EFFECT OF INDOOR RADON VARIABILITY ON THE DURATION AND INTERPRETATION OF RADON MEASUREMENTS

by A. G. Scott
AMERICAN ATCON INC.
Wilmington, DE 19899

ABSTRACT

A variety of different methods are available to estimate the radon concentration indoors. The effective sampling time associated with each method ranges from a few seconds to a year or more. The radon concentration in a house is known to vary with time, and so the meaning of a measurement made by a method depends largely on the frequency and amplitude of the radon concentration variations.

The variations of indoor radon concentrations have been measured with continuous radon monitors over periods of up to 100 hours in a number of houses with elevated radon concentrations in both Pennsylvania and Ohio. Examples are presented of the extreme short-term variations produced by use of water with high radon concentrations, diurnal variations caused by occupant activities and cyclic temperature changes, and longer period (several-day) changes associated with changes in wind speed and direction. The effect of these changes on different measurement methods is largest on those methods with the shortest integration periods. Charcoal collection methods deal adequately only with the diurnal fluctuations. The major influence on the accuracy of integrating measurements is the day to day fluctuation, and integration periods of more than 15 days are needed to provide a stable estimate of the average radon concentration.

Since the average radon concentration also varies with season, even these measurements must be repeated at different times throughout the year if the annual average radon concentration is to be measured.

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

INTRODUCTION

The EPA has a continuing program to develop and demonstrate cost-effective methods to reduce radon concentrations inside houses. As part of this program, continuous radon monitor measurements are made in selected houses before and after installation or activation of mitigation systems. The data presented here were collected in EPA program houses in the Reading Prong area of Pennsylvania, and in the Dayton area of Ohio.

These measurements are made only to give a rapid indication of success or failure of the installed mitigation system. The final judgement is made by long term measurements over several months with Alpha-Track detectors during winter months. The challenges to the mitigation system are highest at that time, and the performance of the system is at the lowest.

The monitors used are the Pylon AB-5 with a 285 cm^3 scintillation cell, and are programmed to make 1 measurement an hour. The raw count-rate data are transferred from the unit to a portable computer, and processed to compensate for the activity deposited in the cell by previous samples. The reported radon concentration is therefore the estimated radon concentration in the house air at the time of the sample, and there is no "reading lag" as occurs with uncorrected monitor readings.

MEASUREMENT METHODS AND EFFECTIVE INTEGRATION TIME

All measurement methods estimate the radon concentration averaged over a time. This is never less than the time needed for the concentration to change significantly, which is comparable to the house ventilation period. Even if the sample is taken "instantly", as with scintillation cell grab sample measurements of radon, or filter measurements of radon progeny, the effective integration period in closed houses is 2 to 3 hours. Repeated spot measurements at shorter intervals than this essentially measure the same thing, and are not independent samples. (This does not mean that grab-sampling cannot be used to obtain an average concentration, but it requires a statistical estimate by multiple independent samples spread out over the period of interest.)

Detection systems that collect and store the radon for later analysis, such as charcoal or low-flow pump and bag systems, have an effective integration period no longer than the mean life of radon (5 days) - but it can be as short as 1 day if the system does not fully retain collected radon during low concentration periods. Systems that convert the collected radon into a signal and store it, such as Alpha-Track, Electret, PERM, and electronic pulse machines, have much longer integration times. The maximum time is largely a function of the instrument design, and ranges from 2 weeks to more than a year.

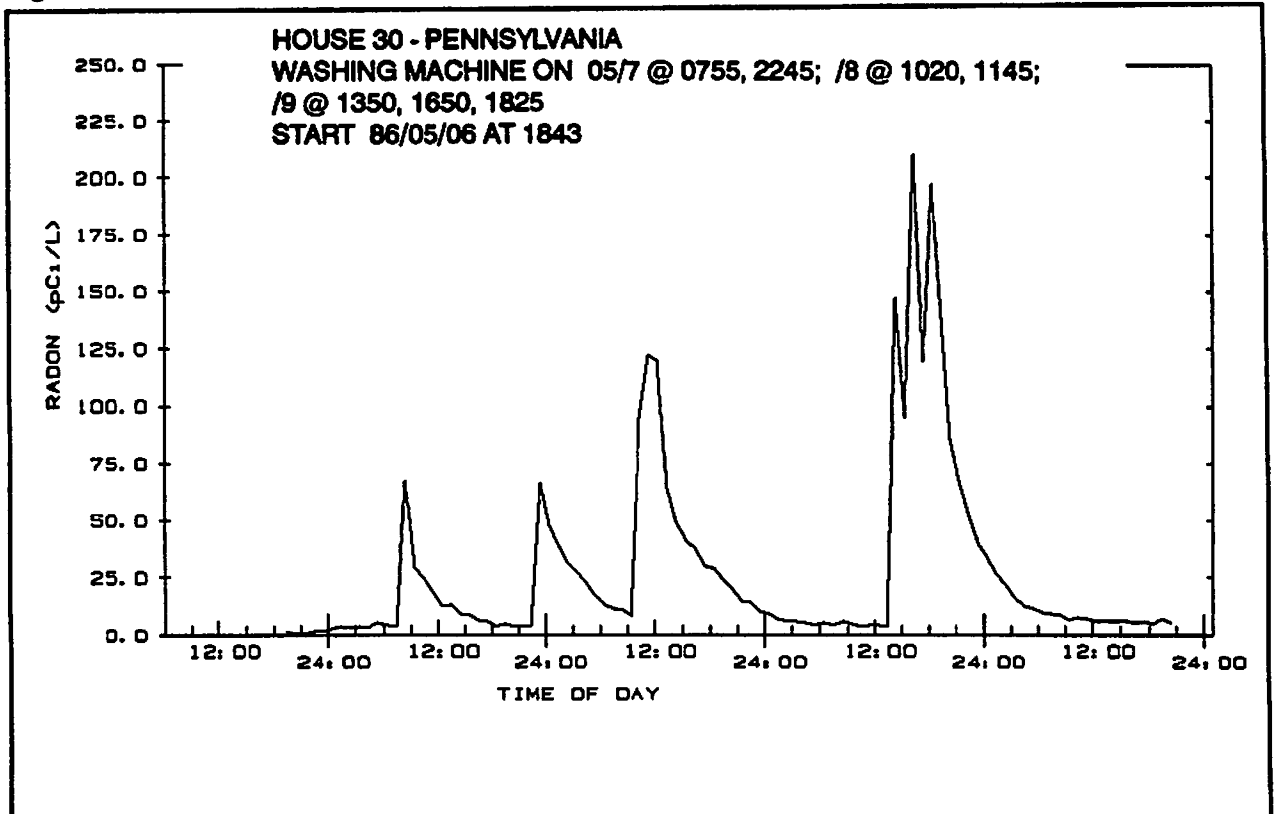
The risk from radon is proportional to exposure, and this is related to the average radon concentration in a house over the entire period of occupancy. This cannot be measured for most people, and so we seek to estimate this quantity by measurements over a shorter period. If the radon concentration in a house were constant, then the task would be simple, but the radon concentration in a house undergoes large changes from day to day. The obvious thing to do is to make the practical simplifying assumption that the average radon concentration over 1 year is representative of the average concentration over all years, and take measurements over a year to obtain an annual average. However, frequently an estimate is required sooner than in 1 year, and the question then becomes: "How short a measuring period will give a reasonable estimate of the long term average?". This can be answered only if we know the frequency and magnitude of the fluctuations.

SHORT-TERM VARIATIONS

The radon concentration in a house is set by the balance between radon supply and ventilation rate. The changes in radon concentration produced by large radon pulses are shown in Figure 1. The radon pulses were produced by the washing machine, for the radon concentration in the well water supply was 200 000 pCi/L. A single load of washing releases about 25 μCi of radon into the basement in less than an hour. The concentration falls exponentially, indicating a basement ventilation period with the basement windows closed of about 4 hours (0.25 ac/h).

This is an extreme case of occupant induced variability, for the peak air concentration is essentially fixed by the size of the basement, the size of the washer, and the water radon concentration, but the average air radon concentration is directly dependent on how rapidly their

Figure 1 VARIATIONS PRODUCED BY RADON IN WATER



clothes get dirty. A wintertime basement Alpha-Track measurement prior to this gave an average of 17 pCi/L (close to the "10 000 pCi/L in water gives 1 pCi/L in air" rule of thumb), but shortly after this run, the wife had a second baby, and the water use doubled, increasing the average concentration to 35 pCi/L.

This kind of radon concentration variation poses the most severe challenge to any measurement system. The radon pulses rise very rapidly, and then fall continually reaching background concentrations about 10 hours after the end of the release. Concentrations are low for most of the time. Successive short-term spot measurements with associated sample times of a few minutes to a few hours will give wildly differing answers depending on when the water was used relative to when the sample was taken. For an accurate and stable estimate of the average radon concentration, the measurement must be long enough to sample several radon pulses; i.e., several days of washing.

DIURNAL VARIATIONS

The radon concentration in houses varies periodically over the day as a result of changes in the natural forces that drive radon into the house, and routine occupant activities that often affect the ventilation rate. One of the largest forces operating is the indoor-outdoor temperature difference; since temperatures indoors are fairly constant, and outdoor temperatures are lowest at night, one would expect increased radon supplies at night, reaching a maximum around dawn. This is demonstrated in Figure 2, where measurements were made in a closed basement in summer. The rise at the start of the run is the result of closing the basement window. The basement door was kept closed throughout, so there was no connection to the upper part of the house, where the windows were kept open. Radon concentrations reach a low at about 1800 h, and peak at about 0600 h, as expected. The variation in concentration here is from 50 to 125 pCi/L, typical of the 2:1 range seen in temperature-driven diurnal variations.

In wintertime the percentage change in temperature difference from day to night is often smaller than in summer, and the "natural" diurnal cycles are usually smaller or even absent, as shown in Figure 3. Not only are there no cyclic changes over the last 2 days, but radon concentrations start to rise at 0600 h when external temperatures rise. This may be due to an increase in wind speed during the day increasing the pressure drop across the building shell, and increasing the radon supply by more than the increase in basement ventilation rate.

Figure 2 THERMALLY INDUCED DIURNAL CYCLES IN SUMMER

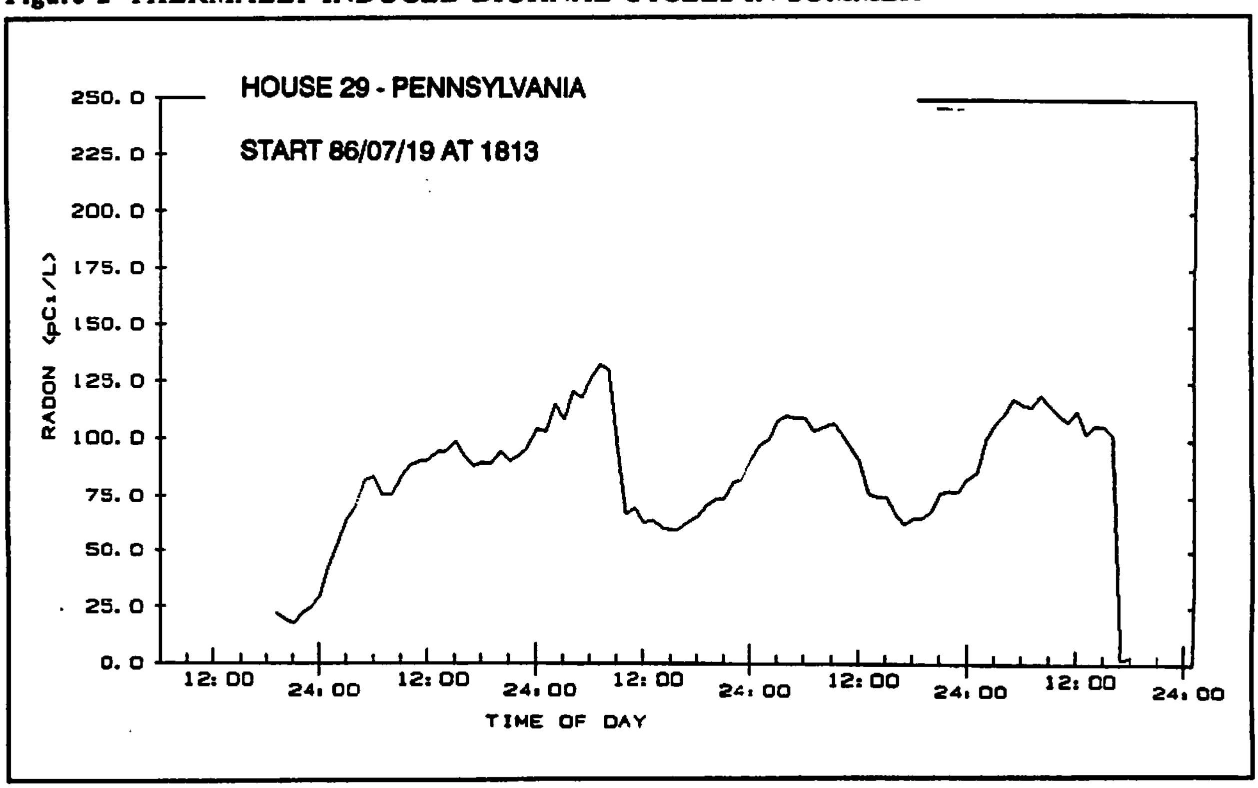
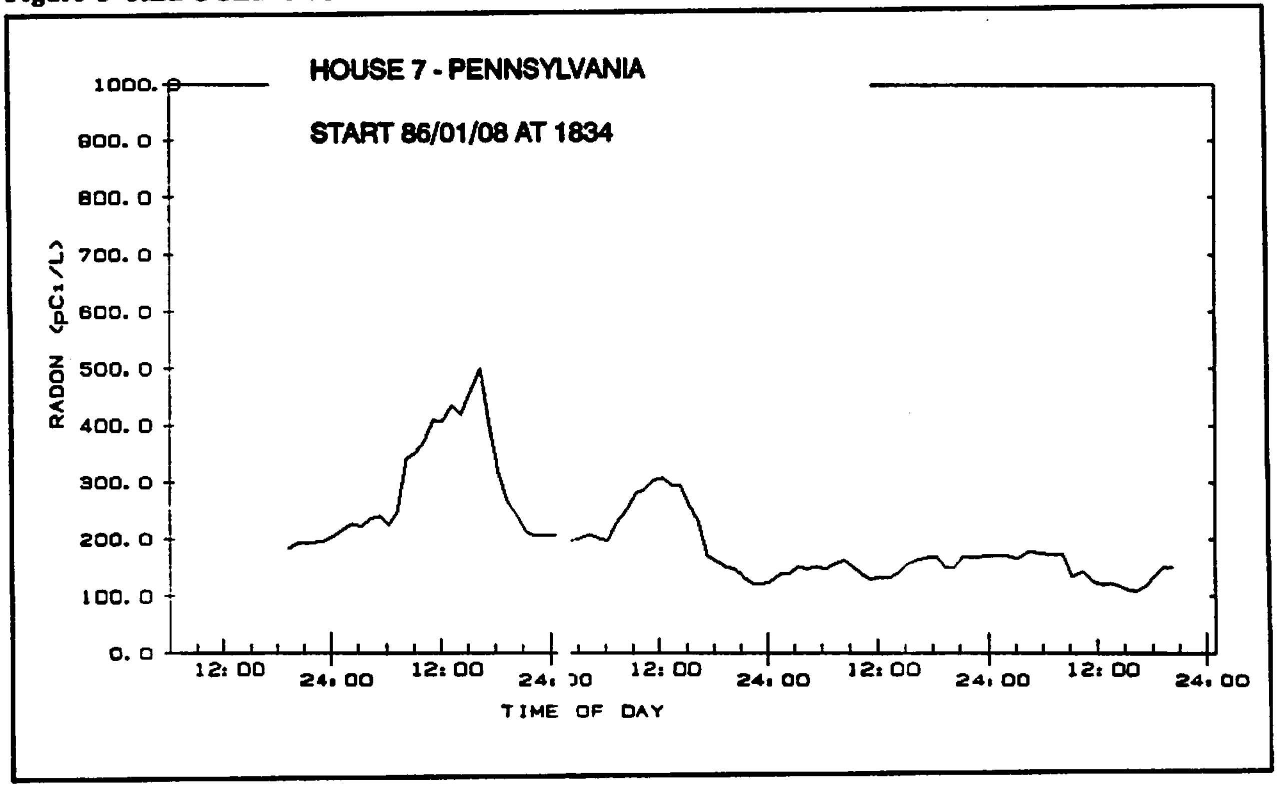


Figure 3 REDUCED DIURNAL CYCLES IN WINTER



Occupant-driven diurnal changes are usually much larger than the natural cycles, as illustrated in Figure 4. This house was on a sloping site, and a garage was built into the basement. The rapid decreases in radon concentration measured in an enclosed basement workroom are associated with the garage door being open. This not only increases the basement ventilation rate, but decreases the house/soil pressure differential and hence the supply rate simultaneously.

The most common occupant-induced changes involve opening doors and windows, which reduces the radon concentration by increasing the ventilation rate. Not all occupant effects have such obvious causes. Figure 5 shows marked cyclic variations. The cause was first suspected to be house depressurization from daily operation of a clothes dryer, but then it was found that the drier vented back into the house for heat recovery. The owner was interviewed, and the clue to the cause was that the concentration rose at about the time the occupants got up each morning. They turned up the thermostat, and the furnace ran continually for about an hour. This was a slab-on-grade house with the heating ducts beneath the floor, and leakage from the central furnace plenum forced air beneath the floor and up into the house at the floor perimeter joints, carrying in radon.

The radon concentration changes continually during a diurnal cycle, so no measurement with an effective sampling time of less than 24 hours can determine the average concentration over that period. If the cycles are occupant generated, they may differ from day to day, and even natural cycles are not identical from day to day. It is necessary to integrate over several cycles to obtain a realistic and stable estimate of the average radon concentration.

Figure 4 OCCUPANT-INDUCED CONCENTRATION DECREASES

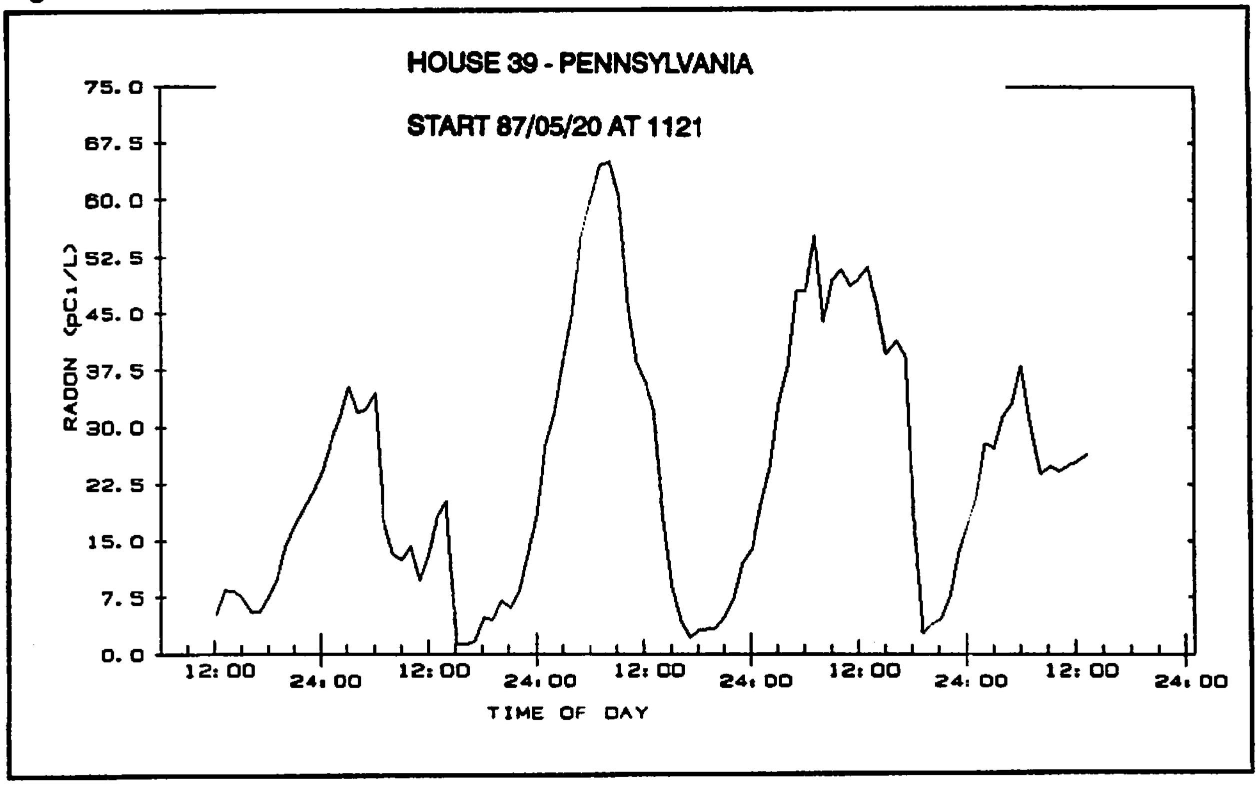
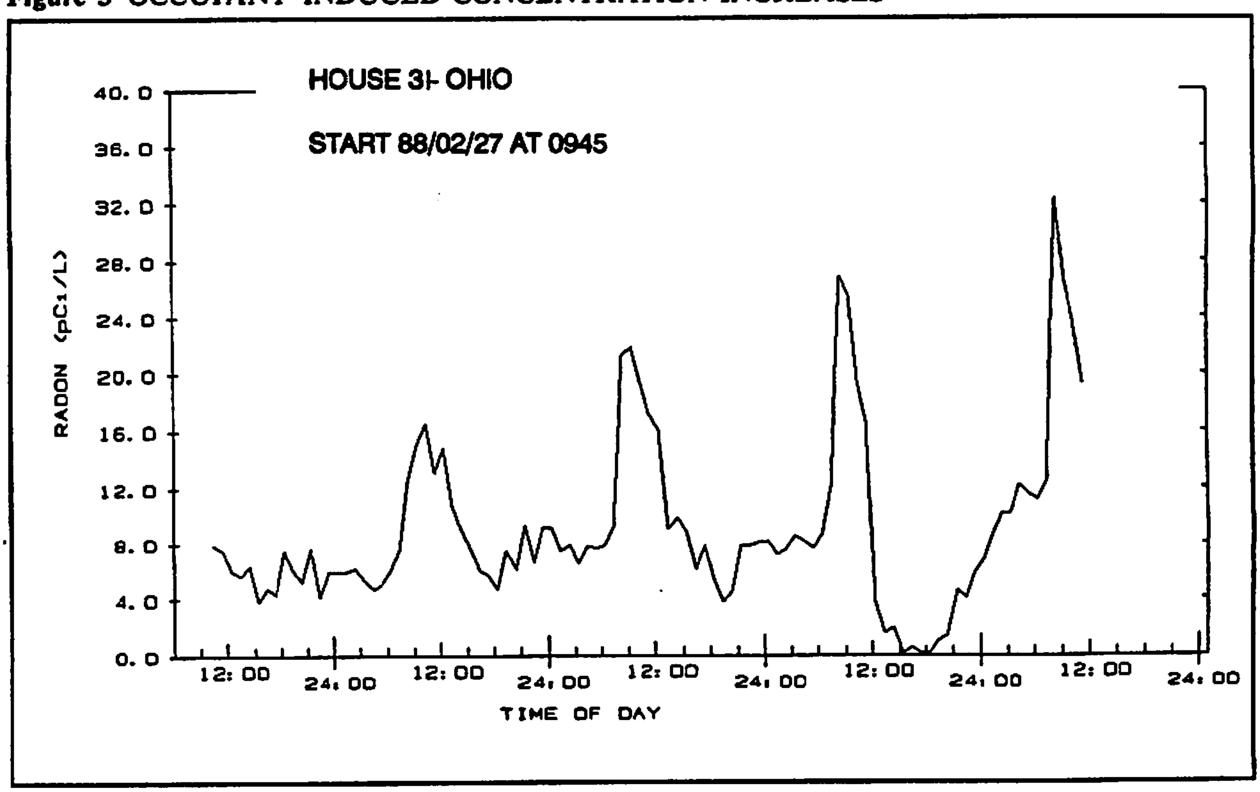


Figure 5 OCCUPANT-INDUCED CONCENTRATION INCREASES



LONGER PERIOD VARIATIONS

Weather patterns cross North America at intervals of about 4 days, and the passage from one system to another is usually marked by a weather change. The wind changes speed and direction, the air temperature changes, dry weather turns to rain, and vice versa. These changes all cause changes in the pressure distribution around the house and in the soil permeability, so it should be no surprise that they also affect the radon concentration in the house. This longer term variability makes it difficult to compare before and after measurements on a mitigation system. There is always the possibility that the effect seen is not the effect of the installation, but just an artifact of the weather cycles.

In Pennsylvania, the pre-mitigation radon concentrations were very high, and reductions to a few pCi/L were achieved (95 to 99% reduction). In these conditions, the cyclic variation was much less than the variation in radon concentration produced by an effective sub-slab ventilation system, and the system effect could be estimated from runs of 2 days before system activation, and 2 days after. This was not the case in Ohio, where concentrations were lower and percentage variability greater. The most dramatic example of this is shown in Figure 6, where radon concentrations in a closed basement in winter range from 250 to 4 pCi/L over the course of 2 days. A second, less extreme example is shown in Figure 7, where there is a significant change in radon concentration over the 4 day run. The presence of these large-amplitude long-period fluctuations meant that measurements had to be made over a 4 day period to be sure that any reductions were the result of mitigation system operation, and not just a fluctuation.

Figure 6 EXTREME LONG-PERIOD VARIATION

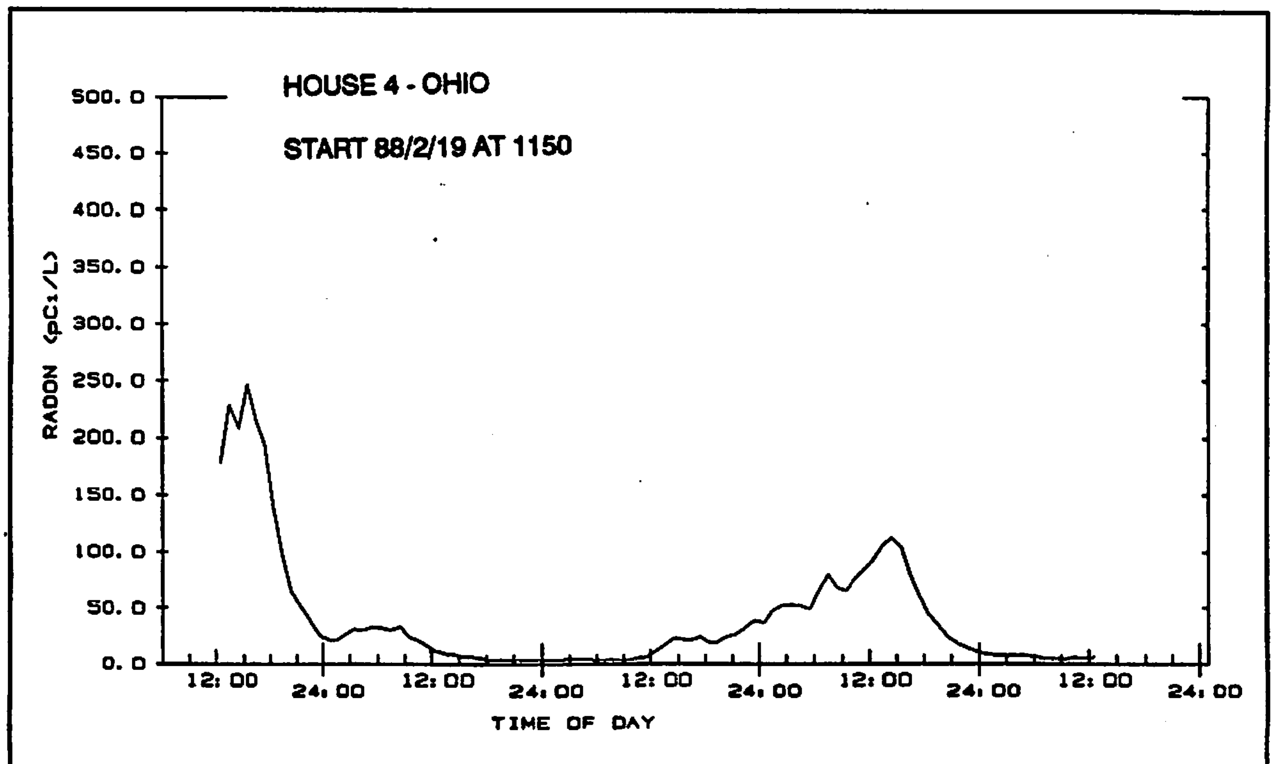
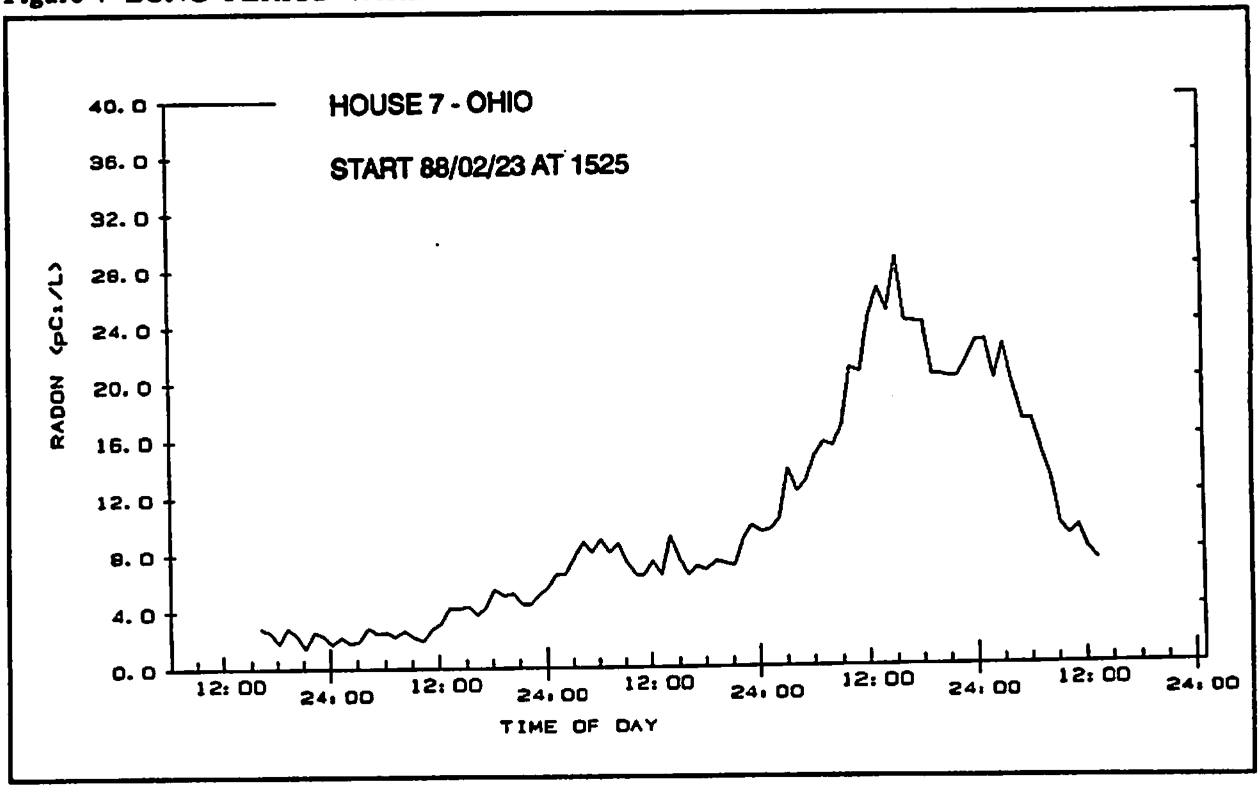


Figure 7 LONG-PERIOD VARIATION



CONCLUSIONS

Most of the fluctuations have a strong 24 hour periodicity, so the minimum integrating period to obtain a valid average is about 24 hours. Sampling theory and common sense show that the average of a cyclic quantity requires measurement over at least 1 complete cycle, and preferably over several complete cycles. If 24 hours is the dominant period, then the averaging period used should be multiples of 24 hours to avoid biasing the average by including only part of a cycle. The measurement must extend over at least four complete cycles (i.e., 4 days) to limit the part-cycle error to less than the measurement uncertainty, which is about 15% for most systems. The practical implications of this are that the longest integration times available from radon collection system dosimeters are just long enough to be unaffected by diurnal variations, and that the systems with integration times much shorter than the mean-life of radon will only give stable results if the exposure time is a multiple of 24 hours. This condition is usually met with in practice, as people tend to take the detectors out at the same time as they put them in, and so most charcoal measurements are probably unaffected by diurnal cycles.

The presence of these large-amplitude cycles with a mean period of 4 days means that sampling periods over at least 4 cycles or 15 days are needed to ensure that the average concentration measured is close to the actual value of the average radon concentration over the period. From an operational point of view, this means either multiple measurements over a period of at least 15 days with short integration period detectors, or else use of a signal storage detector exposed for at least that length of time.

There are seasonal variations in the radon concentration, and the average radon concentration in the summer is not the same as in the winter. If the annual average is to be measured, then either there must be several 15-day measurements over the course of the year, or else use of a detector that can store a signal for up to a year.

These conclusions are unaffected by standardization of measurement conditions. Standardization is a step toward obtaining reproducible measurements, but does not eliminate variability. All the graphs shown here were obtained under standardized EPA Indoor Radon Measurement Protocol conditions. Besides, standardizing the ventilation rate by keeping doors and windows closed may reduce variability, but the radon concentration pattern will no longer be that to which the occupants are normally exposed. The average obtained may be reproducible, but may not be realistic.