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The 1991 International Symposium on Radon and Radon Reduction Technology

Volume IV: Radon Reduction Methods

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Volume IV
Radon Reduction Methods

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COMPARATIVE DOSIMETRY OF RADON IN MINES AND HOMES: AN OVERVIEW OF THE NAS REPORT

by: Jonathan M. Samet, M.D.
Department of Medicine,
and New Mexico Tumor Registry
University of New Mexico Medical Center
Albuquerque, NM 87131

ABSTRACT

The findings of the recent report by a National Academy of Sciences panel on radon dosimetry are reviewed. The committee was charged with comparing exposure-dose relations for the circumstances of exposures in mines and homes. The community first obtained data on the various parameters included in dosimetric lung models and then selected values that it judged to be best supported by the available evidence. Dosimetric modeling was used to calculate the ratio of exposure to radon progeny to dose of alpha energy delivered to target cells for various scenarios. The committee's modeling shows that exposure to radon progeny in homes delivers a somewhat lower dose to target cells than exposure in mines; this pattern was found for infants, children, men, and women.

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INTRODUCTION

Radon, an inert gas, is a naturally occurring decay product of radium-226, the fifth daughter of uranium-238. Radon decays with a half-life of 3.82 days into a series of solid, short-lived progeny; two of these progeny, polonium-218 and polonium-214, emit alpha particles. When radon progeny are inhaled and these alpha emissions occur within the lungs, the cells lining the airways may be injured and damage to the genetic material of the cells may lead to the development of cancer.

Radon has been linked to excess cases of lung cancer in underground miners since the early decades of the twentieth century. Epidemiologic evidence on radon and lung cancer, as well as other diseases is now available from about 20 different groups of underground miners (1,2). Many of these studies include information on the miners' exposure to radon progeny and provide estimates of the quantitative relation between exposure to progeny and lung cancer risk (2,3); the range of excess relative risk coefficients, describing the increment in risk per unit of exposure is remarkably narrow in view of the differing methodologies of these studies (2).

As information on air quality in indoor environments was collected during the last 20 years, it quickly became evident that radon is ubiquitous indoors and that concentrations vary widely and may be as high as levels in underground mines in some homes. The well-documented and causal association of radon with lung cancer in underground miners appropriately raised concern that radon exposure might also cause lung cancer in the general population. The risk of indoor radon has been primarily assessed by using risk assessment approaches that extend the risks found in the studies of miners to the general population. Risk models that can be used for this purpose have been developed by committees of the National Council on Radiation Protection and Measurements (NCRP) (4), the International Commission on Radiological Protection (5) (1987), and the National Academy of Sciences (Biological Effects of Ionizing Radiation (BEIR) IV Alpha Committee) (1).

Extrapolation of the lung cancer risks in underground miners to the general population is subject to uncertainties related to the differences between the physical environments of homes and mines, the circumstances and temporal patterns of exposure in the two environments, and potentially significant biological differences between miners and the general population (Table 1). A number of these factors may affect the relation between exposure to radon progeny and the dose of alpha-particle energy delivered to target cells in the tracheobronchial epithelium; these factors include the activity-aerosol size distribution of the progeny, the ventilation pattern of the exposed person, the morphometry of the lung, the pattern of deposition and the rate of clearance of deposited progeny, and the thickness of the mucous layer lining the airways.

The activity-aerosol size distribution refers to the physical size distribution of the particles containing the alpha activity. The term "unattached fraction" has historically been applied to progeny existing models that it judged to be best supported by the available evidence. The committee then utilized a dosimetric model, developed in part by the Task Group of the International Commission for Radiological Protection, to compare exposure-dose relations for exposure to radon progeny in homes and in mines. While the report provides the exposure-dose figures, the committee expressed its principal findings as a ratio, termed K in the BEIR IV report (1). K, a unitless measure, represents the quotient of the dose of alpha energy delivered per unit of exposure in a home to the dose per unit exposure for a male miner exposed in a mine. If the K factor exceeds unity, the delivered dose per unit exposure is greater indoors whereas if it is less than unity, the delivered dose per unit exposure is less indoors.

Factors other than lung dosimetry of radon progeny also introduce uncertainty in extrapolating risks from the studies of underground miners to the general population. The committee briefly reviewed the evidence on cigarette smoking, tissue damage, age at exposure, sex, and exposure pattern. These sources of uncertainty were considered in a qualitative rather than a quantitative fashion.

THE COMMITTEE'S FINDINGS

The committee selected several different sets of exposure conditions in homes and in mines (Table 2,3). The mining environment includes the areas of active mining, the haulage drifts, and less active and dusty areas such as lunch rooms. In some analyses, the values for active mining and haulage ways were averaged to represent typical conditions. Separate microenvironments considered in the home included the living room and the bedroom. Parameters for the living room and the bedroom were averaged to represent a typical scenario for the home. The effects of cooking and cigarette smoking on radon progeny aerosol characteristics were also considered. While the contrast between the home and mining environments was somewhat variable across the scenarios, homes were characterized as having greater unattached fractions and smaller particles. Higher average minute volumes were assumed for the mining environment (Table 2,3).

The committee also examined uncertainties associated with other assumptions in the dosimetric model. Doses to basal and secretory cells in the tracheobronchial epithelium were calculated separately, because all types of cells with the potential to divide were considered to be potential progenitor cells for lung cancer. The committee also compared the consequences of considering: lobar and segmental bronchi rather than all bronchi as the target; radon progeny as insoluble or partially soluble in the epithelium; of breathing through the oral or nasal route exclusively; of varying the thickness of the mucus lining the epithelium and the rate of mucociliary clearance; and cellular hyperplasia leading to thickening or injury causing thinning of the epithelium.

Across the wide range of exposure conditions and exposed persons considered by the committee, most values of K were below unity (Table 4). For both secretory and basal cells, K values indicated lesser doses of alpha energy per unit exposure, comparing exposures of infants, as ions, molecules, or small clusters; the "attached fraction" designates progeny attached to ambient particles (6). Using newer methods for characterizing activity-aerosol size distributions, the unattached fraction has been identified as ultrafine particles in the size range of 0.5 to 3.0 nm (6). Typically, mines have higher aerosol concentrations than homes and the unattached fraction would be expected to be higher in homes than in mines. Because of differing sources of particles in the two environments, aerosol size distributions could also plausibly differ between homes and mines.

The physical work involved in underground mining would be expected to increase the amount of air inhaled in comparison with the generally sedentary activities of time spent at home. The greater minute ventilation of miners would result in a higher proportion of the inhaled air passing through the oral route, in comparison with ventilation during typical activities in residences. The physical characteristics of the lungs of underground miners, almost all adult males, differ significantly from those of infants, children and thickness of the epithelial layer could also plausibly differ, comparing miners with the general population, because of the chronic irritation by dust and fumes in the mines.

Methods are available for characterizing the effects of these factors on the relation between exposure to radon progeny and the dose of alpha energy delivered to target cells in the respiratory tract. Using models of the respiratory tract, the dose to target cells in the respiratory epithelium can be estimated for the circumstances of exposure in the mining and indoor environments. One of the recommendations of the 1988 BEIR IV Report (1) was that "Further studies of dosimetric modeling in the indoor environment and in mines are necessary to determine the comparability of risks per WLM [working level month] in domestic environments and underground mines". The BEIR IV Report had included a qualitative assessment of the dosimetry of progeny in homes and in mines, but formal modeling was not carried out.

Consequently, the U.S. Environmental Protection Agency asked the National Research Council to conduct a study addressing the comparative dosimetry of radon progeny in homes and in mines. This paper reviews the findings of the recently published report of the committee (Panel on Dosimetric Assumptions Affecting the Application of Radon Risk Estimates). The panel was constituted with the broad expertise, covering radon measurement and aerosol physics, dosimetry, lung biology, epidemiology, pathology, and risk assessment, needed for this task.

THE COMMITTEE'S APPROACH

To address the charge of undertaking further dosimetric modeling, the committee obtained data on the various parameters included in dosimetric lung models that contributed to uncertainty in assessing the risk of indoor radon. The committee not only reviewed the literature, but obtained recent and unpublished information from several investigators involved in relevant research. After completing this review, the committee selected values for parameters in dosimetric

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children, men and women in homes with exposures of male miners underground. While the highest values of K were calculated for children, the values for children did not exceed unity, suggesting that children exposed to radon progeny are not at greater risk for lung cancer on a dosimetric basis.

The committee explored the sensitivity of the K factors to underlying assumptions in the dosimetric model. The general pattern of the findings was comparable for secretory and basal cells. The K factors remained below unity regardless of whether the radon progeny were assumed to be insoluble or partially soluble in the epithelium. The K factor was also not changed substantially with the assumption that lobar and segmental bronchi, rather than all bronchi, are the target. Assumptions regarding breathing route also had little impact. After the committee had completed its principal analysis, new data became available suggesting that recent higher values for nasal deposition reported by Cheng et al. (7) might be preferable to lower values from the 1969 report of George and Breslin (8); other new evidence suggested that a value of 0.15 um should be used for aerosol size in the haulage drifts. Inclusion of these two modifications of the committee's preferred parameter values in the dosimetric model reduced the values of K by about 20 percent.

The committee did not attempt to reach quantitative conclusions concerning sources of uncertainty not directly addressed by the dosimetric modeling. It noted the paucity of data on such factors as cigarette smoking, age at exposure and particularly the effect of exposure during childhood, and exposure pattern. The evidence on these factors received detailed review in the BEIR IV report (1) and the present committee did not reach any new conclusions on these sources of uncertainty. The committee also commented on the potential effects of the miners' exposures to dust and fumes while underground. Increased cell turnover associated with these exposures may have increased the risk of radon exposure for the miners.

SUMMARY

The Panel on Dosimetric Assumptions Affecting the Application of Radon Risk Estimates comprehensively reviewed the comparative dosimetry of radon progeny in homes and in mines. The committee's modeling shows that exposure to radon progeny in homes delivers a somewhat lower dose to target cells than exposure in mines; this pattern was found for infants, children, men, and women. This finding was not sensitive to specific underlying assumptions in the committee's modeling. Assuming that cancer risk is proportional to dose of alpha energy delivered by radon progeny, the committee's analyses suggests that direct extrapolation of risks from the mining to the home environment may overestimate the numbers of radon-caused cancers.

TABLE 1. POTENTIALLY IMPORTANT DIFFERENCES BETWEEN EXPOSURE TO RADON IN THE MINING AND HOME ENVIRONMENTS*

Physical Factors	
Aerosol characteristics:	Greater concentrations in mines; differing size distributions
Attached/unattached fractions:	Greater unattached fraction in homes
Equilibrium of radon/decay products:	Highly variable in homes and mines
Activity Factors	
Amount of ventilation:	Probably greater for working miners than for persons indoors
Pattern of ventilation:	Patterns of oral/nasal breathing not characterized, but mining possibly associated with greater oral breathing
Biological Factors	
Age:	Miners have been exposed during adulthood; entire spectrum of ages exposed indoors
Gender:	Miners studied have been exclusively male; both sexes exposed indoors
Exposure pattern:	Miners exposed for variable intervals during adulthood; exposure is lifelong for the population
Cigarette smoking:	The majority of the miners studied have been smokers; only a minority of U.S. adults are currently smokers

*Taken from Table 1-2 in reference (6).

TABLE 2. ASSUMPTIONS FOR EXPOSURE SCENARIOS ASSUMED FOR MINES AND HOMES*

SUMMARY OF RADON PROGENY AEROSOL CHARACTERISTICS ASSUMED TO REPRESENT EXPOSURE CONDITIONS IN MINES AND HOMES

Exposure Scenario	f_p	AMD of Room Aerosol (μm)	AMD of Aerosol in respiratory tract (μm)
<u>Mine</u>			
Mining	0.005	0.25	0.5
Haulage drifts	0.03	0.25	0.5
Lunch room	0.08	0.25	0.5
<u>Living Room</u>			
Normal	0.08	0.15	0.3
Smoker - average	0.03	0.25	0.5
- during smoking	0.01	0.25	0.5
Cooking/vacuuming	0.05	0.02/0.15+ (15%/80%)	0.02/0.3 (15%/80%)
<u>Bedroom</u>			
Normal	0.08	0.15	0.3
High	0.16	0.15	0.3

*Based on Tables 3-1 and 3-2 in reference 6.

+The radon progeny aerosol produced by cooking/vacuuming has three size modes; 5% of potential alpha energy is unattached, 15% has an AMD of 0.02 m, and 80% has an AMD of 0.15 μm. The 0.02 μm AMD mode is hydrophobic and does not increase in size within the respiratory tract.

TABLE 3. ASSUMPTIONS FOR EXPOSURE SCENARIOS ASSUMED FOR MINES AND HOMES*

LEVELS OF PHYSICAL EXERTION AND AVERAGE MINUTE VOLUMES ASSUMED FOR UNDERGROUND MINERS AND FOR ADULTS IN THE HOME

Exposure Scenario	Level of Exertion	Average $\dot{V}_E$ (liters/min) Man	Woman
Underground Mine			
Mining	25% heavy work/75% light work	31	--
Haulage way	100% light work	25	--
Lunch room	50% light work/50% rest	17	--
Home-Living Room			
Normal and smoker	50% light work/50% rest	17	14
Cooking/vacuuming	75% light work/25% rest	21	17
Home-Bedroom			
Normal and high	100% sleep	7.5	5.3

*Based on Tables 3-1 and 3-2 in reference 6.

TABLE 4. SUMMARY OF K FACTORS FOR BRONCHIAL DOSE CALCULATED FOR NORMAL PEOPLE IN THE GENERAL ENVIRONMENT RELATIVE TO HEALTHY UNDERGROUND MINERS*

Subject Category	K Factor for Target Cells Secretory	Basal
Infant, age 1 month	0.74	0.64
Child, age 1 year	1.00	0.87
Child, age 5-10 years	0.83	0.72
Female	0.72	0.62
Male	0.76	0.66

*Taken from Table 5-1 in reference 6.

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 $\pm$ 0.001 in. WG ($\pm$ 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.

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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	Winter-Quarter Averages[4] 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.

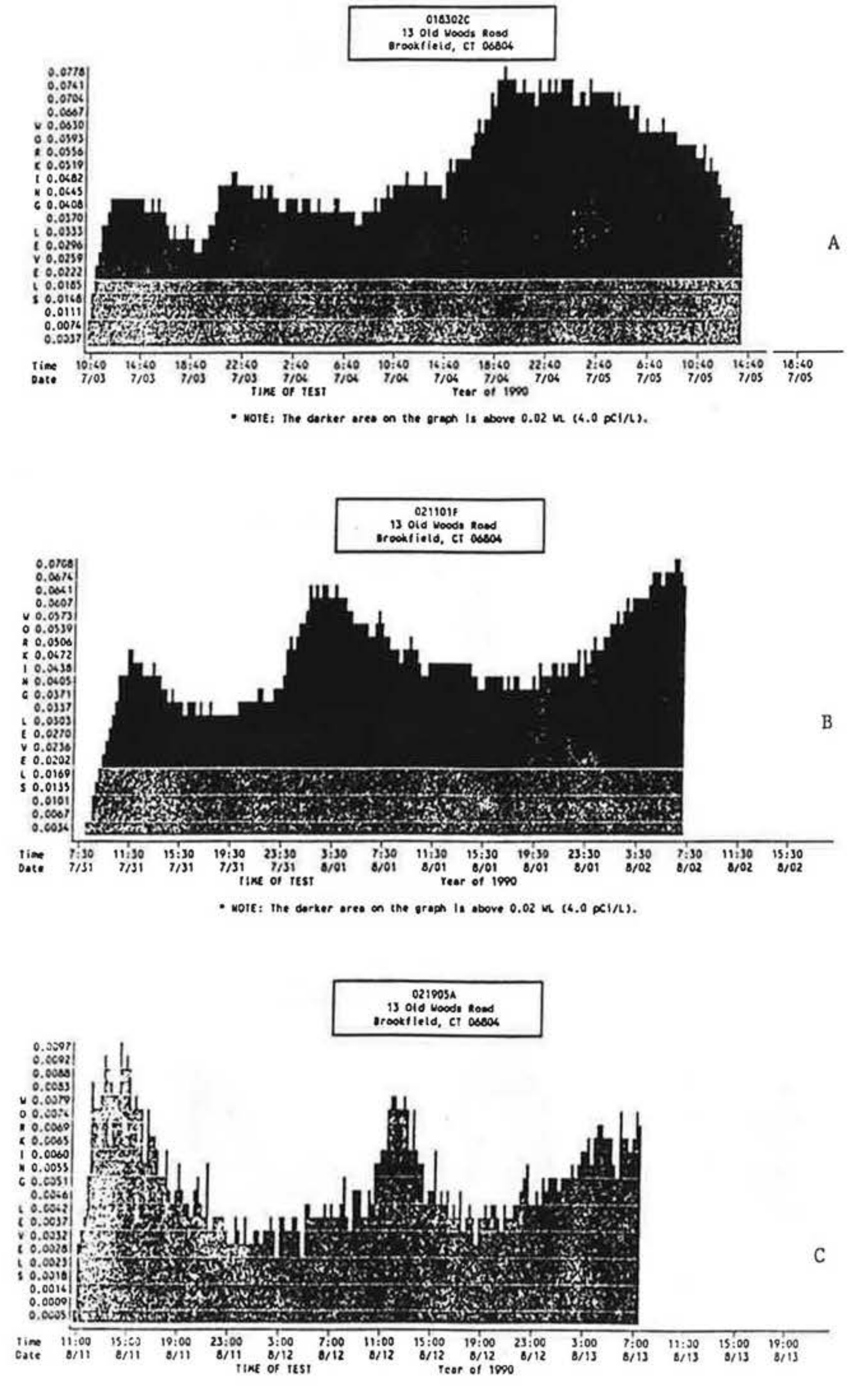
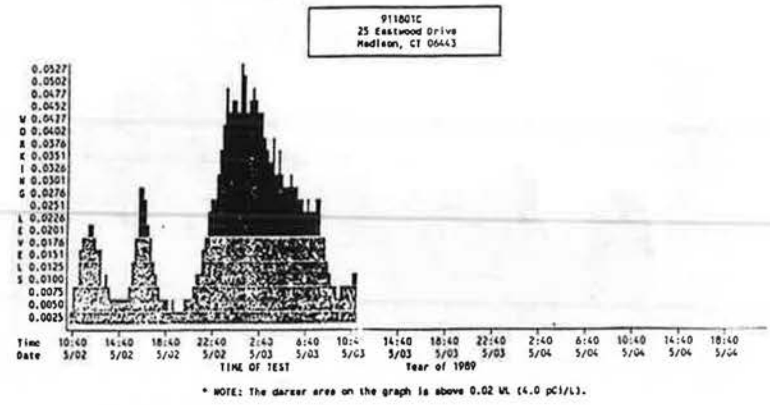
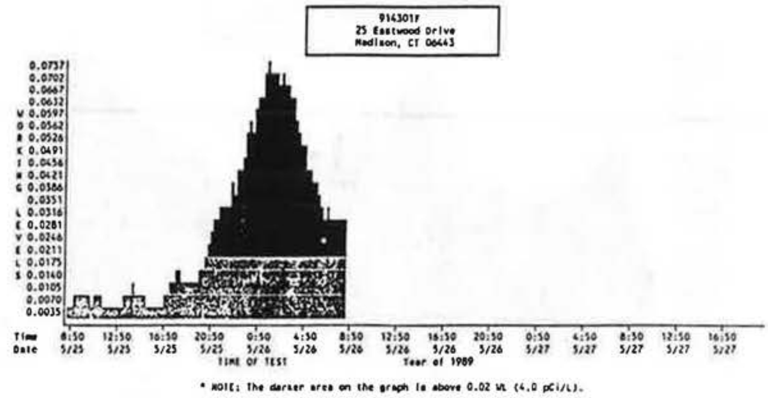


Figure 1. Mitigation Case 1





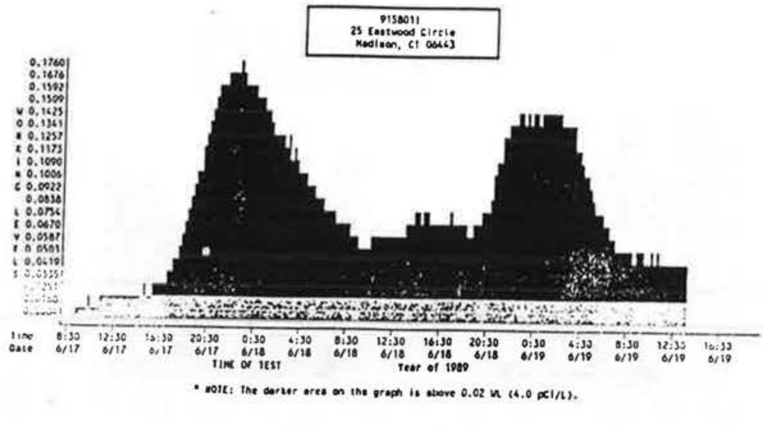
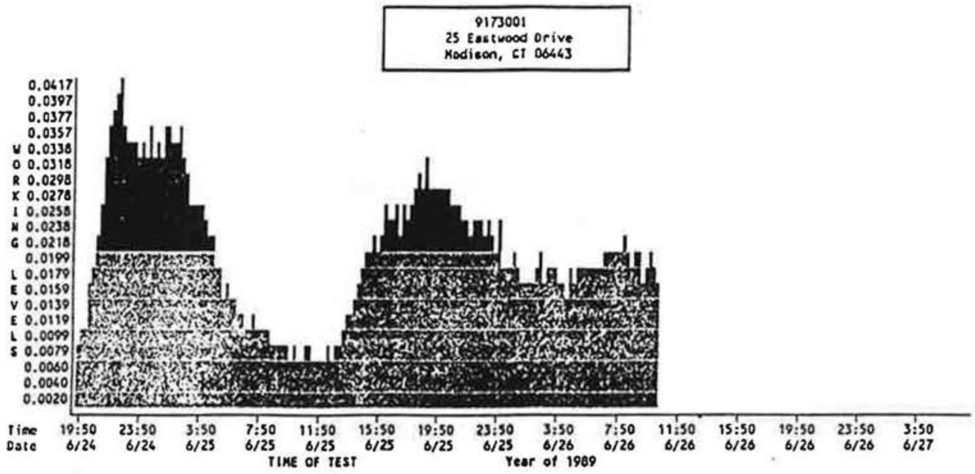


Figure 2. Mitigation Case 2



* NOTE: The darker area on the graph is above 0.02 WL (4.0 pCi/L).

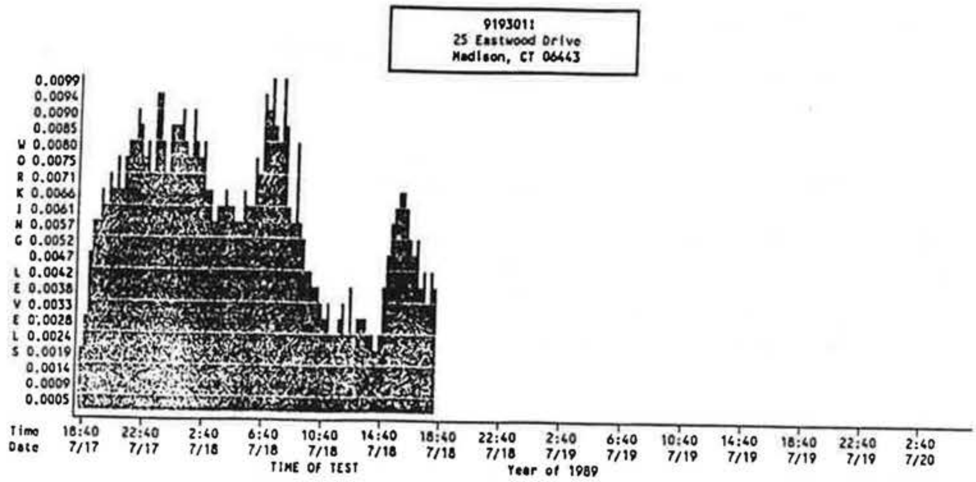


Figure 2 (continued) Mitigation Case 2

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?**

PRESSURE FIELD EXTENSION USING A PRESSURE WASHER

NEW JERSEY DEP SPONSORED PROJECT INNOVATIVE MITIGATION RESEARCH AWARDS

BILL BRODHEAD
2844 SLIFER VALLEY RD.
RIEGELSVILLE, PA., 18077
215-346-8004

ABSTRACT

This project was delayed because of contract negotiations and is presently in the preliminary stages. Although only a limited amount of data is available, the technique was successful done.

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. Two buildings with the appropriate tight non-rocky soil were tested for pressure field extension before and after tunneling with the high pressure washer.

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 limited choices for suction hole locations.

PRESSURE FIELD EXTENSION
USING A HIGH PRESSURE WATER JET

PROBLEM STATEMENT:

If we are to achieve levels as low as reasonably possible, techniques must be developed that are simple and effective for all types of housing and soil. New data is showing that even levels as low as the 4 pCi/l guideline may still result in a substantial relative risk of developing lung cancer. This makes it more critical to optimize the mitigation systems to produce the maximum benefit while still being cost effective.

This project addresses a technique to be used with buildings that have a problem with sub-slab ventilation systems. The problem building addressed in this project is partially finished and built without any gravel under the concrete floor with no significant settling of the sub-soil. It is what we refer to in the industry as a soil with poor communication. This condition can be revealed in the initial site visit if a diagnostic communication test is done. The test requires an approximate 1" hole to be drilled through the concrete floor and a shop vac set up to suck on the hole. Small test holes are drilled at varying distances from the shop vac hole and the pressure change with the shop vac on versus off is measured along with the total amount of air flow. A tight soil is indicated if the results of the test reveal limited air coming out of the vacuum cleaner and very limited pressure field extension. If their is a lot of air flow but limited pressure field extension then this indicates good communication but significant leaks or porosity in the soil.

This project addresses the tight soil condition, especially in situations where the finished condition of the space makes it costly or impossible to practically add additional suction holes. A goal of this project is to determine if it is more practical in unfinished spaces to add suction holes than to use this technique.

HRV's - Mitigators in the past have often had to fall back on using air to air heat exchangers in houses with finished areas and poor sub-soil communication. This, however, has not been a satisfactory solution. Ventilators increase the heating load and add excess humidity in the summer. The performance of ventilators often deteriorates when maintenance is not performed on a regular basis. With ventilators, homeowners have no easy way to determine if the system is operating properly, other than to continually test for radon. Sub-slab systems are preferred over HRV's because they require very little maintence, there is less deterioration of performance over time, their is less operating cost, the system can be monitored with a pressure gauge and generally costs less to install.

FAILED SUB-SLAB SYSTEMS - The present industry standard for radon action is 4 pCi/l. There are, however, many sub-slab systems that are installed which fail to reduce the radon levels below 4 pCi/l. Often this failure is due to incomplete pressure field extension of the sub-slab vacuum system. This incomplete vacuum or pressure field is often due to a tight sub-soil without any stone base. Most newer buildings have a stone base although some basement concrete floors are poured directly on packed sand or screenings. Older buildings often had the concrete floor poured on the dirt and the basement space is now finished. A finished basement complicates the situation because it is difficult to add extra suction points.

SUCTION PITS - Some mitigators will dig a pit to enhance the pressure field in poor communication soils. Digging a pit, however, beyond what can be dug out of a single five inch hole, will typically only extend the pressure field the distance that the pit is dug out. This is because hole size enlargement produces diminishing reductions in pressure loss due to the limited amount of air flowing through the tight soil. There will actually be little pressure drop reduction once the hole has a few gallons of sub-soil dug out of it. Other mitigators have tried digging long ditches and filling the ditch with gravel and then replacing the floor. This would be more effective than a suction pit, but is very labor intensive, produces a lot of dust, and requires additional equipment to open up the floor, haul the dirt out and replace with gravel and new concrete.

WATER JET ALTERNATIVE - Poor communication soils can be effectively mitigated with sub-slab suction systems, but we need to develop more good techniques for dealing with this situation. If the same effect as trenching could be obtained by tunneling under the concrete floor through the existing 5" suction hole, a large cost savings could be realized without all the drawbacks and could give better results than a pit suction. Pressure washer equipment that can produce from 800 to 3000 psi pressure is readily available. The cost of these units runs from $450 to $2500. The smaller units are powered by an electric motor. The larger units use a gas powered motor. One component of the study is to determine if the less expensive and troublesome electric powered pressure washer is adequate or is it necessary to use the larger more bothersome gas powered unit. Both of these units are within the cost of other equipment used by the mitigators, such as hammer and core drills.

HOUSE SELECTION - The ideal house to use this technique on would have one or more of the following characteristics: a soil that is free from rocks larger that an inch or two; the requirement for additional pressure field extension but difficult and expensive because of the finished condition of the basement or obstructions preventing easy pipe routing; a source of water; an outside entrance to the basement near the unfinished section to make hauling and adjustment of power equipment easier; a work area around the suction hole; a place that the water and sludge used in this technique can be discarded as the work is being done.

PRESSURE WASHING EQUIPMENT - The equipment used in this project was purchased through Grainger's which has warehouses throughout the US. The electric power washer is model # 3Z829. It uses a 1 1/2 horsepower electric motor and produces 1000 psi with a flow 2 gallons per minute. Its retail cost is $840.91. This unit can be set up to run in the basement.

The gasoline powered unit has 11 horse power and produces 2900 psi with a flow rate of 3 1/2 gallons per minute. The model # is

5Z169 and presently retails for $1711.20. Both units require an additional 25 feet of 1/4" hydraulic hose that will handle the water jet pressure. A solid cap is installed on the end of the hydraulic hose and it is installed in the wand spray trigger handle that comes with the units. A 1/32" hole is drilled in the hose cap. This unit must be run outside or in an open garage with the hoses run between the basement and the unit. One concern if you live in a northern climate is the possibility that the water left in the pressure washer will freeze if the unit is left in the truck at night.

FIRST TRY - We had begun a mitigation of a school dormitory building and had not been able to do initial diagnostic communication tests. The center suction hole revealed a clay soil and limited pressure field extension with a F150 fan pulling directly on the dug out suction hole. The gasoline power pressure washer was used with a two man crew. One man controlled the trigger and the other held the hose in the suction hole and slowly pushed the spray head through the soil. Occasionally the hose would get stuck as it was pushed away from the hole or in trying to retrieve it out of the hole. It also took two hands to force the hose to tunnel away from the hole as the water pressure pushed back. The shop vac did a good job of sucking up the muck but you often mistakenly fill the shop vac container full of water. Carrying a shop vac full of water up a set of basement stairs will either put hair on your chest or give you a hernia. Having a place to dump the slurry at the job site will save a lot of hauling of sloshing buckets. Digging the hole out, although a muddy job, is fairly easy.

Protective gloves are critical as the kick of the hose upon start up would forces your hands into the jagged concrete which in this case also contained broken wire mesh. Protective equipment including eye goggles is a good idea to prevent what could be a serious injury.

We were able to get at least 10 gallons of clay out of the hole and the pressure hose extended about five feet in several directions.

When we tested the pressure field extension we were surprised to find that the readings were about 20% weaker than before we had used the water jet. Three days later when we recheck the same test holes we found that we now had approximately doubled the original vacuum readings. Two of the readings reversed from .001" and .003" positive to .001" and .002" negative. It seems that the water temporarily clogs up the pores of the soil until it has a chance to dry.

We continued to use the pressure hose on three other suction holes and the final pressure readings under the slab were excellent and the radon concentrations fell to below 2 pCi/l.

FIRST HOUSE - The first house in the study is a thirty year old two story colonial that has a partially finished basement, a small dirt floor crawl space, an attached garage, and a slab on grade patio that has been converted into an enclosed spa room. The basement has a set of stairs leading to the garage as well as a standard set of stairs between the basement and the first floor. The foundation is block walls that are capped on top. The radon levels measured 20.8 pCi/l in the basement.

A communication test revealed that their was screenings, which is a fine crushed rock, under the concrete floor. The soil communication in the stretched half way across the unfinished portion of the basement. A two hole suction system was installed in the basement and a rubber EPDM barrier was sealed on top of the dirt floor of the crawl space. A dampered suction pipe was install through the crawl space barrier. The pipe was routed through a hall closet in a single story portion of the house into the attic and out the roof. A F150 fan was installed in the attic.

INITIAL SYSTEM PERFORMANCE - All pressure readings were taken with a EDM digital micromanometer. Airflow measurements were taken with the digital micromonometer and a pitot tube.

The vacuum in the two basement suction pipes was 1.2" and the floor vacuum ranged from .040 negative to .013 positive in the far end of the finished area. The air flow in the basement suction pipes was about 10 CFM while the crawl space suction pipe was moving 67 CFM even with the damper partially closed.

RADON LEVELS - The first followup radon measurements before the high pressure water jet was tried were 9.4 in the finished area and 9.3 in the unfinished area near the crawl space entrance.

Although the primary reason for developing this technique is to reduce the radon levels, the success of this technique is more quantitatively measured with pressure changes in the surrounding sub-soil, rather than radon measurements. Radon can vary so much from day to day that, changes in the concentration are more difficult to interpret. Failure to reduce the levels significantly may be due to other radon sources in the building that are not part of the area that the pressure field is being extended to. This source could be the block walls that are adjacent to the slab on grade spa room or the garage slab.

WATER JET PROCEDURE - All of the following procedures were done with one person. The center hole in the basement was opened up and enlarged to 6" to allow more room to work. This took about 15 minutes. An additional eight gallons of screenings and soil was removed from the hole. This took about 30 minutes. The pipe was then replaced and the pressure field extension test holes remeasured. There was no change in the pressure reading in the finished area and about a 10 to 20% increase in the test holes in the same room. These holes are twelve and eighteen feet from the suction hole. This took about 30 minutes to set up the pipe and remeasure the test holes.

The hole was then opened again and the water jet set up. The end cap of the hydraulic hose was modified with two additional 1/32" drilled holes that slanted to the back. This was done to reduce the back pressure of trying to push the hose through the soil, to cause a larger tunnel to be formed and to assist removal of the hose when it becomes stuck.

About five tunnels were dug approximately six feet through the screenings that were just below the slab. The screenings were only an inch or two thick so the tunneling more than likely went through the soil. In this case, there was no accumulation of water compared to the commercial job done previously as it must have soaked into the screenings. An additional four to six gallons of soil and screenings was removed from the hole. If the tunnels traveled in a straight line , which is hard to determine, then the suction hole was actually enlarged to a diameter of over ten feet. This procedure took about 30 minutes.

WATER JET FOLLOW MEASUREMENTS - The sub-slab pipes were hooked back up and the pressure field extension measurements were repeated and once again there seemed to be a reduction in vacuum readings of about 10% for the test holes that were relatively close to the suction pipe. The air flow and pressure measurements in the pipe did not change significantly. These final measurements took about 30 minutes to do again and clean up took about 15 minutes.

Three days later I repeated the floor pressure measurements and was surprized that they had not changed. Upon opening the pipe into the floor to inspect the suction hole I discovered that most of the pipe inlet had become blocked by loose plastic that was used as a backer rod around the pipe in the enlarged hole. Once the barrier was removed and the pipe resealed into the hole the pressure field extension measurements improved dramatically. The percentage increase was from no increase in the far end of the finished area to a 10%, 25%, 50%, 175%, and 250% increase in negative pressure under the floor.

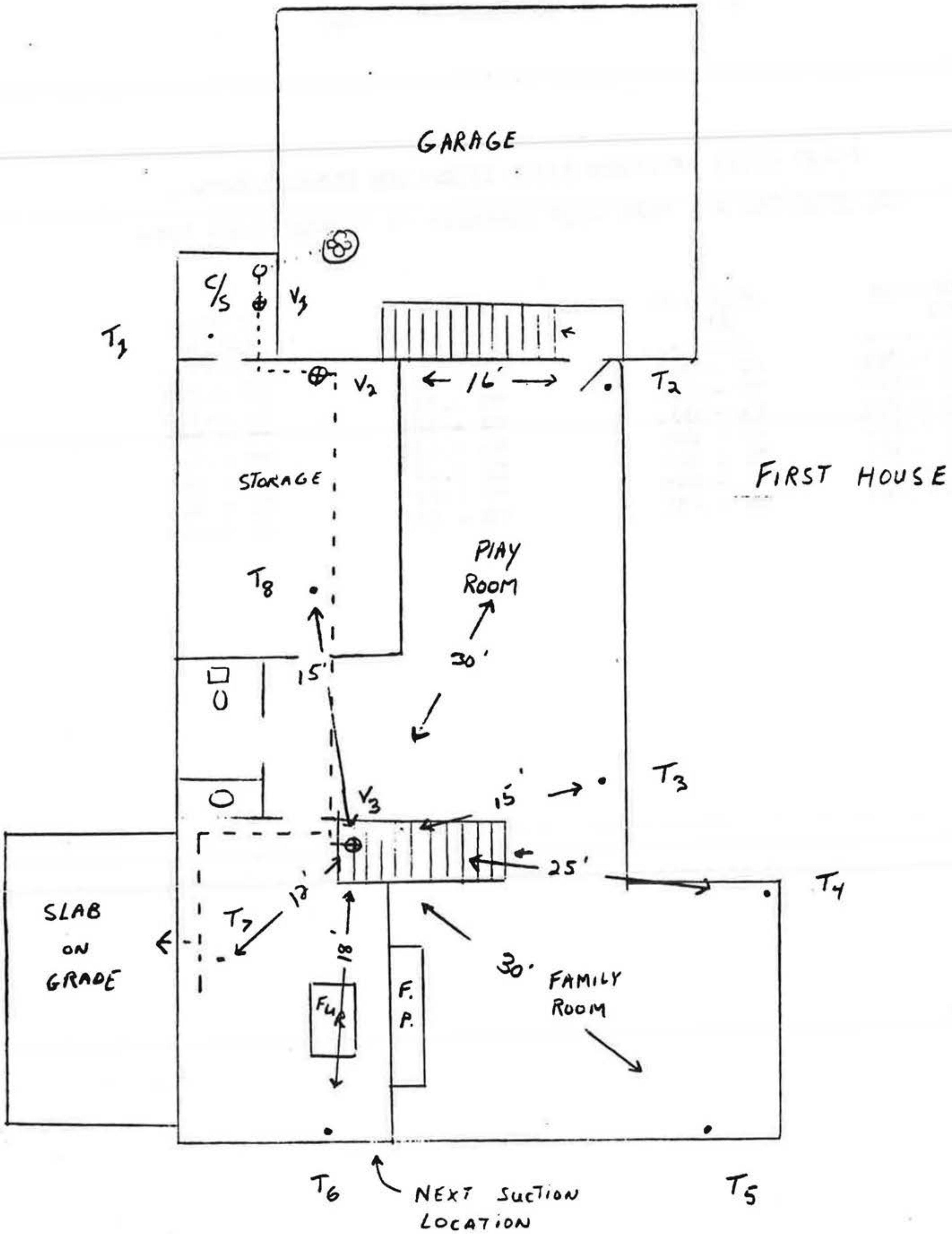
POST WATER JET RADON LEVELS - Followup radon measurements after the high pressure water jet were 7.1 in the finished area and 8.1 in the unfinished area near the center suction hole. Because the back room measured slightly higher than the finished area it was decided that a suction should be installed into the slab on grade spa room sub floor from the basement. Although this would lessen the amount of available suction to the sub- floor it might eliminate a major source of the remaining radon. The suction point was installed so that it would draw from the soil and not directly from the block wall and a damper was installed to control excessive air flow. A followup radon test however indicated that this extra suction had little effect on the radon levels. It appears that the remaining problem is still due to the lack of vacuum in the finish area and an additional suction point will have to added with pipes run across the finish ceiling or a third suction hole might be installed in the unfinished area with a repeat of the water jet procedure.

PRESSURE FIELD EXTENSION
USING A HIGH PRESSURE WATER JET

FIRST HOUSE PRESSURE FIELD EXTENSION MEASUREMENTS

ALL MEASUREMENTS DONE WITH BASEMENT TO OUTSIDE DOOR OPEN

SUB-SLAB ONLY	HOLE DUG OUT	FRESH WATER JET	3 DAYS LATER
T2 -.064	T2 -.053	T2 -.053	T2 -.059
T3 -.020	T3 -.020	T3 -.016	T3 -.050
T4 +.002	T4 +.001	T4 +.002	T4 +.001
T5 +.000	T5 -.000	T5 +.000	T5 -.000
T6 -.025	T6 -.027	T6 -.027	T6 -.041
T7 -.038	T7 -.045	T7 -.042	T7 -.056
T8 -.092	T8 -.091	T8 -.080	T8 -.159


GARAGE
C/S
V1
T1
V2
← 16' →
T2
FIRST HOUSE
STORAGE
PLAY ROOM
T8
30'
15'
15'
T3
V3
25'
T4
SLAB ON GRADE
T7
12'
18'
FUR
F. P.
30'
FAMILY ROOM
T6
T5
NEXT SUCTION LOCATION

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

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[1] Eberline Instrument Corp, Airport Rd, Santa Fe, NM

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 $°C^{-1}$ m^{-1}. In the house under study, this amounted to an average depressurization of 0.1 Pa $°C^{-1}$. 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):

$$E =((C*L*dp)/(V*P))*(G/(12W^3)+ACOSH((2Z)/W)/(PI*K))^{-1} \quad \text{(in Bq m}^{-3}\text{ s}^{-1}\text{)}$$

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})

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[1] Kanalflakt, 1121 Lewis Ave., Sarasota, Fl.

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 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).

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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.

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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

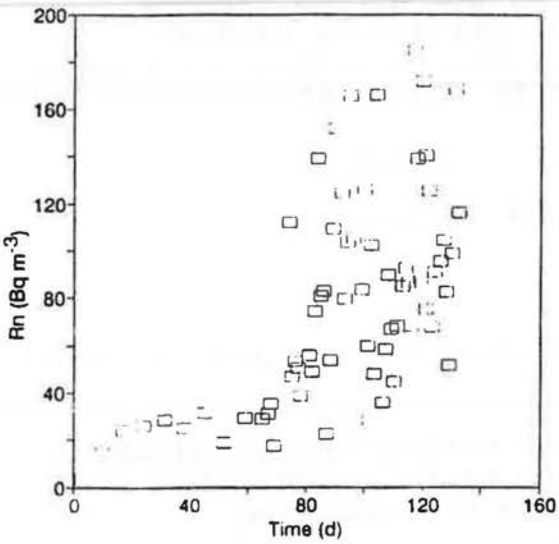

Fig. 1. Rn Levels as a Function of Time (Day 1 = 3 Sept 1989)

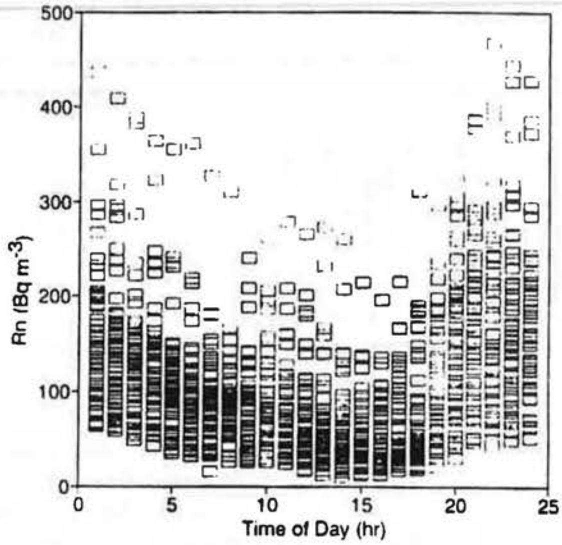

Fig. 2. Hourly Rn Levels (Winter 1989-90)

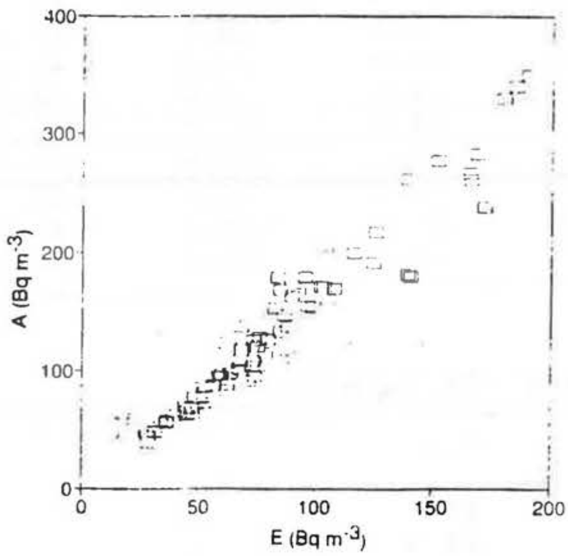

Fig. 3. Rn Levels in Bathroom (A) vs. Bedroom (E)

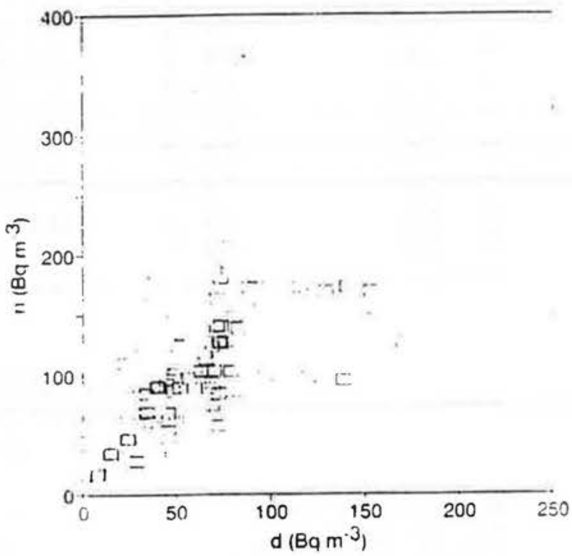

Fig. 4. Rn Levels, Day (d) vs. Night (n)

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

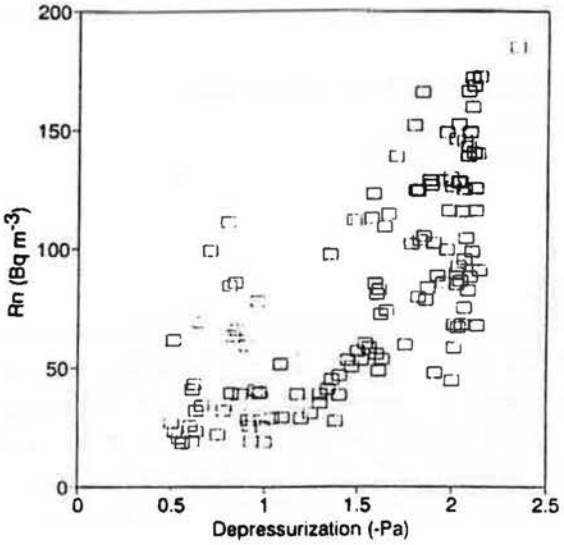

Fig. 5. Room Depressurization vs. Rn Activity

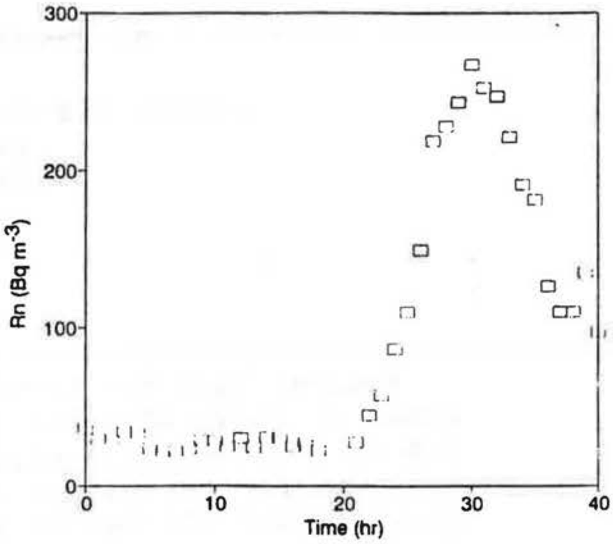

Fig. 6. Depressurization Ending at 18:00 Hrs

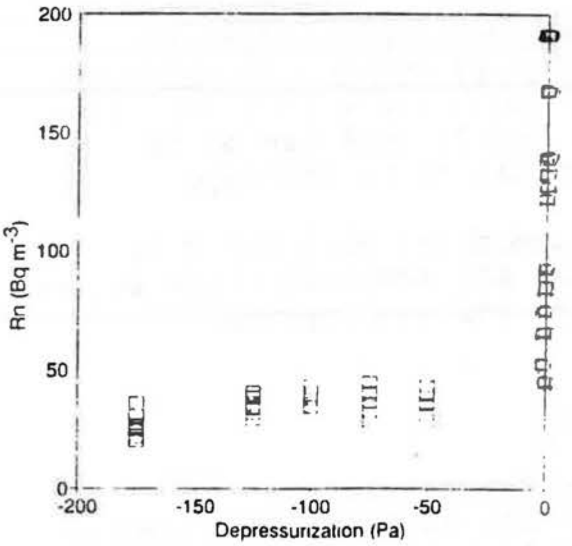

Fig. 7. Indoor Rn as a Function of Subslab Depressurization

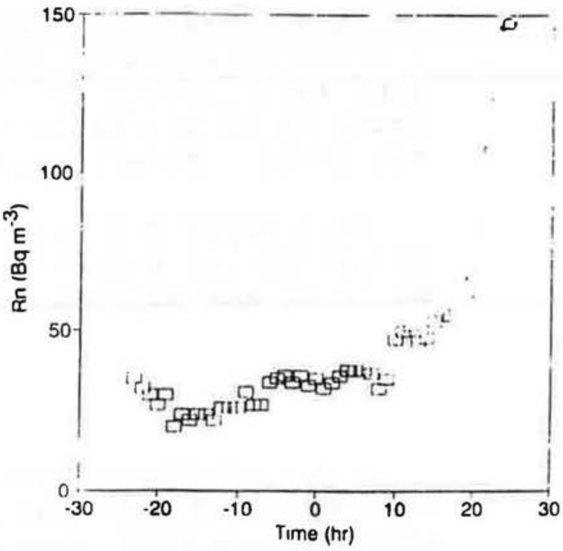

Fig. 8. Indoor Rn as a Function of Time (-50 Pa depressurization ending at 0 hrs)

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.

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*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.

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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

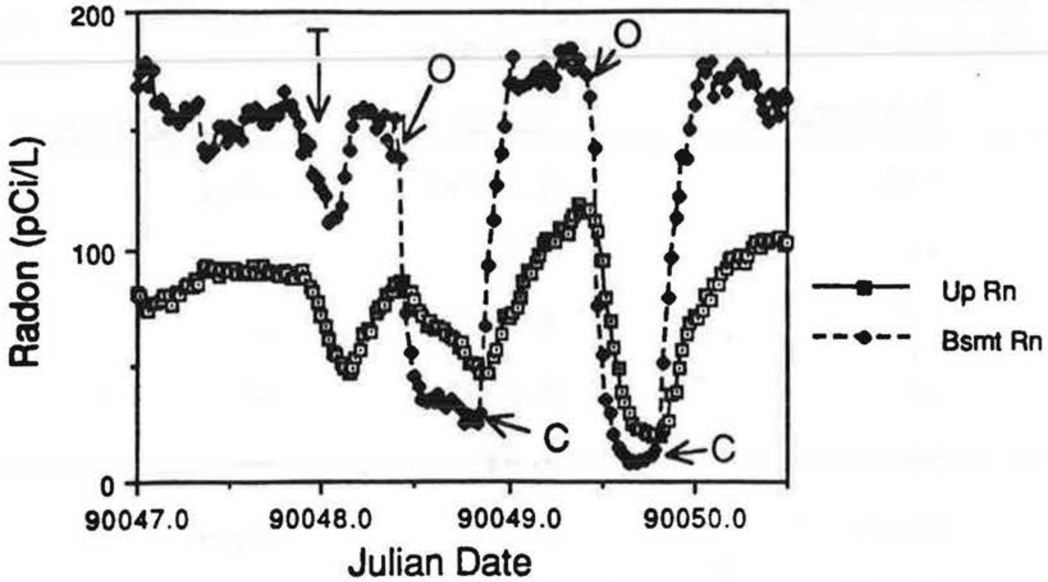

Figure 1a. Basement, Upstairs Radon Level vs Julian Date
Sequence of Window Open and Window Closed, PU21
O=Open; C=Closed; T= Temperature Spike

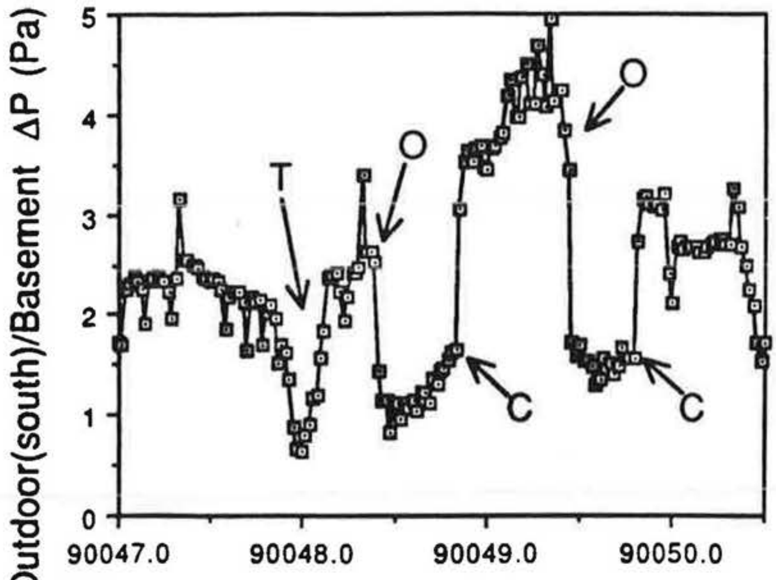

Figure 1b. Outdoor/Basement Pressure Differential vs Julian Date;
Sequence of Window Open and Window Closed, PU21
O=Open; C=Closed; T=Temperature Spike

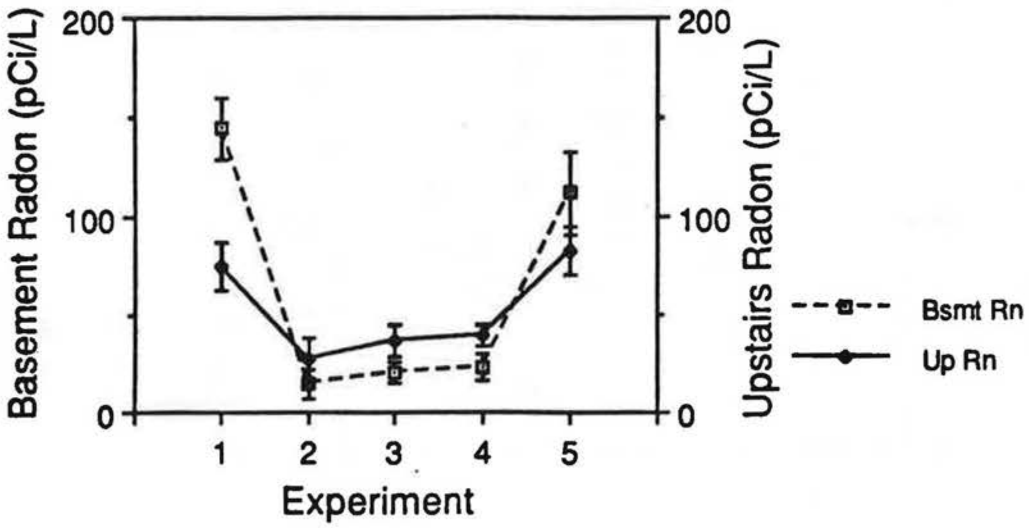

Figure 2. Basement, Upstairs Radon,PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

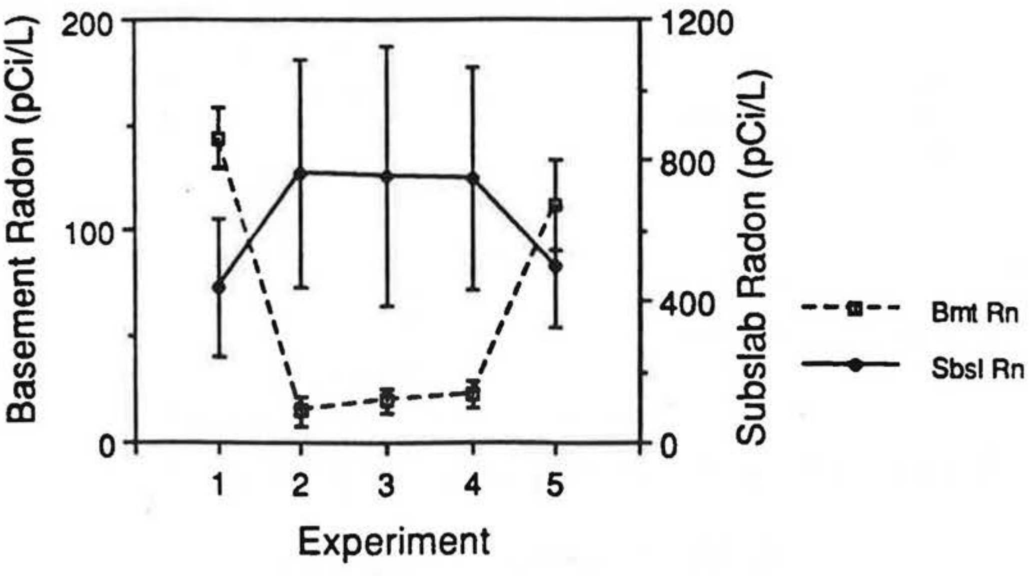

Figure 3. Basement, Subslab Radon PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

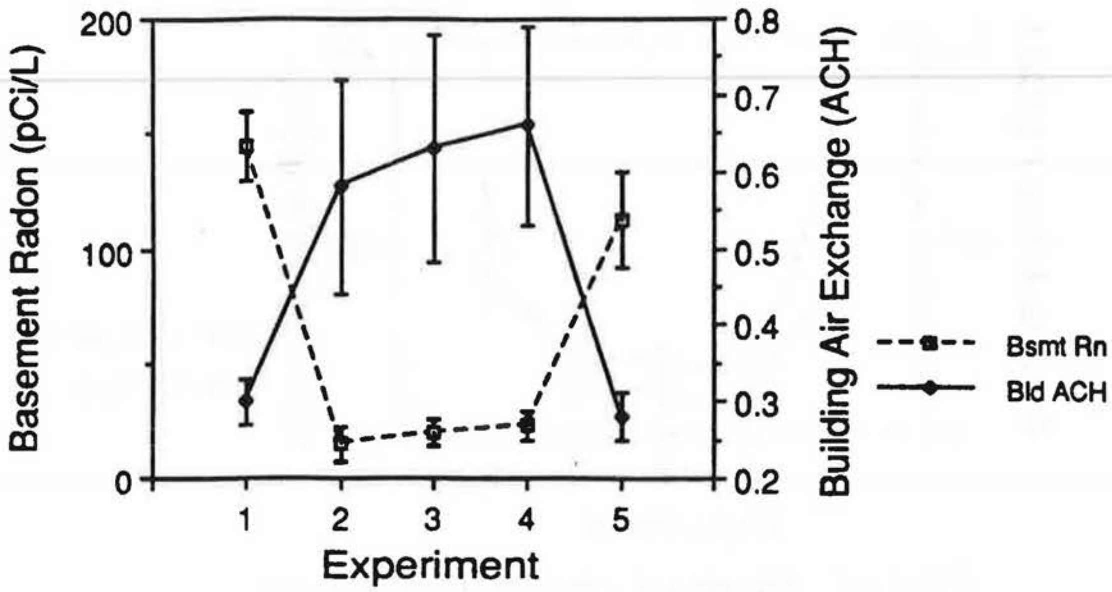

Figure 4. Building ACH, Basement Radon,PU21
Experiments 1,5 Window Open;
Experiments 2,3,4 Window Closed

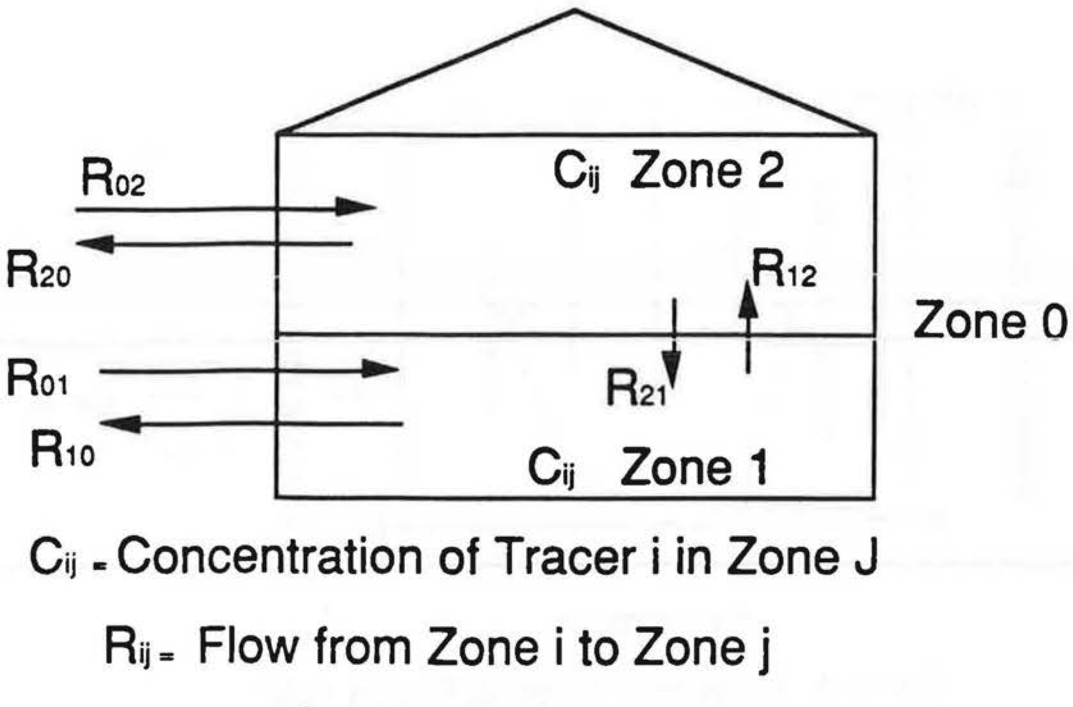

Figure 5. Flows and Tracer Concentrations for Two Zones

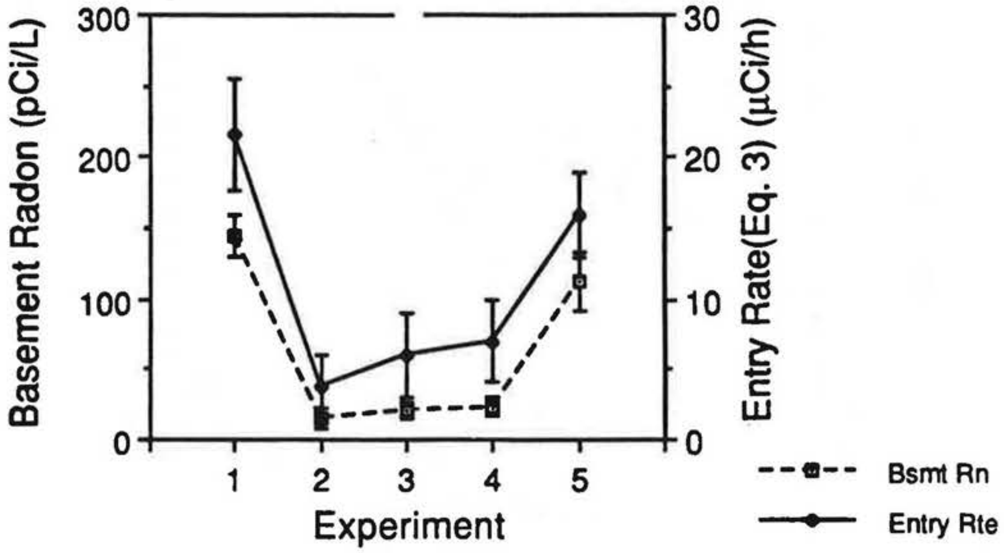

Figure 6. Basement Radon Entry Rate, Basement Radon,PU21
Experiments 1,5 Windows Closed;
Experiments 2,3,4 Windows Open

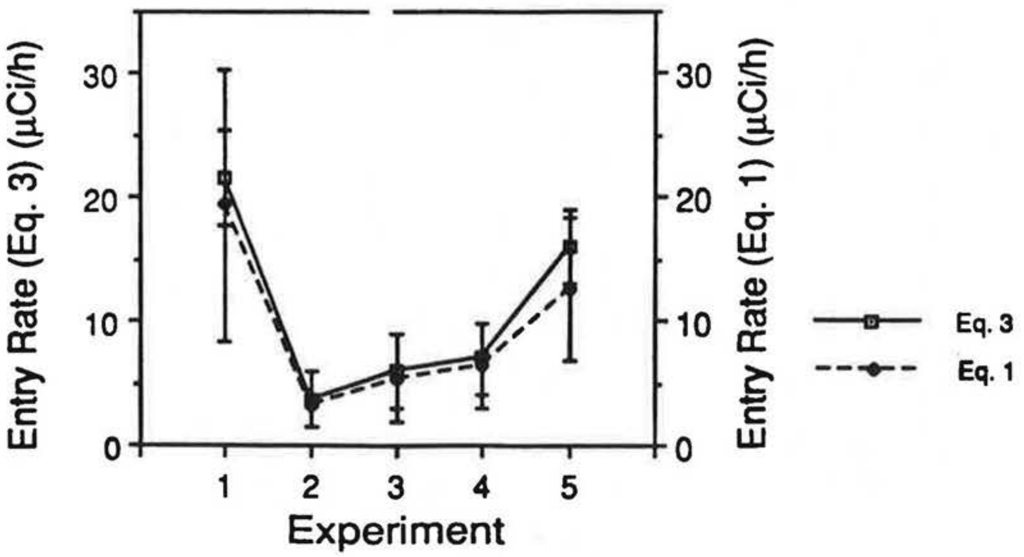

Figure 7. Entry Rate Calculations Compared, PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

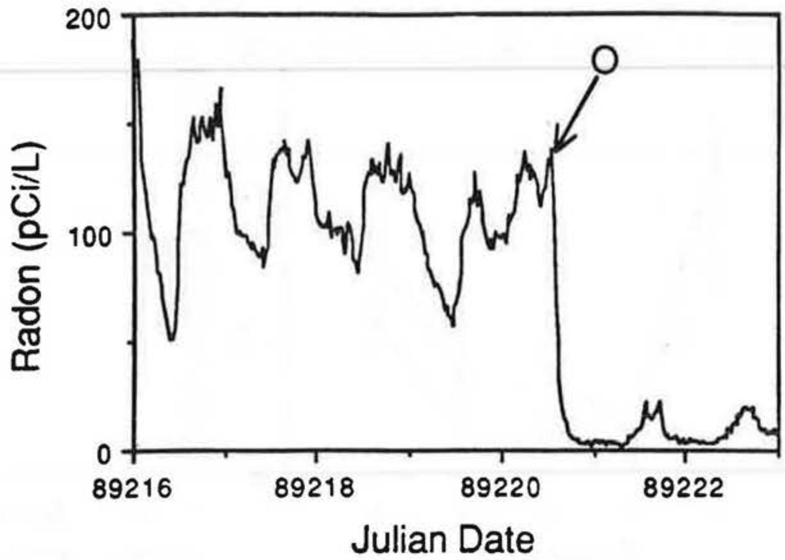

Figure 8. Basement Radon vs Julian Date, PU31. In This Experiment, Two Basement Windows Were Opened (O) at JD 89220.6.

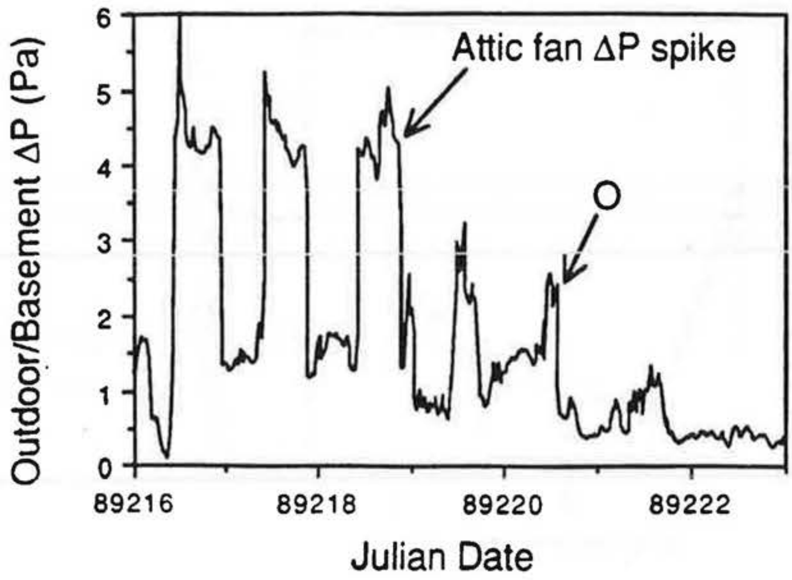

Figure 9. Outdoor/Basement Pressure Differential (ΔP) vs Julian Date. Basement Windows Opened (O) at JD 89220.6; Note Effect of Attic Fans.

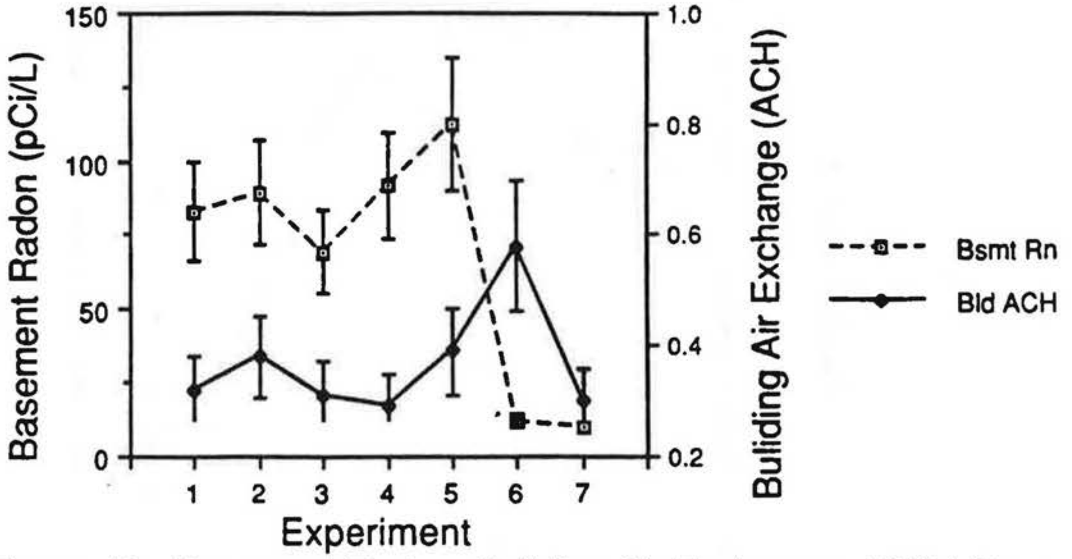

Figure 10. Basement Radon, Building Air Exchange , PU31 Summer
Experiments 1-5, Baseline (normal house operation)
Experiment 6, Windows Open, Fan On;
Experiment 7, Windows Open, Fan Off

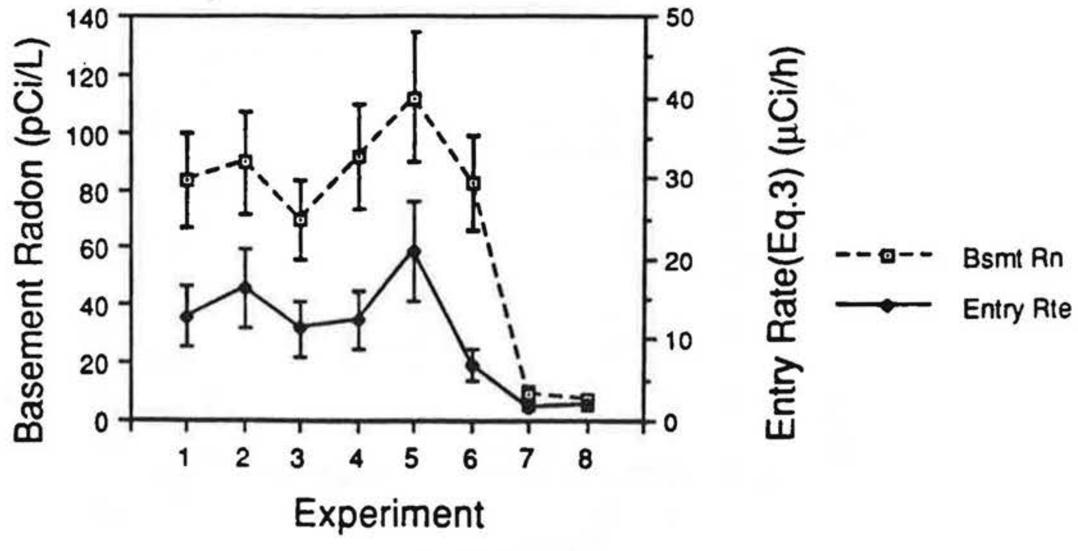

Figure 11. Basement Radon Level, Entry Rate; PU31 Summer
Experiments 1-5, Baseline (normal house operation);
Experiment 6, Windows Closed, Fan Off;
Experiments 7-8, Windows Open, Fan Off

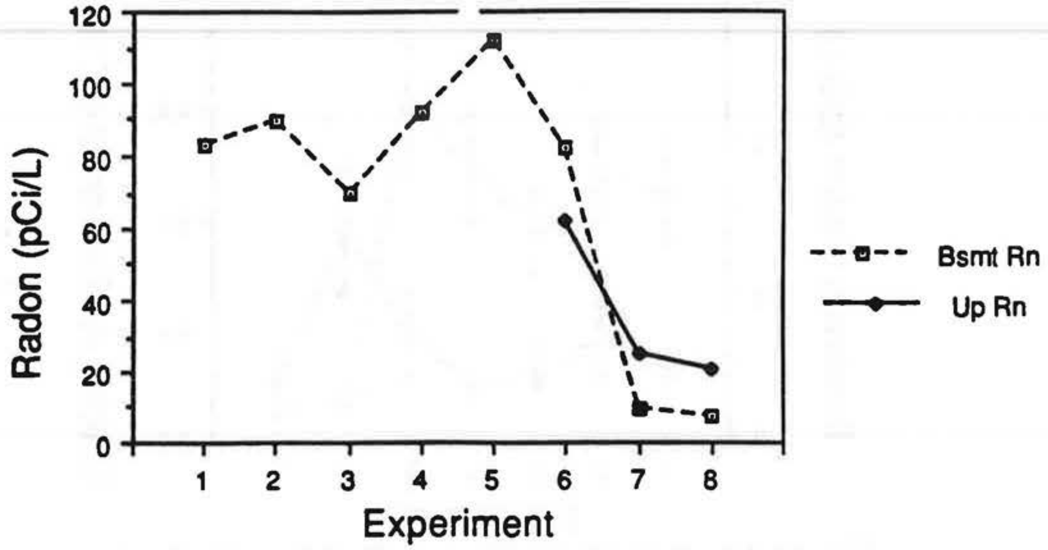

Figure 12. Basement, Upstairs Radon Level,PU31 Summer
Experiments 1-6, Baseline (normal house operation);
Experiments 7-8, Windows Open

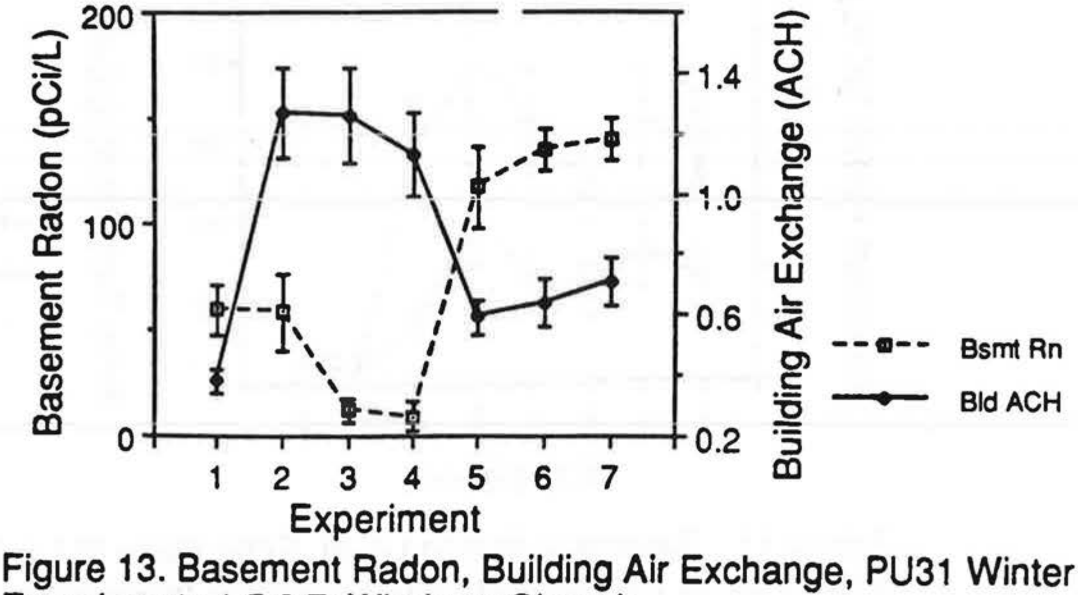

Figure 13. Basement Radon, Building Air Exchange, PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3: East and West Open;
Experiment 2: East Open;
Experiment 4: West Open

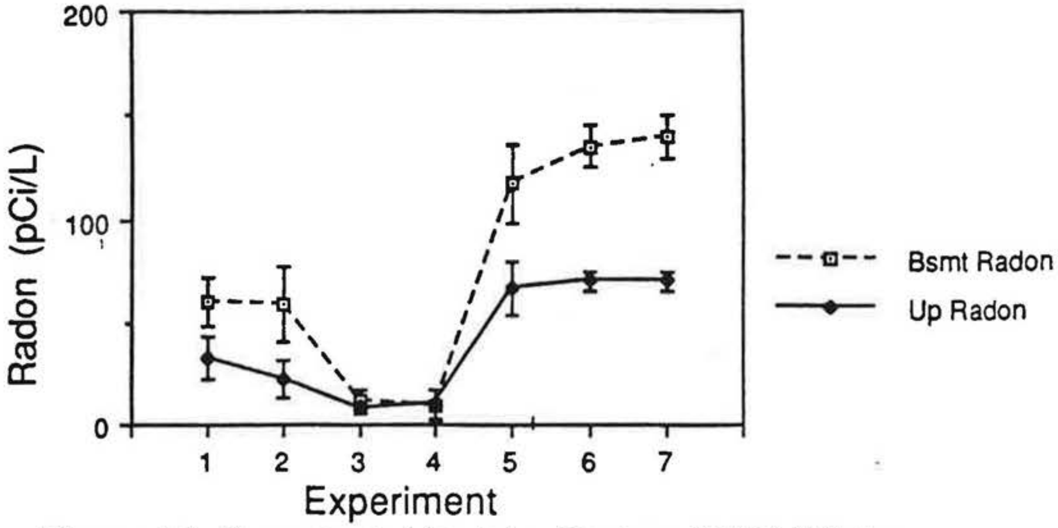

Figure 14. Basement, Upstairs Radon; PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3: East and West Open;
Experiment 2 :East Open;
Experiment 4: West Open

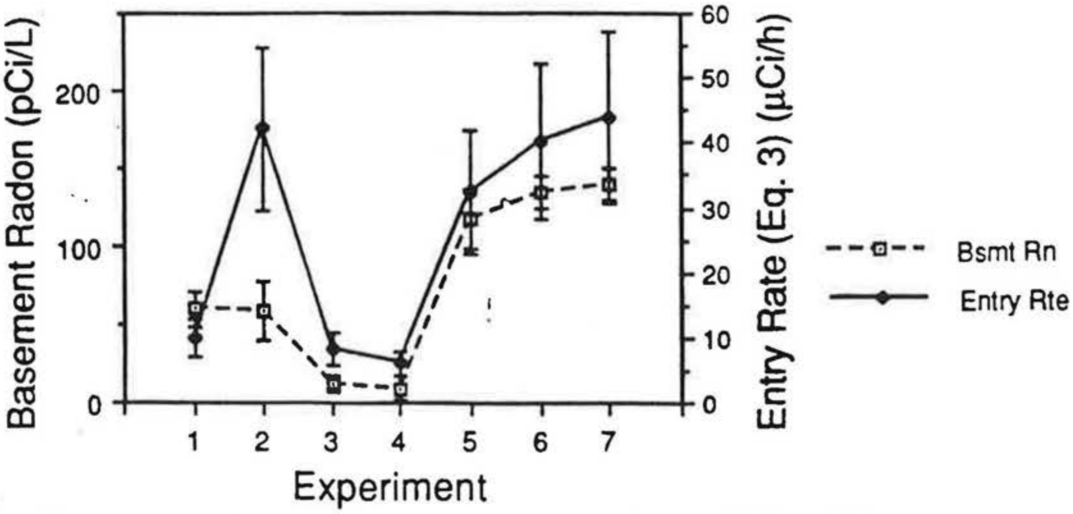

Figure 15. Basement Radon, Entry Rate PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3, East and West Open;
Experiment 2, East Open;
Experiment 4, West Open

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.

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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.

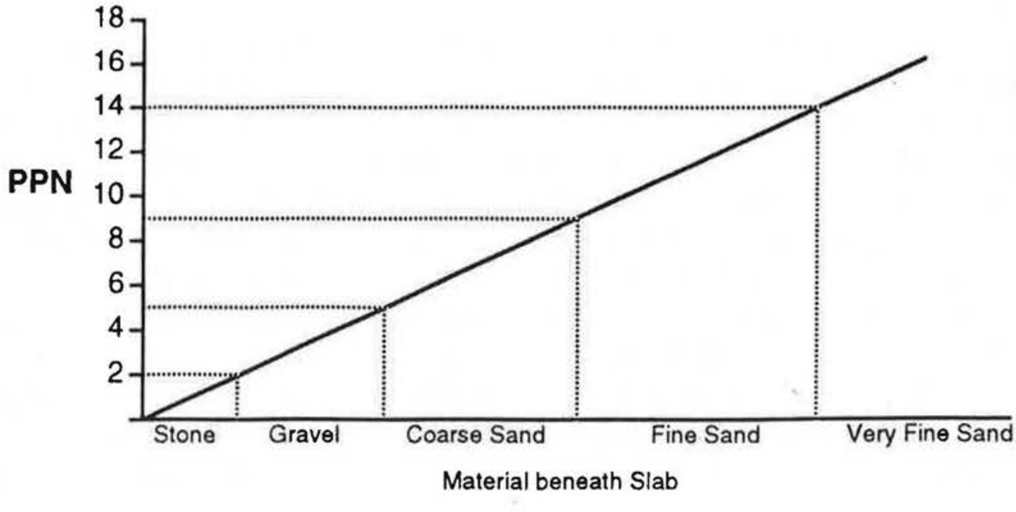


Figure 1. PPN soil classification of material beneath slabs (1)

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.

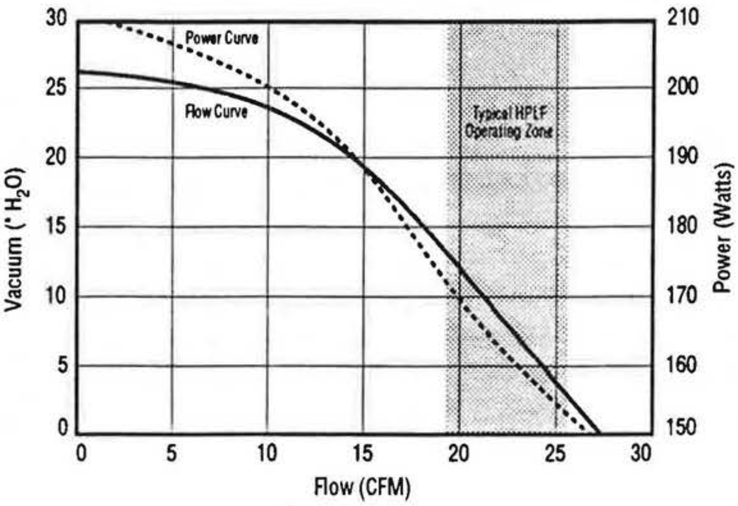


Figure 2. Air flow vs. vacuum pressure and power for S-3 blower

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. <u>Maximum static pressure</u>

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. <u>Electric power consumption</u>

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. <u>Noise</u>

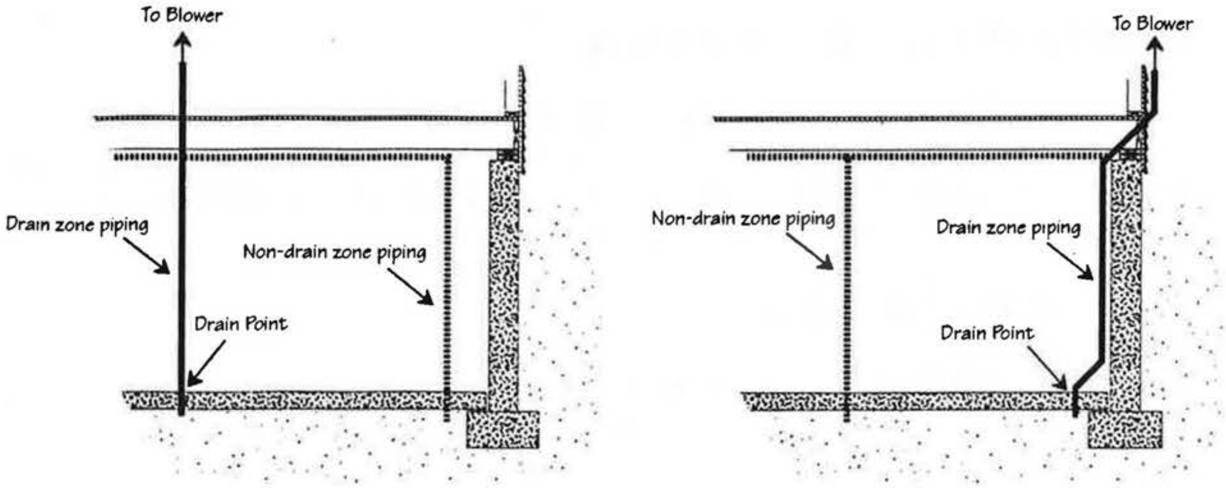
The blower housings are lined with industrial soundproofing. The blowers are often installed in attics and the soundproofing enables them to be located even directly over bedrooms. The 4 inch diameter Schedule 40 PVC pipe that discharges effluent from the blower to atmosphere above the roof line has 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. <u>Long service life</u>

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

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).

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.

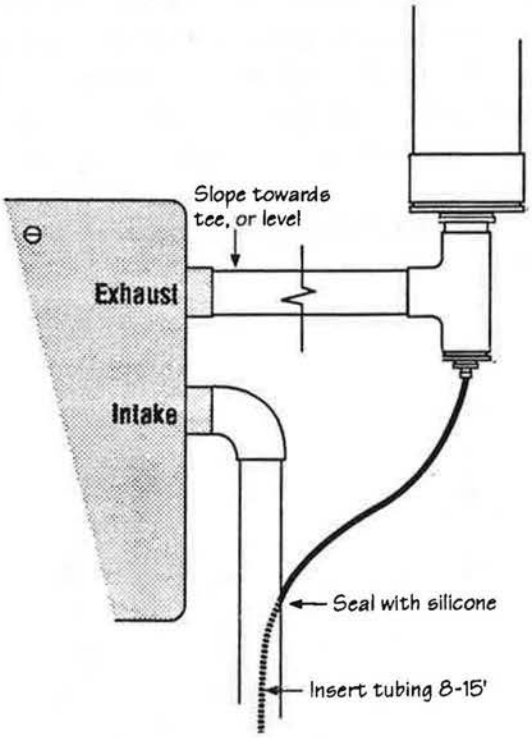


Figure 4. Condensate bypass arrangement in attics

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.

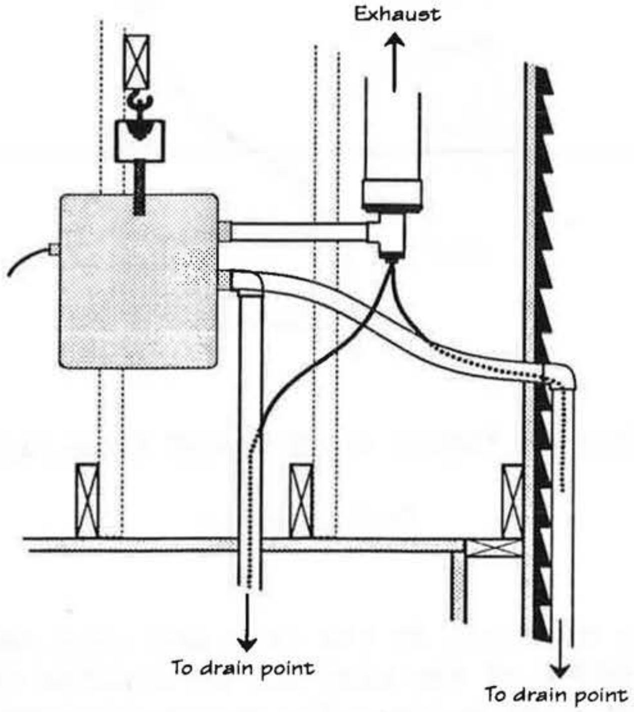


Figure 5. Typical Pelican HPLF attic installation.

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.

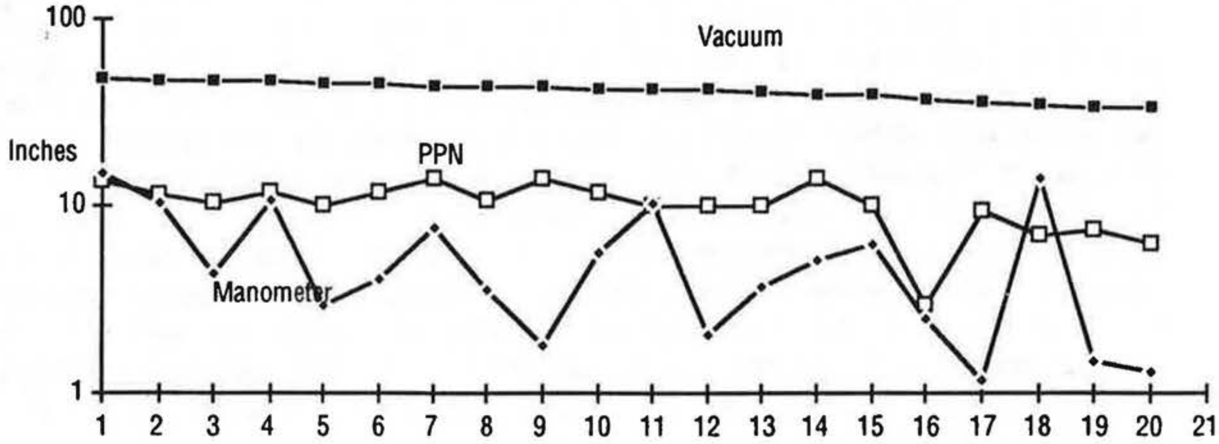


Figure 6. Diagnostic data and manometer readings for 20 HPLF installations.

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.

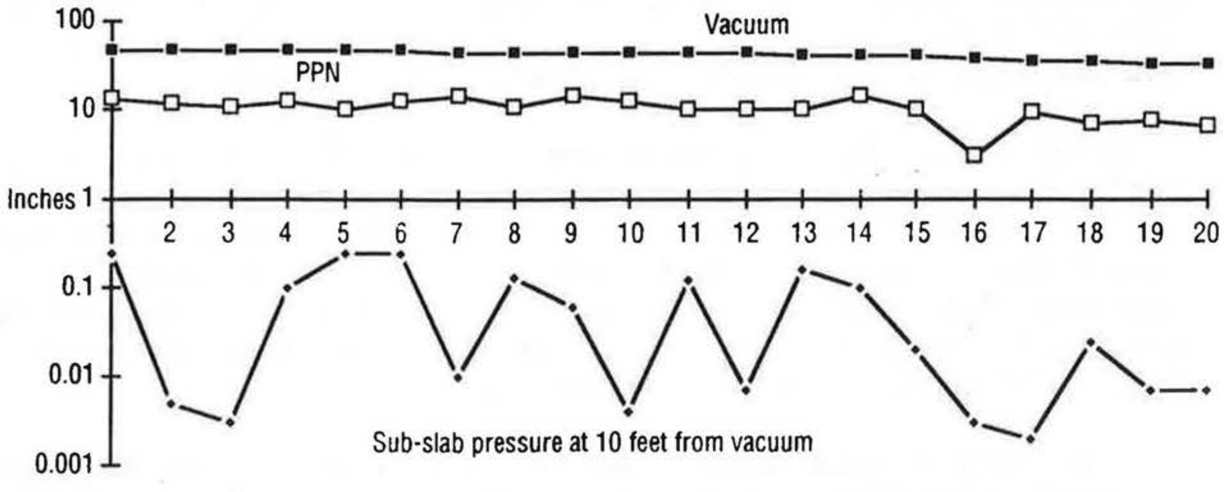


Figure 7. Diagnostic data and sub-slab pressure at 10 ft from applied vacuum for 20 HPLF installations.

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.

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A LABORATORY TEST OF THE EFFECTS VARIOUS RAIN CAPS ON SUB-SLAB DEPRESSURIZATION SYSTEMS

By: Mike Clarkin
Terry Brennan
David Fazikas
Camroden Associates, Inc.
R.D. #1 Box 222 East Carter Road
Oriskany, NY 13424

ABSTRACT

Many sub-slab depressurization systems are installed with some type of rain cap intended to keep rain water from entering the exhaust pipe. There is some question among researchers and radon mitigators whether a rain cap in necessary, and what effects a rain cap has on the sub-slab depressurization system. This paper makes no effort to explore the necessity of a rain cap, only the effect that certain rain caps have on the system. To help answer that question, a series of tests were performed to determine: 1. the additional resistance the caps place on a pipe, and, 2. the effect of wind on the system with the various rain caps installed. The results of those tests are presented in this paper.

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.

INTRODUCTION

Many radon mitigation contractors routinely install some type of cap on the end of a sub-slab depressurization system to prevent rain from entering the exhaust pipe. While the use of a rain cap may or may not be necessary, this paper takes neither side of the argument. The objectives of the tests described herein were to explore the effect that various types of hardware that are often used as rain caps have on sub-slab depressurization systems. To reach those objectives, a series of measurements were made to determine the backpressures the rain caps induced on the system. Additional tests were made to determine the draft generated by each rain cap on a passive sub-slab depressurization system.

TYPE OF CAPS TESTED

OPEN PIPE

The open pipe was a length of 4 inch, schedule 20, PVC plastic pipe.

CAP A

This cap is manufactured for the purpose of preventing rain from entering a sub-slab depressurization system. The cap consists of a PVC plastic collar which slips over the end of the exhaust pipe, a PVC plastic cover to keep rain out, and a PVC grill on each end to keep other objects out of the exhaust pipe.

Air, flowing vertically up the SSD exhaust pipe, strikes the cover, and is diverted horizontally through the grills. This cap is designed to slide over the end of the SSD exhaust pipe, therefore the area available for exhausting air is not reduced by the cap.

DRYER VENT CAP

This type of cap is manufactured for the purpose of capping a horizontal clothes dryer exhaust pipe. The cap is constructed of plastic and has movable louvers which remain normally closed until an airflow of sufficient volume and velocity opens the louvers. The cap is designed to fit on the inside of the 4 inch exhaust pipe, which decreases the exhaust pipe area from to 12.7 to 10.3 square inches. The louvers, depending on the degree of opening, causes a change in exhaust area that ranges from nearly nothing when closed, to approximately 9.7 square inches when fully open.

DRAFT INDUCER

The draft inducer tested was a 6 inch diameter stainless steel unit. The inducer was connected to the test system with a 6 in. to 4 in. rubber reducing fitting.

Draft inducers are designed to be placed on the end of a chimney to increase the amount of draft and assist in the proper exhaust of combustion gases. The draft inducer is designed to fit over the end of the exhaust pipe, therefore exhaust pipe area is not reduced. Air, flowing vertically up the SSD exhaust pipe, strikes the top of the inducer and is diverted horizontally. The draft inducer, when used in radon control systems, is usually used to provide additional suction in a passive SSD system, and is not normally installed for the purpose of keeping rain from entering the system.

TURBINE VENT

The turbine vent tested was a 4-inch diameter, galvanized steel unit. The turbine rotates on bearings with passing breezes, and creates an upward draft of air. The bearing assembly reduces the exhaust pipe area to approximately 10 square inches.

Turbine ventilators are designed for removing hot air from a building in summer and moisture-laden air in the winter. The turbine vent, when used in radon control systems, is usually used to provide additional suction in a passive SSD system, and is not normally installed for the purpose of keeping rain from entering the system.

Figure 1 illustrates each type cap tested.

Figure 2 illustrates the areas available for the exhausting of air for an open pipe, and each cap tested.

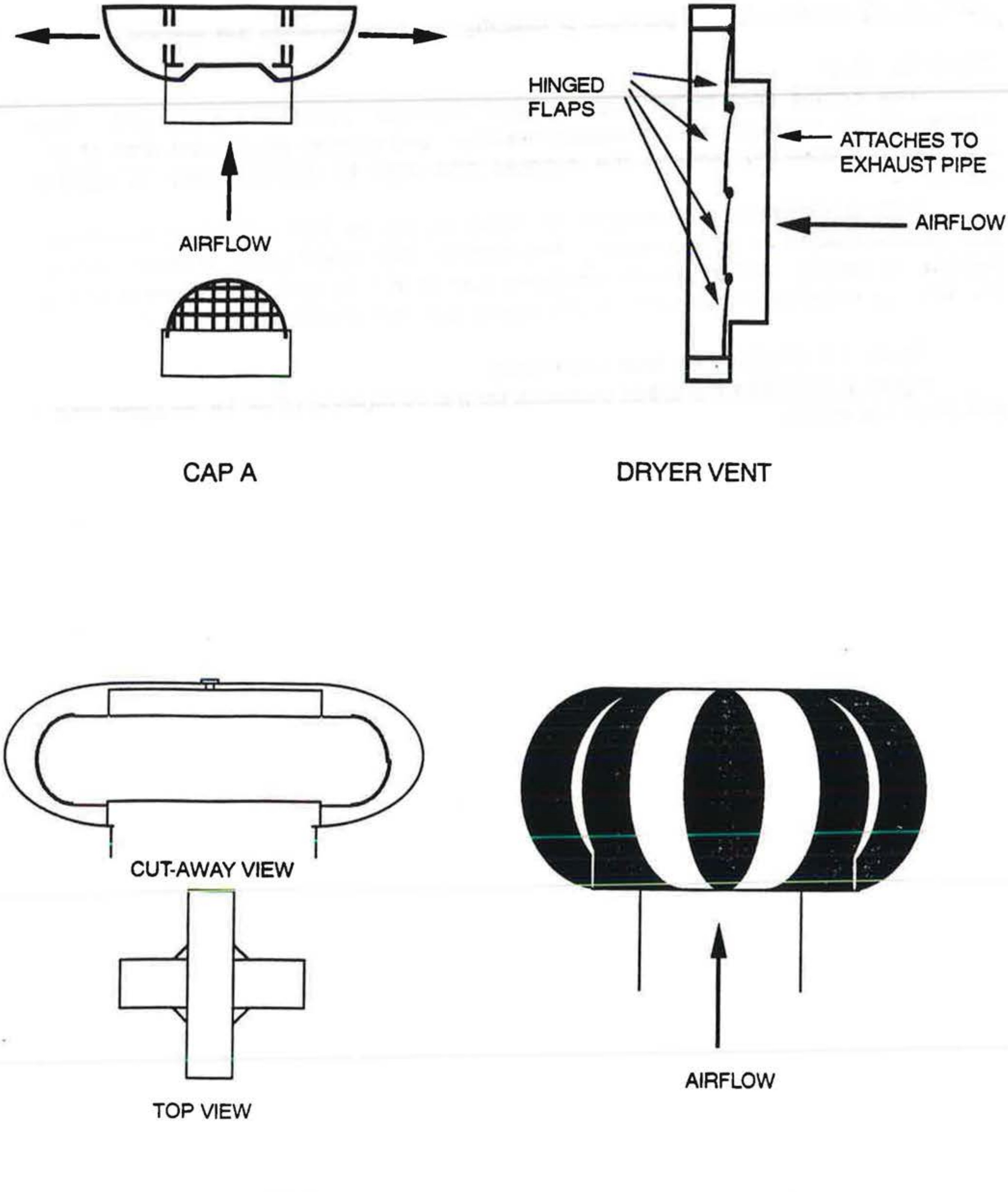

Figure 1. Types of caps tested.

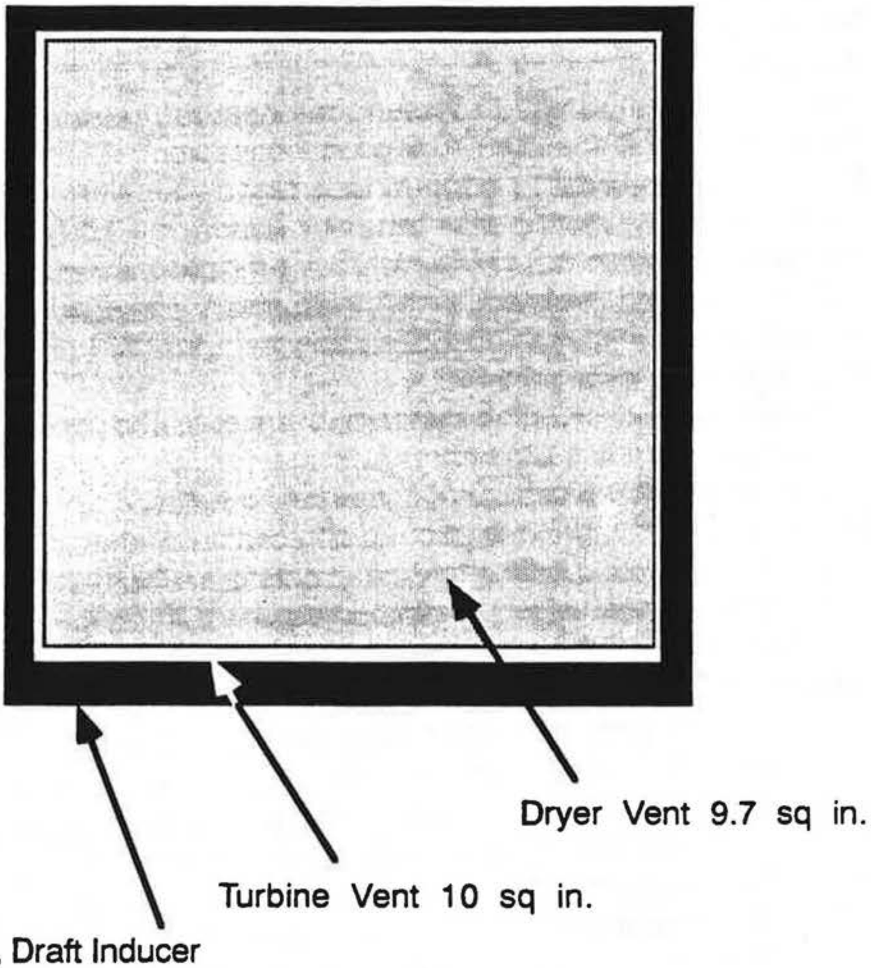

Figure 2. Relative exhaust areas. Drawings are approximately to scale.

TEST PROCEDURES

BACKPRESSURES CAPS PLACE ON THE PIPE

The objective of a sub-slab depressurization system is to create an air pressure field beneath the floor slab that is less than the air pressure in the building. This is commonly referred to as the "negative pressure". To maintain the negative pressure beneath the slab, the system must overcome conditions which tend to equalize the pressure differences between the sub-slab and the interior of the building. Air, exhausted from the house by temperature differences, wind effects, and the exhausting of inside air by ventilation fans all tend to create a low pressure in the house. Restrictions in the sub-slab depressurization system tend to create a high pressure in the system.

Techniques that can be used to lessen the negative pressures in the home are often out of the scope of the radon mitigation contractor. This is not to say the mitigation contractor is not able to perform those techniques. In fact, many mitigation contractors were insulating, weatherproofing, or performing HVAC work long before they got into the radon business. However, as a mitigation contractor, they are at a clients home to fix a radon problem. One of the primary methods is with a sub-slab depressurization system, therefore, the SSD designer normally is concerned with the sub-slab depressurization system only.

There are chiefly two issues of concern to the sub-slab depressurization system designer. The first concern is the amount of air that will flow through the system. The second is the amount of backpressure that is resisting the flow of air.

As air flows through the exhaust pipe, obstructions, changes in airflow direction (elbows), and even air friction inside the pipe create a resistance to the flow of air. This resistance in turn creates a backpressure in the pipe. An increase in backpressure can decrease the strength of the negative pressure field beneath the slab, to a point where the negative pressure field no longer exists, or is not sufficiently strong or extensive enough to prevent radon from entering the building.

To determine the effect that different rain caps had on the airflow and backpressures, the cap under test was placed on the end of a length of 4 inch PVC pipe. Airflow through the pipe was produced by an in-line fan. A micromanometer was used to measure the pressure differentials between the inside and outside of the exhaust pipe. The micromanometer and flow grid was used to measure the pitot pressure in the pipe from which the volume of air flowing through the pipe was determined. A variac was used to change the speed of the fan to provide several data points at different airflows and pressure differences. Figure 3 illustrates the equipment configuration for this test.

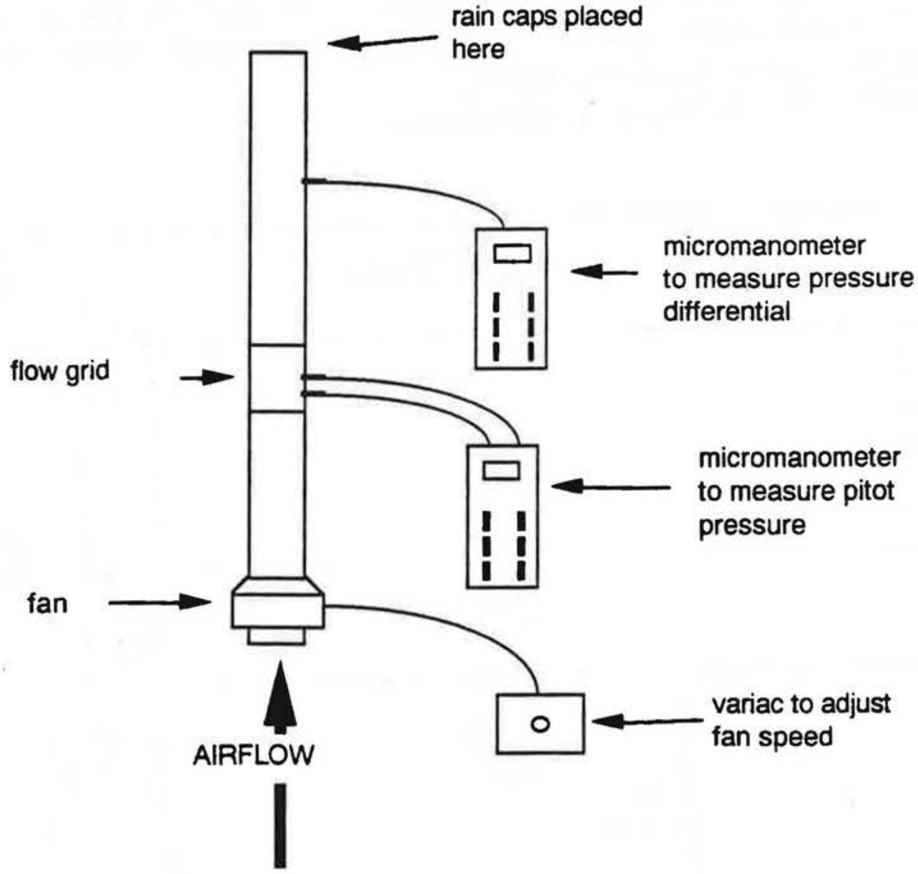

Figure 3. Equipment layout for system backpressure tests.

INDUCED DRAFT TESTS

Passive sub-slab depressurization systems rely on means other than an electrically powered fan to develop the desired negative pressure field beneath the floor slab. Natural forces, such as the stack and wind effects, if the conditions are correct, can produce an upward movement of air within a sub-slab depressurization system. The negative pressure field can be rather weak in a passive system, therefore rain caps that increase the backpressures may have a serious detrimental effect on a passive system. Conversely, a cap that is designed to induce airflow may have a positive effect on the system.

To determine the draft that the cap induced on a passive sub-slab depressurization system, pressure differences between the interior of the pipe and the outside air were measured at various wind speeds. A wind tunnel was constructed to direct the flow or air across the cap. The cap to be tested was placed on a length of 4 in. PVC pipe within the wind tunnel. A large blower door fan was used to draw air from the open end of the tunnel and across the cap. A vaned anemometer was used to measure the windspeed at different locations within the tunnel, and the average windspeed was calculated. The pressures induced in the pipe by the wind were measured with a micromanometer. Curves representing pressure differences at those windspeeds were generated for each cap tested.

Figure 4 illustrates the equipment configuration.

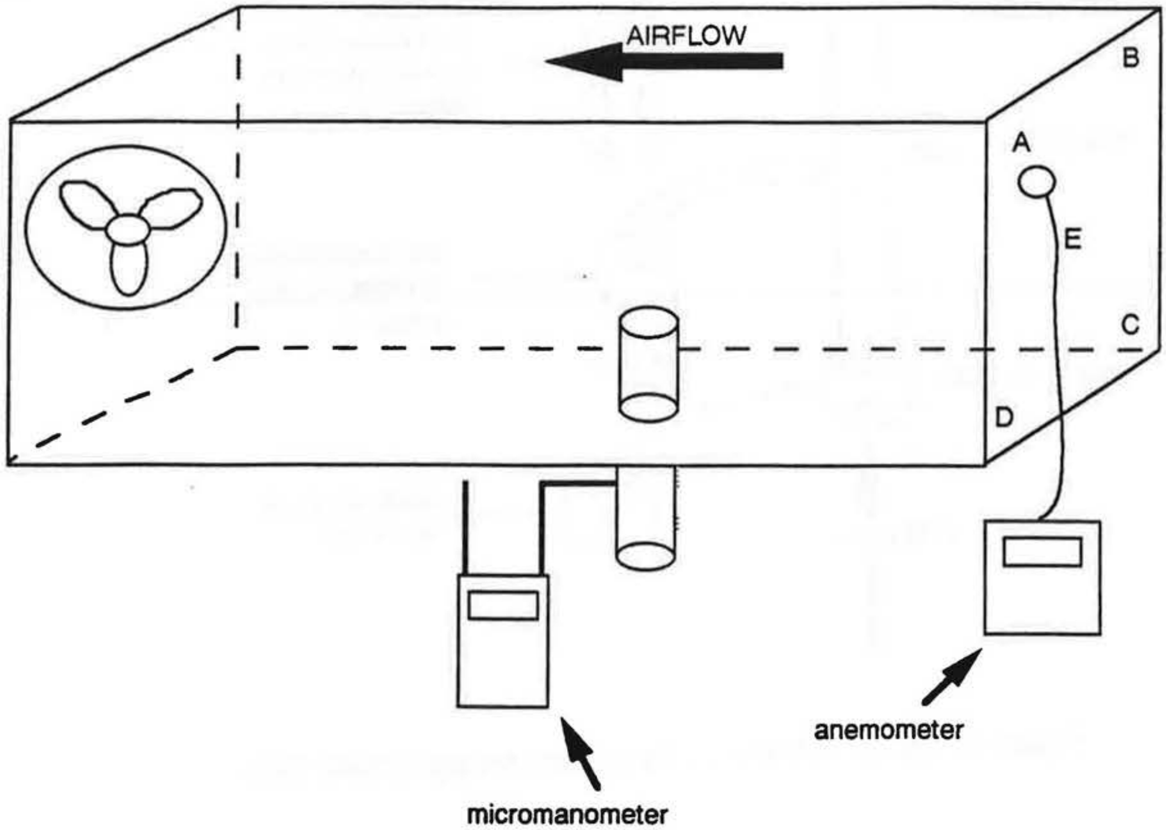

Figure 4. Equipment layout for induced draft tests.

RESULTS

BACKPRESSURE TESTS

As illustrated on Figure 5, all caps tested developed an additional resistance within the exhaust pipe when compared to an open ended pipe. The best performer was the draft inducer, which resulted in the least amount of backpressure across the entire operating range of the fan. The worst performer was the dryer vent. Note that the curve for the dryer vent is inverted when compared to the other caps tested and the open ended pipe. The inversion is due to the vanes on the vent cap opening wider at the higher airflows. All caps resulted in a backpressure that could cause a marginally operating sub-slab depressurization system to fail to reduce indoor radon concentrations.

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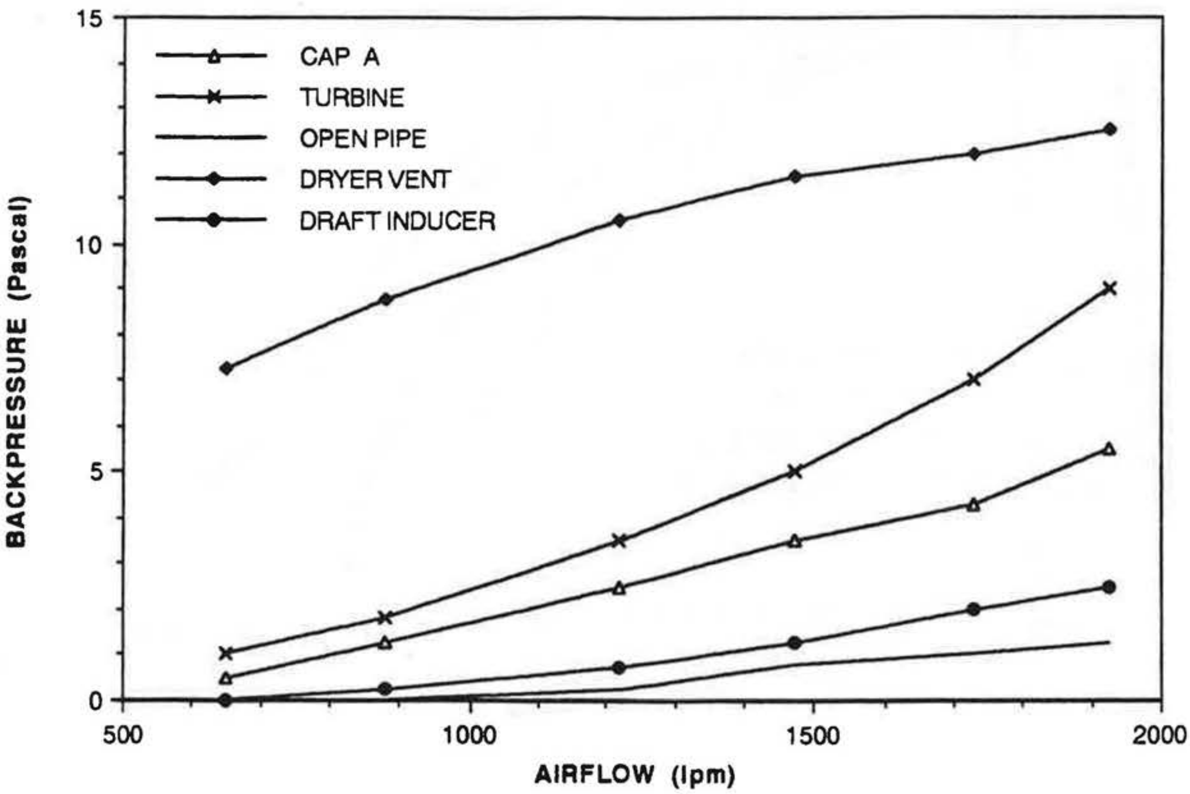


Figure 5. Backpressure in pipe due to caps.

INDUCED DRAFT TESTS

All caps, and the open ended pipe, produced a negative pressure in the pipe when air was flowing across the cap, however, Cap A, which produced a fairly strong negative pressure within the pipe when the airflow was perpendicular to the cap, produced a backpressure in the pipe when the open end of the cap was parallel to the airflow. Perhaps a modification to Cap A, which moved the cap so that the open end was always parallel to the wind would improve the overall performance of this cap. The best performer, when all windspeeds are considered, was the turbine ventilator, which produced a negative pressure in the pipe that ranged from -3 pascals at 11 kph (-0.01 in. at 6.5 mph) to -31 pascals at 27 kph (-0.12 in. WC at 17 mph). Figure 6 shows the results of the tests performed.

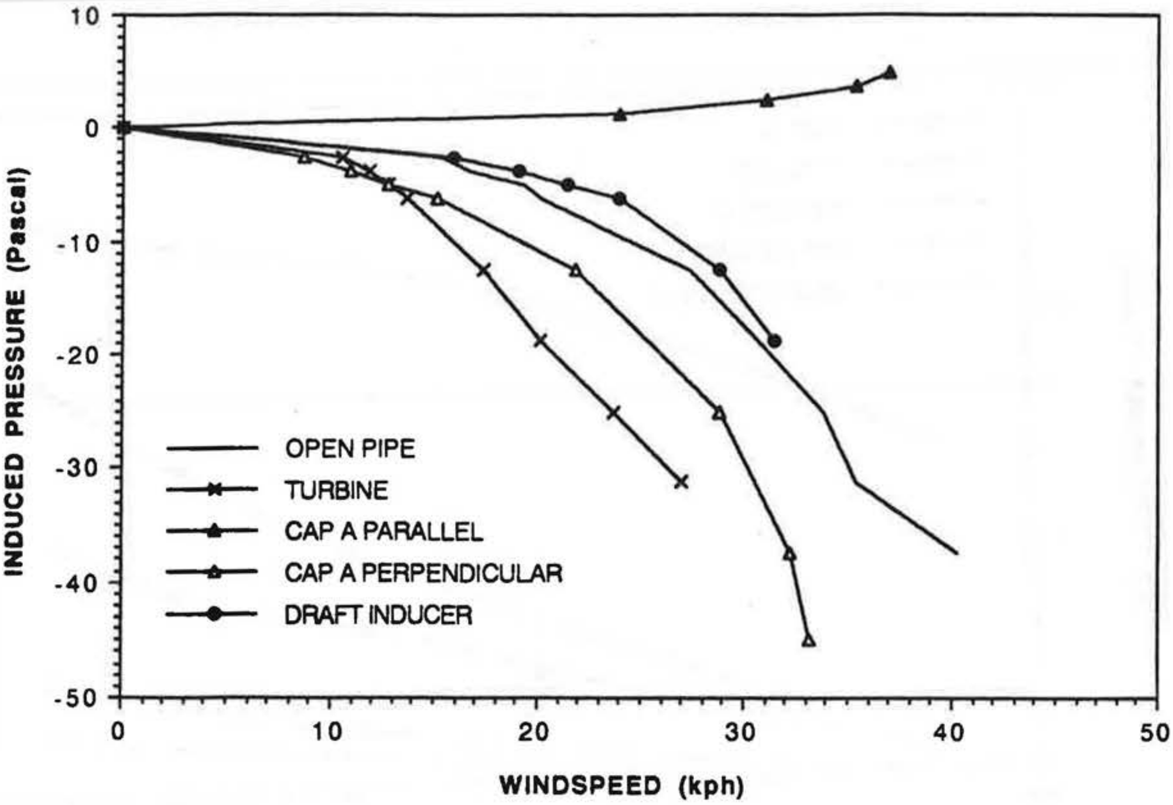


Figure 6. Induced pressure results.

CONCLUSIONS

Caps, when placed on the end of a sub-slab depressurization system can increase the amount of backpressure in the system. In order of increased backpressures, the open pipe results in the least backpressure, followed by the draft inducer, Cap A, the turbine vent, and finally, with the greatest amount of backpressure, the dryer vent. This comes as no great surprise. If we had considered the open exhaust area of each cap with regard to a resistance to airflow, and the diversion of the flow of air from the vertical to the horizontal as another resistance to airflow, we probably could have predicted quite accurately how each cap would rank. However, that would have resulted in a very short paper. The test results indicate that backpressures created by the caps amount to 10 to 12 pascals at most, and, are more likely to be 2 to 5 pascals at the airflows encountered in most SSD installations. This is not a significant backpressure when the air pressure induced under a slab is 50 to 200 pascals. However, when the pressure under the slab is only 5 to 10 pascals, as it may be in a passive SSD, or on very permeable soils, or in spots where there is fine sand or clays under the slab, the backpressure from the caps becomes significant. The best recommendation is when considering whether to use a cap is to measure the sub-slab pressures with the pipe uncapped, and with the cap temporarily installed. If the cap seems to make a significant difference in the sub-slab pressure, don't use it.

A substantial draft can be induced on a passive sub-slab depressurization system when wind blows across the end of the exhaust pipe. Of all the caps tested, the turbine ventilator created the strongest draft at high windspeeds. The worst performer was the dryer vent. Notice that there is very little difference between open pipe and other caps until a wind speed of greater than 12 kph is reached. This makes caps most useful in windy sites, but it must be understood that windspeeds are extremely variable, and the prudent mitigation contractor should not count on the wind to be of much help.

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.

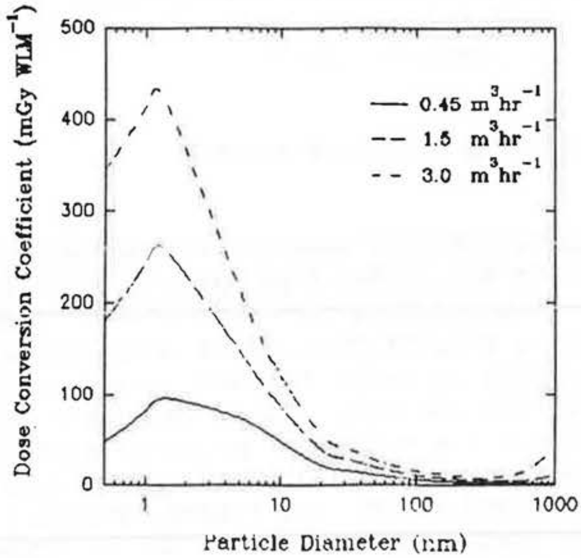


Figure 1. Dose to bronchial secretory cells as a function of the size of radon decay products for an adult male (6)

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:

$$\frac{D_s}{E_p} = \sum_{i=1}^{i=n} f_i D_{si} \quad (1)$$

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.

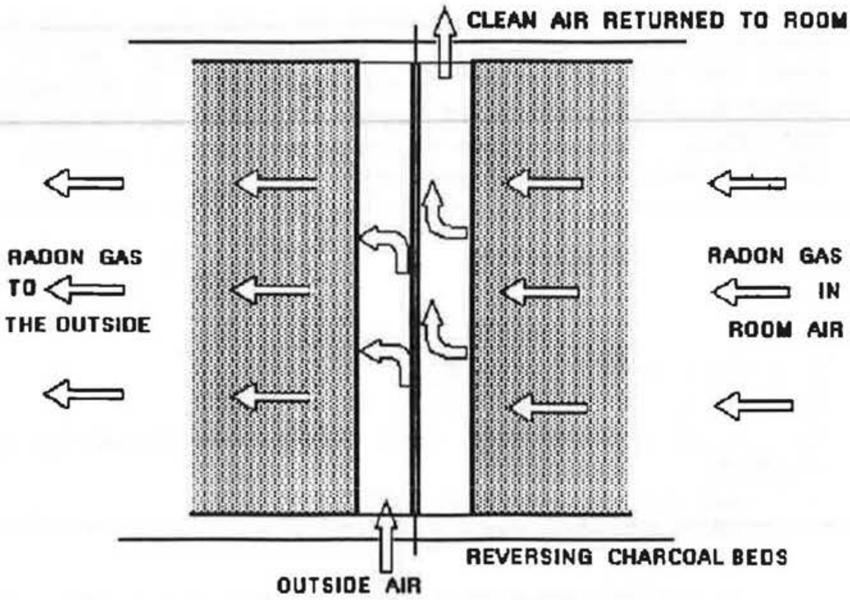


Figure 2. Schematic diagram of the RAdsorb system

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.

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.

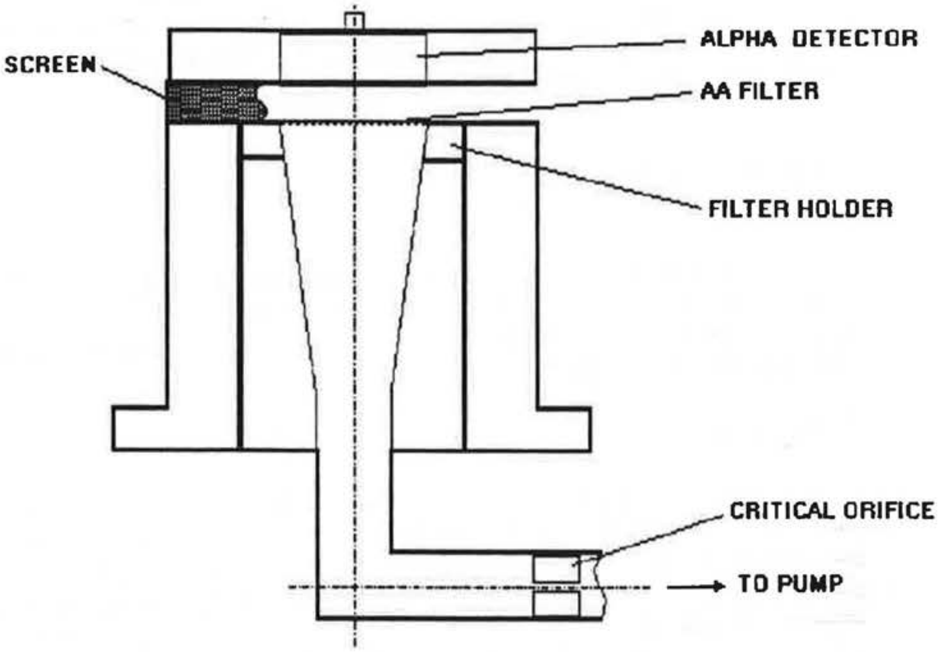


Figure 3. The cross-section of the sampler unit

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.

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}.

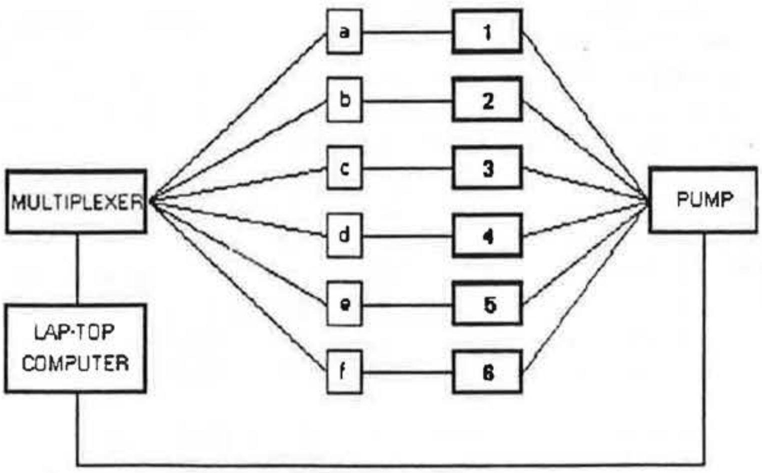
Particle Concentration

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.

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.



1,2,3,4,5,6 - SAMPLERS
a,b,c,d,e,f - AMPLIFIERS

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

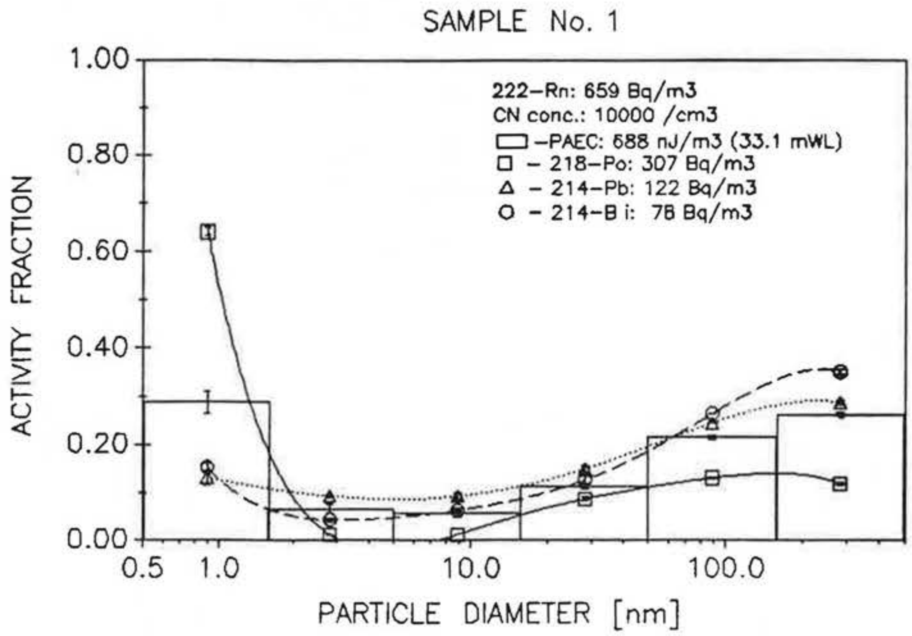
^{222}Rn [Bq m^{-3}]	PAEC [mWL]	0.5-1.58 nm PAEC fraction	Secretory Cell Dose [mGy y^{-1}]
630	30.8	0.428	55.8

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



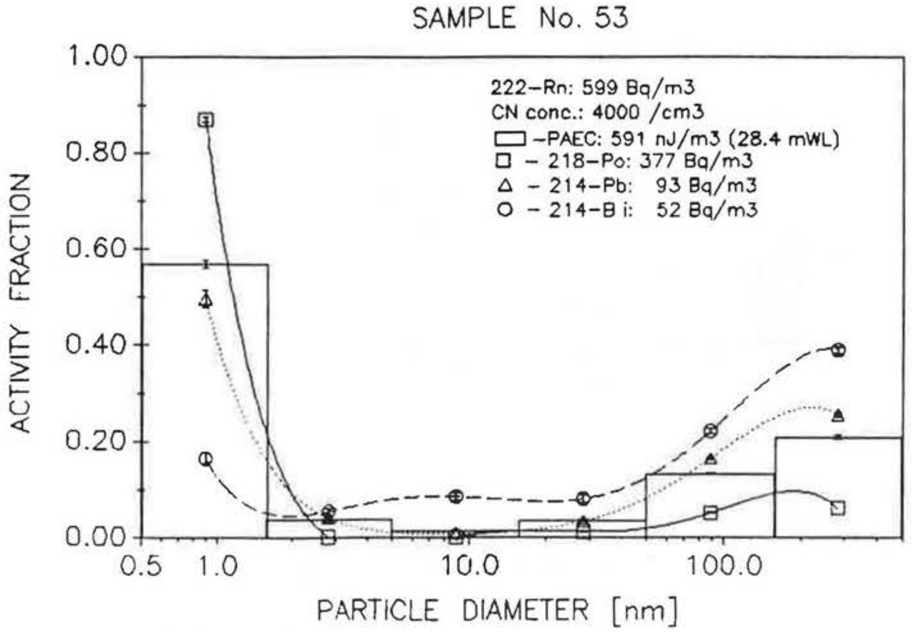


Figure 5. Typical activity size distributions in "background" conditions (no mitigation devices in operation)in the Shrewsbury house.

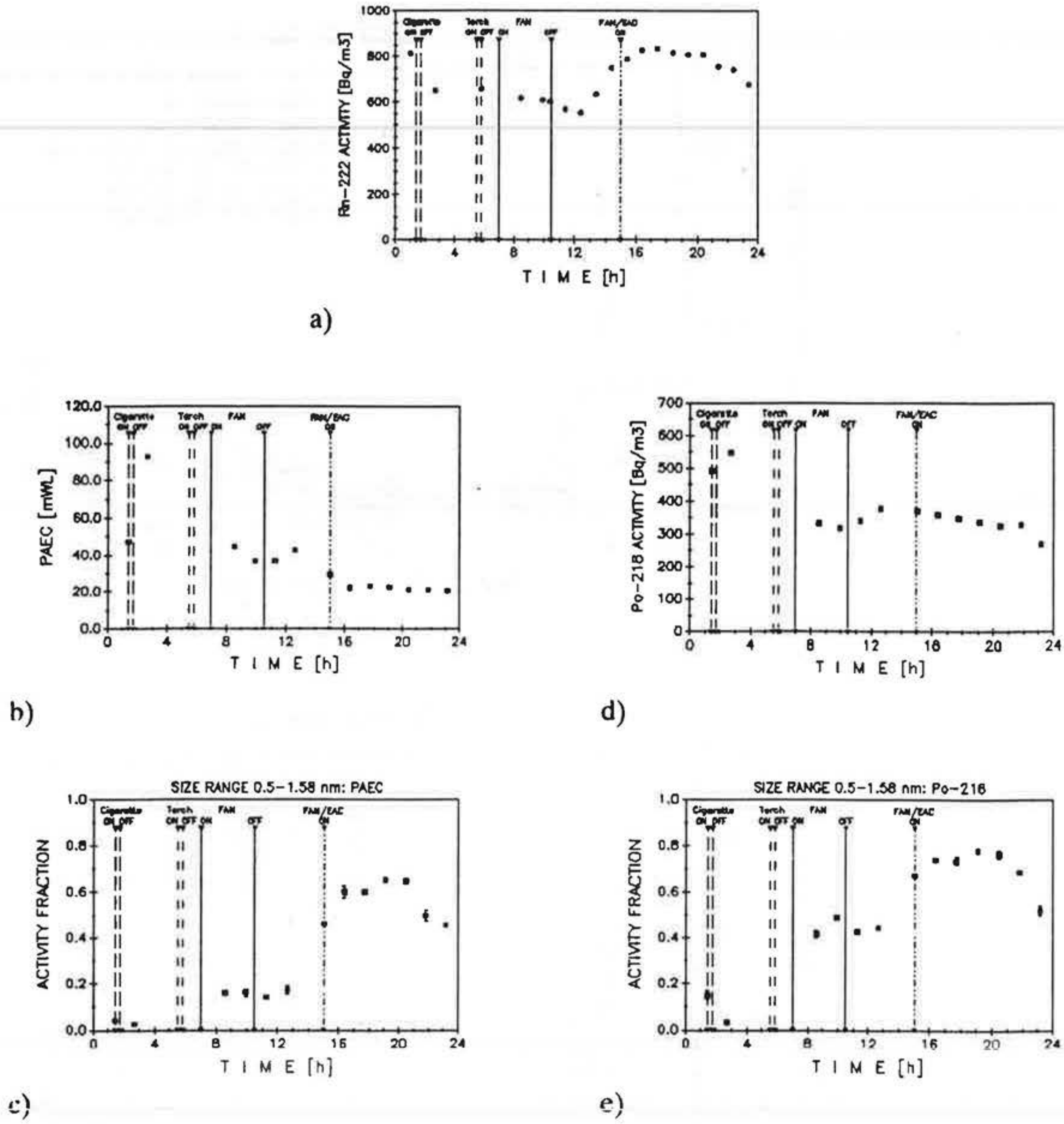


Figure 6. The influence of a fan and electronic air cleaner (EAC) on indoor radon and its decay products:
a) ^{222}Rn concentration,
b) potential alpha energy concentration (PAEC),
c) activity fraction of PAEC in the size range 0.5-1.58 nm,
d) ^{218}Po concentration,
e) activity fraction of ^{218}Po in the size range 0.5-1.58 nm

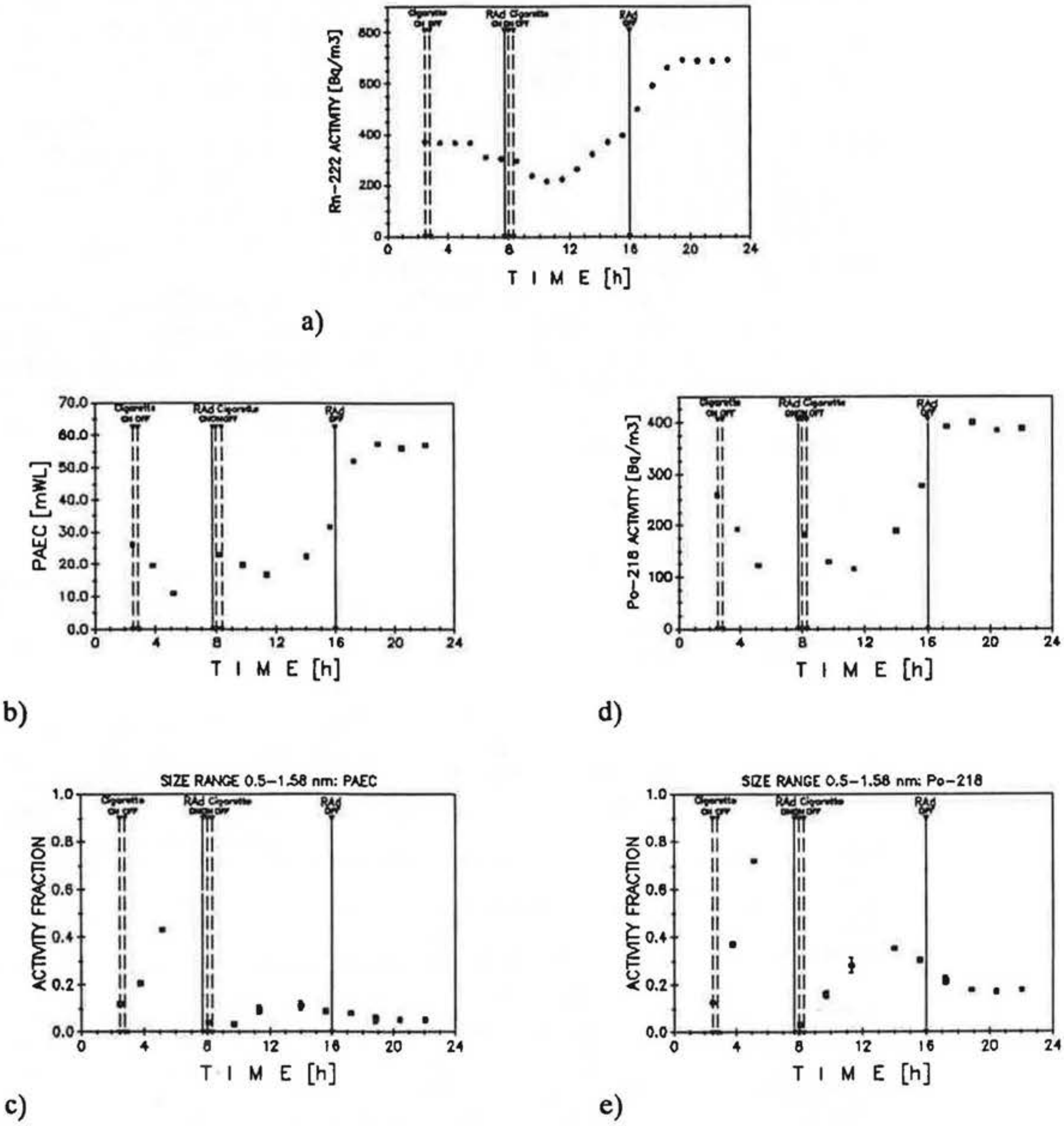


Figure 7. The influence of the RAdsorb system on indoor radon and its decay products:

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

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.

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:

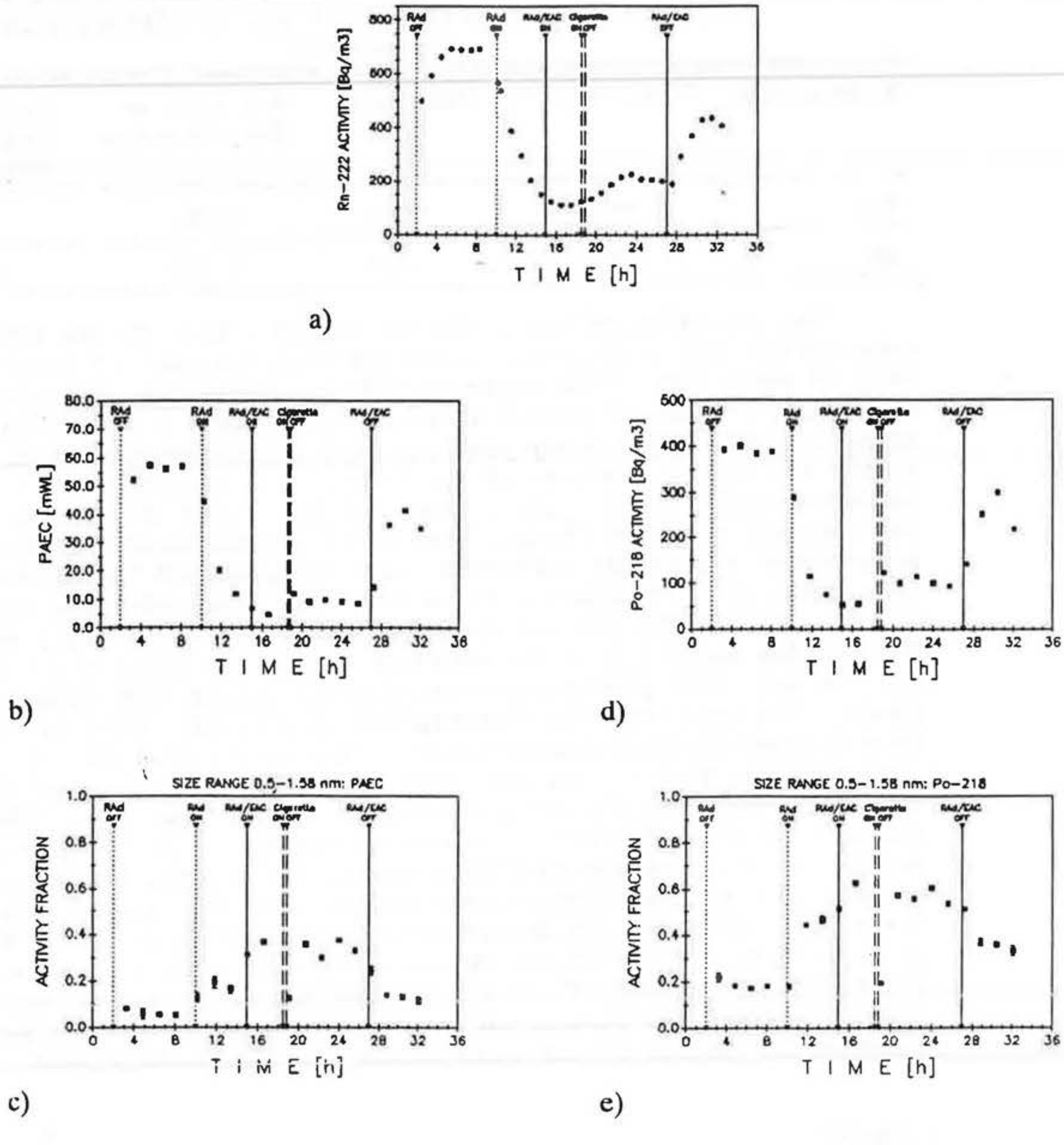


Figure 8. The performance of the RAdsorb system (RAd) alone and combined with a electronic air cleaner (EAC):
a) ^{222}Rn concentration,
b) potential alpha energy concentration (PAEC),
c) activity fraction of PAEC in the size range 0.5-1.58 nm,
d) ^{218}Po concentration,
e) activity fraction of ^{218}Po in the size range 0.5-1.58 nm

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.

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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 depressurizing the tank room with the fan. This can readily be done by extending a small line through the ceiling into the attic. The suction line from the tank top should extend to a fan located in the attic. This description is for a single tank and would be duplicated for the other tanks with two or more tanks connected to one fan.

Option (1) did not have to be tested: vacuum stripping is an established but costly process operation. NFH personnel located and installed an unused vacuum stripper already owned by the Fish and Wildlife Service. This system is currently providing removal of the radon before it enters the building. Follow-up tests have not been completed.

Continuous radon measurements made one night without any radon mitigation system operating suggested the possibility of a radon problem associated with soil gas infiltration. A Pylon AB-5 continuous monitor fitted with a diffusion cell was placed in operation in the locked fish tank room at 6 PM on 5/3/90, and 30 minute readings were taken until 8:00 AM on 5/4/90 when the fish tank room was unlocked. Results are plotted in Figure 4. Radon levels peaked at 3:00 AM and then fell dramatically by 8:00 AM. This type of "diurnal effect" is commonly observed in buildings with a radon problem from soil gas infiltration, but the peak is usually around 6:00 AM. However, it could also have been caused by increased air turnover ratio (diluting the levels) caused by a stack effect if the outdoor temperature dropped below room temperature during the night (which probably happened). The stack effect would have been exaggerated by the 4 by 4 ft ceiling section removed for this test. The air could easily have been drawn in through the untrapped drain from the sump trench. A weather front passing through during the night could also have affected the outdoor air infiltration rate.

CONCLUSIONS

Since the end of this testing program, at least one other NFH has reported high radon levels in a similar tank building. From these experiences in NFHs, other indoor water treatment facilities using stripping/aeration towers should be concerned about possible elevated radon levels. Such radon emissions have been mitigated easily and inexpensively.

METRIC EQUIVALENTS

Readers more familiar with metric units may use the following to convert to that system:

Non-Metric	Times	Yields Metric
cfm	0.00047	m^3/s
ft	0.30	m
gal./day	0.000000044	m^3/s
gpm	0.000063	m^3/s
in.	0.025	m
in. WC	249	Pa

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.

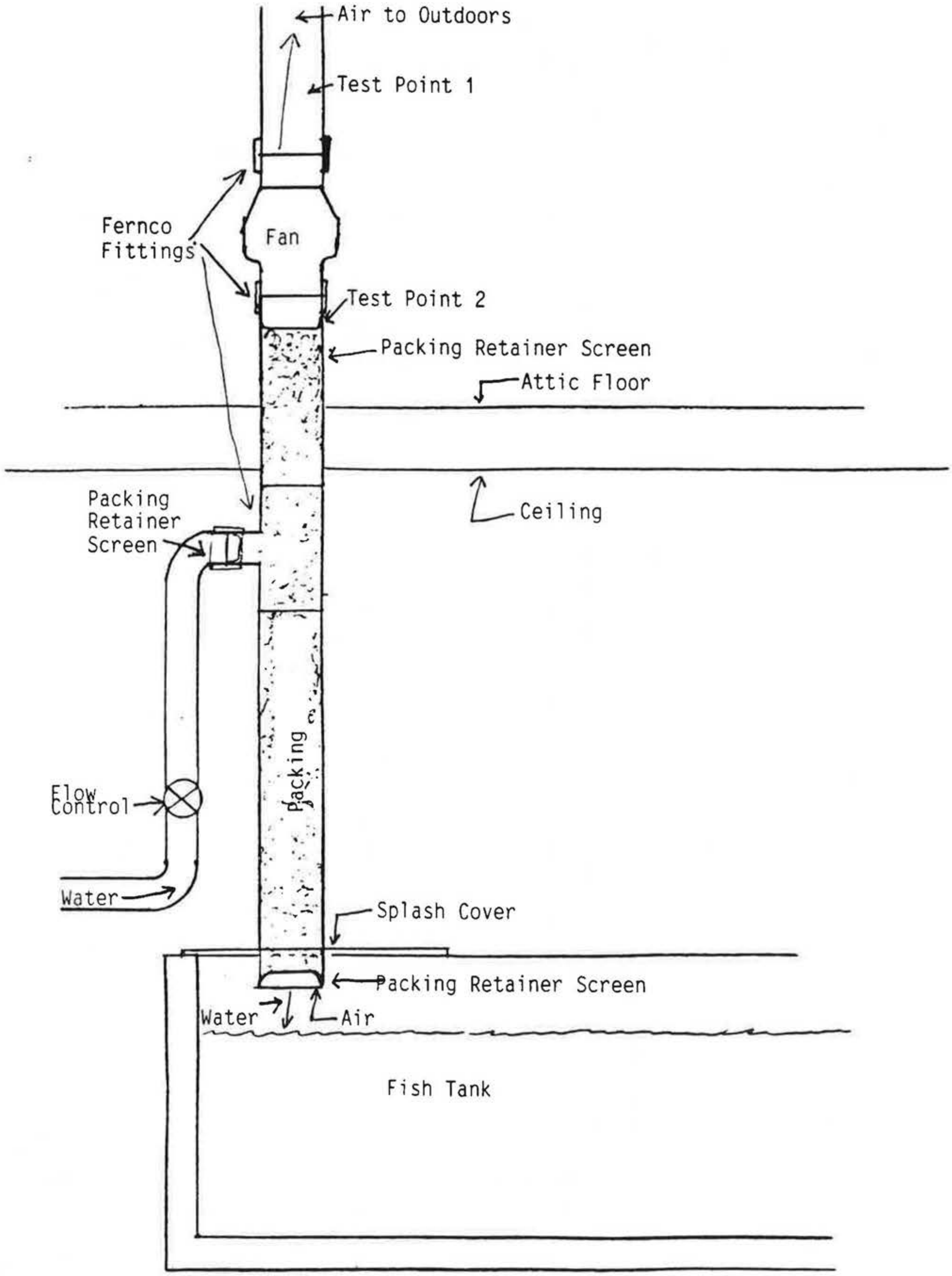

FIGURE 1. MODIFIED STRIPPING/AERATION COLUMN

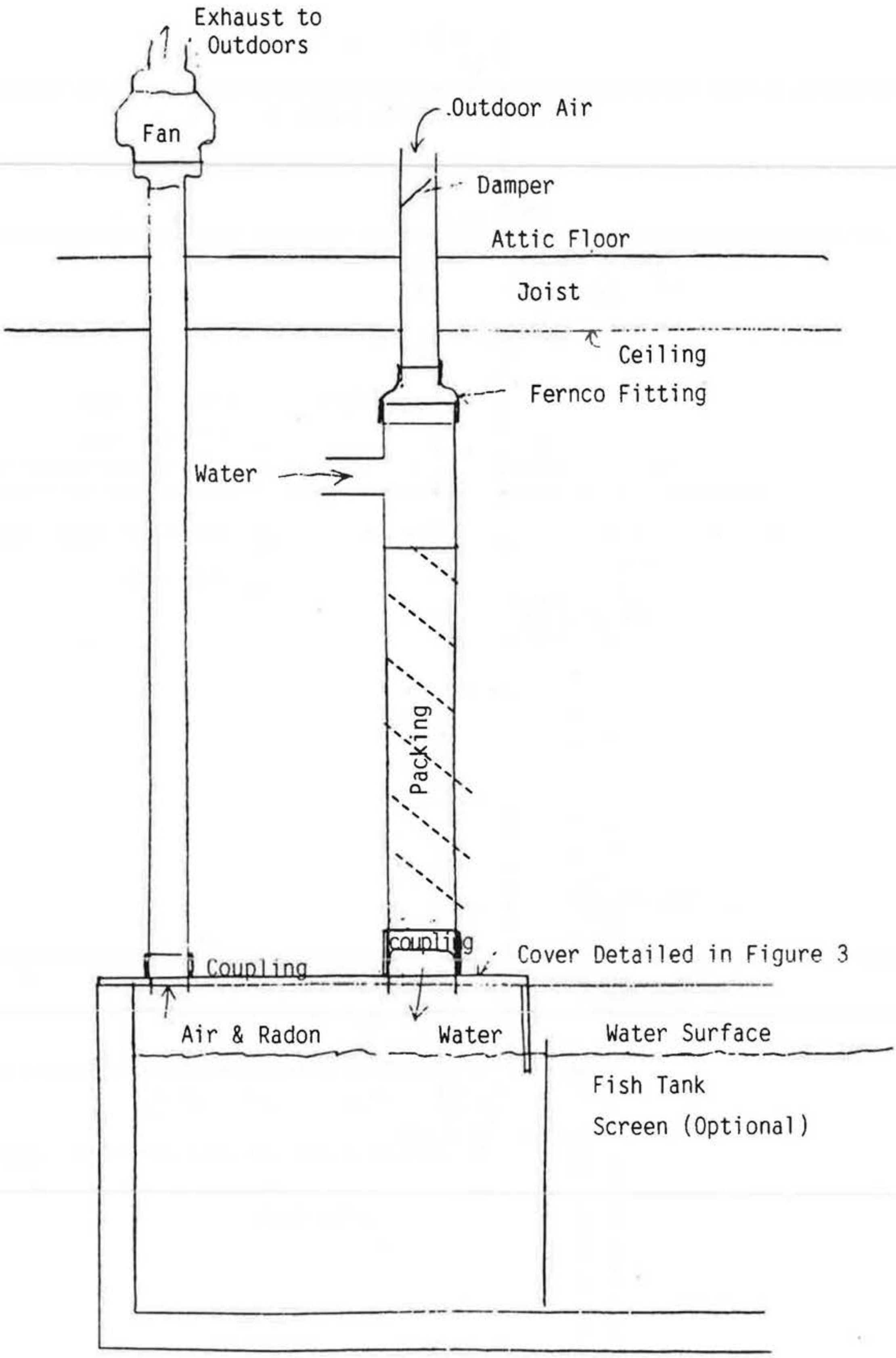

FIGURE 2. TANK RADON MITIGATION SYSTEM

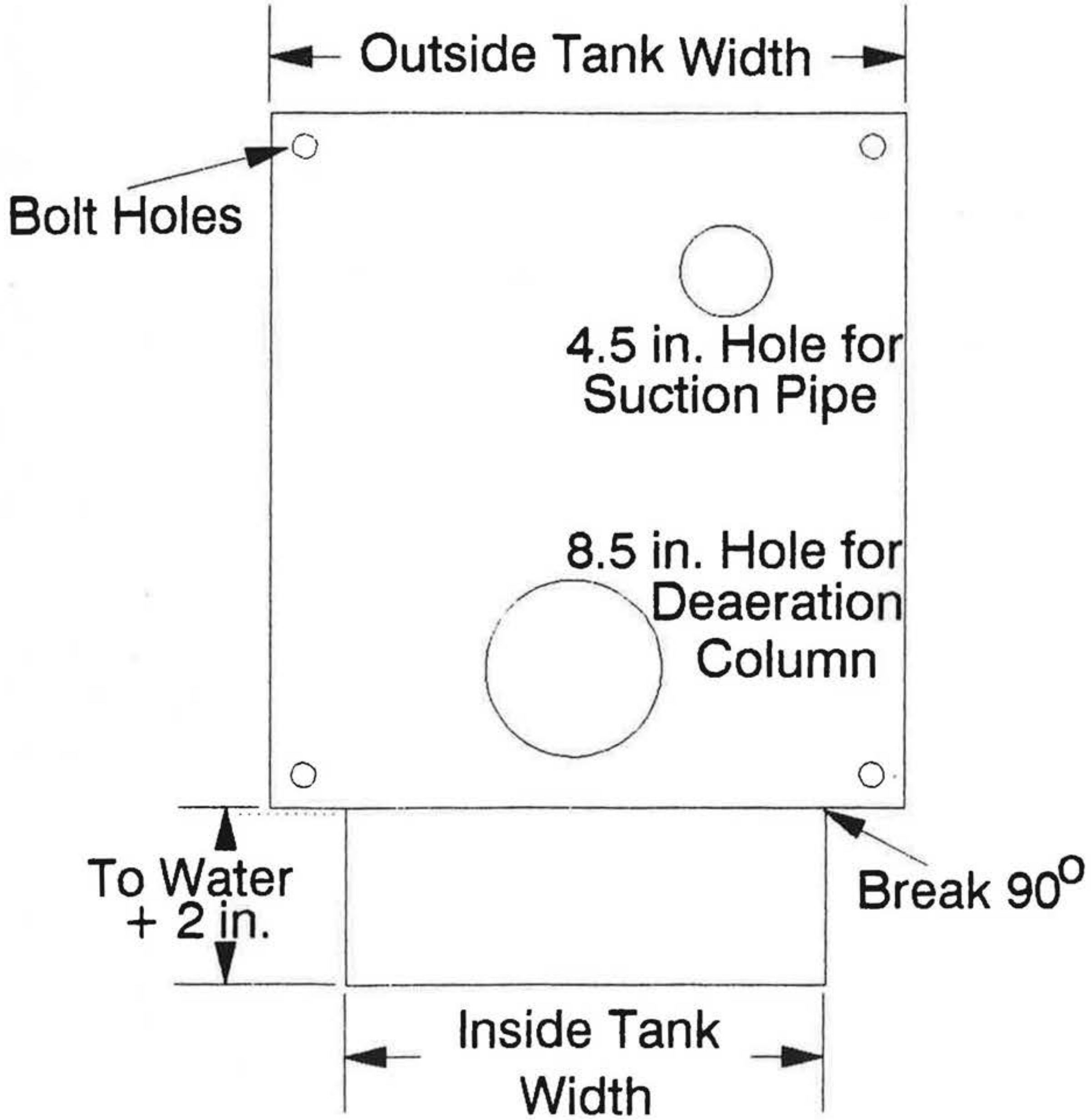

Figure 3. HOOD/TANK COVER

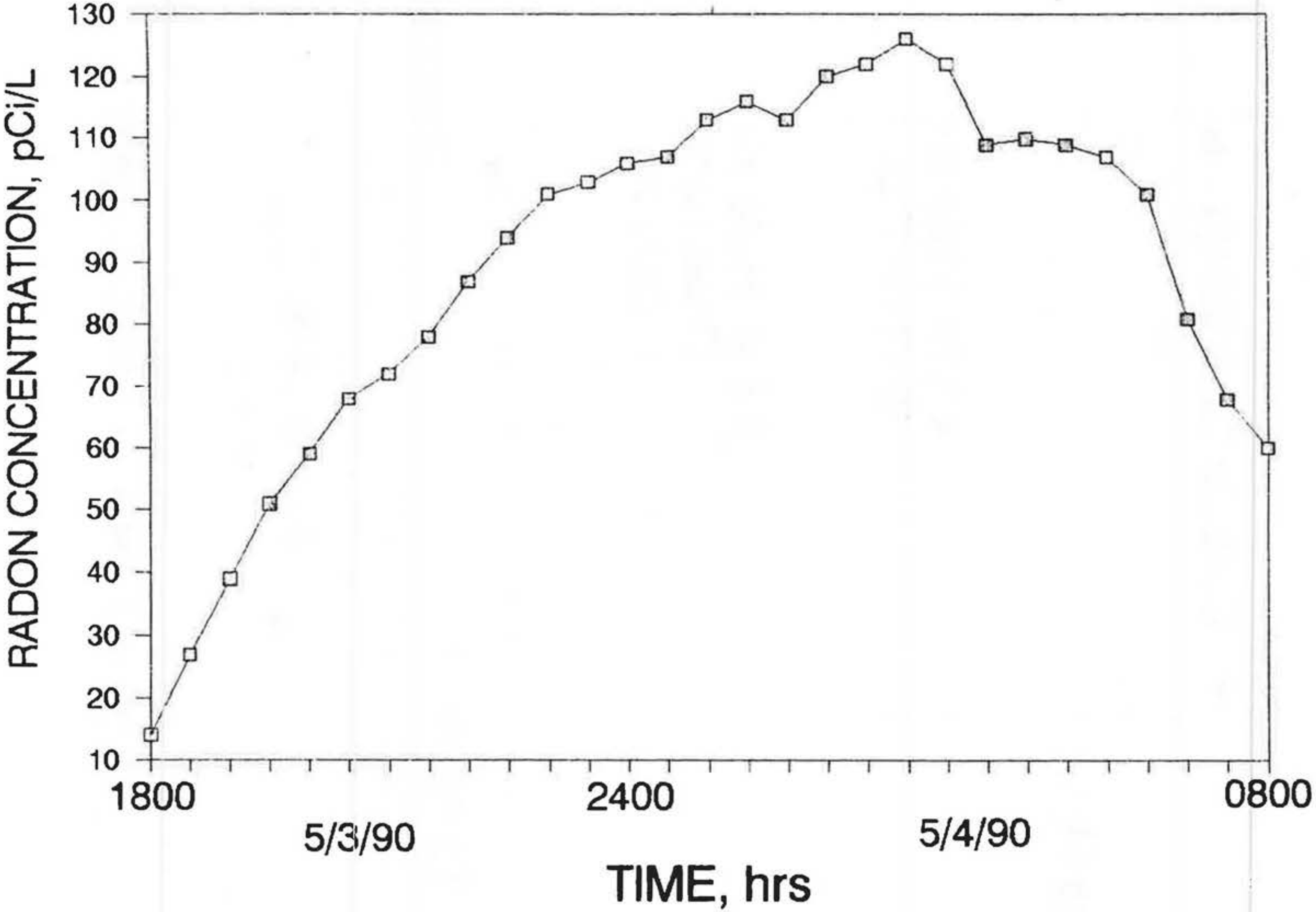

Figure 4. **NEOSHO NFH RADON CONCENTRATIONS**

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