0	0
16:42:03	353	26	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
16:57:03	346	34	159	174	40	84	74	51	0000	0000	ISI	022	191	0	0
17:12:03	326	35	159	174	40	84	74	51	0000	0000	ISI	022	192	0	0
17:27:03	336	29	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
17:42:03	349	20	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
17:57:03	348	30	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
18:12:03	342	40	159	174	40	84	74	51	0000	0000	ISI	022	191	0	0
18:27:03	304	37	159	174	40	84	74	51	0000	0000	ISI	022	191	0	0
18:42:03	359	24	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
18:57:03	314	32	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
19:12:03	353	46	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
19:27:03	328	23	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
19:42:03	360	34	159	174	40	84	73	51	0000	0000	ISI	022	191	0	0
19:57:03	303	46	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
20:12:03	311	24	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
20:27:03	351	23	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
20:42:03	320	21	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
20:57:03	336	35	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
21:12:03	317	25	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
21:27:03	324	25	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
21:42:03	330	30	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
21:57:03	336	26	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
22:12:03	365	35	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
22:27:03	325	30	159	174	40	84	73	51	0000	0000	ISI	022	189	0	0
22:42:03	347	49	159	174	40	84	73	51	0000	0000	ISI	022	190	0	0
22:57:03	353	26	159	174	40	84	73	51	0000	0000	ISI	022	189	0	0
23:12:03	333	28	159	174	40	84	73	51	0000	0000	ISI	022	189	0	0
23:27:03	338	20	161	174	40	84	73	51	0000	0000	SDI	113	189	0	0
23:42:03	315	30	161	173	40	84	73	51	0000	0000	SSI	015	189	0	0
23:57:03	353	32	161	173	40	84	72	51	0000	0000	SSI	015	189	0	0

Figure 2. Raw data from graph of Figure 1

Time	Cnt1	Cnt2	Flo	Bar	FP	MV	MI	Ref	Status	Flow	Temp	I	S
00:12:03	363	30	161	173	40	84	73	51	0000 0000	SSI 015	189	0	0
00:27:03	336	27	161	173	40	84	73	51	0000 0000	SSI 015	189	0	0
00:42:03	350	37	161	173	40	84	73	51	0000 0000	SDI 113	189	0	0
00:57:03	358	30	161	173	40	84	73	51	0000 0000	SSI 015	189	0	0
01:12:03	354	24	161	173	41	84	73	51	0000 0000	SDI 113	189	0	0
01:27:03	362	19	161	173	40	84	73	51	0000 0000	SSI 015	189	0	0
01:42:03	370	35	161	173	40	84	73	51	0000 0000	SDI 113	188	0	0
01:57:03	344	41	161	173	40	84	73	51	0000 0000	SSI 015	189	0	0
02:12:03	347	40	161	173	41	84	73	51	0000 0000	SSI 015	189	0	0
02:27:03	353	37	161	173	40	84	73	51	0000 0000	SSI 015	188	0	0
02:42:03	336	41	161	173	41	84	73	51	0000 0000	SDI 113	188	0	0
02:57:03	392	27	161	173	40	84	73	51	0000 0000	SSI 015	189	0	0
03:12:03	387	34	161	173	40	84	72	51	0000 0000	SDI 113	188	0	0
03:27:03	366	42	161	173	40	84	72	51	0000 0000	SDI 113	188	0	0
03:42:03	356	33	161	173	41	84	72	51	0000 0000	SSI 015	188	0	0
03:57:03	365	26	161	173	41	84	73	51	0000 0000	SSI 015	188	0	0
04:12:03	377	31	161	173	41	84	72	51	0000 0000	SSI 015	188	0	0
04:27:03	356	40	161	173	41	84	73	51	0000 0000	SDI 113	188	0	0
04:42:03	377	35	161	173	41	84	72	51	0000 0000	SDI 113	188	0	0
04:57:03	386	37	161	173	41	84	73	51	0000 0000	SDI 113	188	0	0
05:12:03	360	28	161	173	41	84	73	51	0000 0000	SDI 113	188	0	0
05:27:03	387	39	159	174	42	84	73	51	0000 0000	IDI 120	188	0	0
05:42:03	374	31	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
05:57:03	368	24	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
06:12:03	397	27	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
06:27:03	391	29	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
06:42:03	360	34	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
06:57:03	425	37	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
07:12:03	405	24	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
07:27:03	391	31	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
07:42:03	376	28	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
07:57:03	347	24	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
08:12:03	352	24	161	175	42	86	74	51	0000 0000	SDS 105	188	0	0
08:27:03	356	29	161	175	42	86	74	51	0000 0000	SDS 105	188	0	0
08:42:03	368	23	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
08:57:03	330	31	161	175	42	86	74	51	0000 0000	SDS 105	188	0	0
09:12:03	303	34	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
09:27:03	331	20	161	176	42	86	73	51	0000 0000	SDS 105	188	0	0
09:42:03	319	33	161	176	42	86	73	51	0000 0000	SDS 105	188	0	0
09:57:03	317	20	161	176	42	86	74	51	0000 0000	SDS 105	188	0	0
10:12:03	296	29	161	176	42	86	73	51	0000 0000	SDS 105	188	0	0
10:27:03	284	30	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
10:42:03	301	33	161	176	42	86	74	51	0000 0000	SDS 105	188	0	0
10:57:03	289	21	161	176	42	86	73	51	0000 0000	SDS 105	188	0	0
11:12:03	291	32	161	176	42	86	73	51	0000 0000	SDS 105	188	0	0
11:27:03	261	31	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
11:42:03	242	36	161	175	42	86	74	51	0000 0000	SDS 105	188	0	0
11:57:03	223	29	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
12:12:03	284	34	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
12:27:03	259	39	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
12:42:03	295	29	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
12:57:03	237	39	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
13:12:03	248	27	161	173	42	86	74	51	0000 0000	SDS 105	188	0	0
13:27:03	288	36	163	173	42	86	74	51	0000 0000	DDS 202	188	0	0
13:42:03	246	25	163	173	42	86	73	51	0000 0000	DDS 202	188	0	0
13:57:03	290	28	163	173	42	86	74	51	0000 0000	DDS 202	187	0	0
14:12:03	279	30	163	173	42	86	73	51	0000 0000	DDS 202	187	0	0
14:27:03	278	31	163	173	42	86	73	51	0000 0000	DDS 202	188	0	0
14:42:03	284	31	163	173	42	86	73	51	0000 0000	DDS 202	187	0	0

Figure 2. (continued).

Time	Cnt1	Cnt2	Flo	Bar	FP	MV	MI	Ref	Status		Flow		Temp	I	S
14:57:03	293	35	163	173	42	86	73	51	0000	0000	DDS	202	187	0	0
15:12:03	294	33	163	173	42	86	73	51	0000	0000	DDS	202	187	0	0
15:27:03	274	37	163	173	42	86	73	51	0000	0000	DDS	202	187	0	0
15:42:03	306	25	163	173	42	86	73	51	0000	0000	DDS	202	187	0	0
15:57:03	266	25	163	173	42	86	74	51	0000	0000	DDS	202	187	0	0
16:12:03	296	33	163	173	42	86	74	51	0000	0000	DDS	202	186	0	0
16:27:03	293	30	163	173	42	86	73	51	0000	0000	DDS	202	187	0	0
16:42:03	261	29	161	174	42	86	73	51	0000	0000	SDS	105	187	0	0
16:57:03	295	36	161	174	42	86	73	51	0000	0000	SDS	105	187	0	0
17:12:03	265	34	161	174	42	86	73	51	0000	0000	SDS	105	187	0	0
17:27:03	288	42	161	174	42	86	74	51	0000	0000	SDS	105	187	0	0
17:42:03	323	30	161	175	42	86	74	51	0000	0000	SDS	105	187	0	0
17:57:03	265	38	161	175	42	86	73	51	0000	0000	SDS	105	187	0	0
18:12:03	285	30	161	175	42	86	73	51	0000	0000	SDS	105	187	0	0
18:27:03	277	42	161	175	42	86	73	51	0000	0000	SDS	105	187	0	0
18:42:03	284	37	161	175	42	86	73	51	0000	0000	SDS	105	187	0	0
18:57:03	281	51	161	176	42	86	73	51	0000	0000	SDS	105	187	0	0
19:12:03	268	17	161	176	42	86	74	51	0000	0000	SDS	105	187	0	0
19:27:03	280	39	161	176	42	86	73	51	0000	0000	SDS	105	187	0	0
19:42:03	301	38	161	176	42	86	73	51	0000	0000	SDS	105	187	0	0
19:57:03	241	21	161	176	42	86	73	51	0000	0000	SDS	105	187	0	0
20:12:03	260	33	161	176	42	86	74	51	0000	0000	SDS	105	187	0	0
20:27:03	256	24	161	177	42	86	73	51	0000	0000	SDS	105	187	0	0
20:42:03	233	40	161	177	42	86	73	51	0000	0000	SDS	105	187	0	0
20:57:03	267	44	161	177	42	86	73	51	0000	0000	SDS	105	187	0	0
21:12:03	270	52	161	177	42	86	74	51	0000	0000	SDS	105	187	0	0
21:27:03	268	29	161	177	42	86	74	51	0000	0000	SDS	105	187	0	0
21:42:03	245	31	161	177	42	86	73	51	0000	0000	SDS	105	187	0	0
21:57:03	297	46	161	177	42	86	74	51	0000	0000	SDS	105	188	0	0
22:12:03	276	37	162	177	42	86	74	51	0000	0000	SDS	105	187	0	0
22:27:03	280	42	161	178	42	86	74	51	0000	0000	SDS	105	187	0	0
22:42:03	274	39	162	178	42	86	73	51	0000	0000	SDS	105	187	0	0
22:57:03	274	25	161	178	42	86	74	51	0000	0000	SDS	105	187	0	0
23:12:03	278	52	162	178	42	86	74	51	0000	0000	SDS	105	188	0	0
23:27:03	281	36	162	178	42	86	74	51	0000	0000	SDS	105	187	0	0
23:42:03	260	38	162	178	42	86	73	51	0000	0000	SDS	105	187	0	0
23:57:03	285	20	162	178	42	86	73	51	0000	0000	SDS	105	188	0	0
00:12:03	284	42	162	178	42	86	74	51	0000	0000	SDS	105	188	0	0
00:27:03	274	14	162	178	42	86	74	51	0000	0000	SDS	105	188	0	0
00:42:03	275	23	162	179	42	86	73	51	0000	0000	SDS	105	188	0	0
00:57:03	259	28	162	179	42	86	74	51	0000	0000	SDS	105	188	0	0
01:12:03	288	46	162	178	42	86	74	51	0000	0000	SDS	105	188	0	0
01:27:03	261	33	162	179	42	86	73	51	0000	0000	SDS	105	188	0	0
01:42:03	257	36	162	179	42	86	73	51	0000	0000	SDS	105	188	0	0
01:57:03	266	23	162	179	42	86	74	51	0000	0000	SDS	105	189	0	0
02:12:03	264	21	162	179	42	86	73	51	0000	0000	SDS	105	188	0	0
02:27:03	268	29	162	179	42	86	73	51	0000	0000	SDS	105	189	0	0
02:42:03	243	33	162	179	42	86	73	51	0000	0000	SDS	105	189	0	0
02:57:03	265	38	162	179	42	86	73	51	0000	0000	SDS	105	189	0	0
03:12:03	219	30	162	180	42	86	73	51	0000	0000	SDS	105	189	0	0
03:27:03	247	29	162	180	42	86	74	51	0000	0000	SDS	105	189	0	0
03:42:03	212	30	162	180	42	86	74	51	0000	0000	SDS	105	190	0	0
03:57:03	235	34	162	180	42	86	74	51	0000	0000	SDS	105	189	0	0
04:12:03	229	19	162	180	42	86	74	51	0000	0000	SDS	105	190	0	0
04:27:03	217	26	162	180	42	86	74	51	0000	0000	SDS	105	190	0	0
04:42:03	207	37	162	180	42	86	74	51	0000	0000	SDS	105	191	0	0
04:57:03	210	31	162	180	42	86	74	51	0000	0000	SDS	105	190	0	0
05:12:03	198	25	162	180	42	86	73	51	0000	0000	SDS	105	190	0	0
05:27:03	248	34	162	180	42	86	74	51	0000	0000	SDS	105	191	0	0

Figure 2. (continued).

Time	Cnt1	Cnt2	Flo	Bar	FP	MV	MI	Ref	Status		Flow		Temp	I	S
05:42:03	212	30	162	181	42	86	74	51	0000	0000	SDS	105	191	0	0
05:57:03	205	30	162	181	42	86	74	51	0000	0000	SDS	105	191	0	0
06:12:03	237	37	162	181	42	86	74	51	0000	0000	SDS	105	191	0	0
06:27:03	223	19	162	181	42	86	74	51	0000	0000	SDS	105	191	0	0
06:42:03	211	30	162	181	42	86	74	51	0000	0000	SDS	105	192	0	0
06:57:03	228	24	162	181	42	86	74	51	0000	0000	SDS	105	191	0	0
07:12:03	208	23	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
07:27:03	210	41	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
07:42:03	234	34	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
07:57:03	262	25	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
08:12:03	229	40	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
08:27:03	244	33	162	182	42	86	74	51	0000	0000	SDS	105	193	0	0
08:42:03	248	24	162	183	42	86	74	51	0000	0000	SDS	105	192	0	0
08:57:03	251	20	162	183	42	86	74	51	0000	0000	SDS	105	192	0	0
09:12:03	203	24	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
09:27:03	253	33	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
09:42:03	227	28	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
09:57:03	218	24	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
10:12:03	228	21	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
10:27:03	246	25	162	183	42	86	75	51	0000	0000	SDS	105	193	0	0
10:42:03	222	33	162	183	42	86	75	51	0000	0000	SDS	105	193	0	0
10:57:03	196	24	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
11:12:03	197	36	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
11:27:03	193	33	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
11:42:03	230	26	162	183	42	86	74	51	0000	0000	SDS	105	192	0	0
11:57:03	224	35	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
12:12:03	207	29	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
12:27:03	207	26	162	182	42	86	74	51	0000	0000	SDS	105	193	0	0
12:42:03	199	27	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
12:57:03	190	29	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
13:12:03	232	22	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
13:27:03	225	28	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
13:42:03	209	24	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
13:57:03	236	29	162	182	42	86	75	51	0000	0000	SDS	105	192	0	0
14:12:03	236	23	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
14:27:03	228	33	162	182	42	86	74	51	0000	0000	SDS	105	192	0	0
14:42:03	236	27	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
14:57:03	237	27	162	182	42	86	73	51	0000	0000	SDS	105	191	0	0
15:12:03	247	35	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
15:27:03	296	33	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
15:42:03	265	38	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
15:57:03	257	30	162	182	42	86	75	51	0000	0000	SDS	105	191	0	0
16:12:03	251	32	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
16:27:03	270	38	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
16:42:03	283	33	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
16:57:03	272	25	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
17:12:03	293	36	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
17:27:03	297	31	162	182	42	86	74	51	0000	0000	SDS	105	190	0	0
17:42:03	308	34	162	182	42	86	74	51	0000	0000	SDS	105	190	0	0
17:57:03	303	27	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
18:12:03	307	37	162	182	42	86	74	51	0000	0000	SDS	105	191	0	0
18:27:03	296	31	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0
18:42:03	296	39	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0
18:57:03	317	39	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0
19:12:03	339	41	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0
19:27:03	303	32	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0
19:42:03	321	22	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0
19:57:03	276	27	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0
20:12:03	333	36	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0

Figure 2. (continued).

Time	Cnt1	Cnt2	Flo	Bar	FP	MV	MI	Ref	Status		Flow		Temp	I	S
20:27:03	307	28	162	183	42	86	75	51	0000	0000	SDS	105	191	0	0
20:42:03	341	16	162	183	42	86	74	51	0000	0000	SDS	105	191	0	0
20:57:03	316	24	162	183	42	86	75	51	0000	0000	SDS	105	192	0	0
21:12:03	345	27	162	183	42	86	74	51	0000	0000	SDS	105	192	0	0
21:27:03	326	50	162	183	42	86	74	51	0000	0000	SDS	105	192	0	0
21:42:03	336	29	162	183	42	86	75	51	0000	0000	SDS	105	192	0	0
21:57:03	318	39	162	183	42	86	75	51	0000	0000	SDS	105	192	0	0
22:12:03	327	33	162	183	42	86	75	51	0000	0000	SDS	105	192	0	0
22:27:03	336	30	162	183	42	86	75	51	0000	0000	SDS	105	192	0	0
22:42:03	345	37	162	183	42	86	75	51	0000	0000	SDS	105	192	0	0
22:57:03	377	34	162	183	42	86	74	51	0000	0000	SDS	105	192	0	0
23:12:03	315	45	162	183	42	86	75	51	0000	0000	SDS	105	192	0	0
23:27:03	320	32	162	183	42	86	75	51	0000	0000	SDS	105	193	0	0
23:42:03	336	42	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
23:57:03	342	44	162	183	42	86	74	51	0000	0000	SDS	105	192	0	0
00:12:03	356	23	162	183	42	86	75	51	0000	0000	SDS	105	193	0	0
00:27:03	340	27	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
00:42:03	354	35	162	183	42	86	75	51	0000	0000	SDS	105	193	0	0
00:57:03	370	29	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
01:12:03	376	25	162	183	42	86	75	51	0000	0000	SDS	105	193	0	0
01:27:03	364	26	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
01:42:03	356	35	162	183	42	86	75	51	0000	0000	SDS	105	193	0	0
01:57:03	359	27	162	183	42	86	75	51	0000	0000	SDS	105	193	0	0
02:12:03	371	20	162	183	42	86	74	51	0000	0000	SDS	105	193	0	0
02:27:03	378	28	162	183	42	86	74	51	0000	0000	SDS	105	194	0	0
02:42:03	360	22	162	183	42	86	74	51	0000	0000	SDS	105	194	0	0
02:57:03	364	20	162	183	42	86	75	51	0000	0000	SDS	105	194	0	0
03:12:03	372	26	164	183	42	86	75	51	0000	0000	DDS	202	194	0	0
03:27:03	355	33	162	183	42	86	75	51	0000	0000	SDS	105	194	0	0
03:42:03	386	21	162	183	42	86	75	51	0000	0000	SDS	105	194	0	0
03:57:03	366	37	162	183	42	86	74	51	0000	0000	SDS	105	194	0	0
04:12:03	373	30	164	183	42	86	74	51	0000	0000	DDS	202	195	0	0
04:27:03	336	17	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
04:42:03	342	26	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
04:57:03	343	33	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
05:12:03	352	30	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
05:27:03	345	29	164	183	42	86	74	51	0000	0000	DDS	202	195	0	0
05:42:03	351	21	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
05:57:03	336	27	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
06:12:03	310	27	164	183	42	86	74	51	0000	0000	DDS	202	195	0	0
06:27:03	322	22	164	183	42	86	74	51	0000	0000	DDS	202	195	0	0
06:42:03	318	36	164	183	42	86	74	51	0000	0000	DDS	202	196	0	0
06:57:03	339	27	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
07:12:03	352	20	164	183	42	86	74	51	0000	0000	DDS	202	195	0	0
07:27:03	349	24	164	183	42	86	74	51	0000	0000	DDS	202	195	0	0
07:42:03	331	42	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
07:57:03	350	37	164	183	42	86	74	51	0000	0000	DDS	202	195	0	0
08:12:03	333	33	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
08:27:03	364	35	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
08:42:03	318	31	164	183	42	86	74	51	0000	0000	DDS	202	195	0	0
08:57:03	336	27	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
09:12:03	320	36	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
09:27:03	335	35	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
09:42:03	290	27	164	183	42	86	75	51	0000	0000	DDS	202	195	0	0
09:57:03	324	30	164	182	42	86	75	51	0000	0000	DDS	202	195	0	0
10:12:03	328	31	164	182	42	86	75	51	0000	0000	DDS	202	195	0	0
10:27:03	361	30	164	182	42	86	75	51	0000	0000	DDS	202	194	0	0
10:42:03	339	31	162	182	42	86	75	51	0000	0000	SDS	105	194	0	0
10:57:03	396	28	162	182	42	86	75	51	0000	0000	SDS	105	194	0	0

Figure 2. (continued).

Time	Cnt1	Cnt2	Flo	Bar	FP	MV	MI	Ref	Status		Flow		Temp	I	S
11:12:03	389	28	162	182	42	86	74	51	0000	0000	SDS	105	194	0	0
11:27:03	360	42	164	182	42	86	75	51	0000	0000	DDS	202	194	0	0
11:42:03	363	38	162	181	42	86	74	51	0000	0000	SDS	105	194	0	0
11:57:03	354	35	162	181	42	86	74	51	0000	0000	SDS	105	194	0	0
12:12:03	361	31	162	181	42	86	75	51	0000	0000	SDS	105	194	0	0
12:27:03	325	28	162	180	42	86	74	51	0000	0000	SDS	105	193	0	0
12:42:03	354	37	162	180	42	86	74	51	0000	0000	SDS	105	193	0	0
12:57:03	357	39	162	180	42	86	75	51	0000	0000	SDS	105	193	0	0
13:12:03	374	39	162	179	42	86	75	51	0000	0000	SDS	105	193	0	0
13:27:03	354	40	162	179	42	86	74	51	0000	0000	SDS	105	193	0	0
13:42:03	351	41	162	179	42	86	74	51	0000	0000	SDS	105	193	0	0
13:57:03	343	45	162	179	42	86	74	51	0000	0000	SDS	105	193	0	0
14:12:03	387	36	162	178	42	86	74	51	0000	0000	SDS	105	193	0	0
14:27:03	354	36	162	178	42	86	74	51	0000	0000	SDS	105	192	0	0
14:42:03	381	29	162	178	42	86	74	51	0000	0000	SDS	105	192	0	0
14:57:03	389	19	162	178	42	86	74	51	0000	0000	SDS	105	192	0	0
15:12:03	381	20	162	178	42	86	74	51	0000	0000	SDS	105	192	0	0
15:27:03	398	29	162	177	42	86	74	51	0000	0000	SDS	105	192	0	0
15:42:03	424	35	162	177	42	86	74	51	0000	0000	SDS	105	192	0	0
15:57:03	379	34	162	177	42	86	74	51	0000	0000	SDS	105	191	0	0
16:12:03	407	31	162	177	42	86	74	51	0000	0000	SDS	105	192	0	0
16:27:03	433	50	162	177	42	86	74	51	0000	0000	SDS	105	192	0	0
16:42:03	389	28	161	177	42	86	74	51	0000	0000	SDS	105	191	0	0
16:57:03	414	31	161	177	42	86	74	51	0000	0000	SDS	105	191	0	0
17:12:03	445	43	161	177	42	86	74	51	0000	0000	SDS	105	191	0	0
17:27:03	438	36	162	177	42	86	74	51	0000	0000	SDS	105	191	0	0
17:42:03	409	41	161	176	42	86	74	51	0000	0000	SDS	105	191	0	0
17:57:03	387	34	161	176	42	86	75	51	0000	0000	SDS	105	191	0	0
18:12:03	374	42	161	176	42	86	74	51	0000	0000	SDS	105	191	0	0
18:27:03	429	32	161	176	42	86	75	51	0000	0000	SDS	105	191	0	0
18:42:03	439	34	161	176	42	86	74	51	0000	0000	SDS	105	191	0	0
18:57:03	412	26	161	176	42	86	74	51	0000	0000	SDS	105	191	0	0
19:12:03	444	27	161	176	42	86	75	51	0000	0000	SDS	105	191	0	0
19:27:03	377	32	161	176	42	86	74	51	0000	0000	SDS	105	191	0	0
19:42:03	419	24	161	176	42	86	74	51	0000	0000	SDS	105	191	0	0
19:57:03	411	20	161	176	42	86	74	51	0000	0000	SDS	105	190	0	0
20:12:03	407	32	161	175	42	86	74	51	0000	0000	SDS	105	191	0	0
20:27:03	420	30	161	175	42	86	74	51	0000	0000	SDS	105	191	0	0
20:42:03	411	33	161	175	42	86	74	51	0000	0000	SDS	105	191	0	0
20:57:03	389	29	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
21:12:03	389	32	161	175	42	86	74	51	0000	0000	SDS	105	191	0	0
21:27:03	393	34	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
21:42:03	408	26	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
21:57:03	398	22	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
22:12:03	401	39	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
22:27:03	400	29	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
22:42:03	388	25	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
22:57:03	387	19	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
23:12:03	399	25	161	175	42	86	75	51	0000	0000	SDS	105	190	0	0
23:27:03	382	37	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
23:42:03	376	29	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
23:57:03	379	28	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
00:12:03	439	41	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
00:27:03	361	36	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
00:42:03	370	26	161	174	42	86	74	51	0000	0000	SDS	105	189	0	0
00:57:03	351	26	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
01:12:03	364	16	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
01:27:03	362	25	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
01:42:03	411	44	161	174	42	86	74	51	0000	0000	SDS	105	189	0	0

Figure 2. (continued).

Time	Cnt1	Cnt2	Flo	Bar	FP	MV	MI	Ref	Status		Flow		Temp	I	S
01:57:03	372	32	161	174	42	86	74	51	0000	0000	SDS	105	189	0	0
02:12:03	394	22	161	174	42	86	74	51	0000	0000	SDS	105	190	0	0
02:27:03	415	30	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
02:42:03	391	34	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
02:57:03	397	38	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
03:12:03	410	31	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
03:27:03	390	36	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
03:42:03	379	27	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
03:57:03	368	34	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
04:12:03	396	34	161	175	42	86	74	51	0000	0000	SDS	105	190	0	0
04:27:03	381	37	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
04:42:03	366	38	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
04:57:03	385	40	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
05:12:03	370	26	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
05:27:03	389	31	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
05:42:03	329	30	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
05:57:03	363	36	161	176	42	86	74	51	0000	0000	SDS	105	190	0	0
06:12:03	354	34	161	176	42	86	74	51	0000	0000	SDS	105	190	0	0
06:27:03	381	31	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
06:42:03	361	21	162	176	42	86	74	51	0000	0000	SDS	105	189	0	0
06:57:03	365	38	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
07:12:03	354	32	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
07:27:03	361	34	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
07:42:03	370	28	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
07:57:03	328	38	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
08:12:03	390	29	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
08:27:03	328	37	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
08:42:03	344	36	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
08:57:03	343	27	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
09:12:03	352	36	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
09:27:03	360	30	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
09:42:03	328	20	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
09:57:03	342	18	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
10:12:03	304	36	162	178	42	86	74	51	0000	0000	SDS	105	190	0	0
10:27:03	371	29	162	178	42	86	74	51	0000	0000	SDS	105	190	0	0
10:42:03	333	22	162	178	42	86	74	51	0000	0000	SDS	105	190	0	0
10:57:03	320	36	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
11:12:03	327	36	162	177	42	86	74	51	0000	0000	SDS	105	191	0	0
11:27:03	328	36	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
11:42:03	321	23	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
11:57:03	338	37	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
12:12:03	324	29	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
12:27:03	384	31	162	177	42	86	74	51	0000	0000	SDS	105	190	0	0
12:42:03	350	24	162	176	42	86	73	51	0000	0000	SDS	105	190	0	0
12:57:03	376	34	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
13:12:03	347	36	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
13:27:03	362	37	161	176	42	86	73	51	0000	0000	SDS	105	190	0	0
13:42:03	362	39	161	176	42	86	73	51	0000	0000	SDS	105	190	0	0
13:57:03	352	23	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
14:12:03	357	32	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
14:27:03	358	35	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
14:42:03	399	34	161	176	42	86	73	51	0000	0000	SDS	105	189	0	0
14:57:03	355	39	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
15:12:03	386	45	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
15:27:03	388	34	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
15:42:03	399	30	161	176	42	86	74	51	0000	0000	SDS	105	189	0	0
15:57:03	412	26	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0
16:12:03	393	47	161	176	42	86	73	51	0000	0000	SDS	105	189	0	0
16:27:03	347	32	161	175	42	86	74	51	0000	0000	SDS	105	189	0	0

Figure 2. (continued).

Time	Cnt1	Cnt2	Flo	Bar	FP	MV	MI	Ref	Status	Flow	Temp	I	S
16:42:03	398	33	161	175	42	86	73	51	0000 0000	SDS 105	189	0	0
16:57:03	393	43	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
17:12:03	438	36	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
17:27:03	384	31	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
17:42:03	385	29	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
17:57:03	434	45	161	175	42	86	74	51	0000 0000	SDS 105	188	0	0
18:12:03	415	38	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
18:27:03	450	29	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
18:42:03	424	34	161	175	42	86	74	51	0000 0000	SDS 105	188	0	0
18:57:03	414	35	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
19:12:03	408	32	161	175	42	86	74	51	0000 0000	SDS 105	188	0	0
19:27:03	428	27	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
19:42:03	438	32	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
19:57:03	460	39	161	175	42	86	74	51	0000 0000	SDS 105	188	0	0
20:12:03	381	38	161	175	42	86	73	51	0000 0000	SDS 105	188	0	0
20:27:03	431	31	161	174	42	86	73	51	0000 0000	SDS 105	189	0	0
20:42:03	410	32	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
20:57:03	422	29	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
21:12:03	420	34	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
21:27:03	396	33	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
21:42:03	453	21	161	174	42	86	74	51	0000 0000	SDS 105	188	0	0
21:57:03	405	34	161	174	42	86	73	51	0000 0000	SDS 105	188	0	0
22:12:03	396	30	163	174	42	86	74	51	0000 0000	DDS 202	188	0	0
22:27:03	433	33	161	173	42	86	74	51	0000 0000	SDS 105	188	0	0
22:42:03	364	37	163	173	42	86	74	51	0000 0000	DDS 202	188	0	0
22:57:03	422	36	163	173	42	86	73	51	0000 0000	DDS 202	187	0	0
23:12:03	442	29	163	173	42	86	73	51	0000 0000	DDS 202	187	0	0
23:27:03	379	31	163	173	42	86	73	51	0000 0000	DDS 202	188	0	0
23:42:03	373	22	163	173	42	86	73	51	0000 0000	DDS 202	187	0	0
23:57:03	388	39	163	173	42	86	74	51	0000 0000	DDS 202	187	0	0
00:12:03	379	27	163	172	42	86	74	51	0000 0000	DDS 202	187	0	0
00:27:03	373	28	163	172	42	86	73	51	0000 0000	DDS 202	187	0	0
00:42:03	426	31	163	172	42	86	73	51	0000 0000	DDS 202	187	0	0
00:57:03	360	26	163	172	42	86	74	51	0000 0000	DDS 202	187	0	0
01:12:03	380	41	163	172	42	86	73	51	0000 0000	DDS 202	187	0	0
01:27:03	365	26	163	172	42	86	73	51	0000 0000	DDS 202	187	0	0
01:42:03	393	28	163	171	42	86	73	51	0000 0000	DDS 202	187	0	0
01:57:03	411	32	163	171	42	86	74	51	0000 0000	DDS 202	187	0	0
02:12:03	450	30	163	171	42	86	73	51	0000 0000	DDS 202	187	0	0
02:27:03	405	36	163	171	42	86	74	51	0000 0000	DDS 202	186	0	0
02:42:03	399	29	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
02:57:03	385	29	163	171	42	86	74	51	0000 0000	DDS 202	187	0	0
03:12:03	382	28	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
03:27:03	385	39	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
03:42:03	400	30	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
03:57:03	428	31	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
04:12:03	372	42	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
04:27:03	371	43	163	170	42	86	73	51	0000 0000	DDS 202	186	0	0
04:42:03	421	24	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
04:57:03	397	21	163	170	42	86	73	51	0000 0000	DDS 202	186	0	0
05:12:03	406	47	163	170	42	86	73	51	0000 0000	DDS 202	186	0	0
05:27:03	425	26	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
05:42:03	377	43	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
05:57:03	361	38	163	171	42	86	74	51	0000 0000	DDS 202	185	0	0
06:12:03	421	45	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
06:27:03	461	21	163	171	42	86	73	51	0000 0000	DDS 202	185	0	0
06:42:03	434	34	163	171	42	86	73	51	0000 0000	DDS 202	185	0	0
06:57:03	424	27	163	171	42	86	73	51	0000 0000	DDS 202	186	0	0
07:12:03	436	44	163	172	42	86	73	51	0000 0000	DDS 202	186	0	0

Figure 2. (continued).

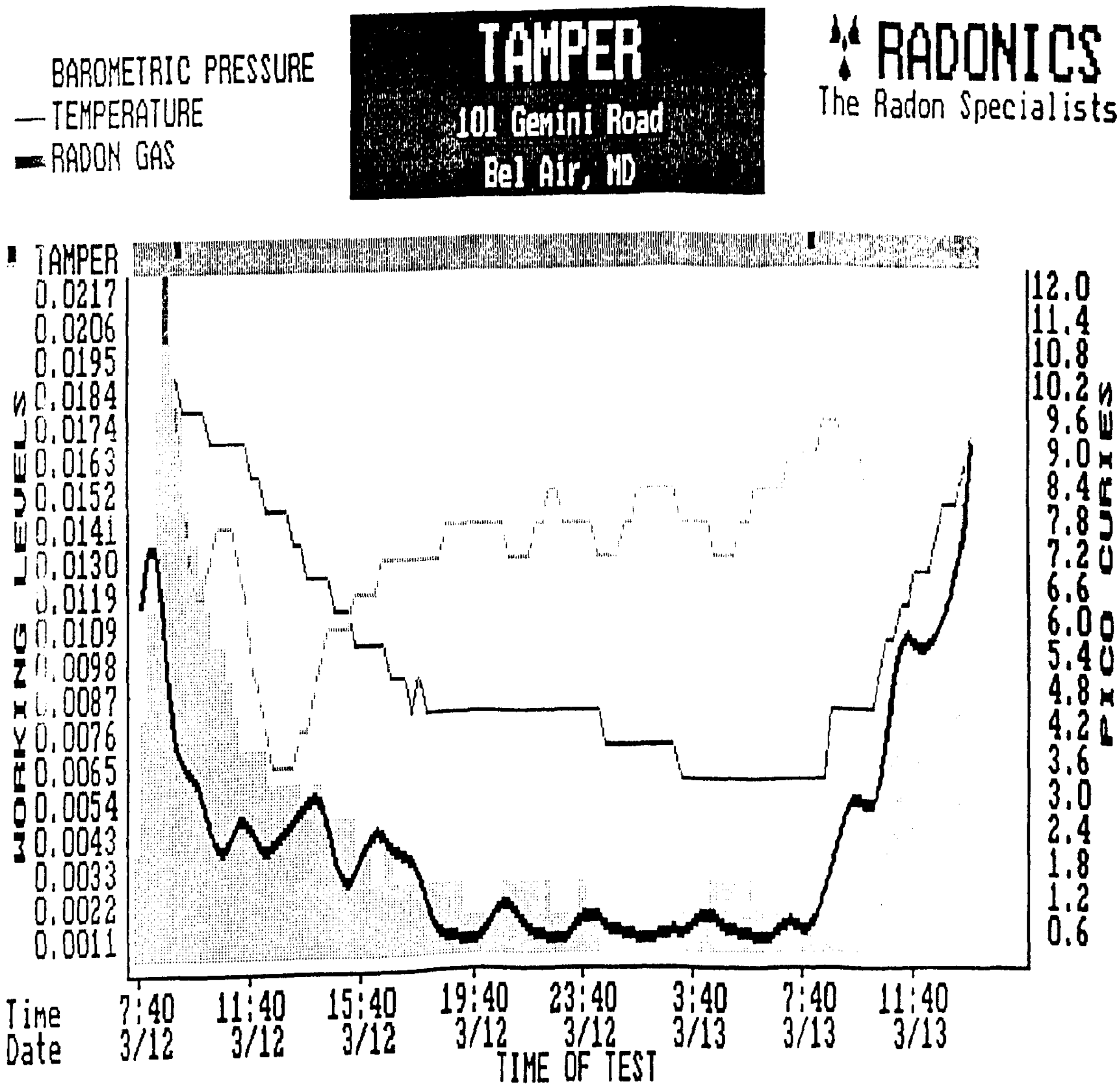


Figure 3. Graph showing dramatic variances in radon levels.

USE OF GRAB SAMPLES AS A QUALITY ASSURANCE TOOL TO ENHANCE OVERALL RADON MEASUREMENT ACCURACY AND REPRODUCIBILITY

by: Brian Fimian
Radonics, Inc.
McLean, VA 22102

Richard Tucker
Gemini Research
Cockeysville, MD 21030

ABSTRACT

Discussion regarding the benefit of grab sampling to place measurement devices, ensure primary measurement device operation, and identify owner induced variances within the structure (tampering). The paper will demonstrate how grab sampling as a secondary measurement strategy is becoming an excellent quality assurance and evaluation tool for radon measurements during real estate transactions.

Quality assurance is the single most important aspect of any radon gas or radon progeny measurement. This is true in all cases but it has special significance when measurements are conducted in the context of a real estate transaction.

A significant percentage of the residential radon testing that is currently taking place is being performed during a real estate transaction. Because of the time constraints that are typical in this environment, purchasers of real estate are frequently limited to a single radon measurement on the property they are purchasing; often a measurement upon which all parties involved in the transaction place complete reliance. This underscores the importance of measurement firms producing the highest quality result within the imposed time limitations and demonstrates the importance of providing the maximum level of quality assurance throughout the measurement process.

The focus of this paper is to demonstrate how the use of instantaneous grab samples can provide a meaningful contribution to the quality assurance process when performing radon/radon progeny measurements in the context of a real estate transaction. It must be noted here that grab sample measurements are entirely inappropriate as a primary radon measurement method because of their short term nature and inability to correctly represent average radon/radon progeny concentrations in a given structure.
They are, however, an excellent secondary technique for relative radon assessment and, if utilized properly, can provide a very useful source of information to supplement the primary measurement.

There are several advantages to performing grab sampling as a secondary measurement technique and as a quality assurance tool in support of a primary measurement strategy. The focus of this paper will be the three most beneficial uses of instantaneous air samples during radon or radon progeny measurements. They are as follows:

- Proper deployment location of the primary system.
- Corroboration of data from the primary system.
- Tamper detection.

PROPER DEPLOYMENT LOCATION OF THE PRIMARY SYSTEM

The Environmental Protection Agency (EPA) has stated in the February 1987 Interim Protocols For Screening And Follow-up Radon And Radon Decay Product Measurements that "The screening measurement should be made in the room or area in which the highest and most stable radon or radon decay product concentration is expected."

Screening measurements are intentionally conducted in areas of the property where one expects to find the highest radon concentrations and additionally are performed under "worst case" conditions (i.e. EPA defined "closed house" conditions in the lowest livable area regardless of whether or not that area is occupied). This is done to "...estimate the highest potential concentration to which an occupant may be exposed." This insures that most properties with the potential for elevated radon are not overlooked in the screening process (i.e. false negatives).

One of the easiest ways to determine the appropriate placement of a primary device is to use instantaneous air samples as a guide for locating the highest and most stable radon/radon progeny concentrations in the structure. In theory, equal mixing of the radon gas is both predicted and assumed to take place at distances greater than a few feet from the source, usually the underlying soil for radon infiltration. What actually occurs, however, is a phenomenon that may allow concentrations in one area of a basement (say a bedroom) to be as much as 50% higher than concentrations in another area. This is due in part to the ventilation patterns within a given structure and other factors such as the HVAC system design and the building construction techniques.

To the extent with which the EPA guidance intends to minimize "false negatives" and to the extent with which a measurement firm is interested in performing a high quality and "meaningful" service, some form of quality assurance must take place to insure that the primary measurement system is properly located within the structure. Instantaneous air samples are one means of accomplishing this end. In fact, because of the concentration differences that sometimes occur, even on the same level of a structure, it is prudent to ascertain the area of the structure which has the highest concentrations of radon in order to adequately assess health risk. The primary measurement device should be deployed in that area. Grab sampling is a very effective tool in achieving that goal.

CORROBORATION OF DATA FROM THE PRIMARY SYSTEM

A second and very important benefit of employing grab samples as a quality assurance mechanism in the context of a real estate transfer is the comparison of data from the primary system to the instantaneous air samples. This is important for a number of reasons, not the least of which is to ensure that the primary system is operating correctly.

Though grab sampling is limited to providing corroboration with a primary measurement only at those times when instantaneous samples are possible (typically during device installation and retrieval), it at least provides somewhat of a baseline measurement which can be used for comparison. The normal corroboration that takes place between the two measurement methods employed often provides a source of credibility to the primary measurement system and a level of comfort that the reported results are both valid and meaningful.

This approach for providing quality assurance is not new. The Department of Energy (DOE) and the EPA have used this technique in their chamber facilities for verifying radon and radon progeny concentrations during the chamber cross-check and intercomparison program for years.

It is appropriate to note that any corroboration of this secondary technique with a primary system must be conducted in "like" units (i.e. both primary and secondary measurements should be either radon gas or radon progeny). It is useless to draw any conclusions from the comparison of a primary and secondary test if, for example, the primary system is a radon gas measurement and the secondary test is working level or vice versa. This is primarily because of the unpredictable nature of the equilibrium ratio between gas and progeny from structure to structure and the difficulty in "time calibrating" concentrations between gas and progeny.

Figure 1 illustrates the usefulness of grab sampling as a secondary tool when measurements are made in "like" units. This example is specific to a primary continuous data logging device, either working level or gas. As indicated by the graph, instantaneous air samples are expected to be in the range (darkened portion of the two bars) of the continuous measurement data machine time correlated both at test initiation and at test completion when the results of the primary system are analyzed. If clear corroboration with the primary measurement system does not exist in the review process, then perhaps the primary device has either failed or the testing environment has been compromised. Of course, there is no substitute for a high quality measurement in the real estate environment and therefore, an effort must be made to use a high quality primary measurement system.

TAMPER DETECTION

Because of the time-compressed nature of the real estate industry and the enormous economic incentive of a property owner not to have radon, tampering with measurement devices and compromising measurement conditions have become commonplace in residential real estate transfers. Though there are many novel approaches to tamper detection, not the least of which is taping closed all the windows and doors in the structure during the test period, the most obvious means of identifying and deterring tampering is through the use of continuous data logging measurements. Many continuous monitors have at least some ability to detect rapid fluctuations in radon or radon progeny concentrations, especially when they are attributable to an open door or window. These devices, by their very nature, are therefore much more adept at tamper detection and even deterrence than are passive devices.

Another technique for detecting impropriety is using instantaneous air samples in areas of the home which otherwise might be difficult to ventilate. It is not uncommon to detect elevated radon/radon progeny levels in the interior rooms of a basement or in a closet area when measurements conducted in open basement areas produce no evidence of elevated radon. This might indicate tampering especially if the only source of infiltration for the interior room or closet area is from the underlying soil. Certainly, consideration must be given to the fact that these rooms are often unoccupied and have little or no natural ventilation. But what must also be given due consideration the ability of grab sampling to provide measurement firms with a baseline concentration against which the rest of the structure is measured.

There are some other benefits for performing grab samples that are not quality assurance related. Grab sampling devices can be simple tools for qualifying a potential radon hazard. The most common uses are for diagnosis of relative radon concentrations in a structure known to have elevated radon levels. These measurements often provide a mitigation contractor with enough information to allow him to make the most appropriate mitigation design decisions. Additionally, verifying proper remediation procedures by spotting leaks on the positive pressure side of a mitigation system or potential re-entrainment of the exhausted gas is easily accomplished by utilizing instantaneous air samples.

Still another very important benefit is found in verifying whether or not measured airborne concentrations of radon are attributable to radon in household water or simply to the underlying soil. This is most easily accomplished by running a shower in a bathroom for a few minutes and then obtaining an instantaneous radon/radon progeny concentration in that area. Though this is not appropriate for exacting quantitative concentrations of radon in the water, it does provide a measurement firm with information useful in isolating the source of the radon problem if levels are elevated.

In concluding, one fact is clear. Great reliance is all too often placed on a single primary measurement during the course of a real estate transfer. It is precisely because of this fact that all measurement firms MUST take the appropriate quality assurance measures specific to their testing techniques and work to provide the general public with accurate results that are both meaningful and valid. Only those primary measurement strategies which can stand the test of time and provide a high level of reproducibility will have a place in the radon industry. Instantaneous air sampling as a secondary measurement method is an excellent quality assurance tool for achieving this end.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

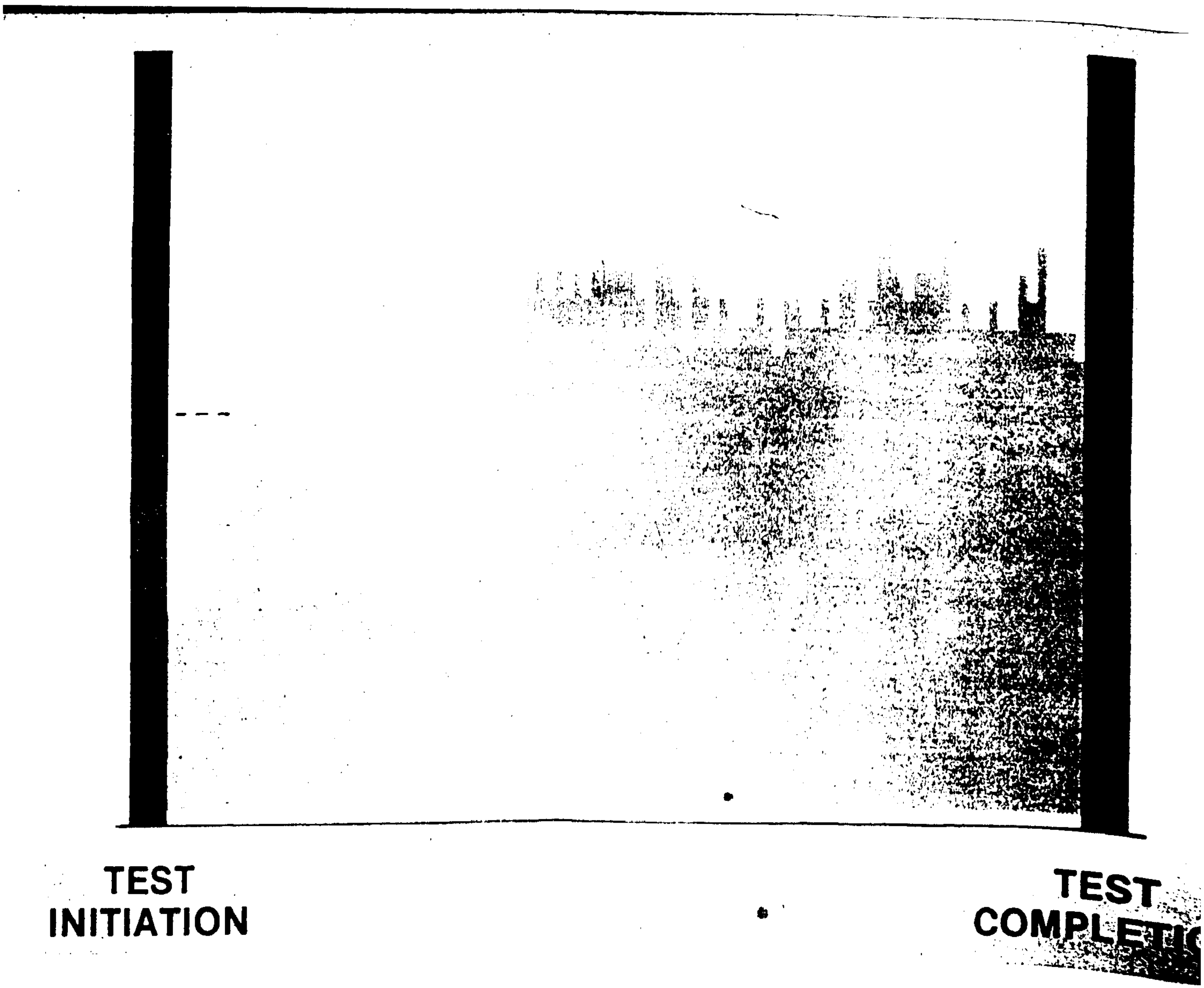


Figure 1. Grab correlation.

Session III:

Measurement Methods -- PANEL

"Short-term/Long-term Measurement"

PREDICTING LONG-TERM INDOOR RADON CONCENTRATIONS FROM SHORT-TERM MEASUREMENTS: EVALUATION OF A METHOD INVOLVING TEMPERATURE CORRECTION

by: T. Agami Reddy, A. Cavallo, K. Gadsby, and R. Socolow
Center for Energy and Environmental Studies
Princeton University
Princeton, NJ 08544

ABSTRACT

Most studies which seek to determine uncertainty bounds in predicting long-term indoor radon concentration from short-term measurements, do so assuming radon variability to be a random quantity. The objective of this paper is to evaluate the potential of decreasing these uncertainty bounds if one assumes indoor radon variations to be in part influenced by certain time-varying known physical driving forces. From daily averaged data from three occupied unmitigated residences, for which continuous measurements were taken for about a year, the stack effect (as also the ambient temperature) has been identified as the predominant physical driving force. We find that the uncertainty bounds for predicting long-term radon concentrations, when explicit recognition is given to the year-long variation in stack effect, are reduced drastically in one house, less so in another, and marginally in the third. Probable physical causes behind these observations are also discussed. A general mathematical equation is derived for predicting these uncertainty bounds in terms of climatic variability, a factor dependent on house and surrounding soil characteristics, and the strength of the physical model. Though the mathematical equation is correct within the framework of the assumptions made, more associated studies and analysis involving a larger data base are required before the benefits and scope of this technique could be fully appreciated in terms of practical applicability and relevance.

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.[1]

STATEMENT OF PROBLEM

The issue of defining bounds to the uncertainty associated with predicting

[1]This work was funded by the U.S. Environmental Protection Agency under Cooperative Agreement No. CR-817013.

the long-term (by which one generally implies, yearly) average[2] of indoor radon concentrations from single short-term (i.e., 1 to 15 day period) observations has generated great interest in the radon research community. This has arisen not only because of the practical implications in terms of health hazards to inhabitants, but also because of mandatory indoor radon testing laws required for realty transactions. The problem is especially complex given that indoor radon concentrations vary widely during the day, from day-to-day, and often show strong seasonal patterns which are house specific since they depend upon soil type, climate, house construction, house dynamics, and occupant behavior (1-5). Though the number of studies addressing the issue of predicting yearly indoor radon levels from short-term screening tests is relatively small, it would nevertheless be appropriate to start by taking stock of past research in this area.

There are basically two types of research thrusts: (a) one that involves analysis of survey data from a large number of houses, for example (6), and (b) one that involves detailed analysis of a few houses in which continuous measurements have been performed (3-5). The advantage of approach (a) is that it enables statistically rational and generalizable uncertainty bounds to be determined, while the disadvantage is that the uncertainty bounds are rather large. Ref. (6) finds an uncertainty range of 5 times the short-term screening value for 95% confidence level when no consideration is given to time of year, and of the order of 3 times when one explicitly considers the season during which the single measurement was performed. One way of decreasing these uncertainty bounds is to perform additional survey tests with stratified sampling which consists of partitioning the population into groups each of which is more homogeneous than the population itself. The stratified sampling could distinguish between season, geographic location, soil type, house construction and equipment type. Such an approach, which has been used in previous studies, for example, Ref. (7), could be investigated in the framework of certain current programs, for example, the Florida Radon Research Program (FRRP) (8).

The basic disadvantage of approach (b) is that practical and generalizable uncertainty bounds are difficult to establish given the wide differences from one house to another. However, what such an approach does provide is insight into the day-to-day variability of indoor radon concentrations and how and to what extent these are affected by the various climatic and house-specific parameters. Such information would also enable sound experimental design and proper identification of the sample strata in the framework of approach (a).

Indoor radon concentrations vary widely from day-to-day and also show strong seasonal patterns (4,5). A former study (9) had suggested that an average of screening measurements taken during two different seasons of the year would provide a more satisfactory estimate of the yearly average than a

---

[2]Current scientific thinking seems to assume that the arithmetic mean concentration is more representative of the exposure risk than are other indices, such as median or geometric mean.

single measurement. A short-term measurement strategy which involved performing measurements during each of the four seasons of the year (although impractical in terms of actual implementation) was shown to provide long-term estimates within 25% accuracy (when the associated instrument error is overlooked).

Parameter sets affecting indoor radon concentrations can be divided into three groups. The first includes the intrinsic properties of the soil and the location and concentration of the radon source with respect to the house. The second set is made up of the characteristics of the building sub-structure and super-structure and of the equipment in the house. The third set consists of climatic parameters like ambient temperature, and wind magnitude and direction. The coupled influence of the second and third sets is generally acknowledged to be the primary cause of the day-to-day year-long variability of indoor radon concentrations, while the mean concentration level is largely influenced by the first set of parameters. Note that the primary concern in the present study is to capture the variability of radon and not to predict the magnitude of the mean concentration level as such.

Thus, predicting long-term indoor radon concentrations from short-term measurements is essentially an uncertain process since indoor radon concentrations vary during the year. Most studies, though implicitly acknowledging that this variation is the result of variation in certain physical driving forces, have limited themselves to treating (i.e., analyzing) indoor radon concentration data as made up of random observations. The specific objective of this study is to evaluate a technique whereby the indoor radon data are analyzed as being the response of a physical system subject to varying input physical forces. Since random effects are bound to be present in any physical system, the total observed radon variation over a year can be visualized as consisting of two components: a deterministic component resulting from certain physical forces, and an unexplained random component. The practical relevance of such an approach is that it would have the potential of decreasing the uncertainty bounds, at a prespecified confidence level, in predicting the long-term indoor radon concentration when a single short-term measurement is made.

DESCRIPTION OF DATA

This study is based on year-long continuous data collected by Princeton University in three occupied residences, designated H2, H21, and H22, in the Princeton area of New Jersey. H2 is a two-story structure with a full basement made up of hollow cinder-block walls, and an attached garage that was built in 1980. It has very little tree cover and sits in the middle of several acres of open land. Heating is provided by a gas fired forced air heating system while cooling is supplied by a central air-conditioner. The house has a gravel bed under the slab, while the soil underneath is relatively impermeable.

H21 is a single-story ranch-style house with a partial basement, the remainder of the house being of slab-on-grade construction. This house, which is about 30 years old, is surrounded with trees. The basement walls are of hollow cinder block. This house also has a gravel bed under the slab. The heating system is a gas furnace while a central air-conditioner supplies cooling.

H22 is a 60 year old balloon-construction three-story house with a partial basement and floor drains. There is tree coverage on two sides while the other two sides are exposed. Unlike the other two houses, the subslab material is soil. The house is heated by radiators, while cooling is provided by a central air-conditioner. Because of this, the air handler is used only for cooling. Detailed descriptions of the houses and of the continuous data taken during the period the houses were unmitigated can be found in Ref. (4).

We have screened and reduced the data stored as 1/2 hour averages into daily averages since this is more appropriate for this study. Periods during which data were available for all three houses are given in Table 1, while the parameters selected for analysis are described in Table 2. Variations in temperature differences are often more appropriate than those of temperature to explain indoor radon variations (4). For example, differences between TB and TA have been designated as TBA in this study. Table 3 assembles the mean and standard deviation of the various parameters over the entire period during which data were available. One notes that the standard deviations are generally large compared to the mean values for most parameters.

IDENTIFICATION OF PHYSICAL MODEL

The first step is to describe the system in terms of a model. One approach is to construct a physical model based on mass balances akin to that of, say, Ref. (10). This approach is not only involved mathematically but is also house specific in that the physical geometry of the house dictates the inclusion, or exclusion, of certain air and radon flow paths, which themselves may be uncertain. An alternative approach, and the one adopted in this study, is to formulate a statistical model; for example, a simple linear regression model. We shall have to identify the model parameters (i.e., the important driving forces) and the regression coefficients from the data at hand.

Table 4 presents the correlation coefficients [see any statistics book, say (11), for definition] of the radon quantities (RNB and RNL) with the other parameters which are described in Table 2. TLA is strongly collinear with TBA and has not been included in Table 4. We note that the correlation coefficients of H21 are strongest while those of H2 and H22 are lower [which is consistent with Ref. (4)]. What is most surprising is that RNL variability is much better explained (i.e., has stronger correlation coefficients) than that of RNB. One would have expected the reverse since the conventional understanding is that soil gas first enters the house via the basement from where it finds its way to the living area by a combination of several house-specific pathways. The stack effect, represented by TBA (and TLA), seems to be the most important [again, consistent with Ref. (4)]. The effect of HAC on indoor radon values is smaller (correlation coefficients about 0.25). Moreover, since TLA and HAC are collinear, there does not seem to be much incentive in using regression models for radon with HAC as a second variable (4)[3]. Though TSB seems collinear with RNL for H21, the interpretation of the TSB measurement as a physical parameter may be spurious, given that the temperature probe is close enough to the basement to be affected by both basement and soil temperatures (4).

Table 5 assembles the values of the adjusted coefficients of determination (11), i.e., the adjusted R^2 values obtained by a linear regression of indoor radon parameters (RNB and RNL) with four different models. We note that there is much greater variation in quality of fit (i.e., in R^2 values) of the regression models across houses than between models. Whatever variability the models fail to account for is dominated by certain house-level factors that are not greatly influenced by the model parameter sets chosen. Radon models for H21 are generally satisfactory (R^2 ~ 0.6 - 0.8) despite the fact that the basement window was open during a large portion of the time. On the other hand, models for RNB in H2 are extremely poor, an occurrence which could be attributed to the fact that the subsoil is relatively fine-grained and compacted thereby offering large resistance to radon migration in the soil. Consequently, for the same magnitude of the forcing functions, the resulting variation in indoor radon levels would be less important than in other houses. Models for RNB in H22 are also poor. Probable causes are that the house has distinct zones and prior experiments indicate the presence of short-circuit air flow paths from the subslab to the attic via the walls.

We find that models with TA (Model 1) or TBA (Model 2) are equally good while there does not seem to be any advantage in including HAC as an additional parameter. A previous study (12) had indicated that at half-hour time intervals the physical mechanism affecting radon entry into the basement is akin to a one-way valve dictated by temperature differences between soil, basement, and ambient. Consequently, we have also investigated a model explicitly separating the positive and negative values of TBA. This pertains to Model 3 of Table 5. We note that, though Model 3 has higher R^2 values, the improvement is generally only a few percentage points and does not justify the added complexity in the model structure when daily time scales of averaging are used.

We have also investigated model structures of the form RNB, RNL = $f(TBA - c)^+$ where c is a coefficient to be determined by regression and the + sign indicates that only positive values are retained in the regression analysis. This model structure, it will be noted, is akin to that used in building energy studies where comfort energy requirements are often regressed against degree-days (13). The improvement in R^2 values of such a model over those of Models

[3]One of the findings of Ref. (4) was that there was limited, if no, incentive in formulating a model for indoor radon levels over the entire year which included HAC as a second variable. However for models on a seasonal basis, the inclusion of HAC does improve the models. These conclusions are however specific to the scope of Ref. (4) which was limited to three residences in central New Jersey.

1 and 2 was at most a few percentage points, while R^2 values were lower than those of Model 3.

ALTERNATIVE APPROACH TO ANALYZING INDOOR RADON DATA

In this section we shall seek to determine whether, and by how much, the two following approches of analyzing data narrow down the confidence bounds, or alternatively, the percentiles (11):

(a) entire variation of indoor radon concentration over the year is random. As noted earlier, this is the approach followed by most studies to date. In this case we shall merely inspect the data series of the normalized variable ($RN/\overline{RN}$) where RN could be either RNB or RNL, and $\overline{RN}$ is the long-term (i.e., the annual) average of RN;

(b) variation of indoor radon concentration is partly the result of variation in certain known physical forces which drive indoor radon. Only the residual variation, or the variation in indoor radon not explained by the model, is random.

The statistical analysis in the previous section suggested [as also did several studies, say (4)] that the most influential parameter which explains indoor radon levels is the stack effect, characterized by TBA or by TA. The following model structure is used to describe the output of the system:

$$\widehat{RN}_i = a' + b' \cdot TBA_i \tag{1}$$

where RN could be either RNB or RNL,
a' and b' are the intercept and slope of the linear regression line,
subscript i represents individual observations, and
$\widehat{RN}$ is quantity deduced from the model rather than from measured data.

If $\overline{TBA}$ and $\overline{RN}$ are the long-term (i.e., the annual) averages of TBA and RN, respectively, then

$$(\widehat{RN}_i/\widehat{\overline{RN}}_i) = (a' + b' \cdot TBA_i)/(a' + b' \cdot \overline{TBA}) \tag{2}$$

Subsequently, replacing $\widehat{RN}_i$ by RN_i, we have

$$\widehat{\overline{RN}}_i = RN_i \cdot (a'+b' \cdot \overline{TBA}) / (a'+b' \cdot TBA_i) \tag{3}$$

Note that $\widehat{\overline{RN}}_i$ would be the value of the long-term indoor radon concentrations predicted from an individual or short-term observation RN_i by applying the temperature correction approach. Finally, this value has been normalized by dividing it by $\overline{RN}$, where $\overline{RN}$ is the long-term average of RN deduced from data (and assembled in Table 3). The data available for all three houses have been processed both as explained above and also by assuming them to be random; i.e., by merely dividing the RN_i values by $\overline{RN}$.

The percentiles of the associated distribution of daily values without [i.e., of ($RN_i/\overline{RN}$) data series] and with [i.e., of ($\widetilde{RN}_i/\widetilde{RN}$) data series] temperature correction are given in Fig. 1. We note that there is a marked decrease in the uncertainty bounds for the indoor radon levels of H21, a smaller improvement in H22, and negligible improvement for H2. These are consistent with the R^2 values of the associated regression model, i.e., higher the R^2 value, more the improvement. The interpretation of the numbers in Fig. 1 is straightforward. For example, the results of RNL for H21 seem to indicate that we could hope to narrow the 90% uncertainty bounds in predicting the annual radon levels from a factor of 2.4 with no temperature correction down to 1.4 when the temperature correction is applied.

STATISTICAL METHODOLOGY TO DETERMINE BOUNDS ON PREDICTION ACCURACY

The scope of the evaluation in the previous section was limited since actual data from only three houses in the Princeton area were available. Though we were unable to demonstrate a significant advantage in our approach, reappraisal in the framework of future studies seems justified. In this section, we shall derive a mathematical equation to predict the theoretical uncertainty bounds resulting from our physical approach. This would permit our approach to be generalized to any climate and to different types of houses and soil conditions.

We shall assume a simple linear model structure between indoor radon concentration and a single driving force (say, ambient temperature since it is a variable easier to obtain than TBA, and has been found to be as good a predictor of RN as is TBA) such as:

$$RN = a + b \cdot TA \tag{4}$$

Given inherent "noise" in the data and also that the effects of other driving forces are overlooked, the model will not be a perfect fit. This can be represented statistically as (11):

$$RN_i = a + b \cdot TA_i + \varepsilon_i \tag{5}$$

where ε_i is the error term in the individual observations.

The model implies that the observed RN variability could be due to a large variability in the driving force (i.e., TA) along with a small coupling coefficient (i.e., b) or vice versa. Thus we have separated the problem of long-term indoor radon variability into a location-dependent climatic effect and a climate-independent, location-, and house-characteristics-dependent effect.

If the variables RN and TA are assumed to be normally distributed variables[4] with no serial correlation, ε will be normally distributed, have zero mean, and a constant variance of $\sigma^2(\varepsilon)$; i.e., homoscedasticity is assumed in the basic physical process. Let n be the number of observations and R^2 the goodness-of-fit of the model given by eq. (4). Then, from the definition of R^2 (11):

$$R^2 = \frac{\sum_{i=1}^{n} (\widehat{RN}_i - \overline{RN})^2}{\sum_{i=1}^{n} (RN_i - \overline{RN})^2} \tag{6}$$

where $\widehat{RN}_i$ is the model predicted value [from eq.(4)], $\underline{RN}_i$ is the observed value, and $\overline{RN}$ the long-term average of RN.

Also

$$\sum_{i=1}^{n} (\widehat{RN}_i - \overline{RN})^2 = \sum_{i=1}^{n} b^2 \cdot (TA_i - \overline{TA})^2$$

$$= b^2 \cdot \overline{TA}^2 \cdot (n-1) \cdot \sigma^2 \left(\frac{TA_i}{\overline{TA}}\right) \tag{7}$$

Introducing this in eq. (6) we have

$$\overline{RN}^2 \cdot \sigma^2 \left(\frac{RN_i}{\overline{RN}}\right) = \frac{b^2}{R^2} \cdot \overline{TA}^2 \cdot \sigma^2 \left(\frac{TA_i}{\overline{TA}}\right) \tag{8}$$

From the above and from the definition of R^2, we find

$$\sigma^2(\varepsilon_i) = \frac{1 - R^2}{R^2} \cdot b^2 \cdot \overline{TA}^2 \cdot \sigma^2 \left(\frac{TA_i}{\overline{TA}}\right) \tag{9}$$

The standard deviation of the standardized quantity $(\varepsilon_i/\overline{RN})$, which is analogous to the Coefficient of Variation (11), is finally obtained

$$\sigma\left(\frac{\varepsilon_i}{\overline{RN}}\right) = \left(\frac{1 - R^2}{R^2}\right)^{1/2} \cdot \sigma\left(\frac{TA_i}{\overline{TA}}\right) \cdot \left(\frac{a}{b \cdot \overline{TA}} + 1\right)^{-1} \tag{10}$$

Eq. (10) is simply an equation which correlates the variation (quantified

---

[4] Several studies [for example Ref. (4)] have found that the variable TA (and TBA) exhibits a normal distribution over an entire year, while indoor radon variables have no consistent agreement with either a normal or a log-normal distribution, though the latter is usually better.

by the standard deviation) of RN not explained by the model in terms of three sets of parameters describing:

(a) location specific variation in the ambient temperature; i.e., $\sigma\ (TA_i/\overline{TA})$;

(b) house and surrounding soil dependent quantity specified by the factor (a/b), which has units of °C; and

(c) strength of the regression model between RN and TA designated by the R^2 value. Recall that the physical interpretation of the R^2 value is that it represents the percentage of the total variation in the response variable explained by (i.e., directly the result of variation in) the exogenous variable.

Since the variables RN_i and TA_i are assumed to be normally distributed, the critical values at different significance levels would correspond to the uncertainty ratios at different probability levels. For example, a 95% probability level would correspond to $(2 \cdot \sigma)$ [see Ref. (11)].

The above derivation could be easily extended to linear model structures with more than one driving force. One could adopt a similar methodology for the more-often-encountered case when the variable RN is not normally distributed while the variable TA is.

APPLICATION TO ACTUAL DATA

We shall illustrate how eq. (10) could be applied to specific locations. From 1 year's data of daily TA values provided by NOAA (14), we find for the Princeton area, $\sigma\ (TA) \simeq 8.5°C$ while $\overline{TA} = 12.8°C$. Values of the parameters a and b of eq. (4) are assembled in Table 6 for the three houses. From Table 6, we find (a/b) factors for RNB to be 78 for H2, 21.8 for H21, and 145 for H22. Interestingly, H21 is a one-story residence; H2, two-story, and H22, three-story. Thus one notes that (a/b) factors seem to increase with the height of the building. This observation is perhaps premature and needs to be evaluated further.

How the theoretical standard deviation of the variable $(\varepsilon_i/\overline{RN})$ would vary with R^2 for a wide range of (a/b) values for the Princeton area is shown in Fig. 2 generated from eq. (10). From the limited number of houses studied (other than H21 where basement window opening may be an abnormal occurrence), values of (a/b) are in the 80-150 range. Even for low values of R^2 (=0.2), one notes that the temperature correction approach could result in prediction intervals at the 95% confidence level (i.e., 2 standard deviations) not exceeding 1.4. This is a significant observation since it implies that uncertainty bounds of prediction can be drastically reduced by our physical approach even in a house where the indoor radon variability is weakly influenced by variation in the stack effect.

As a preliminary illustration, Table 7 assembles values of σ (TA) and $\overline{TA}$

for a few locations in the U.S for different averaging times. To within one decimal accuracy, the arithmetic mean is essentially independent of averaging time interval while the standard deviation decreases with length of averaging interval. If the standard deviation values for each location are normalized with respect to the 1-day value, we note that the decrease with averaging time is fairly linear and location independent (Fig. 3). Thus, we note that an averaging interval of 15 days will lead to a 35% decrease in the standard deviation of the ambient temperature variability over the year as compared to a 1-day time scale of averaging, while an averaging interval of 1 week would result in a 20% decrease. Though an exponential fit to these data points would be more accurate, we find that a linear fit to the normalized standard deviation versus averaging time (in days) yields an R^2 of 0.93 with a slope of -0.023 (SEM = 0.002).

The possible range of variation of the factor (a/b), representative of the soil conditions and house construction practices prevalent in widely different geographic locations in the U.S., is unknown at present. Either analyzing existing radon survey data or gathering data explicitly for this purpose may be tasks worth evaluating in the framework of future radon projects. An alternate, and perhaps more promising, approach is to infer the parameters a and b from the house response when certain simple "stressed" experiments on the house are performed. Such experimental protocols have yet to be satisfactorily formulated and validated, but initial attempts are underway in the Research House Study of the FRRP (8). Efforts such as the above would, hopefully, permit numerical values of a and b to be specified dependent on generic building construction type and soil conditions.

CONCLUSIONS

The physical approach advocated in this study, whereby one visualizes indoor radon variations as the response of a physical system acted upon by certain varying and known forces, has been shown to have the potential of decreasing the uncertainty bounds associated with the problem of having to predict long-term indoor radon levels from short-term screening tests. The physical system can be described by a regression model with the stack effect as the single most influential driving force. How such a model approach fares with respect to the conventional procedure, of assuming indoor radon variability to be random, has been evaluated with daily averaged data for over a year in three occupied houses. It has been found to be distinctly advantageous in one house, moderately advantageous in another, and marginally so in the third.

The theoretical uncertainty bounds of prediction resulting from the physical approach can be predicted from a mathematically derived equation expressing the normalized standard deviation of the variation of indoor radon not explained by the model (i.e. the random component), in terms of three sets of parameters: location-dependent statistics of ambient temperature, a factor describing the coupling between the soil and the house, and the strength of the regression model. How the equation could be applied to individual geographic locations has been illustrated by generating a figure of the theoretical uncertainty bounds for the Princeton area. An important observation is that the strength of the regression model is not a significant parameter provided the corresponding R^2 values of the regression model are greater than about 0.2, thereby suggesting that the approach could be potentially useful over a variety of housing stock and soil conditions. However, more associated studies and analysis involving a larger data base are required before the benefits and scope of the present technique could be fully appreciated in terms of practical applicability and relevance.

ACKNOWLEDGEMENTS

We would like to acknowledge critical comments and discussions with W. Rosen of PU/CEES, R. Moseley, and D. Sanchez of US EPA/AEERL, R. Leadbetter of University of North Carolina, and R.Sextro of LBL.

REFERENCES

1. Nazaroff, W.W. and Nero, A.V. (Eds.), Radon and Its Decay Products in Indoor Air, John Wiley and Sons, NY, 1988.

2. Hopke, P.K., (Ed.), Radon and Its Decay Products, American Chemical Society, 1987.

3. Yuill, G.K. and Associates Ltd., A study of the statistics of radon measurements in houses, Report to Energy, Mines & Resources, Division of Environmental Affairs, Ottawa, Canada, File 9290/92900604, March, 1989.

4. Reddy, T.A., Molineaux, F.B., Gadsby, K.J., and Socolow, R.H., Statistical Analyses of Radon Levels in Residences Using Weekly and Daily Averaged Data, PU/CEES Report No. 249, March 1990.

5. Hull, D.A., and Reddy, T.A., Study on the reliability of short-term measurements to predict long-term basement radon levels in a residence, paper presented at the 1990 International Symposium on Radon and Radon Reduction on Technology, Feb. 19-23, Atlanta, Georgia, 1990.

6. Roessler, C.E., Revell, J.W., and Wen, M.J., Temporal patterns of indoor radon in North Central Florida and comparison of short-term monitoring to long-term average, paper presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Feb. 19-23, Atlanta, Georgia, 1990.

7. Cohen, B.L. Surveys of radon levels in homes by University of Pittsburgh Radon Project, paper presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Feb. 19-23, Atlanta, Georgia, 1990.

8. Sanchez, D.C., Dixon, R., and Williamson, A.D., The Florida radon research program: Systematic development of a basis for statewide standards, paper presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Feb. 19-23, Atlanta, Georgia, 1990.

9. Harley, N. and Terilli, T., Predicting annual average 222 Rn exposure, Health Physics, 1988.

10. Hubbard, L.M., Bolker, B., Socolow, R.H., Dickerhoff, D. and Mosley, R.B., Radon dynamics in a house heated alternately by forced air and by electric resistance, in Proceeding: the 1988 Symposium on Radon and Radon Reduction Technology, Volume 1, EPA-600/9-89-006a (NTIS PB89-167480), March 1989.

11. Sachs, L. Applied Statistics, 2nd Ed. Springer-Verlag, New York, 1984.

12. Hull, D., Time series linear regression of half-hourly radon levels in a residence, paper presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Feb. 19-23, Atlanta, Georgia, 1990.

13. ASHRAE, Fundamentals, American Society for Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia, 1985.

14. National Oceanic and Atmospheric Administration (NOAA), "Local Climatological Data - Monthly Summary," National Climatic Data Center, Asheville, NC, 1978.

TABLE 1. PERIODS DURING WHICH DATA WERE AVAILABLE.

House	Period	No. of Months
H2	10/15/1986 - 6/24/1987	8
H21	1/15/1988 - 10/31/1988	10
H22	3/11/1988 - 9/28/1989	18

TABLE 2. DESCRIPTION OF VARIOUS PARAMETERS CHOSEN FOR THIS STUDY.

TA	-	Ambient dry-bulb temperature, (°C)
TB	-	Basement temperature, (°C)
TL	-	Living area temperature, (°C)
TBA	-	Difference between basement and ambient air temperatures, (°C)
TLA	-	Difference between living area and ambient air temperatures, (°C)
HAC	-	Fraction of the time during which the heating and air-conditioning equipment was on,
RNB	-	Radon level in the basement, (pCi/L)
RNL	-	Radon level in the living area, (pCi/L)

TABLE 3. MEAN AND STANDARD DEVIATION OF CERTAIN IMPORTANT PARAMETERS FOR ALL THREE HOUSES OVER THE ENTIRE PERIOD OF DATA AVAILABILITY.

	H2			H21			H22		
	Arithmetic Mean	St. Dev.	Geometric Mean	Arithmetic Mean	St. Dev.	Geometric Mean	Arithmetic Mean	St. Dev.	Geometric Mean
TA (°C)	7.4	8.52	-	12.5	8.64	-	13.8	8.80	-
TB (°C)	16.1	2.16	16.0	19.4	2.06	19.3	23.2	3.75	-
TL (°C)	19.8	2.73	19.3	21.1	2.81	20.9	21.4	2.44	21.3
TBA (°C)	8.6	6.72	-	6.8	7.92	-	9.4	9.48	-
TLA (°C)	12.1	7.99	-	8.2	6.61	-	7.2	6.82	-
HAC (-)	0.20	0.151	-	0.18	0.214	-	0.16	0.273	-
RNB (pCi/L)	22.8	10.21	21.4	93.0	106.25	42.4	63.6	46.44	49.9
RNL (pCi/L)	15.3	5.44	13.6	36.8	39.82	19.8	13.6	11.03	8.2

TABLE 4. CORRELATION COEFFICIENTS OF RADON WITH PHYSICAL PARAMETERS USING THE ENTIRE DATA SET. THE VARIABLE TLA HAS NOT BEEN INCLUDED SINCE IT IS STRONGLY COLLINEAR WITH TBA, AND THE STRENGTH OF THE CORRELATION COEFFICIENTS OF THIS VARIABLE WITH RADON LEVELS IS ESSENTIALLY SIMILAR TO THAT OF TBA.

	H2				H21				H22			
	TA	TBA	HAC	TSB	TA	TBA	HAC	TSB	TA	TBA	HAC	TSB
RNB	0.12	-0.09	-0.24	-	-0.81	0.78	-0.20	0.04	0.05	-0.12	-0.23	0.04
RNL	-0.52	0.49	0.29	-	-0.84	0.87	-0.02	0.51	-0.56	0.54	-0.29	-0.09

TABLE 5. ADJUSTED R^2 VALUES OF DIFFERENT INDOOR RADON MODELS USING DAILY AVERAGE DATA.

	Model 1	Model 2	Model 3	Model 4
RNB				
H2	0.02	0.01	0.02	0.04
H21	0.66	0.62	0.64	0.67
H22	0.02	0.01	0.04	-
RNL				
H2	0.26	0.23	0.26	0.26
H21	0.71	0.76	0.81	0.81
H22	0.31	0.29	0.30	-

Model 1: RNB, RNL = f (TA)
Model 2: RNB, RNL = f (TBA)
Model 3: RNB, RNL = f [$(TBA)^+$, $(TBA)^-$]
Model 4: RNB, RNL = f (TA, HAC)

TABLE 6. VALUES OF THE REGRESSION COEFFICIENTS OF DAILY AVERAGE INDOOR RADON USING THE LINEAR MODEL IN TA (Eq. 4).

	RNB				RNL			
	Intercept (pCi/L)	SEM	Slope (pCi/L/°C)	SEM	Intercept (pCi/L)	SEM	Slope (pCi/L/°C)	SEM
H2	21.72	0.94	0.28	0.16	17.71	0.43	-0.33	0.04
H21	218.30	6.70	-9.99	0.44	85.41	2.33	-3.87	0.15
H22	50.62	4.70	0.35	0.29	23.35	0.93	-0.71	0.06

TABLE 7. YEARLY MEAN AND STANDARD DEVIATIONS OF DAILY AVERAGE AMBIENT TEMPERATURE FOR A FEW LOCATIONS [FROM DATA SUPPLIED BY REF.(14) FOR 1978]. THE ARITHMETIC MEAN VALUE FOR ALL LOCATIONS IS ESSENTIALLY NOT AFFECTED BY THE TIME SCALE OF AVERAGING.

City	State	Mean (°C)	Standard Deviation (°C) 1-day	3-day	7-day	15-day
1.Atlantic City	NJ	12.8	9.8	9.0	8.2	6.2
2.Houston	TX	19.3	7.9	7.2	6.5	5.2
3.Miami	FL	24.3	4.4	3.8	3.5	2.7
4.Newark	NJ	12.6	9.6	8.7	7.6	5.1
5.Portland	OR	12.9	6.0	5.5	5.0	4.0
6.Tallahassee	FL	19.1	7.4	6.8	6.3	4.9

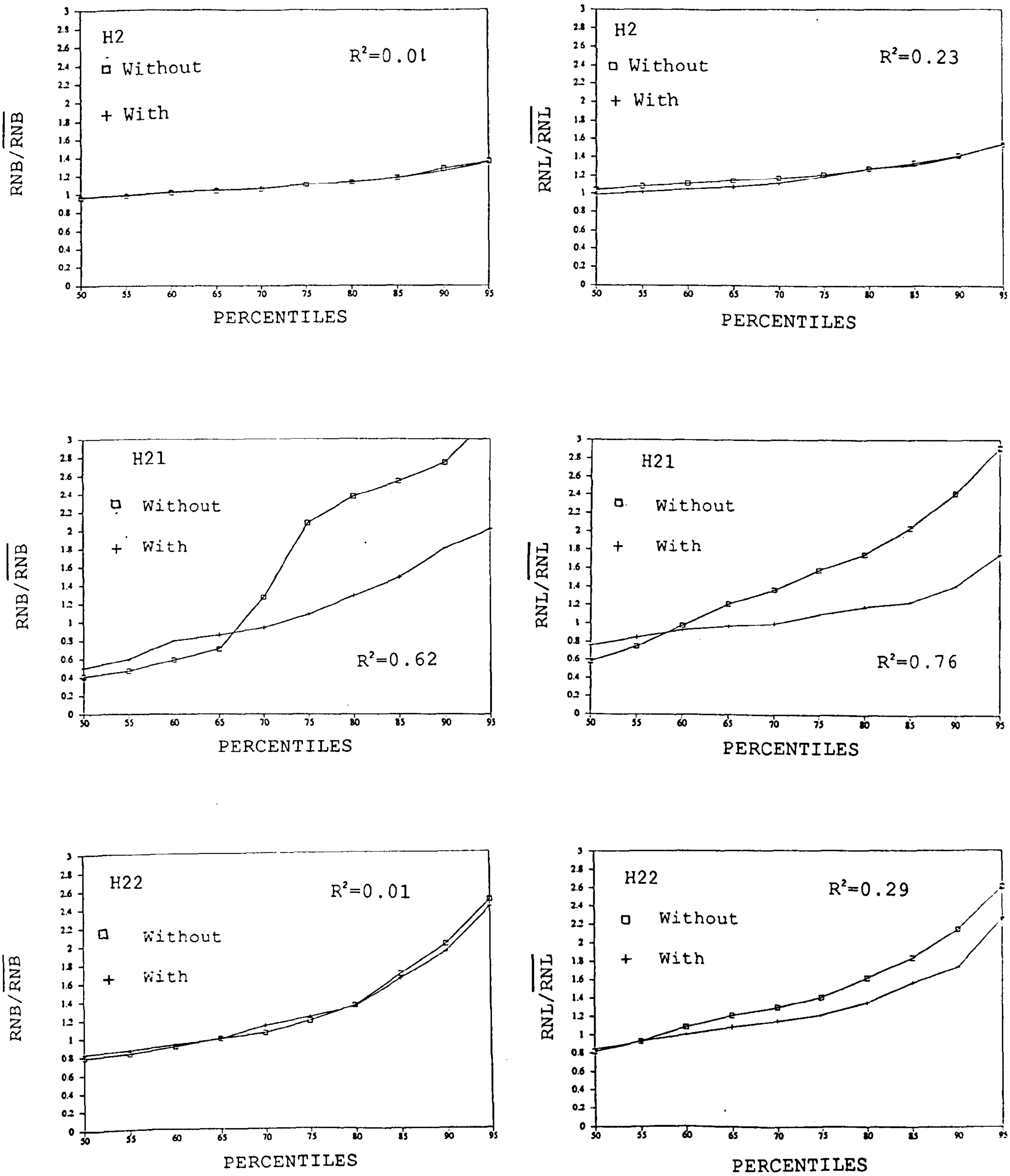


Figure 1. Percentiles of 1-day ratios of normalized basement and living area radon concentrations with and without temperature correction for all three houses. The associated R^2 values of the regression model given by eq. (1) are also shown.

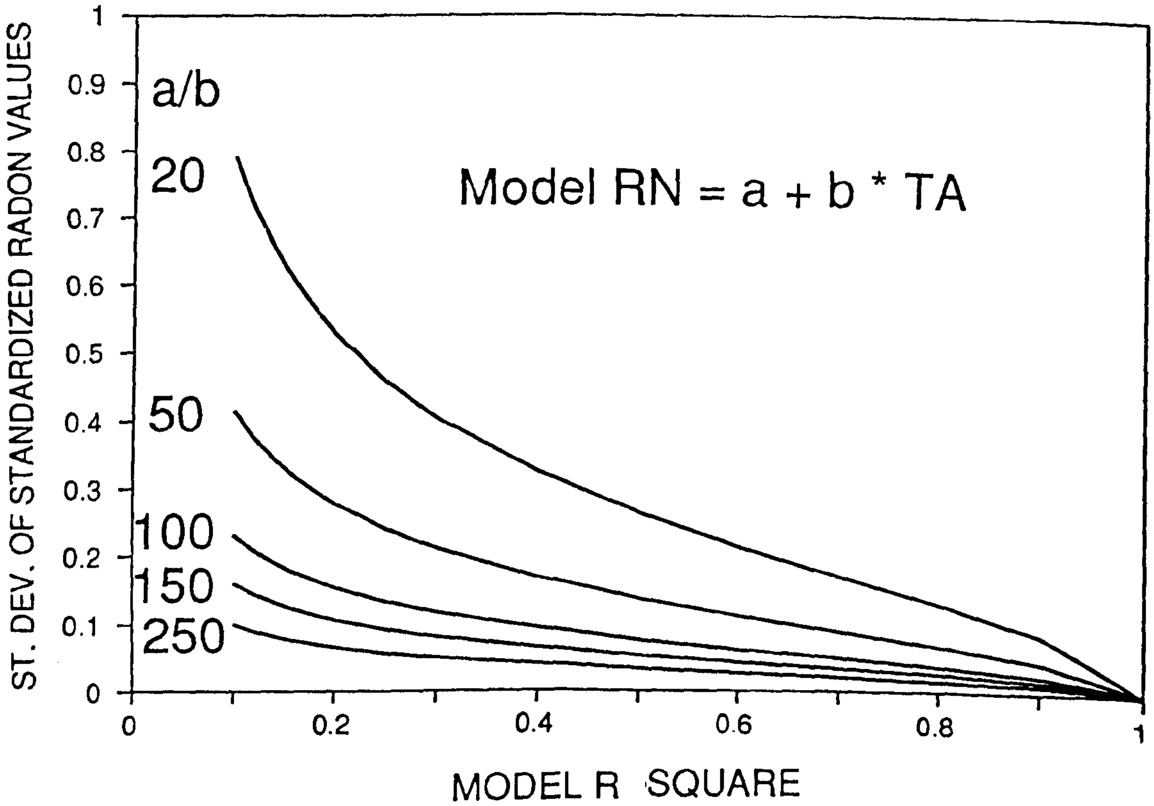


Figure 2. Variation of the theoretical uncertainty bounds versus model R^2 given by eq. (10) for different values of the factor (a/b) and for a day-to-day ambient temperature variation corresponding to the Princeton, NJ, area.

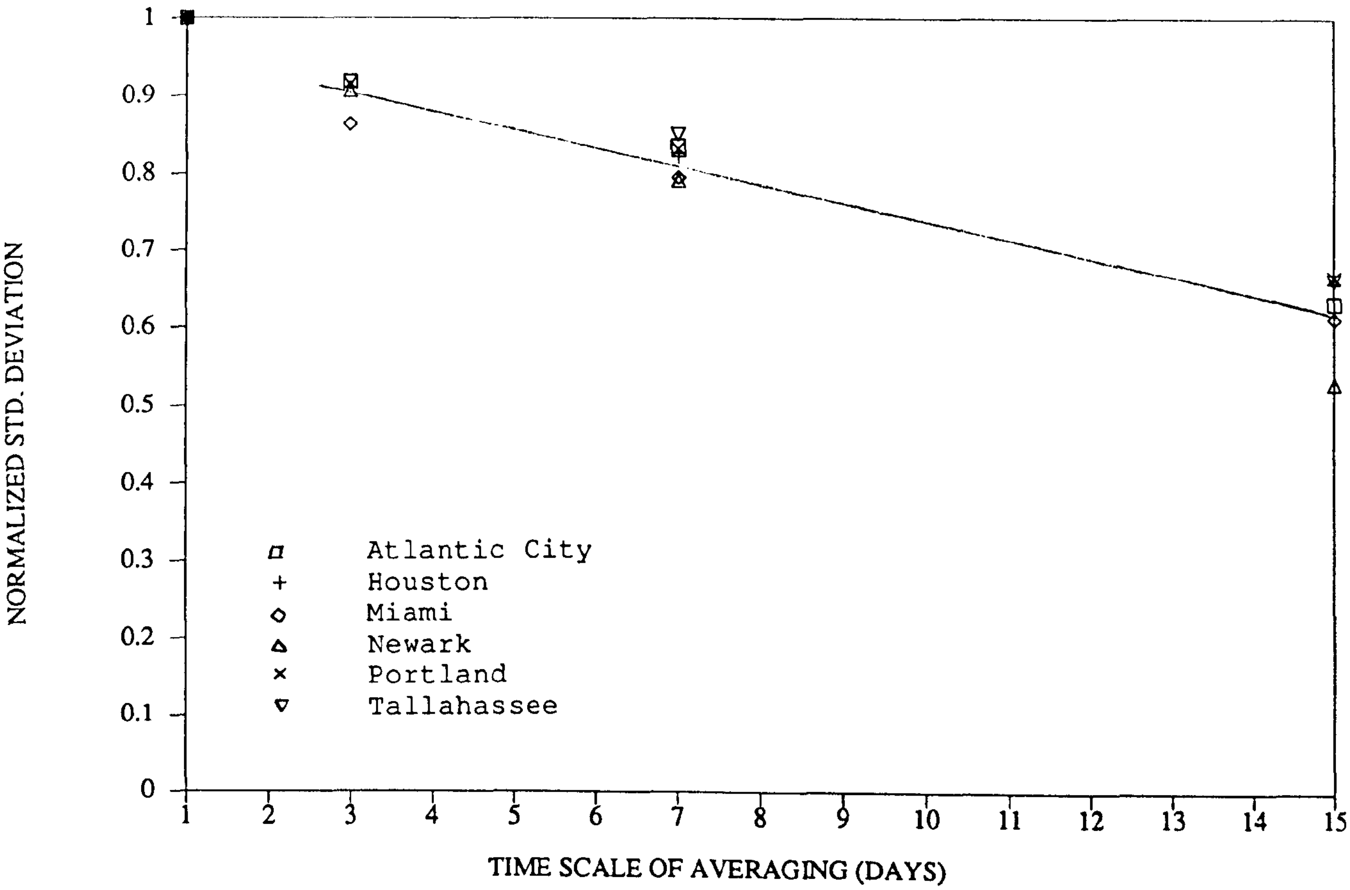


Figure 3. Normalized standard deviation values of ambient temperature versus time scale of averaging for six locations. The variation is close to being linear and is fairly location independent.

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

By: Susan McDonough and Ashley Williamson
Southern Research Institute
Birmingham, AL 35255-5305

and

David C. Sanchez
Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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.

REFERENCES

1. Sanchez, D.C., Dixon, R. and Williamson, A.D. The Florida Radon Research Program: Systematic Development of a Basis for Statewide Standards. Presented at The 1990 International Symposium on Radon and Radon Reduction Technology; Atlanta, GA, February 19-23, 1990.

2. Nagda N.L., Koontz M.D., Fortman R.C., Schoenborn, W. A., and Mehegan, M.A., 1987. Florida Statewide Radiation Study. Publication No.05-029-057, Florida Institute of Phosphate Research. (NTIS PB88-213970).

3. Roessler, C.E., Revell, J.W., and Wen, M.J. Temporal Patterns of Indoor Radon in North Central Florida and Comparison of Short-Term Monitoring to Long Term Averages. Presented at The 1990 International Symposium On Radon and Radon Reduction Technology; Atlanta, GA, February 19-23, 1990.

4. Roessler, C.E., Roessler, G.S., and Bolch, E. Indoor Radon Progeny Exposure In The Florida Phosphate Mining Region: A Review. Health Physics, 45:389, 1983.

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.

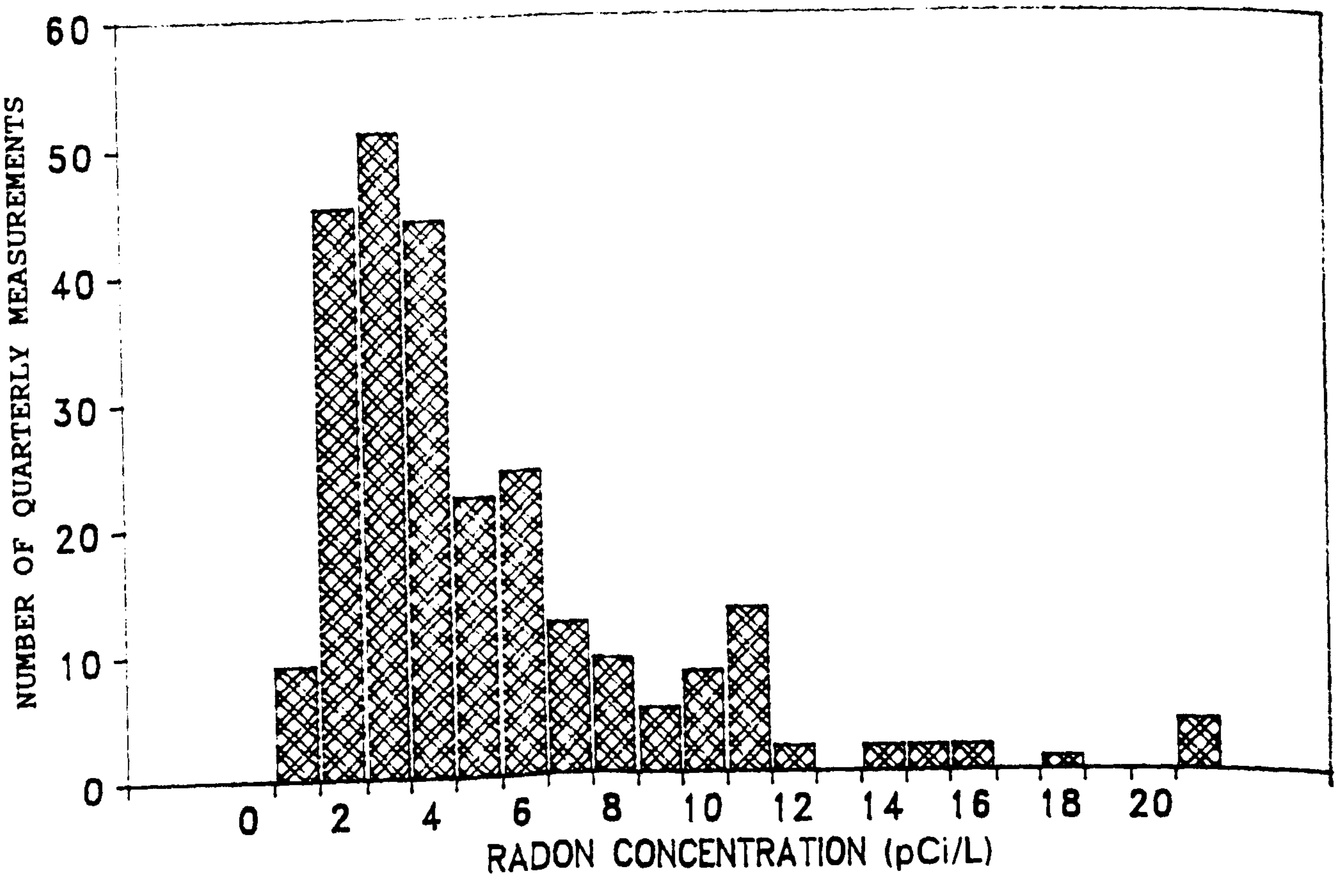


Figure 1. Distribution of quarterly average radon concentration in study houses.

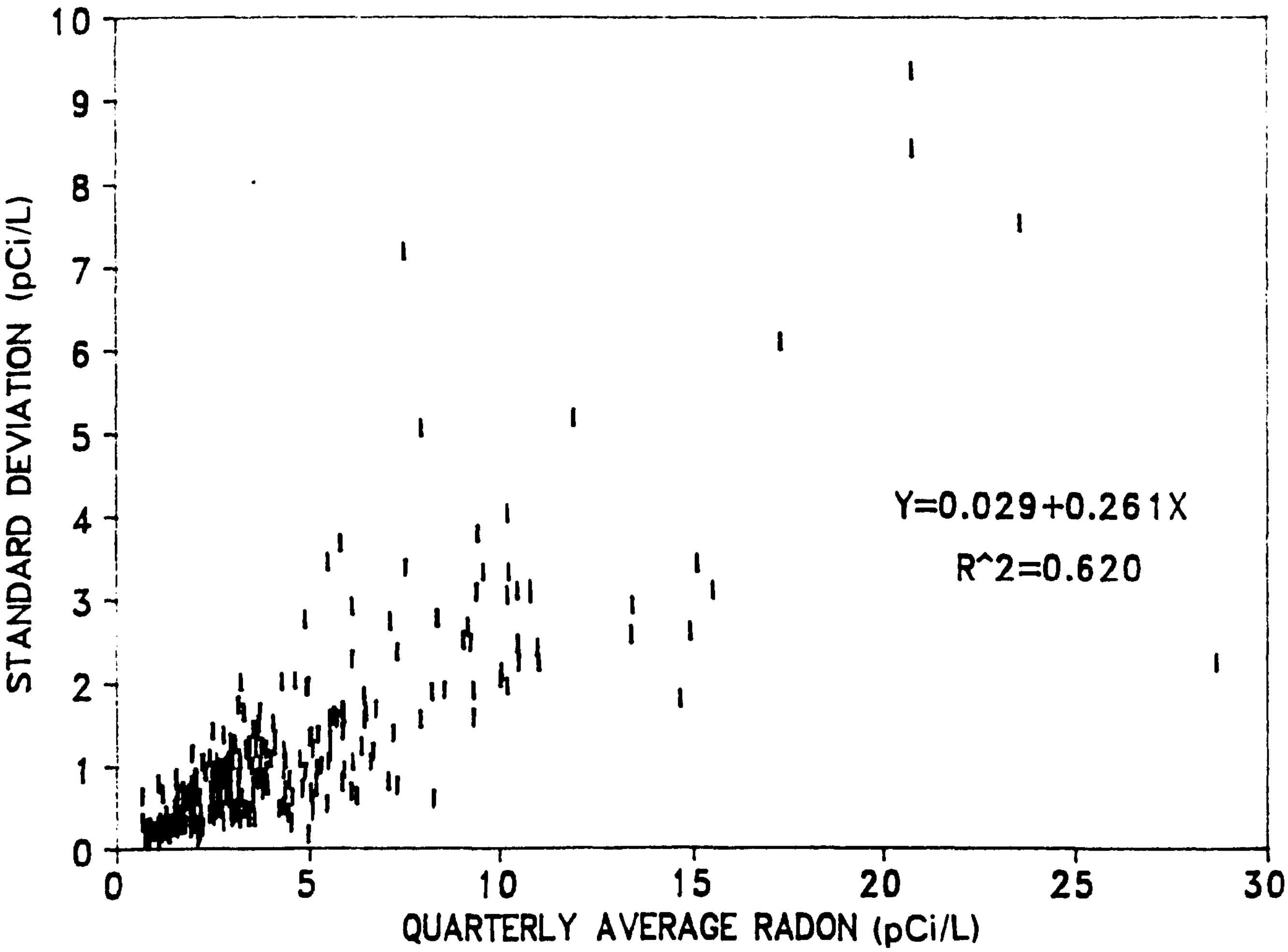


Figure 2. Standard deviation of individual short-term electret concentrations compared to quarterly mean concentration in study houses.

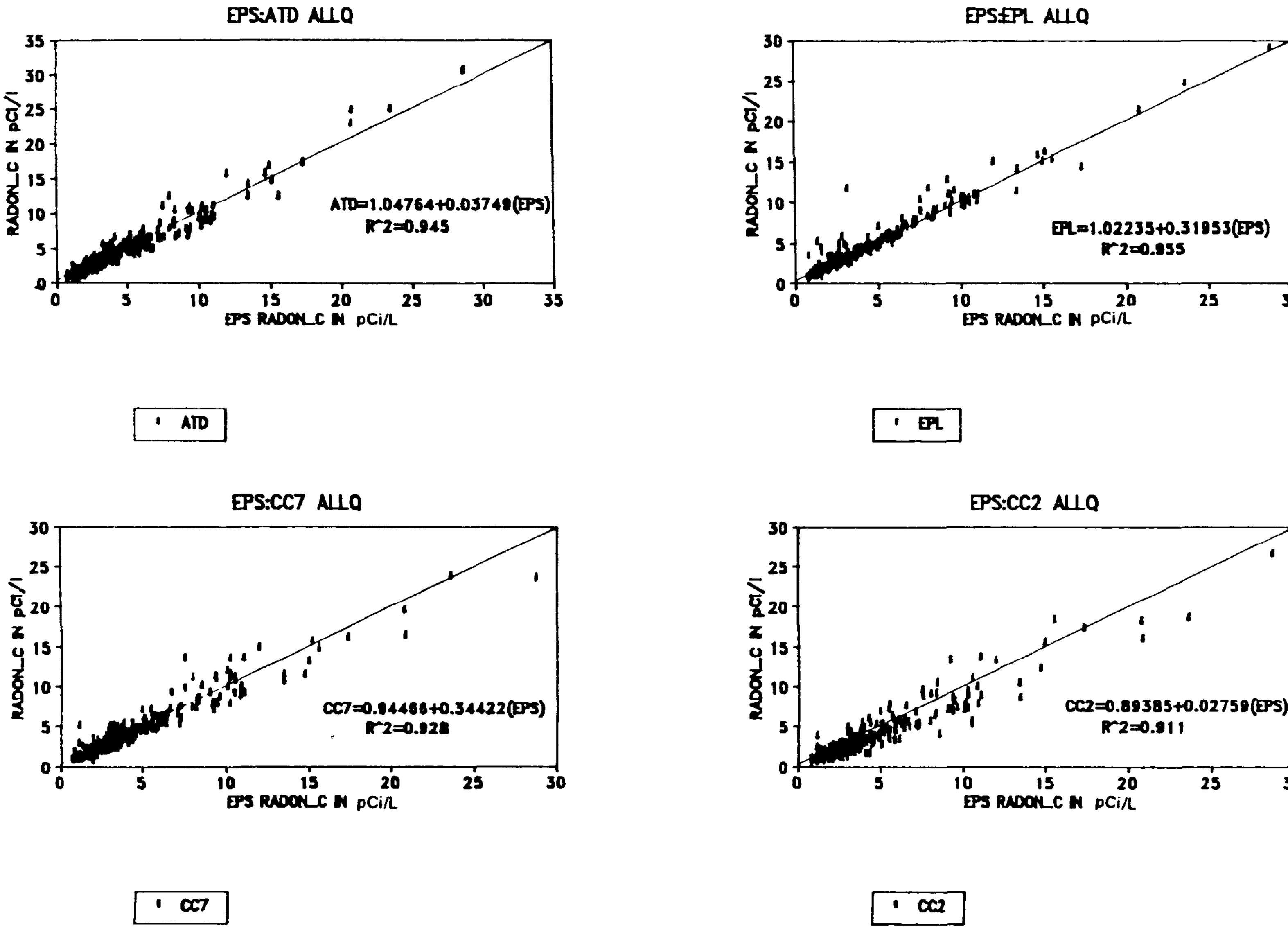


Figure 3. Linear regression between the quarterly average radon concentrations measured by short-term electret and each other device.

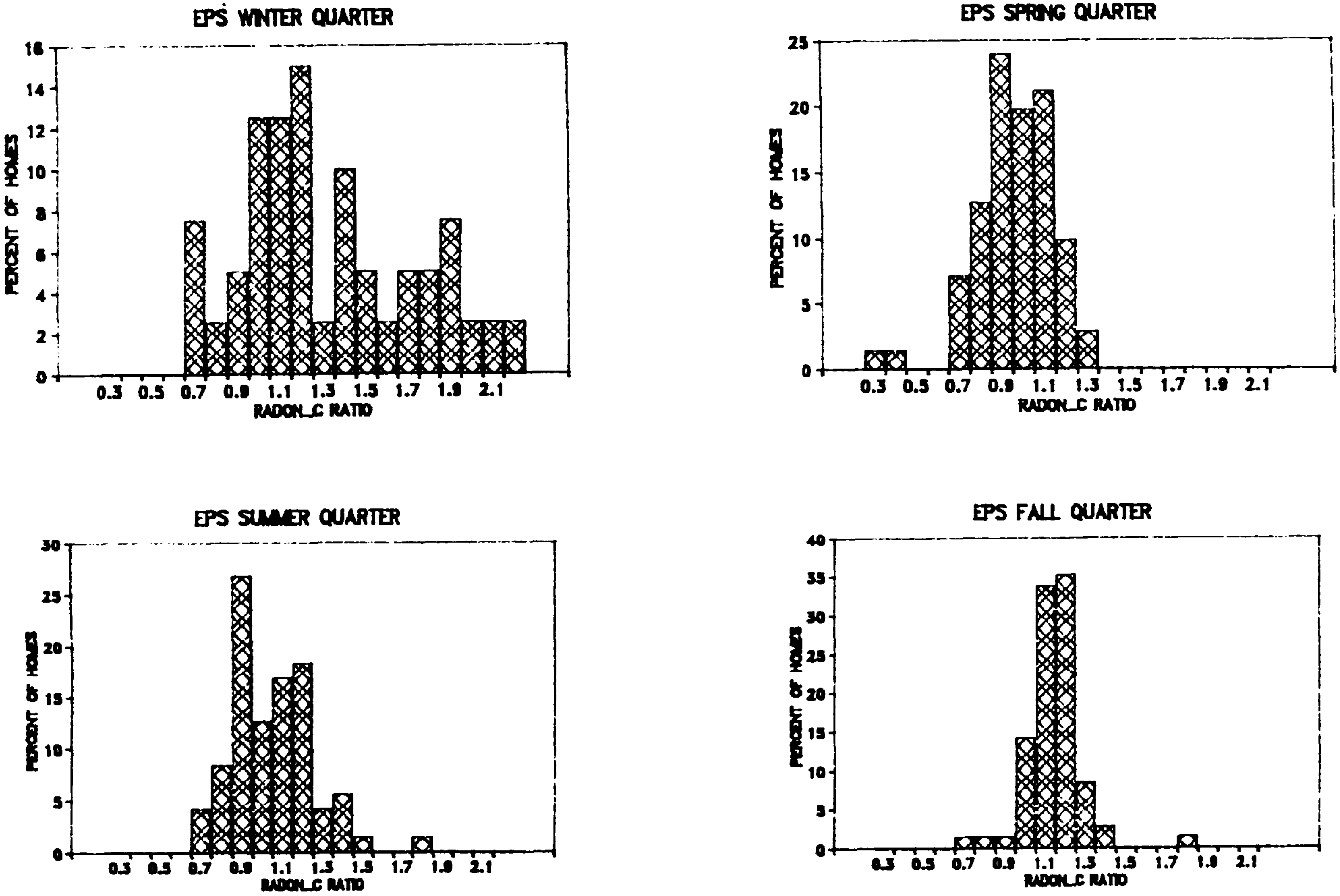


Figure 4. Relative frequency distribution of the quarterly average radon concentrations normalized to a 9-month average.

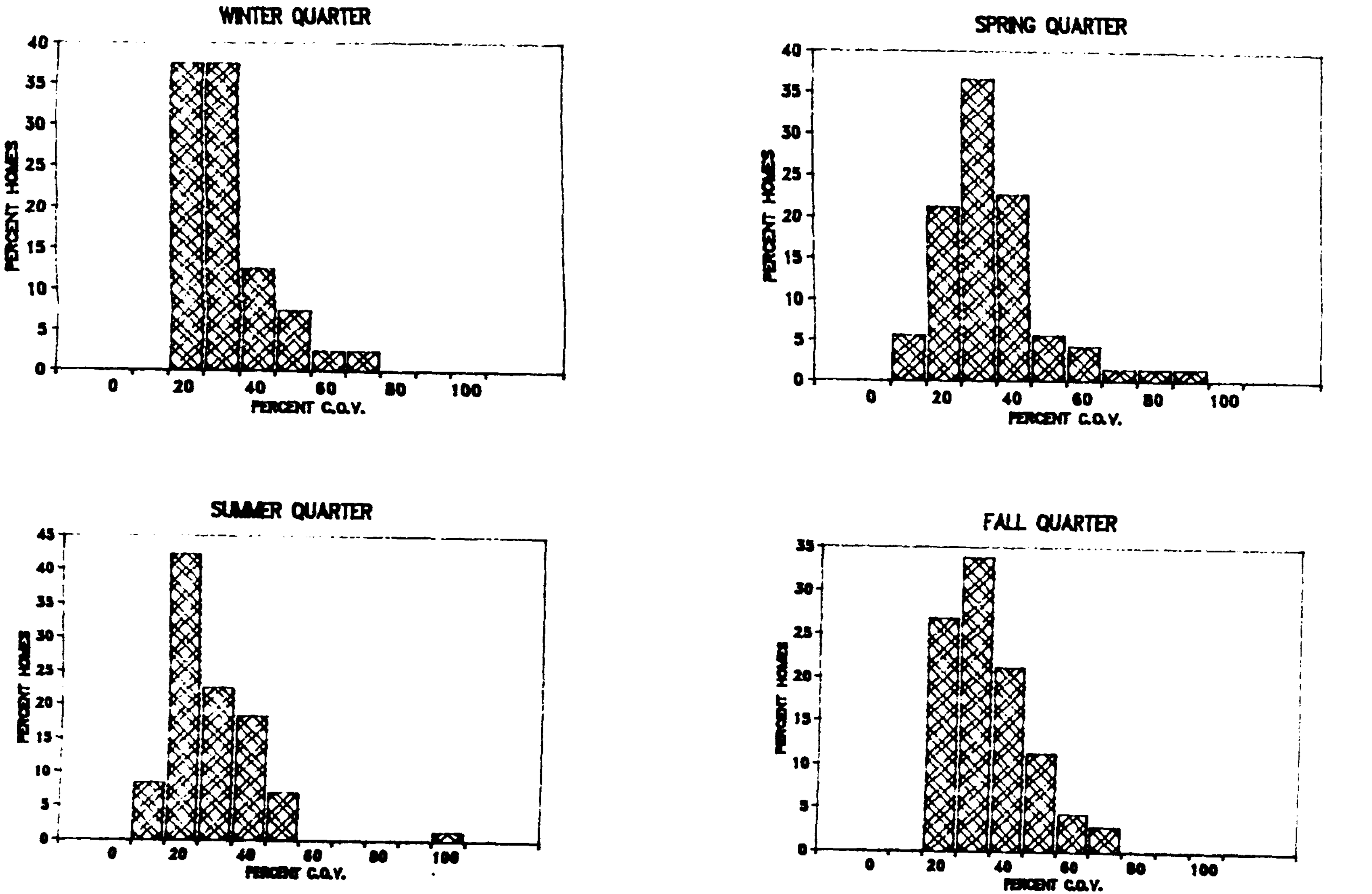


Figure 5. Distribution of quarterly coefficient of variance values from short-term electret data.

RELATIONSHIP BETWEEN 2-DAY SCREENING MEASUREMENTS OF ^{222}Rn AND ANNUAL LIVING AREA AVERAGES IN BASEMENT AND NONBASEMENT HOUSES

by: S. B. White, N. F. Rodman and B. V. Alexander
Research Triangle Institute
Research Triangle Park, N.C. 27709

J. Phillips and F. Marcinowski
U.S. Environmental Protection Agency
Office of Radiation Programs
Washington, D.C. 20460

ABSTRACT

As part of an EPA/State cooperative program, a random sample of 41,648 houses from 30 of the 48 conterminous states have been screened for ^{222}Rn over the past four years. Charcoal canisters were placed in the lowest livable level and exposed for two days. In addition, 1-year alpha track detectors were used in a random subsample of houses with at least one detector placed on each livable level.

This paper describes the relationship between annual living area averages (ALAA) and wintertime, closed-house, 2-day screening measurements. Both 2-day and 1-year measurements of ^{222}Rn were made on 995 houses located in 13 states. A broad range of climates, geologic conditions, and housing types are represented in the sample. Equations for predicting ALAA are derived for screening measurements taken in the basement and on the first floor of nonbasement houses. These relationships are used to obtain predicted values of ALAA for the 41,648 houses for which screenings measurements are available. The distribution of predicted values of ALAA by house type are then characterized. To the extent that the 30 states represent the 48 conterminous states, these distributions apply to the nation as a whole.

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

Short-term screening tests for ^{222}Rn are used to determine if additional testing (usually one year duration) is needed to more accurately characterize health risks to Rn exposure. The extent to which screening tests can properly identify houses needing further testing is governed by the degree to which short- and long-term measurements are related. This relationship has not been studied extensively. In a review of the published literature, Ronca-Battista (1) found only nine studies in which this issue was addressed and most of these had sample sizes less than 100 houses. This study attempts to provide a better understanding of this relationship.

A component of the EPA/State Indoor Radon Surveys involves two types of ^{222}Rn measurement devices in a subsample of houses. Each participating house is tested with a 2-day charcoal canister placed in the lowest livable level and 1-year alpha track detectors (ATDs) placed on each livable level. The 2-day test is carried out in the winter season under closed-house conditions. A total of 995 houses provided data for establishing the relationship between 2-day measurements and 1-year measurements.

OBJECTIVES

The purposes of this study were (1) to examine the overall relationship between 2-day screening measurements and annual living area averages (ALAA), (2) to determine if a screening measurement can be effectively used to predict the ALAA for an individual house, and (3) to examine the distribution of predicted values of ALAA for some 40,000 randomly selected houses for which screening measurements are available.

METHODOLOGY

Two indoor radon measurements (X, ALAA) were obtained from houses covering a 13-state area.[1] X is the 2-day charcoal canister measurement observed in a given house and ALAA is the annual living area average obtained by averaging all ATD readings taken on that house. In multiple level houses, a single ATD was placed on each livable level with a maximum of four ATDs per house. Two ATDs were used in one-story nonbasement houses. Averaging measurements from each level is one of several ways of characterizing the annual concentration in a house. Other ways include

---

[1]States providing both short-term and long-term measurements include: Alaska, Arizona, Indiana, Iowa, Maine, Massachusetts, Minnesota, Missouri, North Dakota, Ohio, Tennessee, Vermont, and West Virginia.

using only the first floor ATD measurement or using a weighted average of the ATD measurements from each level, where the weights reflect the proportion of time spent on each level.

This report examines the relationship between X and ALAA in basement and nonbasement houses. Values of X and ALAA for a given house are considered usable in the analysis if 1) the canister floor code matched the lowest floor code of the ATDS, 2) the ATDS used in calculating the ALAA had been exposed between 305 days and 425 days, 3) the canister was exposed within 30 days of the beginning of the ATD exposure period, and 4) a valid ATD reading was reported for each ATD originally placed in the house. A total of 997 houses provided data that met these requirements. After examining the data, two houses were excluded as outliers (one in Massachusetts and one in Tennessee). The relationships reported herein are consequently based on 995 houses--609 basement houses and 386 nonbasement houses.

A scatter plot of the data shows that ALAA is linearly related to X and that the variation in ALAA tends to increase as X increases. A relationship between X and ALAA is derived using a model which reflects these visual observations in the data. A specification of the model is given below.

The results in this paper employ a mathematical model that assumes that long-term measurements of ^{222}Rn are linearly related to short-term measurements and have variances that are proportional to their expected values. That is,

$$ALAA_i = (\alpha + \beta X_i) + \sigma Z_i(\alpha + \beta X_i)^{1/2} \qquad (1)$$

where

$ALAA_i$ = annual living area average calculated for the i^{th} house,

X_i = canister measurement on the i^{th} house,

α, β, σ = parameters to be estimated, and

Z_i = random error for i^{th} house, assumed to be normally distributed with mean 0 and variance 1.

In order to convert (1) to a model having a homogeneous error structure, we divide by $(\alpha + \beta X_i)^{1/2}$ and substitute $\sqrt{ALAA_i}$ for $(\alpha + \beta X_i)^{1/2}$ on the left hand side of (1):

$$\sqrt{ALAA_i} = (\alpha + \beta X_i)^{1/2} + \sigma Z_i. \qquad (2)$$

The parameters in (2) were estimated using nonlinear least squares. The prediction equation $\widehat{\sqrt{ALAA}} = (\hat{\alpha} + \hat{\beta}X)^{1/2}$ was squared to obtain predictions of long-term concentrations for given short-term measurements. Similarly, endpoints of the 95% confidence interval for $\widehat{\sqrt{ALAA}}$ were squared to obtain a corresponding interval estimate for the long-term concentration.

RESULTS

SHORT- VS LONG-TERM RELATIONSHIP

Results of fitting equation (2) to data from basement houses and from nonbasement houses are given in Table 1. For each type of house, Table 1

TABLE 1. EQUATIONS FOR PREDICTING ANNUAL LIVING AREA AVERAGES FOR BASEMENT AND NONBASEMENT HOUSES

Type of House	Sample Size	Prediction Equation	Correlation (X, ALAA)	Residual Error ($\hat{\sigma}$)
Basement	609	$\widehat{ALAA}$ = 0.69 (0.08)* + 0.54X (0.02)	0.82	0.51
Nonbasement	386	$\widehat{ALAA}$ = 0.53 (0.04) + 0.61X (0.02)	0.90	0.34

* (Standard error of parameter estimate.)

gives the sample size, the prediction equation, the correlation between X and ALAA, and the standard deviation, $\hat{\sigma}$, from the fitted model. The prediction equations are

Basement House: $\widehat{ALAA} = 0.69 + 0.54X$ (3)

Nonbasement House: $\widehat{ALAA} = 0.53 + 0.61X$ (4)

where $\widehat{ALAA}$ is the expected (or predicted) value of the annual living area average in a house that has a screening measurement of X on the lowest livable level. The prediction equation for nonbasement houses reflect the exclusion of two (X, ALAA) data points considered to be suspect - (24.0, 2.2) and (39.6, 3.6). If these data points are included the prediction equation becomes $\widehat{ALAA} = 0.61 + 0.52X$.

Scatter plots of the data for basement and nonbasement houses are shown in Figures 1 and 2, respectively. Note that as the canister measurements get larger the ALAA measurements show greater dispersion. As noted previously, this increase in variability in long-term measurements is taken into account by the model used in the data analysis. Superimposed on each scatter plot are three lines. The center line is the prediction equation. The other two lines (designated as UCL and LCL) represent the estimated upper and lower 95 percent confidence limits on the predicted value for an individual house. The interpretation of the confidence limits in Figures 1 and 2 is as follows: if a 2-day canister reading is X for a given house, there is a 95 percent chance that the true ALAA for that house would be covered by the interval falling between the upper and lower lines corresponding to X. For instance, for a basement canister measurement of X = 10 pCi/L, we can be 95 percent confident that the interval (2.2-12.0) will cover the true ALAA for that house. The vertical spread in the data for a given value of X (as reflected by the distance between the upper and lower confidence limits) indicates that the ALAA varies widely among houses having the same canister measurement.

FALSE POSITIVE/NEGATIVE ERRORS

EPA currently recommends additional testing if the screening measurement exceeds 4 pCi/L. Furthermore, EPA recommends mitigation if a 1-year test exceeds 4 pCi/L. In this case, a perfect screening test would correctly classify a house as to whether its annual concentration would exceed 4 pCi/L. Although there is no perfect test, one can, however, assess the performance of a screening test by characterizing the probability of an incorrect decision. One of two incorrect decisions can be made on the basis of a screening measurement--if a screening measurement is ≤4 pCi/L, one may incorrectly conclude that the house annual concentration is ≤4 (false negative); if a screening measurement exceeds 4 pCi/L, one may incorrectly conclude that the house annual concentration is also greater than 4 pCi/L (false positive).

The probability that the ALAA will exceed 4 pCi/L, given a specified screening measurement, X, is given by

$$P\left[Z < \frac{(a + bX)^{1/2} - 2}{\hat{\sigma}} \;\middle|\; X\right] \qquad (5)$$

where Z is a standard normal deviate, a and b are the estimated model parameters, and $\hat{\sigma}$ is the standard deviation from the fitted model. This probability was calculated for screening measurements, X, ranging from 1 to 16 pCi/L for basement and nonbasement houses by substituting the appropriate parameter estimates from Table 1 into equation (5); the results are shown in Figure 3. The regions of false positive and false negative errors are noted and the probability of an error associated with a given screening measurement can be determined directly from the plotted curves.

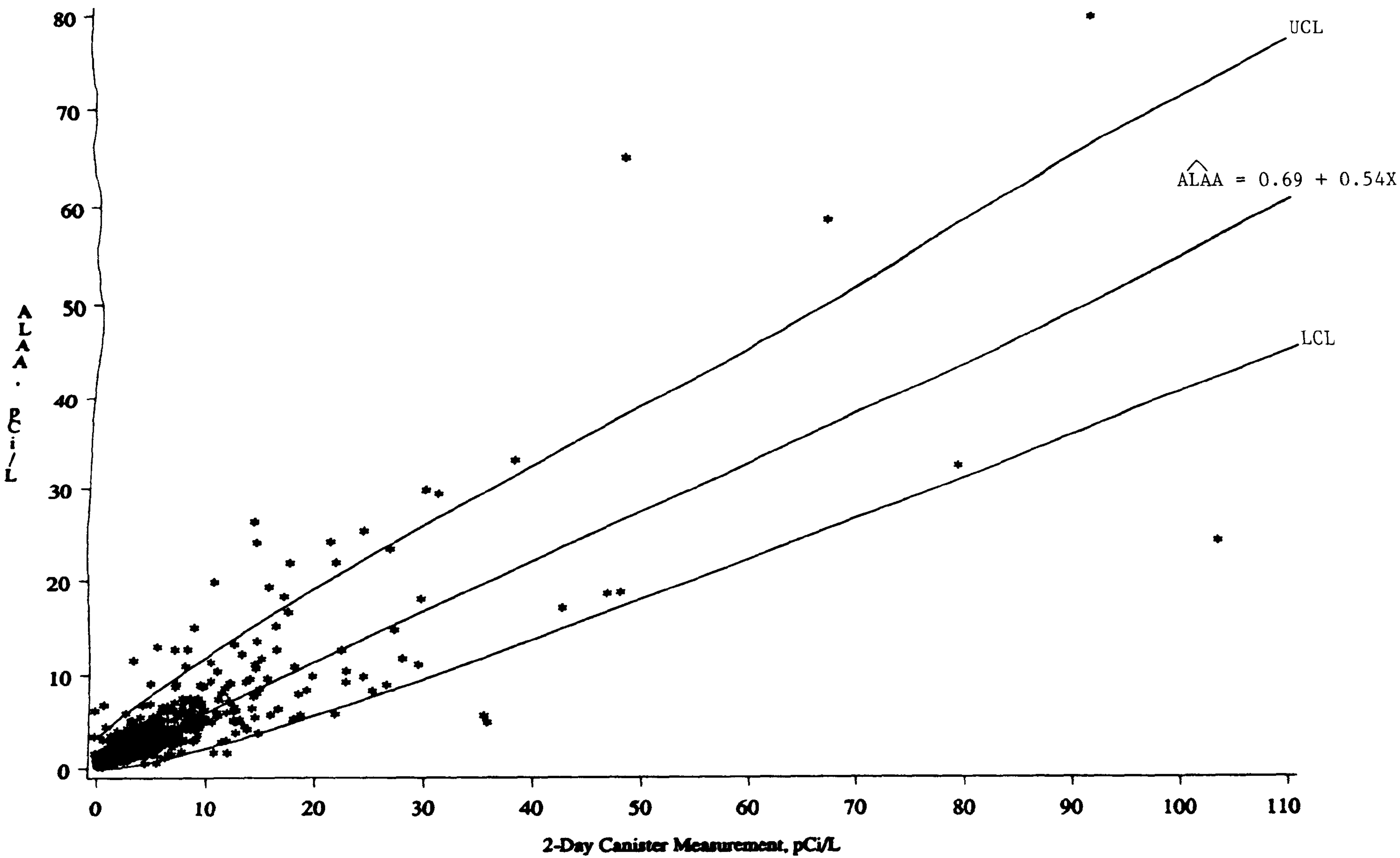


Figure 1. Relationship Between 2-Day Charcoal Canister Measurement And Annual Living Area Average - Basement Houses

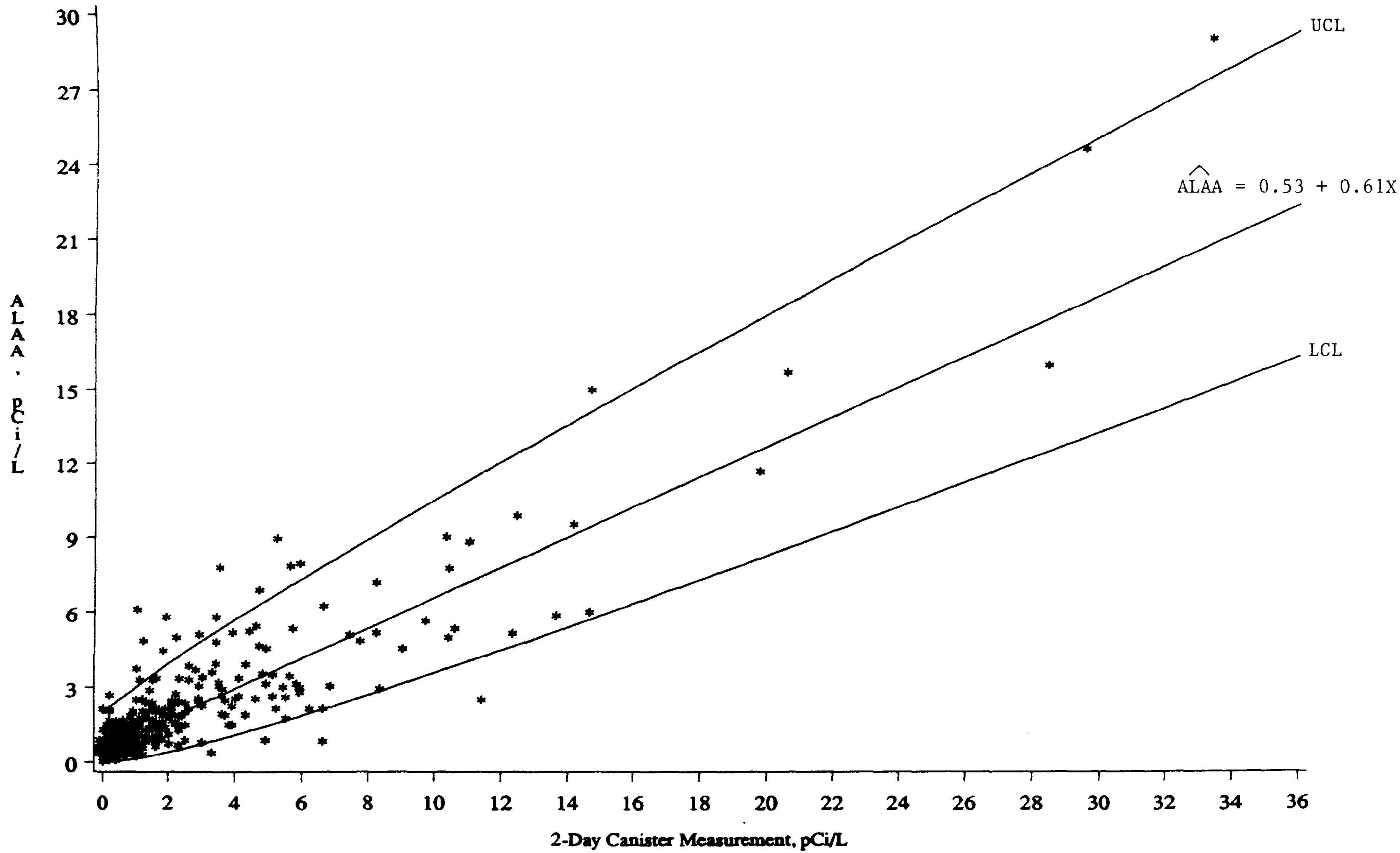


Figure 2. Relationship Between 2-Day Charcoal Canister Measurement And Annual Living Area Average - Nonbasement Houses

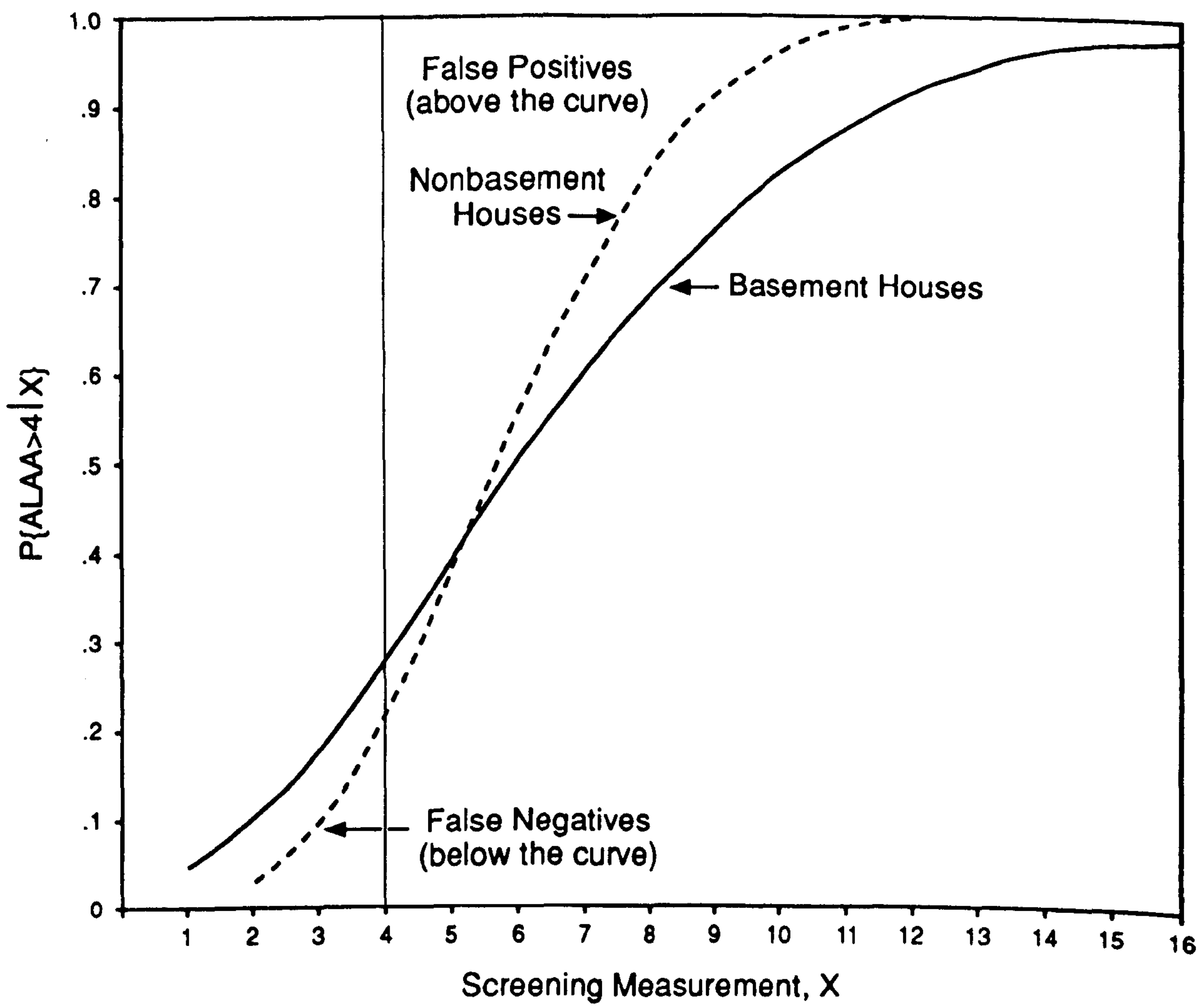


Figure 3. Probability that annual living area average exceeds 4 pCi/L as a function of screening measurement

For instance, the probability of a false negative error is approximately 0.17 for a screening measurement of 3 pCi/L in a basement house and approximately 0.09 for a screening measurement of 3 pCi/L in a nonbasement house. On the other hand, the probability of a false positive error is approximately 0.41 (= 1.00 - 0.59) for a screening measurements of 7 pCi/L in a basement house and approximately 0.29 (= 1.00 - 0.71) for a screening measurement of 7 pCi/L in a nonbasement house.

DISTRIBUTION OF $\widehat{ALAA}$

The relationships between short-term and long-term measurements of indoor ^{222}Rn as given by equations (3) and (4) provide an opportunity to use an existing data base of screening measurements to characterize the distribution of $\widehat{ALAA}$.

Under the EPA/State Indoor Radon surveys initiated in 1986, 30 of the 48 conterminous states have conducted statistically designed surveys. A probability-based sample of owner-occupied main residences having a listed telephone number, a permanent foundation, and at least one floor at or below grade level was selected in each state. Sample houses were tested with a 2-day charcoal canister placed in the lowest livable level. Tests were conducted during the heating season under close-house conditions. Although other surveys have used probability sampling (2,3), and other data sets include more test houses (4,5), the state surveys collectively provide the largest existing data base formed from studies that 1) use probabilities in making house selections, 2) have common objectives, 3) utilize the same measurement method, 4) employ the same protocol, and 5) sample the same target population. The 30 state surveys have produced

20,768 basement measurements, and
20,880 first floor measurements in nonbasement houses.

The basement screening measurement, X, for a given house was substituted into equation (3) to obtain a value of $\widehat{ALAA}$ for that house. In making the translation from X to $\widehat{ALAA}$, the sampling weight for the house was retained for use in future analyses. This process was repeated for all basement screening measurements and produced 20,768 $\widehat{ALAA}$ values and associated sampling weights from a random sample of basement houses covering a 30-state area. Similarly, each first floor screening measurement was substituted into equation (4). This generated 20,880 $\widehat{ALAA}$ values and associated sampling weights from a random sample of nonbasement houses covering a 30-state area.

Table 2 gives, in tabular form, the weighted cumulative distribution of $\widehat{ALAA}$ for basement houses, for nonbasement houses, and for all houses in the 30-state area. In addition, the distribution for basement and for nonbasement houses are presented graphically in Figure 4. Summary statistics (weighted) relating to these distributions of $\widehat{ALAA}$ are given in

TABLE 2. CUMULATIVE DISTRIBUTIONS OF $\widehat{ALAA}$ FOR 30-STATE AREA

$\widehat{ALAA}$	Basement Houses	Nonbasement Houses	All Houses
.4	0.0	3.4	1.6
.6	0.1	12.9	5.9
.8	1.2	28.6	13.7
1.0	5.4	45.2	23.6
1.2	15.7	58.3	35.1
1.4	26.2	70.5	46.4
1.6	33.0	76.2	52.7
1.8	41.3	80.4	59.1
2.0	48.1	84.8	64.8
2.2	52.4	87.4	68.4
2.4	57.2	89.3	71.9
2.6	61.5	90.6	74.8
2.8	65.1	92.1	77.4
3.0	67.6	93.0	79.2
3.5	74.6	94.7	83.8
4.0	79.1	96.1	86.8
4.5	82.4	97.0	89.1
5.0	85.1	97.6	90.8
6.0	89.4	98.4	93.5
8.0	93.6	99.2	96.1
10.0	95.8	99.5	97.5
15.0	98.0	99.9	98.8
20.0	98.8	99.9	99.3
25.0	99.2	99.9+	99.5

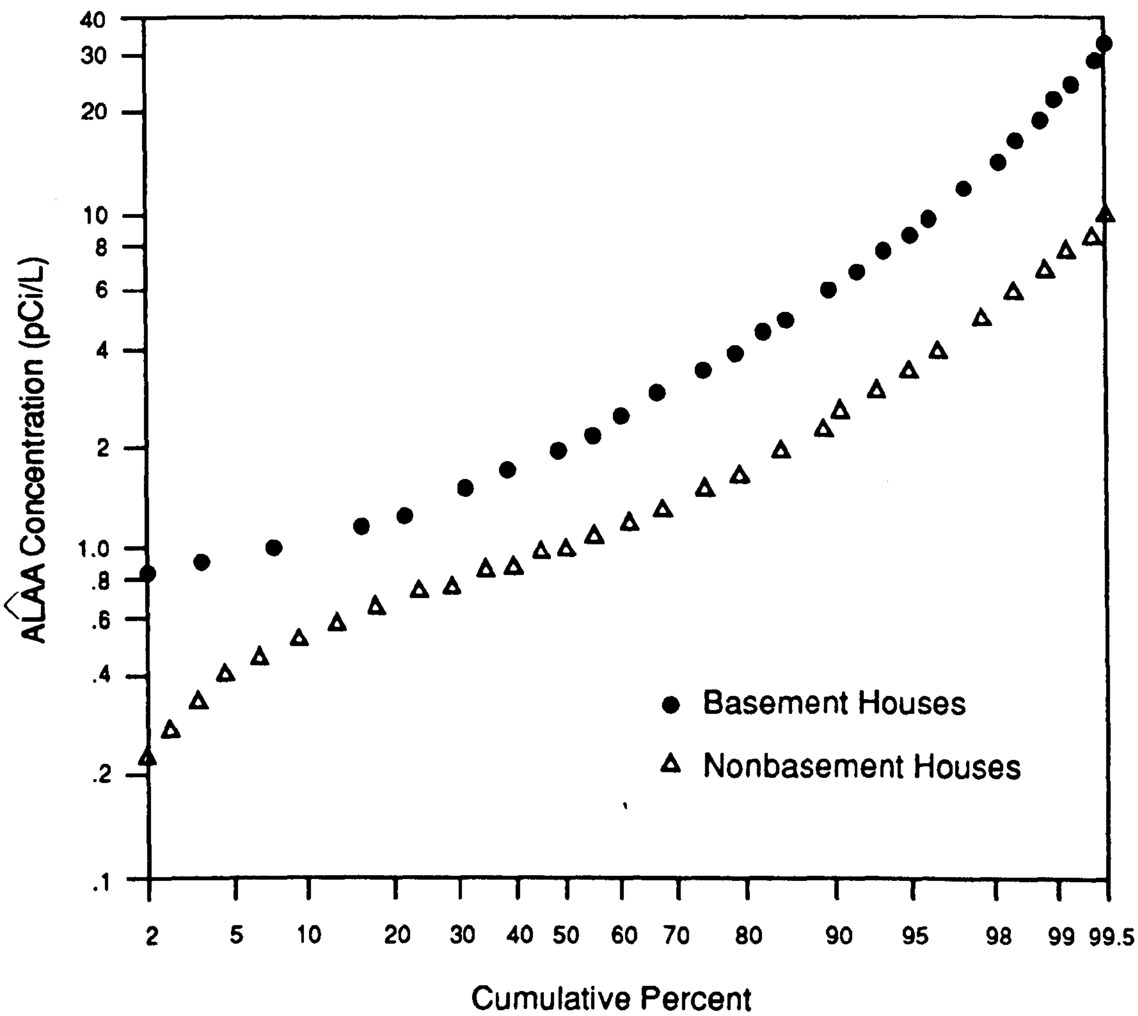


Figure 4. Normal probability plot of $\widehat{ALAA}$ for houses in 30-state area

Table 3. It is clearly evident that $\widehat{ALAA}$ is higher in basement houses. For example: the median (50th percentile) is 2.05 pCi/L for basement houses as compared to 1.02 pCi/L for nonbasement houses and the arithmetic mean for basement houses is more then double that for nonbasement houses (3.4 pCi/L as contrasted to 1.4 pCi/L).

Figure 4 indicates that the distribution of $\widehat{ALAA}$ cannot be satisfactorily approximated by a lognormal distribution since the data points for each house type depart substantially from a straight line plot. This was anticipated and can be explained by examining the prediction equations (3) and (4). Prediction equation (3), for example, converts the variable X, basement screening measurement, into the variable $\widehat{ALAA}$ through the relationship $\widehat{ALAA} = 0.69 + 0.54X$. X is assumed to be lognormally distributed and there is strong evidence to support this assumption. Under this assumption, $\widehat{ALAA}$ is lognormally distributed <u>only</u> if the intercept term in the relationship is zero. If the intercept is zero, then $\ln(\widehat{ALAA})$ is normally distributed since it is the sum of a normally distributed variable ($\ln X$) and a constant ($\ln 0.54$). The data show, however, the intercept (estimated at 0.69) to be statistically greater than zero.

The empirical distribution of $\widehat{ALAA}$ shows more houses in the tail of the distribution than the number obtained by using a lognormal distribution. For instance, the empirical distribution (Table 2 or Figure 4) shows 1.2% of basement houses have $\widehat{ALAA}$ exceeding 20.0 pCi/L as contrasted to an estimate of 0.2% based on a lognormal distribution with a geometric mean of 2.4 pCi/L and a geometric standard deviation of 2.1. Applying these percentages to a base of several millions of houses produces an enormous difference in the two estimates of the number of houses with $\widehat{ALAA}$ exceeding 20.0 pCi/L. The empirical distribution is based on tests from more than 40,000 houses and should be used in estimating proportions rather than using a geometric mean and geometric standard deviation.

The percentage of houses with $\widehat{ALAA}$ exceeding 4, 10 and 20 pCi/L are, respectively, 13.2%, 2.5% and 0.7% (Table 3, 3rd column). In contrast, the distribution of annual average radon concentration in U.S. houses reported by Nero (6) shows: 7.4% of the houses above 4 pCi/L; 1.0% above 10 pCi/L; and, 0.13% above 20 pCi/L (these percentages were calculated using a geometric mean of 0.9 pCi/L and a geometric standard deviation of 2.8). The differences may be attributable, in part, to differences in the dependent variables, to the way basement houses are defined, and to the sampled populations. For this study, a basement house is defined as any house where the lowest livable level has at least one wall built against earth.

A scientific study is now under way by EPA to characterize the nationwide distribution of annual concentration of indoor ^{222}Rn in residential houses (7). This study should resolve many issues/questions

TABLE 3. A$\widehat{LA}$A SUMMARY STATISTICS FOR 30-STATE AREA

Parameter	Basement Houses	Nonbasement Houses	All Houses
Arithmetic Mean*	3.4	1.4	2.5
Geometric Mean*	2.4	1.1	1.7
Geometric Standard Deviation	2.1	2.0	2.2
Median*	2.05	1.02	1.50
% $>$ 4 pCi/L	20.9	3.9	13.2
% $>$ 10 pCi/L	4.2	0.5	2.5
% $>$ 20 pCi/L	1.2	0.1	0.7

* Units of measurement - pCi/L.

relating to levels of ^{222}Rn to which occupants are exposed. Until such times that results from this national assessment study become available, the information provided by the distribution of $\widehat{ALAA}$ serves to add to the existing body of data on nationwide annual concentration of ^{222}Rn in the living area.

CONCLUSIONS

Two-day charcoal canisters and 1-year alpha track detectors were used to measure ^{222}Rn in 609 basement houses and 386 nonbasement houses. Results from this two-year study show there is a strong positive relationship between 2-day screening measurements and annual living area averages (ALAA). The equations for predicting ALAA from a screening measurement for basement and nonbasement houses are, respectively, $\widehat{ALAA} = 0.69 + 0.54X$ and $\widehat{ALAA} = 0.53 + 0.61X$. The results also show that ALAA varies widely among houses having the same screening measurement. The derived relationships were used to obtain predicted values of ALAA for a probability-based sample of 41,648 houses covering a 30-state area. A characterization of the distribution of predicted values for basement and for nonbasement houses is given. For example, an estimated 7.0% of the nonbasement houses have predicted values exceeding 3.0 pCi/L as compared to 32.4% for basement houses. To the extent that the 30 states represent the 48 conterminous states, the distributions of ALAA shown herein apply to the nation as a whole.

REFERENCES

1. Ronca-Battista, M. Radon in U.S. homes: A summary of the available literature on annual and screening radon concentrations, season variations, and differences between floors. Unpublished report prepared for U.S. Environmental Protection Agency, Washington, D.C., September 1989.

2. Perritt, R.L., Hartwell, T.D., Sheldon, L.S., Cox, B.G., Clayton, C.A., Jones, S.M., Smith, M.L., and Rizzuto, J.E. Radon-222 levels in New York state homes. Health Phys. 58: 147-155, 1990.

3. Rahman, M., Hoyle, W., and Tuccillo, K. Radon measurements in New Jersey. Paper presented at the 1988 Symposium on Radon and Radon Reduction Technology, Denver, Colorado, October, 1988.

4. Cohen, B.L. and Gromicko, N. Variation of radon levels in U.S. homes with various factors. JAPCA 38: 129-134, 1988.

5. Alter, H.W. and Oswald, R.A. Nationwide distribution of indoor radon measurements: A preliminary data base. JAPCA 37: 227-231, 1987.

6. Nero, A.V., Schwehr, M.B., Nazaroff, W.W., and Revzan, K.L. Distribution of airborne radon-222 concentrations in U.S. homes. Science 234: 992-997, 1986.

7. Bergsten, J.W., Holt, N.A., Lucas, R.M., and Smith, M.L. The national residential radon survey design report. Unpublished report prepared for the Environmental Protection Agency, RTI/4240/02-04F, 1989.

TITLE: The Use of Multiple Short-Term Measurements to Predict Annual Average Radon Concentrations

AUTHOR: Frank Marcinowski, EPA

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

EPA has been working to establish a policy for addressing radon in the context of a real estate transaction. Much of the work to date has focused on policy alternatives such as escrow accounts and long-term contract clauses. The principle difficulty with addressing radon in a housing transaction is the short testing period necessary to get information in time for house closing. The use of multiple short term measurements has been suggested as one method for reducing the uncertainty inherent in the use of short-term tests to characterize long-term radon levels. A statistical model was established to compare the expected performance of short-term procedures which apply simultaneous tests to the expected performance of a single short term test. The analysis examined multiple measurements that were separated temporally (taken at different times) and spatially (taken simultaneously on one or more house levels).

Session III:

Measurement Methods -- POSTERS

CHARACTERIZATION OF STRUCTURES USING SIMULTANEOUS SINGLE SOURCE CONTINUOUS WORKING LEVEL AND CONTINUOUS RADON GAS MEASUREMENTS

By: Brian Fimian
Radonics, Inc.
McLean, VA 22102

John E. McGreevy
Radonics, Inc.
McLean, VA 22102

ABSTRACT

Hundreds of simultaneous single-point working level/radon gas measurements have been used for the following study in order to demonstrate the behavior of the time synchronized equilibrium relationships between radon gas and progeny. Various normalizing equilibriums schemes will be explored for different structures, homestyles, and HVAC systems. The "equal-mixing" theory will be discussed in great detail as it applies to radon gas and progeny and to real world measurement data.

INTRODUCTION AND SCOPE

A commonly held belief by the scientific and radon measurement community is that radon variances from season to season are far greater than any measurement device's accuracy in a given measurement situation. When considering the large number of variables in the radon assessment equation, one can easily become uncomfortable with a single measurement approach for the purposes of a mitigation decision. Practical reality, however, has dictated that the EPA move towards a one measurement scenario for the purposes of a mitigation decision. Therefore, much attention must now be paid towards providing the best measurement possible in a single-measurement scenario.

Homeowners are very reluctant to test initially, and on those rare occasions in which they do, it is almost impossible to motivate them to perform a long term follow-up test as the EPA recommends. Real estate transactions prevent follow-up measurements due to the severe time constraints of the transaction itself. Escrow of funds is commonly objected to by realtors and sellers because of the "transaction tail" it creates and because of possible future legal liability problems.

So then, in light of the practical considerations in both homeowner and real estate testing, one is left with but one option and that is to make a single measurement and base the decision of whether or not to mitigate on that measurement.

Assessing true health risk now becomes a completely impractical objective. A screening measurement can only assess "radon potential". Radon potential is determined by placing a structure under what would be considered to be the worst-case conditions for the purposes of maximizing the probability of finding elevated elevated radon. The measurement made under these conditions would determine if any radon potential actually exists which could pose a health threat.

IDENTIFYING RADON POTENTIAL- MAJOR ISSUES TO ADDRESS:

- Validation of EPA closed-house conditions.
- Accuracy and precision of the measurement device itself.
- Correctly identifying the highest and most stable radon concentration in the structure (i.e. lowest liveable area, least ventilated area, closest to the source).
- Assurance that short-term weather conditions will not unfairly bias the test in one direction or the other.
- Provide as much assurance as possible with current measurement technology that internal house variables do not unfairly bias the test high or low.

- o Ensure that standard house operating conditions do not produce misleading results (i.e. furnace on or off, house occupied or unoccupied)

- o Ensure that post-mitigation measurements provide as much assurance as possible that the mitigation system will be effective for the long-term.

Simultaneous measurements of both radon and its progeny can eliminate many of the variables present and improve the chances of obtaining a truly meaningful measurement for the purposes of assessing radon potential. The definition of a "good" radon test is simply a test that will withstand all future radon measurements in the structure. Radonics is focused on this definition of a "good" radon test which has led to a preference whenever possible for making simultaneous radon gas and progeny measurements. Unfortunately, the machines that provide these kinds of measurements are still fairly expensive. As test volumes increase and requirements for a single measurement for the basis of a decision become commonplace, the cost of both the equipment and services will decrease significantly.

VALIDATION OF CLOSED HOUSE CONDITIONS AND DETECTION OF INTENTIONAL TAMPERING

Equilibrium relationships are a good indication of the maintenance of closed house conditions due to the fact that under normal situations equilibrium variances remain within a fairly narrowly defined range, approximately 15%. Some of this normal variance is due to limitations within the measurement device itself in that it is very hard to calculate instantaneous equilibrium relationships (1). A lag exists between the infusion of radon gas into the structure and the ensuing creation of the progeny for that gas (See Fig.1). To correctly calculate an instantaneous equilibrium relationship, such things as time delay for creation of progeny, calculation from continuous to instantaneous measurement for both gas and progeny, and instrumentation lag times must be all be assessed before a meaningful number can be derived.

Violation of closed house conditions produces dramatic changes in the equilibrium relationships over very short periods of time. This volatility can sometimes be correlated with large temperature swings that occur in the structure close to the times of the large equilibrium changes. If temperature swings do occur simultaneously with these large equilibrium changes, the reason would most likely be the opening of doors and/or windows in the same level of the structure where the measurement device is located (See Fig. 2). The more difficult to detect violations of closed-house conditions come from a more knowledgeable occupant. Opening of upstairs windows coupled with the operation of the HVAC system blower will dilute the basement air gradually over a few hours with the fresh air that exists in the upper levels of the structure. This of course causes a gradual transition towards lower radon/radon progeny levels. Equilibrium relationships during this transition move slightly downward at a very gradual pace. This gradual movement is sometimes very difficult to detect.

Data from a radon gas and progeny measurement that does not follow or track one another also leads the measurement firm to hold the final results suspect. Such things as operation of electronic air filters and ion generators can cause progeny levels to deviate from their normal correspondence with the radon gas levels (See Fig. 3). This is simply another indication that the closed-house conditions of the structure are being violated in order to defeat the radon measurement.

Finally, the use of a HVAC blower running constantly reduces both the radon gas and progeny levels, irrespective of whether or not the house is open upstairs. A "mixing bowl" action occurs within the air handler, providing for the entire volume of the house to be mixed with the basement air. This of course causes a significant dilution of the basement radon levels, typically down to about one third (depending on upstairs volume) and can significantly alter the test results.

EPA Protocols have yet to address the HVAC blower situation. Caution should be applied to ensure that both finished (open return duct) and unfinished (no return duct) basements are well characterized. Our measurement data has clearly indicated that there is a dramatic reduction in radon and radon progeny levels when an HVAC system is run constantly in **either a finished** or **unfinished basement.** Presumably this is due to the leakage factor on both the positive and negative side of the HVAC system in unfinished basements and the open return air duct present in the lowest liveable area in finished basement.

VARIATIONS IN HOUSE TYPES THAT INFLUENCE RESULTS

Newer homes in the United States typically have somewhat lower air exchange rates than older homes. Different areas of the country have different housing make-ups that account for the variables in the equation. For instance, New England's housing stock is typically older than housing stock in Atlanta or Washington, DC. When measurements are constantly made in older homes of any type there is a general trend towards slightly lower equilibrium relationships because of the increased air exchanges per hour in these structures. On the other hand, newer homes produce equilibrium relationships that are somewhat higher because of lower exchange rates.

Testing in the lowest liveable area, which is typically an unfinished basement, produces equilibrium relationships (in houses that are less than 25 years old) of 60% to 70%. Finished basements in the same type of structures with forced hot air systems tend to produce equilibriums closer to 50% because of the mixing bowl action that is occurring within the air handler from the on/off action of the HVAC system. One point of concern in this area comes up when measuring older homes that are likely candidates for future energy improvements. In such homes marginal radon levels could become elevated radon levels once the home is insulated and such things as new windows are installed.

HVAC TYPES

The following are four groups of HVAC systems commonly found in the United States:

1.) Forced air HVAC with either electric, heat pump, oil, or natural gas with blower unit or air handler in the lowest liveable area.

2.) Hot water baseboard or radiant heat with electric, oil, or natural gas with boiler in the lowest liveable area.

3.) Electric baseboard heat.

4.) Forced air heat with the air handler not in the lowest liveable area.

5.) A combination of forced-air (typically air conditioning) and baseboard type heat.

Forced hot air systems with the air handler in the lowest liveable area tend to have equilibrium relationships in the 50% range. Upstairs radon levels in the winter season tend to be similar to the basement radon levels due to the operation of the furnace. This is predominantly because of the mixing action that occurs in the air handler and the distribution of the basement radon level throughout the structure. Summer radon levels in this type of house also tend towards being somewhat evenly-distributed when AC units are operating.

Forced air systems with the air handlers in upper floors tend to act very similarly to hot water baseboard and electric baseboard systems in that there does not seem to be nearly the mixing action that occurs with all floors. The exception to this rule occurs when there is not a door at the top of the stairs that leads down to the basement which will allow air mixing between the first and second levels. Also, hot water baseboard or radiant systems in general tend to have much greater concentrations in the lowest liveable area because of the inability of the radon to effectively mix itself with the floors above. Electric baseboard heat also acts in a very similar manner.

The two largest sources of error occur when either an air-handler is operating continuously or in situations where houses are tested with the heating system not in operation and the structure is unoccupied. These homes that are tested when they are unoccupied tend to act like baseboard heat houses, raising the measured radon levels.

POST-MITIGATION

Post-mitigation performance can only be truly assessed using simultaneous radon/ radon progeny measurements. Most pre-mitigation levels in the United States lie between four and eight picoCuries. It is currently impossible to remove all of the radon gas with a sub-slab mitigation system. Typically, 20% to 30% of houses that are mitigated have radon gas levels between two and four picoCuries. These radon levels can create progeny levels that are in excess of the EPA action guideline. Newer homes that are energy efficient and have unfinished basements may produce a low radon gas level while still having quite elevated post-mitigation progeny levels.

Thoron has also been discovered to be a problem in a number of U.S. homes. Radon gas measurement devices do not typically measure thoron and hence miss detecting a potential health risk (2).

COST

The cost of simultaneous radon/radon progeny measurement hardware and the associated quality assurance requirements will continue to decrease. However, in the overall measurement equation it is certainly not the measurement device alone that determines the cost. The key elements are manpower, transportation costs, scheduling, quality assurance, and the consultation with the customer after the results are reported. The equipment costs typically only run 10 to 14% of the overall transaction cost, whether it be active devices capable of performing simultaneous working level/gas measurement or passive devices without this capability.

CONCLUSION

With the entire radon measurement process becoming a test/fix environment, tremendous focus and energy will be put into the requirement of making a "good" measurement, i.e. one that stands the test of time. As customer demand for "good" radon measurements increases, firms will encourage the use of simultaneous radon/radon progeny measurements to assess radon potential in the worst case home use scenario. Should a radon gas measurement be made without consideration for the progeny and a portion of the house is changed (i.e. older homes being tightened up), elevated progeny could be present and the homeowner would be completely unsuspecting. Conversely, should a progeny measurement alone be made with the right set of conditions present for elevated gas and low progeny, and these conditions changed, the homeowner could then also be harmed. The logical conclusion is to measure both radon gas and progeny.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

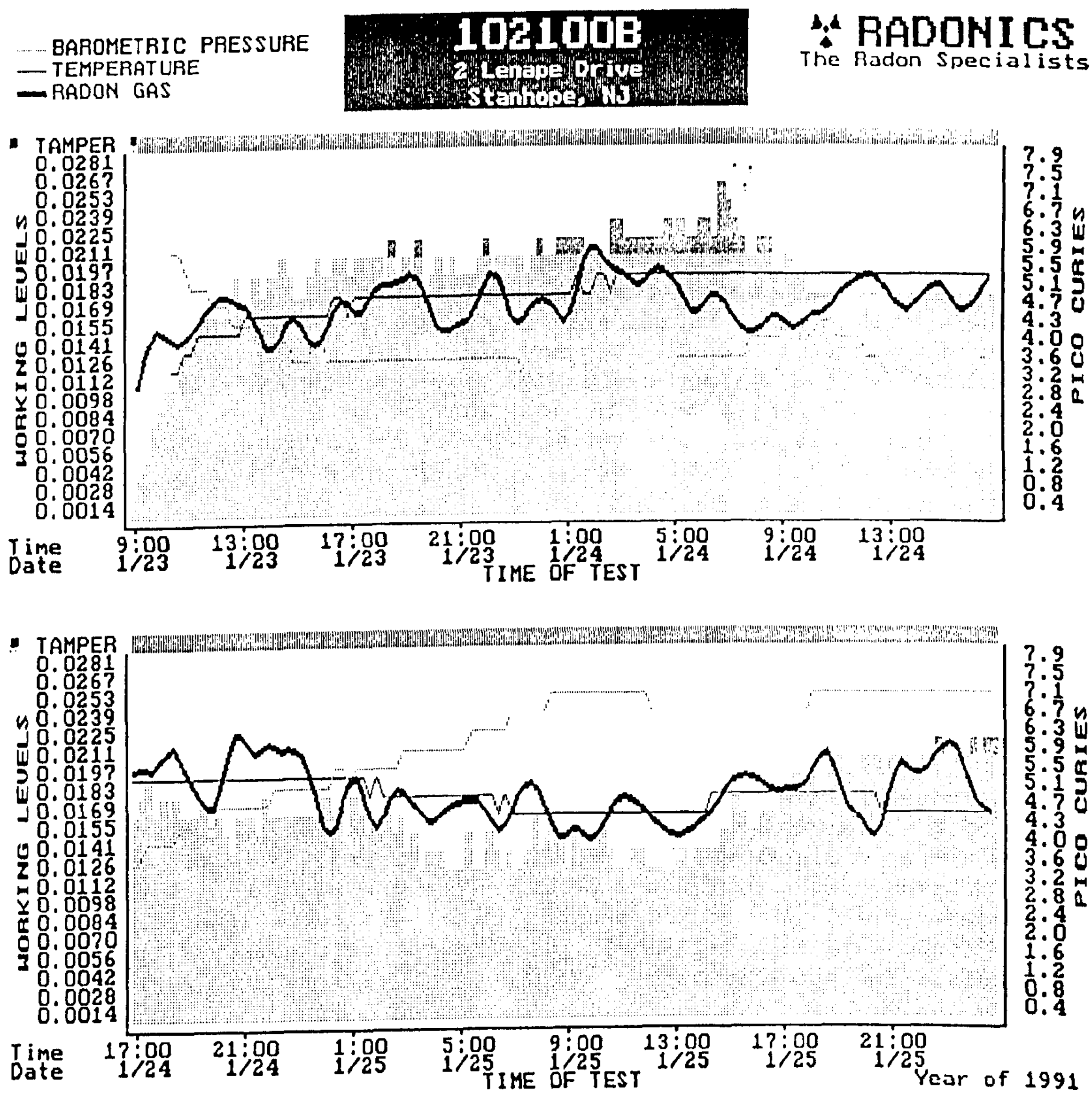


Figure 1. Radon gas leads progeny.

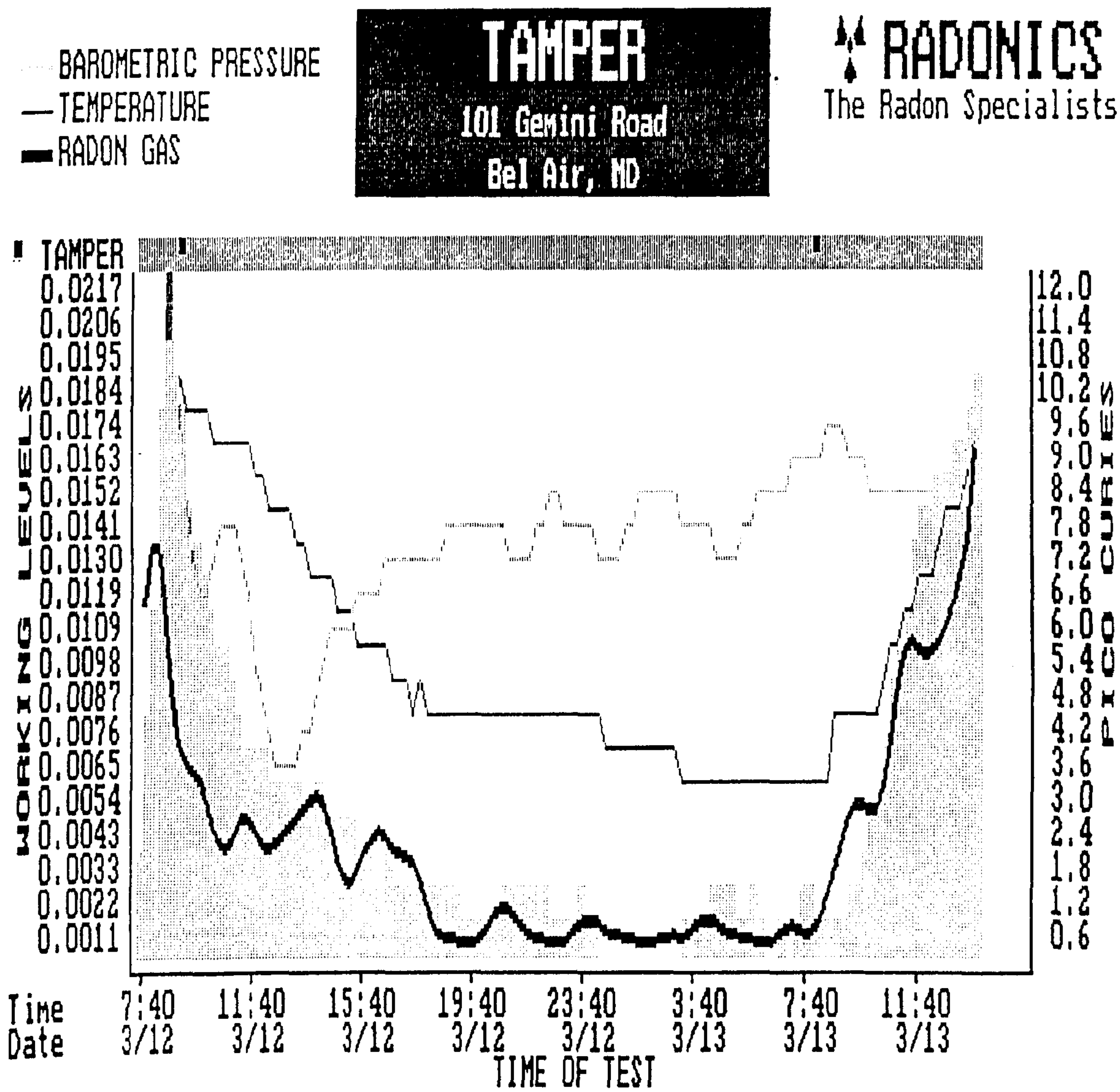


Figure 2. Tampering.

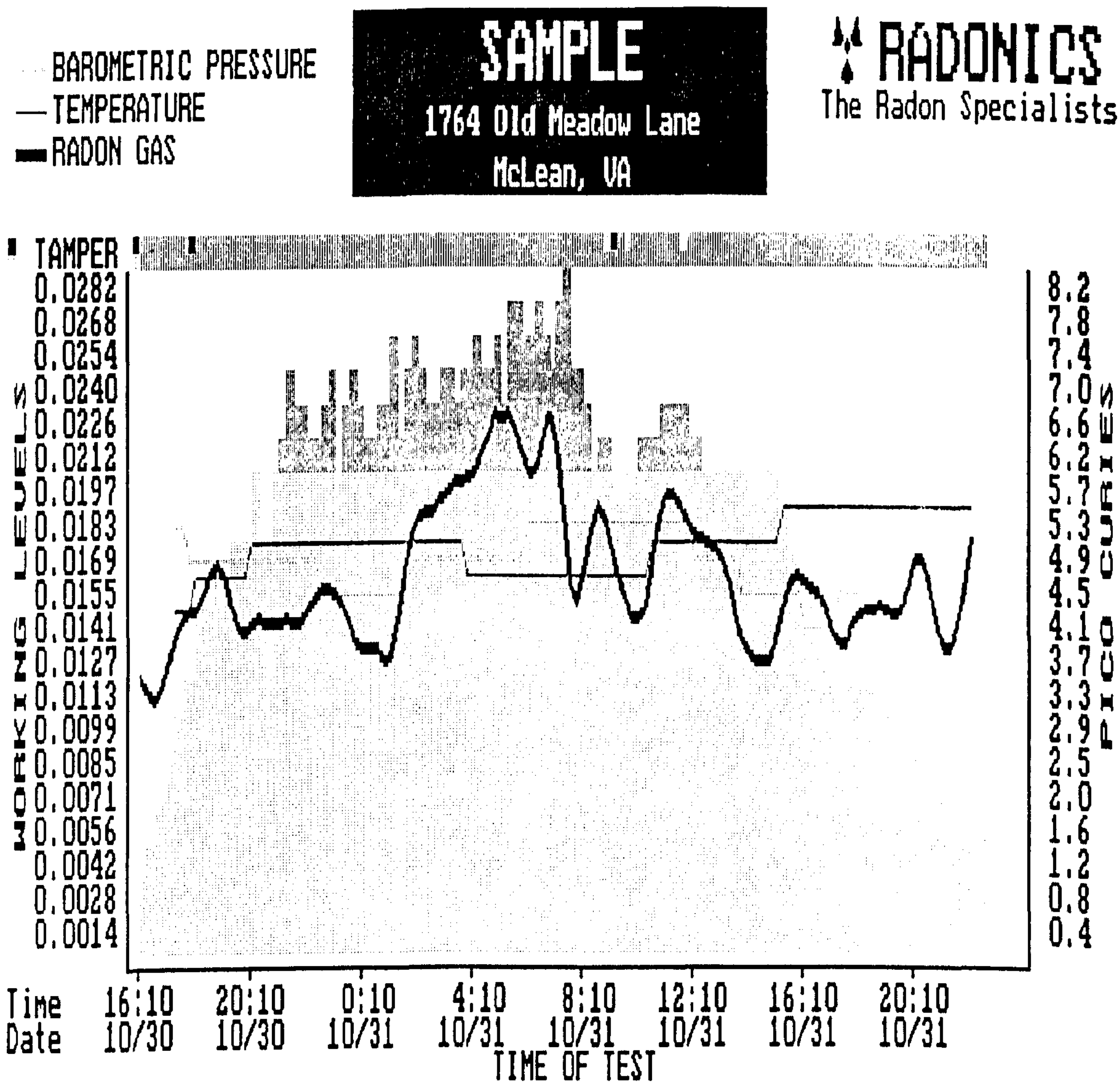


Figure 3. Progeny Deviation.

REFERENCES

1. Busigin, Van Der Vooren, Phillips. "Interpretation of the Response of Continuous Radon Monitors to Transient Radon Concentrations". Health Physics, Vol. 37, pp. 659-667, November 1979.

2. Martz, Falco, Langner. "Time-Averaged Exposures to Radon and Radon Progeny in Colorado Homes". Health Physics, Vol. 58, No. 6, pp. 705-713, June 1990.

TITLE: Pennsylvania Department of Environmental Resources Radon in Water Measurement Intercomparison

AUTHOR: Douglas Heim and Carl Granlund, Pennsylvania Department of Environmental Resources

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

Abstract

An intercomparison of laboratories offering radon in water measurement services to homeowners was performed. Nine laboratories including the Pennsylvania Department of Environmental Resources and the Environmental Protection Agency participated. Six different wells located near Harrisburg were sampled in triplicate. Sampling locations were arranged to cover a wide range of concentrations, e.g., 60 pCi/l to over 100,000 pCi/l. Laboratory information was also gathered on sampling procedures, sample analysis, and data reduction. Information gathered showed a wide range of sampling and analysis techniques. Reported results were within +/- 25%, with the exception of one laboratory. Reported lower limit of detection (LLD) values were as high as 300 pCi/l. Recommendation for future work includes developing a standardized sampling technique and standardized analysis methods, the liquid scintillation counting and the electret methods.

TITLE: A Field Comparison of Several Types of Radon Measurement Devices

AUTHOR: Elhannan L. Keller, Trenton State College

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

A six month comparison study of activated carbon canisters, alpha tracks, electret passive environmental radon monitors (E-PERM), cellulose nitrate foil track etch detectors, and at various times a continuous radon monitor, was conducted on the campus of Trenton State College throughout the winter heating season. Monitors were placed at ten sites in various buildings (dormitories and offices) throughout the campus. The monitors were subjected to actual environmental conditions for this time period. Temperature, humidity and barometric pressure were measured biweekly, with canisters being exchanged at the same rate. E-PERMs were read and calculated biweekly as well. Both types of track etch detectors were exchanged on a one, three and six month basis. All data were evaluated and compared relative to the effects of temperature, humidity and pressure. A preliminary analysis of the data has shown that temperature and humidity have a significant effect on certain of these measurement devices.

RADON AND WATER VAPOR CO-ADSORPTION ON SOLID ADSORBENTS

by

Neguib M. Hassan, Tushar K. Ghosh, Sudarshan K. Loyalka
and Anthony L. Hines*

College of Engineering
University of Missouri-Columbia
Columbia, MO 65211

and
Davor Novosel
Gas Research Institute
Chicago, IL 60631

* To whom correspondence should be directed

ABSTRACT

The potential health hazard posed by radon and its daughters has led to increased efforts to develop effective methods for reducing radon concentrations in indoor air. One promising method for reducting radon in homes is to adsorb it on solid adsorbents such as activated charcoal, silica gel, and molecular sieves. Activated charcoals are currently used for the measurement of radon concentrations in indoor environments, whereas silica gel and molecular sieves are finding increasing application in desiccant based air conditioning systems. Although radon measurements are carried out in humid air, literature data describing radon adsorption in the presence of water vapor are limited.

An experimental system has been designed to measure radon concentrations in the solid and gas phases simultaneously at equilibrium. The uptake of radon by commercially available BPL activated charcoal, silica gel (grade 40), and molecular sieve-13X were measured at room temperature (298 K) from dry nitrogen and moist nitrogen under both dynamic and static conditions. Radon adsorption isotherms were of Type III for all the three adsorbents with adsorption capacities being highest for activated charcoal and the lowest for silica gel. The presence of water vapor reduces the adsorption capacities for radon on BPL activated charcoal considerably. The applicability of these data to improve the radon measurement by charcoal canisters and to design a removal system are also discussed.

INTRODUCTION

The ability of activated charcoals to adsorb and retain radon has been employed in the design of charcoal canisters that are used to measure radon concentrations indoors. The amount of radon that is adsorbed per unit weight of charcoal at a particular temperature is a function of the gas phase concentration. This relationship can be expressed by a curve known as "isotherm". Therefore, radon adsorbed from air by charcoals in a canister can reach equilibrium corresponding to its gas phase concentration, provided sufficient time is allowed. From the knowledge of solid phase radon concentration, the equilibrium isotherm can be used to measure the concentration of radon in the gas phase. However, physical properties of the charcoal such as surface area, pore size distribution, and chemical nature of the surface play an important role in the uptake capacity. The presence of water vapor also can influence the adsorption process.

Several researchers have studied the effects of these parameters on the radon adsorption capacities of charcoals. Most researchers agree that an increase in the temperature or relative humidity or both decreases the uptake of radon. However, Cohen (1) stated that the correction due to the change in relative humidity was not more than 6%. However, George (2), Ren and Lin (3), Scaripitta and Harley (4), and Ronca-Battista and Gray (5) concluded from their experimental results that relative humidities can decrease the radon uptake by as much as 50% when relative humidities changed from 20 to 100%. Ren and Lin (3) and George (2) also reported that the amount of radon adsorbed by canisters did not change significantly when temperature was changed from 17 to 27°C. On the other hand, Cohen (1) observed a change of 1.5% in adsorption capacity for each 1°F change in temperature. Pojer (6) assessed the effects of temperature and humidity, both theoretically and experimentally, on the performance of a diffusion barrier charcoal canister. The adsorption capacity for radon decreased by 30% when the temperature was increased from 13 to 35°C, and by a factor of 3 when the relative humidity was increased from 15 to 90% at 35°C.

The effects of relative humidity and temperature on the adsorption capacity of radon by charcoal have been taken into account by employing a "calibration factor" which has a dimension of $Lmin^{-1}$. This procedure has also been adopted by the United States Environmental Protection Agency for measuring radon concentration in homes. Recently, the General Accounting Office, GAO (7), found that the radon detectors recommended by the EPA can give an average concentration error ranging from 16 to 40%. The charcoal canister type detector can give an error as high as 133% with an average error of ±19%.

Although adsorption isotherm data are needed to determine radon concentrations, there does not appear to be any recent data in the open literature. Most studies were conducted from 1950 to 1960 (8-12). Also, the equilibrium data were taken on adsorbents that were specially prepared or are not commercially available at the present time. In those previous studies, the equilibrium data were obtained by using air, argon, hydrogen, nitrogen, and carbon dioxide as carrier gases at atmospheric pressure and near room temperature. The experimental data from these studies also indicated that the radon adsorption capacities were less for silica gel and molecular sieves than for activated charcoal.

Although activated carbons are used to measure radon concentration, they have not been employed in the design a radon removal unit. In the past, however, activated charcoal has been used to control radon concentrations in uranium mines (13-16). Such a radon removal method could have several advantages over present radon removal techniques (increased ventilation, sealing of cracks and and joints, and source control). For example, an adsorption process may be more energy efficient than one that employs increased ventilation, since radon can be allowed to decay in the bed and the bed would not require a great deal of energy for regeneration. A few studies have been reported that relate to the development of a commercial radon removal unit (16-19). In those studies, the effects of temperature, relative humidity, radon concentration, air flow rate, and the concentration of carbon dioxide on radon adsorption were investigated. Recently, Bocanegra and Hopke (20) investigated the adsorption of radon on several types of activated carbons in the presence of several pollutants including iso-octane, ethylene chloride, and formaldehyde. The dynamic adsorption coefficients and the number of theoretical stages also were obtained at 20 ^{o}C. No dynamic studies have been reported in the literature where either silica gel or molecular sieves were employed as adsorbents.

In the present study, the equilibrium uptake of radon by commercially available BPL activated charcoal, silica gel (grade 40), and molecular sieve-13X were measured at 298 K from dry and moist nitrogen under both dynamic and static conditions. The equilibrium data were correlated with a modified Freundlich equation. The applicability of these data to improve the radon measurement by charcoal canisters and to design a removal system are discussed.

EXPERIMENTAL SECTION

Materials: The adsorbents used in this study were BPL activated charcoal provided by Calgon Carbon Corporation, and molecular sieve 13X and silica gel (grade 40) provided by Davidson Chemical Division of the W.R. Grace & Co., Baltimore, Maryland. The properties of these adsorbents are presented in Table I. Radon gas was generated from a model Rn-1025 Pylon flow-through source by flowing dry nitrogen gas from a cylinder. The source is a sealed container, containing dry powder of ^{226}Ra with a stated activity of 22.6 kBq. The source is capable of producing a constant radon gas at 2.847 Bq/min (76.87 pCi/min). A certified gamma calibration source, model Ra-226-Sc, obtained from The Nucleus, Inc., Oak Ridge, Tennessee, was used as a reference to calibrate the NaI(TI) spectroscopy system before each run. It had a stated activity of 548 Bq (14800 pCi).

PROCEDURES:

Equilibrium Adsorption: The equilibrium adsorption studies were carried out using an all glass apparatus. A schematic diagram of the system is shown in Figure 1. The sample holding tube was a 0.5 m x 48 mm diameter glass tube that was made with a flat bottom to match the geometry of the gamma calibration source. A copper circulation coil wrapped around the sample holding tube was used to control the adsorption temperature within ± 0.1 K of the desired value by circulating water through the coil. The bottom of the tube was positioned to provide direct contact with a lead-shielded 50 mm x 50 mm NaI(TI) detector, which was coupled to a multichannel pulse height analyzer with associated electronics. Radon gas was continuously flushed into a 2.8-liter glass chamber by flowing dry nitrogen from a cylinder through the source at a constant flow rate. The flow rate was monitored by a flow meter. The radon-laden nitrogen was vented through a fume hood equipped with filters. The method of calibration prior to each run and radioactivity calculation was described in our previous paper (21). Adsorbent samples were spread uniformly on the bottom of the sample holding tube, which has the same geometry as the gamma calibration source. By trial and error, it was found that 5 g of the sample is sufficient to achieve statistically significant counts from the NaI(TI) detector. The 5 g of the sample was generally stacked in a 2-3 layers at the bottom of the sample tube. It was noticed that when larger amounts of the sample were used, radon was adsorbed on the top layer of the adsorbent and the gamma activity decreased significantly before being detected by the NaI(TI) detector; a longer time was required before any significant count was obtained from the detector. When amounts smaller than 5 g of the sample were used, however, the counts from the detector were insignificant relative to the background level, even after adsorption was continued for 40 hours.

The sample was regenerated by heating it under vacuum at a temperature of 573 ± 0.1 K for 12 hours. After regeneration, the sample was cooled to the desired adsorption temperature, and a background count obtained from the Lucas cell was recorded. The sample holding tube was then placed directly on the top of the NaI(TI) detector and radon-laden nitrogen was introduced into the system in small pressure increments of approximately 50 mmHg. After each increment, 3.5 hours were allowed for radon and its daughters on the adsorbent to reach radioactive equilibrium; It should be noted that this equilibrium is different from the adsorption equilibrium, which was established between radon in the gas and solid phases in approximately 15 minutes. This was explained earlier (21). Once radioactive equilibrium was reached, the gas phase and solid phase counts were obtained simultaneously at ten minute intervals. Subsequent data points were obtained by admitting more radon-laden nitrogen into the system and following the same procedure.

The isotherm data of radon and water vapor co-adsorption were obtained by initially equilibrating the adsorbent with water vapor up to the desired relative humidities i.e., 40%, 60%, 80%. The radon-laden dry nitrogen was then introduced into the system in small pressure increments of approximately 50 mmHg, and radon and its daughters were allowed to equilibrate in the usual manner. The dry radon-laden nitrogen stream from the radon source was bubbled through water in two saturators in series. The saturators were immersed in a constant temperature bath whose temperature was controlled within ± 0.1 K to maintain the desired relative humidity of the gas stream. The gas stream could be admitted into either a 2.8-liter glass chamber, so that humid radon in nitrogen can be introduced into the system in small pressure increments, or directly passed through the packed bed during the dynamic study.

Dynamic Adsorption: The adsorption column was packed with approximately 50 grams of adsorbent sample. A bed diameter to particle ratio of 17.5 was maintained in the bed to avoid channeling and wall effects. A superficial gas velocity of 0.198 $Lmin^{-1}$ was maintained in the bed during experimental runs. The concentration of radon in the inlet nitrogen stream was maintained at 220 ± 20 pCi/L throughout the experiments. The bed was regenerated by flowing dry nitrogen at 473± 0.1 K for 10 hours. After regeneration, the adsorbent bed was cooled to the desired adsorption temperature, and a background measurement was obtained using the Lucas flow-through cell. The nitrogen was directed to the source, which was flushed for one hour at a constant flow rate. The dry or moist radon-laden nitrogen was then passed from the top of the column, and the radon activity at the column exit was measured by the Lucas cell along with the AB-5 radiation monitor at five minute intervals. The radon was allowed to flow into the column until the breakthrough was complete and the counts of the effluent reached a maximum constant value, equal to that of the inlet gas stream.

RESULTS AND DISCUSSION

Equilibrium Isotherm Data: The equilibrium data of pure water vapor were first obtained on BPL activated charcoal, silica gel, and molecular sieve 13X at 298 K. As can be seen from Figure 2, the shapes of the isotherms are different for different adsorbents. The isotherms are Type I on silica gel, Type II on molecular sieve-13X, and Type V on activated charcoal, which suggest different adsorption mechanisms. Small amounts of water vapor were adsorbed on charcoal for relative humidities below 40%, followed by a sharp rise in the uptake at relative humidities from 40 % to 60%. This is mainly due to the pore filling of the capillaries.

The experimental data for radon adsorption on BPL activated charcoal, silica gel (grade 40), and molecular sieve 13X at 298 K are shown in Figure 3. The error in the count rate of the gas phase was determined at the one sigma significance level and it ranged from 4.79 % to 11.92 %. The minimum detectable activity due to background count was found to be 21.2 counts per minute at the three sigma significance level. Adsorption measurements were repeated for each run to check the reproducibility of the data. Although radon adsorption is a random process, the experimental data were reproducible, with an average error of less than 5%, as indicated in Figure 3. The uptake of radon by activated charcoal was considerably higher than that of silica gel and molecular sieve 13X. However, molecular sieve 13X exhibited a higher affinity for radon than was found for Type 5A (10). This may be due to the larger pore diameter of Type 13X. The silica gel exhibited a relatively low radon adsorption capacity. The equilibrium data exhibited a Type III isotherm. Once an atom or a molecule is adsorbed, adsorbate-adsorbate interactions promote the adsorption of further atoms or molecules so that the isotherm becomes convex to the pressure axis. The Type III isotherms were also obtained by Przytycka (11), Brutt and Kurbatov (12), and Coleman et al. (10).

The equilibrium data of radon on BPL activated charcoal, pre-adsorbed with water vapor at 40%, 60%, and 80% relative humidities are compared in Figure 4 with that obtained for dry nitrogen. The isotherms were also of Type III in the presence of water vapor. However, the amount of radon adsorbed on a pre-equilibrated activated charcoal was lower than that adsorbed on a dry charcoal. It may be noted that when radon-laden nitrogen was introduced into the system a small amount of water vapor was desorbed from the charcoal. In a separate run, radon-free nitrogen was introduced into the system under similar conditions and the same results were observed, suggesting that probably some other impurities in nitrogen is displacing water vapor from the charcoal surface. The interaction between radon and charcoal is not strong enough to displace the preadsorbed water vapor. Thomas (17) and Strong and Levins (18) made the same conclusion from their dynamic adsorption studies; however, the results contradicted other investigators' conclusions (6,2).

Dynamic Adsorption Data: Breakthrough curves for radon on BPL activated charcoal, silica gel (grade 40), and molecular sieve 13X are shown in Figure 5. The bed lengths for activated charcoal, silica gel, and molecular sieve were 10.16, 11.43, and 13.97 cm, respectively. The superficial velocity for nitrogen gas through the adsorbent bed was 0.198 cm/min, and the pressure drop across the bed varied from 10 to 15 mmHg. The flow rate of nitrogen through the radon source was maintained approximately constant at 0.35 $Lmin^{-1}$. This flow rate produces an inlet radon concentration of about 220 pCi/L (radon partial pressure of 1.2×10^{-12} mmHg) with minor fluctuations of ± 20 pCi/L for all experimental runs. It was noted that the various solid adsorbents exhibit different steady state outlet concentrations for the same inlet radon concentration. According to Madey (22), the steady state concentration of radioactive gas at the outlet of a column of length L is related to the inlet concentration through the expression

$$C_{outlet} = C_{inlet} \exp(-\gamma L) \qquad (1)$$

where γ is the decay constant for the radioactive gas. The breakthrough curves for radon from the radon-water vapor mixture on BPL activated charcoal were measured at different relative humidities. The results are shown in Figure 6. The steady state radon concentration at the column outlet was found experimentally to be more than the inlet concentration. This may be due to increased radon plate out on the inside of the Lucas cell. A similar observation was reported earlier by Boncanegra and Hopke (20), who found that the presence of water vapor causes neutralization of ^{218}Po ions and results in their deposition in the detector. The adsorption of radon on BPL activated charcoal from humid nitrogen is considerably less than that from a dry nitrogen stream. The presence of water vapor in the nitrogen stream reduced the uptake capacities for radon due to the strong competition by water vapor molecules for the available sites. However, it is interesting to note that radon broke through the bed approximately at the same time irrespective of the relative humidities of the nitrogen stream. Water vapor molecules, having a stronger affinity for activated charcoal than radon, might be adsorbed near the inlet section of the bed at a faster rate. As adsorbed water front progresses through the bed it is displacing radon, resulting in a faster radon breakthrough from the bed. As shown in Figure 7, repeated experiments for radon adsorption from dry and moist nitrogen on the activated charcoal verified the reproducibility of the results.

Equilibrium Data Correlation: The Freundlich equation has been modified to correlate the equilibrium adsorption data of radon from dry nitrogen. The modified equation can be written as

$$q = k_1 \left(\frac{P}{P_o}\right)^n \qquad (2)$$

or

$$\ln q = \ln k_1 + n \ln\left(\frac{P}{P_o}\right) \qquad (3)$$

where q is the amount of gas adsorbed, P is the system pressure, P_o is a reference pressure and is arbitrarily set to 10^{-14} mmHg. Here, k_1 is a measure of the volume of gas adsorbed per unit mass of adsorbent and n is the intensity of adsorption. Figure 8 shows good agreement between the experimental data and the predicted values. The value of n was set to 1.75 and k_1 has the following temperature dependence:

$$k_1 = 2.10\times10^{-11} - 6.58\times10^{-14}\ T \qquad (4)$$

Thus, the amount of radon adsorbed on BPL activated charcoal corresponding to the gas phase concentration can be expressed as

$$q = (2.10\times10^{-11} - 6.58\times10^{-14}\ T)\left(\frac{P}{1\times10^{-14}}\right)^{1.75} \qquad (5)$$

Knowing the solid phase concentration, the gas phase concentration can be obtained in pCi/L from the equation

$$C = \frac{5.48\times10^{3}\ q^{0.571}\ T^{-1}}{(2.10\times10^{-11} - 6.58\times10^{-14}\ T)^{0.571}} \qquad (6)$$

The equilibrium isotherms of radon, such as the ones shown above, can be used for measuring radon concentrations in homes provided accurate isotherm data are available for the activated charcoal. From the knowledge of the solid phase radon concentration, the equilibrium isotherms corresponding to the particular field conditions, temperature and humidity, can be used to determine the concentration of radon in the gas phase.

Another application for the dynamic and static adsorption data is in the design of an adsorber unit for removing radon from indoor air. The design of such a unit may range from a single packed column to a complex system of multiple columns.

Acknowledgements: This work was supported by the Gas Research Institute, Chicago, IL. and ASHRAE, Atlanta, GA. under contract No. 5089-246-1821, and a grant from the Weldon Spring Funds. The authors gratefully acknowledge Calgon Carbon Corporation for providing the activated carbon samples, Davidson Chemical Division of W. R. Grace & Co., Baltimore, Maryland for providing the molecular sieve and silica gel samples, and Porous Materials, Inc., Ithaca, New York for carrying out the pore size analyses of the adsorbents.

REFERENCES

1. Cohen, B. L., and Nason, R., "A Diffusion Barrier Charcoal Adsorption Collector for Measuring Rn Concentrations in Indoor Air,", Health Physics; 50(4), pp. 457-463 (1986a).
2. George, A. C., "Passive, Integrated Measurement of Indoor Radon Using Activated Carbon", Health Physics; 46(4), p. 867 (1984).
3. Ren, T. and Lin, L., "A Passive Integrating Indoor Radon Detector with Activated Carbon," Radiat. Prod. Dosim. 19, 121 (1987).
4. Scarpitta, S. C., and Harley, N. H., (New York University Medical Center), "Adsorption and Desorption of Noble Gases on Activated Charcoal II: Radon Studies in a Monolayer and Packed Bed.", (Prepared for: U.S. Department of Energy) 1989.
5. Ronca-Battista, M.; Gray, D., "The Influence of Changing Exposure Conditions on Measurements of Radon Concentrations with the Charcoal Adsorption Technique", Technical Exchange Meeting on Passive Radon Monitoring; Grand Junction, Colorado (Sept. 21-22, 1987).
6. Pojer, P. M., Peggie, J. R., O'Brien, R.S., Solomon, S. B. and Wise, K. N., "Performance of a Diffusion Barrier Charcoal Adsorption ^{222}Rn Monitor Under Conditions of Varying Humidity and Temperature," Health Phys. 58(1), 13 (1990).
7. GAO, United States General Accounting Office, Report GAO/RCED-90-25 Radon Testing (1989).
8. Gubeli, V. O., and Stammbach, K., "Zur Adsorption von Radon an Aktivkohle und Silicagel", Helvetica Chimica Acta; 34(154), pp. 1257-1263 (1951).
9. Gubeli, V. O., and Stori, M., "Zur Mischadsorption von Radon an Aktivkohle mit verschiedenen Tragergasen", Helvetica Chimica Acta.; 37(260), pp. 2224-2231 (1954).
10. Coleman, R. D.; Kuznetz, H. L.; Woolrich, P. F., and Holaday, A. D., "Radon and Radon Daughter Hazards in Maine Atmosphere", American Industrial Hygiene Association Quarterly; 17 (1957).
11. Przytycka, R., "Sorption of Radon on Activated Polish Charcoals", Nukleonika; 6(1), pp. 23-32 (1961).
12. Burtt, B. P., and Kurbatov, J. D., "Mixed Adsorption of Radon and Argon on Silica Gel", Journal of American Chemical Society; 70, pp. 2278-2282 (1948).
13. Ackley, R. D., (Oak Ridge National Laboratory), "Removal of Radon-220 from HTGR Fuel Reprocessing and Refabrication Off-Gas Streams by Adsorption (Based on A

Literature Survey)", Report No. ORNL-TM-4883, (Prepared for: Chemical Technology Division (ERDA)) (1975).

14. Fusamura, N.; Kurosawa, R., and Ono, S., "On the Study of Radon Removal with Active Carbon", Nippon Kogyo Kaishi (Jap); 79, pp. 590-597 (1963).

15. Lucas, H. F., (Argonne National Laboratory), "The Low-Level Gamma Counting Room: Radon Removal and Control", Report No. ANL-7360, (Prepared for: DOE) (1963).

16. Anderson, B. V., and Palmer, R. F., (Battelle, Pacific Northwest Laboratory), "Cleanup of Radon Inhalation Study Effluents", Report No. BNWL-SA-5541, (Prepared for: U.S. Energy Research and Development Administration) (1975).

17. Thomas, J. W., "Evaluation of Activated Carbon Canisters for Radon Protection in Uranium Mines", Report No. HASL-280 (1974).

18. Strong, K. P.; Levins, D. M., "Dynamic Adsorption of Radon on Activated Carbon", 15th DOE Nuclear Air Cleaning Conference; p.Conf-780819 (1978).

19. Scheibel, H. G.; Porstendorfer, J., and Wicke, A., "Radon Adsorption in a Gas Flow by Activated Charcoal", Health Physics; 38, pp. 83-85 (1980).

20. Boncanegra, R., and Hopke, P. K., "Radon Adsorption on Activated Carbon and the Effects of Some Airborne Contaminants", The Science of the Total Environment; 76, pp. 193-202 (1988).

21. Hassan, N.M., Ghosh, T. K., Hines, A. L., Loyalka, S. K., and Ketring, A., " New Experimental Apparatus for Measuring Radon Adsorption on Solid Adsorbent", Submitted for Publication to Ind.& Eng. Chem. Res, Nov. 1990.

22. Madey, R., Barker, J. J., Beebe, M. R., and Stephenson, T. E., "Adsorption of Krypton-85m on activated carbon", Trans. Am. Nucl. Soc., 3(2), pp. 373 (1960).

NOMENCLATURE

k_1	first empirical constant in the modified Freundlich equation
n	constant in the modified Freundlich equation
P	equilibrium partial pressure of radon (mmHg)
P_0	reference pressure (mmHg)
q	volume of radon adsorbed per unit weight (cm^3 Rn/g adsorbent)
R	gas constant
T	temperature (K)

LIST OF TABLES

LIST OF FIGURES

Table I. Properties of Microporous Solid Adsorbents.

Property	BPL Activated Charcoal	Silica Gel (Grade 40)	Molecular Sieve 13X
Particle size, (Å)[b]	6 x 16 mesh	6 x 12 mesh	8 x 12 mesh
Surface area, S (m^2/g)[a]			
micropores	823	663	294
meso and macropores	50	9	101
total	874	672	395
Pore volume, V (cm^3/g)[a]			
micropores	0.47	0.38	0.14
meso and macropores	0.10	0.02	0.27
total	0.57	0.40	0.41
Average pore diameter, 4V/S (Å)[a]	26	24	41.7[c]
Bulk density (g/cm^3)[b]	0.60	0.72	0.72
Equilibrium water capacity (% wt.)[b]	-	-	29.5
Moisture content as shipped (% wt.)[b]	<1	-	< 1.5

[a] Analysis made by Porous Materials, Inc. Ithaca, New York.

[b] Analysis provided by the manufacturer.

[c] based on total surface area and pore volume.

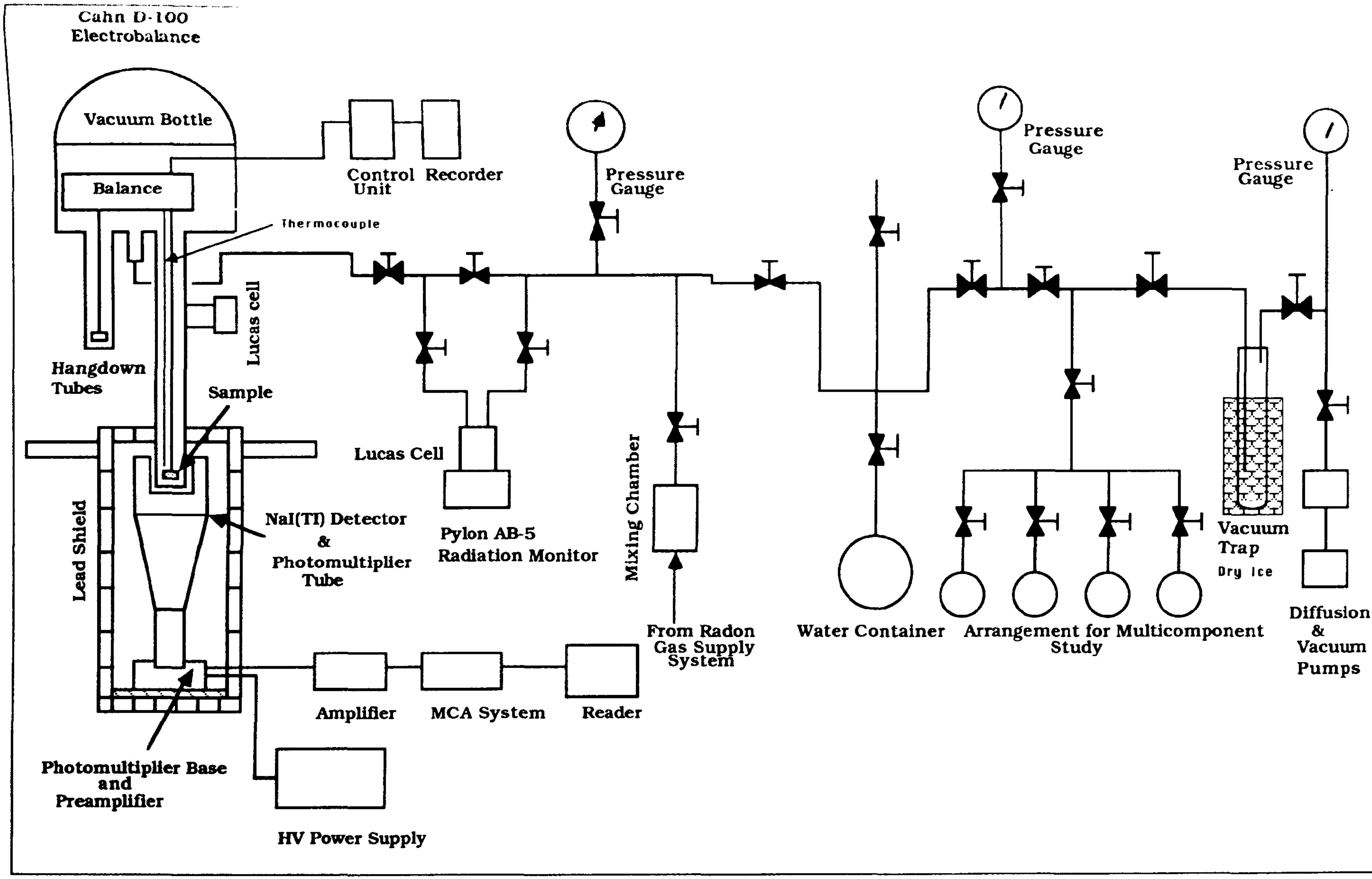


Figure 1. Schematic Flow Diagram of Radon Adsorption Apparatus

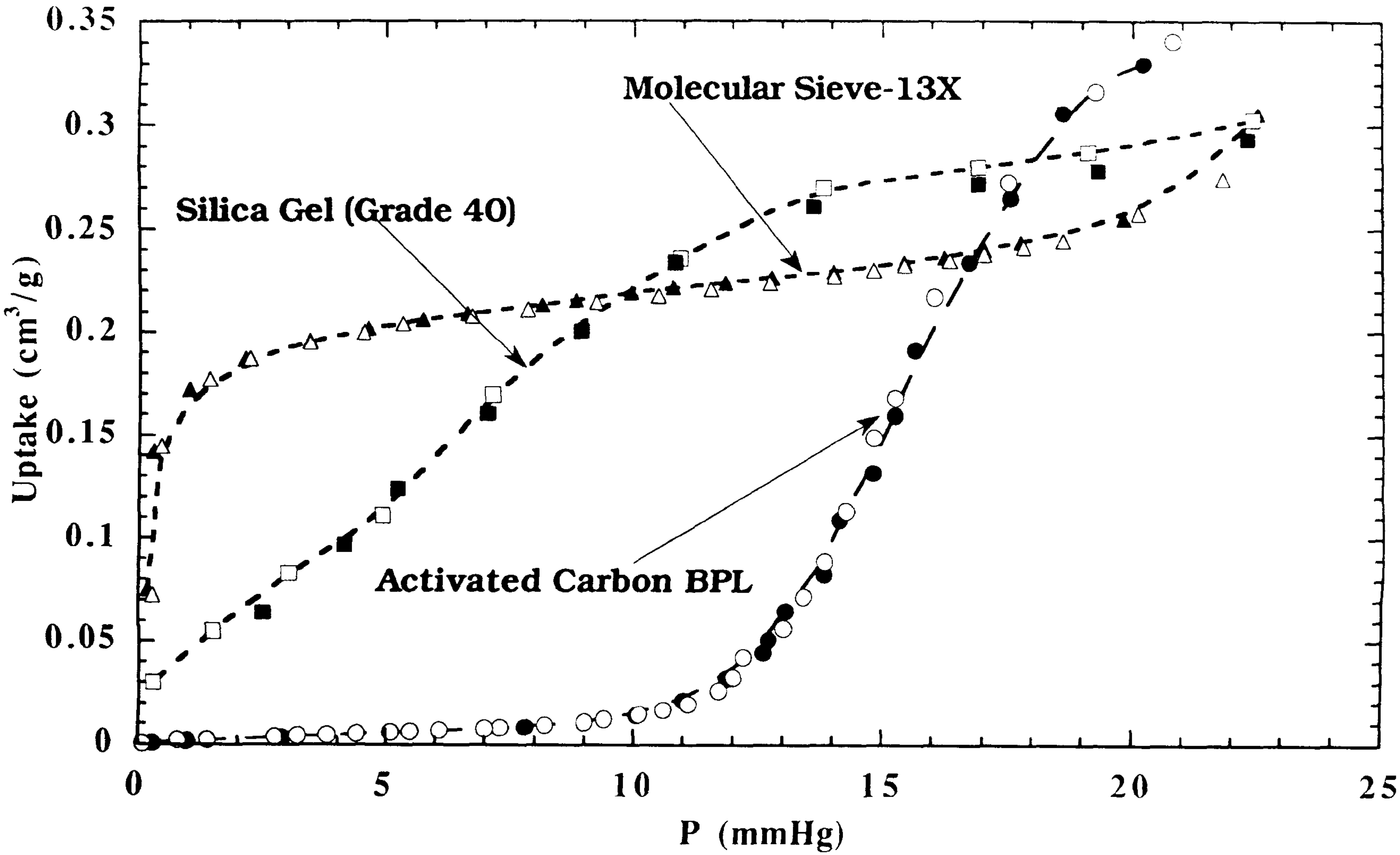


Figure 2. Adsorption isotherms of water vapor on various solid adsorbents at 298 K.

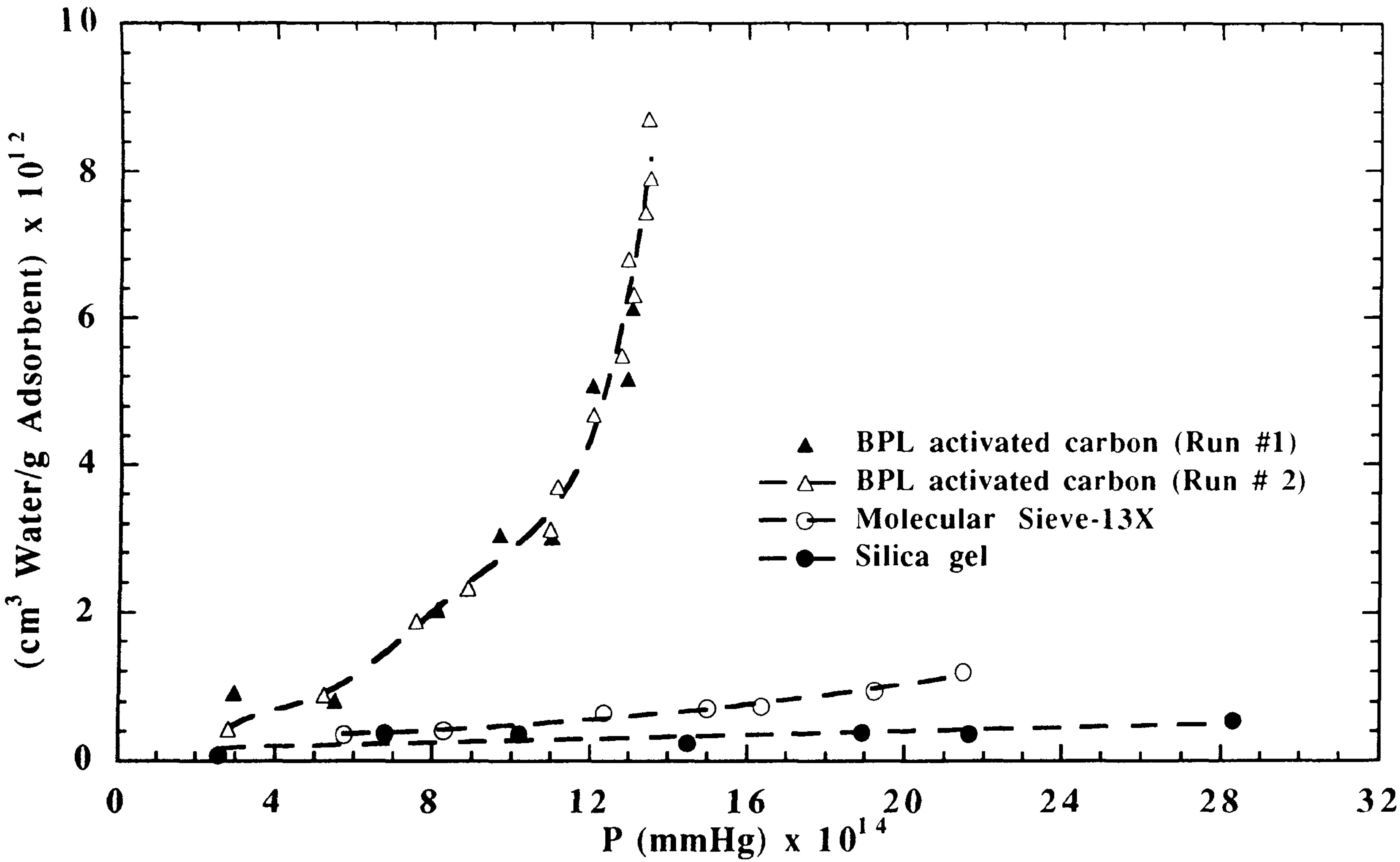


Figure 3. Adsorption isotherm data for radon on various solid adsorbents at 298 K.

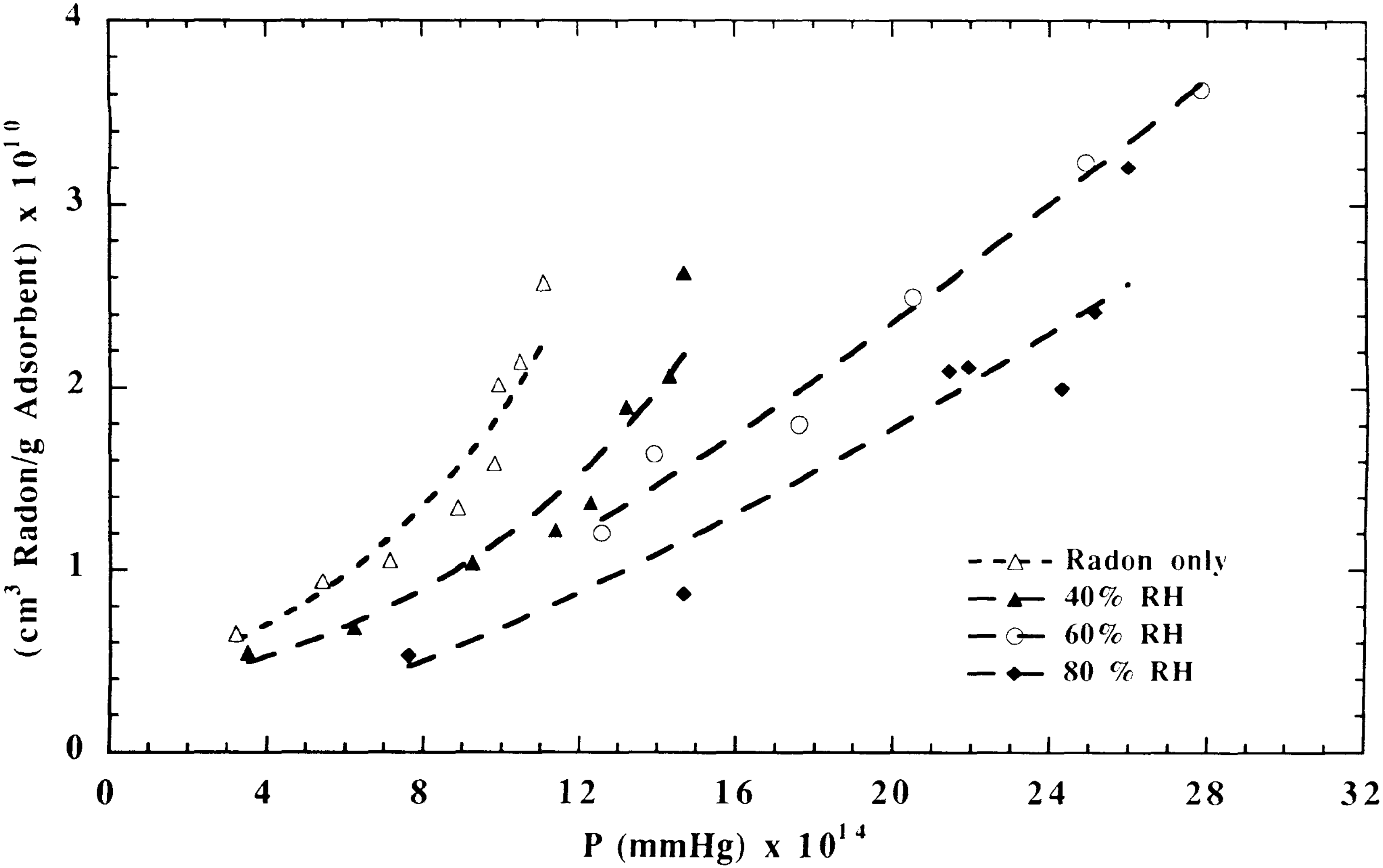


Figure 4. Radon and water vapor co-adsorption data on BPL activated carbon at 298 K.

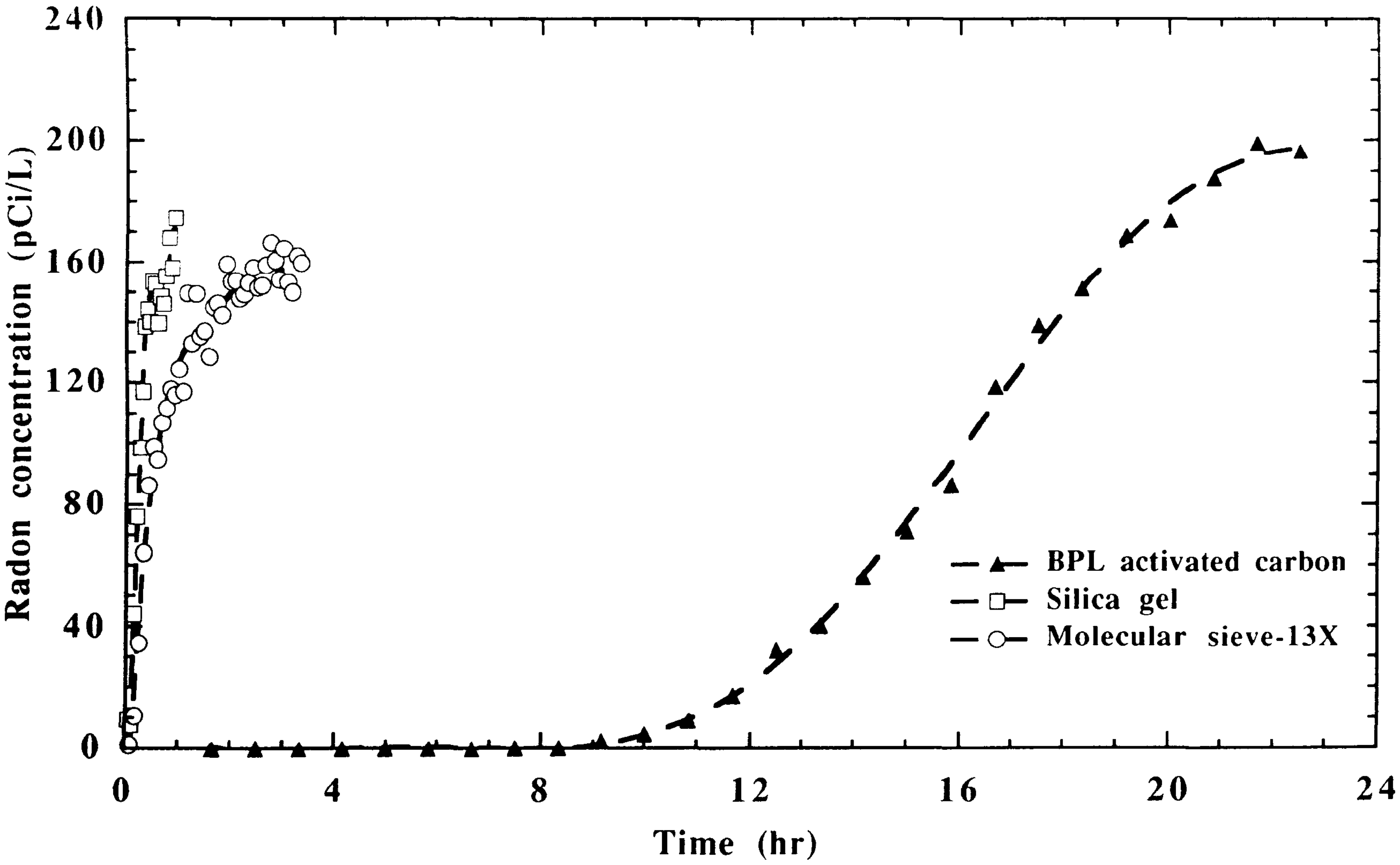


Figure 5. Experimental breakthrough curves for radon on solid adsorbents at 298 K.

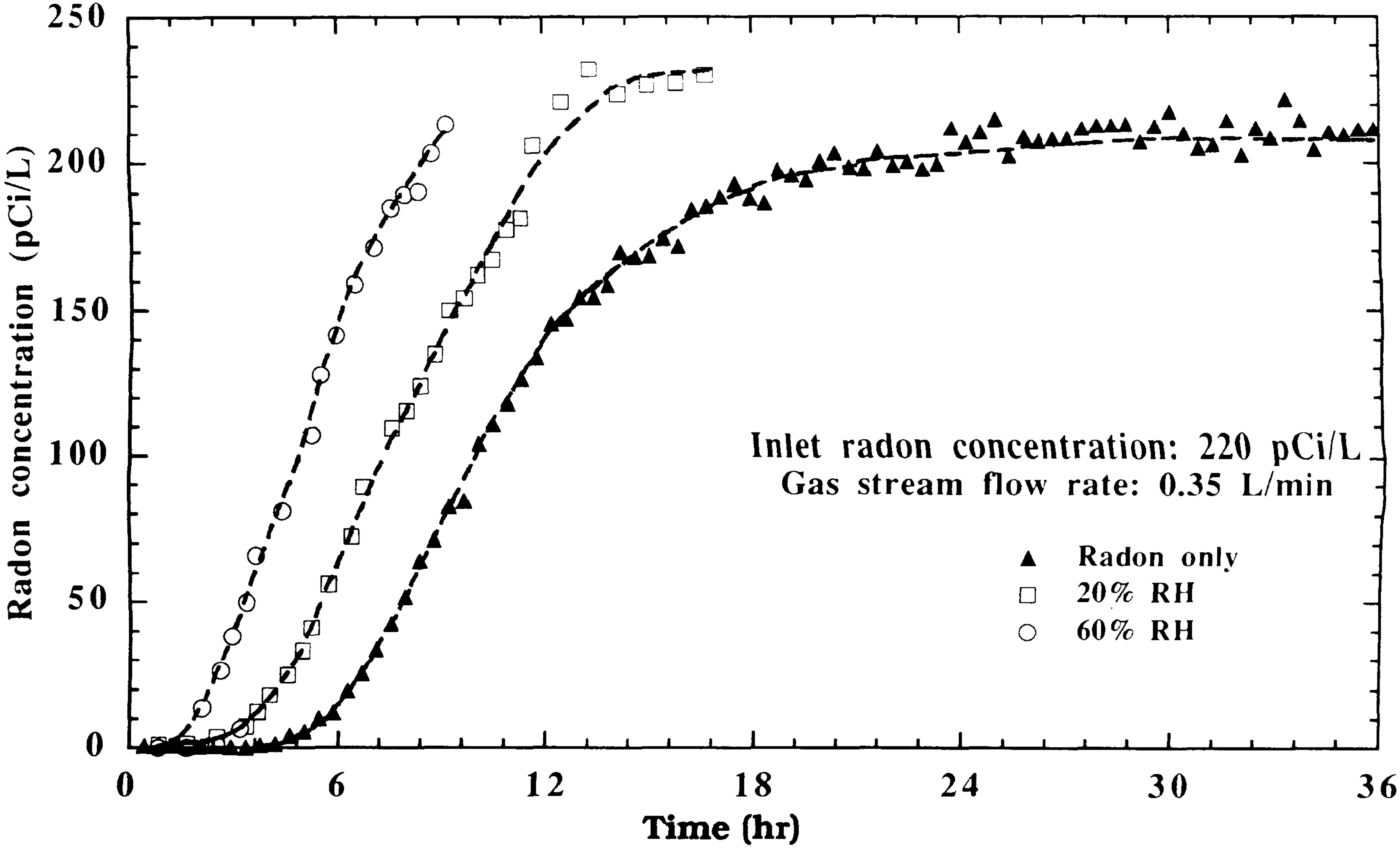


Figure 6. Breakthrough curves for radon from moist nitrogen stream on BPL activated carbon at 298 K.

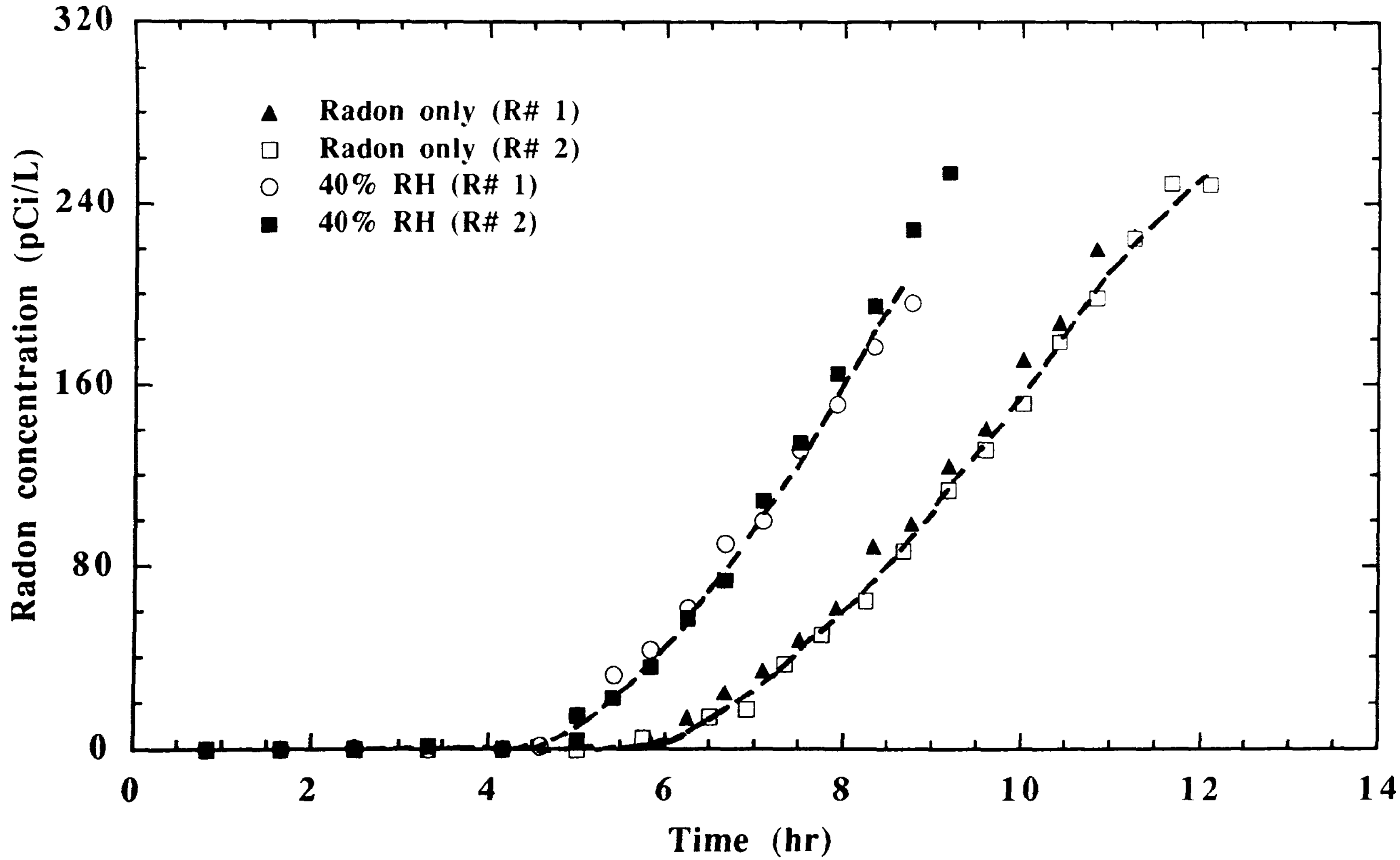


Figure 7. Reproducibility of radon breakthrough curves on BPL activated carbon 298 K.

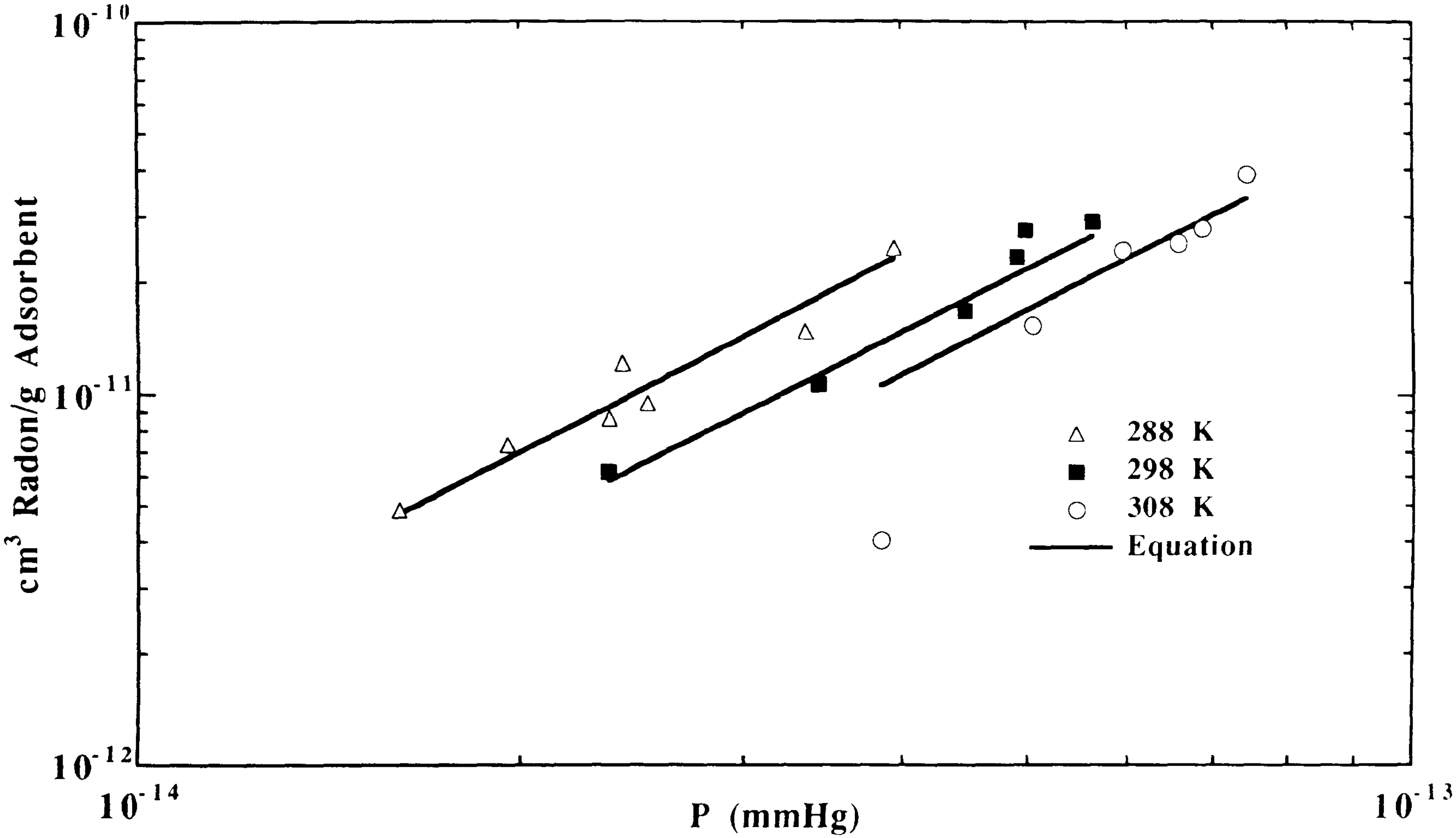


Figure 8. Correlation of radon adsorprion data with the modified Freundlich equation.

CALIBRATION OF MODIFIED ELECTRET ION CHAMBER FOR PASSIVE MEASUREMENT OF RADON-220 (THORON) IN AIR

by: P. Kotrappa, Ph.D., and J. C. Dempsey
Rad Elec, Inc.
5310 H Spectrum Drive
Frederick, MD 21701 USA

ABSTRACT

A commercially available electret ion chamber known as the E-PERM^{R*} (Electret-Passive Environmental Radon Monitor) is now widely used for both indoor and outdoor radon-222 (radon) measurements. This unit was designed to minimize the response to radon-220 (thoron) by restricting the diffusion entry time. The chamber of such a unit was modified by increasing the filtered diffusion area from 0.3 cm2 to 30 cm2 to allow thoron to enter the chamber in and out with very little delay time. Such an E-PERM is termed a Radon-Thoron E-PERM or RT E-PERM since it responds to both radon and thoron. A steady state thoron concentration was generated in a room using a Pylon thoron source, a pump and a large fan. Several R E-PERMs (radon) and RT E-PERMs were positioned at a location from where a 24-hour sample was also drawn by a large double filter unit (18 liters) for measuring the average thoron concentration at that location. This paper describes the calibration procedures and the use of an E-PERM and RT E-PERM side by side to obtain both radon and thoron concentrations in a location. The units have sufficient sensitivity to measure 1 pCi/L of thoron in five days. Such units are useful in thorium rich areas or thoron refineries or in some special cases where thoron can either be a problem or an interference.

---

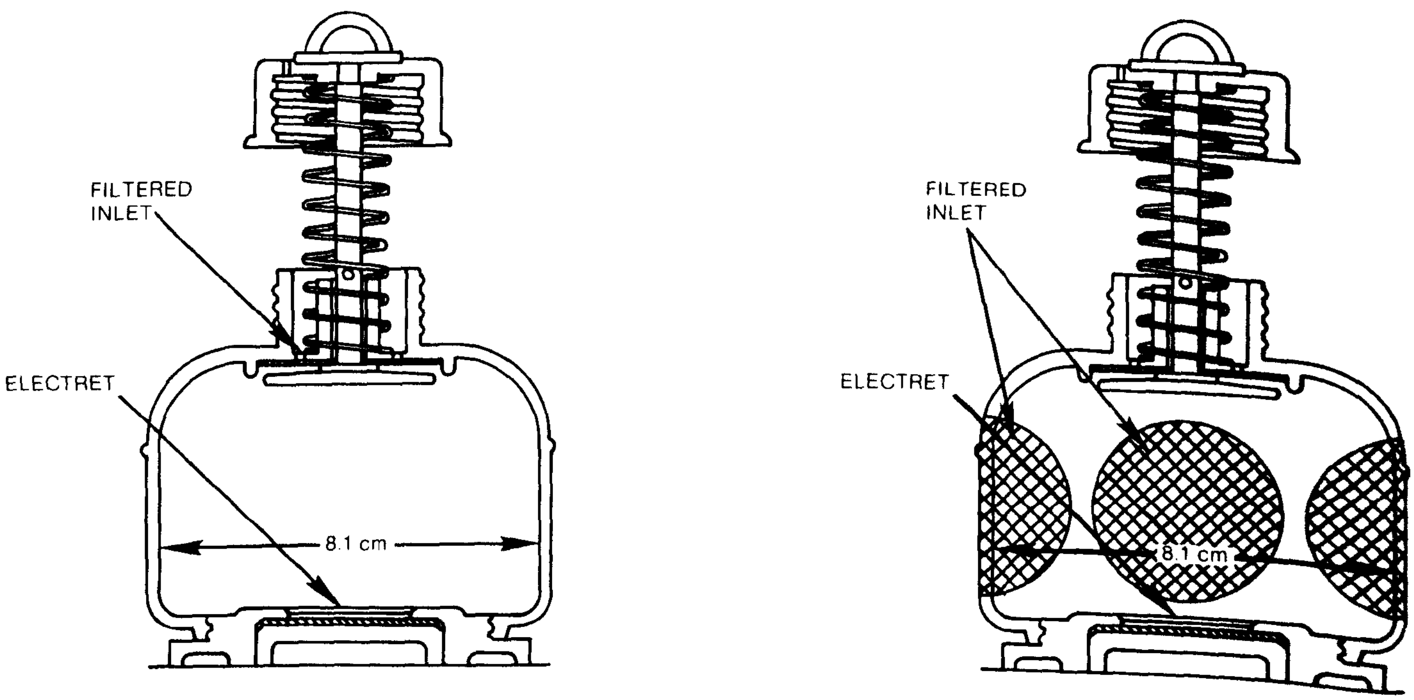
*E-PERM^{R} is the registered trademark of the product patented and manufactured by Rad Elec Inc., Frederick, MD 21701 USA.

INTRODUCTION

A commercially available electret ion chamber known as an E-PERM (Electret-Passive Environmental Radon Monitor) is now widely used for both indoor and outdoor radon-222 (radon) measurements. This unit was designed to minimize the response to radon-220 (thoron) by restricting the diffusion entry time. These units are fully described in literature (1, 2). To increase the response of these devices to thoron, it is possible to modify the unit by increasing the area of the filtered inlets so that thoron can get in and out more readily. Such a modified unit is a Radon-Thoron E-PERM or RT E-PERM since it responds both to radon and thoron. The purpose of the present work was to calibrate the units and describe a procedure for making a measurement of thoron in air. The principle and the analysis procedure is somewhat similar to those made by Pearson (3) for alpha track detectors.

DESCRIPTION OF RADON AND RADON-THORON E-PERMS

Figure 1 gives a schematic view of the two units. The left half of Figure 1 shows the standard E-PERM. This has a small filtered inlet area (0.3 cm2) to restrict the entry of thoron. The right side of Figure 1 shows the modified unit.



"S" Chamber Schematic (210 mL)

RADON E-PERM®

"S" Chamber Schematic (210 mL)

RADON-THORON E-PERM®

Figure 1

A series of holes were drilled in the body of the chamber, and the holes were subsequently closed using an electrically conducting filter paper. The area of the opening was about 30 cm2. In both the units, the electret can be covered or uncovered bringing the unit to the "off" or "on" position, respectively (1, 2). Standard short-term electrets are used in these devices (1, 2).

CALIBRATION

To calibrate these devices for thoron, it was necessary to produce a steady state thoron concentration in the room air. An upper floor closed room with a dimension of about 12 x 12 x 8 feet was chosen for generating a steady state of thoron. This room was known to have a radon concentration of less than 0.5 pCi/L. A Pylon^{R}** Model TH-1025 flow-through thoron gas source was used as a source of thoron. An air flow rate of 5 liters per minute was established through the source using an appropriate pump and a flowmeter. The outlet of the source was taken through a polyethylene tube and was positioned at the center of a large fan to disperse the thoron into the room air. The system was run for at least one day to achieve a steady state thoron concentration.

A small table was located at a distance of about 7 feet from the fan in the direction of the air flow. This location was chosen as a reference location for measurement of thoron.

An air sample was drawn from the center of the table through a large (18 liter volume) double filter unit (4, 5) for 24 hours. The second filter paper of the double filter unit was counted for alpha activity in a standard alpha scintillation counting unit after a delay of 12 hours. Standard procedure was used for analyzing the results. Table 1. gives the thoron concentration in air over a period of eight days from the 24-hour samples collected each day.

A set of three R E-PERMs and set of three RT E-PERMs were also located on the same test table for the entire period of eight days. The electrets were read at the end of each day and reloaded back into the units for the next run. Table 1. gives successive electret readings taken at the end of each day.

The calibration factor is obtained (Table 1.) by dividing the net average electret voltage drop per day by the average thoron concentration over the experimental period.

**Pylon^{R} is a registered trademark of Pylon Electronic Development Company, Canada and USA.

TABLE 1. CALIBRATION OF R AND RT E-PERMS FOR THORON. SECOND ROW GIVES THE AVERAGE THORON CONCENTRATION ON THAT DAY. R-1 to R-3 GIVE SUCCESSIVE ELECTRET VOLTAGE READINGS OF R-EPERMS. RT-1 TO RT-3 GIVE SUCCESSIVE ELECTRET VOLTAGE READINGS OF RT E-PERMS

Time (Days)	0	1	2	3	4	5	6	7	8
Thoron (pCi/L)	-	26.6	24.4	23.0	24.8	24.5	23.5	25.2	26.0
R-1 (volts)	515	507	501	491	479	471	463	453	447
R-2 (volts)	518	512	504	492	482	472	464	456	448
R-3 (volts)	550	542	534	524	514	502	494	488	480
RT-1 (volts)	702	660	611	560	507	452	398	355	308
RT-2 (volts)	701	659	606	552	494	435	376	330	280
RT-3 (volts)	438	384	331	283	237	196	155	113	-

AVERAGE DAILY THORON CONCENTRATION	=	24.8 pCi/L
AVERAGE VOLT DROP PER DAY FOR R E-PERM	=	8.7 volts
NET*	=	7.0 volts
AVERAGE VOLT DROP PER DAY FOR RT E-PERM	=	49.6 volts
NET*	=	47.9 volts
AVERAGE CALIBRATION FACTOR FOR R E-PERM	=	0.2823 **
AVERAGE CALIBRATION FACTOR FOR RT E-PERM	=	1.9314 **

* Subtracting contribution from gamma background of 10 uR/h

**Calibration factors are in units of volts per pCi/L-day

RESULTS

Table 1. gives the results. It can be seen that thoron concentration did not vary from day to day in any significant way justifying taking the average thoron concentration over the entire period as nearly constant. The voltage drop per day also remained nearly the same. The E-PERMs are recommended to be used with electrets in the voltage range of 200 to 700 volts (1, 2). The data indicated that the calibration factor did not change significantly with the operating voltage over the voltage ranges studied. More sophisticated and accurate work may indicate a marginal dependence of the calibration factor with the operating voltage as is found with E-PERMs for radon (1, 2). It is not expected to be more than 6% to 8%.

DERIVATION OF AN EQUATION FOR CALCULATING THORON CONCENTRATION FROM THE SIMULTANEOUS DATA OBTAINED WITH R AND RT E-PERMS

Let the radon concentration be R pCi/L.
Let the thoron concentration be T pCi/L.
Let the gamma radiation background be 10 uR/h.
Let both detectors be exposed to D days at the same location, and let the voltage drops be V1 and V2 volts, respectively.

Detector #1 (known as the Radon E-PERM) and #2 (known as the Radon-Thoron E-PERM) have the same responses for radon and gamma radiation but different responses for thoron because of modifications done to detector #2.

Let the calibration factor for radon be C(R) volts per pCi/L-day.
Let the gamma response be G volts per 10 uR/h -day.
Let the calibration factor for thoron for detector #1 be C(T1) volts per pCi/L-day.
Let the calibration factor for thoron for detector #2 be C(T2) volts per pCi/L-day.

Then V1 and V2 are given by equation (1) and (2).

$$V1 = C(R) \times D \times R + C(T1) \times D \times T + G \times D \quad \text{--- (1)}$$

$$V2 = C(R) \times D \times R + C(T2) \times D \times T + G \times D \quad \text{--- (2)}$$

Solving equation (1) and (2) for T leads to:

$$T = (V1 - V2) / (D \times (C(T1) - C(T2))) \quad \text{--- (3)}$$

Example: Data on R-1 and RT-1; V1 = 394 volts; V2 = 68 volts; D = 8 days;

$$T = (394 - 68) / (8 \times (1.9314 - 0.2823)) = 24.5 \text{ pCi/L}$$

RECOMMENDED PROCEDURE

Colocate a R and a RT E-PERM at the location where the thoron concentration has to be measured. Leave them for 2 to 7 days. Use the data for analyzing the thoron as illustrated in the earlier section. Data on the R E-PERM can be used for calculating the radon concentration using the standard procedure (1, 2). If one wishes to measure cumulative thoron concentrations which are relatively higher (more than 250 pCi/l-days), a long-term electret (1, 2) can be used. Long-term electrets have calibration factors which are approximately lower by a factor of 10.5 .

DISCUSSIONS

Work described by Pearson (3) indicated that a simultaneous use of two alpha track detectors (one sensitive to thoron and the other not sensitive to thoron) as a method of determining the thoron concentration in air. The calibration was done (3) at very high concentrations (1,000 to 20,000 pCi/L-days) compared to the concentrations used in the current work (25 to 200 pCi/L-days) mainly because of the sensitivity limitations of alpha track technology. The E-PERM technique appears to give a practical method of measuring thoron concentrations usually found in homes with an acceptable accuracy and in relatively short time intervals.

GENERAL

The work described in this paper was not funded by the U.S. Environmental Protection Agency, and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

ACKNOWLEDGEMENTS

The authors are grateful to Mr. Carl Granlund of the Department of Environmental Resources in Harrisburg, PA, for loaning the thoron source and the alpha counting unit. The authors are also grateful to Leena Kotrappa for her help in experiments and in data analysis and to Lu markland for editorial assistance.

REFERENCES

1. Kotrappa, P., Dempsey, J. C., Hickey, J. R., and Stieff, L. R. An electret passive environmental Rn-222 monitor based on ionization measurement. Health Physics 54:47-56, 1988.

2. Kotrappa, P., Dempsey, J. C., Ramsey, R. W., and Stieff, L. R. A practical E-PERM[R] environmental radon monitor system for indoor radon measurement. Health Physics 58:461-467, 1990.

3. Pearson, M. D. Calibration of alpha-track monitors for measurement of thoron (Rn-220). In: The 1990 International Symposium on Radon and Radon Reduction Technology. United States Environmental Protection Agency. Atlanta, GA, 1990. Paper III-P-6.

4. Kotrappa, P., Soman, S. D., and Mayya, Y. S. Modified double filter apparatus for measuring radon/thoron in the environment and in exhaled breath. In: IAEA International Symposium on Advances in Radiation Protection Monitoring. Stockholm, 1978. Paper IAEA-SM-229-31, page-413.

5. Thomas, J. W. Thoron determination by two-filter method. USAEC Health and Safety Report. HASL-TM-71-1. 1971.

TITLE: Unit Ventilator Operation and Radon Concentrations in a Pennsylvania School

AUTHOR: William P. Brodhead, WPB Enterprises

This paper was not received in time to be included in the preprints and the abstract was not available. Please check your registration packet for a complete copy of the paper.

Session IV:

Radon Reduction Methods

CAUSES OF ELEVATED POST-MITIGATION RADON CONCENTRATIONS IN BASEMENT HOUSES HAVING EXTREMELY HIGH PRE-MITIGATION LEVELS

by: D. Bruce Henschel
Air and Energy Engineering Research Laboratory
U. S. Environmental Protection Agency
Research Triangle Park, NC 27711

Arthur G. Scott
AMERICAN ATCON, INC.
Wilmington, DE 19899

ABSTRACT

Forty basement houses in Pennsylvania which had received EPA-sponsored indoor radon mitigation systems in 1985-87 as part of an earlier project, were re-visited in 1989-90 to permit further testing. These houses had generally had very high pre-mitigation radon concentrations (commonly 50 to 600 pCi/L, or 2 to 22 kBq/m^3); a significant fraction still have residual (post-mitigation) levels greater than EPA's original guideline of 4 pCi/L (148 Bq/m^3), based upon alpha-track detector measurements. The objective of the follow-up testing was to assess why levels were still elevated, and what additional steps would be required in order for these houses to achieve both the original guideline of 4 pCi/L, and a more challenging goal of 2 pCi/L (74 Bq/m^3).

In houses having sub-slab and drain-tile depressurization systems, the primary single cause of elevated residual levels was re-entrainment of the high-radon fan exhaust; airborne radon resulting from radon in well water was an important secondary contributor in some houses. Care in design of the system exhaust, and treatment of the water, would be required to reduce these houses below 2 pCi/L. In only one house with a sub-slab system did the elevated residual levels clearly appear to be due to inadequate depressurization beneath the slab. However, in houses having block-wall depressurization systems, inadequate sub-slab depressurization appeared to be the major cause of the residual levels; exhaust re-entrainment and well-water radon also played a role in some houses with block-wall systems.

Elevated outdoor radon concentrations, and emanation of radon from poured concrete slabs and foundation walls, were not major contributors to the residual indoor concentrations, with each of these factors contributing on the order of 0.2 pCi/L (7 Bq/m^3).

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

During the period June 1985 through June 1987, developmental indoor radon reduction systems were installed and tested in a total of 40 houses in the Reading Prong region of eastern Pennsylvania (Reference 1). Most of these installations involved some form of active soil depressurization (ASD), including sub-slab depressurization (SSD), drain-tile depressurization (DTD), and block-wall depressurization (BWD). Other mitigation approaches tested in a few of the houses included active soil pressurization, heat recovery ventilators (HRVs), and radon removal from well water. All of the houses had basements, sometimes with an adjoining slab-on-grade or crawl-space wing. These houses were generally difficult to mitigate, for two primary reasons:

1) The source term was often extremely high, with soil gas concentrations as high as 50,000 pCi/L (1.8 MBq/m^3) measured in one case. As a result, pre-mitigation indoor concentrations were very high, commonly in the range of 50 to 600 pCi/L (about 2 to 22 kBq/m^3). The high source term requires careful treatment of all entry routes, and care in avoiding re-entrainment of ASD exhaust, among other considerations.

2) Communication beneath the basement slabs was sometimes poor or uneven, complicating the application of ASD systems.

The radon concentrations in the basements and living areas of these houses have been measured using alpha-track detectors (ATDs) with 3- to 4-month exposure periods, during each of the winter quarters since the mitigation systems were installed (References 1, 2, and 3). In addition, an annual ATD measurement in the living area was completed during the period December 1988-December 1989 (Reference 4). The average winter-quarter concentrations for each house, and the annual average living-area concentration, are presented in Table 1. As shown in the table, of the 38 houses still participating in the program, the average basement concentration over the past two or three winters has been above 4 pCi/L (148 Bq/m^3) in 18 of them, and above 2 pCi/L (74 Bq/m^3) in 28 of them. The average winter-time living area concentration has been above 4 pCi/L in 11 of the houses (about 30%), and above 2 pCi/L in 22 (about 60%). The annual average readings in the living area are somewhat more favorable than the winter-quarter results, with about one-quarter of the houses above 4 pCi/L and half above 2 pCi/L according to the annual measurement.

Thus, even though the percentage radon reductions were substantial in essentially all of these high-level houses, a significant number have residual (post-mitigation) radon levels greater than EPA's original guideline of 4 pCi/L. An even greater number have residual levels above 2 pCi/L, suggesting that there could be difficulty in achieving the goal of near-ambient indoor concentrations, specified in the Indoor Radon Abatement Act of 1988.

Accordingly, during the winter of 1989-90, additional testing was carried out in all of these difficult houses in order to better understand why residual radon levels were still elevated, and what additional steps would be necessary to reduce the indoor levels to near-ambient. Five possible explanations for the elevated residual levels were investigated:

1) failure of the suction fields generated by ASD systems to adequately extend beneath the slab and around the footings, thus leaving some soil gas entry routes inadequately treated;

2) re-entrainment of high-radon exhaust from the ASD systems back into the house;

3) release into the air of radon contained in well water;

4) contribution of ambient (outdoor) radon to indoor levels; and

5) emanation of radon from concrete slabs and foundation walls.

For mitigation approaches not involving ASD, another consideration is possible inherent limitations in the effectiveness of the mitigation approach.

RESULTS

Adequacy of Suction Fields Generated by ASD Systems

The first concern was that the suction fields being generated by the ASD systems might not be adequately extending beneath the slab, and might not adequately be preventing soil gas entry into block walls. In view of the extremely elevated soil gas concentrations at many of these houses, any untreated entry route could have a significant impact on indoor levels.

In each house having an ASD system, between 4 and 22 test holes were drilled through the basement slab and the slab of any adjoining wing, to permit measurements of sub-slab depressurization being created by the system. Usually, a test hole was drilled in each corner of the slab, with a series of additional holes drilled in that quadrant where the depressurization being created by the system appeared to be poorest based upon the results from the corner hole. Sub-slab pressure measurements were made with a micromanometer sensitive to ± 0.001 in. WG (± 0.2 Pa), with all test holes plugged except the one at which the measurement was being made. As a rule of thumb, it is estimated that the sub-slab depressurization at a given point should be at least 0.015 in. WG (about 4 Pa) in order to reliably prevent soil gas flow up through slab openings at that point. This value of 0.015 in. WG approximately equals the theoretical thermal stack depressurization created in the basement of a two-story house during cold weather. It is believed that a sub-slab depressurization of 0.015 in. WG will be overwhelmed only a small percentage of the time by weather effects and by homeowner activities. As an added safety margin, a depressurization of 0.04 in. WG (10 Pa), if maintained, should almost never be overwhelmed.

As a separate measurement of sub-slab communication, the sub-slab depressurizations at these test holes were also measured with the mitigation system off, with suction being generated by an industrial vacuum cleaner. Using a simple mathematical model, the results from these vacuum cleaner diagnostics were used to calculate a "Standard Suction Distance" (SD) for each slab. The SD is nominally the distance over which suction drawn through a 4-in. (10-cm) diameter SSD suction hole would fall to 1% of that being maintained under the slab immediately under the SSD pipe. One percent of the suction under the SSD pipe would typically be about 0.005 to 0.010 in. WG (about 1 to 2 Pa), of the magnitude of the 0.015 in. WG rule of thumb considered above. In general, a SD greater than 1,000 ft (about 300 m) is interpreted as very good communication, suggesting that one SSD suction pipe should easily treat the entire slab. A SD less than 10 ft (3 m) is interpreted as poor communication, indicating the need for multiple SSD pipes.

The results of these measurements are summarized in Table 2 for those houses having ASD systems. As shown, almost all houses having SSD systems have sub-slab depressurizations at all test holes greater than 0.015 in. WG, sometimes by an order of magnitude. In many of the SSD houses, most or all of the sub-slab readings are above the more conservative value of 0.04 in. WG. Of the houses with SSD systems having residual radon levels greater than 2 pCi/L, in only one case -- House 39 -- does the elevated level appear to be due to inadequate distribution of a suction field under the slab by the system. It is noted that effective sub-slab depressurizations are generally being maintained even in houses where the SD is less than 10 ft. This is due to the fact that most of the SSD systems were conservatively designed with multiple suction pipes (usually between three and seven). However, even this number of SSD pipes should be insufficient in the poorest-communication houses, if the SD were in fact an accurate predictor of the distance over which a single pipe can provide treatment. The SD consistently over-predicts the number of SSD pipes actually required.

ASD systems other than SSD are less effective at depressurizing the sub-slab. Of the five houses (Houses 10, 12, 15, 26, and 27) having exterior DTD systems (i.e., drain tiles outside the footings), three houses have at least one sub-slab reading below 0.015 in. WG. Understandably, the suction being developed around the exterior of the footings is impeded in extending into the sub-slab region. However, all three of the houses with at least one marginal depressurization measurement are below 4 pCi/L, and two are below 2 pCi/L. Thus, it would not appear that inadequate suction field extension is responsible for elevated residual levels in the houses with DTD systems. Testing to be described later tends to confirm that the residual radon in these houses is indeed due to factors other than inadequate sub-slab depressurization. Exterior DTD systems probably function primarily by diverting soil gas away from the footings (preventing entry into the block walls), and perhaps by intercepting the gas before it reaches the immediate sub-slab region; thus, maintenance of high depressurizations immediately under the entire slab might not be necessary for successful performance.

Sub-slab measurements were permitted in five of the houses (Houses 3, 8, 14, 16, and 20) having BWD systems, or systems with a significant BWD component. All five of these houses have multiple readings below 0.015 in. WG (although it is noteworthy that the BWD systems do produce some depressurization of the sub-slab). It is likely that the marginal sub-slab depressurizations in the BWD houses are partly responsible for the elevated residual radon levels in many of these houses. However, inadequate depressurization of the sub-slab is not the only problem. Other testing in some of the BWD houses demonstrated that good depressurization of the sub-slab by an SSD system in those houses was not sufficient, by itself, to provide the desired radon reductions. Thus, part of the problem with the BWD systems (and with the SSD systems that were also tested in some of these houses) is that they were not adequately treating the block walls.

In summary, inadequate depressurization of the sub-slab appears to be largely or partly responsible for the elevated residual levels in SSD House 39, and at least partially responsible in the BWD houses. However, it is not generally responsible for the significant number of still-elevated houses having SSD and DTD systems.

Re-Entrainment of ASD Fan Exhaust

Measurements in the ASD exhaust piping indicated radon concentrations ranging from 10 to 27,000 pCi/L (0.37 to 1,000 kBq/m^3) in the exhaust. Many of the SSD systems had exhaust concentrations exceeding 1,000 to 2,000 pCi/L (37 to 74 kBq/m^3). At these levels, re-entrainment of even a fraction of 1% of the exhaust back into the house could create indoor concentrations exceeding 4 pCi/L.

Based upon the flow rate and radon concentration of the exhaust, and upon the volume and estimated natural ventilation rate of the house, a calculation was made of the indoor radon concentration that would result if only 0.1% (i.e., one one-thousandth) of the exhaust was re-entrained. The calculations indicated that 0.1% re-entrainment would cause an incremental increase of more than 1 pCi/L (37 Bq/m^3) in nine of the houses, and of more than 0.5 pCi/L (18 Bq/m^3) in 14 of them, all having SSD or DTD systems. Most of these "top 14" houses had winter-quarter ATD measurements exceeding 4 pCi/L, suggesting a possible correlation between re-entrainment and elevated residual radon levels.

The majority of these ASD installations have the exhaust fan mounted outside the house at grade level, exhausting straight upward immediately beside the house. This exhaust configuration is conducive to re-entrainment.

Two types of testing were conducted to quantify the effects of re-entrainment on residual indoor levels in these houses. In the first approach, 9 houses from among the top 14 were selected to have their exhaust configurations modified, with Pylon measurements in the house to evaluate the effects of the exhaust modifications on indoor radon. In the second approach, five of the houses were selected for perfluorocarbon tracer (PFT) gas measurements.

The results of the exhaust modification testing are summarized in Table 3. For each house, the alternative exhaust configurations that were tested are listed, along with resulting radon concentrations that were measured in the basement and/or living area. Each radon result is the average of 2 to 4 days of hourly radon measurements with a Pylon continuous radon monitor. As shown, of the nine houses, the exhaust modifications: reduced three of the houses below 2 pCi/L (Houses 22, 25, and 34); reduced another two below 4 but not below 2 pCi/L (Houses 7 and 27); and failed to reduce the other four houses below 4 pCi/L on at least one story (Houses 10, 13, 20, and 24).

From Table 3, horizontal-at-grade exhausts, directed 90° away from the house, were modified to become vertical-above-the-eave exhausts in two houses (Houses 20 and 24). In both houses, there appeared to be no significant reduction in re-entrainment by converting to the above-eave configuration. In the one other house originally having a horizontal exhaust directed 90° away from the house (House 34), indoor levels were fairly low to begin with (2.4 pCi/L, or 89 Bq/m^3) despite the extremely high concentrations in the exhaust (8,000 pCi/L, or 296 kBq/m^3). Extension of the exhaust piping 15 ft (about 5 m) away from the house was required to achieve a significant additional reduction in indoor levels. Thus, horizontal exhaust at grade might be as acceptable as the above-the-eave method of exhausting ASD systems, especially when radon concentrations in the exhaust are not very high, as long as the horizontal exhaust is directed 90° away from the house. However, from the other results in Table 3, it would never appear appropriate to exhaust horizontally at grade parallel to the house (or at an angle significantly less than 90°), nor would it ever appear appropriate to exhaust vertically at grade immediately beside the house.

The actual reductions in indoor radon concentrations achieved by these exhaust modifications, shown in Table 3, were compared against the calculated increase that 0.1% re-entrainment should contribute to indoor levels, discussed earlier. This comparison should suggest the degree of re-entrainment that was eliminated by re-directing the exhaust. In all cases except House 22, the measured reductions in indoor levels suggested that re-entrainment was reduced on the order of 0.1%. In House 22, the reduction was about 2%, consistent with the high re-entrainment that might have been expected based upon the original exhaust configuration in this house (horizontal at grade parallel to the house, underneath an overhung bay window).

In view of the residual radon levels following the modifications to the system exhausts, it is doubtful that the modifications eliminated all re-entrainment in any of the houses. Rather, re-entrainment was simply reduced to some lesser value.

In an effort to obtain a more quantitative measure of the actual re-entrainment with the different exhaust configurations, PFT tracer gas measurements were made in five of these houses. In each case, one specific PFT gas ("lime") was released into the ASD exhaust piping. To quantify house ventilation rates, "red" PFT was released into the house upstairs, and "gold" PFT was released into the basement. PFT detectors were deployed on both levels. From these results, it should have been possible to quantify the amount of re-entrainment on both stories of the house.

The results from the PFT testing are summarized in Table 4. Unfortunately, some of the detectors were lost during shipment to the analytical laboratory, so that results for some of the exhaust configurations in some of the houses are missing. Table 4 compares basement radon concentration that would be predicted based upon the PFT results, with the actual measured concentration for the particular exhaust configuration, from Table 3. As shown, the PFT-predicted basement levels are always significantly greater that the levels actually measured, suggesting some problem with the technique by which the tracers were used in this study, and preventing any meaningful interpretation of the results.

Contribution of Well Water to Airborne Radon

All but five of the study houses in this project are served by private wells. The radon concentrations in the well water ranges between 530 and 266,000 pCi/L (20 and 9,800 kBq/m^3) from house to house. Much of this waterborne radon is released into the indoor air when water is used in the house.

The widely used rule of thumb -- based upon typical water usage rates, house volumes, and house ventilation rates -- is that 10,000 pCi/L (370 kBq/m^3) of radon in well water will contribute approximately 1 pCi/L (37 Bq/m^3) to the airborne concentration, on the average over time. Using this rule of thumb, the well water in these houses could be contributing between <0.1 and 7.5 pCi/L (<4 and 278 Bq/m^3) to the airborne concentrations (excluding the one house originally having 266,000 pCi/L, which has since been provided with a water treatment unit). Eleven of these houses could have a water contribution to the air levels greater than 1 pCi/L.

To confirm the practical accuracy of this rule of thumb, "temporary" granular activated charcoal (GAC) units were installed to remove the radon from the water in four houses where the water could be contributing more than 1 pCi/L to the air concentrations. To determine the effect of water treatment, radon measurements were made in the basement and upstairs using Pylon monitors, over 2-week periods both immediately before, and immediately after, the GAC units began treating the water.

The "temporary" GAC units consisted of a standard fiberglass water-softener cylinder filled with 0.2 ft^3 (6 L) of charcoal. These units were being marketed locally for organics removal; they were not specifically designed for radon removal, and thus could be subject to a deterioration in radon removal performance over time. However, water radon measurements indicated that these units were providing high radon removals (94 to 99.6%) for the relatively short duration of the current study.

The effects of the GAC units on airborne radon concentrations are summarized in Table 5. The table includes not only the current results for the four houses tested here, but also the results from two permanent GAC units installed and tested in two other houses in 1986, during the original project.

In four of the six houses in Table 5 (Houses 10, 23, 30, and 34) the ratio of the water radon to its apparent airborne contribution ranges between 7,900:1 and 12,800:1; i.e., within about $\pm$ 25% of the 10,000:1 rule of thumb. Thus, this rule of thumb generally appears to be a rough but reasonable predictor of water effects. The expected role of waterborne radon in contributing to the residual airborne levels in these houses is thus confirmed. Except perhaps for House 23, none of these houses could be reduced below 2 pCi/L (74 Bq/m^3) without permanent water treatment.

House 20 is the one house with reliable data where the observed ratio differs from the 10,000:1 rule of thumb by greater than $\pm$ 25%. In this house, the apparent actual contribution of waterborne radon (3.1 pCi/L, or 115 Bq/m^3) is only about half of the 7 pCi/L (259 Bq/m^3) that would have been predicted. It is not clear why this should have been the case. The owners have small children, and operate the washing machine frequently; thus, lower-than-usual water usage is not the explanation. The house is somewhat larger than average (about 2,600 ft^2, or 240 m^2), but not sufficiently to explain the significant deviation from the rule of thumb. A higher-than-average natural ventilation rate of the house would also help explain the elevated ratio; it is not known what the ventilation rate of this house is. A reduced fraction of radon released from the water upon use in the house would also help explain this ratio, but there is no reason to expect the release rate from the water to be unusually low.

The apparent ratio in House 2 would also appear to be dramatically different from the 10,000:1 rule of thumb. However, the results from House 2 are so uncertain, for the reasons indicated in the table, that these results are not felt to be meaningful.

Contribution of Outdoor Levels to Indoor Radon

In view of the highly elevated soil gas radon concentrations in some locations, it was considered that higher-than-average ambient (outdoor) radon concentrations could possibly be contributing to the elevated residual indoor levels.

To assess the extent of this contribution, measurements of outdoor concentrations were made near seven of the study houses distributed around the study area. Three alpha-track detectors, shielded by weather-protection cups, were hung from trees near the houses (but well away from the ASD exhausts). The detectors were deployed in December 1989 and returned to the laboratory for analysis in February 1990, after 3 months' exposure. The measured concentrations over this exposure period at the seven sites ranged from 0.0 to 0.8 pCi/L (0 to 30 Bq/m^3). Excluding the one site (near Oley, PA) giving the 0.8 pCi/L, the other six sites averaged 0.2 pCi/L (7 Bq/m^3), definitely no higher than the national average.

Accordingly, it would appear that the ambient levels are not contributing unduly to the indoor concentrations.

Radon Emanation from Building Materials

It was not anticipated that building materials were generally a major contributor to indoor radon. Gamma measurements in all of the houses had shown indoor readings (5 to 13 μR/hr, or 13 to 34 x 10^{-10} C/kg air/hr) somewhat lower than the outdoor readings (averaging between 5 and 20 μR/hr, or between 13 and 52 x 10^{-10} C/kg/hr). On this basis, it would be expected that the concrete slabs and foundation walls did not contain unusually elevated radium concentrations, and should not be contributing an amount of indoor radon significantly greater than might be expected in other parts of the country.

Typical concretes contain roughly 1 pCi of radium per gram of concrete. This radium content will commonly result in an emanation of 10 to 40 pCi of radon/hr/ft^2 (4 to 16 Bq/hr/m^2). Depending upon the house ventilation rate, and whether the basement has poured concrete foundation walls, this typical emanation could contribute approximately 0.25 pCi/L (approximately 10 Bq/m^3) to indoor levels.

As a more quantitative estimate of the emanation from the concretes of these houses, a flux test was conducted on the slab and concrete foundation wall of Houses 33 and 34 under the current project. Inverted stainless steel bowls having a volume of 0.2 ft^3 (6 L) were sealed over the slab and wall, and the increase in radon concentration was measured inside the bowls after 1 hour. For the dimensions of these bowls, an increase of 1 pCi/L/hr (37 Bq/m^3/hr) inside the bowl would correspond to a radon emanation rate of 8 pCi/hr/ft^2 (3.2 Bq/hr/m^2). The changes in radon concentration in the bowl over 1 hour during this testing were small, in the range of 1 pCi/L, indicating approximate emanation rates of 2.3 pCi/hr/ft^2 (1 Bq/hr/m^2) from the slab, and 12 pCi/hr/ft^2 (5 Bq/hr/m^2) from the walls in House 33. In House 34, emanation from the slab was comparable to House 33, and emanation from the walls was slightly higher (28 $pCi/hr/ft^2$, or 12 $Bq/hr/m^2$). Because of the short duration of the test and the small concentration increases/low emanation rates, the uncertainties in these emanation rates are large, about $\pm$ 10 $pCi/hr/ft^2$ ($\pm$ 4 $Bq/hr/m^2$). However, it is clear that the emanation rates are not elevated compared to rates from slabs in other parts of the country. In both houses, the emanation rates would suggest that the concrete is contributing less than 0.2 pCi/L (7 Bq/m^3) to the indoor concentrations.

In conclusion, it would appear that building materials are not a significant contributor to the residual indoor radon concentrations in these houses.

Inherent Limitations of Certain Mitigation Approaches

In several of the houses not having ASD systems, the failure of the house to have been reduced below 2 pCi/L (74 Bq/m^3) is felt to be the result of inherent limitations in the effectiveness of the selected mitigation approaches.

All three of the houses having block-wall pressurization systems (Houses 2, 5, and 9) have basement and living-area ATD results greater than 4 pCi/L (148 Bq/m^3). These results suggest an inherent problem of wall pressurization systems in establishing an effective pressure/flow field to prevent soil gas entry into the block cores, or through slab cracks.

Two of the three houses having HRVs have residual concentrations of greater than 4 pCi/L on at least one story (Houses 17 and 18); the third HRV house (House 28) is above 2 pCi/L. These results reflect the fact that ventilation techniques such as HRVs are inherently limited to achieving no greater than moderate (50 to 75%) radon reductions.

The one house being treated solely with a GAC well water removal unit (House 30) is still above 2 pCi/L. This result simply reflects that, while water treatment can be very effective at reducing the waterborne source of radon, it cannot address soil-gas-related entry mechanisms.

CONCLUSIONS

Based upon the testing and assessment conducted during the 1989-90 measurements in the Pennsylvania study houses, it is believed that we now understand the reasons for the residual radon concentrations in all of the houses having residual levels greater than 2 pCi/L (74 Bq/m^3). These reasons are summarized in Table 6.

For SSD and DTD systems, the primary single cause of residual elevated levels is re-entrainment of high-radon fan exhaust, followed in some houses by airborne radon resulting from well water. Care in the design of the exhaust, and treatment of the water, would be required to reduce these houses below 2 pCi/L. In only one house with a SSD system did the elevated residual levels clearly appear to be due to inadequate depressurization beneath the slab.

For BWD systems, inadequate depressurization beneath the slab by the BWD system is probably the major contributor. Re-entrainment and well-water contributions are probably also playing some role in some of the houses.

For other than ASD systems, inherent limitations in the systems are commonly the primary single cause of the elevated residual levels.

Elevated outdoor radon concentrations, and radon emanation from the poured concrete slabs and foundation walls (where present), do not appear to be significant contributors to the elevated residual indoor levels. These factors apparently contribute on the order of 0.2 pCi/L (7 Bq/m^3) each to the indoor concentrations.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the Pennsylvania Department of Environmental Resources, for their support throughout the project, and especially to the homeowners who made their homes available for this testing.

REFERENCES

1. Scott, A. G., A. Robertson, and W. O. Findlay, "Installation and Testing of Indoor Radon Reduction Techniques in 40 Eastern Pennsylvania Houses," EPA-600/8-88-002, January 1988 (NTIS PB88-156617).

2. Scott, A. G., and A. Robertson, "Follow-Up Alpha-Track Monitoring in 40 Eastern Pennsylvania Houses with Indoor Radon Reduction Systems (Winter 1987-88)," EPA-600/8-88-098, September 1988 (NTIS PB89-110035).

3. Scott, A. G., and A. Robertson, "Follow-Up Alpha-Track Monitoring in 40 Eastern Pennsylvania Houses with Indoor Radon Reduction Systems (Winter 1988-89)," EPA-600/8-89-083, October 1989 (NTIS PB90-134172).

4. Scott, A. G., and A. Robertson, "Follow-Up Annual Alpha-Track Monitoring in 40 Eastern Pennsylvania Houses with Indoor Radon Reduction Systems (December 1988-December 1989)," EPA-600/8-90-081, November 1990 (NTIS PB91-127779).

TABLE 1. SUMMARY OF POST-MITIGATION ALPHA-TRACK DETECTOR RESULTS FROM PENNSYLVANIA STUDY HOUSES

House No.	Mitigation System[1]	Pre-Mitigation Radon (pCi/L)[2,3]	Post-Mitigation Radon (pCi/L) Winter-Quarter Averages[4] Basement	Living Area	Annual Average (Living Area)
2	Wall press.	413	4.3	6.9	[5]
3	BWD+SSD	350	3.3	2.1	1.8
4	SSD	25	1.0	0.9	0.5
5	Wall press.	110	4.8	4.4	4.0
6	SSD	60	3.5	3.6	2.3
7	SSD	402	4.5	3.3	[5]
8	BWD	183	3.4	1.4	1.1
9	Wall press.	533	11.5	14.8	[5]
10	DTD	626	11.5	8.4	12.1
12	DTD	11	2.5	2.3	1.3
13	SSD+DTD	64	2.5	2.9	[5]
14	BWD	36	0.8	1.0	[5]
15	DTD	18	1.2	1.2	0.9
16	BWD	395	5.3	1.8	1.5
17	HRV	9	8.1	5.1	2.7
18	HRV	12	11.7	3.5	3.6
19	BWD	32	31.3	0.7	[5]
20	SSD+BWD +DTD	210	6.9	9.7	10.0
21	SSD	172	2.3	2.7	3.7
22	SSD	24	9.0	3.8	[5]
23	SSD	98	2.5	1.6	1.6
24	SSD	66	4.1	4.0	3.2
25	SSD	122	6.8	4.8	6.4
26	DTD	89	1.3	1.4	1.0
27	DTD	21	4.5	2.2	3.9
28	HRV	21	3.6	4.9	3.6
29	DTD+SLD	61	1.9	1.9	3.0
30	Water	17	3.6	1.7	1.9
31	SSD	485	2.3	7.0	[5]
32	SSD	6	0.9	3.6	4.0
33	SSD	82	5.6	1.0	0.6
34	SSD	470	5.3	4.9	5.8
35	SSD	144	1.4	0.9	0.7
36	SSD	300	1.2	0.8	0.7
37	SSD	87	0.9	1.0	0.9
38	SSD	309	7.8	7.2	6.6
39	SSD	111	7.5	1.8	4.1
40	SSD	148	1.9	1.2	[5]

Footnotes for Table 1

1 SSD = sub-slab depressurization; DTD = drain-tile depressurization; BWD = block-wall depressurization; SLD = sub-liner depressurization (crawl spaces); HRV = heat recovery ventilator; wall press. = block-wall pressurization.

2 1 pCi/L = 37 Bq/m^3

3 Pre-mitigation measurements were usually made in the basement by the Pennsylvania Department of Environmental Resources using ATDs, prior to the mitigation project.

4 Each reported radon value is the average of winter-quarter ATD measurements, usually for two or three winters.

5 Annual average ATD measurement was not successfully completed in this house, usually because system was turned off, or was not fully operational, during part of the measurement period.

TABLE 2. SUB-SLAB DEPRESSURIZATIONS CREATED BY MITIGATION SYSTEMS (HOUSES WITH ASD SYSTEMS ONLY)

House No.	Mitigation System	No. of SSD Pipes	Range of Sub-Slab Depressurizations Created by System (in. WG)[1,2]	Range of SD (ft)[1,3]
3	BWD+SSD	1[4]	0.004-0.012	1,600 to >30,000
4	SSD	6	0.008-0.234	0.3 to 6
6	SSD	3	0.129-0.194	2 to 45
7	SSD	7	0.093-0.375	90 to >30,000
8	BWD	0[4]	0.004-0.007	3,900 to >30,000
10	DTD	0[5]	0.056-0.085	>30,000
12	DTD	0[5]	0.014-0.018	8,800 to >30,000
13	SSD+DTD	4	0.109-0.605	3 to >30,000
14	BWD	0[4]	0.006-0.012	110 to >30,000
15	DTD	0[5]	0.014-0.072	1 to 580
16	BWD	0[4]	0.001-0.006	3,300 to >30,000
19	BWD	0[4]	Owner did not permit measurements.	
20	SSD+BWD +DTD	5[4]	0.008-0.202	1 to 25
21	SSD	1	0.117-0.169	>30,000
22	SSD	4	0.322-0.399	170 to 2,200
23	SSD	4	0.669-0.706	45 to >30,000
24	SSD	3	0.847-1.109	75 to 190
25	SSD	4	0.020-0.274	6 to 270
26	DTD	0[5]	Pos.-0.008	2 to 990
27	DTD	0[5]	0.056-0.081	>10,000
29	DTD+SLD	0[5]	0.625-0.685	>30,000
31	SSD	6	0.113-0.738	5 to 380
32	SSD	7	0.282-0.706	2 to 4
33	SSD	1	0.322-0.637	6,100 to >30,000
34	SSD	6	0.685-1.391	1 to 40
35	SSD	4	0.014-0.171	1 to 30
36	SSD	5	0.056-0.181	80 to >30,000
37	SSD	6	0.968-1.012	>30,000
38	SSD	2	0.044-0.258	45 to >30,000
39	SSD	3	0.001-0.102	0.7 to 2
40	SSD	20	0.001-0.256	1 to 3

Footnotes for Table 2

1 The range of depressurizations and 1% suction distances (SDs) reflect the range of results from the different test holes.

2 1 in. WG = 248 Pa

3 1 ft = 0.30 m

4 House has a block-wall depressurization system only, or a SSD system with a major BWD component; thus, depressurization beneath the slab will be low in comparison with typical SSD systems.

5 House has a drain-tile depressurization system. In all cases except House 29, the drain tiles are outside the footings; thus, sub-slab depressurizations will be low in comparison with typical SSD systems.

TABLE 3. PYLON RESULTS FROM MODIFICATION OF ASD EXHAUST CONFIGURATIONS

House No.	Radon in Exhaust (pCi/L)	Exhaust Configuration	Average Pylon Result (pCi/L) Basement	Living
7	3,500	1. Vertical at grade, immediately beside house (original configuration).	5.2	--
		2. Stack extended up to eaves; elbow directs exhaust horizontally, 90° away from house, at eave level.	4.9	--
		3. As in 2 above, except stack ends vertically above eaves.	2.1	--
10	2,300	1. Vertical at grade, immediately beside house (original config.) Incl. water treatment.	9.4	5.8
		2. Elbow on fan outlet directs exhaust horizontally at grade level, at a 20° angle away from house (i.e., almost parallel). Water treatment.	2.1	10.8
13	580	1. DTD fan exhausting vertically at grade (original configuration). SSD system off.	7.3	--
		2. Elbow on DTD fan outlet directs exhaust horizontally at grade level, at 60° angle away from house, toward corner of house. SSD off.	15.6	--
20	2,200	1. Horizontal at grade, directed 90° away from house (original config.). Incl. water treatment.	4.6	~5-10
		2. Stack extended up outside house, vertical discharge above eaves. Incl. water treatment.	--	5.2
22	1,550	1. Vertical at grade, immediately beside house (original configuration).	14.5	--
		2. Elbow on fan outlet directs exhaust horizontally at grade level, 90° away from house; hose on horizontal outlet of elbow leads exhaust 10 ft away from house.	1.6	--

(continued)

TABLE 3 (continued)

House No.	Radon in Exhaust (pCi/L)	Exhaust Configuration	Average Pylon Result (pCi/L) Basement	Living
24	2,000	1. Horizontal at grade, directed 90° away from house (original configuration). (Fan reduced.)	5.4	--
		2. Stack extended up outside house, vertical discharge above eaves. (Fan reduced.)	4.9	--
25	1,200	1. Horizontal at grade, parallel to house, under deck (original configuration).	4.6	--
		2. Horizontal at grade, directed 90° away from house, with exhaust pipe extending 10 ft away from house (to end of deck).	0.5	--
27	650	1. Vertical at grade, immediately beside side of house (original configuration).	6.9	--
		2. Horizontal at grade, directed 90° away from rear of house, with exhaust pipe extending 4 ft away from rear of house (under deck stairs).	2.7	--
		3. Stack extended up outside of house, vertical discharge above eaves.	2.4	--
34	8,000	1. Horizontal at grade, directed 90° away from rear of house by sliding glass door (original configuration). (Temporary well water treatment system also operating.)	2.4	3.4
		2. Horizontal at grade; 90° elbow on fan outlet directs exhaust parallel to rear of house, with a 14-ft length of pipe directing the exhaust to the corner of the house, where it is discharged parallel to the rear but 90° away from the side of the house. (Temporary water treatment system operating.)	3.5	--
		3. As in 2 above, except horizontal exhaust piping extended an additional 15 ft, diagonally away from the corner of the house. (Water treated.)	1.4	--

TABLE 4. PREDICTED INDOOR RADON CONCENTRATIONS BASED UPON PFT RESULTS, COMPARED WITH MEASURED RADON LEVELS

House No.	Exhaust Configuration[1]	Bsmt Tracer Ratio[2] (x 10^7)	Radon Release[3] (pCi/hr) (x 10^{-7})	Expected Basement Radon Conc. from Re-Entrainment (Based Upon PFT Results)[4] (pCi/L)	Radon Measured in Bsmt[5] (pCi/L)
10	2. Horizontal at grade	0.4	45	18	2.1
22	2. Horizontal at grade	1.1	20	22	1.6
23	Vertical above eaves	0.9	32	29	0.9
24	1. Horizontal at grade	6.5	12	78	5.4
25	1. Horizontal at grade, parallel to house	1.5	27	40	4.6
34	1. Horizontal at grade, directed 90° away	1.3	39	51	2.4
	2. Horizontal at grade, extended to corner	1.9	39	74	3.5
	3. As in 2 above, extended 15 ft	1.0	39	39	1.4
38	Horizontal at grade	1.4	24	34	5.1

1 Configuration numbers shown here are identified in Table 3.

2 The ratio of (Lime PFT concentration in basement, in PFT units/L):(Lime release rate in ASD exhaust, in PFT units/hr).

3 The rate of radon release from the ASD exhaust, in pCi/hr, determined from the exhaust flow rates and radon concentrations.

4 The predicted basement radon concentration, based upon PFT measurements, is calculated by multiplying the radon release rate times the PFT tracer ratio, (basement PFT concentration)/(PFT exhaust rate from ASD system).

5 The measured basement radon concentration listed here is generally the average of the 4-day Pylon measurement made during, or just before, the PFT measurements.

TABLE 5. EFFECT OF WATER TREATMENT UNITS ON AIRBORNE RADON LEVELS

House No.	Story	Water Radon[1] (pCi/L)	Airborne Radon (pCi/L) Without Water Treatment	With Water Treatment	Reduction	Water Radon: Airborne Reduction[2]
Current Testing						
10	Upstairs	26,200	7.4	4.1	3.3	7,900:1
10	Basement[3]	26,200	10.1	7.1	3.0	8,700:1
20	Basement[3]	69,900	8.2	5.1	3.1	22,500:1
23	Basement[3]	11,500	1.7	0.8	0.9	12,800:1
34	Upstairs[3]	26,800	5.4	2.8	2.6	10,300:1
Prior Testing (Reference 1)[4]						
2	Basement[3]	53,200	2.8[5]	2.2	0.6	Questionable[5]
30	Basement[3]	206,000	29.1	5.2	23.9	8,600:1

[1] For houses tested under current project, the water concentrations shown here are the averages of two pre-treatment measurements, made in December 1989 and January 1990. For the houses tested under the original project (Houses 2 and 30), the values shown are the average of the original 1985-86 analyses and of several analyses made during the period August 1986 through March 1987, since these were made closer to the time that the airborne radon measurements were made with the GAC on and off.

[2] The ratio of the water radon concentration to the reduction in airborne levels achieved by operating the GAC system, which should approximately equal the contribution of waterborne radon to the airborne levels. For comparison against the 10,000:1 rule of thumb.

[3] Washing machine is on this story.

[4] The measured effects of the GAC units on airborne radon are thought to be much less accurate in the prior testing, since the GAC on/off measurements were not made back-to-back in the earlier testing, and the measurements under "GAC on" and "GAC off" conditions were shorter than the 7 days used in the current project.

[5] Results from House 2 very uncertain because: Pylon measurement with GAC off far too short (only 20 hours in duration); possible basement ventilation by owner during measurement period makes results uncertain.

TABLE 6. APPARENT REASONS WHY STUDY HOUSES ARE STILL ABOVE 2 pCi/L

House No.	Mitigation System	Pre-Mitigation Radon (pCi/L)[1]	Post-Mitigation Radon (pCi/L)[2]	Reasons for Elevated Residual Radon
Houses greater than 4 pCi/L				
2	Wall press.	413	4.3	System limitations; water.
5	Wall press.	110	4.8	System limitations.
7	SSD	402	4.5	Re-entrainment.
9	Wall press.	533	11.5	System limitations; water.
10	DTD	626	11.5	Re-entrainment; water.
16	BWD	395	5.3	Inadequate sub-slab depressurization.
17	HRV	9	8.1	System limitations.
18	HRV	12	11.7	System limitations.
19	BWD	32	31.3	Inadequate sub-slab depressurization.
20	SSD+BWD +DTD	210	6.9	Water; perhaps re-entrainment; marginal sub-slab depress.
22	SSD	24	9.0	Re-entrainment.
24	SSD	66	4.1	Re-entrainment.
25	SSD	122	6.8	Re-entrainment.
27	DTD	21	4.5	Re-entrainment.
33	SSD	82	5.6	Unsealed entry route.
34	SSD	470	5.3	Re-entrainment; water.
38	SSD	309	7.8	Probably re-entrainment; water.
39	SSD	111	7.5	Inadequate sub-slab depressurization.
Houses between 2 and 4 pCi/L				
3	BWD+SSD	350	3.3	Inadequate sub-slab depressurization.
6	SSD	60	3.5	Probably re-entrainment; water.
8	BWD	183	3.4	Inadequate sub-slab depressurization.
12	DTD	11	2.5	Marginal sub-slab depressurization; probably re-entrainment; water.
13	SSD+DTD	64	2.5	Re-entrainment.
21	SSD	172	2.3	Probably re-entrainment.
23	SSD	98	2.5	Water; perhaps re-entrainment.
28	HRV	21	3.4	System limitations.
30	Water	17	3.6	System limitations.
31	SSD	485	2.3	Probably re-entrainment; water.

[1] 1 pCi/L = 37 Bq/m^3

[2] Post-mitigation radon level is average of two or three winter-quarter ATD measurements in the basement.

A Measurement and Visual Inspection Critique to Evaluate the Quality of Sub-Slab Ventilation Systems

by: Richard W. Tucker
Gemini Research, Inc.
Cockeysville, Maryland 21030

Keith S. Fimian
Radonics, Inc.
McLean, Virginia 22102

ABSTRACT

The reliability of radon testing and the effectiveness of radon mitigation systems are critical areas of concern because of the detrimental health effects that can result when a home owner may believe that his radon exposure is less than he is actually experiencing. This paper provides measurement and inspection criteria that are oriented towards ensuring that an installed radon sub-slab depressurization system is actually performing properly and is likely to continue to do so for several years. Particular attention is paid to the typical house that is experiencing mitigation where the pre-mitigation levels were between four and eight picocuries. Continuous-based data logging measurements are used to show the reaction of certain dwellings to particular mitigation work. A visual inspection list is provided to identify installation deficiencies which would lead to the possibility of long-term or short-term operational problems which could result from improper mitigation system installation.

OVERVIEW

Mitigation systems are installed in dwellings to reduce the levels of harmful radon progeny in the dwellings. Mitigation efforts are undertaken when levels are detected which exceed those felt to have acceptable health risk. This determination of health risk is made by either the owner of the dwelling, the potential owner of the dwelling or in some cases by regulation or legal determinations. In most cases the figure of 4 pCi/l or .02 WL is used as the level at which to initiate mitigation efforts. The distribution of radon in residential dwellings in the U.S. is such that, greater than 60% of dwellings having levels in excess of 4 pCi/l or .02 WL contain levels between 4 pCi/l and 8 pCi/l or .02 WL and .04 WL.

There are numerous methods of radon reduction available. Caulking and sealing and sub-slab ventilation are used in the majority of cases. The typical home owner will first attempt to perform his own caulking and sealing work. In many cases, after this work has been completed, there is no additional testing as the assumption is that the efforts were effective since the levels were less than 8 pCi/l to begin with. In the cases where additional testing is performed, the home owner will usually find that there was little or no reduction and possibly an increase in radon levels. If the owner decides to proceed with the installation of an active mitigation system, sub-slab ventilation is usually chosen. Because of the dangers of improperly installed active systems, these should be installed by a professional mitigation contractor.

This paper addresses methods and procedures to be followed to ensure that an operational sub-slab radon mitigation system has been installed in a manner to provide both short-term and long-term protection and does not cause other collateral problems. The focus is on operational and mechanical evaluations. Other types of operational and diagnostic tests should be performed during the initial dwelling and system installation evaluations but are not addressed in this paper. For example, the differential pressure across the slab should be measured as part of the system installation performance testing.

The EPA does not regulate the installation of radon mitigation systems. The EPA does, however, provide technical guidance for radon remediation in two documents, entitled "Radon Reduction Techniques for Detached Houses" (Techniques) dated January 1988 and "Application of Radon Reduction Methods" (Methods) dated August 1988. Because the EPA does not regulate the installation of radon mitigation systems, the strongest language the EPA is able to use when referring to specific features of a system in its technical guidance is "preferred" and "recommended." These preferred and recommended practices are given for the protection of the occupant of the dwelling.

THE RATIONALE FOR POST MITIGATION PERFORMANCE TESTING AND INSPECTION

Improper installation of a radon mitigation system can result in serious danger to the occupants of the dwelling from many causes, depending upon the nature of the installation. These dangers are common enough and serious enough, that our firm recommends that the installation of active radon mitigation systems only be performed by professional radon mitigation firms, certified by the EPA and in accordance with all of the current EPA "recommended" and "preferred" procedures. Our sample of homes where the homeowner installed his own sub-slab depressurization system, is very disturbing. In general, it would not be going too far to say that in the long run, the homeowner is at <u>more</u> risk after the system installation than before.

The dangers that can result from the improper installation of a sub-slab depressurization system are several. First is the danger associated with the radon itself. This particular danger comes in two forms. The first danger comes from a system failing to perform its primary mission. In this situation, the radon level is allowed to exceed the intended maximum level due to some system malfunction or due to the inability of the system to deal with certain dwelling operating conditions or changes in outside environmental conditions such as rain, low pressure systems or high wind conditions.

The second danger from radon is even more dangerous than the first in most cases. Most houses that are mitigated are less than 20 pCi/l before mitigation. If the system simply fails to work, the radon levels in the dwelling will probably only rise to their former level. If caught within a few weeks or months, this does not represent a serious increase in health threat. If however, the system fails in such a manner that the potentially huge levels of radon that typically exist below the slab are introduced into the living areas of the structure, even short term failures can lead to significant increases in health risks to the occupants of the dwelling.

In addition to dangers from radon, there is the potential for danger to the occupants from several other factors. Many of these other potential dangers are addressed under the local and national code guidelines and regulations. These are areas such as fire, electrical, and structural installation considerations.

The final area of danger from an incorrectly installed sub-slab depressurization system, arises from possible alterations in the pressure field in the houses vis-a-vis the outside pressure and the effect on devices and systems in the house that are concerned with the handling of combustion input materials or by-products. In particular there are many potential dangers that can result when a sub-slab depressurization system also results in an inordinate reduction of the pressure field within the house, interfering with the ability of combustion systems to efficiently remove toxic by-products from the dwelling.

VISUAL INSPECTION

EPA technical guidance for radon mitigation contained in Techniques and Methods lists many different ways to install a sub-slab depressurization system. However, EPA technical guidance "recommends" a very precise system design using a very limited number of system features. These EPA "preferred" and "recommended" system features are less failure-prone and more efficient than EPA techniques merely described in EPA technical guidance that are not "preferred" or "recommended." These "preferred" and "recommended" features may not be required to get the levels in a structure below the desired level, but they do provide long-term operational benefits. Therefore, EPA "preferred" and "recommended" techniques should be followed at a minimum to insure the best possible system based on current technology. The visual inspection of a system is designed to ensure that a system contains these EPA "preferred" and "recommended" features.

A set of questions in Appendix I provide assistance in the evaluation of a sub-slab depressurization system. Appendix I questions answered with a negative response are intended to identify deficiencies that may exist in a system visually inspected in light of EPA recommendations. Each of the categories of questions in Appendix I are discussed in some detail here. Specific references to EPA documentation are also given.

Alarm. Section 7.1 of Methods says, "it is advisable to install an alarm" on a radon mitigation system to warn house occupants "if the fan becomes ineffective", if the pipe becomes blocked, or if the system fails in any other way. Radon cannot be seen, smelled, or otherwise detected without the use of sophisticated measurement equipment. A system that does not audibly or visually alert house occupants upon the occurrence of a partial or total system failure does not meet the requirements for long term system operation and may pose a substantial increase in health risks.

The system alarm should be triggered by reduced air flow and/or differential pressure. Reduced air flow can occur as a result of several problems, including blockage due to condensation collection or freezing, fan failure and super-saturation of sub soil air passages. Even a partial blockage could seriously reduce system effectiveness even while the fan appears to be running at its normal rate.

Separate circuit wiring should be provided to the alarm to ensure that a current disruption to the mitigation system does not impair the functionality of the alarm. For example, a tripped circuit breaker to the fan circuit could go undetected if the alarm circuit was also on the same circuit breaker.

Fan. Section 7.1 of Methods says, "the fan should be durable and resistant to weather conditions, capable of sustaining a pressure differential of 0.5 to 1.0 inches WC (124 to 228 paschals) at a flow rate of 150 to 200 CFM (.071 to .094 CMS)." The minimum flow rate numbers in this EPA guidance have been discussed to a great extent both within and without of the EPA. The current prevalent consensus is that 150 CFM is higher than required under normal circumstances. 60 CFM is now generally believed to be the minimum flow required for good system performance.

Fans capable of generating this much power should be specifically designed for the purpose of radon remediation. Bathroom or kitchen fans not designed for radon remediation must not be used. These fans are not designed to run continuously at high speed. They leak and experience a significant reduction in capability when operated in this way.

Section 7.3 of Methods adds, "in all cases, care should be taken to insure adequate support for all pipes and fans installed." Vibration caused by these powerful system fans can be significant. If the fan is not properly and securely mounted, this vibration will accelerate the incidence of system leakage.

Fan Mounting. Section 7.3 of Methods says, "all fans should be mounted vertically to prevent water from collecting and all horizontal runs of pipes should be sloped toward the sub-slab vent point so that condensed water can drain back to the soil."

The EPA estimates that an average radon remediation system handles approximately two quarts of water per day in an average house. This volume of condensation will accumulate in the location of the system fan if the fan is mounted horizontally or if the fan is mounted in a low point along a horizontal run of pipe.

EPA also recommends that the fan be outside the negative pressure field of the house so that radon leakage will not contaminate the house. The negative pressure field of the house constitutes all interior portions of the house, including basements, crawl spaces, and garages beneath or adjacent to living areas of the house. This means, at a minimum, the fan and the pipe on the positive pressure side of the fan (the portion of pipe between the fan and the exhaust) should be located in the attic. The safest operation occurs when the fan is located completely outside of the house.

Section 7.2 of Methods says, "where the pipe penetrates the roof, the fan should be mounted either in the attic or on the roof." Mounting the fan on the roof has the advantage of reducing noise and the risk of re-intrainment. Mounting the fan in the attic has the advantage of protecting the fan from the effects of weather. The EPA recommendation is based on the fact that the constant vibration applied by the fan to nearby system elements can result in structural fatigue and system leaks.

If a fan is located in a garage and develops a substantial leak, not only could very high levels of radon be pumped into the garage, but the fan could pressurize the garage to the point where gasoline fumes that accumulate on the floor of the garage would be forced into the living quarters of the house. This poses both an explosive risk and a toxic fumes risk.

Sump. Section 7.2 of Methods says, "For the sump ventilation to be effective, the cover must be sealed airtight. This cover can be made of sheet metal, plywood, or another suitable material. It will usually be convenient to fabricate the cover in two pieces so it can be fitted around the pipes which penetrate the sump. The possibility of needing to service the sump pump should be taken into consideration when designing the sump cover. Caulk and sealants can be used to insure an airtight fit. The cover should be secured to the floor with masonry bolts. If water sometimes enters the sump from the top of the slab then an airtight seal that allows water to drain must be installed."

Section 7.2 also states, "When the sump is covered, it is recommended that the existing sump pump be replaced by a submersible pump if such a pump is not already present. The submersible pump is recommended to avoid problems of corrosion with the pump motor and/or for ease of sealing the sump."

Section 7.2 continues with, "The ventilation pipe that penetrates the sump cover must extend up through the house shell to exhaust the soil gas extracted through the sump. Figure 9 shows two alternative exits for the exhaust pipe. In one, the pipe penetrates the house shell through the band joist and extends up outside the house. It is recommended that the exhaust be above the eaves of the house and away from windows in such an instance. In the other case, the pipe extends up through the house to the roof and exhausts soil gas above the roof line."

Pipe. Section 7.3 of Methods says, "piping used to construct ventilation systems should be made of plastic, such as PVC sewer pipe for durability as well as for corrosion and leak resistance. Flexible hose such as clothes dryer vent hose is not recommended because it is easily damaged and not conducive to draining water that condenses in the line. It will tend to sag under condensed water creating traps which could result in reduced effectiveness of the ventilation system." For these reasons, flexible hose is not acceptable.

Section 7.3 further states, "In EPA's experience, the ventilation system usually consists of 4 inch PVC pipes." Also, "The size of the pipe can also influence system performance. If the diameter of the pipe is too small, the fan cannot depressurize the soil because of increased pressure drop in the pipe. Long runs of pipe or turns and elbows have a similar effect. Since small diameter pipe takes up less space and is more easily hidden, it may be desirable to use small pipe in some instances."

EPA provides no further guidance or a specific "recommendation" concerning the size of the PVC pipe. The interior diameter of the pipe is not critical as long as a sufficient pressure drop across the slab is maintained. Smaller diameter PVC pipe may sufficiently reduce radon levels depending upon the characteristics of an individual property.

Section 7.2 of Methods advises, "the pipe must be supported with mounting brackets either on the basement wall or at the floor penetrations. Horizontal piping runs should be supported by clamps or brackets attached to floor joists."

Vibration of the pipe and normal wear and tear caused by weather conditions, system fans, and general operation will accelerate the incidence of system leakage if the pipe is not adequately and securely mounted.

Pipe slope. Section 7.2 of Methods says, "horizontal runs of pipe should be sloped slightly so that condensed water can drain to the ground or to an outside drain. It is imperative that no low points exist in the line. If a natural trap exists in the exhaust line condensed water can collect and block the air flow." Section 7.3 further states, "all horizontal runs of pipe should be sloped toward the sub-slab vent point so that condensed water can drain back to the soil."

System exhaust. Section 7.1 of Methods states, "if the [radon remediation system] exhaust is near the house it is recommended that it be extended above the eaves." Section 7.2 adds, "it is recommended that the exhaust be above the eaves of the house and away from windows."

Section 7.3 says, "Options for exhausting the soil gas above the eaves of the house include either penetrating through the roof from inside the house or extending the exhaust pipe outside the house."

"If any part of the line on the exhaust side of the fan is indoors, it should be carefully leak tested because it will release radon in the house if it leaks. For this reason the fan should be mounted in the attic, on the roof, or outside wherever possible."

The fans in these systems are powerful and they operate continuously. Prolonged exposure to the continuous vibration caused by these fans will likely cause the fan or nearby joints to eventually leak. A pinhole sized leak in the positive pressure side of the pipe (the portion of pipe after the fan) will pump high concentrations of radon into the living quarters if the fan is located inside the house.

Section 7.1 specifies that, "whether the exhaust is mounted on the roof or away from the house, consideration should be given to the possibility that it could become covered, either by debris or by snow and ice."

Section 7.3 adds that, "vents through the roof should be capped with a rain guard that does not impede air flow. The possibility that the outlet could be covered by snow accumulation or drifts should also be considered." Therefore, the exhaust port should extend high enough above the roof surface to ensure that snow accumulations that could be expected for the area in which the system is being installed would not prevent proper system performance.

System insulation. Section 7.3 of Methods says, "in cold climates insulation might be needed on the exhaust pipe to prevent ice from blocking it." If the system is equipped with an adequate alarm capable of detecting when air flow is impeded due to system blockage caused by ice, snow or other conditions, the alarm would alert the occupants of this fact. Preference should be given to extending the ventilation pipe up through the interior of the house shell in cold climates.

If schedule 40 or greater PVC (or equivalent) is used, 5000 degree days is considered to be a cold climate. Should less than schedule 40 PVC or equivalent be used, then 4200 degree days is considered to be a cold climate.

Electrical, Mechanical, Building Code Compliance. Local building codes must be followed in the installation of any mitigation system. Local electrical code must be followed to insure that electrical current provided to a system has been wired in a manner that would prevent electrical shock to persons working or playing around the system and that no fire hazard is created. Depending on the location of the of the fan, some localities may require ground fault interruption circuits be installed. To insure wiring has been installed in accordance with local electrical code, evidence of inspection by a qualified electrician must be provided by the radon remediation company. Other mechanical considerations include insuring that fire wall penetrations are protected with fire dampers. These types of requirements depend heavily on the local code requirements. The inspection process should ensure that the necessary inspections have been performed.

OPERATIONAL TEST AND EVALUATION

Once a system has been determined to meet the aforementioned visual inspection requirements, an actual measurement of the radon levels in the dwelling should follow. These measurements are currently being made in several ways. Two preferred methods for this measurement are given here however.

The first preferred method is performed with a combination of a short term passive test and a long term passive test. A short term test is conducted shortly after the completion of the mitigation work, with enough time allowed for the house to stabilize with respect to the new conditions. A waiting period of about 24 hours is recommended. The short term test should be conducted in accordance with the requirements of the device being used. It should be remembered that in a post-mitigation environment where sub-slab depressurization was performed, the levels should normally be in the range of 0.5 to 2.0 pCi/l. The length of test should be sufficient for the device being used to have reasonable accuracy at those levels. In any case a minimum two day test should be performed. Three days is recommended. If the short term test indicates that the radon levels have been sufficiently reduced, then a one year test should be performed. This approach does not guarantee that radon levels may not at some points be very high, but it does indicate the long term exposure.

The second preferred method is performed by making a short term test with a continuous logging active monitor. A device with good resolution over the range of 0.2 pCi/L to 10 pCi/L must be used. A measurement period of two or three days should be used. The data provided by this method will yield not only an average level for the test, but can show the performance of the system as living conditions and barometric pressure vary.

Our data for post mitigation tests shows that radon levels in dwellings with adequate sub-slab depressurization, do not vary significantly with changes in barometric pressure, rainfall or living patterns. When the pressure differential between the area above the slab and the area below the slab is maintained so that the pressure below the slab is sufficiently less than the pressure above the slab, radon levels are consistently abated.

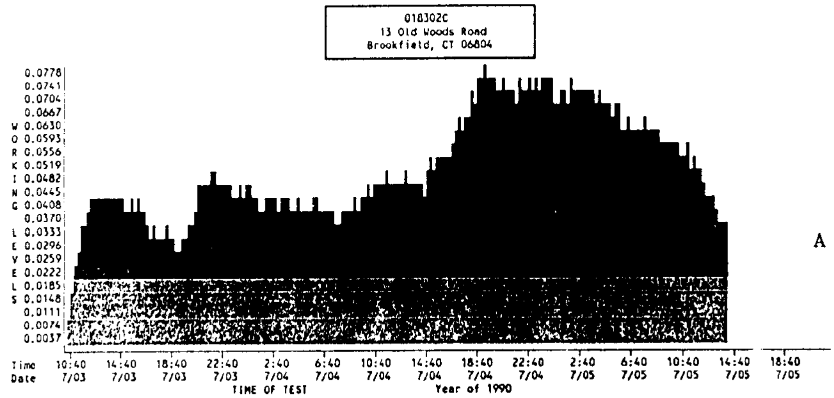
The use of a single short term passive test in a post mitigation environment is not recommended. It provides no information about what kind of variations are occurring and may also provide a poor indication of the long term performance.

Figure 1 illustrates a sequence of three tests made with continuous logging equipment. The top plot (Figure 1A) shows the initial screening test. The radon level averaged over the entire test period was 0.0501 WL. The maximum variance in the radon levels was about two to one. The homeowner next attempted to mitigate the house himself by the use of caulking and sealing. As is typical after homeowner caulking and sealing, the new average radon level was within a few percent of the original reading. The middle plot (Figure 1B) shows the test made after the caulking and sealing which yielded an average level of .0467 WL. Again the radon variations are about two to one. After homeowner caulking and sealing, the levels are higher than before the mitigation as often as they are lower. When caulking and sealing is done by professional mitigators the results may be a little better, but usually not markedly so.

The bottom plot (Figure 1C) shows the results after a sub-slab depressurization system was installed by a professional mitigator. The average radon level was .0050 WL. At no time did the level exceed .01 WL. This system exhibited fairly good performance, although the variance of almost three to one would be a concern if the maximum levels were higher.

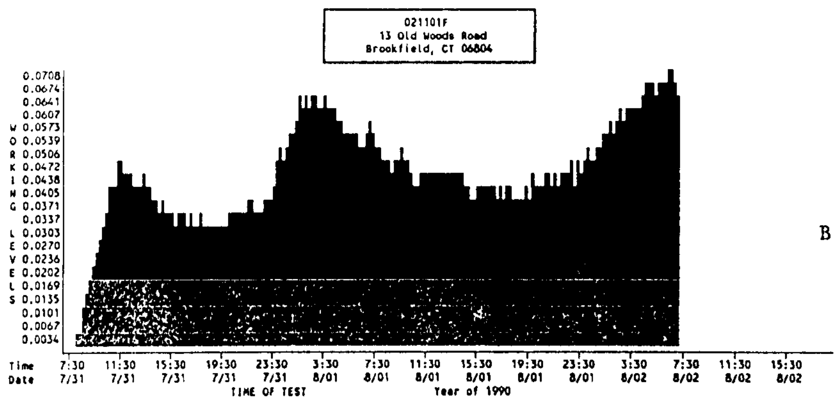
The next example shows a dwelling with a great amount of radon variance. On the initial test (Figure 2A), the average radon level was .0214 WL. A sub-slab mitigation system was installed and an additional test performed. The second test (Figure 2B) showed great variance in the radon levels and yielded an average of .0300 WL. The system was tuned by the contractor and again was tested. The levels now rose to .0840 WL with peaks to .1760 WL. Additional work was performed. The average radon level got back to the pre-mitigation level of .0214 WL. The maximum level of .0417 WL, however indicates that the system is far from performing adequately. At this point, the frustrated contractor put in an air to air heat exchanger. The final test yielded an average radon level of .0061 WL. Again there was an excessive amount of radon variation, but the levels were consistently below .01 WL.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.



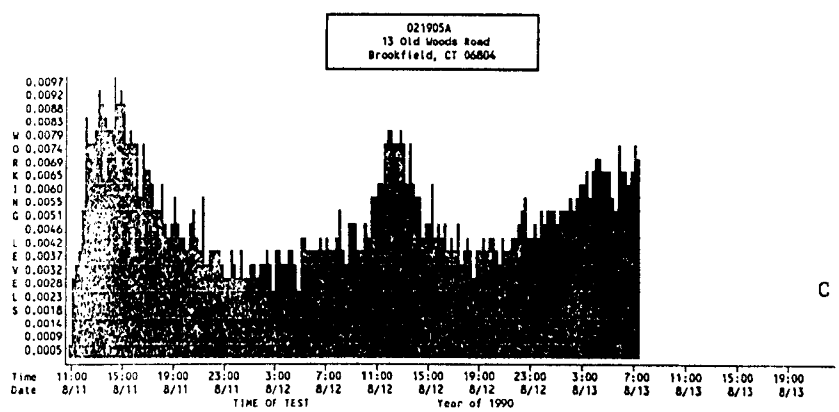
A

* NOTE: The darker area on the graph is above 0.02 WL (4.0 pCi/L).



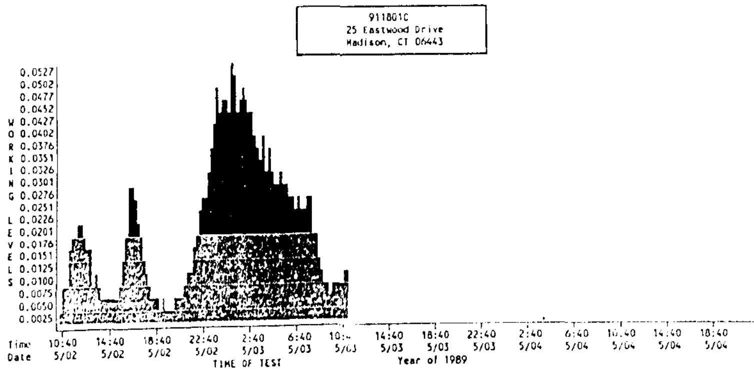
B

* NOTE: The darker area on the graph is above 0.02 WL (4.0 pCi/L).

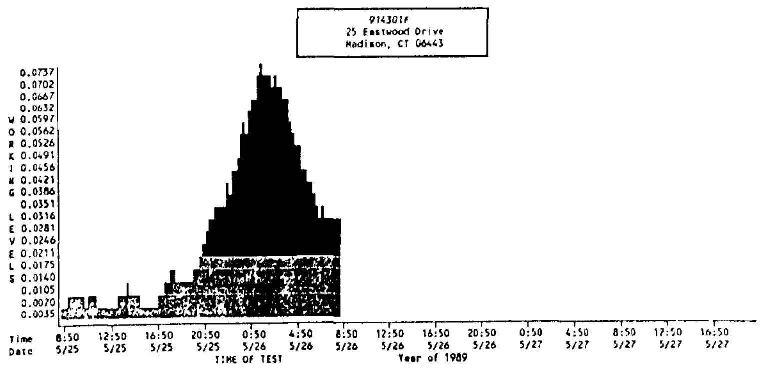


C

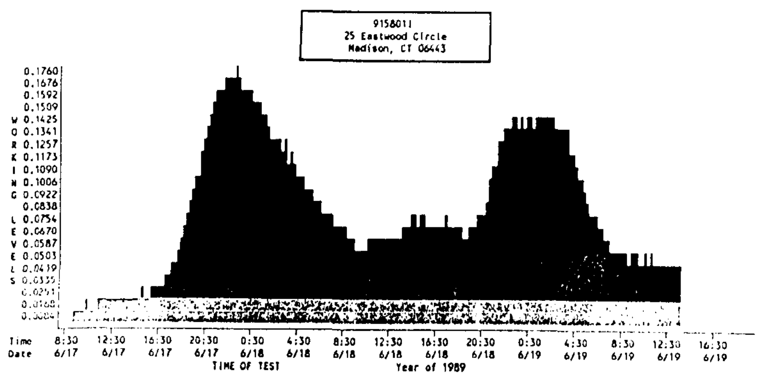
Figure 1. Mitigation Case 1



* NOTE: The darker area on the graph is above 0.02 WL (4.0 pCi/L).



* NOTE: The darker area on the graph is above 0.02 WL (4.0 pCi/L).



* NOTE: The darker area on the graph is above 0.02 WL (4.0 pCi/L).

Figure 2. Mitigation Case 2

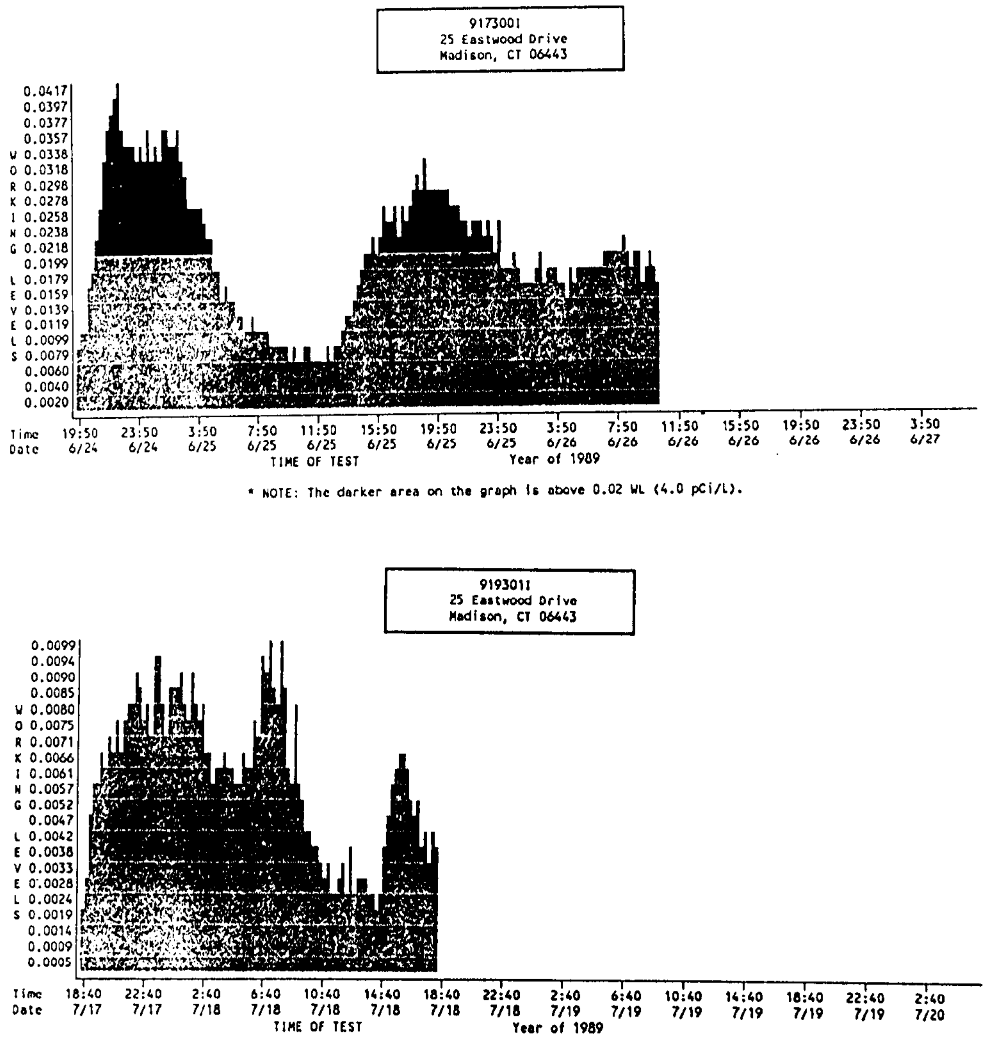


Figure 2 (continued) Mitigation Case 2

APPENDIX I

Alarm.

(1) Does the sub-slab depressurization system have an alarm?
(2) Is the alarm triggered by reduced air flow and/or differential pressure?
(3) Is the system alarm wired to a separate electrical circuit or backed up by a battery, should the mitigation system's electrical circuit fail?

Fan.

(4) Is the system fan capable of sustaining a pressure differential of at least .5 inches WC at a flow rate of greater than or equal to 60 CFM (standard 4 inch mitigation fan or larger?)

Fan mounting.

(5) Is the system fan mounted vertically?
(6) Is the fan properly mounted and adequately supported?
(7) Is the system fan mounted outside the negative pressure field of the house?

Note: Fans located inside the house, garage, or crawlspace are inside the negative pressure field of the house.

If the fan is located in the attic answer questions 8, 9, and 10.
(8) Does attic have external air vents?
(9) Is the attic free from a permanent stairwell (not including a pull-down stairwell) to living areas below?
(10) Is the attic free from a chase that enters the attic from the living areas below?

Sump.

If the house contains a sump, answer questions 11-14.
(11) Is the sump capped?
(12) Is the sump capped with a plastic, metal or wood cover?
(13) Is the sump cover caulked and sealed to the floor?
(14) Is the sump cover secured to floor with masonry bolts?

If the sump contains a pump or if a pump was present prior to mitigation, answer questions 15 and 16.
(15) Does the sump contain a submersible pump?
(16) Does the sump discharge line contain a reverse flow valve?

If the sump was used as a floor drain prior to mitigation, answer question 17.
(17) Does the sump cover contain an air tight water drain that allows water accumulating on the basement floor to drain into the sump?

If the floor drain drains to sump, answer question 18.
(18) Is the floor drain trapped at the drain or at the point where the drain line enters the sump?

Sump/Drain Tile Suction System.

If any floor drains, window well drains, gutter down-spouts, etc. connect to the drain tile, answer question 19.

(19) Have these connections to the drain tile system been properly trapped to prevent exterior air from entering the system?

If an exterior drain tile suction system is used, answer question 20.

(20) Is there a check valve or trap in the piping between the fan and the drain tile?

If a trap exists, answer question 21.

(21) Does the trap design permit the owner to check water level in the trap and add water?

Pipe.

(22) Does the system use PVC pipe or a durable equivalent?
(23) Is the system free of dryer vent hose or flexible pipe?

Pipe slope.

(24) Are horizontal runs in pipe sloped toward the sub-slab vent point so that condensed water drains to the ground?
(25) Is the pipe free of low points in horizontal pipe runs that can collect condensed water and block air flow?

System exhaust.

(26) Does the sub-slab depressurization exhaust extend above the eaves of the house?
(27) Is the exhaust port at least six feet from the structure if vented through garage roof or other lower level roof?
(28) Is the exhaust port at least 8" above the roof line so that it can not be blocked by snow?
(29) Is the exhaust pipe capped with a rain guard and or covered by a protective screen?

If the exhaust port exits near dormers or skylights, answer question 30.

(30) Is the system exhaust port at least 10 feet from windows and skylights.

System insulation.

If schedule 40 or greater PVC (or equivalent) is used in a climate with greater than 5000 degree heating days, answer questions 31 and 32.

(31) Are all interior exhaust pipe runs (i.e. pipe runs in unheated crawlspaces or attics) that are located in untempered space insulated?
(32) Are all exterior exhaust pipe runs insulated?

If less than schedule 40 PVC (or equivalent) is used in a climate with greater than 4200 degree heating days, answer questions 33 and 34.

(33) Are all interior exhaust pipe runs (i.e. pipe runs in unheated crawlspaces or attics) that are located in untempered space insulated?
(34) Are all exterior exhaust pipe runs insulated?

Electrical, Mechanical, Building Code Compliance.

(35) Has the installation of the system passed local code requirements by a county/city inspector and proof thereof been produced?

TITLE: Correlation of Diagnostic Data to Mitigation System Design and Performance as Related to Soil Pressure Manipulation

AUTHOR: Ronald F. Simon, R.F. Simon Company

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

The U. S. Environmental Protection Agency has identified the Montclair, Glen Ridge, West Orange, New Jersey site as being contaminated with radium tailings. In order to control indoor radon concentrations as a product of these tailings, the Environmental Protection Agency has initiated a state-of-the-art diagnostic and mitigation program. Through this program extensive diagnostics have been performed, directed toward mitigation strategies that incorporate soil pressure manipulation.

Typically, soil depressurization in permeable soils can readily be accomplished. However, in a tight soil configuration, soil pressure manipulation becomes more difficult due to the inherent properties of the soil.

The information collected during diagnostics is compared to installed system performance to aid in effective system design and installation . The information presented in this paper will allow the diagnostician and installer to interpret and apply site specific diagnostic data directly to the design and installation of soil pressure manipulation systems. This data represents a missing link that will allow systems to be sized appropriately and reduce the number of system failures.

TITLE: Pressure Field Extension Using A Pressure Washer

AUTHOR: William P. Brodhead, WPB Enterprises

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

ABSTRACT

Radon remediation is typically done with sub-slab ventilation systems. Sub-slab ventilation installation failures are often due to an incomplete pressure field extension that allows radon to continue to enter the building. Over half the homes we mitigate do not have a good gravel base under the slab. This project investigated a technique for extending the pressure field in tight soils from a single suction point by the creation of sub-floor tunnels using commonly available high pressure washers. Houses with the appropriate tight non-rocky soil were tested for radon and pressure field extension before and after tunneling with the high pressure washer. Different equipment and techniques were used and described.

The tunneling under the slab was an effective method for extending the pressure field. This technique holds good promise for mitigators dealing with tight soils and restrictions with where they can locate suction holes.

A VARIABLE AND DISCONTINUOUS SUBSLAB VENTILATION SYSTEM AND ITS IMPACT ON Rn MITIGATION

WILLY V. ABEELE.
NEW MEXICO ENVIRONMENTAL IMPROVEMENT DIVISION
1190 St FRANCIS DRIVE
SANTA FE, NM 87503

Abstract- A house, with a high specific area in contact with earth materials, was chosen as the site for a long-term Rn mitigation study. Close to 30 000 Rn readings were collected and intensive use of statistics was made to determine locations, time periods and external parameters promoting high Rn activity. Several Rn mitigation methods were studied such as passive subslab ventilation, active subslab pressurization and active continuous and discontinuous subslab depressurization. Varying degrees of subslab depressurization were also combined with discontinuous fan activation to determine the most cost-effective method of Rn mitigation. Recommendations are for a -50 Pa subslab depressurization either on a full-time or a part-time basis. The most cost-effective method used for Rn mitigation was sealing of a slab opening. The minimum Rn concentrations were obtained, whether the opening was sealed or not, upon activation of the subslab depressurization system. The influence of cold weather and subsequent increased stack effect is clearly reflected in higher Rn concentration readings.

INTRODUCTION

Lack of adequate ventilation in a house may allow Rn and its decay products to reach levels well above the average outdoor levels. The potential primary sources of Rn in the house under study are the adjacent earth materials and existing building materials. The significant sources of Rn, as well as its primary pathways, will be examined, as will be the influence of subslab ventilation on indoor Rn concentration. Passive subslab ventilation, active subslab pressurization and depressurization will be examined as potential remediation. A simple analysis will be used to determine the potential role of each source. This will be derived from the efficiency with which a particular remedial system is controlling the Rn level in the house. Whereas in a typical house (including garage), an average volume of 500 m^3 has a 200 m^2 surface in contact with earth materials, with a subsequent specific contact surface of 0.4 m^{-1}, the house under study (including garage), has a volume of 500 m^3, with 300 m^2 in contact with earth materials and a subsequent specific contact surface of 0.6 m^{-1}. This high proportion of surface in contact with earth materials (50% higher than average) is due to the house under study being built into the side of a hill. The house design is one of slab over footing which eliminates the vertical floor/wall transition joint. It is noteworthy that the building has all its windows but one facing south, with the exception facing east. The building is to be considered very tight, with little or no cross-ventilation.

The purpose of this study is to examine the close to 30 000 Rn readings that were collected over a time period of two years ending in June 1990. Readings taken during the summer period, when windows were left open around the clock, were recorded but not incorporated in the study. The study ran from September 1988 to June 1989 and from September 1989 to June 1990.

RADON EMANATION AND EXHALATION

To study radon emanation from soils and its exhalation from building materials, a correct assessment of parent material and long-lived progeny present in these materials is necessary. The house is almost totally built of concrete. Polystyrene forms were used to shape the walls. These forms were then filled with concrete. The polystyrene remained subsequently in place and served as an internal and external insulation layer. Approximately 120 m^3 of concrete was used during construction. This includes the prestressed concrete roof of the garage which serves as floor to the kitchen but does not include patios, walkways, detached walls etc.. A concrete sample was taken every estimated 10 m^3. The twelve samples were collected, during construction, in Marinelli beakers for radiological assessment. With n=12, ^{226}Ra averaged 37.3 Bq kg^{-1}, with a standard deviation of 8.1 Bq kg^{-1}, while ^{238}U averaged 41.5 Bq kg^{-1}, with a standard deviation of 5.5 Bq kg^{-1} and ^{210}Pb was right at 80 Bq kg^{-1} with a standard deviation of 24.9 Bq kg^{-1}. Unrelated to ^{222}Rn but radiologically significant, ^{235}U averaged 1.7 Bq kg^{-1} while ^{212}Pb had a mean of 28 Bq kg^{-1}.

The highest calculated transmission fraction was for ^{214}Pb, a Rn progeny, with a photon energy of 351.9 keV. Fifty mm of concrete would have a transmission factor of 0.532 for ^{214}Pb, while ^{226}Ra would have one of 0.434 at 186 keV through 50 mm of concrete.

Soil samples taken around the house foundation revealed a ^{226}Ra concentration of 36 Bq kg^{-1}, while ^{238}U averaged 29 Bq kg^{-1} and ^{210}Pb equaled 44 Bq kg^{-1}. The ^{234}U mean was 26 Bq kg^{-1} and ^{230}Th averaged a concentration of 34 Bq kg^{-1}. The unrelated radioisotope of significance, ^{232}Th, measured 36 Bq kg^{-1}.

The slightly higher ^{226}Ra activity found in concrete does not make up for the much smaller emanation coefficient or escape to production ratio of ^{222}Rn found in concrete. It is unlikely that concrete will be found to be a major source of ^{222}Rn.

The assumption was made, subject to a revision based on observation, that the most important Rn entry process is the pressure driven flow of Rn through the substructural system (soil+slab). This is normally orders of magnitude higher than Rn entry rates from building materials, water and outdoor air. Entry rates by diffusion directly through the masonry substructure is even less (1). The Rn entry rate due to pressure-driven flow is primarily a function of a pressure differential driving this flow (2), soil Rn activity and substructural (soil+slab) permeability. Pressure differentials that activate Rn entry are, among others, the easily identifiable ones triggered by temperature differentials and combustion devices that draw indoor air needed for the combustion process.

INSTRUMENTS AND DESIGN

The ^{222}Rn activity was measured using charcoal canisters and the Working Level Reader (WLR) in conjunction with several Working Level Meters (WLM) from Eberline[1] for continuous sampling. The WLMs are really measuring the equilibrium equivalent concentration of Rn (EER), which is that activity concentration of Rn in radioactive equilibrium with its short-lived daughters which has the same potential alpha-energy concentration as the actual non-equilibrium mixture (3). This will be reported in this paper more simply as Rn activity.

The WLM provides the function of sample collection and data storage. These data points are stored in memory until retrieved by the WLR. The WLM microcomputer turns the pump on at the preset starting time, and the activity on the filter paper is counted for the total time period specified. Calibration of the WLM at the Technical Measurement Center, Grand Junction, Colorado , showed the instruments to be highly precise. Occuring inaccuracies were corrected through calibration. All the WLM readings were on the low side and had to be corrected by factors varying from 1.437 to 2.031. On the other hand, the repeatability of the measurements, no matter how originally inaccurate, yielded an average coefficient of variation of 3.19%, which is a measure of the precision of the instrument.

Subslab ventilation consisted of a network of perforated pipe installed horizontally underneath the existing slab. Such a comprehensive system is likely to provide a better performance than when a vertical pipe perforates the slab and a relatively strong pressure gradient with limited pressure field is induced.

In any case, good subslab communication is required. The subslab material consists of a 0.1 m layer of gravel with assumed high permeability. Ventilation could be passive or active. Active ventilation could result in subslab pressurization or

---

[1] Eberline Instrument Corp, Airport Rd, Santa Fe, NM

The values in parentheses represent actual measurements, calculated averages, a derivation from measurements (such as the soil gas concentration derived from soil ^{226}Ra analyses) or a best guess (such as the ventilation rate). Accordingly, a soil would have to have a permeability of $4.25*10^{-10}$ m^2 to sustain a Rn entry rate of 0.0142 Bq m^{-3} s^{-1}, which in turn would lead to an indoor Rn concentration of 142.8 Bq m^{-3}, which is the average Rn concentration measured inside the bedroom in 1988-89. A permeability value of $4.25*10^{-10}$ m^2, although high, is indeed acceptable. Average soil permeabilities range anywhere from 10^{-16} to 10^{-7} m^2 but may be impermeable to the point of reaching values of 10^{-21} m^2, which are ideal for waste containment and are indeed the permeabilities evaluated to exist at the Waste Isolation Pilot Plant in the Salado formation in Carlsbad, New Mexico (4).

RESULTS (1988-1989)

When averaged, the Rn activity peak was found to be located at around 23.2 hrs (11.2 P.M.), while the minimum activity seemed to be centered around 10.8 hours (with standard deviations of 4.10 hours and 3.87 hours respectively). This seemed to correspond well with the computed timings of maximum and minimum depressurization. Maximum depressurization and consequent peak Rn activity seem to occur earlier than in the average home (5). This could be occuring because the heat is not controlled by thermostat and the house is mostly responding to solar heating patterns. The fact that the temperature is solely controlled by a solar heat sink could be at the origin of a maximum indoor-outdoor temperature difference occuring earlier than in a thermostat controlled home because of an early drop in indoor temperature and, consequently, earlier maximum temperature differential and the maximum depressurization that inevitably follows.

A computed depressurization of 1.87 Pa corresponded with a Rn activity of 142.7 Bq m^{-3}. The regression analysis of Rn activity on depressurization was run on the computed corresponding daily means. The correlation coefficient between depressurization and Rn activity is 0.32, which with 196 degrees of freedom (d.f.) is still highly significant (at the 1% level).

The correlation is significant at the 1% level because of the high degrees of freedom. The remarkable aspect of this regression analysis is that high depressurization was always associated with high Rn activity, although the reverse was not necessarily true. High Rn activities were also noticed at low depressurizations.

This would lead to the obvious conclusion that other factors besides thermally induced depressurization play a role in causing high Rn emanation rates into the house. Two of the factors, wind velocity and direction (6,7), and soil moisture (8), known to influence indoor Rn emanation, were not studied because of lack of equipment, although soil temperature was monitored. Because of the depressurization and is produced by an on-line centrifugal fan well suited to conditions of moderate static pressures. The fan in use is a 90 Watt T-2 centrifugal fan from Kanalflakt[1] with a flow rate of 0.1275 m^3 s^{-1}.

STACK EFFECT

Temperature differentials produce pressure differentials across vertical walls. This pressure differential is directly proportional to the height of the walls. Making a few assumptions about temperature uniformity, the expression:

$$dp = (r*g*z*dT)/(T_i+273)$$

reflects the pressure difference at any distance z from the neutral pressure plane, with dT the temperature difference and T_i the indoor temperature. The soil gas density (in kg m^{-3}) is expressed by r while g is the acceleration due to gravity (in m s^{-2}). This expression can be simplified, after filling average values in for r and g, to reveal an average depressurization of 0.04 Pa $^oC^{-1}$ m^{-1}. In the house under study, this amounted to an average depressurization of 0.1 Pa $^oC^{-1}$. The effect of soil temperature was considered separately.

The Rn entry rate in the bedroom, whose floor averages a depth of 2 m below the soil surface, is expressed by the equation (1):

$$E =((C*L*dp)/(V*P))*(G/(12W^3)+ACOSH((2Z)/W)/(PI*K))^{-1} \quad \text{(in Bq } m^{-3}\ s^{-1}\text{)}$$

where
- V = volume of house (500 m^3)
- C = soil gas concentration (40000 Bq m^{-3})
- L = crack length (10 m)
- G = slab thickness (0.15 m)
- dp = pressure differential (1.873 Pa)
- P = soil gas viscosity ($1.7*10^{-5}$ Pa s)
- W = floor crack width (0.002 m)
- K = soil permeability ($4.25*10^{-10}$ m^2)
- Z = floor depth below soil surface (2 m)
- E = Rn entry rate (Bq m^{-3} s^{-1})

The steady state mass balance equation for the corresponding indoor Rn concentration can consequently be calculated.

$$Rn = (E+(N-E/C)*Rn_0)/(N+d) \quad \text{(in Bq } m^{-3}\text{)}$$

where
- N = ventilation rate (10^{-4} s^{-1})
- Rn_0 = outdoor Rn concentration (4 Bq m^{-3})
- d = decay constant of Rn ($2.1*10^{-6}$ s^{-1})

----

[1] Kanalflakt, 1121 Lewis Ave., Sarasota, Fl.

particular microclimate of a hillside topography, wind velocities and directions could not be assumed to be related to the ones measured at the airport, located on a plain on the other side of town. Acquisition of an anemometer and wind vane was not considered because of cost and dubious results originating from the warped topography. Cost was also a factor in not measuring soil moisture, although studies show that the emanation coefficient is strongly influenced by it. (9) show that the emanation coefficient increases nearly four times as the moisture content by mass increases from 0.2 to 5.7% to drop drastically as the soil becomes saturated.

Analysis of the Rn activity in the bedroom shows that in 64% of the cases, the nighttime average is significantly higher than the daytime readings, while in 28% of the cases daytime averages are significantly higher. In 8% of the instances there is no significant difference between daytime and nighttime averages. It is also noteworthy that in 46% of the instances, nighttime averages exceeded 150 Bq m^{-3}, while the 200 Bq m^{-3} level was exceeded 22% of the time, the 300 Bq m^{-3} level 6% of the time and the 400 Bq m^{-3} level was exceeded only once. A t-test of daytime vs nighttime means show a p-value of 0.0026 which demonstrates a very significant difference between those two averages. The maximum **hourly** average ever recorded was $1.33*10^3$ Bq m^{-3}.

A woodstove was ignited on 16 nights during the study period. Measurements show that Rn activity was 235 Bq m^{-3} or 164.4% of average during that period, which seems to indicate that woodstoves, or low outside temperatures, or cloudy days accompanied by snow on the ground (thereby additionally capping the soil and decreasing Rn exhalation) may be linked to an increased pressure differential.

Simultaneous depressurizations and Rn activity levels were measured or calculated simultaneously for the bedroom and the garage. Despite the fact that the garage floor was crisscrossed by shrinkage cracks, the Rn activity measured consistently lower in the garage. This could be due to a lower depressurization in the garage. If simultaneous depressurization and Rn activity readings were taken in the bedroom and the garage, time related uncertainty elements would be eliminated. In this case, the coefficient of correlation rose to 0.87 with 24 degrees of freedom (instead of 0.32 with 196 degrees of freedom where time and fluctuations thereof were a factor).

When the indoor Rn levels in the bedroom were compared to the indoor levels in the bathroom, a remarkable similarity emerged. Although the bathroom levels were consistently higher, the periods of maximum Rn activity in the bathroom and the bedroom show a high degree of concurrence with the maximum centered around 23.2 hours and r = 0.98, while the minimum centered around 10.8 hours and r = 0.95. The readings in both rooms are in almost perfect synchronization.

The Rn daughter activity, as measured with the WLM (W), is related to the Rn activity, measured with the charcoal canister (C), by the equation $W = -65.8622 + 0.8439*C$, with $r = 0.57$ and 54 degrees of freedom.

It is important to remember that even if readings were gathered every hour, all the above statistical analyses are based on computed daily averages. All the above experiments were performed with the venting system blocked off and inoperative. The subslab venting system was put in operation shortly before the annual deadline dictated by the arrival of summer (which meant a radical increase in room ventilation and subsequent Rn removal other than by quantitatively controlled means such as subslab ventilation controlled by a regulated fan).

The Rn activities, now measured by the hour because of the short study period remaining in 1988-1989, show a drastic drop when either convectional venting or active subslab pressurization was applied.

Table 1 shows the Rn activity in the bedroom before the system was in operation (I), when the system was convectionally venting or passive (P), and when the subslab was actively and continuously pressurized (A).

It is important to notice, that the data for P and A are statistically much less significant than the data for I because they cover a much shorter period of time (hours instead of days for I). It is also important to note the drastic drop in the standard deviation or the coefficient of variation (c.v.) when the system is activated.

When the subslab is pressurized, the trend of maximum and minimum activity seems to be curbed. This is reflected in the smaller standard deviation of the readings. House depressurization does not seem to influence Rn entry noticeably because of the overwhelming effect of subslab pressurization.

Four rooms were regularly checked and their Rn activity could be ranked as follows by decreasing order of activity: bathroom, bedroom, living room and kitchen. The fact that the remedial system equalizes the indoor Rn activity points the finger at the soil as the main source of Rn since the subslab pressurization only inhibits the soil gases entry but does nothing to prevent the Rn emanation from tap water and could only activate the emanation of Rn trapped in the slab. The subslab pressurization system affects Rn inhibition equally strongly in both bathroom and bedroom pointing again at the soil as the main source (water, available in the bathroom but not in the bedroom, does not seem to be a main source of Rn).

It is important to note that active subslab ventilation seems more effective in reducing Rn activity in the house than room ventilation.

Two remarks remain to be made. First, the effectiveness of the passive system was demonstrated by the appearance of an ice plume at the vent outlet. This can be explained by the fact that even a dry soil has a relative humidity of close to 100%. As the soil gases escape in winter, their saturation point is reached as the temperature drops. If the temperature is low enough, the condensate freezes to preserve the proof of the escape! Second, it is believed that for subslab pressurization to be effective, the system must create airflow to dilute the Rn in the subslab gas. The same problem is not faced when subslab depressurization takes place. This is why some authors believe subslab pressurization to be less effective than depressurization (10).

RESULTS (1989-1990)

NO SUBSLAB VENTILATION

During this period, the day-to-day correlation between Rn concentration and house depressurization due to temperature differential was poorer than during the previous season and was consequently found not to be significant. Only on a long-term basis could a trend be observed. The Radon concentration increased steadily from September 3 through January 12, as the average temperature continued to decrease. Figure 1 seems to indicate a strong relationship between average ambient temperature, and consequent room depressurization, and indoor Rn activity. More importantly, the Rn activity seems equally closely related to the soil temperature which plays a pivotal role in influencing the depressurization process since the house is built into the side of a hill and that differential pressure is consequently for a good part governed by soil temperature (The soil temperature underwent a steady drop during this period, which meant increased stack effect and consequent increased house depressurization followed by increased Rn intake). During the earlier part of the testing period, occasional opening of doors and windows took place as comfort requirements mandated.

To measure the impact of subslab depressurization on Rn infiltration, cyclical periods of high and low Rn concentration in the building had first to be established for that season. Daily t-tests were evaluated that showed a significant difference between nighttime and daytime Rn concentration. It was therefore determined to divide the 24 hour day (which is also a 24 readings day) into two uninterrupted halves respectively centered around a maximum and a minimum Rn concentration. Two WLMs were in uninterrupted use, out of a total of four for continuous rotation purpose. One WLM was again located in the bathroom, while the other was once more placed in the bedroom. Continuous rotation of the four WLMs took place to avoid bias. A concurrent intention was to check how well last seasons' results could be replicated.

Based on the various t-tests, it was decided to compare, in both the bathroom and the bedroom,the results obtained from 19:00 hrs to 6:00 hrs (night) against those obtained from 7:00 hrs to 18:00 hrs (day). The maximum readings (fig 2) occured around the same time period as the previous year (23.2 hrs). To check the effectiveness of subslab depressurization, it was determined to run a t-test of day vs. night on the Rn concentration obtained over a period of two and a half months in both the bathroom and the bedroom, without any ventilation taking place.

The Rn readings were again always higher in the bathroom. This was confirmed by readings obtained using Rn canisters located at regular interval in connecting rooms. The canisters were situated in the bathroom, the bedroom, the living room and the kitchen, with the bedroom, living room and kitchen canister located along an airway respectively 10 m, 20 m and 30 m from the canister in the bathroom. These readings were repeated ten times and, without any exception, the decreasing order of the activities remained unchanged: bathroom, bedroom, living room and kitchen. This seemed to indicate that the bathroom is the main entry route for Rn into the building. Although there is no ideal statistical method to express the existing relationships, some type of quantification of the strong path evidence can be demonstrated by applying a regression analysis which yielded:

$$Y = 263.9 - 5.06X \quad \text{with } r = 0.999$$

where Y = Rn concentration in Bq m^{-3}
X = distance from the alleged source in m

Concurrent readings obtained from the WLMs showed that, without any single exception, and despite rotation of the WLMs, readings in the bathroom, which were taken during the day as well as during the night, were always higher than in the bedroom.
In both cases, day or night, the bathroom readings were more than 50% higher than in the bedroom (fig 3). Although the parallelism in the readings is as good as during the previous year, there is a greater discrepancy in the activity levels during the 1989-1990 season. This is mainly due to a strong drop in Rn levels in the bedroom.

Parallelism in the readings and, by extension, precision, can be concluded from a multiple regression analysis where one of the WLMs was chosen at random as the dependent variable whereas the three others were designated as independent variables. The adjusted coefficient of multiple determination, R^2, was found to be, after 106 consecutive measurements, equal to 0.985 (which is highly significant). The same test demonstrated further evidence of the precision through the low coefficients of variation (4.71%) existing between the various instruments in use.

A t-test performed on the Rn measurements taken in the bathroom demonstrated that for a nighttime average of 147.8 Bq m^{-3} and a daytime average of 85.6 Bq m^{-3}, the p-value was $7.6*10^{-6}$, which means that the chance that the two sets of samples (day and night) might belong to the same population (or not be different), is very slim indeed.

After applying the Behrens-Fisher correction where necessary, it was found that 80% of the bathroom readings were significantly higher at night than during the day (fig 4), while 14% of the readings did not show any significant difference and 6% of the measurements showed significantly higher daytime values (at the 5% significance level).

The t-test performed on the Rn measurements taken in the bedroom illustrate that for a nighttime average of 85.9 Bq m^{-3} and a daytime average of 56.4 Bq m^{-3}, the p-value was $4.2*10^{-5}$, which still demonstrated a very significant difference between nighttime and daytime means. The nighttime readings in the bedroom were significantly higher in 70% of the cases, not significantly different in 23% of the cases and 7% of the readings showed a significantly higher daytime reading. Table 2 compares the 1988-1989 with the 1989-1990 measurement period.

As can be seen, these Rn activities are quite a bit lower than the ones measured the year before. This is also confirmed by the Rn canister readings. One can only speculate about the effect of the sunny (and often warm) days that occured in the 1989-1990 fall and winter, causing lower room depressurization and consequent lower Rn concentrations (fig 5). Much more frequent use of the woodstove during the previous winter seemed to correspond to higher Rn activities in the house. The drop was also found to be much more drastic in the bedroom (which happens to be much closer to the stove).

The averaged daily coefficients of variation (CV) are significantly higher for daytime measurements in the bathroom (36.3% vs 25.5%) and the bedroom (35% vs 23.2%) with p-values of daytime vs. nighttime of $1.4*10^{-4}$ and $5*10^{-6}$ respectively. This shows daytime and nighttime CV to be significantly different, with daytime readings showing the highest variability, thereby indicating a higher variability in the spread of the readings recorded from one day to the next.

DISCONTINUOUS SUBSLAB VENTILATION

The active ventilation system was now used to depressurize the subslab. The depressurization time was gradually increased. The subslab depressurization was measured to be -175 Pa.

Depressurization time: 6 hours/day at -175 Pa.

The fan was activated from 0:00 hrs until 6:00 hrs. The decrease of Rn activity in the house was measured to be within one hour of start of activation, so that the time of maximum Rn activity remained at 23:00 hrs. Radon activity in the house bottomed out about 5 hours after fan activation to 35 Bq m^{-3} or less and remained near that level for about 10 hours, so that the period of lowest Rn activity did not correspond to the period of subslab depressurization.

Depressurization time: 12 hours/day at -175 Pa.

The daily subslab depressurization period lasted from 18:30 hrs until 6:30 hrs. The time of maximum activity in the house was now measured at 19:00 hrs, so that one could conclude that Rn abatement was measurable within one and a half hour of subslab depressurization. The half-day periods measuring the highest Rn activity were from 14:00 hrs until 1:00 hrs. Again, Rn activity bottomed out about 5 hours after fan activation. Although of questionable value, since the data sets are not independent, a t-test of "high" activity vs "low" activity showed that the difference was still significant.

Depressurization time: 24 hours/day at -175 Pa (from 6:00 hrs until 6:00 hrs).

Depressurization occurs from 6:00 hrs until 6:00 hrs the next morning, only to be deactivated for the next 24 hours and reactivated again the following day at 6:00 hrs. As was the case previously, fan activation caused an immediate lowering of the Rn activity with the readings again bottoming out after 5 hours and resulting further in a curve sharply reduced in amplitude. After the fan was deactivated the next morning at 6:00 hrs, a rather rapid rise in Rn activity occured at 16:00 hrs or about 10 hours after the fan was deactivated. The maximum readings obtained during the deactivation period were around 23:00 hrs. During depressurization of the subslab no trend at all was apparent.

Depressurization time: 24 hours/day at -175 Pa (from 18:00 hrs until 18:00 hrs).

Depressurization occurs now from 18:00 hrs until 18:00 hrs, ending consequently around the time that Rn activity normally starts to climb. Within a few hours after fan deactivation (at 18:00 hrs), a rapid rise in Rn activity is now witnessed (fig 6). While the subslab was depressurized, on the other hand, high Rn activity was inhibited, so that during this period, a flat curve appeared, contrasting sharply with the curve obtained after the fan was deactivated (before the diurnal peaks of Rn activity).

Since Rn levels remained low up to 10 hours after fan deactivation, it was concluded that activating the fan 12 hours/day during the period corresponding to that of highest indoor Rn activity was the most cost-effective way to use the discontinuous subslab depressurization system (at -175 Pa).

SUBSLAB DEPRESSURIZATION AT VARYING FAN SPEEDS.

It was obvious at this stage that, regardless of any remedial action taken, the bathroom measurements remained significantly higher than measurements taken in any other room. On investigation as to the probable cause,and removal of a trapdoor accessing the bathtub, a large slab opening was found. After sealing that opening with expanding polyurethane foam, only a sporadic and intermittent difference remained between the Rn concentration found in the bathroom and the rest of the house. The Rn levels now average 68 Bq m^{-3} throughout the house without any subslab ventilation taking place (average of the last 5 weeks in both the bathroom and the bedroom; table 3). Table 4 indicates the hourly maxima and minima obtained under varying circumstances. It is noteworthy that subslab depressurization results are not significantly different if measurements are taken before or after sealing of the slab opening.

Investigation of the influence of varying subslab depressurization on Rn concentration indicated that after sealing the slab opening, no drastic decrease in indoor Rn activity took place beyond -50 Pa depressurization, which is the smallest depressurization attainable through fan activation (Fig 7). The influence of warmer weather and subsequent decreased stack effect can be seen once more as time progresses. Weekly measurement cycles featuring daily increases in depressurization (from 0 to -175 Pa) show a trend of decreasing Rn concentrations as weeks (wk) progress towards springtime (table 3). Subslab depressurization appears to be effective if the fan is activated during the peak Rn activity hours (18:30 hrs until 6:30 hrs the next morning). Practically no activity occured until the fan was left deactivated during the peak Rn activity period (fig 8).

CONCLUSIONS

Probably the most cost-effective method used for Rn mitigation was the sealing of the slab opening under the bathtub. For research purposes, it was a boon that such action took place late in the study. Results show that indoor Rn activities were strongly dampened after sealing the slab opening and some relationships even disappeared totally thereafter (Such as the distance from "source" and Rn activity relationship).

The intermittent activation of the fan shows that the Rn mitigation is effective, in most cases, long after fan deactivation, showing a certain degree of "exhaustion" of Rn as a soil gas (probably replaced by atmospheric gases). This rule does not seem to apply if fan deactivation occurs around the time that indoor Rn activity normally starts to climb.

Equally low Rn concentrations could be obtained with the depressurization system in operation, regardless of whether the slab opening was sealed or not.

Before sealing the slab opening, decreases in Rn activity of 95% were obtained through subslab depressurization (at -175 Pa) because of the high initial Rn concentration. A noticeable drop in temperature (-2^{0}C) was also experienced when the system was fully depressurized. After sealing the slab opening, it appears that the increased benefits obtained from running the fan at full speed are marginal and that an overall decrease in Rn activity of 85.3 % of maximum (obtained at a subslab depressurization of -175 Pa) can be obtained by running the fan at -50 Pa. Due to the much lower initial Rn concentration, this only amounts to a decrease of 51.6 % of the incipient Rn activity. A t-test shows no significant improvement to be obtained by depressurizing the subslab at -175 Pa instead of -50 Pa (p-value :0.033). A satisfactory reduction in Rn activity was obtained by depressurizing the subslab at -50 Pa for only 12 hours/day during the peak Rn activity hours (18:30 hrs until 6:30 hrs).

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Acknowledgments-The support of Kirkland Jones, Neil Weber and Eloy Montoya is acknowledged for making this report possible. Thanks are also going to Benito Garcia and Bill Floyd for liberal use of their equipment, to Loren Berge of the State Laboratories for the radiological analyses and to Ed Essington of the Los Alamos National Laboratory for the graphics.

REFERENCES

Journal

1. Mowris, R. J. and Fisk, W. J. Modeling the effects of exhaust ventilation on ^{222}Rn entry rates and indoor ^{222}Rn concentrations. Health Physics Vol. 54 No. 5 pp. 491-501, 1988.

2. Nazaroff, W. W. Entry by pressure-driven flow or molecular diffusion? A reassessment of Rn concentrations measured in an energy efficient house. Health Physics Vol 55: 1005-1014; 1988.

3. Swedjemark, G. A. and Makitalo A. Recent Swedish Experiences in ^{222}Rn Control. Health Physics Vol.

58 No 4 pp 453-460, 1990

Report 4. Lappin, A. R. and Hunter, R. L. Systems Analysis, Long-Term Radionuclide Transport and Dose Assessments; Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; 1989; SANDIA REPORT SAND89-0462*UC-70; DOE contract DE-AC04-76DP00789

5. Hall, A. Unpublished Rn data from New Mexico Environmental Improvement Division taken from over 250 houses in Northern New Mexico, 1986-1987.

Journal 6. Jonassen, N. On the effect of atmospheric pressure variations on the Rn concentrations of unventilated rooms. Health Physics Vol 29:216-220; 1975.

7. Stranden, E. and Berteig, L. Radon in dwellings and influencing factors. Health Physics Vol 39: 275-284; 1980.

8. Schery, S. D.; Gaeddert, D. H. and Wilkening, M. H. Factors affecting exhalation of Rn from a gravelly sandy loam. J. Geophys. Res. Vol 89: 7299-7309; 1984.

9. Strong, K. P. and Levins, D. M. Effect of moisture content on radon emanation from uranium ore and tailings. Health Physics Vol. 42 No 1 pp. 27-32,1982.

Symposium 10. Henschel, D. B.; Scott A. G.; Findlay, W. O. and Robertson, A. Testing of indoor radon reduction methods in 16 houses around Dayton, Ohio. 1988 symposium on radon reduction technology. Denver, Colorado.

Table 1: Rn activity (Bq m^{-3}) in 1988-1989

System	Mean	Std. Dev.	d. f.	c.v. (%)
Inactive	142.7	66.5	196	46.6
Passive	82.9	38.6	166	46.6
Active	30.6	6.66	200	21.7

Table 2: Comparison of Rn concentrations in bedroom (E) during 1988-89 and during 1989-90 and in bathroom (A) during 1989-90

	88-89(E)	89-90(E)	89-90(A)
Xn (Bq m^{-3})	155	85.9	147.8
Xd (Bq m^{-3})	129	56.4	85.6
p-value	$2.6*10^{-3}$	$4.2*10^{-5}$	$7.6*10^{-6}$
Xn > Xd (%)	64	70	80
Xd > Xn (%)	28	23	6
no difference (%)	8	7	14

Table 3: 0 to -175 Pa consecutive (8) weekly depressurization cycles and their influence on Rn (in Bq m^{-3}). (A refers to bathroom and E to bedroom)

Depress.(Pa)	0	-50	-75	-100	-125	-175
Rn (A)	138					25.0
" (E)	132					19.6
" (A)	122					36.5
" (E)	128					24.2
" (A)	190	43.5				
" (E)	167	35.0				
" (A)	92.9	35.0	40.1	38.2	35.6	36.4
" (E)	87.9	39.1	45.0	39.0	34.8	36.3
" (A)	51.0	36.0	32.7	40.5	38.7	31.0
" (E)	44.9	28.6	25.6	33.9	33.9	25.4
" (A)	65.2	43.0	35.9	43.7	40.7	26.9
" (E)	52.7	35.6	28.3	34.6	33.3	21.5
" (A)	83.3	31.6	34.7	37.7	29.2	25.6
" (E)	73.9	27.0	32.0	34.5	26.8	22.5
" (A)	73.1	28.4	30.6	29.5	38.9	31.0
" (E)	50.7	24.7	23.6	22.6	29.1	24.1

Table 4: Hourly extremes (in Bq m^{-3}):

	Max	Min
Before sealing	1330	37
After sealing	299	12.3
-175 Pa depressurization	50.8	2.73

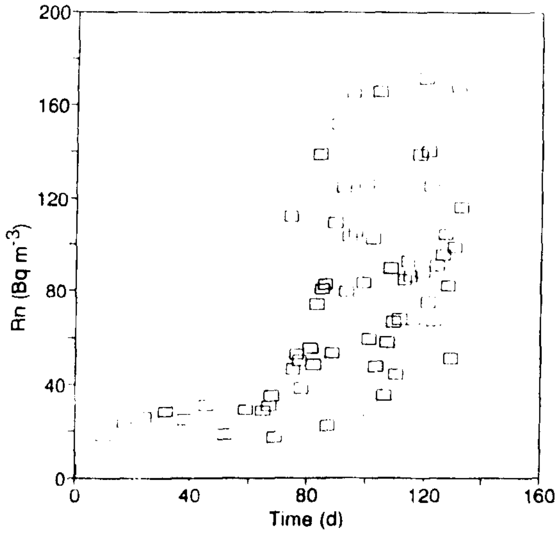


Fig. 1. Rn Levels as a Function of Time (Day 1 = 3 Sept 1989)

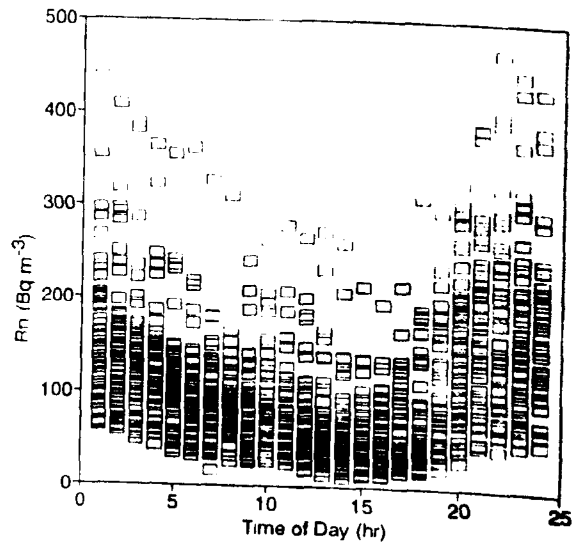


Fig. 2. Hourly Rn Levels (Winter 1989-90)

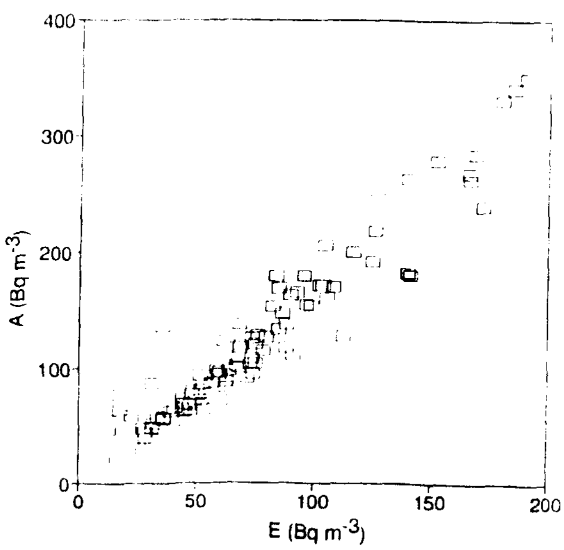


Fig. 3. Rn Levels in Bathroom (A) vs. Bedroom (E)

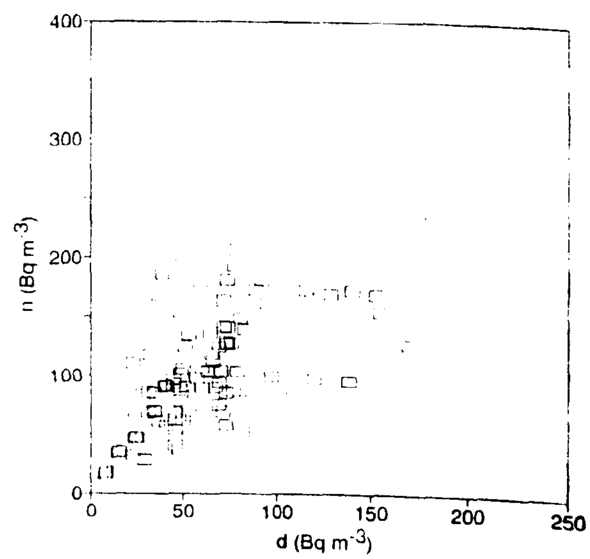


Fig. 4. Rn Levels, Day (d) vs. Night (n)

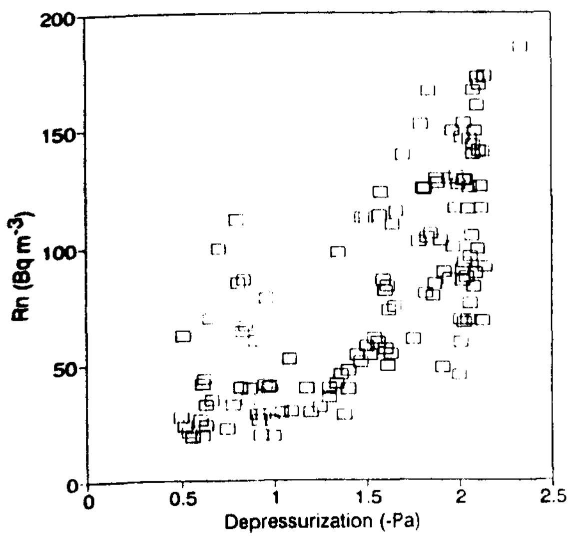


Fig. 5. Room Depressurization vs. Rn Activity

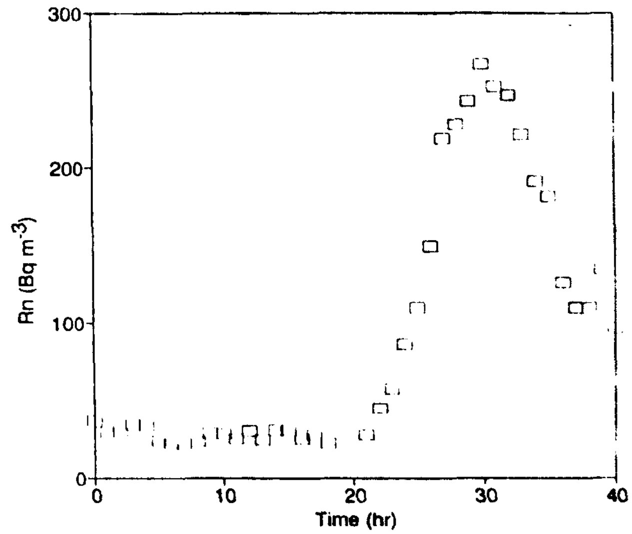


Fig. 6. Depressurization Ending at 18:00 Hrs

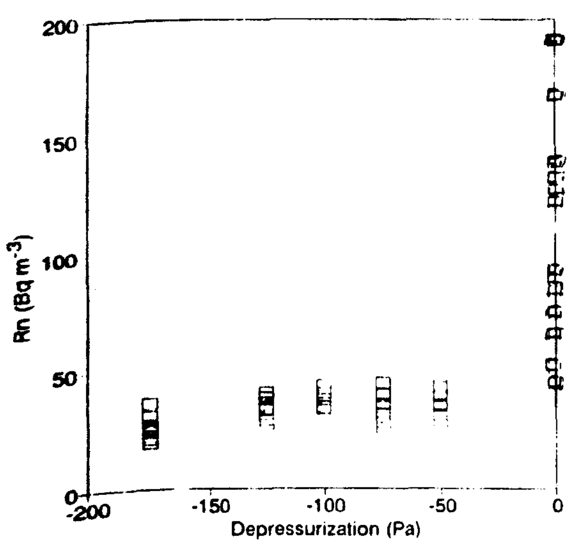


Fig. 7. Indoor Rn as a Function of Subslab Depressurization

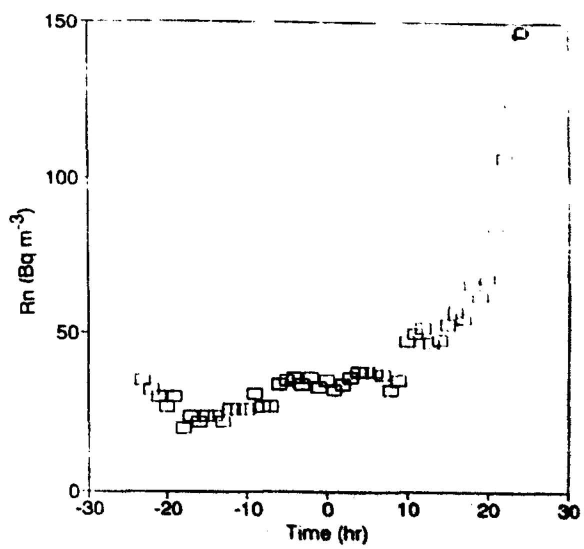


Fig. 8. Indoor Rn as a Function of Time (-50 Pa depressurization ending at 0 hrs)

Natural Basement Ventilation as a Radon Mitigation Technique

A. Cavallo, K. Gadsby, T.A. Reddy

Center for Energy and Environmental Studies
Princeton University
Princeton, NJ 08544 USA

Abstract

Natural basement ventilation has always been recommended as a means of reducing radon levels in houses. However, its efficacy has never been documented. It has generally been assumed to be a very inefficient mitigation strategy since it was believed that dilution was the mechanism by which radon levels were reduced.

Natural ventilation has been studied in two research houses during both the summer cooling season and the winter heating season. Ventilation rates, environmental and house operating parameters, and radon levels have been monitored; it can be concluded that natural ventilation can reduce radon levels two ways. The first, evidently, is by simple dilution. The second, less obvious, way is by providing a pressure break which reduces basement depressurization and thus the amount of radon contaminated soil gas drawn into the structure.

Thus, basement ventilation can be a much more effective mitigation strategy than was previously believed. It might be especially useful in houses with low radon concentrations (of the order of 10 pCi/L) or those with low levels that cannot be mitigated cost-effectively with conventional technology.

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

Radon emanation from naturally occurring soils, as distinguished from building materials and mine tailings used as construction fill, has been suspected of being a significant source of indoor air pollution in single family houses since the early 1980s [1,2,3,4]. This concern grew out of studies undertaken after the first energy crisis in 1973 to understand energy consumption patterns in homes and to reduce energy consumption, among other ways, by sealing up structures and reducing building air exchange rates [5]. It was immediately realized that reducing ventilation rates had the undesirable side effect of causing an increase in trace gases such as volatile organic compounds, oxides of carbon and nitrogen, and moisture, decreasing both comfort and safety.

It was initially believed that the effect of ventilation on indoor radon concentration was the same as for all other indoor air pollutants, that is that ventilation reduced indoor radon levels by dilution. This is based on a very simple model [6,7]: if the radon entry rate S_{Rn} is assumed to be constant and set equal to the removal rate, we have: $S_{Rn} = \lambda_v C_{Rn}$, where λ_v is the air exhange rate and C_{Rn} is the radon concentration.

Results from initial experiments [8,9] in which it was found that basement radon concentrations were inversely proportional to the ventilation rate, as predicted by the above equation, seemed to confirm this hypothesis. Thus, to reduce radon levels by a factor of 10 would require an increase in the air exchange rate by that same factor, which in most cases is neither practical nor desirable. The experiments were done using an air to air heat exchanger to control the basement ventilation rate. An air to air heat exchanger operates in a balanced mode with inflow and outflow equal and would neither pressurize nor depressurize the basement.This is actually very different from natural ventilation in which a basement window is opened, providing a pressure break; nevertheless it resulted in ventilation's being thoroughly discredited as a means to control indoor radon.

However, the mechanisms which bring radon into a structure are completely different from those causing high levels of many other indoor air pollutants. Most often, the source of undesirable indoor chemicals is found within the structure itself, such as poorly sealed paint cans and cleanser containers, or rug pads and foam stuffing in furniture. Radon entry into a building is dominated by pressure-driven flow of soil gas rather than by emissions from building materials. The subsoil pressure field of the building is caused by the following factors: wind generated depressurization of the structure, basement depressurization caused by air handler operation, and most importantly, by basement depressurization induced by the temperature difference between the outdoor environment and the building interior (the stack effect).

It is clear from the above discussion that the radon entry rate S_{Rn} cannot be a constant but must be a function of the basement to subsoil pressure differential. Thus, basement ventilation can theoretically reduce indoor radon levels both by dilution and by providing a pressure break which reduces the basement to subsoil pressure differential which reduces the radon entry rate [10].

Experiments

The effect of natural basement ventilation, that is opening basement windows, on indoor radon levels has been examined in two Princeton University research houses (PU31 and PU21) during the winter heating season and the summer cooling season.

The houses have been instrumented as follows:

1. Pressure differentials across the building shell and between the basement and the upstairs (PU21 only) are measured with differential pressure transducers.
2. Basement, living area (PU21 only), and outdoor temperatures are monitored using thermistors.
3. Basement, living area, subslab, and in-the-block radon levels (PU21 only) are monitored with a CRM (Lawrence Berkeley Continuous Radon Monitor) or a PRD (Pylon passive radon detector).
4. Basement relative humidity is monitored with a CS 207 relative humidity probe.
5. Heating and air conditioning system usage is monitored using a sail switch.
6. A PFT (perfluorocarbon tracer) system is used to measure building air exchange rate and interzonal flows. Up to four gases may be used in this system, but for these experiments only two were needed. Emitters (four to eight per zone) are placed in temperature regulated holders in the basement and living area.

In addition, a weather station at Princeton University monitors temperature, rainfall, relative humidity, barometric pressure, and wind speed and direction.

The weather station data as well as house dynamics data are read every 6 seconds and averaged over 30 minutes, while the air infiltration and interzonal flow measurements are averaged over a minimum of 2 days.

EXPERIMENTS IN RESEARCH HOUSE PU21

Natural ventilation experiments have been carried out in research house PU21 during the winter heating season; the results of these experiments are summarized here.

The research house has the following characteristics:

SIZE: 1970 ft^{2*} living area, 525 ft^2 basement.
TYPE: Modified ranch. The living room/dining room has a cathedral ceiling with a large window area facing almost due south. A cinderblock basement underlays about one third of the house, with the remainder being built on a slab. There is a cinderblock chimney stack in the center of the house.
FIREPLACE: Large fireplace in the living room.
HEATING SYSTEM: Central gas forced air heat, furnace in basement.
COOLING SYSTEM: Central air conditioning.
HOT WATER: Gas hot water heater located in basement.
RADON LEVEL: ~120 pCi/L in basement.

The house had been mitigated with a subslab mitigation system which was turned off during the ventilation experiment. The perimeter floor/wall shrinkage crack had also been sealed and Dranger© basement drain seals installed as part of the mitigation.

The effect of opening a basement window on indoor radon levels and the basement/outdoor pressure differential in PU21 is illustrated using continuous radon and pressure data in Figs. 1a and 1b. Data points are 30 minute averages of the parameters; the experiment was carried out between Julian Date (JD) 47, 1990 (90047) and JD90050.5. Shown in Fig. 1a are basement radon levels as measured with a pumped CRM, which has a response time of less than 30 minutes, and upstairs radon levels as measured with a Pylon PRD, which has a response time of about 3 hours. Plotted in Fig. 1b is the pressure differential across the south wall of the basement (positive values indicate that the basement is depressurized relative to the outdoors). A normally closed basement window was opened at times JD90048.4 and JD90049.45, and closed at times JD90048.83 and 90049.8.

*Readers more familiar with metric units may use the factors at the end of this paper to convert to that system.

The basement/outdoors pressure differential responds immediately to the closing or opening of the window with a ~1.5 Pa change in this parameter. (Note that, even with the window open, the basement still remains depressurized relative to the outdoors.) This is a strong indication that the radon entry rate into the basement must change; this is in fact the case, as verified by measurements in other experiments of building air change rates and interzonal flows, radon levels, and radon entry rates.

Radon levels respond over a longer period of time to a window's opening or closing. This is to be expected since the total basement air exchange rate (defined as the flow of outdoor air plus the flow from the living area into the basement) is approximately 1 air change per hour (ACH), and the building air exchange rate is about 0.3-0.6 ACH. Thus, the time necessary to achieve a new steady state must be of the order of 2 or 3 hours. In addition, the response time of the upstairs radon detector is itself of the order of 3 hours, which is why there is such a difference in the time response of the upstairs and basement radon levels.

It is also of some importance to note that there are natural variations in the building's behavior which are of the same order of magnitude as those caused by opening a basement window. An example of this occurs around time JD 90048. The decrease in indoor radon and basement depressurization in this time period was caused by an unusual midwinter temperature spike in which the outdoor temperature rose and fell by 8 °C in a 12 hour period, changing the indoor/outdoor temperature differential and the magnitude of the stack effect. It is essential that an experiment be of sufficient duration to be able to average over such excursions.

The natural ventilation experiment in PU21 was conducted over a 17 day period in February; two periods of 2 and 3 days each were used to determine the baseline building conditions (windows closed), and three 4 day periods were used to determine the building operating parameters with a single basement window (~2.2 ft^2 window area) open. In Figs. 2 through 4, described below, experiments 1 and 5 are periods when the basement window was closed, and experiments 2, 3, and 4 are periods when the basement window was open.

The effect of basement ventilation on basement and upstairs radon levels is shown in Fig. 2. With the windows closed, basement radon levels were about 120 pCi/L, while upstairs levels were about a factor of 2 or less lower (80 pCi/L). This is a fairly typical result and is a consequence of the basement's being isolated from the living area. With one basement window open, the upstairs levels were about a factor of 2 higher than the basement levels. This is quite unusual and indicates a radon entry route into the living area which bypasses the basement. This result was checked by making two simultaneous continuous measurements of the upstairs radon levels. A similar result was noted in the measurements made in the summer of 1989 on PU31 and will be discussed further; this indicates one way that basement ventilation, while certainly reducing indoor radon levels, might not be as effective in reducing living area radon levels as in reducing basement levels.

Another consequence of a reduction in basement radon entry rate is an increase in subslab and basement radon levels. This is indeed observed, as shown in Fig. 3, in which basement and subslab radon levels are plotted for the different experiment periods. The strong decrease in basement radon levels with the window open and the simultaneous increase in subslab radon levels are clearly present. The expected magnitude of the increase in subslab radon levels is not obvious, since it would depend on the details of the amplitude and spatial distribution of subslab soil permeability, moisture, and radium content. Qualitatively, the effect is certainly present.

A critical factor in this experiment is to quantify the effect that basement ventilation has on the building air change rate, since the observed reduction in radon levels could be caused by a large increase in the ventilation rate. This has been done using the perfluorocarbon tracer (PFT) system, and results are illustrated in Fig. 4, in which building air exchange rate and basement radon levels are plotted. The building air exchange rate increases by a factor of 2, from 0.3 to 0.6 ACH, when the basement window is opened. Note that the basement radon levels decrease by a much larger factor (~6-8), again indicating that dilution cannot account for the entire decrease in radon levels. The doubling of the air exchange rate corresponds to a ventilation rate of 115 cfm, very roughly comparable to that achieved by a subslab depressurization system, which for this house reduces radon to much lower levels than basement ventilation. However, the main application of natural ventilation is expected to be in lower level homes where installation of a subslab system might not be justified.

Using the interzonal flows and tracer gas concentrations measured by the PFT system, the basement and living area radon entry rates can be calculated. The two zone system of flows and tracer concentrations is illustrated in Fig. 5. Radon entry rates S_{iRn} (i=1,2) can be calculated two ways. The first method is to use the flow rates deduced from tracer gas measurements but assume that C_{11} and C_{12} are the radon concentrations in zones 1 (basement) and 2 (living area), respectively.

$$S_{1Rn} = (R_{10} + R_{12}) C_{11} - R_{21}C_{12} \quad (1)$$

$$S_{2Rn} = (R_{21} + R_{20}) C_{12} - R_{12}C_{11} \quad (2)$$

The second method [11] is to assume that the tracer gas and radon behave in the same fashion once they enter the house, so that the ratio of the tracer gas emission rate in zone 1, S_{11}, to the concentration of tracer gas in zone 1, C_{11}, is the same as the ratio of the radon entry rate in zone 1 to the radon concentration in zone 1:

$$S_{11}/C_{11} = S_{1Rn}/C_{1Rn} \quad (3)$$

Results of the entry rate calculation using Eq. 3 are shown in Fig. 6. There is a factor of 3 decrease in the entry rate with natural basement ventilation compared to that without ventilation, and this difference is substantially outside the error bars of the individual data points.

The two different methods for calculating the entry rate are compared in Fig. 7. Using the computed interzonal flow rates (Eq. 1) results in substantially more uncertainty than when Eq. 3 is used; this is a consequence of the errors inherent in the interzonal flow calculations using tracer gas measurements [12]. There is, nonetheless, general agreement between the two methods. The computation using the interzonal flows always yields a lower entry rate than the other method: this is consistent with the presence of an entry route into the living area which bypasses the basement.

The entry rate of radon into the living area can be calculated from Eq. 2 using the interzonal flow data from those periods when the basement window was open and upstairs radon levels were approximately twice as large as the basement levels. It is found that the radon entry rates in both zones are about equal in this case, about 5 µCi/h. With the basement window closed the basement radon entry rate, approximately 20 µCi/h, predominates. This does add an extra complication to the use of natural ventilation as a mitigation strategy. It remains to be seen how widely this effect is observed.

Therefore, measurements in PU21 clearly demonstrate the mechanisms by which natural ventilation acts to lower radon levels. Both dilution and reduction of the basement/outdoor pressure differential and the concomitant reduction in radon entry rate are factors, with the second effect being the more important.

EXPERIMENTS IN RESEARCH HOUSE PU31.

Natural ventilation experiments have been conducted in research house PU31 over a complete seasonal cycle; that is, during the summer cooling season and the winter heating season. The results of these experiments are summarized for both.

Research house PU31 has the following characteristics:

SIZE: 1600 ft^2 living area, 1300 ft^2 basement.
TYPE: Ranch with full attic and full basement, half of an attached slab-on-grade, two-car garage converted to TV room, cinderblock wall basement with a sump, and cinderblock chimney stack in the center of the house.
ATTIC: Two 1100 cfm attic fans, thermostatically controlled; insulated with 8 in. blown-in insulation.
FIREPLACES: Two: one in living room, one in kitchen.
HEATING SYSTEM: Central gas forced air heat, furnace located in basement.
COOLING SYSTEM: Central air conditioning.
RADON LEVEL: ~80 pCi/L in the basement.

Research house PU31 has been instrumented in a similar fashion to PU21, except that subslab and cinderblock wall radon are not measured, and the pressure field of the basement is measured at three heights on each basement wall and at three subslab locations.

Cooling Season Measurements

The summer season natural ventilation experiment was conducted in the following manner. A 17 day period was used to establish an operating baseline for the house. During this time the house functioned normally; e.g., thermostatically controlled attic fans operated automatically. Basement and upstairs windows were kept closed, as is normally the case since the house is centrally air conditioned. (Upstairs windows were of excellent quality and could be closed tightly. The basement windows were low quality steel frame casements which could not be shut very tightly.)

After the baseline operating conditions of the building were established, two basement windows (one on the west wall and the other on the east wall, each 2.2 ft^2) were opened and the relevant parameters compared to those obtained in the baseline conditions.

The effect of opening two basement windows on basement radon levels and the soil to basement pressure differential is shown in Figs. 8 and 9. Basement radon levels are shown in Fig. 8; there is clearly a significant drop in this parameter, from an average of about 90 pCi/L to about 10 pCi/L when the windows are opened on JD89220.6. The magnitude of this drop was completely unexpected. The large diurnal variation in basement radon levels is due to the operation of the attic fans which depressurize the entire house, increasing the ventilation rate as well as the radon levels. Measurements of a typical differential pressure transducer are illustrated in Fig. 9 (positive pressure indicates that soil pressure is above that of the basement). The large peaks (~3 Pa) in soil/basement pressure differential are due to the operation of the attic fans. There is an abrupt pressure drop when the windows are opened, indicating that the pressure field of the building has been modified. It is clear that, for this house only, a very small pressure differential (~0.5 Pa) is needed to drive the radon level to 10 pCi/L. This result again strongly suggests that a modification of the basement/soil pressure differential is important in reducing the basement radon level; however, the measurement of the building air exchange rate and interzonal flows and calculation of the radon entry rate are essential for a definitive evaluation of this problem.

The behavior of the basement air exchange rates and basement radon level is shown in Fig. 10; these two parameters are plotted for seven experiments, each of 3-4 days duration. This period of time was needed to obtain reasonable levels of the PFT gas in the capillary adsorption tubes. Baseline conditions for the building (with the attic fans thermostatically controlled) were about 0.3 ACH for the entire building with an average basement radon level of about 80 pCi/L.

With the basement windows opened, the building air exchange rate increases by about a factor of 2, to 0.6 ACH. Basement radon levels decrease to about 12 pCi/L, a factor of about 7 below the levels with the windows closed. This decrease is far larger than the increase in the building air exchange rate (about a factor of 2), and indicates that the change in the pressure field of the building is much more important in decreasing radon levels than the increase in the building air exchange rate.

To investigate the impact of the attic fans on building air exchange rates, the two basement windows were left open and the attic fans switched off. The building air exchange rate dropped by about a factor of 2, while the basement radon level dropped by about 20%. Such a large decrease in the air exchange rate without any increase in radon level is yet another indication that the modification of the pressure field of the basement and thus the entry rate S_{1Rn} (which is a function of the soil to basement pressure differential) is of prime importance in determining the radon level of this basement.

As for house PU21, the basement radon entry rate of house PU31 can be computed using the air infiltration and interzonal flow measurements. Results from this calculation using Eq. 3 are shown in Fig. 11. If the baseline house operation (Experiments 1-5 of Fig. 11) is compared to house operation with the attic fans off and the basement windows open (Experiments 7-8 of Fig. 11), radon entry rate decreased by about a factor of 7. For house operation with attic fans off and basement windows closed (Experiment 6) compared to that with the fans off and windows open (Experiments 7-8), the basement radon entry rate decreased by about a factor of 3. This demonstrates clearly that the radon entry rate decreases significantly with natural basement ventilation.

Although basement radon levels have been emphasized in the above analysis, radon levels in the living area are of most concern. These have also been measured during the natural ventilation experiments. With all windows closed, the upstairs radon level (~62 pCi/L) was lower than the basement radon level (~80 pCi/L), as would be expected. However, with basement windows opened, the upstairs radon level (~25 pCi/L) was about 2.5 times higher than the basement radon level (~10 pCi/L) (see Fig. 12). Instrumental error has been carefully ruled out in this case. It is clear that radon can enter the upstairs zone of this house two ways. The first is the usual one in which soil gas is drawn into the basement and then flows into the upstairs zone. The second entry route must bypass the basement but could not be localized. It may be associated with the central cinderblock chimney stack or the slab-on-grade garage which has been converted into a TV room. This second route is unaffected by the pressure break provided by the open basement windows.

Heating Season Measurements.

A series of measurements on natural basement ventilation were conducted in PU31 during the winter heating season; a temporary mitigation system was installed in the house in January 1990. This system was turned off and the vent pipe capped during the ventilation experiment.

Measurements to determine the house baseline operating conditions were begun in December 1990. Radon levels in the living area of 70 pCi/L were routinely found, and it was deemed advisable to install a temporary mitigation system immediately. This was done on January 5, 1990, and reduced upstairs radon levels to about 4 pCi/L. The mitigation system was turned off on JD90030 and an attempt made to measure another baseline point. Radon levels were about a factor of 2 less than those found in other baseline measurements (Compare Fig. 13, Experiment 1 with Experiment 5, 6, or 7.) It appears either that it takes several days for the house to return to its unmitigated operating point from the time when the mitigation system is turned off, or that this was an exceptional case, perhaps because of some other change in the house operating point. Since the building air exchange rate was 40% lower for this experiment than for other experiments with the windows closed in this series (see Fig. 13, Experiment 1 compared to Experiments 5,6,7), this change in the operating point certainly could explain much of the discrepancy. Experiment 1 is included for completeness, but the baseline experiments (windows closed) to which others will be compared (windows open) will be Experiments 5, 6, and 7.

Basement radon and building air exchange rate for PU31 are shown in Fig. 13 for the winter ventilation experiments. The baseline air exchange rate is about a factor of 2 larger than that found in the summer measurements (0.3 ACH, summer; 0.65 ACH, winter). This is due to the larger indoor/outdoor temperature differentials which occur in the winter. The air exchange rate doubles, from 0.65 to 1.2 ACH, when either one or two windows (2.2 ft^2 per window) are opened. Basement radon levels, also higher than the summer values, decreased by more than a factor of 10, from ~130 to ~12 pCi/L with the east and west windows open or with the west window open. The west window is just above the sump pump and ~10 ft away from installed instrumentation. It is not clear why the west window should be more effective in reducing basement (and upstairs) radon levels than the east window, but it may be that providing a pressure break immediately above the sump pump, which may be a strong source, is more efficient than locating the pressure break at a distance of 44 ft.

Basement and upstairs radon levels are shown in Fig. 14. Both are strongly reduced by natural basement ventilation, but the reduction in upstairs radon is about a factor of 2 less than that by which basement radon is reduced. This is to be expected when the radon source is located in the basement, and can be understood from the interzonal flow and infiltration and exfiltration measurements.

In contrast to the measurements made during the cooling season, there is no indication that upstairs radon levels are higher than basement radon levels with the basement windows open, and no indication of an entry path which bypasses the basement. It is not clear why this change has occurred.

The radon entry rate and basement radon levels are shown in Fig. 15 for the winter natural ventilation experiments. The first data point shows an anomalously low entry rate and radon level as discussed above. With either the east and west windows open or only the west window open, the radon entry rate is reduced by about a factor of 5, compared to with the windows closed. Note that, with only the east window open, the entry rate is approximately the same as when the windows are closed, although the radon levels are about a factor of 2 lower. This may be the result of an ineffective pressure break with only dilution reducing basement radon levels.

Thus, heating season natural ventilation experiments in PU31 indicate that radon in houses is reduced both by dilution and by the introduction of a pressure break when basement windows are opened. The factor by which radon levels are reduced is even larger in the winter than in the summer: basement radon levels are reduced from much higher winter levels to about the same value as in the summer measurements.

CONCLUSIONS

Natural ventilation experiments conducted during the summer cooling season and the winter heating season in research house PU31 and during the winter heating season in research house PU21 have demonstrated that basement ventilation can reduce indoor radon both by reducing the radon entry rate and by dilution. Calculations based on measurements using the PFT gas system allow the effects of dilution and entry rate reduction to be delineated and quantified: a decrease in the basement radon entry rate of a factor of 2-5 and an increase in the building air exchange rate of about a factor of 2 have been documented. These results contradict earlier assumptions about the efficacy of and mechanisms by which natural ventilation can reduce indoor radon levels, and indicate that natural ventilation can reduce indoor radon levels by much larger factors than was previously believed.

A rough cost estimate for natural basement ventilation in research house PU21 can be made with the following assumptions: 1) 4911 degree days for the Princeton area, 2) 115 cfm constant increase in the winter ventilation rate, 3) furnace efficiency of 0.7, and 4) heating oil costing $1/gal. With these assumptions, the additional heating cost would be $225/yr. This compares surprisingly favorably with the running cost of a subslab depressurization system ($0.12/kWh, 90 W fan, $50-$100 for exhaust of conditioned air) of $140-$190/yr. Thus, in certain circumstances, basement ventilation could indeed be a reasonable mitigation strategy.

Based on the results of these experiments, the following recommendations can be made:

1. Further experiments on natural ventilation should be undertaken in:

   a. Low radon houses (basement radon concentrations of 10 pCi/L or less) to verify that low radon levels can be adequately reduced by this method.
   b. Houses of different construction styles (to document the magnitude of reduction in radon concentration attainable).

2. Other natural ventilation strategies, such as living area ventilation instead of or in conjunction with basement ventilation, should be examined.

3. Forced ventilation using air-to-air heat exchangers should be carefully compared to natural ventilation.

ACKNOWLEDGEMENTS

We would like to thank C. Reynolds for considerable help with data reduction, and R. Gafgen for running and maintaining the PFT

system.

REFERENCES

1. van Assendelft, A.C.E., and Sachs, H.M., Soil and Regional Uranium as Controlling Factors of Indoor Radon in Eastern Pennsylvania, Princeton University Report PU/CEES-145, 1982.

2. Gross,S., and Sachs, H.M., Regional (Location) and Building Factors as Determinants of Indoor Radon Concentration in Eastern Pennsylvania, Princeton University Report PU/CEES-146, 1982.

3. Sachs, H.M., Hernandez,T.L., and Ring,J.W., Regional Geology and Radon Variability in Buildings, Environ. Int. 8, 97 (1982).

4. Scott, A.G., Ch 10 in Radon and Its Decay Products in Indoor Air, W.W. Nazaroff and A.V.Nero, editors, John Wiley and Sons, New York, NY, 1988.

5. Socolow, R.H. ed., Saving Energy in the Home, Ballinger Publishing Co., Cambridge, MA, 1978.

6. See also the discussion in Chapters 1, 2, and 5 of Radon and Its Decay Products in Indoor Air, W.W. Nazaroff and A.V. Nero, editors, John Wiley and Sons, New York, NY, 1988.

7. Radon Reduction Methods: A Homeowner's Guide, U.S. Environmental Protection Agency, OPA-86-005, p 4, August 1986.

8. Nazaroff, W.W., et al., Radon Transport into a Detached One Story House with a Basement, Atmos. Environ.19, 31 (1985).

9. Nazaroff, W.W., et al., The Use of Mechanical Ventilation with Heat Recovery for Controlling Radon and Radon Daughter Concentrations in Houses, Atmos. Environ. 15, 263 (1981).

10. Cavallo, A., Berkner,C., and Gadsby,K., Use of Ventilation to Control Radon in Single Family Dwellings, Proceedings, Fifth International Conference on Indoor Air Quality and Climate, Vol. 3, p 489, Toronto, Canada, August 1990.

11. Hubbard,L., Gadsby,K., Bohac,D., Lovell,A., Harrje,D., Socolow,R., Matthews,T., Dudney,C., and Sanchez,D., Radon Entry into Detached Dwellings: House Dynamics and Mitigation Techniques, Rad. Prot. Dos. 24, 491 (1988).

12. D'Ottavio,T.W., Senum,G.I., and Dietz,R.N., Error Analysis Techniques for Perfluorocarbon Tracer Derived Multizone Ventilation Rates, BNL 39867, Brookhaven National Laboratory, Upton, NY, June 1987.

Conversion Factors

Readers more familiar with metric units may use the following factors to convert to that system.

Non-metric	Times	Yields Metric
cfm	0.00047	m^3/s
ft	0.30	m
ft^2	0.093	m^2
gal.	0.0038	m^3
in.	2.54	cm
pCi/L	37	Bq/m^3

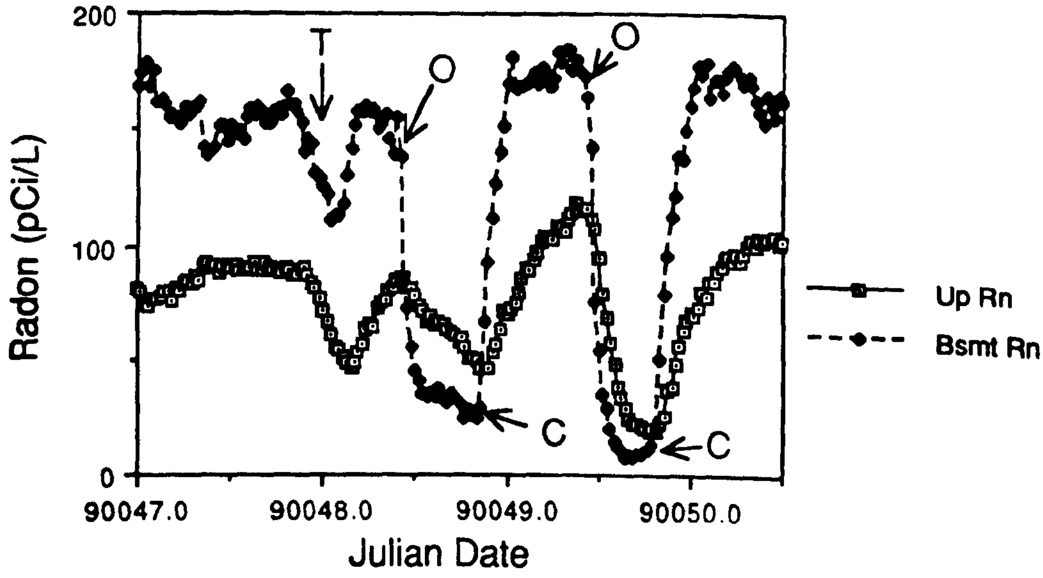


Figure 1a. Basement, Upstairs Radon Level vs Julian Date Sequence of Window Open and Window Closed, PU21
O=Open; C=Closed; T= Temperature Spike

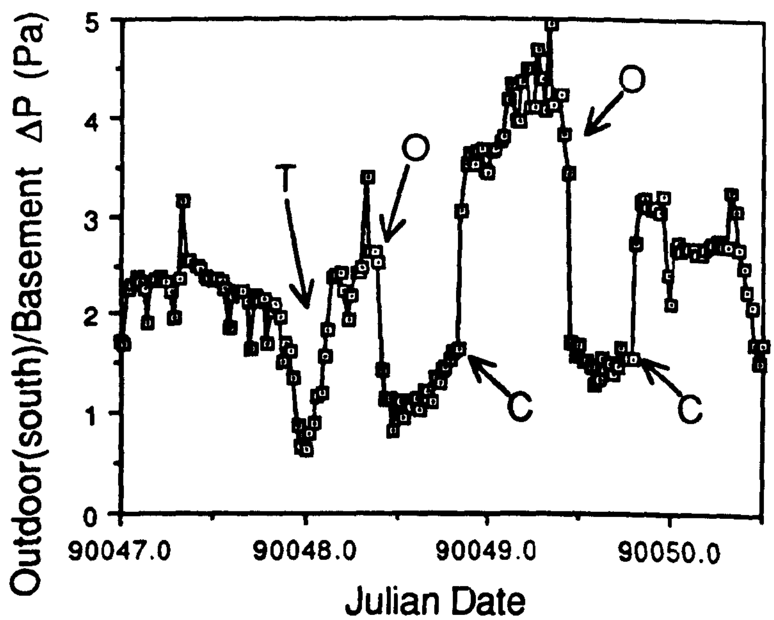


Figure 1b. Outdoor/Basement Pressure Differential vs Julian Date; Sequence of Window Open and Window Closed, PU21
O=Open; C=Closed; T=Temperature Spike

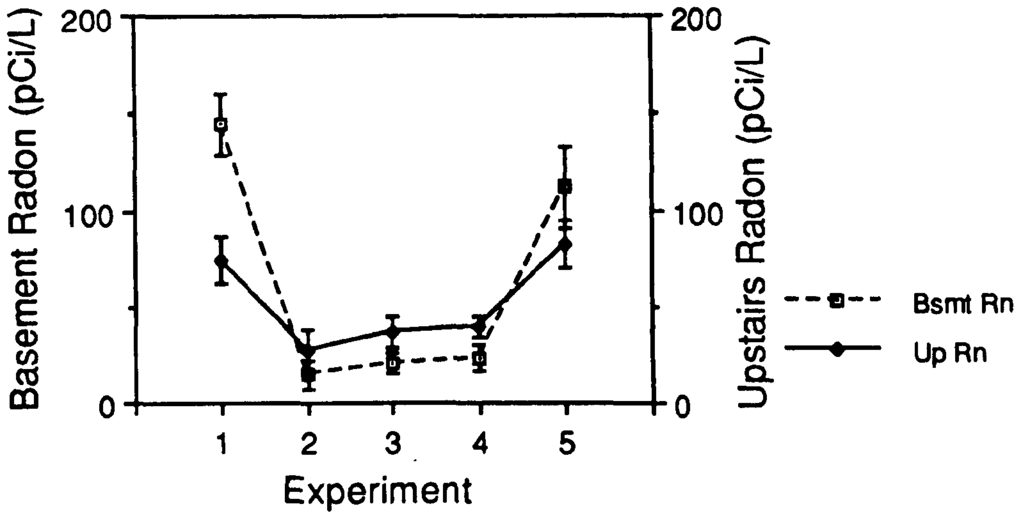


Figure 2. Basement, Upstairs Radon,PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

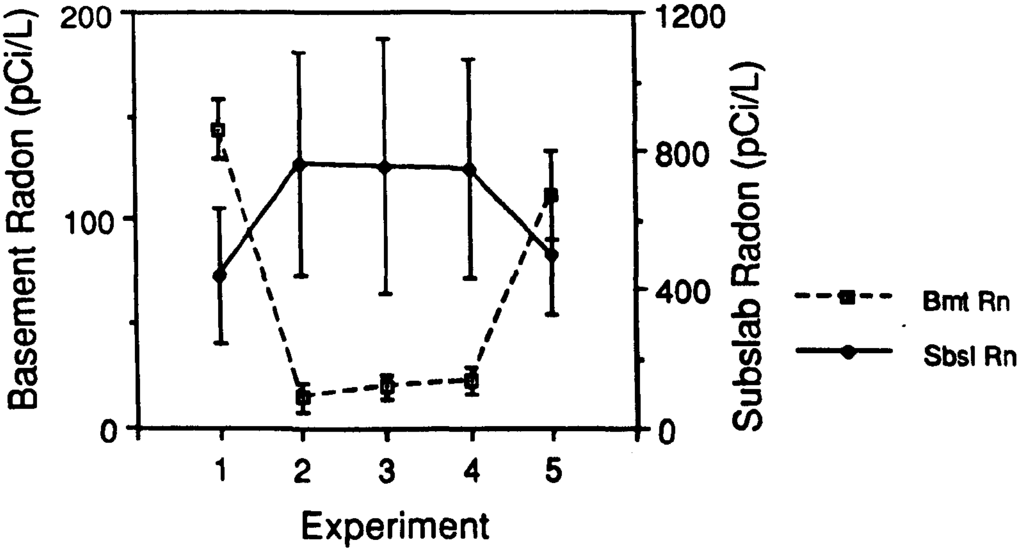


Figure 3. Basement, Subslab Radon PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

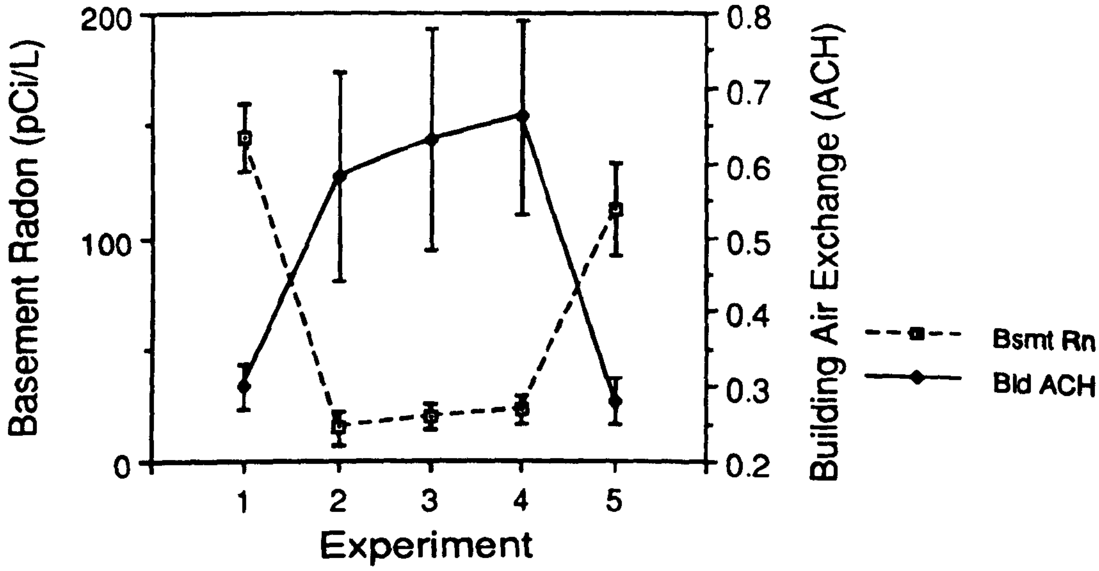


Figure 4. Building ACH, Basement Radon,PU21
Experiments 1,5 Window Open;
Experiments 2,3,4 Window Closed

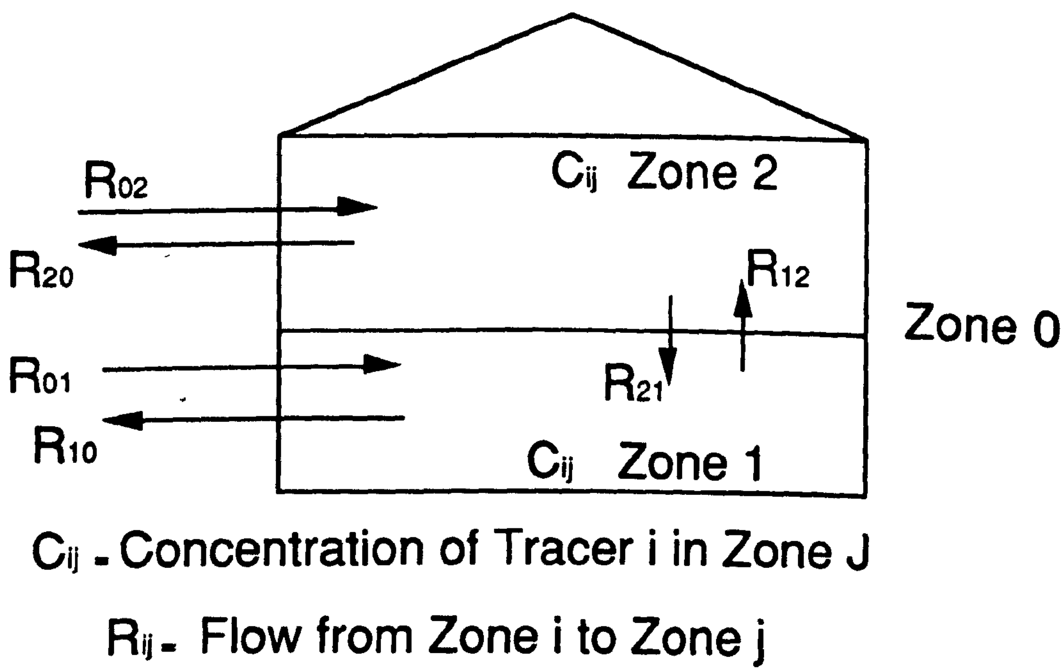


Figure 5. Flows and Tracer Concentrations for Two Zones

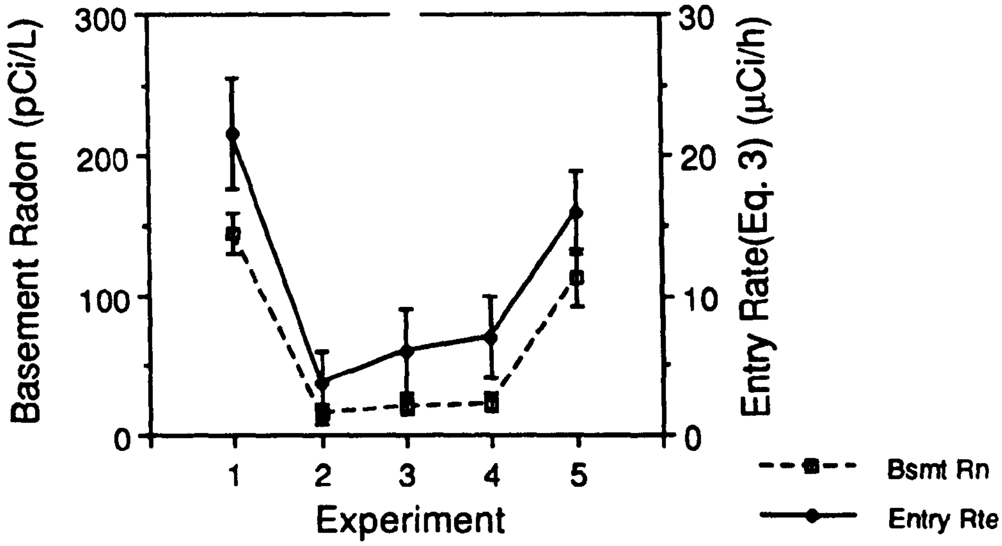


Figure 6. Basement Radon Entry Rate, Basement Radon,PU21
Experiments 1,5 Windows Closed;
Experiments 2,3,4 Windows Open

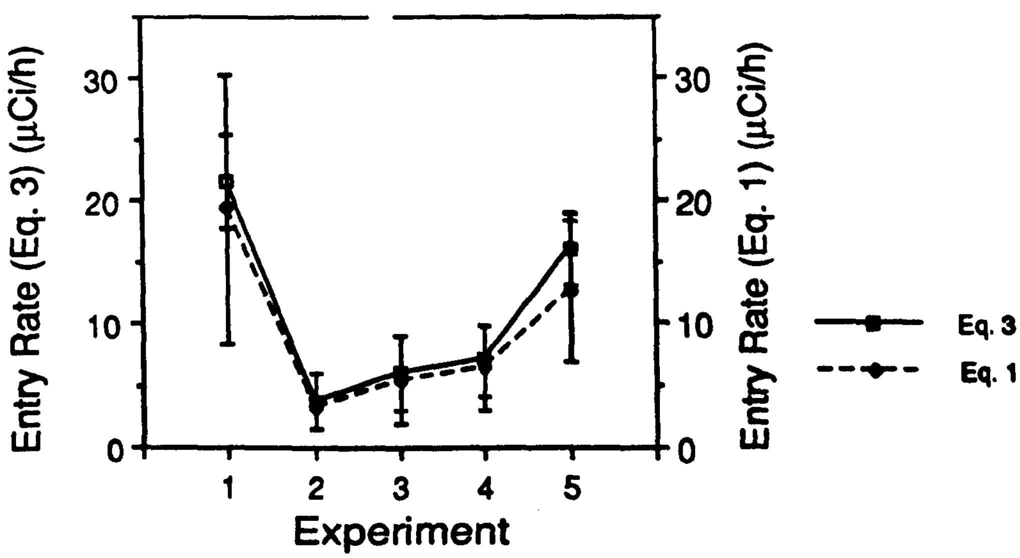


Figure 7. Entry Rate Calculations Compared, PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

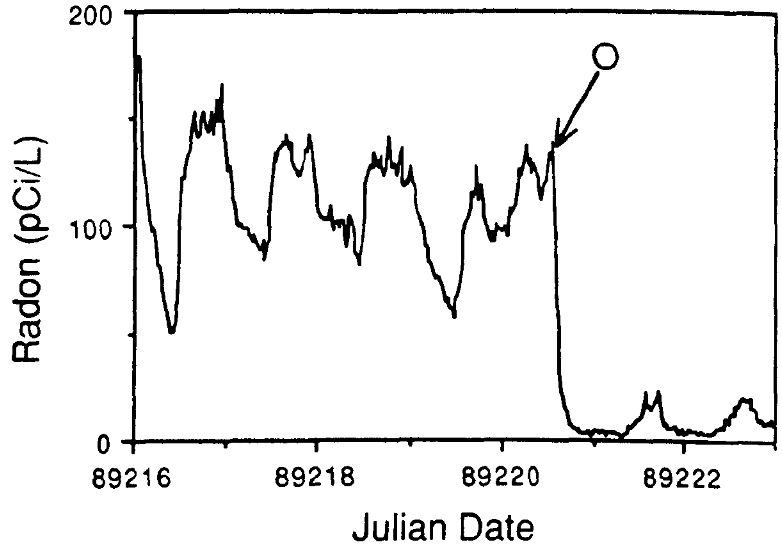


Figure 8. Basement Radon vs Julian Date, PU31. In This Experiment, Two Basement Windows Were Opened (O) at JD 89220.6.

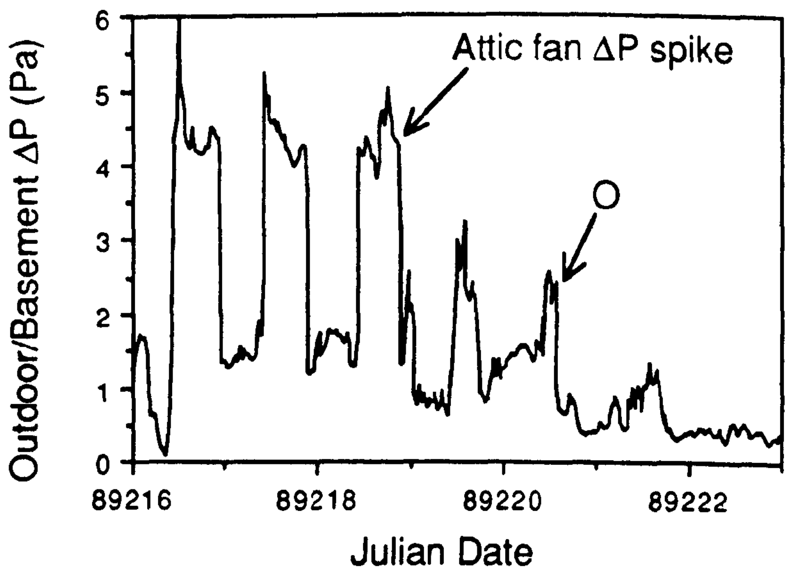


Figure 9. Outdoor/Basement Pressure Differential (ΔP) vs Julian Date. Basement Windows Opened (O) at JD 89220.6; Note Effect of Attic Fans.

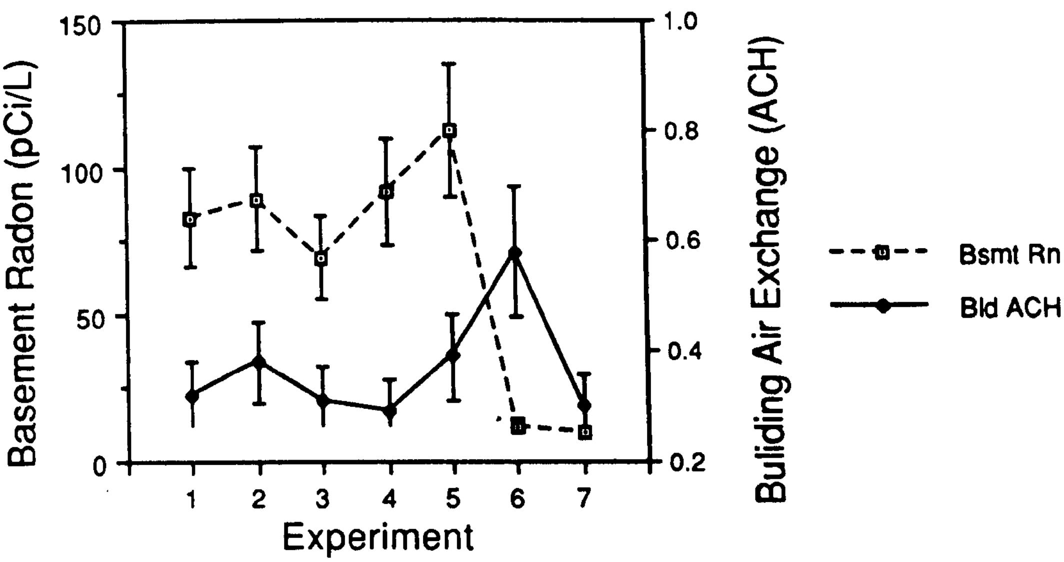


Figure 10. Basement Radon, Building Air Exchange , PU31 Summer
Experiments 1-5, Baseline (normal house operation)
Experiment 6, Windows Open, Fan On;
Experiment 7, Windows Open, Fan Off

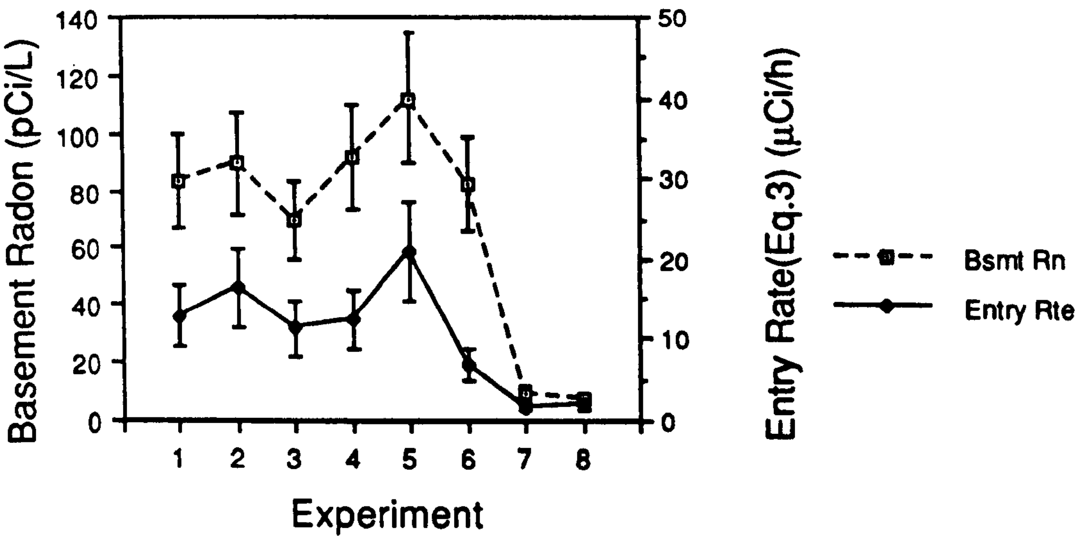


Figure 11. Basement Radon Level, Entry Rate; PU31 Summer
Experiments 1-5, Baseline (normal house operation);
Experiment 6, Windows Closed, Fan Off;
Experiments 7-8, Windows Open, Fan Off

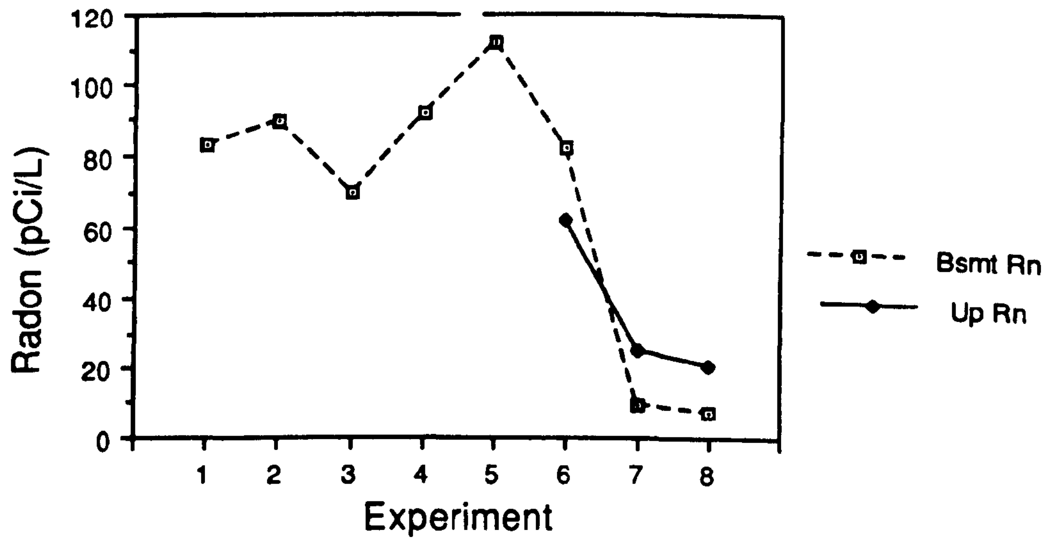


Figure 12. Basement, Upstairs Radon Level,PU31 Summer
Experiments 1-6, Baseline (normal house operation);
Experiments 7-8, Windows Open

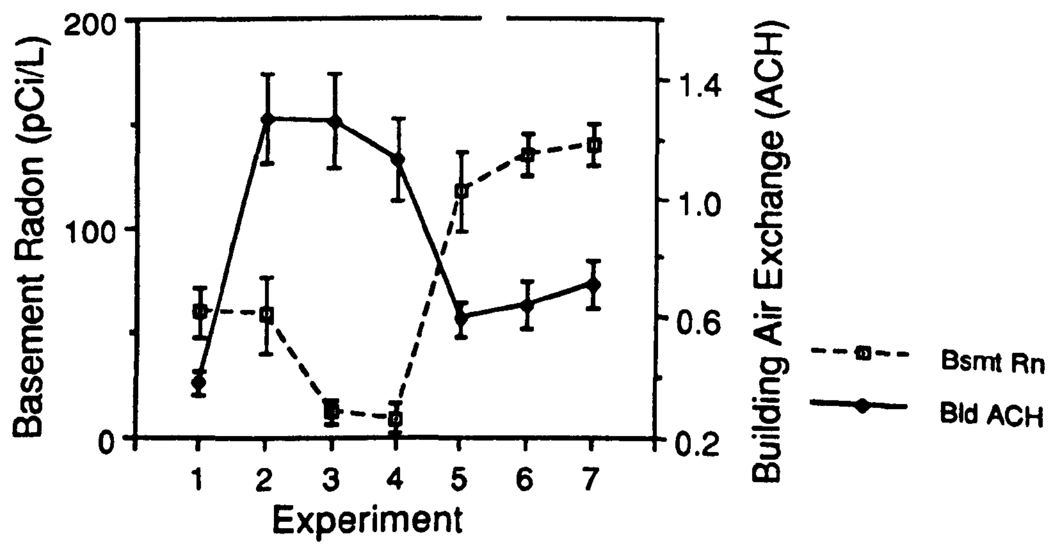


Figure 13. Basement Radon, Building Air Exchange, PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3: East and West Open;
Experiment 2: East Open;
Experiment 4: West Open

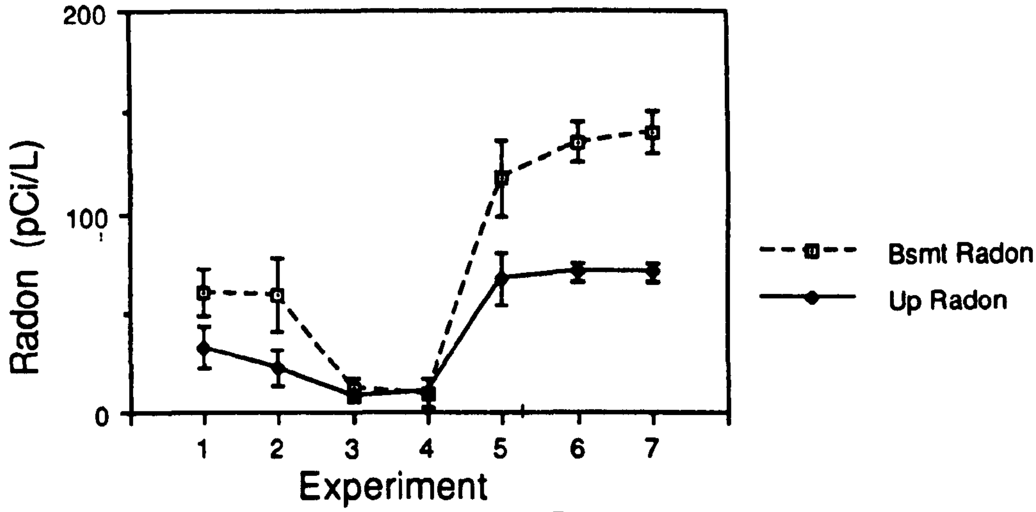


Figure 14. Basement, Upstairs Radon; PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3: East and West Open;
Experiment 2 :East Open;
Experiment 4: West Open

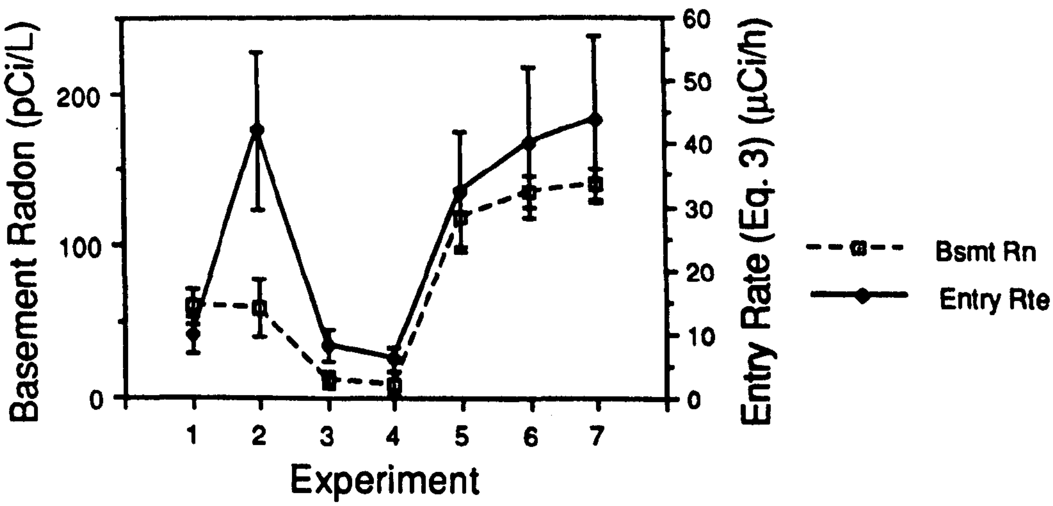


Figure 15. Basement Radon, Entry Rate PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3, East and West Open;
Experiment 2, East Open;
Experiment 4, West Open

TITLE: Attic Pressurization - A Radon Mitigation Technique for Residential Structures

AUTHOR: Myron R. Edelkind, Southern Mechanical

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

In residences, normally occuring attic depressurization can be a primary source of reduction of basement air pressures and, therefore, a considerable factor as a driving force for R_{222} (Radon). The literature does not well document the effects of upward draft in residences created by solar insolation on the roofs of structures, Venturi forces generated as a result of winds and roof design, and the draft induction resultant of the operation of attic ventilation equipment.

In order to guarantee and achieve mitigated radon levels below 2 pCi/L the radon mitigation contractor may wish to apply more than one reduction technique. We show that the alleviation of attic depressurization is highly effective in reducing radon levels in residential structures. Techniques and equipment modifications are described.

Session IV:

Radon Reduction Methods -- POSTERS

RADON MITIGATION FAILURE MODES

by: William M. Yeager
Research Triangle Institute
Research Triangle Park, NC 27709

D. Bruce Harris
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

Terry Brennan and Mike Clarkin
Camroden Associates
Oriskany, NY 13424

ABSTRACT

An EPA study solicited anecdotal information on failure modes of radon mitigation systems from practicing mitigators, state government agencies which monitor radon mitigation, and EPA radon mitigation project officers and contractors. This study identified three categories of failures: design flaws, component problems, and occupant activities which compromised mitigation systems. This paper reviews several examples of failure modes in each of these categories.

Radon mitigation systems, like other mechanical systems, are subject to failure and should be designed accordingly. Mitigators should design systems to minimize the probability of failure and to readily detect failures that do occur. The system design should include a monitor which occupants can use to determine whether or not the system is operating properly. Occupants must realize that even well-designed and properly installed systems have some chance of failure; they should check the system monitor periodically and measure radon levels annually as long as the structure is occupied.

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

BACKGROUND

For several years, the U.S. Environmental Protection Agency (EPA) has been funding radon mitigation demonstration projects in various states. These projects have developed diagnostic measurements and procedures to select the most appropriate mitigation technique for a particular house. A variety of mitigation techniques have been tested in over 170 houses (1). In most houses, post-mitigation measurements have shown that radon concentrations in the living areas were reduced below the EPA's guideline of 4 picocuries per liter (pCi/L).

The EPA has monitored the long-term effectiveness of these mitigation systems with radon measurements during successive heating seasons. Most houses have shown little degradation in the effectiveness of the systems, but in a few, the systems have stopped working altogether. In others, the systems are much less effective than they were initially.

PURPOSE

This project was undertaken to study the failure modes of radon mitigation systems. The study focused on systems which once worked satisfactorily, but stopped working either completely or nearly completely. The study was not intended to deal with "problem houses," where the installed mitigation system never performed satisfactorily, or with systems whose performance has degraded somewhat, but is still generally satisfactory.

Research Triangle Institute (RTI) solicited information on mitigation system failures from practicing mitigators, state government agencies which monitor radon mitigation, and EPA radon mitigation project officers and contractors. During the EPA radon conference in February 1990, RTI convened an impromptu discussion group of approximately 50 attendees to discuss failure modes of radon mitigation systems. Some of them later provided additional details about problems that they had experience or observed. They asked about design flaws, component problems, and resident activities which compromised mitigation systems. This paper discusses the wide variety of radon mitigation system failures noted.

Although the study did not involve any measurements, people who worked for government agencies were asked if they had a data base from long-term follow-up radon measurements or if they knew of anyone who might have one. Unfortunately, the response to this inquiry was uniformly negative. Some data were received on immediate post-mitigation radon measurements from two sources: the New Jersey Department of Environmental Protection (NJDEP) and EPA Region 3 (Philadelphia).

ORGANIZATION

The rest of this paper summarizes the anecdotal information collected during this study. Most of the information refers to subslab depressurization systems, as this is the most common mitigation technique used by commercial mitigators. Sections 2.0 through 4.0 discuss failure modes in the three categories which were established: design flaws, component problems, and resident activities. Section 5.0 draws conclusions and suggests some areas for future work on residential mitigation failure modes.

DESIGN FLAWS

Several people were concerned that conscientious and competent mitigators could not compete with unscrupulous or incompetent ones. If mitigation systems are judged only by radon measurements immediately after installation, poorly designed systems with low quality components may not be distinguishable from better ones. Indeed, cost comparison may favor the poorer systems. The recent listing of mitigators who have passed EPA's Radon Contractor Proficiency (RCP) Program (2) should help homeowners to identify competent mitigators. In addition, several states distribute similar lists of mitigators who have satisfied state requirements.

A major factor in the radon mitigation business is real estate transactions which are contingent upon radon levels below 4 pCi/L. Under these circumstances, there is a strong incentive for a quick and inexpensive solution to the problem, which is seen as a radon measurement > 4 pCi/L, rather than a long-term health risk. Unless the health risk is recognized, the radon level may be viewed merely as a barrier to the transaction which must be surmounted as quickly and inexpensively as possible.

CONDENSATION OF SOIL GAS MOISTURE

Everyone contacted knew that soil gas is very moist and that ducts which exhaust it should be designed with a positive slope so that the inevitable condensation will drain down the duct. Everyone had also seen mitigation systems which failed because of a water trap. Sometimes the trap was part of the design and a drain line had been provided. Such drain lines tend to clog with debris or algae, or to freeze in cold climates. The trap then fills with water, blocking the air flow in the duct. Several mitigators reported rerouting ducts to eliminate such water traps.

Some mitigators reported water accumulating in long horizontal ducts in attics where a slight sag either developed or was not originally noticed. All ducts over a few feet long should have a positive slope.

FROZEN PRECIPITATION OR CONDENSATION

Even when ducts maintain a positive slope, they may be subject to condensation problems if they have long runs in unheated or exterior space, particularly if they have low air flows. Condensation may freeze to the inside of the duct rather than draining down, gradually choking the air flow.

If the duct is exposed to alternate heating and cooling, ice may form and then break loose, dropping down the duct into the fan. One mitigator who works for a national company mentioned that they have a guideline which requires that exterior ducts be insulated if the winter season has more than 5,000 heating degree days.

FAN MOUNTING

Improper fan mounting can lead to a variety of problems with mitigation systems. The EPA recommends that fans be vertically oriented so that condensation will drain through without accumulating in the fan housing. The Agency also recommends that fans be located outside the building envelope so that all ducts inside the building are under negative pressure (3). Thus, if any leaks develop in the duct, indoor air will be pulled in rather than radon-laden soil gas being pushed out. The fans used in radon mitigation systems have powerful motors which tend to vibrate and must be securely mounted to a sturdy support. Two mitigators cautioned about securing fan supports to a frame wall because the wall may act as a sounding board, amplifying the fan noise. One mitigator reported a failure where the fan housing was supporting the weight of a vertical duct and warped enough to bind the fan blade.

Mitigators should also consider the environment in which the fan must operate. Florida attics are hot in the summer; Minnesota attics are cold in the winter. It may be difficult to imagine temperatures of -20 or 120 °F (-29 or 49 °C) when working on a roof in April, but a fan which is mounted there will experience a wide range of environments. Even if the fan is rated for the entire range of environmental conditions which it will encounter, extreme temperatures may contribute to premature failure. Insulating the fan housing or shielding it from direct exposure to wind, rain, and sunlight may moderate effects of extreme conditions.

FOREIGN DEBRIS

Several mitigators mentioned unpleasant experiences with small animals which had entered a duct through an unscreened exterior opening. One noted that children put toys and trash into such openings. Systems which use outdoor air to ventilate or pressurize inside space should have a filter as well as a screen. These filters should be cleaned or changed frequently during times of the year when plant debris (seeds, flower parts, leaves, etc.) may be airborne.

HIGH WATER TABLE

During their pre-mitigation inspection, some mitigators look for a dewatering system or for water stains on basement walls as an indicator of a "problem house." A subslab depressurization system which is blocked by water will not be effective. Even when there is no standing water, some soils will expand when wet and will close off subslab communication. If subslab suction is the selected mitigation technique and there is any indication of an occasional high water table, the pit excavated under the duct penetration through the slab should be enlarged and the duct should extend a minimal distance below the slab. This should provide sufficient volume to accommodate some water accumulation without restricting radial air flow.

Homes in areas with a high water table may have an existing sump which can be used as a suction point for a radon mitigation system. A very effective way to extend a pressure field under the slab is by depressurizing a sump which is connected to footing drains. The sump should be sealed with an air-tight cover, which must be removable to allow servicing or replacement of the pump. If the existing pump is not submersible, it should be replaced with one that is, since rusting of the pump will accelerate when the sump is sealed. The cover should contain a drain to allow the sump to collect water from above, as well as below, the slab. This drain should have a seal which allows water to pass while maintaining suction in the sump. If this seal fails, suction will be reduced. This could seriously reduce the effectiveness of the mitigation system, particularly if there is a low flow rate of soil gas.

RE-ENTRAINMENT

In spite of the EPA guidelines, some people mount fans inside buildings so that some of the duct is under positive pressure. A few mitigators had seen problems with re-entrainment, either from leaks in ducts which were under positive pressure, or from ducts which terminated immediately outside a building wall. This illustrates the importance of following the EPA guidelines for mounting fans outside the building envelope and terminating ducts where re-entrainment will not be a problem (3). If the exhaust is at or near grade, it should be far enough from the house to prevent re-entrainment and in an area of the yard not utilized by people (e.g., away from patios or gardens). Preferably, the exhaust should extend high enough above the roof to prevent blockage by snow, as well as re-entrainment through windows or chimneys. Some building codes specify that plumbing vents terminate at least 2 ft (0.6 m) vertically and 10 ft (3 m) horizontally from any openings.

One person mentioned the potential for leaks in the vent from an aeration system installed to remove radon from well water. The air vented from such systems may have much higher radon concentrations than soil gas. If the fan which exhausts the vent is located inside the house near the aeration unit, any leak in the duct could introduce large amounts of radon into the house.

COMPONENT PROBLEMS

FANS

A long-term follow-up study of 40 houses in Pennsylvania mitigated by an EPA contractor found that 5 of 36 houses with active soil ventilation systems had experienced fan failures (4). Four were due to capacitor failures in the fans' split-phase motors. When the capacitor fails, the motor continues to run at reduced efficiency, but cannot be restarted after a power interruption. Although the fan's performance is greatly reduced, the failure may not be detected unless there is a monitor of air flow or pressure drop across the fan, or a continuous radon monitor.

This failure mode was discussed at the EPA Radon Symposium in February 1990: mitigators were specifically asked about their experience with fan failures. Most mitigators have experienced some failures, but this EPA project had a failure rate far higher than that experience by these mitigators. A distributor who sells over 700 fans per month for radon mitigation reported that less than 1% fail within the 3-year warranty period. Failures may be due to either bearings or capacitors, but bearing failures are more noticeable because the fan begins to produce more noise. Several mitigators reported that fan failures seem to occur within a few months rather than after a year or more.

SYSTEM MONITORS

As mentioned above, drain lines from water traps may freeze in unheated spaces. A similar failure mode exists when condensation accumulates and freezes in the tubes which connect a pressure monitor or switch to the duct. If either tube is blocked, the switch or monitor will not function properly.

System monitors which are electronic or which trigger an electrically powered alarm should be wired to a different circuit than the system itself.

SEALANTS

Most mitigation systems involve some sealing of floor/wall joints as well as of cracks in a slab or wall. Unless the surface is properly prepared, the sealant will not adhere to it. Even with proper preparation, an appropriate sealant must be used. For example, silicone caulk will not stick to concrete, but urethane will. Any sealant used for radon mitigation should last as long as the house. While not technically a sealant failure, it is not uncommon for new cracks to develop in a slab or wall after mitigation. It may be that the drying of soil by a mitigation system stimulates cracks.

Ducts are usually constructed from sections of polyvinyl chloride (PVC) or acrylonitrile-butadiene-styrene (ABS) pipe. PVC pipe can be glued, but ABS pipe must be caulked. It is important that joints fit snugly and be thoroughly cleaned, and that an appropriate adhesive be used to ensure a permanent seal. Metal ducts are a special problem. The joints which are near a fan may be subjected to considerable vibration. The fan should be connected to the duct with rubber couplings to reduce vibration and provide a better seal between the fan and the duct.

PIPES

Since plastic pipe is readily available and easy to work with, it is probably the most common duct material. Some plastic, however, is affected by sunlight; it becomes brittle and more susceptible to impact damage. Only plastic pipe stamped "DWV" (drain, waste, vent) should be used outdoors unless it will be insulated or otherwise protected from sunlight.

RESIDENT ACTIVITIES

INTENTIONAL ACTIONS

Surprisingly, after paying hundreds of dollars for mitigation systems, some people turn them off. Probably the most common reasons are to save energy or to eliminate noise. If a resident thinks that radon is only a problem during the heating season, he or she may turn off the mitigation system during the warmer months, especially if windows are left open (5). Often people do not realize that a typical mitigation system fan uses less electricity than a 100-W light bulb. One mitigator felt that renters had a much lower perception of risk from radon than homeowners and were more likely to be concerned about a mitigation system's operating cost.

Several mitigators reported systems which were turned off by new owners who did not understand their purpose. One new owner had been told that the system was intended to control odors of sewer gas. Another had been advised by the realtor that the system was unnecessary.

UNINTENTIONAL ACTIONS

Several mitigators reported that residents had temporarily turned off systems and forgotten to turn them back on. Acoustic or electrical noise seemed to be the most common reason. One mitigator reported that a system was turned off during a party because the fan noise interfered with conversation. There were several reports of interference with radios and television. Some of these were due to faulty wiring or electrical components of the mitigation system. Often residents did not realize that the system could be fixed or adjusted to reduce or eliminate the noise. Rather than call the mitigator, they turned the systems off when the noise was particularly offensive (6).

Like any other appliance, mitigation systems which are plugged into an electrical outlet can be accidentally unplugged. If the system does not make much noise and has no alarm, it may take some time for a resident to realize that it is not running. This is probably a design failure, stimulated by the desire to avoid the cost of an electrician and possibly an inspection. Radon mitigation systems should be wired so that they cannot be accidentally unplugged. Opinions differed among mitigators as to whether it is better to use a dedicated circuit or an existing circuit. Some felt that a separate circuit would minimize electrical interference with a radio or television. Others felt that tapping into an existing circuit used for lights or appliances would make it more noticeable if the power to the mitigation system were interrupted.

HOME RENOVATION OR REMODELING

Many of the mitigators contacted warned homeowners that a mitigation system may be adversely affected by some typical home renovation or remodeling projects. These include replacing the heating/cooling system, making an addition to the house, or finishing the basement. One EPA contractor reported that a submembrane depressurization system in a crawlspace had been severely damaged by workmen replacing a furnace. Although the contractor had provided a walkway to the furnace, apparently the workmen had dragged the old unit out across the membrane, damaging it.

CONCLUSIONS AND RECOMMENDATIONS

The experiences related in this report show that residential radon mitigation systems do fail for a variety of reasons and that such failures may not be immediately recognized. Mitigators should design systems to minimize the probability of failures. The system design should include a monitor which residents can use to determine whether the system is operating properly. Homeowners must realize that even systems with good design and components have some chance of failure; they should check the system monitor periodically and measure radon levels annually as long as the house is occupied.

SYSTEM MONITOR FOR THE HOMEOWNER

Only a few mitigators reported using system monitors with which they were satisfied; one had personally designed and built the monitor. Some research and development of a suitable monitor for residential radon mitigation systems is needed. The monitor need not have high resolution as it will not be used to monitor minor variations in system performance. It need only be capable of detecting change by a factor of 2 or more. An ideal monitor would have the following characteristics:

- The monitor should be inexpensive so that there is little incentive for mitigators to omit it to cut costs. It could monitor the system operating parameters (e.g., pressure drop) rather than radon concentrations. Such monitors are 2 orders of magnitude less expensive than the least expensive continuous radon monitors.

- The monitor should be adjustable so that the mitigator can set it for the system installed in that house. Mitigators may want to check the settings after a break-in period; two mitigators mentioned that flow rates tend to increase and pressure drops decrease over the first few weeks after system start-up.

- The monitor should be simple enough to be useful to the vast majority of residents. Several mitigators reported that most people do not check monitors when they are provided. Some of those who do check their monitors call the mitigator about minor fluctuations.

- The monitor should be durable. It should not require any adjustment by the resident, who should be able to test whether it is functioning properly. Several mitigators said that many of the reports of mitigation system failure to which they responded were actually failures of the system monitor.

SYSTEM DOCUMENTATION FOR THE HOMEOWNER

It is essential that residents understand the basic principles of the mitigation system and how to interpret the system monitor. If residents are to avoid activities which could compromise mitigation systems and to recognize problems when they occur, they should receive verbal explanation and instruction when the system is installed, as well as written documentation which they may refer to in future years or pass on to a new owner if the house is sold. Such documentation should include:

- Radon concentrations before and after mitigation. The measurement method, duration, and time of year should be documented.

- A description of the principles and specifications of the mitigation system. The basic principle of operation could be taken from EPA's homeowner's guide to radon reduction methods (7). The location of ducts, wires, fans, switches, and the system monitor should be sketched or described. System operating parameters (e.g., pressure drop and air flow) after a break-in period of at least 24 hours should be available.

- An explanation of the system monitor. This would include whether the monitor indicated air flow or pressure drop, and the nominal range for the indicated parameter. If there is an audible or visual alarm, conditions that trigger it and what to do if the alarm goes off.

- A schedule and procedure for periodic inspections. This might simply be to check the monitor monthly.

- A description of any preventive maintenance and of the warranty on any components (e.g., the fan) or on the system as a whole. Homeowner or resident activities that might void the warranty should be listed. Who should be called if there is a problem should be identified.

- The appropriate state or local health department to contact in case of a problem that cannot be resolved by the original mitigator.

- A discussion of the sensitivity of the system to typical home remodeling or renovation projects.

- The importance of measuring radon concentrations annually as long as the house is occupied, even when the mitigation system appears to be operating normally.

- A short, simple summary of all of the above.

This may seem like a tremendous burden for a commercial mitigator, but most of them are already providing such documentation. An EPA survey of commercial mitigators (8) found that over 80% prepare a written mitigation plan and give a copy to their clients; over 60% provide clients with written instructions on how to maintain the systems.

The EPA might develop model documentation which could be copied or modified by commercial mitigators. Most of this documentation could be "boilerplate" which should be easy to assemble for each mitigation technique, with blanks to fill in specifics like radon concentrations and operating parameters. It is essential that the documentation be written so that most residents can understand it; otherwise the mitigation system will remain a "black box." The homeowner or resident will not feel competent to monitor its operation and may not appreciate the need for long-term follow-up radon measurements.

In addition to the documentation described above, the mitigation system should be clearly and permanently labeled with a warning that it is a radon mitigation system, that it protects the residents' health, and that residents should measure radon annually. The label should also identify whom to contact if a problem is identified or suspected.

LONG-TERM FOLLOW-UP

Based on the experiences of the mitigators contacted, few homeowners or residents recognize the potential for failure of their radon mitigation system. When a system monitor is provided, they do not check it regularly. When radon detectors are provided during subsequent heating seasons, they do not expose them. Like any mechanical system, radon mitigation systems are subject to failure. Some way to communicate this fact to current and future residents must be found.

A study involving long-term follow-up radon measurements in a national sample of mitigated houses could show the rate of mitigation system failures. Publicity about such a study might inspire many people to check the performance of their mitigation systems.

REFERENCES

1. Henschel, D.B., U.S. Environmental Protection Agency, personal communication, January 29, 1991.

2. U.S. Environmental Protection Agency. The national radon contractor proficiency (RCP) program: proficiency report. EPA-520/1-90-004 (NTIS PB90-204744), Office of Radiation Programs, Washington, DC, April 1990, 108 pp.

3. Henschel, D.B. Radon reduction techniques for detached houses: technical guidance (second edition). EPA-625/5-87-019 (NTIS PB88-184908), U.S. Environmental Protection Agency, Research Triangle Park, NC, January 1988.

4. Scott, A.G., and Robertson, A. Long-term performance and durability of active radon mitigation systems in eastern Pennsylvania houses. Presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 19-23, 1990.

5. Harrje, D.T., et al. Long term durability and performance of radon mitigation subslab depressurization systems. Presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 19-23, 1990.

6. Prill, R., Fisk, W., and Turk, B. Evaluation of radon mitigation systems in 14 houses over a two-year period. J. Air Waste Manage. Assoc. 40: 740-746, 1990.

7. U.S. Environmental Protection Agency. Radon reduction methods: a homeowner's guide. OPA-87-010, Office of Research and Development, Washington, DC, September 1987.

8. Hoornbeek, J., and Lago, J. Private sector radon mitigation survey. Presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 19-23, 1990.

MITIGATION BY SUB-SLAB DEPRESSURIZATION UNDER STRUCTURES FOUNDED ON RELATIVELY IMPERMEABLE SAND

by: Donald A. Crawshaw, M.S. (Civ. Eng.), MICE
Geoffrey K. Crawshaw
Pelican Environmental Corporation
Wellesley, Massachusetts 02181

ABSTRACT

Effective sub-slab depressurization requires the pressure field to cover the entire area under the slab. This is readily achieved by means of a low pressure, high flow fan system when the sub-slab material is permeable crushed stone or gravel. However, the occurrence of relatively impermeable sub-slab sand presents the mitigator with a number of problems to overcome. Traditional solutions have included using multiple suction points, digging pits and filling them with permeable material and using more powerful in-line fans. Such solutions can not always be used, and may be ruled out by aesthetic considerations, particularly when the mitigation work has to be located in a part of the structure that is fully furnished.

The paper documents results from using a high pressure, low flow (HPLF) fan system that has been developed to address these problems, and successfully used to mitigate radon levels, in various structures founded on relatively impermeable sand.

INTRODUCTION

Active sub-slab depressurization (SSD) has proved to be an effective means of collecting radon in soil gas from beneath slabs in contact with soil. An active SSD system consists essentially of a fan connected to a piping system that collects soil gas from beneath the slab for venting above the roof line. The slab acts as a membrane to form the upper boundary of the required sub-slab pressure field. Ideally the pressure field should cover the total area under the slab and should also extend under the exterior wall/floor joint, this being a usually significant radon entry route.

The type of material immediately under the slab is an important factor governing the design of every SSD system. Crushed stone aggregate under a slab is relatively permeable and typically requires a centrifugal type blower that can move soil gas in some volume (125 to 270 cfm in free air) and generate a maximum static pressure of less than 2 inches WC. On the other hand, sand or dirt under a slab is relatively impermeable in comparison to crushed stone aggregate and requires a fan that can generate considerably greater suction pressure than 2 inches WC to move a lesser volume of soil gas (1).

Traditionally, effective sub-slab depressurization in sand or dirt has required breaking into the slab, excavating a large amount of sand, replacing it with crushed stone and even with perforated PVC piping, and then recasting the slab. Only then can a SSD system with a centrifugal type blower be used to extract the soil gas. This extensive construction work may disturb the occupants, particularly if the work is to be done in the furnished part of the building. The difficulties and costs associated with this method led to the development of the patent-pending Pelican HPLF soil gas reduction system for SSD under structures founded on relatively impermeable material (2).

CLASSIFICATION OF SUB-SLAB MATERIAL

Evaluation of the communication of suction pressures through the sub-slab material between various test holes is a well known diagnostic technique used for designing SSD systems. After conducting diagnostic evaluations for many structures, it became apparent that additional data to help in classifying the sub-slab material can be collected using the same vacuum equipment, hosing and pressure gauges that are used for the communication tests. This entails taking two readings of suction pressure at each test hole with the vacuum equipment operating at full suction:-

(i) with the end of the hose in air
(ii) with the end of the hose tightly inserted in the test hole.

The net difference between these two pressure gauge readings gives the Pelican Permeability Number (PPN). Permeability of a soil is a property that determines the rate of flow through the soil and the PPN is a simple measure in inches W.C. of the resistance to air flow of the sub-slab material subjected to suction pressure applied at the test hole. Figure 1. shows the results obtained from numerous tests of sub-slab material encountered in Massachusetts with a standard 2.25 HP Sears Wet Dry Vac having been used to generate the suction at the test hole.

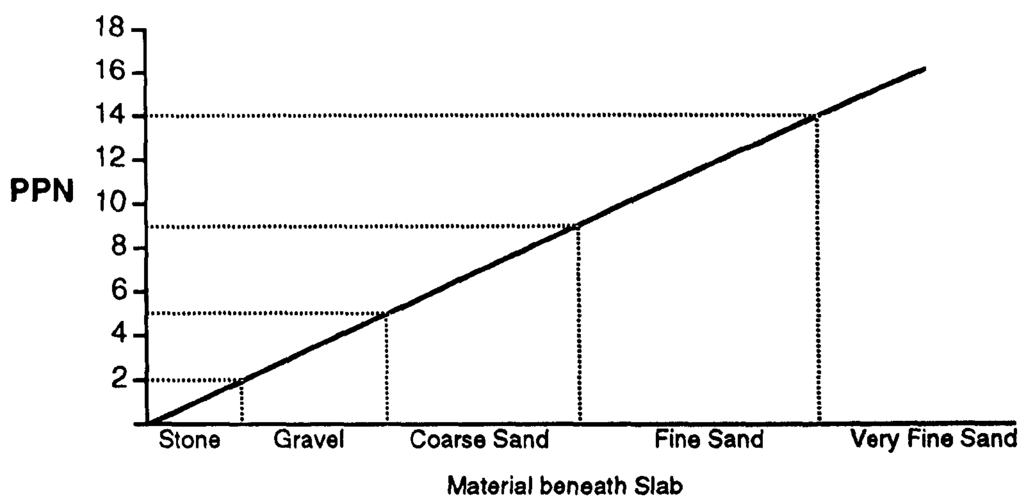


Figure 1. PPN soil classification of material beneath slabs (1)

Visual inspection down the test holes may provide additional confirmation of the class of material, but the PPN value is an in-situ test result that takes into account such variables as particle size, grading and lamination of the soil that are not apparent to the naked eye. The test can be repeated at a number of test holes during the diagnostic evaluation. With this method, PPN values can be readily obtained by a diagnostician without the need of special permeameter equipment and the recorded values are meaningful for the designer of the SSD system in selecting the required type of fan to be used. It is recommended that diagnosticians should construct their own soil classification charts for the sub-slab material which they encounter in their locality, using their vacuum equipment.

The paper covers results obtained with 56 HPLF systems that were installed to reduce radon levels where the sub-slab material was relatively impermeable in comparison to crushed stone or gravel. The paper does not deal with SSD where the sub-slab material is clay .

DESIGN OF HPLF SYSTEMS FOR RELATIVELY IMPERMEABLE SUB-SLAB MATERIAL

PIPE SELECTION

EPA's Reducing Radon in Structures Manual (3) includes a design guide for soil depressurization in various types of sub-slab material. A minimum pipe diameter of 1 1/2" is suggested in the manual where the material under the slab is sand. In practice, this 1 1/2" diameter piping has proved to be very suitable for typical residential applications, particularly in finished living areas, as the piping can be run inconspicuously along beams, in suspended ceilings, behind dry walls, and in closets. Installation of the piping is further facilitated by using thick-walled flexible piping to negotiate awkward bends. Two inch diameter piping is used where the pipe runs are lengthy or in offices or schools where the piping is potentially vulnerable to damage as a result of the large number of people using the building. All piping is Schedule 40 PVC.

BLOWER SELECTION

The PPN value is useful for determining the type of blower to be used. The Pelican HPLF system was selected for PPN values between 3 and 16. Figure 2 shows the fan curve of a S-3 blower that was used in 42 of the 56 projects described in this paper.

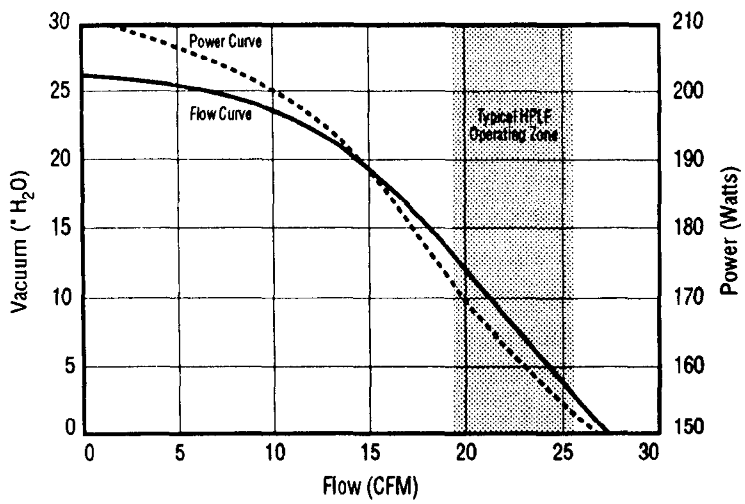


Figure 2. Air flow vs. vacuum pressure and power for S-3 blower

The EPA Manual (3) cites certain criteria that are important in fan selection and which were addressed under the following headings:-

a. <u>Air flow</u>

In the normal operating zone, the air flow moved by the S-3 blower in sand is 19 to 26 cfm, which is low in comparison to that moved by SSD systems in crushed stone or gravel with a centrifugal fan. (It is also low in comparison to a typical natural infiltration rate of more than 100 cfm for basements.) This meets the design requirement to minimize the amount of air that the SSD system can potentially remove from the house so as to minimize energy bills during the heating and cooling seasons and to avoid the risk of downdrafting and spillage from combustion devices.

b. Maximum static pressure

The typical air flow from HPLF systems using this blower,where the sub-slab material falls between dirt to coarse sand (as shown on Figure 1.), has been found to be in the range of 19 to 26 cfm. These operating conditions correspond to a vacuum pressure range of 14 to 4 inches WC. The maximum static pressure of 26 inches WC at 0 cfm air flow has proved to be sufficient for most residential applications in sand or dirt.

c. Electric power consumption

In the typical operating zone, the power curve in Figure 2 indicates power consumption of approximately 165 watts. when operating at 7.5 inches WC vacuum pressure. For an electric power cost of 10 cents/KWH this amounts to a monthly cost of $12.05. This cost can be offset against the reduced energy costs during the heating and cooling seasons as compared to a higher energy costs for a standard centrifugal blower used in SSD systems in crushed stone that may remove considerably more air from the house.

d. Noise

The blower housings are lined with industrial soundproofing. The blowers are often installed in attics and the soundproofing enables them to be located even directly over bedrooms. The 4 inch diameter Schedule 40 PVC pipe that discharges effluent from the blower to atmosphere above the roof line has been acoustically designed as a muffler. When the blower is suspended from the structure, a vibration isolator is used to eliminate any low frequency vibrations from entering living areas (4).

e. Long service life

To meet the design requirement of a long service life, Pelican HPLF systems incorporate a special housing so that the blowers run in a temperature stable environment. The S-3 blowers have double sealed bearings that minimize maintenance.

f. Ease of installation

Installation of the blower is facilitated by customized indoor and outdoor hanging kits and other accessories. Clic hangers are used to install the 1 1/2" diameter Schedule 40 PVC piping. Heavy duty 1 1/2" flexible PVC piping can replace multiple bends and reduce air flow friction losses at the bends; it is glued into standard PVC fittings (4).

g. No leaks from blower housing

The blower housing is under negative pressure to ensure a "safe-leak" design; this ensures that a leak in the housing will suck air into the fan. The blower is mounted in attics out of living areas or outside the structure.

h. Moisture resistance

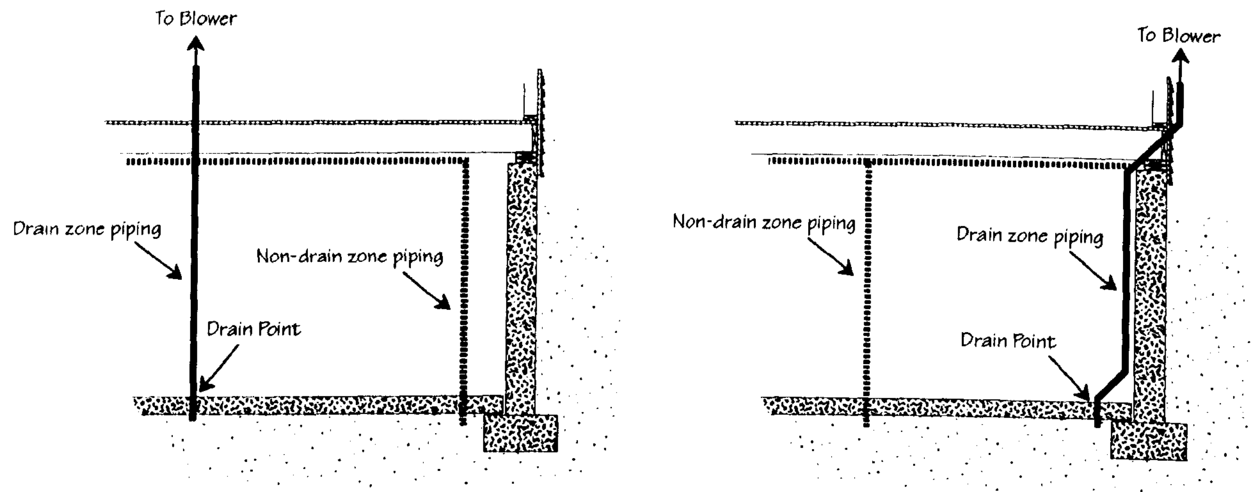
The blowers are weatherproofed and can be installed outdoors, being totally encased in the cylindrical housing shell.

NUMBER OF SUCTION POINTS

The footprint area of each structure is useful information for the designer in estimating the number of suction points to be used. Under favorable conditions, the pressure field generated by the S-3 blower can cover up to 1000 square feet in fine sand but it is prudent to assume coverage of 500 square feet per suction point in such material. One suction point should be near the center of the footprint that is to be covered by the pressure field. The final choice of number and location of suction points should be left to the installation crew as they may gather additional soil data after core drilling through the slab on the day of installation. The extension of the pressure field must be checked with the system in operation as additional suction points may be required and can be readily added by means of extending the 1 1/2 inch diameter piping system at that time.

CONDENSATE CONTROL

Pipe runs must be sloped so that condensate will always gravitate back to drain under the slab. The higher vacuum that is required for HPLF systems in relatively impermeable material works against the condensate, which is draining under gravity, so more slope is needed on the drainage pipes. When designing the piping layout, it is necessary to designate a drain point and then divide the piping network into drain and non-drain zones (4). This is



illustrated in Figure 3.

Figure 3. Condensate zones in piping network

CONDENSATE BYPASS

The condensate bypass arrangement around the blower is shown in Figure 4. It is designed to move condensate from the 4 inch diameter effluent stack to the intake piping where it can safely drain back to beneath the slab. This prevents condensate from running back into the blower or from forming a slug which would block the effluent exhaust (4).

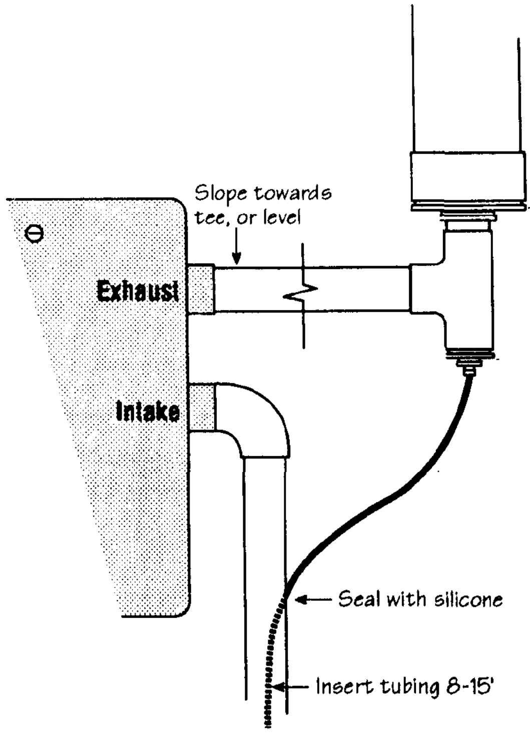


Figure 4. Condensate bypass arrangement in attics

INSTALLATION

Closure of any openings in the slab and some sealing is done to improve the integrity of the slab and to enhance the sub-slab pressure fields of each active HPLF system, but not to act as a primary mitigation system. In the installations described in the paper, major cracks discovered in the slabs during the diagnostic evaluation were sealed with polyurethane. Only unusually wide wall/floor joints were similarly sealed.

Effective slab penetrations are important in order to extend the sub-slab pressure fields and thereby achieve maximum radon reductions. Suction pressures should radiate horizontally through the sub-slab material so five inch nominal diameter holes were core drilled through the floor slabs to allow easy hand excavation of a plenum under the slab at each suction point. Two to five gallons of sub-slab material were excavated to form each cavity, with the larger amount being removed when the material was dirt and the lesser amount when the material was coarse sand. The end of each suction pipe was securely covered with aluminum insect screen to prevent sand from rattling in the lowest part of the pipe (4).

Figure 5. shows a typical installation where the blower was located in the attic.

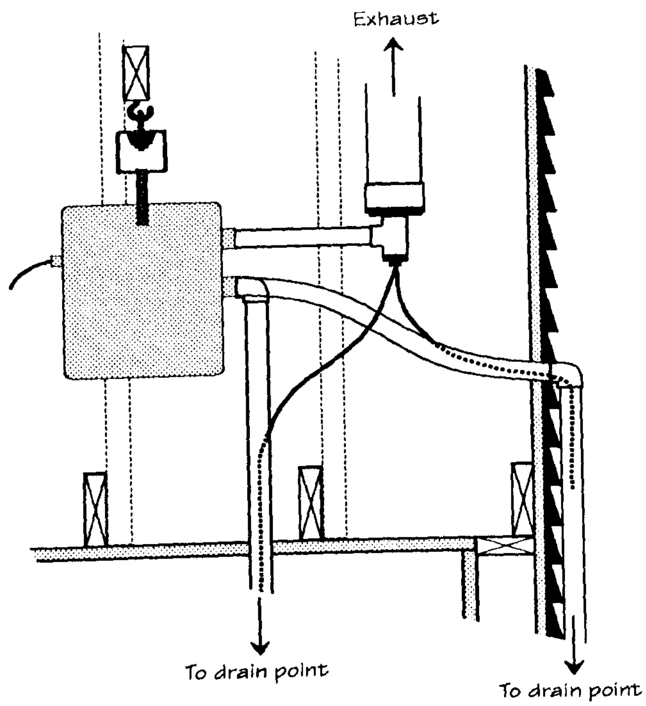


Figure 5. Typical Pelican HPLF attic installation.

In cases where there was more than one sub-slab suction point, the pipes were manifolded into a single pipe which was typically routed through the side of the basement foundation wall, up the outside of the house and into the attic through the gable. (The piping was run up through closets if they lined up from the basement to the attic.) The blower housing was connected to the 4 inch diameter exhaust muffler which vented the effluent through the roof to atmosphere.

All electrical connections of the blower to the power supply were made in accordance with the Massachusetts electrical code by a qualified electrician .

Dwyer U-tube manometers were fitted on the HPLF piping systems in locations convenient for the homeowner to inspect.

Make-up air was ducted to the proximity of the furnace to supply air for combustion and to guard against the possibility of backdrafting flue gases into the basement, wherever this was a concern.

With the mitigation systems operating, sub-slab pressure testing was performed to determine the extent and strength of the negative pressure fields beneath the slab.

RADON RETESTING

On completion of the work, and after the mitigation systems had been operating for at least two days, radon concentrations were retested with two charcoal vials exposed for two days. Retest locations were typically in the basement and on the first floor levels. The homeowners mailed the vials to Niton Corporation for testing and analysis.

In those cases where the work was done for clients such as relocation companies, in addition to retesting with canisters, retesting with a continuous monitor was carried out by Radonics, Inc.

RESULTS

The paper deals with 56 of the Pelican HPLF systems that have been installed. In 42 of them the S-3 blower was used and, for various reasons, HPLF blowers with different fan curves were used in the other 14 homes. Most of the HPLF systems required two suction holes, one of the holes preferably being near the center of the slab and the other being located near the footing of the foundation wall for the purpose of draining condensate. The 56 homes with HPLF systems had an average footprint area of 1115 square feet with an average footprint area per suction point of 500 square feet.

The PPN value was recorded for 27 of the installations and generally ranged from 6 (coarse sand) to 15 (dirt) with an average of 10.9 (fine sand). One installation was in gravel with a PPN of 3.

Short term retest results showed that the radon concentrations in the basements of the 56 homes were reduced by an average of at least 96.4%. The words "at least" are used because the lowest retest values were taken to be 0.4 pCi/L, having been reported by the laboratory as <0.4 pCi/L. The average pre-mitigation basement radon concentration was 19.8 pCi/L and the average post-mitigation basement radon concentration was 0.72 pCi/L. The highest retest result in a basement was found to be 1.8 pCi/L. and 76% of the basement retest results were below 1 pCi/L.

Manometer readings recorded for 43 of the installations had an average value of 6.2 inches W.C. with a maximum value of 16.5 inches and a minimum value of 1.0 inch. Manometer readings for the S-3 blower averaged 5.6 inches WC with a maximum value of 14.3 inches and a minimum value of 1.4 inches.

Table 1. lists data obtained in 20 HPLF installations during the diagnostic evaluation as well as the associated manometer reading with the system operating.

TABLE 1. DIAGNOSTIC DATA AND MANOMETER READINGS.

	1	2	3	4	5	6	7	8	9	10
Applied vacuum, inches W.C.	47.5	47.0	47.0	47.0	45.5	45.0	44.0	43.0	43.0	42.0
Pelican Permeability Number	13.5	11.5	10.5	12.0	10.0	12.0	14.0	11.0	14.0	12.0
Sub-slab pressure at 10ft	0.250	0.005	0.003	0.100	0.250	0.250	0.010	0.130	0.062	0.004
Smoke test 0 (none) - 3 (greatest)	2.0	?	0.0	2.0	3.0	3.0	0.0	2.0	2.0	0.0
System Vacuum, inches W.C.	15.0	10.5	4.5	11.0	3.0	4.1	7.8	3.7	1.8	5.7

	11	12	13	14	15	16	17	18	19	20
Applied vacuum, inches W.C.	42.0	42.0	41.0	40.0	40.0	37.0	36.0	35.0	33.0	33.0
Pelican Permeability Number	10.0	10.0	10.0	14.0	10.0	3.0	9.5	7.0	7.5	6.5
Sub-slab pressure at 10ft	0.120	0.007	0.155	0.095	0.020	0.003	0.002	0.025	0.007	0.007
Smoke test 0 (none) - 3 (greatest)	3.0	2.0	3.0	1.0	1.0	1.0	1.0	3.0	1.0	?
System Vacuum, inches W.C.	10.5	2.1	3.8	5.3	6.5	2.5	1.2	14.3	1.5	1.3

Figure 6. charts the diagnostic data and the manometer readings for the 20 HPLF installations in Table 1.

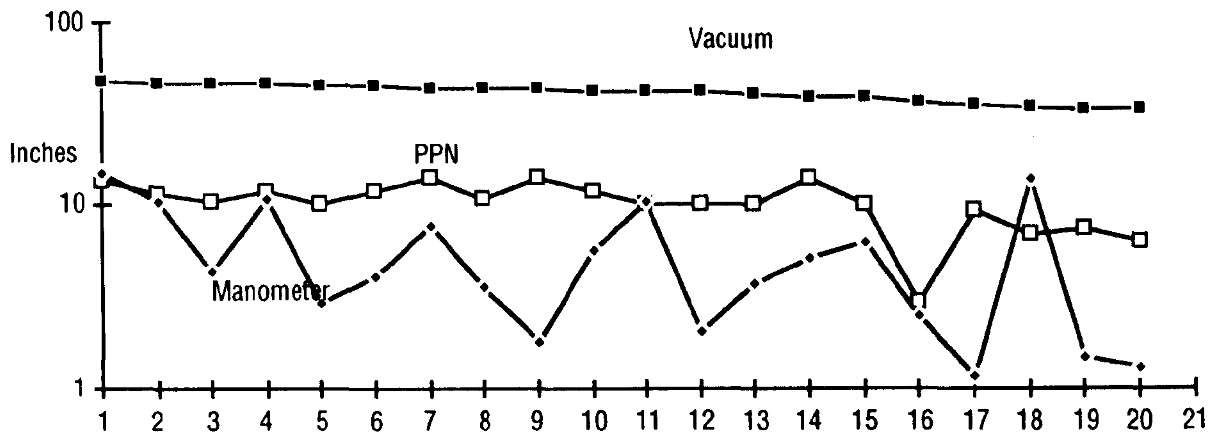


Figure 6. Diagnostic data and manometer readings for 20 HPLF installations.

Figure 7. charts the diagnostic data in Table 1 and the sub-slab pressure at 10 ft from the test hole at which the vacuum was applied, during the diagnostic evaluation.

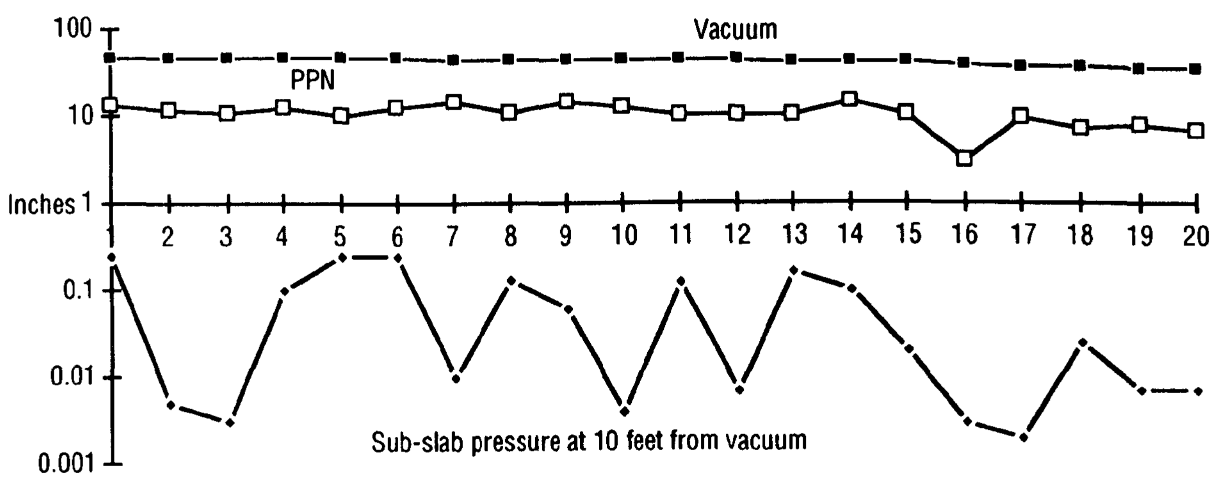


Figure 7. Diagnostic data and sub-slab pressure at 10 ft from applied vacuum for 20 HPLF installations.

DISCUSSION

Mitigation of radon concentrations in homes founded on relatively impermeable material can be achieved in a number of ways. Verified reduction of the radon concentration is of prime importance, but coupled with this requirement, the owner of the home or building has other important needs that must be addressed by the mitigator for successful completion of the mitigation contract. For mitigation by any sub-slab depressurization system, these considerations include noise reduction , visual impact, condensation control, acceptable running costs, reliability and longevity of the blower. The Pelican HPLF System was designed to meet all these requirements and has proved to be effective for sub-slab mitigation of radon concentrations in structures founded on sand or dirt in Massachusetts and New Hampshire.

Basement radon concentrations were reduced to below 2 pCi/L in all of the 56 homes, and 76% of them were reduced to less than 1 pCi/L, despite the fact that the slabs rested on such relatively impermeable material.

For a single-storey Federal building, which had an addition founded on sand, the S-3 blowers were located on the flat roof. Alpha-track retest results showed that the radon retest results were all less than 1.0 pCi/L in the office area. This project is not included in the results discussed in this paper.

For structures founded on sand or dirt, the designer has the option of selecting a HPLF blower coupled with 1 1/2 inch piping; this is particularly useful where the system has to be installed in a furnished part of the dwelling, such as a fully finished basement. The sound proofed housing enables the S-3 blower to be installed near living areas, even directly over bedrooms in attics, without disturbing the occupants.

Placing suction points away from the center of the slab near the wall/floor joint can result in "bypassing ", where basement air rather than soil gas is collected by the pressure field.The initial Pelican HPLF installation was carried out with four suction points located next to the middle of the four basement foundation walls in a house founded on dirt. The radon retest results were acceptably low but a considerable amount of piping was used. On subsequent HPLF installations, it became apparent that it was preferable to locate one suction point nearer the center of the footprint.

The PPN value has been found to be useful for quickly and simply identifying which blower system should be selected for sub-slab depressurization. It can be a useful number for broadly classifying the sub-slab material, particularly for discussing the project and blower selection with people who were not present at the diagnostic evaluation. No apparent relationship was found between the PPN value and the manometer reading except that the PPN usually exceeds the installed manometer reading.

Smoke tests were not found to be a satisfactory indicator of sub-slab communication when the sub-slab material was fine sand or dirt. This is because the relatively impermeable nature of the sub-slab material obstructs the flow of smoke. In a number of cases, although the smoke test was inconclusive, the PPN value indicated that HPLF sub-slab depressurization was a suitable mitigation method.

In the HPLF installations reported in this paper, no apparent relationship was found between the PPN value and sub-slab communication pressure test results at 10 feet distance from the point of suction with vacuum applied to a 3/4" diameter inspection hole. It appears that it is more reliable to base the choice of the blower on the PPN value than on the sub-slab communication test result at 10 feet when the sub-slab material is sand or dirt.

When using blowers with higher suction pressure, it is very important to slope piping correctly to enable condensate to be effectively drained to beneath the slab.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

REFERENCES

1. Crawshaw, D.A. and Crawshaw, G.K. Mitigation of elevated VOC concentrations in buildings arising from contaminated groundwater. In: Proceedings of HMC- Great Lakes '90. Hazardous Materials Control Research Institute, Cleveland, Ohio. September 26-28, 1990.

2. Crawshaw, G.K. Pelican HPLF System, radon solution for slabs poured on sand or dirt. Pelican Environmental Corporation, Framingham, MA. 1990.

3. U.S. Environmental Protection Agency. In: Reducing radon in structures manual. 2nd. Edition, 1989. Considerations in mitigation system design and installation, p. 5-23,24

4. Crawshaw. .K. In: Installation and Design Guide, Pelican HPLF System. Pelican Environmental Corporation, Framingham, MA. 1990

TITLE: A Laboratory Test of the Effects of Various Rain Caps on Sub-Slab Depressuirzation Systems

AUTHOR: Mike Clarkin, Camroden Associates, Inc.

This paper was not received in time to be included in the preprints so only the abstract has been included. Please check your registration packet for a complete copy of the paper.

ABSTRACT

Many sub-slab depressurization systems are installed with some type of rain cap intended to keep rain water from entering the exhaust pipe. In order to determine the effect these rain caps have on the pressures developed in the sub-slab depressurization system, a series of tests were performed to determine: 1. the static pressure losses associated with the use of the rain caps, and, 2. the effect of wind on the system with the various rain caps installed. The results of these tests are presented in this paper.

ANALYSIS OF THE PERFORMANCE OF A RADON MITIGATION SYSTEM BASED ON CHARCOAL BEDS

P. Wasiolek, N. Montassier, P.K. Hopke
Clarkson University
Department of Chemistry
Potsdam, NY 13699-5810

R. Abrams
RAd Systems, Inc.
Westboro, MA 01581

ABSTRACT

The performance of a radon mitigation system based on adsorption of radon onto charcoal beds (RAdsorb system) combined with an electronic air cleaner (EAC) installed in a single family house in Shrewsbury, MA was studied in a series of tests. Semi-continuous measurements were made of the radon gas concentration, potential alpha energy concentration (PAEC), particle concentration with size distribution and radon decay product activity-weighted size distribution with and without additional aerosol sources. The instruments used were a radon gas monitor (EBERLINE, RGM-3), WL-meter (Thomson & Nielsen), and a differential mobility particle sizer (DMPS) by TSI. For measurements of the activity size distribution, an Automated, Semi-continuous Graded Screen Array (ASC-GSA) developed at Clarkson University was utilized. During the time of tests, the conditions in the basement of the house, without the mitigation system in operation, were as follow: radon concentration up to 800 Bq m^{-3}, PAEC up to 650 nJ m^{-3} (30 mWL), particle concentration below 1000 cm^{-3}, and the fraction of PAEC and ^{218}Po in the smallest size range 0.5- 1.58 nm was up to 0.6 and 0.9, respectively. The tests were designed to study the influence of the combined system as well as the separate components of the mitigation system: fan, charcoal bed and EAC on the all of the measured parameters. When all the components of the mitigation system were working, the achieved reductions were radon concentration below 150 Bq m^{-3} (4 pCi L^{-1}) and PAEC below 100 nJ m^{-3} (5 mWL) with the smallest sized fraction of PAEC (0.5- 1.58 nm) of about 0.4. The tests proved that under certain conditions, the charcoal bed/EAC mitigation systems can be a potentially valuable technique for reducing a health risk due to indoor radon.

INTRODUCTION

Inhalation of the short lived decay products of radon (^{222}Rn): ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po, is thought to be the second largest cause of lung cancer after cigarettes smoking. To reduce this potential risk, it is presently recommended that the remedial measures should be taken when the level of radon gas in a home is found to exceed 150 Bq m^{-3} (4 pCi L^{-1}) (1). Several mitigation methods have been tried in houses with elevated radon levels. These techniques might be divided into two main categories:

a) Ones based on the reduction of the radon entry rate into the house, that sometimes required changes in a house construction or house modification e.g." subslab ventilation", "crawl space ventilation",

b) Others based on the removal of radon from indoor air (ventilation, filtration, radon adsorption).

The RAdsorb system built by the RAd Systems Inc. is a carbon adsorption system. The system has been installed in a single family house in Shrewsbury, MA. The RAdsorb radon removal system is based on activated carbon adsorption of radon. A radon gas removal efficiency evaluation was performed by the producer yielding values up to 97% reduction in radon gas concentrations (2). In addition, for this study, an electronic air cleaner (EAC) (Honeywell Model F50E) has been added to the RAdsorb system. The influence of the operation of the RAdsorb system on the indoor radon and its decay products concentrations (PAEC) and activity weighted size distributions are important from the health risk point of view and were the objective of measurements made in this house during September 1990.

HEALTH RISK DUE TO INDOOR RADON

The health risk associated with radon in indoor air is not from radon itself but rather from radon's short lived decay products. Radon as an inert gas with a half-life of more then 3 days may be inhaled and subsequently exhaled with little decay while in the human lung. The decay products of radon, however, are reactive and when inhaled, may deposit within the lung. Since they have short half-lives, further radioactive decay will occur prior to particle clearance from the respiratory tract. The alpha energy emitted during decay is therefore fully deposited in the lung tissue, possibly causing damage to the DNA within the target cells. If the DNA is damaged, the abnormal cell may reproduce and may result in a cancer. The deposition of the radon decay products within the lungs depends to a great extent on the attributes of the particles to which it is attached. The efficiency of deposition of particles in the lung varies with the particle size and hence, knowledge of the particle size distribution and the activity size distributions are important in evaluating the risk attributed to radon progeny. The fraction of radon progeny atoms or ions possibly clustered with other molecules such as H_2O is traditionally defined as the "unattached" fraction. The most recent studies strongly suggest that so-called "unattached" fraction is actually an ultrafine particle mode in the 0.5 - 3.0 to 5.0 nm size range (3). In the absence of active particle sources, the radon decay product activity size distribution may be thought of as bimodal, with a fairly sharp small-diameter mode near the molecular size corresponding to the "unattached" fraction and a broader large-diameter mode corresponding to the "attached" fraction (4). Two physical parameters used in all lung dosimetry models estimating radiation doses from inhaled radon decay products, are the activity median diameter of the "attached" radioactive aerosols and the "unattached" fraction of ^{218}Po. The ^{218}Po is of particular interest because it is the first short-lived decay product in radon chain with a half-life of only 3.1 minutes.

The dosimetric calculations for evaluation of the absorb dose in lung tissue per unit exposure suggest that the dose per unit exposure from the "unattached" fraction could be up to 25 times higher then that for the "attached" fraction (5).

In the most recent dose estimates (6), particle size has been taken into consideration. The basal cell and the secretory cells in the bronchial epithelium were considered as target cells. The resulting dose conversion factors per unit exposure from monodisperse activity D_i, are presented in Figure 1 as a function of breathing rate.

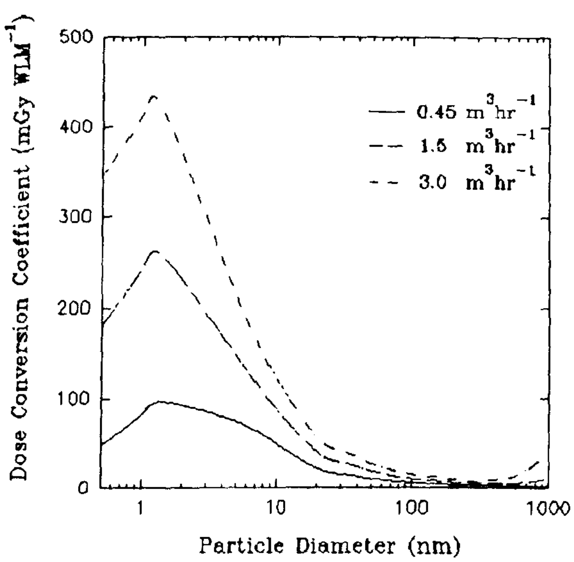


Figure 1. Dose to bronchial secretory cells as a function of the size of radon decay products for an adult male (6)

The graph shows the dose to secretory cells for three different breathing rates equivalent to resting, light activity and heavy work and that for all cases the conversion factor is strongly dependent on the activity median diameter especially for particles smaller then 10 nm. Therefore, to calculate the dose per unit exposure to secretory cells, the following formula applied:

$$\frac{D_s}{E_p} = \sum_{i=1}^{i=n} f_i D_{si} \qquad (1)$$

where,
E_p - exposure to PAEC [WLM]
D_s - total dose to secretory cells [Gy],
D_{si} - dose to secretory cells per unit exposure to PAEC with size i [Gy/WLM],
f_i - fraction of activity with size i,
n - number of size ranges considered.

A similar expression applies for the basal cells. Thus, any action influencing the physical parameters of indoor aerosols should be considered very carefully from the point of view of possible health risk. Because the major effect of any air cleaning system on the radon decay products in indoor air is the alteration of the activity size distribution by reducing the particle concentration, the evaluation of such systems is desirable.

DESCRIPTION OF THE RAdsorb/EAC SYSTEM

In general, air cleaning systems can reduce the concentration of radon decay products and PAEC by three mechanisms. The first is the direct collection of "unattached" and "attached" radon decay products by the air cleaning systems. The second is the enhancement of deposition of the radon progeny to the room surfaces created by the air cleaning system's air circulation. The final mechanism is the shift in average size to smaller particles. The plateout rate then increases because of the higher diffusivity of these smaller particles.

Preventing radon entry into the house is the technique advised by the EPA, but in some cases, the radon must be removed from indoor air. The adsorbing properties of charcoal have been utilize in a unit design by RAd System Inc. The theoretical background for the adsorption of radon in charcoal beds is presented in detail by Abrams and Rudnick (7) and by Bocanegra and Hopke (8). The schematic diagram of the RAd Systems Inc.'s RAdsorb/EAC unit is presented in Figure 2.

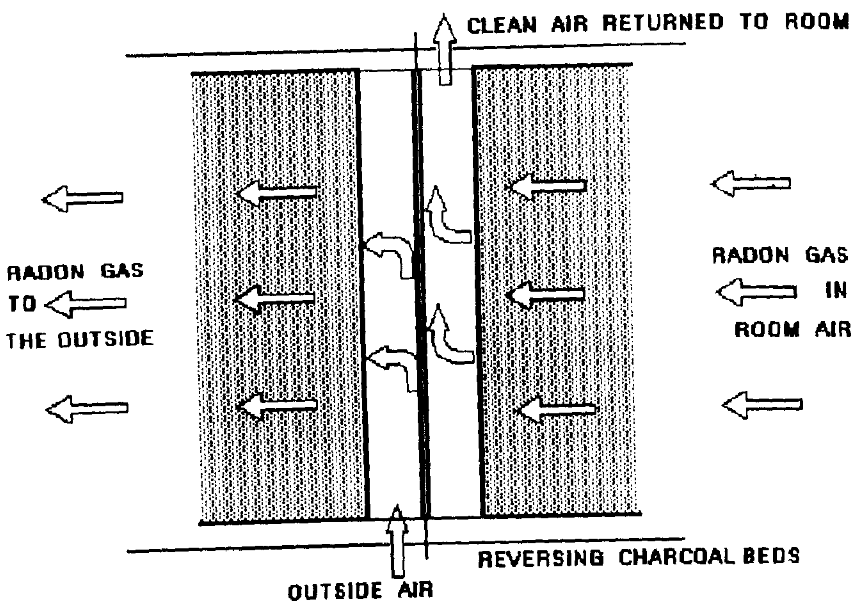


Figure 2. Schematic diagram of the RAdsorb system

The unit contains a cylindrical radon bed 0.9 m high and 0.6 m in outside diameter. It is divided vertically by a solid baffle into two sections; one for adsorption, the other for regeneration. Room air flows into the unit through the EAC. The radon-laden air then flows from the outside of the front bed into the core, while outside air (essentially radon free) flows through the other bed from the core through the bed to the outside and to the outdoors by a duct. The regeneration flow through the bed is at 4 to 10 m^3 min^{-1} and forced by a fan, which is an integral part of the removal unit. When the one bed's adsorptive capacity is expended, the bed rotates 180° and repositions the expended bed in the regeneration zone and the freshly regenerated bed in the adsorption zone. The cycle of adsorption of radon in one half of the charcoal bed and desorption in the second half is repeated continuously on a fixed time cycle. The flow of indoor air is forced by 6 m^3 min^{-1} fan. The unit incorporates the bed, drive, filters and both the room air and outside air blowers in the 0.7 m x 0.7 m x 1.6 m cabinet. The unit also is equipped with an outside air temperature sensor to vary the speed of the outside air blower inversely with temperature for the best desorption of radon. The prototype system was tested under laboratory conditions (2) with very good results yielding up to 97% radon gas removal efficiency. The investigated unit was installed in the basement of the house in Shrewsbury, MA in May 1989 and had been in continuous operation since then.

HOUSE CHARACTERISTIC

The house consists of a living room and kitchen on the first floor and three bedrooms on a second floor. The initial concentration of radon in house basement before mitigation ranged up to 1100 Bq m^{-3} (30 pCi L^{-1}). The RAdsorb system was chosen by house owners as the easiest way of reducing radon levels without significant construction work and changes in a house operation. The dimensions of the basement were 8 m x 7.5 m x 2.3 m, with a volume of about 138 m^3. Standard doors connected the basement with the kitchen and with the outdoors. The sampling location was in the basement close to the RAdsorb/EAC system outlet and near to the outside door. This location was necessary because of the use of the basement as a workshop and storage room by the house owner. The radon concentration on the day of arrival to the house was about 660 Bq m^{-3} (18 pCi L^{-1}) with particle concentration of 10000 cm^{-3}. The average temperature in the basement during the measurements was up 30° C with very high humidity.

INSTRUMENTATION

The physical parameters measured during testing the RAdsorb/EAC system were: radon concentration, particle concentration, potential alpha energy concentration, and activity-weighted size distribution of the radon decay products.

Radon gas

For radon gas concentration measurements, an EBERLINE RGM-3 radon monitor was used. The RGM-3 is a portable, microcomputer-based radon gas measuring instrument which utilizes a 3.3 liter, scintillation cell detector and microcomputer controlled 8 lpm pump to sample radon gas. The instrument allows the operation in the grab sampling mode and a continuous mode. That provides the radon gas concentration at one hour intervals. The microcomputer predicts decay products plateout as a function of time during the first hours of operation and compensates for it. The sensitivity of the device was 0.12 cps/pCi L^{-1}.

Particle Concentration

To measure the airborne particle concentration and size distribution, a TSI Model 3932 Differential Mobility Particle Sizer (DMPS) was used. The DMPS measures the size distribution of submicrometer aerosols by the electrical mobility detection technique. The aerosols are classified with Model 3071 Electrostatic Classifier and their concentration measured with Model 3086 Electrometer.

A microcomputer controls the system, collects the raw data, performs the data inversion to obtain the particle concentration as a function of particle diameter. The diameter range measured in these experiments is 0.01 μm to 0.4 μm with a concentration in the range of 10^3 to 10^5 particles per cm^3.

Activity-Weighted Size Distributions

The activity weighted size distribution was measured with the automated, semi-continuous graded screen array (ASC-GSA) described by Ramamurthi (9) and Ramamurthi and Hopke (10). The ASC-GSA measurement system involves the use of combination of six sampler-detector units (see Figure 3) operated in parallel.

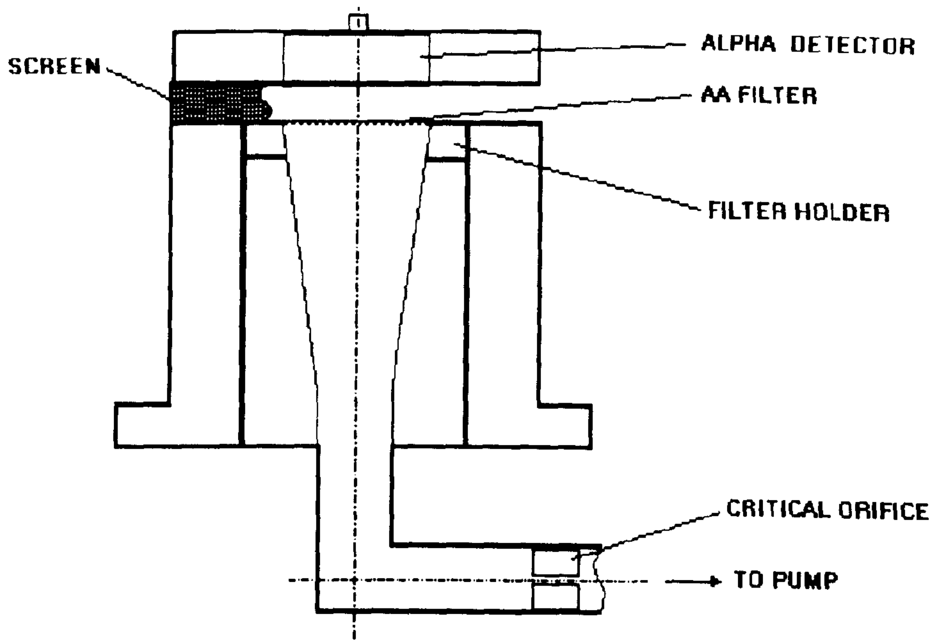


Figure 3. The cross-section of the sampler unit

Each sampler-detector unit couple wire screen penetration, filter collection and activity detection with a solid state detector in a way as to minimize depositional losses. The system samples air simultaneously in all of the units, with a flow of about 15 lpm through the sampler slit between the detector and filter holder section in each unit. The sampled air is drawn through a Millipore filter (0.8 μm, Type AA). The combination of wire screens wrapped around the samplers are presented in Table 1.

TABLE 1. THE PARAMETERS OF THE SIX SAMPLERS OF THE ASC-GSA SYSTEM

Unit	Sampler Slit Width [cm]	Sampler Diameter [cm]	Screen Mesh	Dp_{50} (0.5-350 nm) [nm]
1	0.5	5.3	-	-
2	0.5	5.3	145	1.0
3	0.5	5.3	145x3	3.5
4	0.5	5.3	400x12	13.5
5	1.0	12.5	635x7	40.0
6	1.0	12.5	635x20	98.0

One of the sampler-detector units is operated with an uncovered sampler slit, thus providing information on the total radon decay product concentrations. To detect alpha particles emitted by ^{218}Po and ^{214}Po atoms collected or formed on the filters, ORTEC Model DIAD II, 450 mm^2 surface barrier alpha detectors are used. The signals from the detectors are amplified and routed through a multiplexer to PC-based multichannel analyzer (ORTEC-MAESTRO) installed in an IBM-compatibile laptop computer. The collected spectra are saved on the hard disk of the PC for further analysis. The block diagram of the ASC-GSA system is presented in Figure 4.

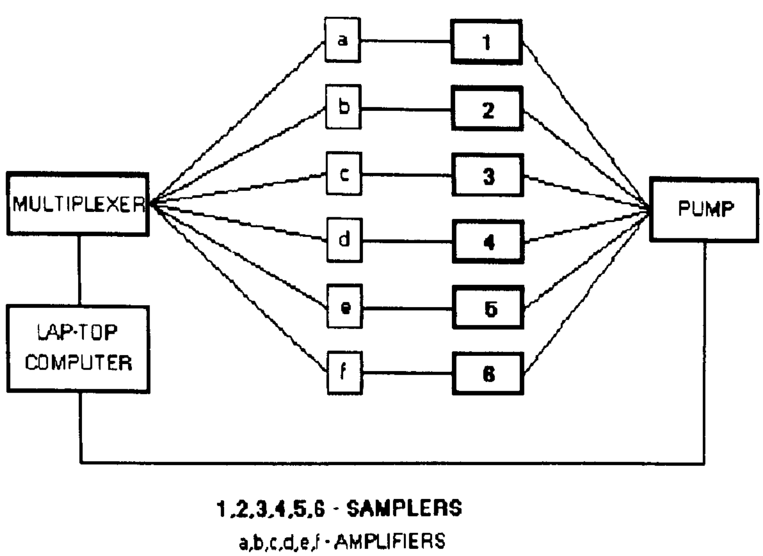


Figure 4. The block diagram of the ASC-GSA system

The computer control of sampling, counting and analysis permits automated, semi-continuous operation of the system with a sampling frequency between 1.5 to 3 hours. The activities of each radon progeny are estimated from alpha spectra collected during two counting intervals: the first one during sampling and the second 20 minutes after end of sampling. The observed concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi are used to reconstruct the corresponding activity-weighted size distributions using the Expectation-Maximization algorithms (11).

The ASC-GSA system allows the determination of the activity weighted size distributions in six inferred size intervals in geometric progression within the 0.5 - 500 nm size range. The performance of the ASC-GSA system was tested during laboratory (9) and field (12) intercomparison measurements showing very good agreement with systems from other leading laboratories.

RESULTS

To study the performance of the RAdsorb/EAC radon mitigation system on radon and radon decay products the experiments were designed to:

a) Test the effectiveness of RAdsorb/EAC in removal of Rn gas and progeny.

b) Determine the changes in the size distributions of Rn-d caused by the RAdsorb/EAC system.

The design approach was to run each component of the RAdsorb/EAC system: Fan, RAdsorb, EAC independently and in combination, establishing the baseline before and after each run. As a control parameter to test the potential health effects of the action during the tests, the dose to secretory cell for a resting adult male was calculated by the method described earlier. The reference levels (the "background" values) of ^{222}Rn concentration, PAEC and activity fractions to which the comparisons were made, were taken as:

1) The mean values of measurements after assuming that the steady-state conditions were established,

2) The mean values of the "background" measurements performed on the day of arrival and on the last day of tests (see Table 4).

The second approach was considered to present the changes in measured quantities in relation to the conditions when no devices were operated and which could be treated as a true "background".

The exposure to PAEC was calculated as follow:

$$E_p = PAEC\frac{8760}{170}n \qquad (2)$$

where,

E_p - exposure to PAEC [WLM],
PAEC - potential alpha energy concentration [WL],
8760 - numbers of hours per year,
170 - number of hours per working month,
n - occupancy factor (n=0.8 was assumed).

"Background" Conditions

To establish the "background" conditions and the operational parameters of the instruments, the first measurement was performed on the day of arrival with the RAdsorb/EAC system turned off 40 hours earlier.
The measured "background" conditions are presented in Table 2.

TABLE 2. THE "BACKGROUND" CONDITIONS IN THE SHREWSBURY HOUSE ON THE DAY OF ARRIVAL

Particle concentration [cm^{-3}]	10000
^{222}Rn concentration [Bq m^{-3}]	659
^{218}Po concentration [Bq m^{-3}]	307
^{214}Pb concentration [Bq m^{-3}]	122
^{214}Bi concentration [Bq m^{-3}]	78
PAEC [mWL]	33.1
Equilibrium factor	0.19
"Unattached" fraction of ^{218}Po	0.65
"Unattached" fraction of PAEC	0.35

The "background" conditions were tested again, after the RAdsorb/EAC system had been turned off for 15 hours during the last day of measurements. The measured variables are presented in Table 3.

TABLE 3. THE "BACKGROUND" CONDITIONS IN THE LAST DAY OF MEASUREMENTS

Particle concentration [cm^{-3}]	4000
^{222}Rn concentration [Bq m^{-3}]	599
^{218}Po concentration [Bq m^{-3}]	377
^{214}Pb concentration [Bq m^{-3}]	93
^{214}Bi concentration [Bq m^{-3}]	52
PAEC [mWL]	28.4
Equilibrium factor	0.18
"Unattached" fraction of ^{218}Po	0.87
"Unattached" fraction of PAEC	0.61

The size distributions of radon decay products and PAEC without RAdsorb/EAC system working are presented in Figure 5. The low particle concentration in the basement for the two background samples resulted in 65% and 87% of the ^{218}Po activity in the smallest inferred size interval with a mid-point diameter of 0.9 nm. The corresponding ^{214}Pb and ^{214}Bi distributions showed activity in the 0.5 to 1.6 nm range below 20% and 50%, respectively. The resulting PAEC distribution followed a standard bimodal distribution with maximums in the range 0.5 to 1.6 nm and 160 to 500 nm. The estimated doses to secretory cells and mean values of PAEC and ^{222}Rn concentrations in "background" conditions are presented in Table 4.

TABLE 4. AVERAGE VALUES OF SOME PARAMETERS IN "BACKGROUND" CONDITIONS

^{222}Rn [Bq m^{-3}]	PAEC [mWL]	0.5-1.58 nm PAEC fraction	Secretory Cell Dose [mGy y^{-1}]
630	30.8	0.428	55.8

Fan

To investigate the influence of the operation of the RAdsorb system's fan, the charcoal canister was blocked allowing free circulation of the air through the device. According to some studies, a fan itself can act as a removal unit by increasing the plateout rate of radon decay products (13). This effect was observed as well during operation of the RAdsorb's fan operating. The results of the experimental runs with fan ON and OFF are presented in Figure 6. As expected, radon gas concentration (Figure 6 a) was not effected by turning on the fan. The fan caused a decrease both in the PAEC and ^{218}Po concentrations (Figure 6 b) and d). This result is due to better mixing of indoor air and an increase in the deposition rate of the progeny on room surfaces. The activity size distributions of PAEC and ^{218}Po were not affected by the fan in any significant way.

Fan/EAC

To study the effect of the combined operation of the RAdsorb unit fan together with its attached EAC, the EAC was turned on while the fan was operating. The results are also presented in Figure 6. The concentrations of ^{222}Rn and ^{218}Po did not show any drastic changes that could be attributed to operating the fan/EAC. PAEC has shown a reduction of a factor of 2 from about 40 mWL to 22 mWL (mean values from four measurements under steady-state conditions before and after turning the device on). For the reference values from the "background" measurements (see Table 4), the reduction of PAEC was about 29%. A much

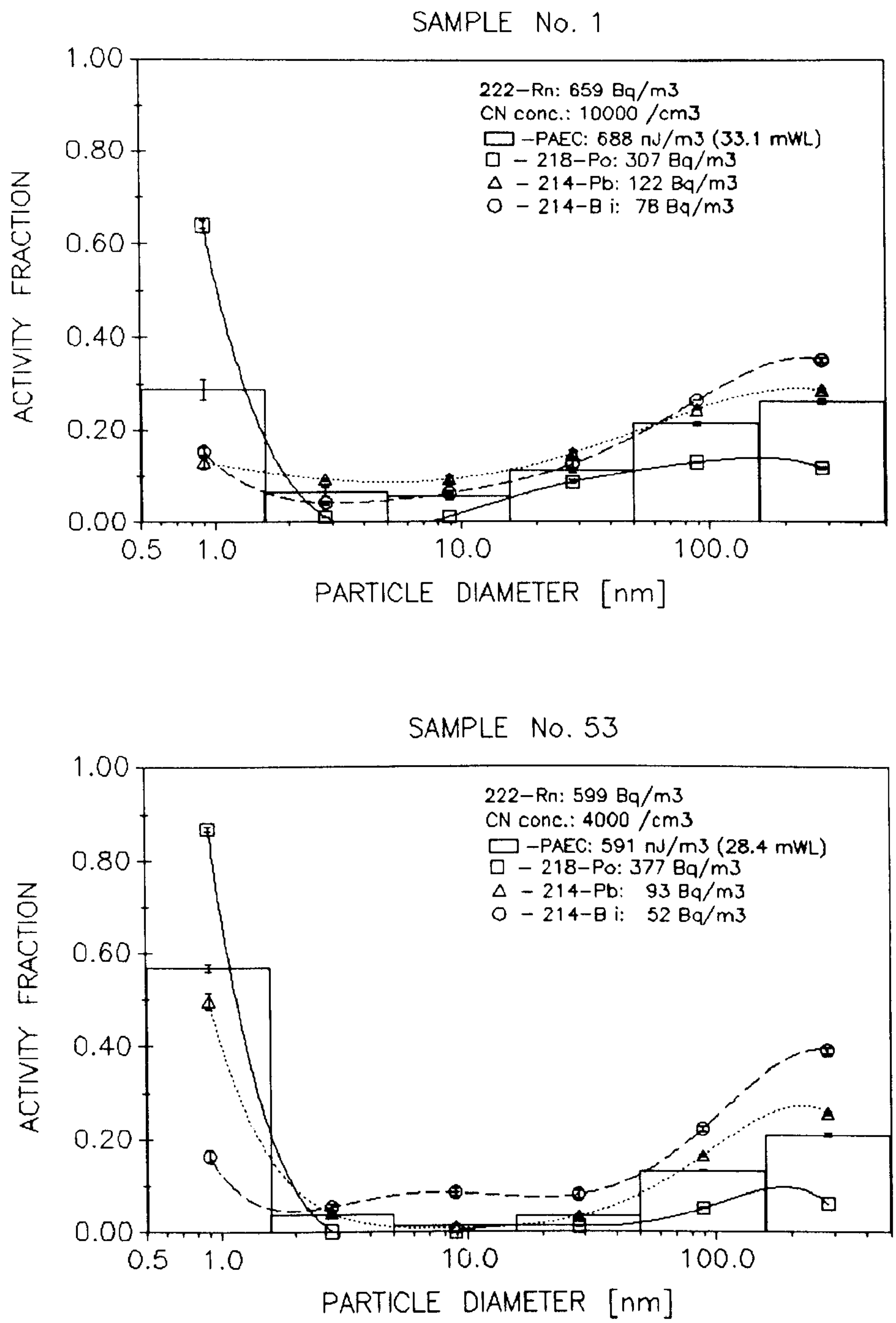


Figure 5. Typical activity size distributions in "background" conditions (no mitigation devices in operation)in the Shrewsbury house.

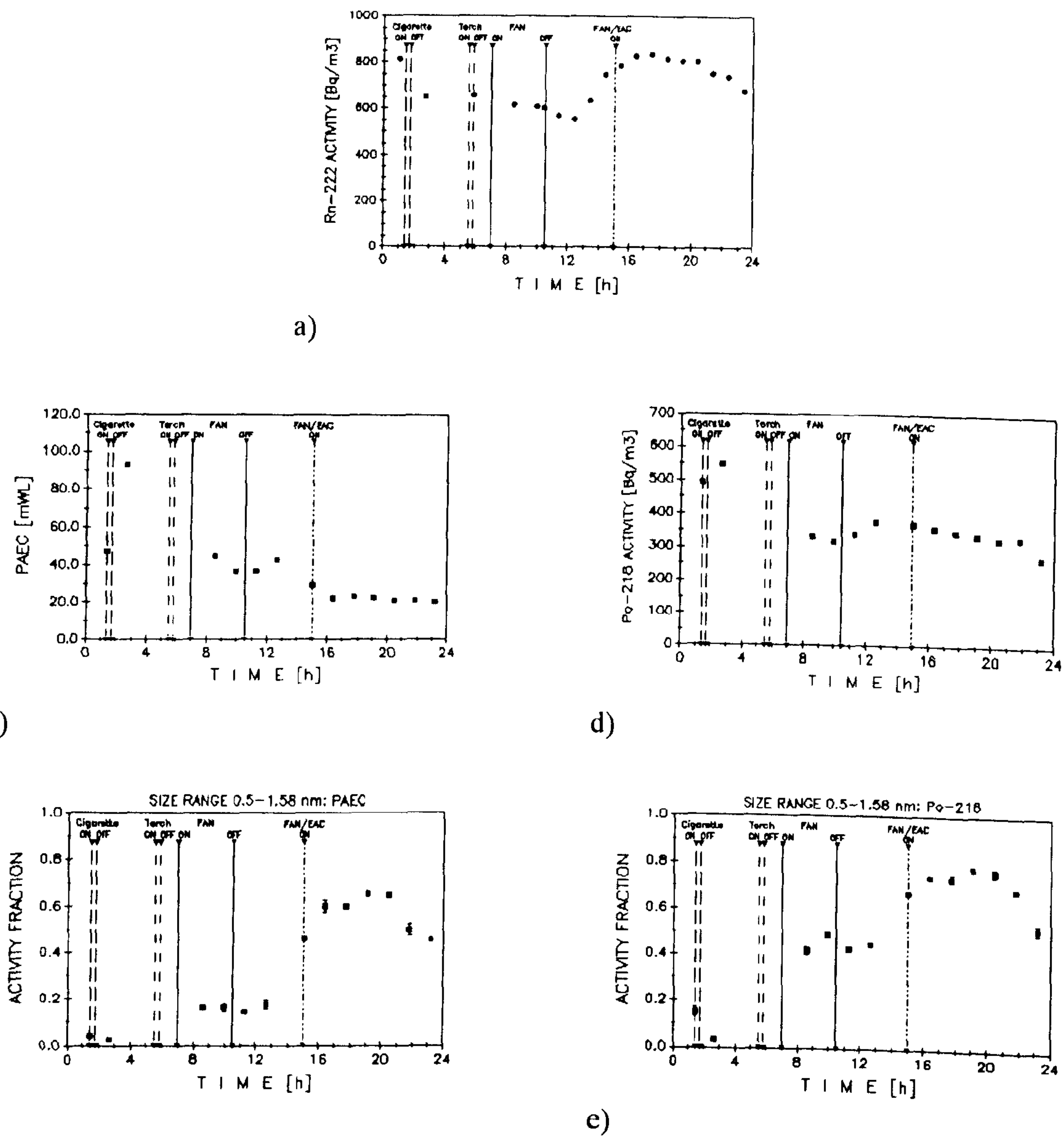


Figure 6. The influence of a fan and electronic air cleaner (EAC) on indoor radon and its decay products:

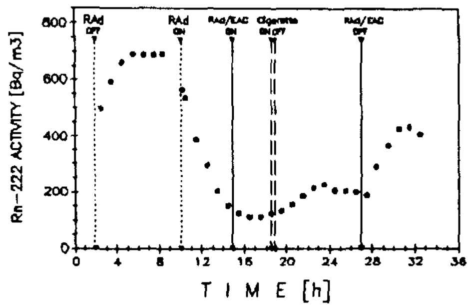
a) ^{222}Rn concentration,

b) potential alpha energy concentration (PAEC),

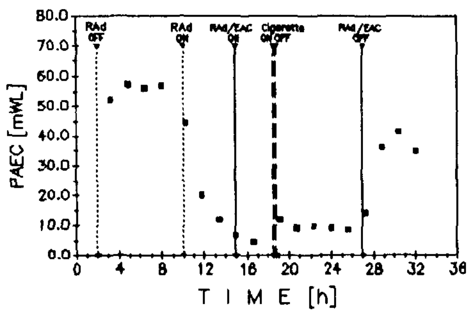
c) activity fraction of PAEC in the size range 0.5-1.58 nm,

d) ^{218}Po concentration,

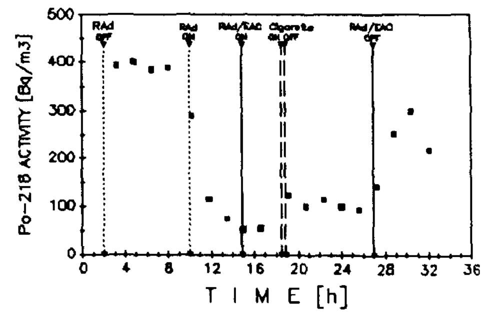
e) activity fraction of ^{218}Po in the size range 0.5-1.58 nm



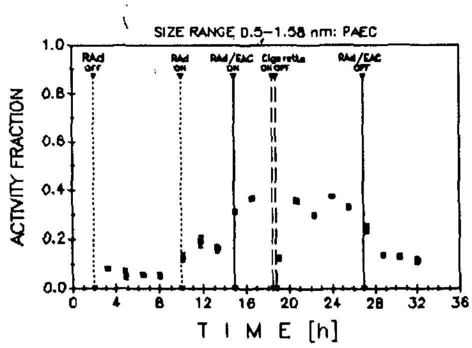
a)



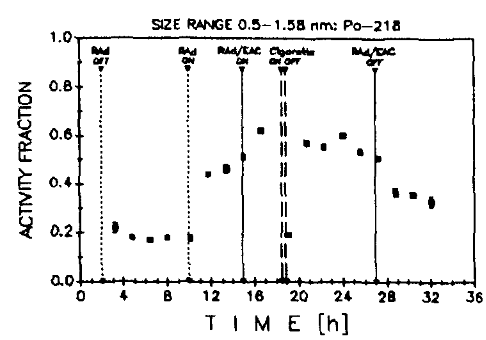
b)



d)



c)



e)

Figure 8. The performance of the RAdsorb system (RAd) alone and combined with a electronic air cleaner (EAC):
a) ^{222}Rn concentration,
b) potential alpha energy concentration (PAEC),
c) activity fraction of PAEC in the size range 0.5-1.58 nm,
d) ^{218}Po concentration,
e) activity fraction of ^{218}Po in the size range 0.5-1.58 nm

TABLE 6. THE CHANGES OF ^{222}Rn CONCENTRATION, PAEC, SIZE DISTRIBUTION AND RESULTING DOSE DUE TO OPERATION OF of RAdsorb/EAC

RAdsorb/EAC	^{222}Rn [Bq m^{-3}]	PAEC [mWL]	0.5-1.58 nm PAEC fraction	Secretory Cell Dose [mGy y^{-1}]
OFF	666	55.6	0.061	37.5
ON	163	8.0	0.339	10.5

The operation of the combined RAdsorb unit with the EAC yielded a substantial reduction in the radon gas concentration of about 76% and PAEC of about 86%. This improved removal efficiency was enough to compensate for the potential increase in the health effect due to changes in the radon decay products size distribution (5 times increase in the 0.5-1.6 nm fraction of the PAEC). The estimated dose to secretory cells of 10.5 mGy y^{-1} was 72% lower then the initial value. The estimation of the changes because of the operation of the combined RAdsorb/EAC system was performed using the measured "background" values (see Table 4). In relation to those values, the radon gas was reduced by 76%, the PAEC by 74% and the dose to the secretory cells by 81%. The results suggest that the combined use of the RAdsorb and electronic air cleaner (EAC) provided greater dose reduction than either operating alone. The data suggests that the EAC is more effective in reducing the dose from radon decay products when radon concentrations are lower (e.g. less than 200 Bq m^{-3}). It was only when the RAdsorb lowered the concentrations that the EAC provided some dose reduction. Since the EAC are often installed to provide removal of pollen and other irritants, the possible ancillary benefit of a reduction in radon progeny dose at low radon concentrations warrants further investigation. Figure 8 a) presents the hourly measurements of radon gas. The data shows a first sharp decrease in the radon concentration reaching the lowest point of about 111 Bq m^{-3} in about 6 hours. Later, the radon level increased and fluctuated around 150-200 Bq m^{-3}. This pattern was observed during all of the experiments with the RAdsorb unit.

SUMMARY

The influence of the RAdsorb/EAC radon mitigation system installed in a single family house in Shrewsbury MA, was studied in a series of tests. The radon gas concentration, PAEC and radon decay products activity-weighted size distributions were measured on semi-continuous bases.

The results obtained confirmed the theoretical predictions:

larger effect was observed in the size distributions both of ^{218}Po and PAEC. The combined operation of the fan/EAC caused an increase in the fraction 0.5-1.6 nm of ^{218}Po from 0.445 to 0.754 (1.7 times increase) and for PAEC from 0.158 to 0.626 (4 times increase).

Using the values obtained in the investigated house (decrease in PAEC of about 50% and the changes in size distributions), the estimated dose to secretory cells was 53 mGy y^{-1} before and 51 mGy y^{-1} after turning the EAC/fan on. For the measured "background" parameters, the estimated dose was 56 mGy y^{-1} (see Table 4). Therefore, no benefit in reducing the health risk was observed.

The increase in "unattached" fraction without substantial reduction in PAEC could lead to an actual increase in the radiation dose, especially considering the relationship between dose per unit exposure and size of particles described earlier (Figure 1). These observations agree with the EPA recommendation not to used air cleaners alone as a device for controlling the risk due to indoor radon.

RAdsorb

The results of operation of the RAdsorb system without the EAC attached to the room air inlet are summarized in Figure 7 and Table 5. The data included in table are mean values of measurements performed after establishing the steady-state conditions.

TABLE 5. THE CHANGES OF ^{222}Rn CONCENTRATION, PAEC, SIZE DISTRIBUTION AND RESULTING DOSE DUE TO OPERATION OF RAdsorb

RAdsorb	^{222}Rn [Bq m^{-3}]	PAEC [mWL]	0.5-1.58 nm PAEC fraction	Secretory Cells Dose [mGy y^{-1}]
OFF	670	55.6	0.061	37.5
ON	289	22.7	0.074	15.5

The operation of RAdsorb system caused a decrease in radon gas and PAEC of about 60%, and an increase in 0.5-1.6 nm fraction of PAEC of about 21%. The resulting decrease in dose to secretory cells was also about 60%. For the measured "background" conditions (see Table 4), the reductions in radon gas, PAEC, and dose were 54%, 26% and 72%, respectively.

RAdsorb/EAC

The fully assembled RAdsorb system with the EAC unit attached to the room air intake was operated continuously for 12 hours. After about three to four hours, a new steady-state was established. The influence of the device on Rn, PAEC, size distribution and dose are presented in Figure 8 and Table 6.

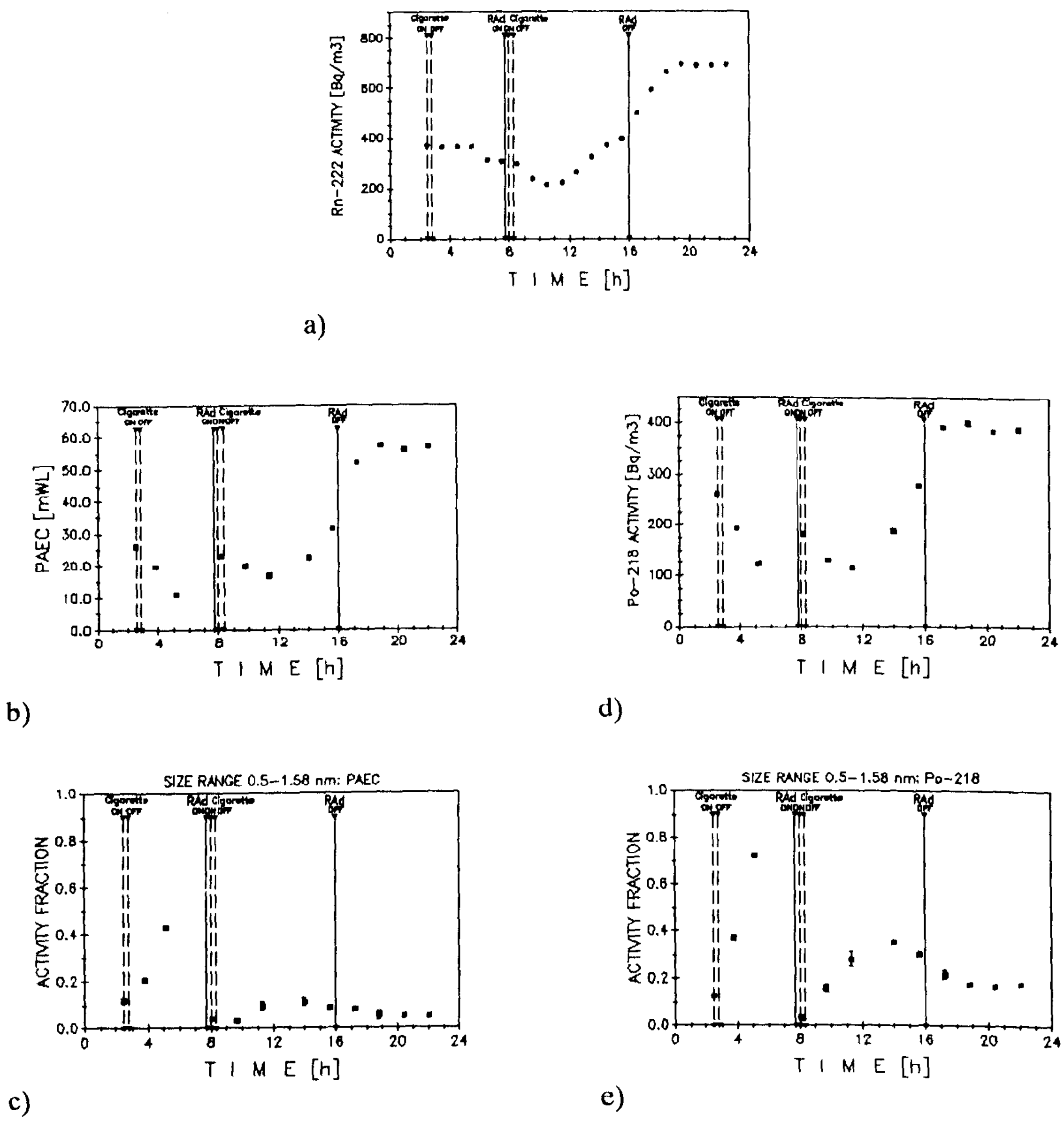


Figure 7. The influence of the RAdsorb system on indoor radon and its decay products:
a) ^{222}Rn concentration,
b) potential alpha energy concentration (PAEC),
c) activity fraction of PAEC in the size range 0.5-1.58 nm,
d) ^{218}Po concentration,
e) activity fraction of ^{218}Po in the size range 0.5-1.58 nm

1) No substantial changes in measured parameters were observed during only the operation of the fan,
2) The EAC caused a shift of the size distribution towards smaller particles,
3) The RAdsorb system decreased the radon gas concentrations without substantial changes in the progeny size distributions,
4) The combined RAdsorb/EAC reduced the radon concentration by about 76%, with the shift in the size distribution towards smaller particles.

To study the effect of the increase in the "unattached" fraction (0.5 - 3 nm), the doses to bronchial secretory cells of adult male resting were evaluated. The estimation of doses before and during the operation of the EAC gave similar results. By comparison, the combined operation of the RAdsorb/EAC system not only substantially decreased the radon gas concentration to a value around the EPA recommended limit of 150 Bq m^{-3} (4 pCi L^{-1}), but also yielded an 86% reduction in the PAEC. The resulting dose reduction was 76% with assumption that the new steady-state conditions were established. If the levels of ^{222}Rn, PAEC and activity fraction measured in the "background" conditions were taken as the point of reference, the dose reduction was about 81%.

The dose estimates presented in the study, are based on the most recent dosimetric calculations. However, it is possible that the conversion factors applied in this study may change in the future due to new development in dosimetric calculations.

In conclusion, the overall performance of the combined operation of the RAdsorb/EAC system was very good in reducing both exposures to and dose from indoor radon and its decay products.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

REFERENCES

1. Environmental Protection Agency (EPA). A Citizen's Guide to Radon. ODA-86-004, EPA, 1986.

2. Abrams, R.F. Field Demonstrations of Radon Adsorption Units. Paper presented at the 82nd Annual Meeting of the Air and Waste Management Association, Anaheim, CA, June 25-30, 1989.

3. Hopke, P.K. A Critical Review of Measurements of the "Unattached" Fraction of Radon Decay Products. Technical Report Series DOE/ER-0451P, U.S. DOE, 1990.

4. Li, C-S. Field Evaluation and Health Assessment of Air Cleaners in Removing Radon Decay Products in Domestic Environments. Ph.D. Thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 1990.

5. James, A.C., Strong, J.C., Cliff, K.D. and Stranden, E. The Significance of Equilibrium and Attachement in Radon Daughter Dosimetry. Radiat. Prot. Dosim. **24**: 451, 1988.

6. James A.C. Dosimetry of Radon Exposure: What Does It Imply for Risk and Measurement of Indoor Exposure? Paper presented at the Twenty-Ninth Hanford Symposium on Health and the Environment, Richland, WA, October 15-19, 1990.

7. Abrams, R.F. and Rudnick, S.N. Radon Removal Unit Development. Paper presented at the EPA 1988 Symposium on Radon and Radon Reduction Technology, Denver, CO, October 17-21, 1988.

8. Bocanegra, R. and Hopke, P.K. Theoretical Evaluation of Indoor Radon Control Using a Carbon Adsorption System. JAPCA **39**: 305, 1989.

9. Ramamurthi, M. The Detection and Measurement of the Activity Size Distributions (d_p> 0.5 nm) Associated with Radon Decay Products in Indoor Air. Ph.D. Thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 1989.

10. Ramamurthi M. and Hopke P.K. An Automated, Semi-Continuous System for Measuring Indoor Radon Progeny Activity-Weighted Size Distributions, d^p:0.5-500 nm. Aerosol Sci. Technol., 1990 (in press)

11. Maher, E.F. and Laird, N.M. EM Algorithm Reconstruction of Particle Size Distribution from Diffusion Battery Data. J. Aerosol Sci. **7**: 127, 1986.

12. Hopke, P.K., Wasiolek, P., Knutson, E.O., Tu, K.W., Gogolak, C., Cavallo, A., Gadsby, K. and Van Cleef, D. Intercomparison of Activity Size Distribution Measurements with Manual and Automated Diffusion Batteries - Field Test. Submitted for presentation at the 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, April 2-5, 1991.

13. Abu-Jarad, F. and Sextro, R.G. Reduction of Radon Progeny Concentration in Ordinary Room Due to a Mixing Fan. Radiat. Prot. Dosim. **24**: 507, 1988.

CONTROL OF RADON RELEASES IN INDOOR COMMERCIAL WATER TREATMENT

by

D. Bruce Harris and A. B. Craig
U. S. EPA
Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

ABSTRACT Water used in some commercial operations is subject to conditioning processes inside buildings which could cause radon to be released into the building's air. The U. S. Fish and Wildlife Service recently found elevated radon levels (100-300 picocuries per liter(pCi/L)) in some of their National Fish Hatcheries (NFHs) even with relatively low (400-600 pCi/L) levels in the incoming water. The EPA's Air and Energy Engineering Research Laboratory/Radon Mitigation Branch investigated possible control techniques at the Neosho, MO, NFH. Data collected by the NFH indicated that the nitrogen stripping packed tower was removing up to 60% of the waterborne radon from 500,000 gal./day* and discharging it into the air above the fish tanks. Two methods were tried to remove the radon: one used countercurrent stripping and the other relied on hooding the area immediately around the column discharge point. The 4 ft height of the column prevented the low pressure fan normally used in radon mitigation from establishing sufficient countercurrent air flow to remove the radon. The pilot test of the local hooding technique proved to be sufficient to control the emissions. Final control was obtained by vacuum stripping the incoming water rather than treating each tank feed separately. Some city and industrial water treatment facilities have reported elevated radon levels in treatment rooms and adjoining offices that may have a similar origin and may be amenable to similar control techniques.

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

BACKGROUND

Ground water is used as the source for many municipal and industrial water systems. Some of the process treatment or use takes place indoors. If radon is present in the water, the

(*) Readers more familiar with the metric system may use the factors listed at the end of this paper to convert to that system.

possibility exists for radon to be released from the water and exhausted into the interior of the process building. Fish hatcheries are one such industrial facility.

The U. S. Fish and Wildlife Service has been testing National Fish Hatcheries (NFHs) for radon as part of the general testing program of federal buildings. Elevated levels were measured in the air of buildings at the Neosho, MO, NFH. Initial levels above 100 picocuries per liter (pCi/L) were found in the tank room and adjoining offices (Table 1). Discussions with EPA Region 7 staff led to a request for assistance from EPA's Office of Research and Development.

PROCESS DESCRIPTION

The Neosho NFH uses water from several springs fed by gravity to eight fish tanks inside the main building and several outdoor tanks. Water flows at 50 gpm through a 4 ft high packed nitrogen stripping/aeration tower and into each tank. This system is similar to that shown in Figure 1 except the pipe extension through the ceiling and the fan are not included and the top of the tee is covered with a plate to prevent splashing. The plate is not sealed, allowing some air into the water, but most of the aeration takes place at the discharge of the column. The 400 pCi/L of radon found in the water wouldn't normally be considered a major source of airborne radon. However, the tower is approximately 60% efficient in stripping the radon as well as the nitrogen. Given the water throughput, calculations show that up to 500 pCi/L could be reached in the hatchery room air assuming 1 air change per hour (ACH).

The radon could be prevented from reaching the tank room air by removing the radon at one of three points in the process: (1) treating the water prior to entry into the hatchery, (2) reversing the flow of air through the stripping tower and exhausting it out the roof, and (3) collecting the tower effluent gases with a hood and exhausting it.

MITIGATION SYSTEMS DESIGN AND TESTING

Neosho personnel modified the water inlet and aeration column to fish tank No. 6 as shown in Figure 1 except for of the fan which was installed by AEERL to test option (2). A Kanalflakt T-2 fan was installed at the top of the column for preliminary tests. This fan pulls air at 270 cfm at no head and 110 cfm at 1 in. WC head, the highest level listed on the performance curve furnished by the manufacturer.

The fan was turned on and the column inlet water was adjusted to 50 gpm. Under these conditions, the air flow rate at Test Point 1 (Figure 1) was only 20 cfm and the pressure at Point 2 was -1.8 in. WC. The pumping action of the water passing through the column was much greater than had been expected and a larger fan (T-3B) would be needed to operate within its design range.

The front half of the tank was then covered with plastic film and the tank filled with water to determine the radon (Rn) levels in the air exiting both ends of the column. When the water was turned on, the film ballooned indicating that air was exiting the bottom of the column as expected. The exhaust fan was then turned on and, surprisingly, the film over the tank continued to balloon, although not quite as much. This indicates that greater than 20 cfm of air is being released by the spring water as it passes through the column.

Rn levels in the air exiting both ends of the column were measured using a Pylon AB-5 continuous monitor. When the fan was on, the air exiting the top of the column contained 15-20 pCi/L and the air exiting the bottom of the column (measured next to the column when the tank was covered by plastic) about 40 pCi/L. When the fan was turned off, the radon in the air in the plastic-covered tank rose to 60-80 pCi/L.

Based on these results and further theoretical considerations, this type of fan installation would not be expected to completely eliminate the flow of air containing radon out the bottom of the column. Consequently, option (3), to enclose the head end of the fish tank and keep that area under a negative pressure with the use of a fan system similar to that used in subslab depressurization systems, is a more viable solution. This approach was tested using plastic sheeting to make a temporary hood over the tank end around the water inlet. Smoke studies showed that this captured the air above the water easily with bleed air entering countercurrently just above the tank water surface.

Figures 2 and 3 show how this option could be implemented to enclose the free space over the column end of the fish tank. This plan evolved during conversations with Neosho NFH personnel as a simple but practical way of enclosing the column end of the tank for evacuation with a minimum effect on day-to-day operation of the fish tank. The tank top would be made of a heavy gauge aluminum (or perhaps plastic) cut as wide as the outside of the tank (about 4 ft) and as long as the desired enclosure plus enough to bend down a lip at a 90° angle to extend into the water about 2 in. when the tank is in normal operation. Two corners of the sheet would be notched so that the lip would just clear the inside of the tank. The cover would be bolted to the top of fish tank for ready removal when access is needed. It could not be removed with the tank in operation. The top would be made airtight with a bead of caulking applied under the lid before bolting down. (A thick soft rubber gasket would be a viable alternative.) The lip would need to be sealed to the side of the fish tank, probably with caulking. Depending upon the fan selected and the amount of air being pumped into the hood by the tower, provisions for bleed air in the end of the cover may be needed.

Two holes in the cover would be necessary for the 8 in. aeration column and a 4 in. suction pipe. These pipes should extend through the cover and be sealed to the cover to prevent air leakage. This can be done very easily as shown in Figure 2 by cutting the pipe and placing a coupling on it at a point to allow the coupling to ride on the cover and, if a short piece of pipe is extended from the coupling through a hole in the cover cut to the OD of the pipe, allow an easy caulk seal. The water column would also have to be supported at the top to carry its weight when operating. Water entry should be through a tee in the column as was done in the experimental setup.

The top of the aeration column should be sealed from the tank room and be supplied with outdoor air to prevent

Table 1. NEOSHO NFH RADON LEVELS

Location	Device	Reading, pCi/L
Office	At Ease	108 average
Office	At Ease	98.2 last 12 hrs
Office	At Ease	108 current
Office	Sniffer	150
Office	E-Perm	116
Secretary's office	At Ease	99.4 average
Secretary's office	At Ease	106 last 12 hrs
Secretary's office	At Ease	106 current
Tank room	E-Perm	241
Tank room	Sniffer	150
Tank room	At Ease	222 average
Tank room	At Ease	263 current
Covered empty tank	E-Perm	270
Covered empty tank	E-Perm	260
Covered empty tank	Sniffer	300
Covered tank with water	E-Perm	>456*
Covered tank with water	E-Perm	>467*
Covered tank with water	Sniffer	475
Spring house	E-Perm	128
Visitor's rest room	E-Perm	20.3

* The E-Perm electrets read zero when checked, so reported reading is an estimate.

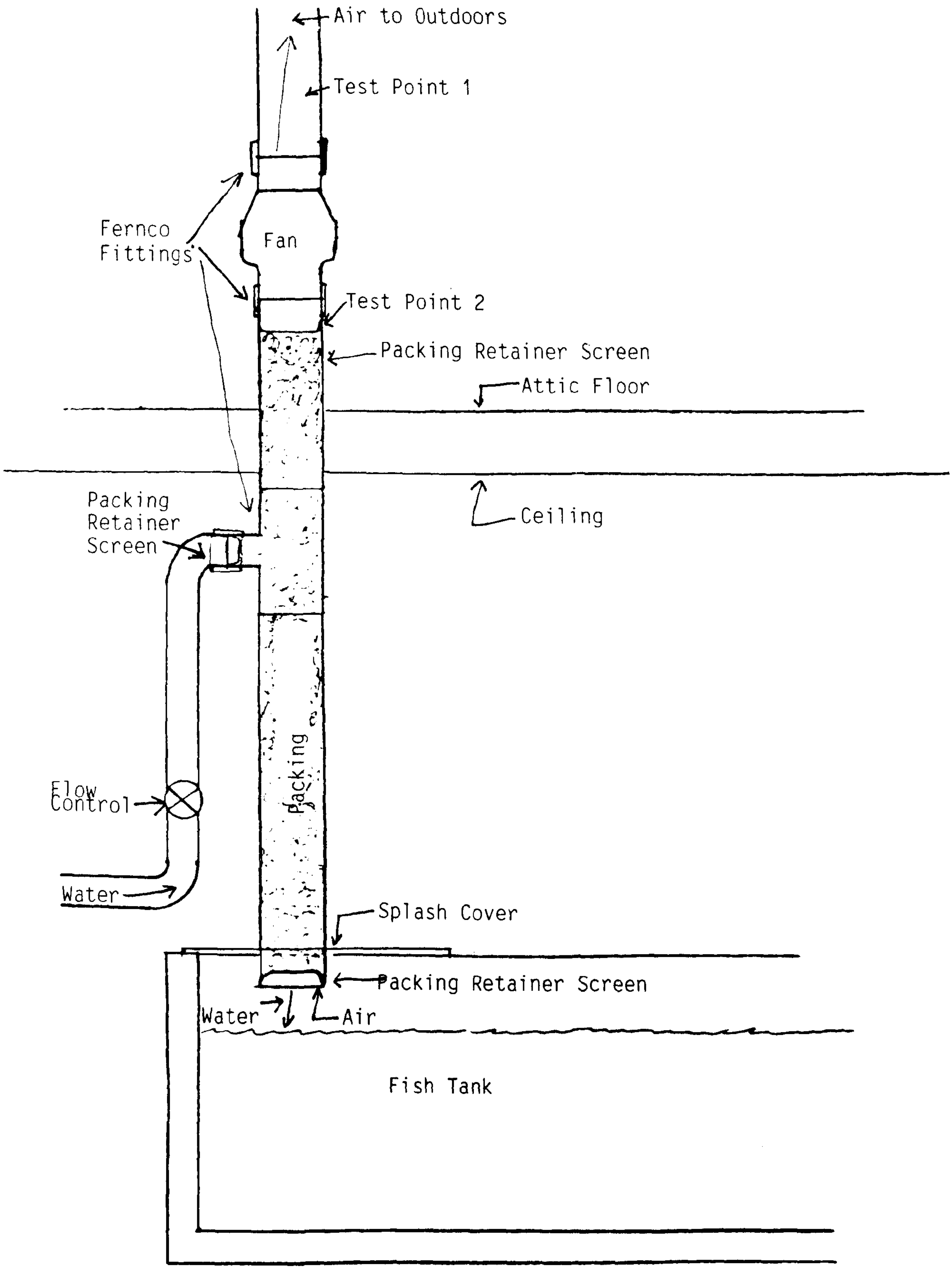


FIGURE 1. MODIFIED STRIPPING/AERATION COLUMN

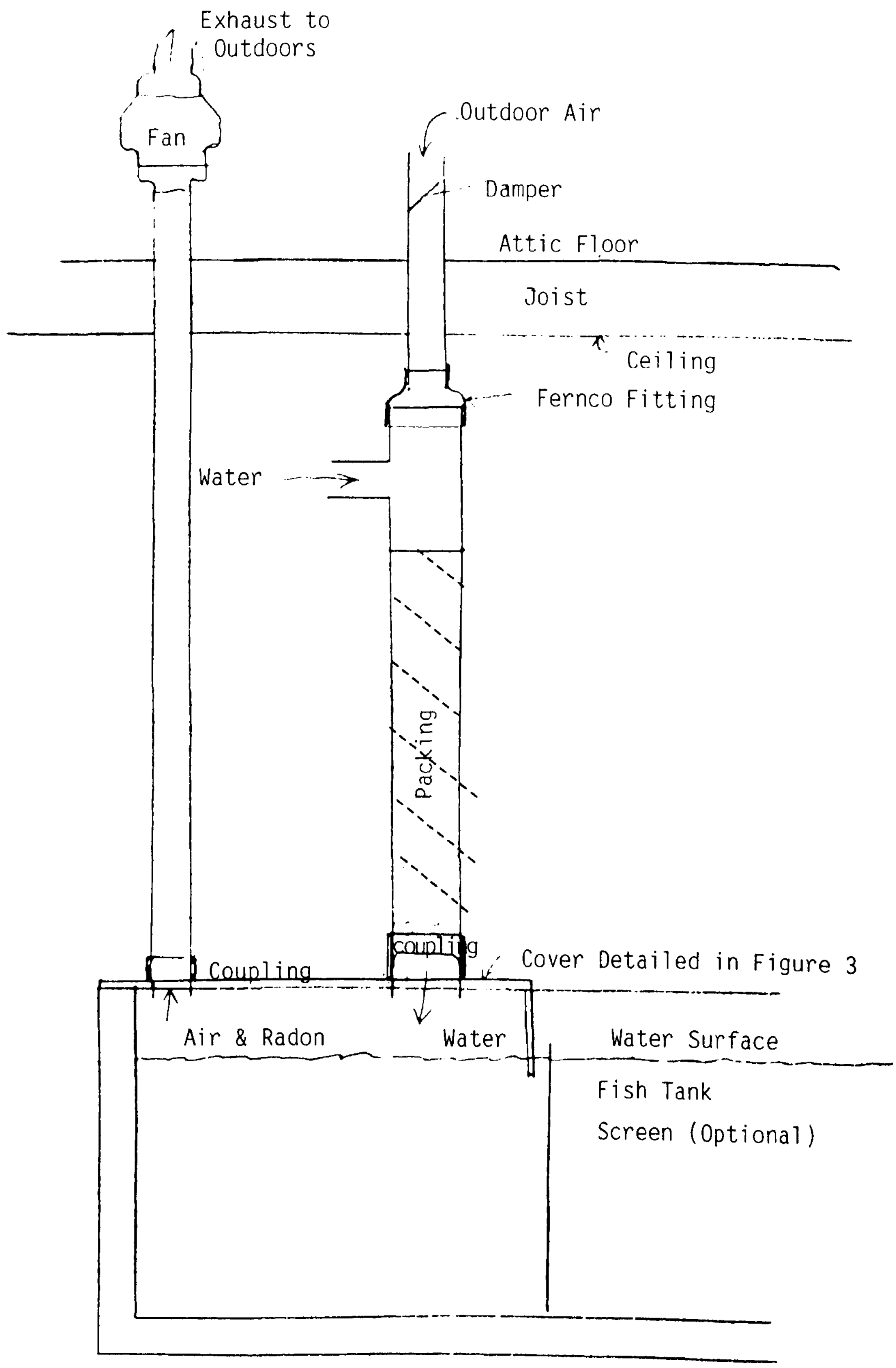


FIGURE 2. TANK RADON MITIGATION SYSTEM

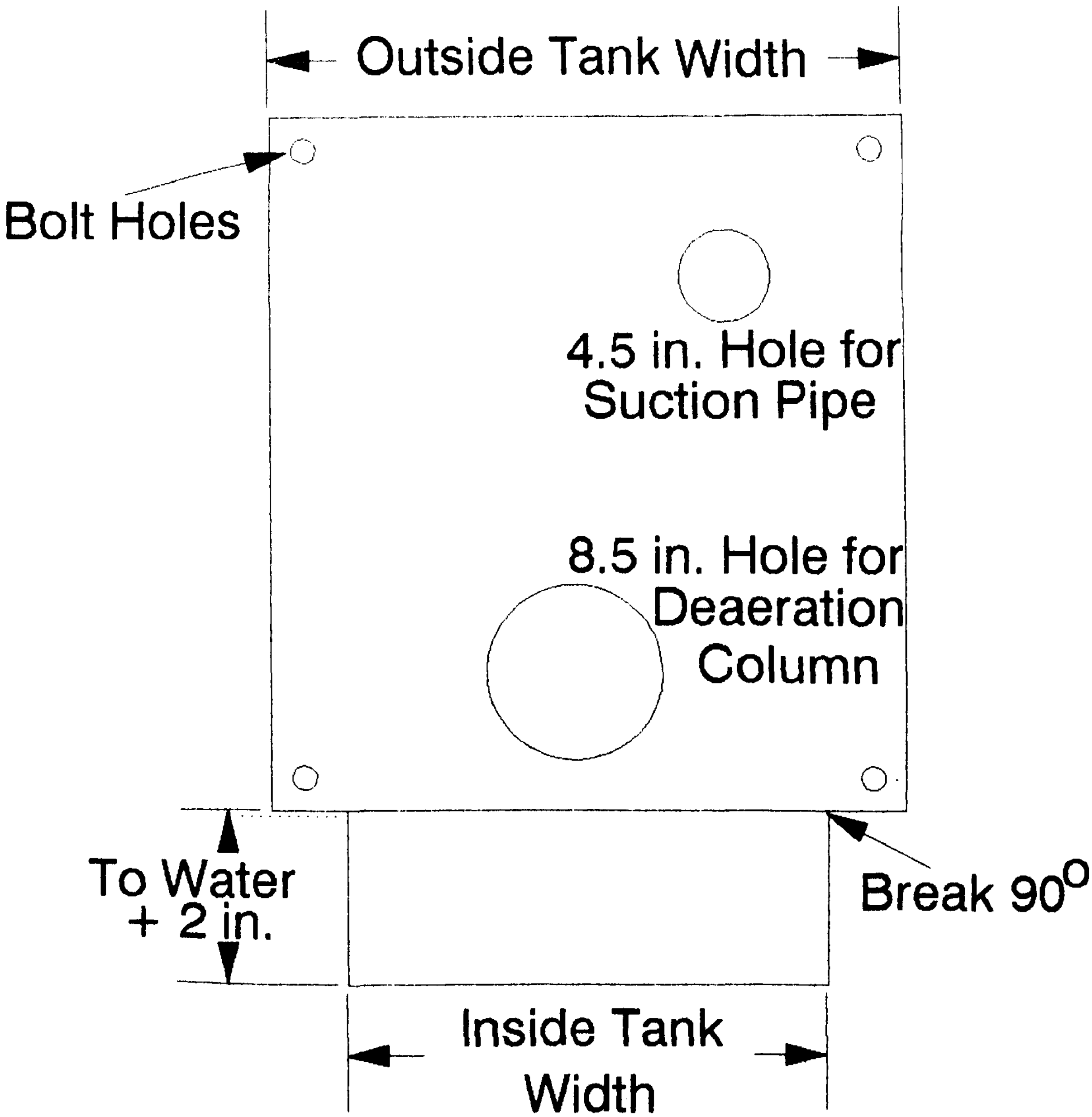


Figure 3. HOOD/TANK COVER

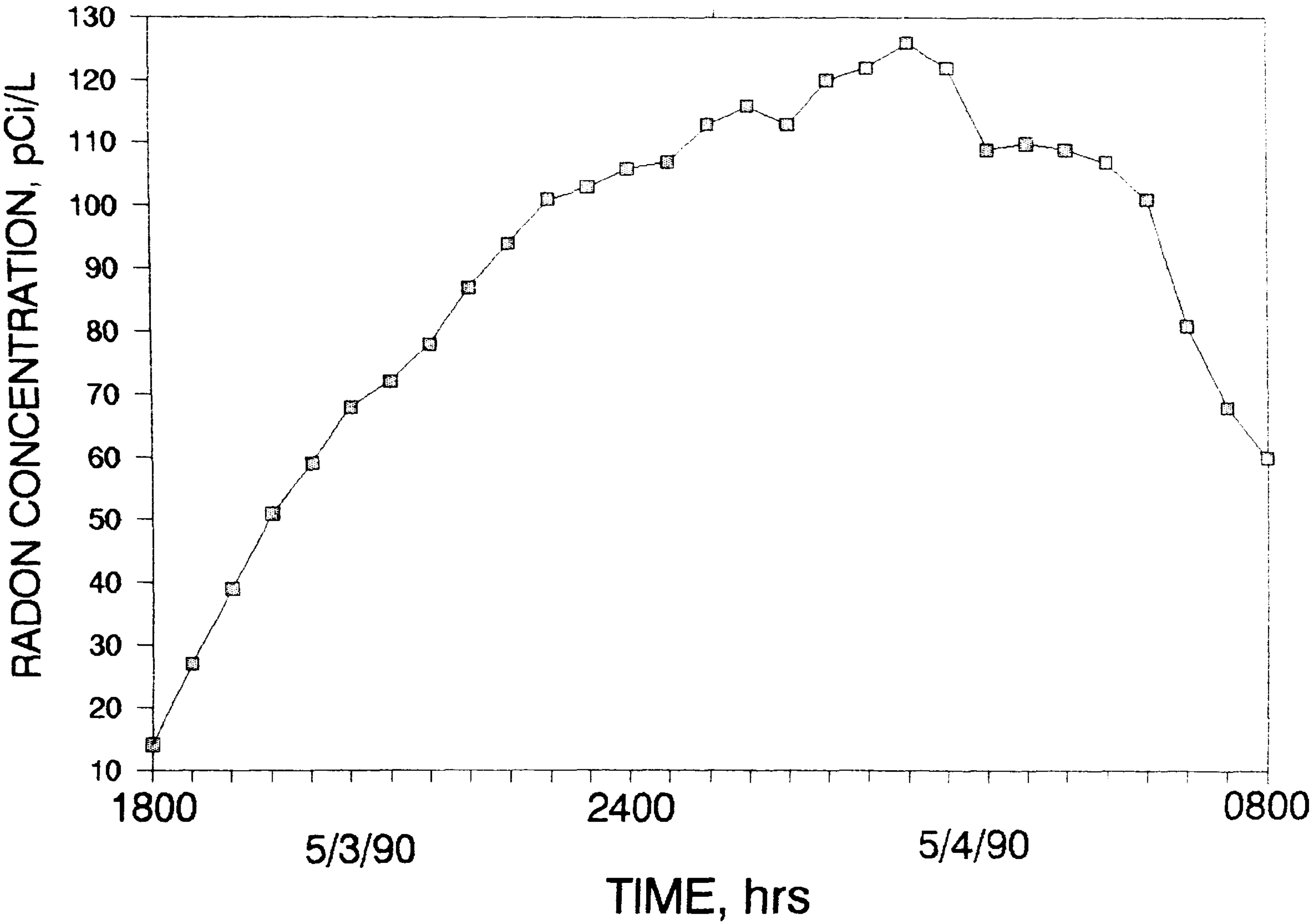


Figure 4. **NEOSHO NFH RADON CONCENTRATIONS**

*U.S. GOVERNMENT PRINTING OFFICE: 1991-548-187/20565