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Session IX: Radon Occurrence in the Natural Environment

Session X: Radon in Schools and Large Buildings

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

The 1991 International Symposium on Radon and Radon Reduction Technology

"A New Decade of Progress"

April 2-5, 1991
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Philadelphia, Pennsylvania

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Opening Session

Opening Remarks . . . . Symposium Co-Chairpersons

Introduction. . . . . Charles M. Hardin, CRCPD, Inc.

Welcome. . . . . .Edwin B. Erickson,
EPA Region III Administrator

An Overview of the NAS Report on Radon Dosimetry . . . . .Jonathan Samet
New Mexico Tumor Registry

The 1991 International Symposium on Radon and Radon Reduction Technology

Table of Contents

Session I: Government Programs and Policies Relating to Radon

Session I Posters

Session II: Radon-Related Health Studies

Session II Panel: Risk Communication

Session II Posters

Session III: Measurement Methods

Session III Panel: Detection of Radon Measurement Tampering

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

Session III Posters

Session IV: Radon Reduction Methods

Section IV Posters

Session V Posters

Session VI: Radon Surveys

Session VI Posters

Session VII: State Programs and Policies Relating to Radon

Session VII Posters

Session VIII: Radon Prevention in New Construction

Session VIII Posters

Session X Posters

Session IX:

Radon Occurrence in the Natural Environment

COMBINING MITIGATION & GEOLOGY: INDOOR RADON REDUCTION BY ACCESSING THE SOURCE

by: Stephen T. Hall
Radon Control Professionals, Inc.
Reston, Virginia 22094

ABSTRACT

Soil radon testing has shown that radon sources are concentrated in narrow linear areas congruent with local geology in the Eastern Piedmont, which should also hold true in any folded mountain belt region with heterogenous geology.

In existing buildings, if micromanometer tests indicate poor communication in the sub-slab environment, soil radon concentration gradients can be mapped with instantaneous sub-slab radon measurements. By then orienting these difficult-to-mitigate homes on a geologic map, we have been able to predict the location of the radon source adjacent to foundation walls. Tapping these source areas with a multi-duct sub-slab depressurization system has been shown to be effective in achieving optimum radon reductions.

By using this method of radon soil testing for the construction of new large buildings, such as schools, to locate areas of sub-slab depressurization, maximum indoor radon reductions can be achieved with minimal installations.

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.

In large buildings, such as schools and office buildings, and in homes without good sub-slab air-flow communication, e.g. no aggregate, we have achieved significant indoor radon reductions by sub-slab ventilation at the source of maximum soil radon concentrations using quantitative diagnostic tests which incorporate the correlation between radon soil testing and local geology.

Recent measurements of soil radon availability numbers by the author (1) have yielded correlations between indoor radon levels in homes, office buildings, and schools and the various geologic units in the Coastal Plain, Piedmont, and Mesozoic Basin. The radon availability number was determined using the equations of Nazaroff, et al (2) and Tanner (3), whereby radon availability number is a function of soil radon content, permeability, and diffusion coefficient. The equipment used consists of a Pylon radon monitor with attached Lucas cell and soil probe developed by the author. The probe has an in-line flow meter and pressure gauge (which must have an appropriate range for the permeability values inherent in the particular soils being measured) and a drying tube, cut-off valve, and Swaglok connector which attaches to the in-ground section of the probe assembly. This in-ground section consists of a three foot long metal tubing surrounded near its base by an inflatable packer to prevent atmospheric dilution.

Because soil permeabilities in the Piedmont, Coastal Plain, and the Mesozoic Basin of Northern Virginia and Maryland are low enough that radon migration is predominately diffusion driven, it was decided to calculate the radon availability number based upon the soil radon concentration and diffusion coefficient of the soil. Soils were then tested around a number of basement homes and schools remediated by RCP. Therefore good data was available on the original radon values and construction characteristics.

Determined radon availability numbers, plotted against indoor radon levels, revealed two distinct populations (Figure 1). The lower population (i.e. those with a higher radon availability number to indoor radon ratio) consists entirely of buildings having one or more of the following four factors:

1. A vented crawlspace,
2. A tight or sealed slab-wall contact,
3. A controlled fill around basement walls that has a low radon availability number,
4. No basement.

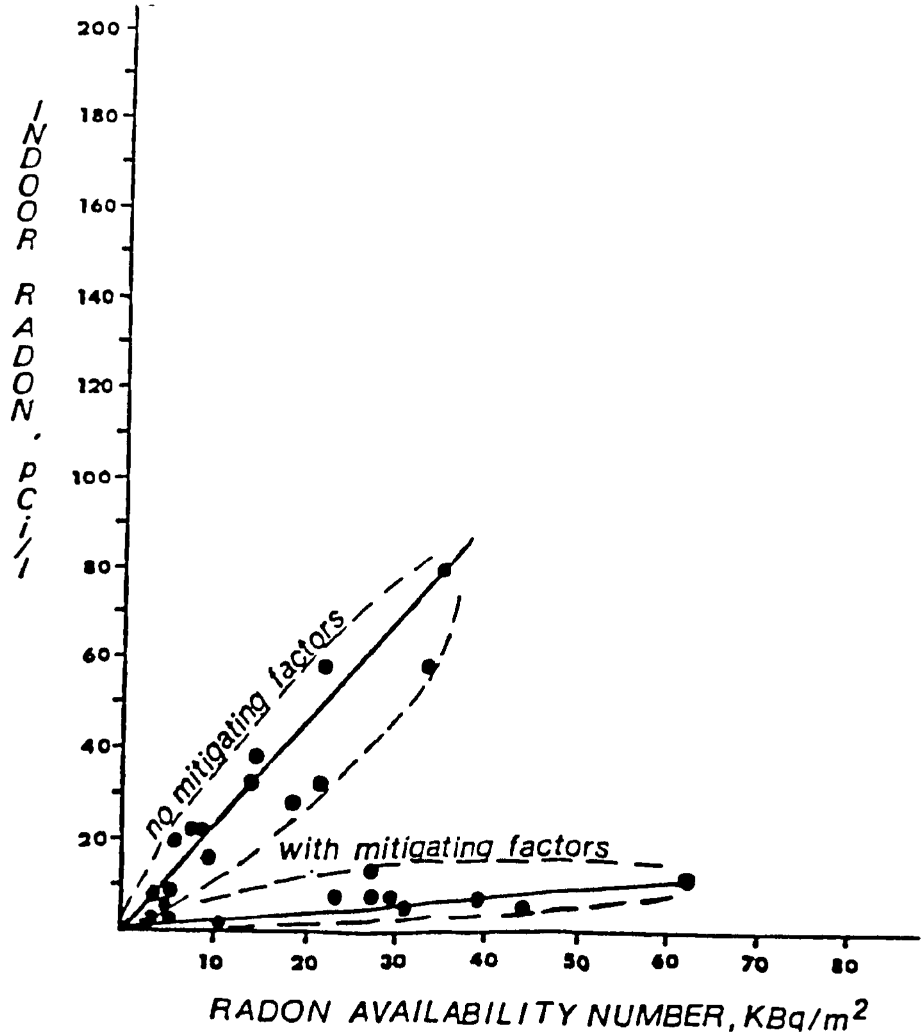

Figure 1. Correlation between soil test results (radon availability number) and indoor radon concentration.

Interestingly, the author had previously discovered in the George Mason University (GMU) Radon Study, that in the same geologic setting, basement homes with crawlspaces tended to have lower indoor radon than those without crawlspaces. Apparently this is a function of the fact that crawlspaces are normally attached at one end of the basement and have fresh air vents to the outside, at least in the local area studied. Crawlspaces are also usually separated from the rest of the basement by a wall, thereby acting as a decoupled unit without the decrease in indoor air pressure that the basement experiences.

The upper population (i.e. those with a lower radon availability number to indoor radon ratio) consists entirely of homes and schools with none of the factors inherent in the lower population. It is this trend that one would want to use to predict magnitudes of indoor radon problems, based upon soil tests for homes or buildings without any radon mitigating factors. Figure 2-7 (highest values darkened), illustrates that both slab-wall separation radon measurements (interior semi-circles) in partially completed schools have corroborated the location of maximum radon potentials determined from soil tests.

In most cases, elevated sub-slab radon levels and soil test results have been shown to be concentrated in linear areas for the various geologic units around the DC metro area, which should also hold true in any folded geologic region with heterogenous geology. These linear areas or "bands" can be one foot to a few tens of feet wide. Importantly, the orientation of the high radon potential lineations correlate well with the trend of local rock layers (generally N30°E), or with the trend of local shear fractures (generally N45°W to N60°W). For example, a boundary between high and low radon potentials is shown in Figure 2, along a N60°W fracture trend and in Figure 3, along a N45°W fracture trend. Figure 4 shows a diagonal band through the central area of the school along a N45°W trending fracture pattern. Figures 5 and 6 show correlations between high radon potentials and N30°E trending rock layers; both revealing a linear band through the interior area of the school.

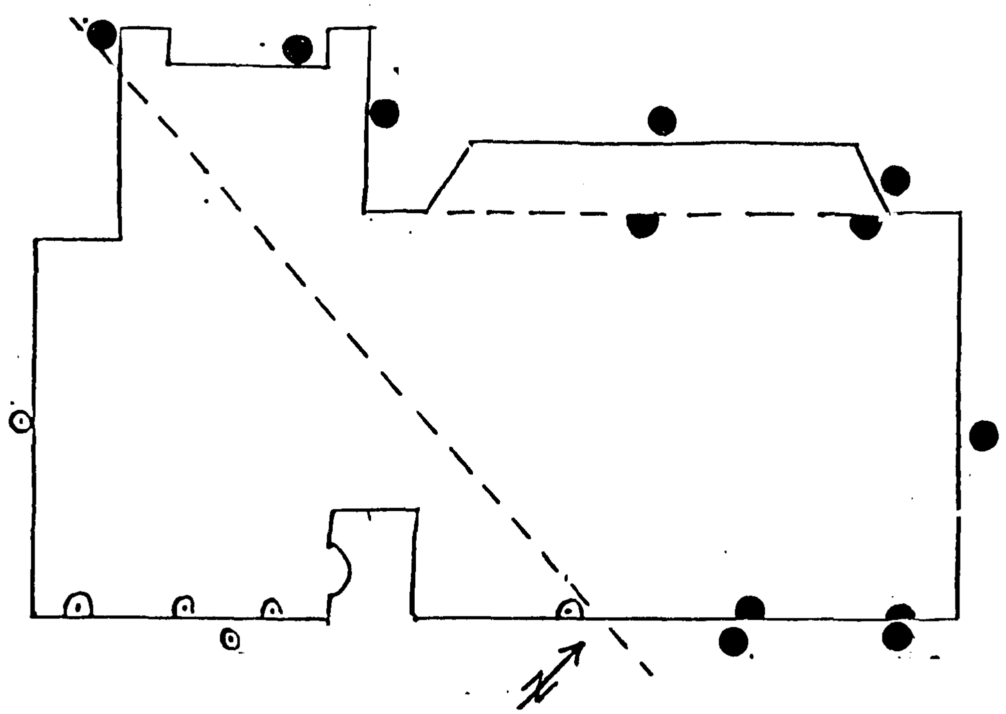

Figure 2. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N60°W fracture trends.

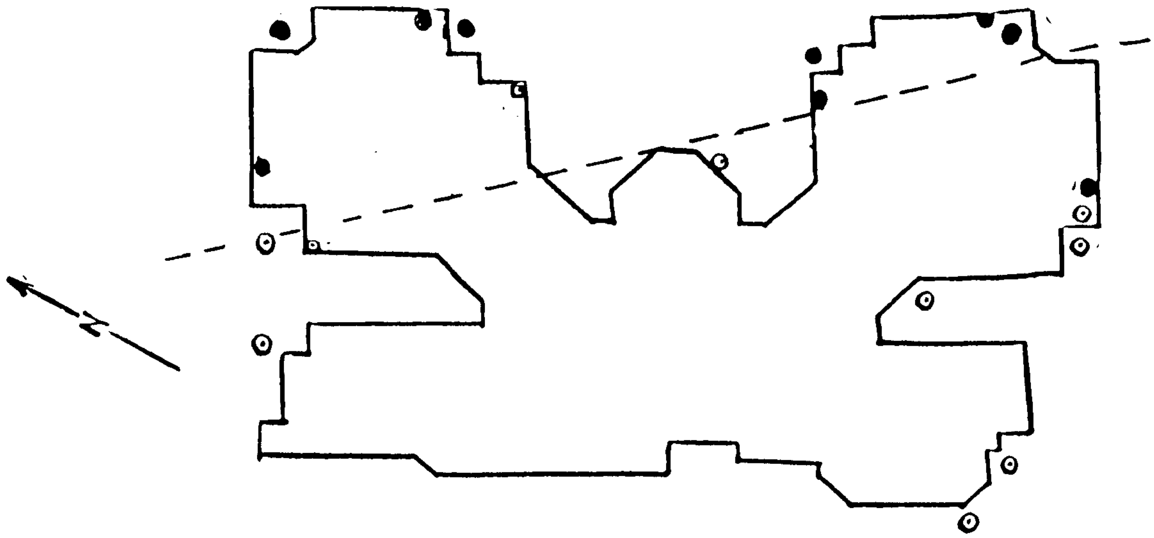

Figure 3. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N45°W fracture trends.

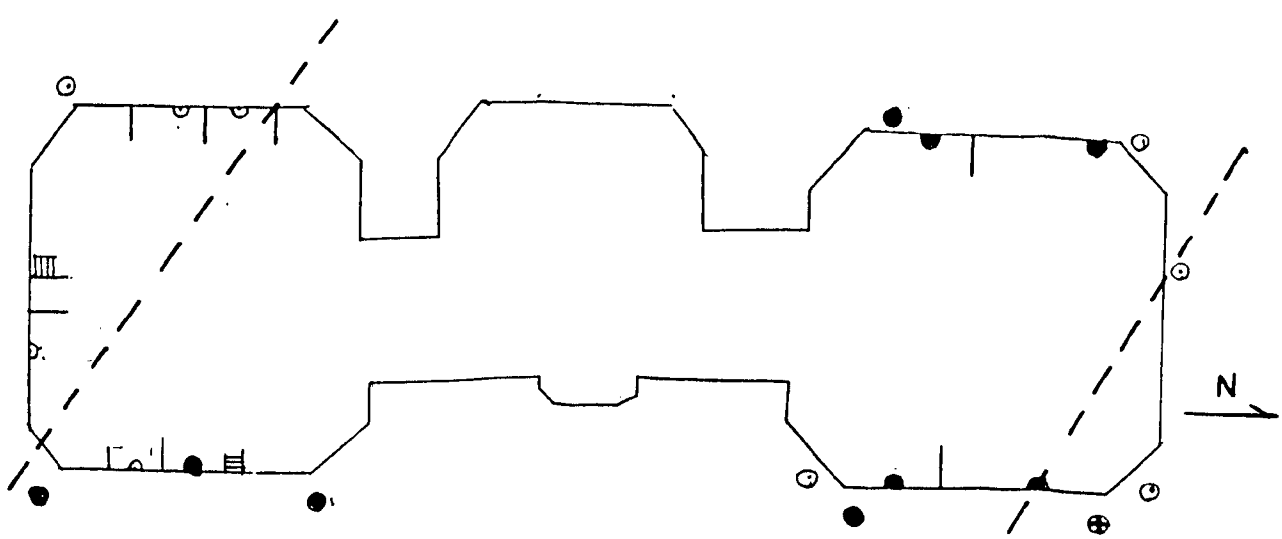

Figure 4. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N45°W fracture trends.

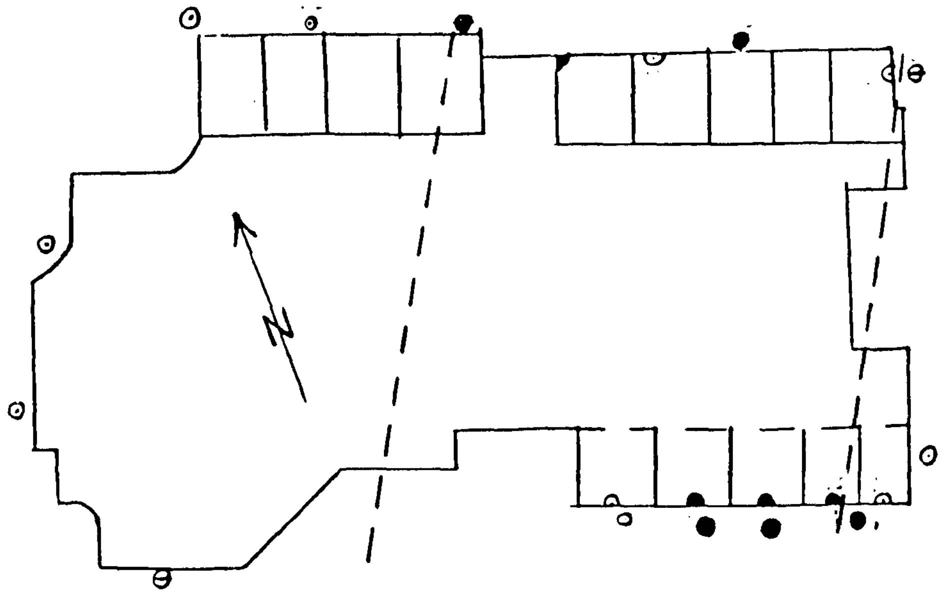

Figure 5. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N30°E trending rock layers.

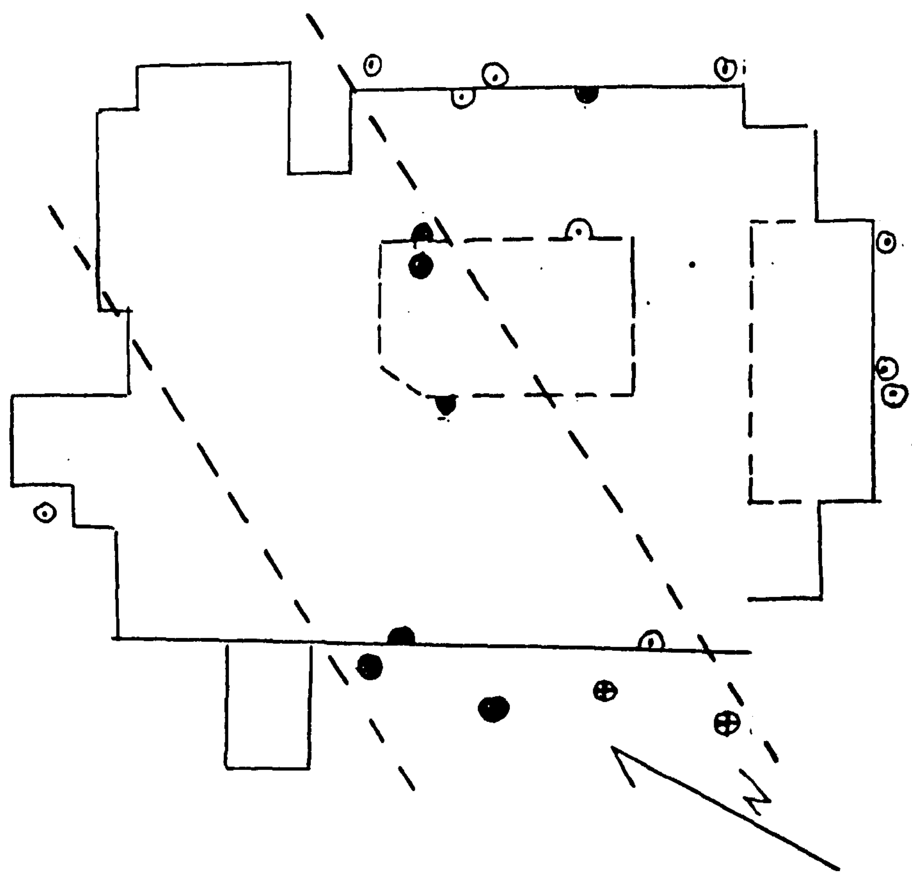

Figure 6. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N30°E trending rock layers.

For the construction of new large buildings, such as schools, radon soil testing has proven valuable in locating the sources of maximum radon availability. By locating sub-slab ventilation points in the vicinity of these areas maximum indoor radon reductions can be achieved with minimal sub-slab ventilation installations.

In existing homes with a footprint area of less than 2000 ft², if sub-slab micromanometer tests indicate good air-flow permeability (good sub-slab communication), the location of ventilation points is not critical because one fan with one penetration will draw radon from everywhere under the slab. However, when sub-slab communication is poor, sub-slab and blockwall radon concentration gradients can be mapped with instantaneous radon measurements to determine the orientation and location of high radon potential lineations under the building, based on a knowledge of the local geology.

For example, Figure 7 shows a home with all the high sub-slab and blockwall radon levels along the NW side, indicating a linear source at the NW end oriented N30°E, parallel to the local rock layers. Micromanometer tests indicated negligible sub-slab communication. A sub-slab ventilation system, installed with one wall and three slab penetrations along the NW end, brought indoor radon levels down to 0.5 pCi/l.

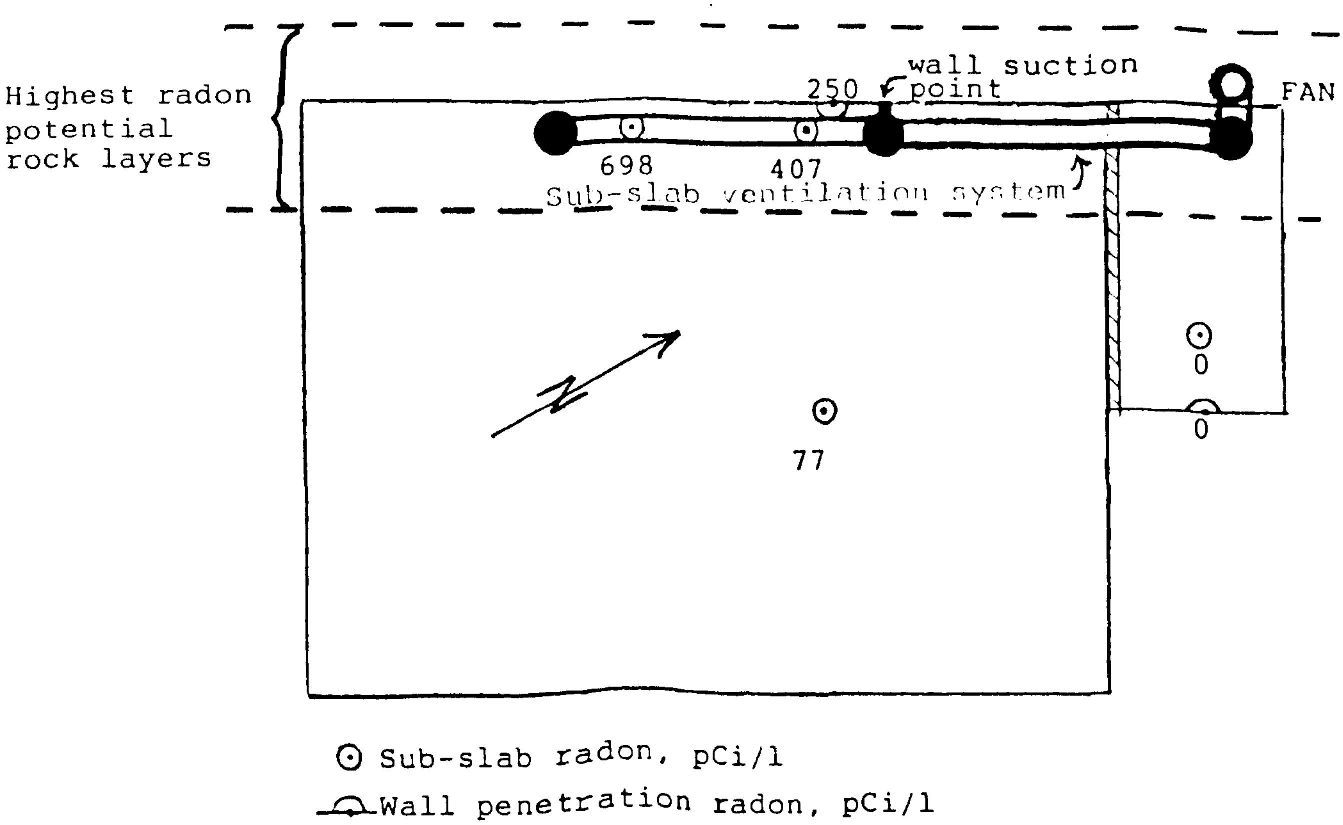

Figure 7. Footprint plan of a home showing numerical values of sub-slab and blockwall radon concentrations that indicate that the radon source is following N30°E rock layers, delineated by dash lines. Sub-slab ventilation systems penetrations are shown as darkened circles.

Figure 8 illustrates a similar house situation where high radon potentials are parallel to N30°E rock layers and generally increase toward the SE. Sub-slab ventilation as shown brought indoor radon levels from 30 pCi/l to 1.5 pCi/l.

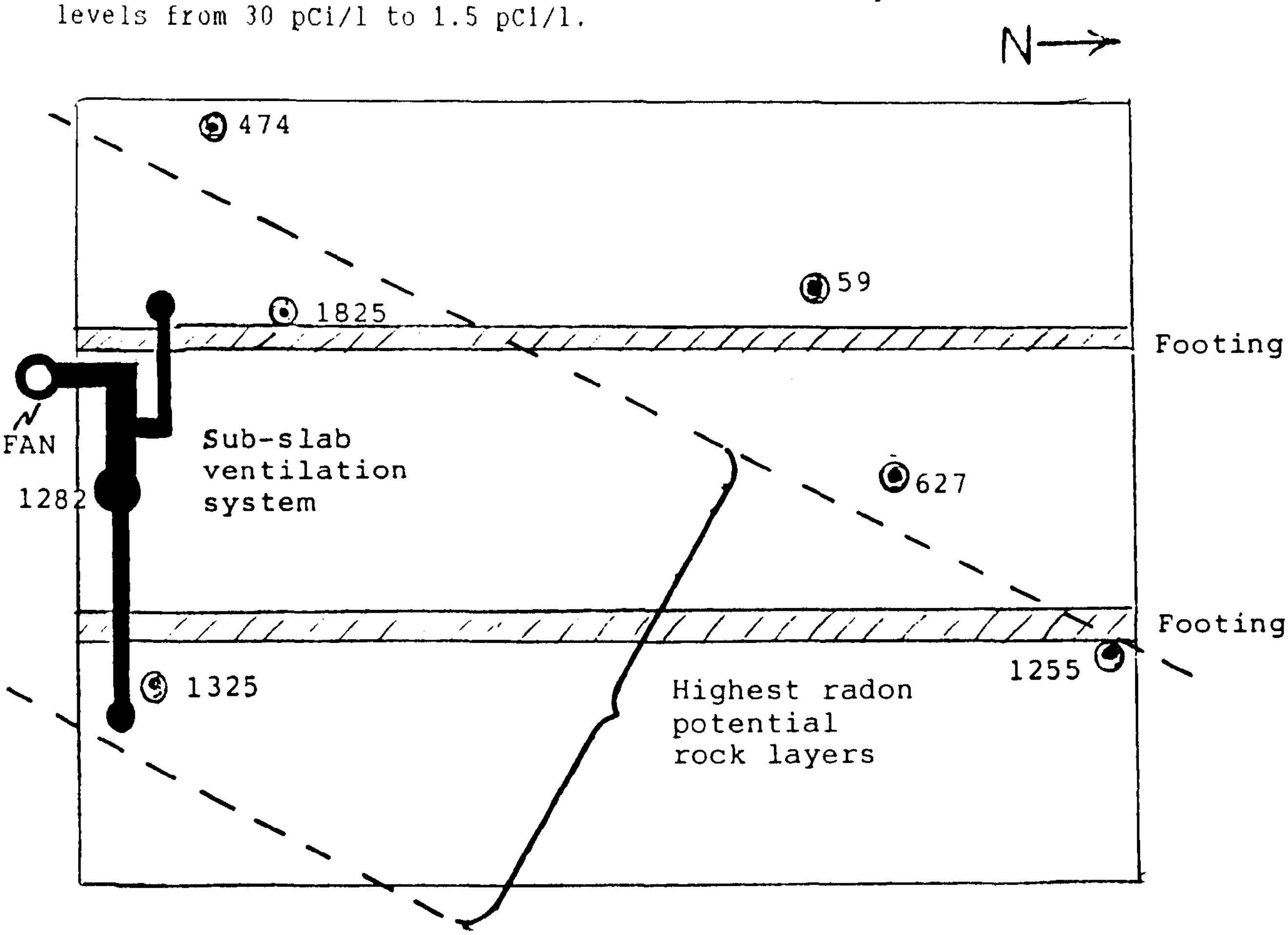

Figure 8. Footprint plan of a home showing numerical values of sub-slab and blockwall radon concentrations that indicate that the radon source is following N30°E rock layers, delineated by dash lines. Sub-slab ventilation systems penetrations are shown as darkened circles.

Figure 9 shows a workplace building with a footprint area less than 2000 ft^2 where micromanometer readings indicated no sub-slab communication because the slab was poured directly on compacted clay. Construction material radon levels tested negative. However, sub-slab radon levels increase towards the SE, congruent with local rock layers oriented N30°E. Thirteen slab penetrations with 2" pipe were necessary to deplete most of the source from the SE end of the building because the negative pressure field around each penetration was so small due to the very poor communication. Indoor radon, which initially was measured as high as 120 pCi/l, was reduced to less than 4 pCi/l.

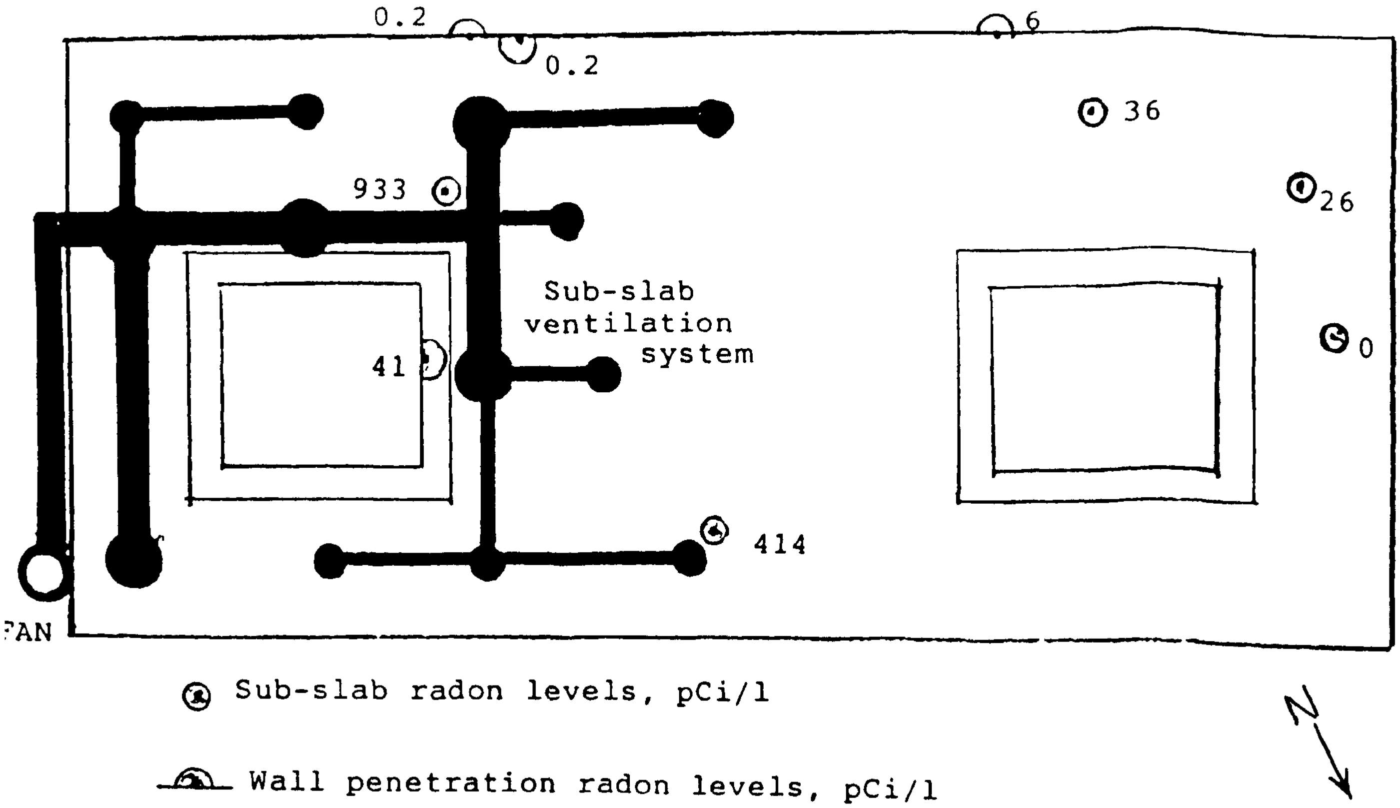

Figure 9. Footprint plan of a home showing numerical values of sub-slab and blockwall radon concentrations that indicate that the radon source is following N30°E rock layers. Sub-slab ventilation systems penetrations are shown as darkened circles.

Therefore, by knowing local geology and by tapping these high radon potential source areas with a multi-duct, single fan, sub-slab ventilation system optimum radon reductions can be achieved in buildings with poor sub-slab communication. Likewise by combining geologic knowledge with sub-slab and blockwall radon measurements in large buildings such as schools, the radon source can be located to determine where to place sub-slab ventilation systems that will achieve maximum radon reductions.

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TITLE: A Comparison of Radon Results to Geologic Formations for the State of Kentucky

AUTHOR: David McFarland, Merit Environmental Services

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

A large bank of radon results for the state of Kentucky are compared to the local geologic formation. These results are discussed in detail. The topic of elevated radon levels as a result of native building materials (for the study area) is also addressed.

TITLE: Geologic Radon Potential of the United States

AUTHOR: Linda Gunderson, U.S. Geological Survey

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

A geologic radon map depicting the major geologic provinces relevant to radon has been constructed for the United States. Indoor radon data from the State/EPA Indoor Radon Survey and from other sources were compared with bedrock and surficial geology, aerial radiometric data, soil properties, and soil and water radon studies to designate and rank the different provinces. The map depicts areas of the country that have the potential for indoor radon (1) less than the national average of 2 pCi/L, (2) greater than the national average, and (3) greater than 4 pCi/L. The areas of the country with the highest radon potential are listed below:

(1) The Proterozoic rocks of the Appalachians and Rockies: These uraniferous metamophosed sediments, volcanics, and granite intrusives and carbonates are highly deformed and often sheared. Shear zones in these rocks cause the highest indoor radon problems in the United States.

(2) Glacial deposits of the northern Midwest, particularly those derived from uranium-bearing shales, and glacial lake deposits. The clay-rich tills and lake clays have high radon emanation coefficients, in part because of their high specific surface areas, and exhibit higher-than-expected permeabilities due to desiccation cracking when dry.

(3) Devonian and Cretaceous black shales: The Chatanooga and New Albany Shales and their equivalents in Ohio, Tennessee, and Kentucky and some members of the Pierre Shale in the Great Plains are often moderately uraniferous and have high emanation coefficients and high fracture permeability.

(4) Phosphorites: Natural and manmade accumulations of phophorites in Florida, phosphatic clays in Georgia and Alabama, and the Permian Phosphoria Formation in Wyoming, Idaho, Utah, and Montana are typically associated with uniformly high concentrations of uranium or anomalously high concentrations of uranium caused by diagenesis.

TITLE: Technological Enhancement of Radon Daughter Exposures Due to Non-nuclear Energy Activities

AUTHOR: Jadranka Kovač, University of Zagreb, Yugoslavia

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

Natural radioactivity is a part of our natural surrounding and concentrations of natural radionuclides in the environment increase with the development of technologies. This is the case with phosphate ore processing in fertilizer industry and during coal combustion in coal-fired power plants. A major source of exposure to the population in the vicinity of non-nuclear industries results from inhalation of the ^{222}Rn daughters. Exposure to radon daughters has been also associated with lung disorders that include cancer among workers. For that reason the radon daughter concentrations in different atmospheres are discussed in this paper.

Working levels were measured as "grab samples" for several years at several stations on-site and off-site of the coal-fired power plant as well as the phosphate fertilizer plant, both located in Croatia. The average maximums, minimums, and mean values of working levels are presented, and measurement techniques are reviewed.

A SITE STUDY OF SOIL CHARACTERISTICS AND SOIL GAS RADON

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

ABSTRACT

In regional surveys, indoor radon is usually the parameter of interest, but occasionally soil gas radon at depths of 1 meter or less is also measured. At statewide scales, even limited data sets can be used to infer relationships between geology and soil gas or indoor radon. However, predicting the radon potential of a single house or even an area the size of a neighborhood is more difficult. As the size of a surveyed area decreases, site-specific variables become more significant.

We recently completed a study of two residential neighborhoods within 7 kilometers of each other near Rochester, Minnesota. Eight holes were augered into glacial sediments to maximum depths of 4.5 meters and samples collected for grain-size analysis, measurement of radon parent/daughter nuclides and radon emanation. A total of 65 homes in the areas were provided with two alpha-track registration detectors for 1 year of indoor monitoring.

Positive correlations were observed between the average soil radon, the average indoor radon, and the precursor/daughter radionuclides. The study area with the most topographic relief also had the highest radionuclide contents, the most variability with depth, and some variation with time and soil moisture; these results were not observed at the low-relief site. The type of study described would best be applied to site-specific preconstruction screening, rather than to predicting radon in existing structures.

INTRODUCTION

This project was designed to collect data on soil type and soil characteristics, radon and other related nuclides at several depths, and porosity and permeability. At the same time, radon levels in basements and living areas of homes built on the soils were also measured.

Two areas were chosen for the pilot study (Figure 1). St. Marys Hills on the west side of Rochester consists of modern, single-family homes on 1/2-acre to 2-acre lots on the west side of a bedrock hill composed of St. Peter Sandstone, Decorah Shale, and Galena limestone, with a total vertical relief of about 40 meters. The bedrock surface is covered by 2 and 6 meters of glacial sediment and loess. Essex Park, about 6.5 kilometers northeast of St. Marys Hills is a mix of modern, single-family and multiple-residence homes on 1/2-acre lots. The topography is subdued, with about 9 meters of relief. Depth to the bedrock (Prairie du Chien Group) is between 3 and 18 meters. The profiles for each area and locations of the sample holes are shown in Figure 2.

Sixty-four owners of single-family homes participated in the study, 45 from Essex Park and 19 from St. Marys Hills. Each received two radon detectors, one for the basement and one for a first-floor living area. Exposures lasted from 9 to 12 months.

METHODOLOGY

The test holes were drilled in October 1988 using a truck-mounted Giddings soil auger with a 5-cm-diameter bit and core tube. Sediment samples collected during drilling were placed in sealable plastic bags.

The following is a summary of the analyses and methods used to study the sediment samples.

1. Moisture content and bulk density: the wet weights were measured within 2 days after collection. Soils were dried for a minimum of 24 hours at 70°C and reweighed. The results are only approximate, because they do not reflect moisture lost prior to measurement.
2. Solid particle density: these measurements were based on a procedure from Luetzelschwab and others (1). These results combined with the wet and dry bulk densities can be used to approximate the pore volume in a sample of soil.
3. Grain-size fractions: the soils were screened into fractions consisting of a bulk sample (undifferentiated as to grain size), >149 μ (sand and gravel), 149-63 μ (very fine sand), and <63 μ (silt and clay by wet sieving).
4. Mineralogy: the mineralogy was determined by examining the >149 μ grain-size fraction with a binocular microscope.
5. Radon: radon emanation was measured from the bulk soil samples, the <63 μ, and the 63-149 μ fractions using a charcoal trap system modified from an unpublished report by Dr. J.N.

Andrews, University of Bath, England. Scatter in the bulk fraction is thought to result from inhomogeneous radium in the sediment. The reproducibility of the other duplicate analyses was very good, and replicate analyses of radium standards varied by less than 10%.

6. ^{210}Po – ^{210}Pb: Polonium-210 was extracted from the sediment with a leaching technique modified from Eakins and Morrison (2), Blake and Norton (unpub.), and D.R. Engstrom (unpub.). The ^{210}Po was assumed to be in radioactive equilibrium with the ^{210}Pb.

7. Radium and thorium: 1-kilogram sediment splits from each depth were analyzed for ^{226}Ra and ^{232}Th by gamma-ray spectroscopy using a high-resolution germanium detector. The measured activities reflect total radium and thorium in the sediments.

8. Radon concentrations in the soil at multiple depths were measured by (1) pumping air from isolated intervals through a liquid scintillation cocktail (active sampling) and by (2) extended monitoring of isolated intervals with alpha-track detectors (passive sampling). Inflatable rubber packers on the outside of hollow PVC pipe were used to isolate each collection point. Each alpha track detector was wrapped in Saran Wrap® to keep out water vapor but still allow diffusion of radon. Initial data from alpha-track detectors is not included in the tables because of large variance in the calibration constant for the detectors used at that time and our doubts about the integrity of the original packers. In 1989, a redesigned system for both the active and passive sampling was used with more reliable packers and flexible barriers, which prevented vertical air movement if a packer failed.

SOIL CHARACTERISTICS

The sediments within the Rochester area are the result of glacial processes and include tills, outwash, colluvium, and loess. Loess, ranging from 0.6 to 2.8 meters thick, covers all of the sample sites except Hole B in St. Marys Hills. The glacial tills below the loess are oxidized; some show the reddish-brown colors of ferric iron to depths of about 4.3 meters (Figure 3).

Moisture ranged from a low of 6.8 weight percent in the loess to a high of 20 weight percent, also in loess. Soil moisture increased slightly with depth, but not in all holes and not more than a few percent. Between the initial sampling in 1988 and measurement of radon in 1989, Hole B (St. Marys Hills) collected water in the bottom meter. This could have been due to seepage from the sediment or water infiltrating from the surface.

There is a fairly broad range of grain-size distributions in the sediment samples, but the means within and between the sites were not statistically different. The available data do not allow us to distinguish between the relative effects of deposition and post-depositional soil development on the grain-size distribution.

Mineralogically the sediments are very similar, being predominantly composed of quartz, feldspar, biotite, and muscovite. Rock fragments form up to 50% of the >149 μ size fraction and include granite, limestone, quartzite, sandstone, and metamorphic and volcanic rocks. Varying percentages of magnetite, pyrite, hematite, and limonite were also observed.

RADIOMETRIC RESULTS

Radon concentrations in the soil gas at St. Marys Hills generally increase with depth and range from 17 to 71 kBq/m^3 (Table 1), with an average of 44 ± 13. In Hole A, both active and passive radon samples were collected. Below 1 meter, the two methods gave concentrations that were, within error, identical. The lower radon value at sample point A1 using the active monitor was probably due to leakage around the original packer. A second group of passive monitors was placed in Hole B during August-November and produced results that were significantly lower than the July-August measurements. Hole B also contrasts with the other St. Marys Hills data in that radon decreases with depth. These trends appear related to increased water retention in the clayey soil of Hole B as well as collection of water in the lower meter.

In Essex Park the radon levels range from 3 to 42 kBq/m^3 with an average of 26 ± 7 kBq/m^3 (Table 2). The level of 3 kBq/m^3 was obtained at a depth of 0.2 meters in Hole G; at a depth of one meter the lowest concentration was 13 kBq/m^3. Some of the holes show an increase in radon with depth; others show relatively uniform levels. Some of the radon concentrations measured by the active sampling are as much as 30% lower than concentrations measured with the passive monitors. However, the means are not statistically different.

A second set of measurements in Hole G during August-November showed lower radon levels than during July-August and correspond to the decrease observed in Hole B at St. Marys Hills. Although the decrease can be attributed to higher water retention in the soil during a rainy fall it is difficult to be sure as only one hole was measured within each area during the late fall.

Radon emanation was measured on the bulk samples, the 63-149 μ and the <63 μ fractions as described above. Replicate analyses gave reproducible results with standard deviations comparable to the error associated with counting statistics. A number of factors, such as moisture, radium content, and location of radium either on grain interiors or secondary coatings, control the amount of radon emanated (3); however, on the average, higher radon emanation would be expected to produce higher radon concentrations in the soil gas. In Tables 3 and 4 the emanation results are given relative to the mass of the sample. The <63-μ fraction includes both silt and clay, and the 63 149 μ (very fine sand) represents about a third of the total sand fraction (up to 2 mm in size). In estimating total emanation, the results from the

63-149 μ measurements were considered representative of all the sand-size fractions.

Differences between the radon emanation rates of the two sites, were comparable with those of the radon concentrations. The average radon emanating from the soils in St. Marys Hills is just over twice that emanating from the Essex Park soils. The difference in means is statistically significant at the 0.025 confidence level. Although emanation rates in St. Marys Hills were divided fairly evenly between the 63-149 μ and <63 μ size fractions, in Essex Park the emanation rates for 9 out of 10 samples was highest in the <63 μ fraction. The variation of emanation rates in Essex Park was much smaller than in St. Marys Hills, in accordance with the more uniform radon concentrations in Essex Park.

The sum of the emanation rates from the grain-size fractions should be comparable with the emanation rate measured from each of the bulk samples. In Essex Park this was the case, but in St. Marys Hills, although most were comparable, some soils, such as A6, had a bulk emanation rate that was larger than either the individual or the sum of the fractional emanations. The overall agreement between the bulk and weighted fractional emanations indicates that the assumption that the 63-149 μ size represents the total sand fraction is reasonable for these samples.

Other radionuclides measured included ^{232}Th, ^{226}Ra, and ^{210}Po (Tables 5 and 6). Both the mean and standard deviation of ^{232}Th are equivalent for both sites. Radium and ^{210}Pb values were higher in St. Marys Hills than in Essex Park and were also more variable both within and between sites than was thorium. If post-depositional migration altered the radionuclide distributions, it did not affect thorium, which is not mobile under near-surface geochemical conditions. Uranium isotopes, however, respond to weathering and changing oxidation/reduction environments, leading to separation from daughter radionuclides and altered distribution patterns. The relatively uniform distributions of radionuclides in Essex Park sediments are consistent with little post-depositional migration, whereas the uneven distributions in St. Marys Hills indicate significant migration, possibly related to enhanced weathering of the sediments on the hill slope.

The activity ratio $^{210}Pb/^{226}Ra$ in the sediment can be a useful indicator of relative radon loss. A ratio smaller than one implies that radon has moved away from the radium source, resulting in less ^{210}Pb activity relative to ^{226}Ra. All but one of the samples (A6) have activity ratios less than unity; in fact the overall activity ratio is about 0.5, with St. Marys Hills having a somewhat higher mean value (significant at the 0.05 confidence level). Lower activity ratios could also result from only partial recovery of polonium from the sediment, with the apparent effect of reducing the Pb/Ra activity ratio. Sample A6, with an activity ratio of 1.25, is at present an anomaly because the individual activities of ^{210}Pb and ^{226}Ra, as well as the activity ratio, are much greater than those of the other samples.

Contrary to expectations, the lowest activity ratios were not always near the surface where radon could easily escape into the atmosphere. The sandy soils in Essex Park with the lowest activity ratios imply that radon has moved away from its source even at depths of 3 meters. Disequilibrium between ^{226}Ra and ^{210}Pb could also result from downward migration of radium during weathering of the sediments or could, as noted above, be partially related to inefficient extraction of polonium from the sediment. We were not able to compare the radon directly with either ^{226}Ra or ^{210}Pb because the units were different (volume vs. mass), and the samples did not always correspond in depth.

We also used a 1-inch NaI detector to measure the total gamma activity at 2-foot intervals in several of the holes. In general the activity versus depth relationship followed the pattern of radium and polonium in the sediment except near the surface, where there may have been accumulations of potassium. Total gamma activity in the sediment appeared higher in St. Marys Hills, in accordance with the other measurements, but not all holes were measured. The results do indicate that subsurface gamma activity is a potentially useful and simple screening technique, which could be improved by using a spectroscopy system that determines the energy of the radiation and identifies the isotopes present.

INDOOR RADON

The summary of the indoor radon information is given in Table 7. Of the 64 homeowners who were given the two detectors, 48 returned them. Of those, 17 were from the St. Marys Hills area and 31 from the Essex Park area. The mean indoor radon levels of St. Marys Hills and Essex Park are different and significant at the 0.025 level for a two-sided t-test. The higher average indoor radon in St. Marys Hills corresponds to the higher average radionuclide contents in the sediments of St. Marys Hills and to the higher radon emanation rates. The range of indoor radon concentrations is similar for both areas; each has levels that exceed 370 Bq m^{-3} and levels that are less than 37 Bq m^{-3}. Although this reduces the probability of predicting radon levels for individual homes, there is a good correlation between the average soil radon concentrations, parent/daughter radionuclides, and indoor radon levels.

CONCLUSIONS

Our primary objective in this study was to measure, in two different areas, radionuclides related to and including radon at several depths within unconsolidated sediments, and to see what, if any, correlation existed between the characteristics of the sediment and indoor radon levels. All of the measurements were made in glacially derived or related material. None were obtained from the limestone bedrock, which was encountered in only three holes. We think that within the study areas the glacial sediments are the primary source of indoor radon and that bedrock probably is not a significant source. A more extensive study is needed to determine which homes were built on or near bedrock and collect additional data on the radon and other radionuclide levels.

Radium-226, ^{210}Pb, radon emanation, and downhole radon levels all have statistically higher averages in St. Marys Hills sediments than those in Essex Park. Indoor radon levels also were statistically higher in St. Marys Hills, and had a positive correlation with the radionuclides in the soil. The mineralogy, moisture levels, and bulk densities were similar in both areas and did not correlate with the radionuclide distribution. Texturally the sediments were variable but showed similar average contents of gravel, sand, and silt/clay; however, more work is needed before firm conclusions can be made about the effect of grain-size distribution on the radionuclide content and distribution within the sediments.

All of the techniques used to assess the radon potential were consistent with each other and could be applied individually or collectively to other areas. We believe that at these sites near Rochester mineralogical characteristics of the sediments and the location of samples within the stratigraphic column were only partially responsible for the observed distribution of radionuclides. We suggest that post-depositional transport of uranium and radium related to weathering processes contributed to the observed distributions. The redistribution of radionuclides was more extensive in the St. Marys Hills area probably owing to the greater vertical relief. In both areas ^{226}Ra/^{210}Pb activity ratios indicate migration of radon independent of the parent/daughter movement.

Predicting radon source areas in regions where sediments are more than a couple of meters thick should not be be based solely on identification of geological materials or on near-surface radon measurements. Evidence for the secondary transport and redistribution of radionuclides is not shown on geologic maps, and near-surface radionuclide characteristics may differ from those at basement depth. The data from this study, although limited in area, indicate that measurement of radon or related radioactive nuclides in soils can be a useful preconstruction indicator of potential indoor radon problems. Survey methods could involve active measurements at depths greater than 1 meter of soil gas radon, subsurface gamma spectroscopy and ^{226}Ra in the sediment.

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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TABLE 7. SUMMARY OF RADON LEVELS (Bq/m^3) IN HOMES WITHIN THE STUDY AREA

	Geometric Mean	Arithmetic Mean	Min.	Max.
St. Marys Hills				
Rn Index No.†	180 *÷ 1.8	220	70	610
Rn Basement	250 *÷ 2.1	270	40	1100
Rn 1st Floor	130 *÷ 3.0	160	30	400
Essex Park				
Rn Index No.	60 *÷ 2.5	90	10	390
Rn Basement	80 *÷ 2.4	130	15	650
Rn 1st Floor	40 *÷ 2.7	70	10	280

†The radon index number is a weighted average of the two radon measurements in the house. The weighting factor for each floor was an estimate of the amount of time an occupant spends on each floor.

TABLE 1. DOWNHOLE RADON MEASUREMENTS, ACTIVE & PASSIVE – ST. MARYS HILLS

Sample No.- Depth (m)	Date mo/yr	Active (kBq/m^3)	Date mo/yr	Passive (kBq/m^3)	Date mo/yr	Passive (kBq/m^3)
A1-1	10/88	17 ± 2	7-8/89	29 ± 4	–	--
A2-2	10/88	40 ± 3	7-8/89	40 ± 6	–	--
A3-3	10/88	61 ± 4	7-8/89	57 ± 8	–	--
A4-4	10/88	68 ± 6	7-8/89	71 ± 9	–	--
B1-1	–	–	7-8/89	42 ± 6	8-11/89	25 ± 2
B2-2	–	–	7-8/89	41 ± 6	8-11/89	28 ± 2
B3-3	–	–	7-8/89	29 ± 4	8-11/89	20 ± 1
B4-4	–	–	7-8/89	water	8-11/89	5 ± 0.4
C1-1	–	–	7-8/89	26 ± 3	–	--
C2-2	–	–	7-8/89	44 ± 6	–	--
D1-1	–	–	7-8/89	44 ± 6	–	--
D2-2	–	–	7-8/89	46 ± 6	–	--
D3-3	–	–	7-8/89	53 ± 7	–	--
Average		–		44 ± 13		--

Error values are one standard deviation based on counting statistics.

TABLE 2. DOWNHOLE RADON MEASUREMENTS, ACTIVE & PASSIVE – ESSEX PARK

Sample No.- Depth (m)	Date mo/yr	Active (kBq/m^3)	Date mo/yr	Passive (kBq/m^3)	Date mo/yr	Passive (kBq/m^3)
E1-1	8/89	22 ± 2	7-8/89	15 ± 2	–	–
E2-2	8/89	21 ± 2	7-8/89	22 ± 3	–	–
E3-3	8/89	21 ± 2	7-8/89	18 ± 3	–	–
F1-1	8/89	15 ± 2	7-8/89	21 ± 3	–	–
F2-2	8/89	26 ± 3	7-8/89	32 ± 4	–	–
F3-3	8/89	27 ± 3	7-8/89	24 ± 3	–	–
F4-4	8/89	27 ± 3	7-8/89	36 ± 5	–	–
G1-1 (0.2)*	8/89	3 ± 0.3	7-8/89	18 ± 3	8-11/89	20 ± 1
G2-2 (1.2)*	8/89	23 ± 2	7-8/89	31 ± 4	8-11/89	28 ± 2
G3-3 (2.2)*	8/89	24 ± 2	7-8/89	33 ± 4	8-11/89	23 ± 2
G4-4 (3.2)*	8/89	31 ± 3	7-8/89	42 ± 6	8-11/89	collapsed
H1-1	8/89	13 ± 1	7-8/89	23 ± 3	–	–
H2-2	8/89	21 ± 2	7-8/89	25 ± 4	–	–
H3-3	8/89	19 ± 1	7-8/89	25 ± 4	–	–
H4-4	8/89	17 ± 1	7-8/89	23 ± 3	–	–
Average		22 ± 5†		26 ± 7		–

*Depth (meters) of active radon measurements in Hole G. Error values are one standard deviation based on counting statistics.

†Average does not include sample from depth 0.2 meters.

TABLE 3. EMANATION RESULTS – ST. MARYS HILLS

Sample No. Depth (m)	Bulk Emanation (Bq/kg)	Sum of Emanation from Sand &(Silt+Clay)* (Bq/kg)	Emanation 63-149 μ (Bq/kg)	Emanation <63 μ (Bq/kg)
A1-1.3	7.6 ± 0.4	14.7 ± 0.7	16.7 ± 0.9	†14.6 ± 1.0
A2-2.1	†10.6 ± 0.7	14.3 ± 0.7	11.0 ± 0.8	†16.9 ± 1.0
A3-2.9	20.1 ± 1.0	18.0 ± 0.9	15.9 ± 0.9	21.3 ± 0.9
A4-3.5	20.2 ± 0.9	22.4 ± 1.1	19.1 ± 1.0	26.8 ± 1.2
A5-4.0	11.0 ± 0.6	12.3 ± 0.6	11.4 ± 0.7	14.5 ± 1.0
A6-4.6	†38.2 ± 3.3	17.5 ± 0.9	†13.7 ± 0.8	†20.3 ± 1.3
B1-1.9	15.6 ± 0.7	9.5 ± 1.2	6.6 ± 0.6	†11.2 ± 1.7
B2-3.4	11.1 ± 0.8	12.2 ± 0.6	20.2 ± 0.9	11.9 ± 0.6
B3-4.6	13.8 ± 0.7	11.1 ± 0.6	†15.0 ± 0.8	†10.9 ± 0.6
C2-1.8	18.8 ± 1.0	11.4 ± 0.6	21.7 ± 1.0	11.2 ± 0.6
C2-2.9	11.0 ± 0.6	12.0 ± 0.6	19.5 ± 0.8	†11.2 ± 1.7
D1-1.2	18.2 ± 0.7	12.1 ± 0.6	32.4 ± 2.0	11.4 ± 0.7
D2-2.7	34.0 ± 2.0	27.1 ± 1.4	21.8 ± 1.0	30.9 ± 1.0
Average	17.7 ± 9.2	–	–	–

*Emanation measured on 63-149 μ size and applied to total sand fraction; emanation from <63 μ size includes both silt and clay. Sum is the measured emanation times the weight percent of each size fraction.
†The number is mean of replicate measurements; error is the standard deviation about the average.

TABLE 4. EMANATION RESULTS – ESSEX PARK

Sample No. Depth (m)	Bulk Emanation (Bq/kg)	Sum of Emanation from Sand &(Silt+Clay)* (Bq/kg)	Emanation 63-149 μ (Bq/kg)	Emanation <63 μ (Bq/kg)
E1-1.9	†6.3 ± 0.6	6.8 ± 0.7	NS‡	16.5 ± 1.0
E2-3.1	8.2 ± 0.5	12.3 ± 1.2	11.4 ± 0.7	14.9 ± 0.8
F1-1.8	9.8 ± 0.7	12.7 ± 1.2	35.5 ± 1.4	10.1 ± 0.6
F2-3.1	11.8 ± 0.6	9.3 ± 0.6	5.0 ± 1.0	9.4 ± 1.0
F3-4.3	8.8 ± 0.6	8.0 ± 0.8	†2.2 ± 0.6	10.0 ± 0.7
G1-1.9	7.4 ± 0.6	5.6 ± 0.8	3.1 ± 0.4	10.6 ± 0.6
G2-3.3	7.2 ± 0.5	6.3 ± 0.8	2.7 ± 0.4	9.5 ± 0.7
G3-4.4	†10.5 ± 0.7	6.7 ± 0.8	†1.2 ± 0.5	†10.7 ± 0.8
H1-1.8	5.6 ± 0.7	5.6 ± 0.8	2.8 ± 0.4	9.4 ± 0.6
H2-3.3	4.7 ± 0.8	5.2 ± 0.8	2.3 ± 0.4	9.7 ± 0.7
H3-4.3	5.2 ± 0.5	4.8 ± 0.7	2.0 ± 0.4	10.0 ± 0.7
Average	7.8 ± 2.3	–	–	–

*Emanation measured on 63-149 μ size and applied to total sand fraction; emanation from <63 μ size includes both silt and clay. Sum is the measured emanation times the weight percent of each size fraction.
†The number is mean of replicate measurements; error is the standard deviation about the average.
‡NS indicates insufficient sample for measurement.

TABLE 5. RADIUM-226, LEAD-210 AND THORIUM-232 IN ST. MARYS HILLS

Sample No. Depth (m)	Ra-226 (Bq/kg)	Pb-210 (Bq/kg)	Th-232 (Bq/kg)	$^{210}Pb/^{226}Ra$ ± ≈ 10%
A1-1.3	82 ± 10	†24.9 ± 0.7	32 ± 14	0.30
A2-2.1	77 ± 10	†18.8 ± 2.6	48 ± 18	0.24
A3-2.9	74 ± 09	37.8 ± 0.6	29 ± 15	0.51
A4-3.5	64 ± 09	37.2 ± 0.5	55 ± 19	0.58
A5-4.0	45 ± 07	26.4 ± 0.5	23 ± 17	0.59
A6-4.6	117 ± 12	†146 ± 46	38 ± 18	1.25
B1-1.9	30 ± 6	23.7 ± 0.6	33 ± 16	0.79
B2-3.4	47 ± 8	26.4 ± 0.5	55 ± 15	0.56
B3-4.6	42 ± 7	27.0 ± 0.7	55 ± 14	0.64
C1-1.8	60 ± 9	39.9 ± 0.8	45 ± 19	0.67
C2-2.9	39 ± 7	25.8 ± 0.6	34 ± 16	0.66
D1-1.2	39 ± 7	32.3 ± 0.7	42 ± 17	0.83
D2-2.7	79 ± 9	†54.9 ± 7	44 ± 13	0.69
Average	61 ± 25	40 ± 33	41 ± 11	0.64 ± 0.25

†The number is the mean of replicate measurements; error is the standard deviation about the average.

TABLE 6. RADIUM-226, LEAD-210 AND THORIUM-232 IN ESSEX PARK

Sample No. Depth (m)	Ra-226 (Bq/kg)	Pb-210 (Bq/kg)	Th-232 (Bq/kg)	$^{210}Pb/^{226}Ra$ ± ≈ 10%
E1-1.9	27 ± 6	16.1 ± 0.4	29 ± 10	0.60
E2-3.1	21 ± 5	10.9 ± 0.4	32 ± 11	0.52
F1-1.8	39 ± 7	19.4 ± 0.5	49 ± 17	0.50
F2-3.1	36 ± 7	18.4 ± 0.8	64 ± 20	0.51
F3-4.3	33 ± 7	16.1 ± 0.7	50 ± 17	0.49
G1-1.9	26 ± 5	13.3 ± 0.3	30 ± 14	0.51
G2-3.3	25 ± 7	14.4 ± 0.4	37 ± 12	0.58
G3-4.4	28 ± 6	†11.9 ± 0.2	29 ± 13	0.42
H1-1.8	30 ± 5	12.8 ± 0.4	33 ± 15	0.43
H2-3.3	23 ± 5	6.5 ± 0.3	32 ± 14	0.28
H3-4.3	25 ± 6	9.2 ± 0.4	31 ± 10	0.37
Average	28 ± 6	14 ± 4	38 ± 12	0.47 ± 0.09

†The number is the mean of replicate measurements; error is the standard deviation about the average.

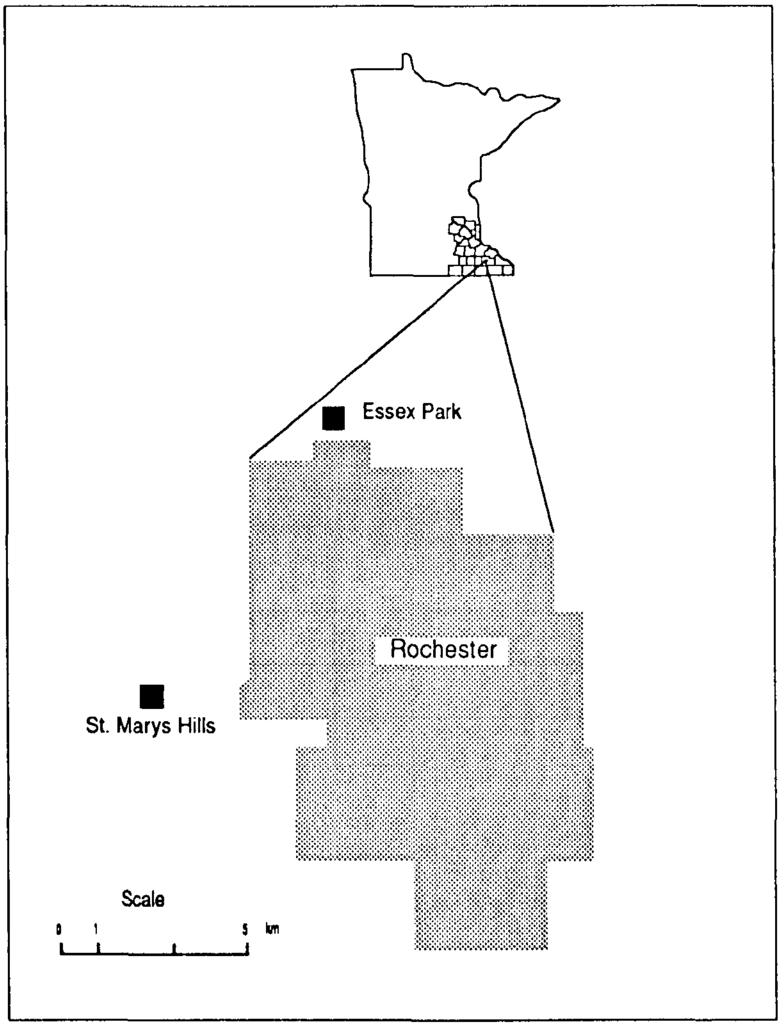

Figure 1. Map showing study areas near Rochester, Olmsted County, Minnesota

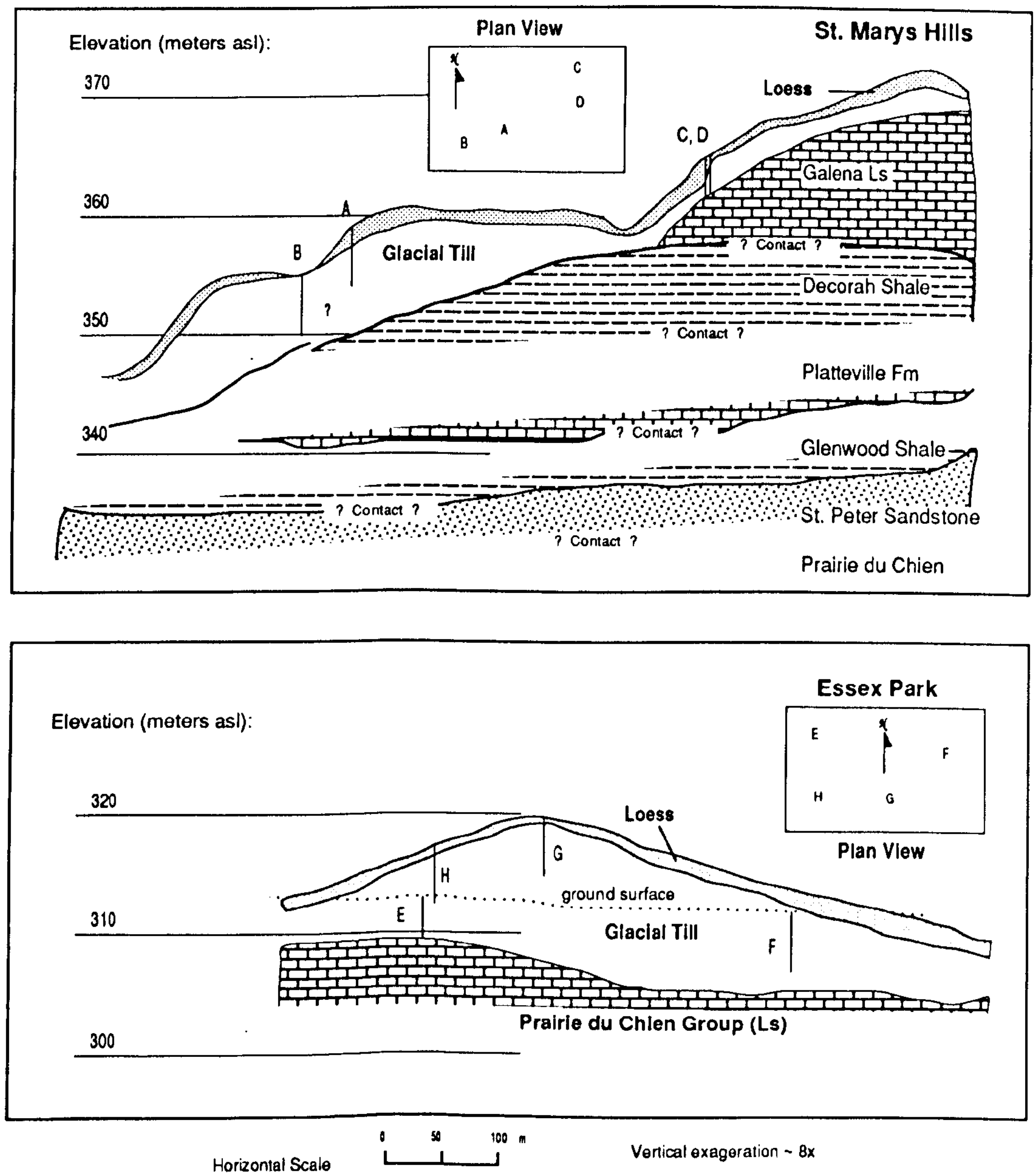

Figure 2. Profiles and location of sample holes. Modified from Plates 2 and 3, Olmsted County Atlas (4,5).

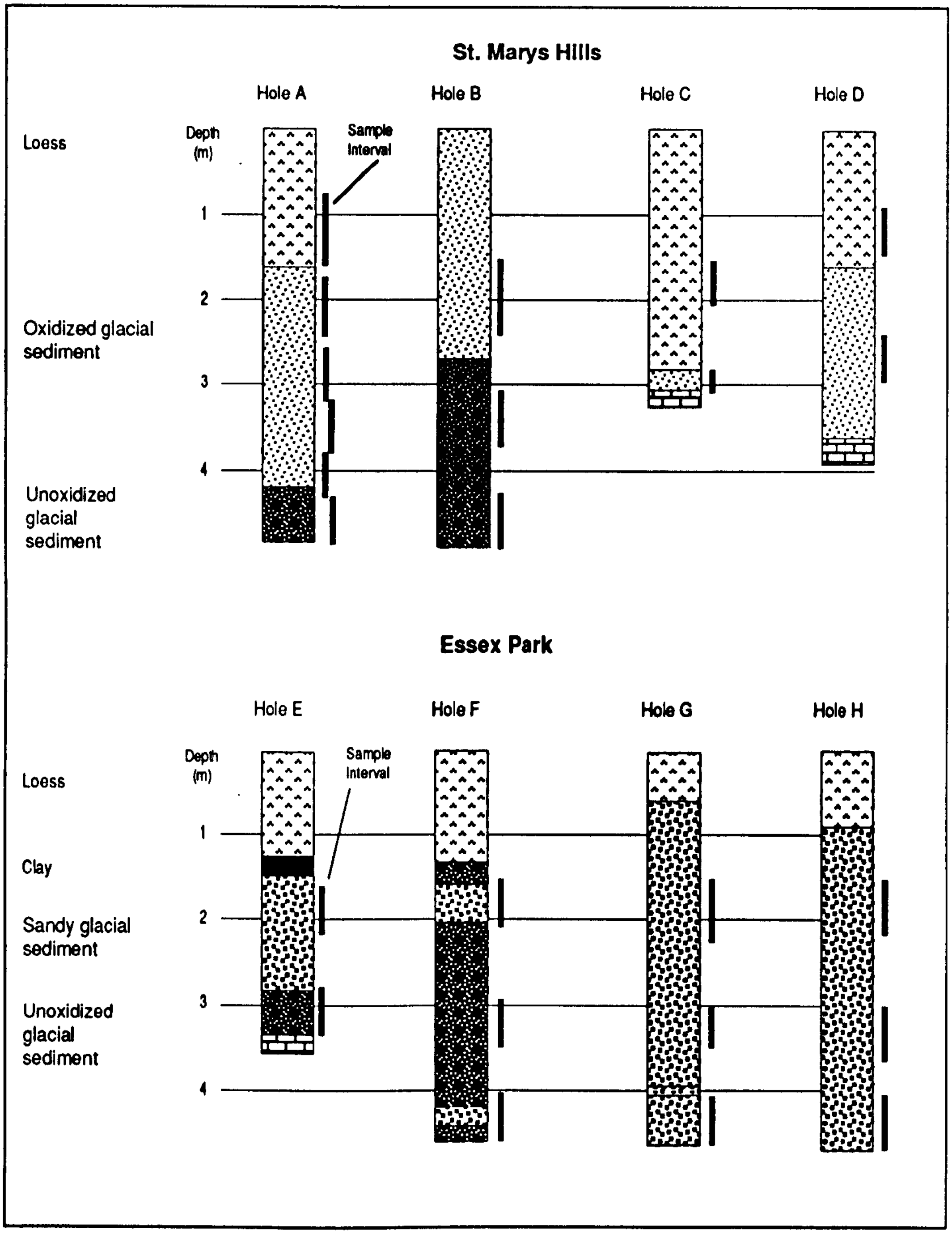

Figure 3. Borehole lithology and sample locations based on field identifications.

GEOLOGICAL PARAMETERS IN RADON RISK ASSESSMENT - A CASE HISTORY OF DELIBERATE EXPLORATION

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ABSTRACT

Geological exploration has identified an unsuspected radon-prone belt in southern California. Detailed analysis of aeroradiometric (NARR) data in relation to geological units, soil-gas radon, soil permeability, and finally indoor radon has identified the Rincon Shale and soils derived predominantly from the Rincon Shale in Santa Barbara County as anomalous in uranium and radon. Roughly 76% of our screening tests to date from homes on the Rincon Shale exceed 4 pCi/l and 26% exceed 20 pCi/l. Measurements under "normal" living conditions show 42% exceeding 4 pCi/l. An estimated 4,000 plus homes are at this level of risk; extensive new construction on the Rincon Shale is limited only by domestic water supply.

Unusually good correlations between aeroradiometry, soil-gas radon at 75 cm depth adjusted for soil-gas permeability, geology, and indoor radon concentrations reflect the unmetamorphosed character of sedimentary host rocks and the tendency for anomalous uranium concentrations to be disseminated throughout a geological unit rather than in erratic mineralized zones. Under these circumstances, deliberate geological exploration can be a more efficient approach to radon risk identification than simple random sampling or non-random testing of homes and by the same token geological parameters can facilitate radon risk assessment on undeveloped lands.

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RATIONALE

Two very different questions can be asked about the incidence and distribution of indoor radon concentrations:

1. What is the probability distribution of indoor radon concentrations among the entire stock of homes in a given region or in the country as a whole?

2. What is the probability of occurrence and the location of radon-prone areas within this given region? This latter question is of much greater interest to individuals.

Answers to the first kind of question, regional probability or frequency distribution, are usually estimated by statistical analysis of measurements from a simple random sample or probability sample of homes in the area of interest. Simple random sampling aims ideally to avoid bias by making every home equally selectable and, as a consequence, obliterating differences among sub-populations which may, or may not, exist within the whole. Ex-post-facto analysis of existing measurements from private and/or public sources is a less expensive and less reliable substitute. Aggregate regional frequency distributions so obtained are usually shown as approaching log-normality with characteristic arithmetic means from 0.8 to 11.3 pCi/l, geometric means from 0.6 to 3.3 pCi/l, and geometric standard deviations from 2.1 to 3.4 pCi/l. In reality the distributions are commonly very irregular, particularly at higher concentrations, and undoubtedly represent multiple populations each with its own characteristic frequency distribution.

The alternative approach, which we among others have taken, is to purposely explore for radon-prone areas using geological reasoning along with inexpensive, practical techniques modified from mineral exploration, engineering, or research methodology already in use or in the literature. In other words we have directly addressed the second kind of question: the probability of occurrence and the location of radon-prone sub-populations. There is now an extensive literature on sources, distribution, and measurement of radon in soils, and on its contribution to indoor radon which we will not cite in detail: a recent primary reference is Nazaroff, *et al.* (1). The following very brief summary establishes the principal assumptions for our work.

Given that the overwhelming preponderance of indoor radon is derived from underlying soils and rocks, and ultimately from U-238, the detection of anomalous natural radon sources is in large measure the detection of anomalous uranium concentrations and therefore quite analogous to the exploration for mineral deposits in general. Uranium is an ubiquitous element, present in trace amounts in all soils and rocks in concentrations ranging from as little as 0.2 ppm (parts per million) or less in sandstones, from 1 to 20 ppm in common igneous rocks, and to as much as 200 ppm, rarely 500 ppm in black shales. Ore-grade concentrations average from 500 to 28,000 ppm, locally much higher, across mineralized zones which are comparatively small, erratic and difficult to find.

Geological controls for uranium distribution are reasonably well known in principle. Lithological and geochemical methods of exploration, including radiometrics, are particularly useful but must take into account the differing geochemical properties of the several isotopes within the U-238 decay series and the consequent likelihood of departure from secular equilibrium. Uranyl ions produced during oxidative weathering, for example, are extremely soluble and mobile in contrast with the insoluble Th-234 and Th-230 compounds. Ra-226 behaves as an alkaline earth: its daughter Rn-222 is an inert gas. Natural secular disequilibrium is commonly found 1) where the deposition of uranium-bearing sediments or rocks (or the later introduction of uranium into host sediments or rocks) has taken place very recently - crudely less than ten million years or so - in which case the radioactive decay products will not have "grown in" completely and will be "deficient" relative to uranium content and 2) where the soluble uranyl ion has been leached from the near surface by weathering while thorium has not in which case the uranium decay products, and their associated radioactivity, may appear to be excessive in relation to uranium. Radium too can migrate from its source under near-surface conditions, in the same way as other alkaline earths. Radon gas, of course, moves easily unless confined which is why the radon content of soil gas close to the surface of the ground approximates that of ambient air even though radon content at depths of a meter or so ranges up to hundreds, thousands, or tens of thousands of pCi/l. Nevertheless, radon anomalies in soil-gas samples taken from comparable depths are often reasonably indicative of uranium anomalies nearby.

The predominant source of gamma radiation in the U-238 series detected by ground or airborne scintillometry is Bi-214 and as a result this isotope is the most widely used geochemical pathfinder in uranium exploration. The fact that Bi-214 is separated from Rn-222 in the decay series by only two extremely short-lived isotopes, Po-218 and Pb-214 helps to maintain a correlative relationship between radon and the observed Bi-214 gamma radiation in spite of the fugacity of radon and in spite of the fact that gamma radiation is essentially blocked by 20 cm or so of typical soil. Airborne gamma-ray spectrometry is an excellent uranium reconnaissance tool. Standard practice is to calculate an apparent uranium concentration from Bi-214 gamma-ray intensity as if secular equilibrium actually obtained and to report this apparent concentration as "equivalent uranium" (eU). This same technique and terminology is equally useful for concentrations of radon (eRn), radium (eRa) or other precursors of Bi-214 in upper layers of the soil.

Geological controls influencing near-surface radon concentration, given the distribution of radium in the underlying soil must take into account: 1) the proportion of Rn-222 newly-produced from Ra-226 able to escape from the solid mineral phase into soil gas - the "emanating fraction," 2) the distribution of fractures, shear zones or other pathways which facilitate upward radon migration and 3) soil-gas permeability. Of these three, soil-gas permeability is the most easily quantified for a particular site. Gas permeability of soils ranges over eight orders of magnitude in the extreme case of gravels and clays, although in typical soil categories the range is reduced to about four or five orders of magnitude (5×10^{-10} cm^2 for silt - clay mixtures to 5×10^{-6} cm^2 for coarse sand). Variations in the emanating fraction are too costly to evaluate and probably relatively insignificant for purposes of radon exploration. Fractures or other pathways are essentially impossible to quantify as controls but sometimes are recognizable visually or by geological inference as confounding factors in particular sites. The seasonal cracking of montmorillonite-rich soils to depths of as much as a meter, as in the case of Rincon-derived soils, may be characteristic of an entire formation and more important than soil permeability. Moisture content is a major non-geological variable - though not the only one - because of its affect on both the emanating fraction and soil-gas permeability. An optimum moisture content for combined radon emanation and migration has been observed by Stranden, et al. (2) at about 25%.

Recognizing all these complexities, and lesser ones, it can nevertheless be argued 1) that radium concentration or soil-gas radon concentration is a good measure of the "source strength" for radon in the soil and 2) that soil-gas permeability is a first approximation of the rate at which radon-bearing soil gas can reach the foundation of a building. A radon index number (RIN) which includes only the two parameters, soil radium concentration and soil-gas permeability was first suggested by DSMA Atcon, Ltd. (3). Tanner (4) subsequently proposed a radon availability number (RAN) defined as the product of soil-gas radon concentration, mean radon migration distance, and soil porosity. At about the same time Kunz, *et al.* (5) developed a simplified RIN based empirically on comparisons with indoor radon measurements in New York State. The Kunz formulation which we have adopted here is:

$$\text{RIN} = 10\,(\text{C})\,(\text{K})^{1/2}$$

where: C is soil-gas radon concentration (pCi/l)

K is the soil-gas permeability (cm^2)

The factor 10 was inserted by Kunz, *et al.* merely to make the RIN roughly comparable with their typical indoor radon levels.

A "depth factor," less than or equal to 1, is added by Kunz for areas where the depth to the water table, bedrock or substantially less permeable soil is known to be less than 10 feet.

The purpose of our work has been to test the practicality of deliberate radon exploration using aeroradiometrics, analyzed to the optimum, as a reconnaissance tool followed by application of the Kunz, *et al.* formulation and, where appropriate, by detailed site studies in a large populated portion of Southern California where the indoor radon risk inferred from random and non-random home tests has been purported to be very low.

For our study we chose the part of Southern California encompassed by the Los Angeles Sheet of the Geological Map of California. This is a one-degree by two-degree sheet (34^0 to 35^0 latitude, 118^0 to 120^0 longitude) including roughly the northern half of Los Angeles and extending from about 8 miles east of Pasadena to about 18 miles west of Santa Barbara.

We were fortunate in that shortly after initiating our analysis of aeroradiometric data, the California Department of Health Services began a three-month alpha track survey in a random sample of homes in a portion of our study area in northwestern Los Angeles - southeastern Ventura counties. Through DHS efforts 82 homeowners (out of a total of 171 DHS participants) made their properties available to us for brief examination, for soil and soil-gas sampling adjacent to the house and for surface gamma-ray measurements. The indoor radon measurements became available after our field measurements and these became the basis for calibration of our methodology.

METHODOLOGY

AERORADIOMETRIC RECONNAISSANCE DATA

Beginning in the mid 1970's, the U.S. Department of Energy sponsored the National Airborne Radiometric Reconnaissance (NARR) to provide a semi-quantitative evaluation of radioactive element distribution in the United States as part of the National Uranium Resource Evaluation (NURE) Program. Gamma-ray data were collected on K-40 for potassium, Tl-208 for thorium, and Bi-214 (using the 1.76 MeV photopeak) for uranium typically by means of helicopter at an average of 400 feet or less above ground surface fitted with a gamma-ray spectrometer and large crystal detectors. Primary flight lines are typically oriented east-west about 3 miles apart; tie lines are typically north-south and about 12 miles apart. Radiometric data were corrected for live time, aircraft and equipment background, cosmic background, Compton scatter, altitude, barometric pressure and temperature. In California the corrected data were statistically evaluated in terms of individual geological units as shown on the The Geologic Map of California. Statistical data were reported on eU ppm, eTh ppm, K %, and on their ratios to 0.01. The compiled data were also presented as pseudo-contour maps, stacked profiles, anomaly maps, and "geological histograms" which are frequency distributions of the e-concentrations and their ratios for each geological unit.

Stacked profiles show eU along each flight line and are the most site-specific graphic presentation of the data. Extrapolations can be made to specific sites between flight lines with varying degrees of reliability. We have done this using the appropriate geological histograms and eU anomaly maps as a basis for checking the extrapolations. The wide spacing of flight lines, particularly the north-south tie lines, and the small scale of the graphical reproductions introduce large uncertainties in the longer extrapolations. A striking case in point is the community of Summerland which is almost entirely on radon-rich Rincon Shale but also entirely between flight lines and therefore not shown as eU anomalous on the aeroradiometric diagrams or maps. The point we would make, however, is that our geological approach led us directly to Summerland, among other areas, as soon as we identified the Rincon Shale as eU and Rn-anomalous in the areas where we had data.

Aeroradiometric data for the Los Angeles Sheet were plotted by geological unit and informally subdivided into six categories having mean values between 1.0 - 1.9 ppm eU and 6.0 - 6.9 ppm eU.

Perhaps the main value of extrapolation between flight lines is that it makes possible the comparisons of aeroradiometric data with soil-gas radon concentrations and with indoor measurements both of which we discuss next.

SOIL-GAS RADON CONCENTRATION

We used the method of Reimer (6) to obtain soil gas samples: A stainless steel probe, 0.80 cm OD, 0.16 cm ID, is pounded into the soil to a depth of 75 cm, an O-ring fitting with a septum is attached and three successive 10 cc samples of soil gas are extracted by hypodermic syringe through the septum after purging the probe. The small diameter of the probe ensures minimal disturbance of the subsurface environment. The 75 cm depth is a compromise between probe refusal or bending and the more ideal depth of 1 to 1.5 m where radon concentration in soil-gas tends to reach an equilibrium value. It also enables sampling from the lower B or upper C horizon. Samples were always collected during the day, not during periods of unstable weather or strong winds, and not after precipitation until dry conditions are allowed to return. Special care was taken to sample natural soil away from any filled zone. The time of sampling was recorded.

Soil-gas samples were then taken to the laboratory for radon measurement by injecting the sample through a valve and septum device into a Lucas cell radon/radon daughter detector (RDA 200, manufactured by EDA Instruments, Inc.). Measurements were made 3 to 24 hours after soil gas sampling, more than sufficient time for decay of Ra-220 (thoron). Earlier experiments showed that radon daughters in the original soil-gas sample or generated up to the time of injection into the Lucas cell are plated out in the hypodermic syringe. Since there is also some adsorption of radon, particularly on the syringe plunger, and other potential complications, the entire assemblage of components for sampling and analysis was calibrated as configured against known radon-bearing gas samples from the EPA operated chamber at Las Vegas, Nevada. Each Lucas cell was partially evacuated to a standard pressure prior to sample injection. Early experiments also showed that truly consistent results require 25 minutes of counting in the Lucas cell detector. Counts up to 5 minutes were found to be insufficiently consistent for the research stage of our work and were omitted from the calculations. Even at moderate concentrations of radon, however, this long counting period results in appreciable contamination of the Lucas cells, as Reimer points out, and for reconnaissance purposes much shorter counting periods may be acceptable.

The formula used to calculate radon concentration is:

$$C = (N_{30} - N_5 - CB) / (T \times SV \times DF \times CF)$$

where:

C = Rn-222 concentration in pCi/l

N_{30} = Counts in 30 minutes

N_5 = Counts in 5 minutes

CB = Cell background prior to sample injection

T = Counting period: 25 minutes

SV = Sample volume: 0.01 liters

DF = Decay factor for radon for elapsed sampling-to-counting time: from standard table.

CF = "Cell Factor" in cpm/pCi from calibration of configured apparatus using known radon chamber samples.

Prior to sampling in the study area, the following indications of precision and reproducibility were obtained from a test plot:

1) Radon measured from soil-gas samples at 75 cm depth from 9 probe sites within a square meter yielded a Gaussian distribution, arithmetic mean = 1,071 pCi/l, standard deviation = 106 pCi/l (coefficient of variation = 10 %).

2) Radon measured from five soil gas samples consecutively drawn from one probe site in the same plot yielded a Gaussian distribution, arithmetic mean = 1,052 pCi/l, standard deviation = 85 pCi/l (coefficient of variation = 8 %).

Standard procedure in the primary subarea was to occupy three probe sites within 0.5 to 4 meters of each house and to take three soil-gas samples at 75 cm depth from each site. If the first two radon analyses from a given probe site were within ten percent of each other, the third sample was discarded, otherwise it was measured. The soil-gas radon value reported for each house location is the mean of the three probe sites. The variation coefficient for each house location ranged from 1.1 % to 63.3 % with a mean of 18.5 %.

SOIL-GAS PERMEABILITY

Recent studies including those of Kunz and Tanner previously cited have adopted a quantitative determination of soil-gas permeability based upon measured gas flow under measured differential pressure during pumping of gas from the ground or pumping of air into the ground. However this apparently rigorous method rests upon assumptions about the size and geometry of the soil volume from which the gas is drawn or pumped into even in the case of uniform soil profiles. It is unclear even in presumably homogeneous soils whether the geometry of the soil volume should be assumed to be spherical or hemispherical, for example. Many soils are not only layered but are randomly penetrated by fractures, root cavities or animal burrows or contain irregular layers of varying permeability.

In-situ measurement of water permeability is not truly indicative of in-situ gas permeability nor are gas permeability measurements on reconstructed soils.

Bearing in mind cost and practicality we have adopted the technique of permeability estimation based upon grain size distribution determined by screening the dried soil. This method is eminently suitable for reconnaissance work and perhaps as good as any for detailed follow-on studies, It has the advantage not only of simplicity but also of avoiding the potentially large errors that might arise during flow-guage-volume pumping measurements due to openings in the soil or zones of varying permeability which are entirely site-specific on a small scale and therefore not necessarily representative of the area under consideration.

Soil samples taken at depths of 25 to 35 cm from the same sites as soil-gas samples were oven dried overnight at 100 degrees C. and sieved by mechanical shaker. Soil types were categorized and permeabilities were assigned on the basis of published tables, e.g. Sextro, *et al.* (7). Because of the large number of samples involved we did not perform wet separation of clay and silt. Even more significant is the disregard of moisture content and degree of compaction or cementation of the soil. Perhaps the permeability assigned in this way should be called pseudo-permeability or at best equivalent permeability but the method is as likely as any to provide a basis for comparison with reasonable cost. Moreover it should be noted that permeability appears in the RIN formulation, above, only as its square root.

RESULTS FROM THE PRIMARY SUBAREA IN NORTHWESTERN LOS ANGELES - SOUTHEASTERN VENTURA COUNTIES

HOUSE CHARACTERISTICS IN THE PRIMARY SUBAREA

Mention was made above of the 82 homes in the DHS three-month alpha track survey which were made available to us for soil-gas radon and soil permeability measurements. Questionnaires about house design and use were completed by all participants. None of the houses had indoor measurements in excess of 2.9 pCi/l and we were not able to show that any of the adjacent soils had more than normal gamma-ray activity at the ground surface using a hand-held scintillometer with a one cubic inch Tl activated NaI crystal. None of the 82 houses have a basement and only 4 % have crawl space construction; the rest are slab-on-grade. Ventilation patterns were approximately similar during the test period which was characterized by mild coastal and near-coastal Southern California weather. It would appear that in this survey building characteristics and meteorological factors probably had less-than-average influence on indoor radon levels.

AERORADIOMETRIC DATA, SOIL-GAS RADON, RIN AND INDOOR RADON IN THE PRIMARY SUBAREA: CORRELATIVE RELATIONSHIPS

Figure 1 shows the relationship observed between airborne equivalent uranium (eU) and soil-gas radon concentrations obtained by soil probe from the vicinities of the 82 houses in the primary subarea. The strength of the correlation probably reflects the proximity of Rn-222 and Bi-214 in the decay series but was somewhat surprising and encouraging nevertheless.

Figure 2 shows the relationship observed between indoor radon and soil-gas radon for the 82 houses in the primary subarea. Again the correlation is very encouraging in spite of some scatter. We believe that it probably reflects in part the similarity between house parameters noted above. However it may also reflect the relatively well-ventilated character

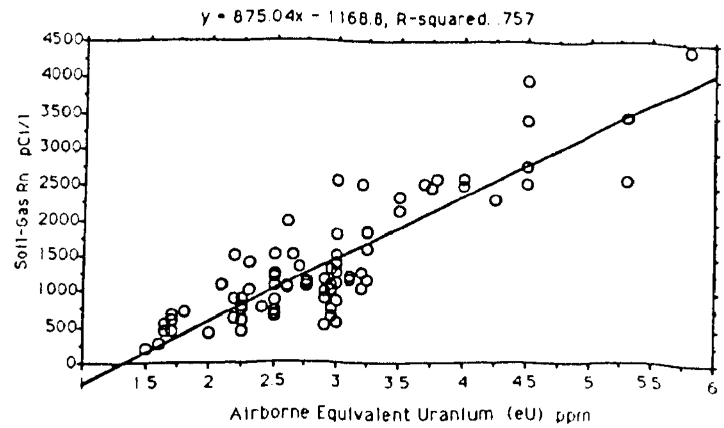

Figure 1. Soil-gas radon in relation to airborne equivalent radon in the primary study area.

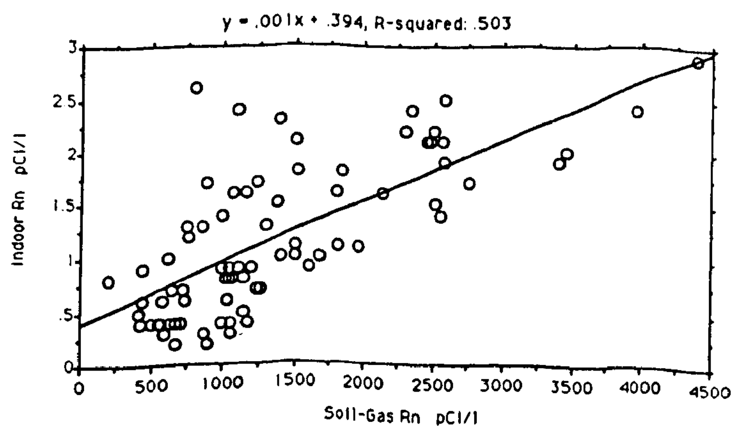

Figure 2. Indoor radon in relation to soil-gas radon in the primary study area.

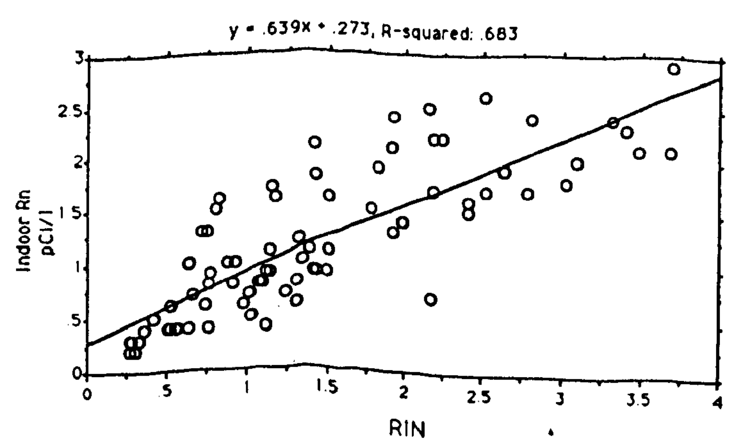

Figure 3. Indoor radon in relation to RIN in the primary study area.

of nearly all homes in the region because, even though some soil-gas radon concentrations were between 2,000 and 4,500 pCi/l, the maximum indoor radon level was only 2.9 pCi/l.

Figure 3 shows the relationship observed between indoor radon and the RIN value. The essential difference between soil-gas radon and RIN is that soil-gas permeability is taken into account in the latter. It is not surprising therefore that the correlation of indoor radon with RIN value is even better than with soil-gas radon.

Equivalent uranium extrapolated from the NARR data in the primary subarea shows a range of 1.5 to 5.8 ppm eU, an arithmetic mean (AM) of 2.9 ppm, a geometric mean (GM) of 2.8 ppm, and an arithmetic standard deviation (ASD) of 0.86 ppm. For soil-gas radon concentrations the range is from 206 to 4,390 pCi/l and the remaining statistics are: AM = 1,388 pCi/l, GM = 1,162 pCi/l and ASD = 859 pCi/l. Indoor radon shows a range of 0.2 to 2.9 pCi/l, and AM = 1.2 pCi/l, GM = 0.99 pCi/l, ASD = 0.70 pCi/l. All three frequency distributions are skewed toward a log-normal pattern but are quite irregular and the sample size is insufficient to demonstrate log-normality.

DISCOVERY OF THE RADON-PRONE RINCON SHALE BELT

AERORADIOMETRIC INDICATIONS

As shown in Figure 1 the primary subarea yielded relatively low airborne eU values. In fact none of the 82 houses tested is underlain by a geological unit with a truly anomalous mean eU level: the highest category is 4.0 to 4.9 ppm eU. However the excellent correlations between eU, soil-gas radon and indoor radon at the low levels observed demanded that we re-examine the aeroradiometric map.

In the northwestern Los Angeles - southeastern Ventura region itself there are a few geological units in category 5.0 to 5.9 ppm eU but these are predominantly in undeveloped terrain. However, to the west of the primary subarea, passing through major parts of Santa Barbara city and vicinity, there is a pronounced east-westerly trending belt with eU in category 6.0 to 6.9 ppm and an adjacent belt in category 5.0 to 5.9 ppm eU. Both of these belts coincide with the generalized unit "ML" (Lower Miocene) as shown on the Los Angeles Geological Map Sheet. ML in this area could encompass parts or all of three geological formations and several members. Lithology pointed to two possible uranium-rich candidates: the dark, moderately organic Rincon Shale and the lower Monterey Formation which is locally organic and locally phosphate-bearing. Uranium tends to associate with organic matter and with phosphate. Probe soil-gas sampling and analysis, followed by radon screening tests in a handful of houses, very rapidly identified the Rincon Shale as the undoubted source of most, if not all, of the anomalous airborne signature.

RADON IN THE RINCON SHALE

To date we have made soil-gas radon measurements at 68 sites on the Rincon Shale extending from near the easterly boundary of Santa Barbara County to Gaviota on the west; a strike length of about 48 miles. The range of radon concentrations is from 1,240 to 16,200 pCi/l, with an AM of 4,480 pCi/l, GM of 3,817 pCi/l, and an ASD of 1,891 pCi/l. The mean values are more than three times higher than the means of soil-gas radon concentrations in the primary study or in non-Rincon units in Santa Barbara County and elsewhere in Southern California that we have tested to date. It may be geologically significant that the highest soil-gas radon concentrations appear to be near the middle of this belt, near Santa Barbara itself, though more data need to be obtained on the east and the west to confirm this pattern. The frequency distribution of soil-gas radon values is bimodal.

INDOOR RADON MEASUREMENTS IN HOUSES ON THE RINCON SHALE

We have now tested 79 homes in Santa Barbara County, the great majority in easterly Santa Barbara city, Montecito and Summerland. Thirty three of these homes are on the Rincon Shale. Slightly over 76 % of the homes on the Rincon Shale have screening test results (three 3 to 7-day activated charcoals) in excess of 4 pCi/l. Twenty six percent exceed 20 pCi/l. Follow-on alpha track measurements of from one to six months duration, under normal living conditions show 42 % exceeding 4 pCi/l and none exceeding 20 pCi/l although some of the worst situations were mitigated prior to completion of the follow-on measurement. Only one home not on Rincon Shale has a follow-on measurement exceeding 20 pCi/l and that home is on a slide area with a badly cracked slab-on-grade at the time of measurement and, almost certainly, deeply cracked soil underneath.

Edward Keller of the Geology Department, University of California Santa Barbara has confirmed our statistics very closely by providing single activated charcoal detectors to nearly 100 homeowners on and off the Rincon Shale (8). An estimated 4,000 plus homes are at the indicated level of risk; extensive new construction on the Rincon Shale is limited only by domestic water supply.

COMPARISONS BETWEEN AREAS AND DISCUSSION

Figures 4, 5 and 6 illustrate relationships between the same parameters as figures 1, 2 and 3 except that these figures represent the two areas combined, i.e. the primary study subarea plus the Santa Barbara Rincon Shale area on the same graphs. The Santa Barbara County data points are indicated with a tick on the circular data symbols. We do not yet have all three categories of data on more than a few houses, hence the small number of

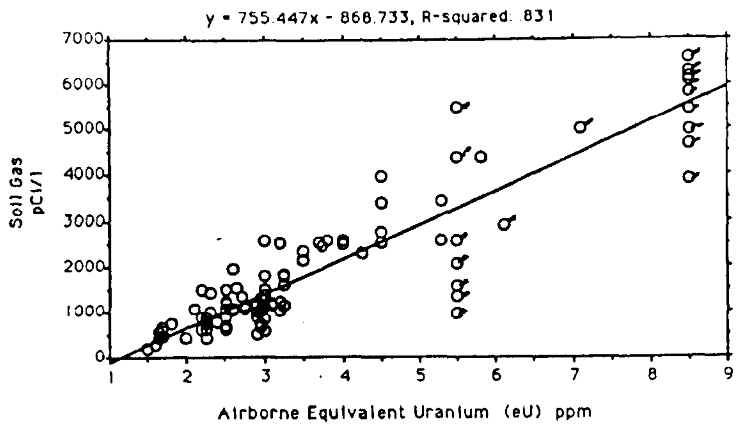

Figure 4. Soil-gas radon in relation to airborne equivalent radon in the entire study area.

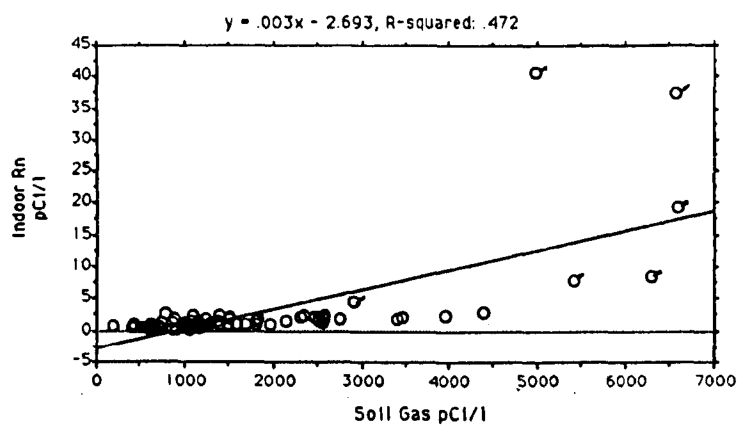

Figure 5. Indoor radon in relation to soil-gas radon in the entire study area.

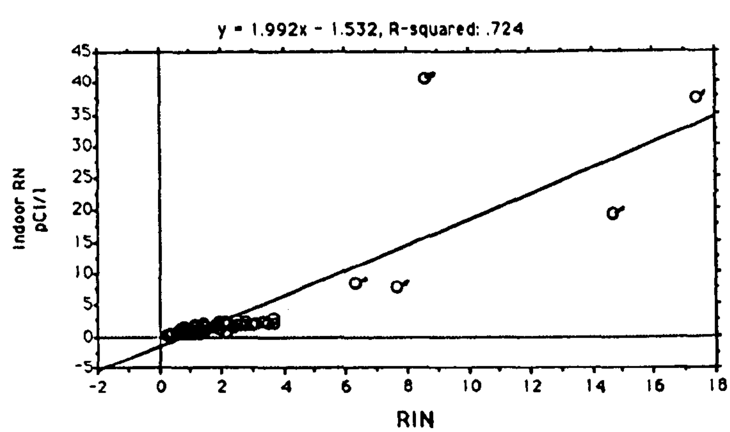

Figure 6. Indoor radon in relation to RIN in the entire study area.

Santa Barbara points. The considerable range in indoor radon relative to soil-gas radon or RIN illustrates the very considerable influence of building design and use in this radon-prone area.

The purpose of combining the data in figures 4, 5 and 6 is not only to make the comparison between areas more visible but also to show that the two areas actually represent two quite different populations. Note that the regression lines shown for the combined data depart considerably from the regression lines for the primary subarea data. The existence of sub-populations needs to be kept in mind whenever attempts are made to use regional frequency distributions of radon occurrence as a basis for predicting national or regional radon risk.

The correlations that we have obtained regionally between aeroradiometry, soil-gas radon at 75 cm depth adjusted for soil-gas permeability, geology, and indoor radon concentrations are apparently better than those reported from other places. In our opinion this probably reflects the fact that the unmetamorphosed sedimentary rocks that we find in much of coastal and central California tend either to have or not to have anomalous uranium concentrations disseminated more or less throughout the unit. This is not to say that erratic uranium-rich zones do not occur in these same rocks: there are many examples of small quite rich uranium concentrations in the Monterey, in the Sespe and several other unmetamorphosed formations. The locations of these erratic concentrations are extremely difficult to predict but, unlike some situations in metamorphosed terrains for example, such concentrations are few and far between. Anomalous amounts of uranium disseminated throughout a rock unit can affect a large number of homes but it is especially in these circumstances that deliberate geological exploration can be a more efficient approach to radon risk identification than simple random sampling or non-random testing of homes. Judging by experience in the mineral industry, exploration based upon geological models of occurrence is infinitely more likely to find anomalous occurrences than is random sampling. Models for geological predictability can also contribute to radon risk assessment on undeveloped tracts of land.

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Session IX:

Radon Occurrence in the Natural Environment -- POSTERS

GEOLOGIC EVALUATION OF RADON AVAILABILITY IN NEW MEXICO:
A Progress Report

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ABSTRACT

The New Mexico Bureau of Mines and Mineral Resources and the Radiation Licensing and Registration Section of the New Mexico Environmental Improvement Division in cooperation with the U.S. Environmental Protection Agency (EPA) have been evaluating geologic and soil conditions that may contribute to elevated levels of indoor radon throughout New Mexico. During the first phase of this evaluation, New Mexico lands have been subdivided into three provisional radon-availability categories (high, moderate, and low). Data sources include 1) aerial radiometric surveys; 2) uranium-resource evaluations; 3) reports on lithologic character and structure of major geologic units, 4) hydrogeologic and geochemical information; and 5) soil surveys (including data on particle size, clay minerals, moisture regimes and permeability). This information was used in selection of private homes tested during an initial random survey of indoor radon in 1989. The New Mexico radon survey was unique in that it was the first in the nation to successfully use a decentralized strategy in the attempt to place charcoal canisters randomly across a state. Results of 1775 homes tested throughout New Mexico during January to March, 1989 indicated that 24% had indoor-radon screening results exceeding the recommended EPA guideline of 4 picocuries per liter of air (pCi/L). Visits were also made to about 50 home sites in north-central New Mexico where preliminary surveys (random and volunteer) indicated that geologic and soil conditions were the major factors contributing to elevated indoor-radon levels (>10 pCi/L).

Studies to date suggest that elevated radon levels are commonly associated with hillside building sites where floors and walls are contiguous to geologic units such as highly-fractured bedrock of varying lithology, limestones with solution enlarged joints, or thick pumice deposits. Bedrock units, associated alluvial-colluvial deposits, and ground water that contain high concentrations of uranium and thorium locally make a significant contribution and need further study. Some homes built on clay-rich expansive soils also have elevated levels of radon. Areas that have been tested in the vicinity of uranium mines and mills have relatively low levels of indoor radon (below 10 pCi/L). A better understanding of the natural factors that affect indoor radon concentrations in New Mexico will only be gained through integrated, site-specific investigations which combine more comprehensive indoor-radon

measurements and home construction information with data on geology, hydrology and soils.

INTRODUCTION

Concern about public health risks to the general population of the State of New Mexico from exposure to radon gas and its decay products in homes, schools, places of employment and office buildings, has been raised over the past few years by the medical, scientific communities, and government agencies. Concern raised by these interest groups has subsequently alerted the general public. While other factors such as cigarettes contribute to lung cancer deaths each year, airborne radon gas exposures may be accountable for 15% to 20% of all lung cancer deaths in the United States.

In 1989, in an effort to evaluate the levels of radon which contribute to public health risks associated with radon exposure in New Mexico, the Radiation Licensing and Registration Section (RLRS) of the Environmental Improvement Division (EID) and the Environmental Protection Agency (EPA) initiated a random radon-screening survey of private homes throughout the State. Such a screening test offers the homeowner an indication of indoor levels of radon gas at a given point in time. This test is of short duration and does not provide information over a long period of time. The EPA recommends that exposure levels be calculated in terms of an annual average before any further action is undertaken. The short screening test is only an indication of the indoor-radon level; and, for this reason, the charcoal canisters are placed in individual homes where they would produce the highest measurements or "worst case conditions." Therefore, tests are conducted in the winter months when closed-house conditions are most likely to be observed. If these screening tests show radon levels of 4 picocuries per liter of air (pCi/L) or above, then it is recommended that long term testing be conducted. If follow-up testing confirms high radon levels, the EPA suggests that a mitigation program should be undertaken. This report outlines the methods used in the random selection of homes for radon-exposure measurements, and gives a preliminary interpretation of the results from this screening.

Results from 1775 houses tested during January to March of 1989 indicate that about 24% of those tested had radon screening results at or above the EPA "action-level" guideline of 4 pCi/L. All of the results of this radon survey indicate "worst case" screening conditions for radon gas tests. The resulting numbers only indicate the homes with a potential radon problem. About 5% of the homes tested had concentrations greater than 10 pCi/L and only about one percent exceeded 20 pCi/L with a maximum value of about 105 pCi/L.

The New Mexico radon survey was unique in that it was the first in the nation to successfully use a decentralized strategy in the attempt to place charcoal radon test canisters randomly across a State. The eighteen states which had previously participated jointly with EPA in randomly placing canisters in owner-occupied homes had relied upon centralized phone calling and canister distribution. Additionally, New Mexico utilized Environmental Improvement Division staff resources (central office, district and field offices) in placing the canisters as well as volunteers from the City of Albuquerque Environmental Health staff and other organization volunteers. This strategy was selected since EID District and Field office staff were known to be familiar with the population centers in their areas as well as with the more isolated areas. Project staff predicted that increasing the proximity of staff to homeowners contacted would also increase the success of the canister placement. Other states had either contracted outside private companies in their canister placement program or had utilized staff and volunteers working from one central location.

New Mexico's decentralized program resulted in the placement of 50 canisters in two days for use in the pilot survey. Past experience in other states had resulted in a pilot project placement time of seven days. While other states required an average of two to three months to place over 2000 canisters, New Mexico successfully placed 1775 canisters in less than six weeks.

Staff believe that the decentralized radon canister placement method used in New Mexico is more cost effective, utilizes existing staff, can be implemented in a more timely fashion and provides indoor radon analytical results more quickly to Health and Environment staff at the local levels. Staff also recommend that the decentralized placement method be used in other states with sparse and widely distributed populations. New Mexico's experience has demonstrated the usefulness of such a strategy.

Another important aspect of the New Mexico survey was the evaluation of geologic, soil and hydrologic conditions that might contribute to elevated levels of indoor radon throughout the state. This work was done by the staff of the Office of State Geologist, New Mexico Bureau of Mines and Mineral Resources (NMBMMR). During the first phase of this investigation, New Mexico counties were placed in three provisional radon-availability categories (high, moderate and low). Data sources included 1) aerial radiometric surveys; 2) uranium-resource evaluations, 3) reports on lithology and structure of major geologic units; 4) hydrogeologic and geochemical information and 5) soil surveys (including data on particle size, clay minerals, moisture regimes, and permeability). This information was used to help the EPA set the random selection of homes for the initial screening survey just discussed.

PRELIMINARY STUDIES (1986-1988)

Preliminary studies prior to the 1989 survey involved 1) random, short-term screening during the winter of 1986-1987 of homes in north-central New Mexico, and 2) a 1988 statewide evaluation of natural conditions that could significantly influence elevated indoor radon levels.

Preliminary Screening Survey of Homes

In order to evaluate the distribution and concentration of radon gas throughout the State of New Mexico, the Radiation Licensing and Registration Section (RLRS) of the NMEID, in conjunction with the four district offices began the screening survey of randomly pre-selected homes in New Mexico.

NMEID staff provided the man hours for the screening process. Materials for testing were provided by EPA, training for EID personnel was handled by EPA staff. Materials for public outreach and educational materials were also provided by EPA. The list of homes was randomly selected by the EPA Statistical Staff. Homeowners' names, phone numbers and addresses after being randomly selected by EPA staff, were used to do the screening.

Another important aspect of the screening survey was a study of the geographic distribution of radon gas in an indoor environment. A preliminary study was conducted in the winter months of 1986-1987 by EID staff in the north-central areas of the State using working level meters in volunteer homes. Either a 24- or a 48-hour period was used to determine the average radon gas concentration and these two values were averaged for reporting purposes. Standard EPA protocol was adhered to throughout the screening process. Results of this preliminary survey were tabulated by counties.

Preliminary Evaluation of Natural Conditions Influencing Indoor Radon (1988); New Mexico Bureau of Mines and Mineral Resources

A major objective of the preliminary phase of this study was to identify and characterize areas in New Mexico where natural conditions (e.g. geology, hydrology, and soils) had the potential for making significant contributions to elevated indoor radon values. Such areas needed to be identified so that a larger percentage of radon detectors could be allocated to those localities during the 1989 survey conducted by the NMEID in cooperation with the EPA. This phase of the investigation (McLemore and Hawley, 1988) was conducted by the New Mexico Bureau of Mines and Mineral Resources-Office of State Geologist (NMBMMR).

Rocks and soils in New Mexico were initially grouped into three radon-availability categories based on geologic and hydrologic interpretations, which are specific to New Mexico conditions. Subsequently, each county and the major cities in the state were given a radon-availability rating based on the predominant availability category established for geologic units in that area (Tables 1 and 2, Fig. 1).

TABLE 1. PRELIMINARY RADON-AVAILABILITY RATING FOR COUNTIES IN NEW MEXICO.

High	Moderate	Low
Doña Ana	Bernalillo	Curry
Hidalgo	Catron	De Baca
Los Alamos	Cibola	Guadalupe
Luna	Chaves	Harding
McKinley	Colfax	Mora
Rio Arriba	Eddy	Otero
Sandoval	Grant	Roosevelt
Santa Fe	Lea	San Miguel
Socorro	Lincoln	Torrance
Taos	San Juan	Valencia
	Sierra	
	Quay	
	Union	

TABLE 2. PRELIMINARY RADON-AVAILABILITY RATING FOR SOME OF THE LARGEST CITIES IN NEW MEXICO (POPULATION FROM WILLIAMS, 1986; POPULATION IN PARENTHESES FROM U.S. CENSUS BUREAU FOR 1990 AS REPORTED IN THE ALBUQUERQUE JOURNAL, JANUARY 26, 1991).

City	County	Population 1984 estimates (1990)	Classification
Albuquerque	Bernalillo	350,575 (384,736)	moderate
Santa Fe	Santa Fe	52,274 (55,859)	high
Las Cruces	Doña Ana	50,275 (62,126)	high
Roswell	Chaves	45,702 (44,654)	high
Farmington	San Juan	37,332 (33,997)	low
Hobbs	Lea	35,029 (29,115)	moderate
Clovis	Curry	33,424 (30,954)	moderate
Carlsbad	Eddy	28,433 (24,952)	high
Alamogordo	Otero	27,485 (27,596)	low
Gallup	McKinley	20,959	high
Los Alamos-White Rock	Los Alamos	19,040	high
Las Vegas	San Miguel	15,364	low
Grants-Milan	Cibola	12,823	moderate
Rio Rancho	Sandoval	12,310 (32,505)	moderate
Artesia	Eddy	11,938	low
Lovington	Lea	11,704	moderate
Silver City	Grant	11,014	low
Portales	Roosevelt	10,456	low
Deming	Luna	10,609	high

It should be emphasized that, even in counties with moderate and high availability ratings, many houses may have very low levels of indoor radon. Procedures used in developing the preliminary rating scheme are discussed in more detail in the following sections.

RADON AVAILABILITY AS A FUNCTION OF GEOLOGY AND SOILS

Introduction

The first step in formulating a sample plan for the survey of indoor radon levels in New Mexico was to evaluate the rocks and soils for radon-availability (McLemore and

Hawley, 1988). Major geologic factors influencing radon-availability include 1) lithology and uranium or radium content of bedrock and unconsolidated geologic deposits, 2) rock structure (faults and fractures), 3) porosity and permeability, and 4) nature of the water in both the saturated and unsaturated zones. Texture, structure, mineralogy, and moisture regimes of surficial soils (~upper 2 meters of unconsolidated earth materials) are also major factors influencing radon availability (Brookins, 1986, 1990; Brookins and Enzel, 1989).

The primary information sources used were published reports and unpublished records in the NMBM&MR files including data from 1) aerial radiometric surveys, 2) geologic maps, 3) uranium resource surveys, and 4) soil surveys. Other sources of information include special reports on geochemical and groundwater investigations, and a limited amount of data on indoor radon concentrations. This information was compiled by McLemore and Hawley (1988) in order to provide the EPA and the NMEID with a preliminary estimate of radon-availability for their 1989 program to randomly sample individual New Mexico homes.

In the fall of 1989 about 50 sites in north-central New Mexico with elevated indoor radon levels (10-105 pCi/L) detected in the random survey were visited as part of a cooperative study with the EPA on indoor-radon mitigation strategies. At that time, detailed observations were also made of on-site geologic and soil conditions that could contribute to indoor radon. This is the only follow-up verification of preliminary test results made to date.

Aerial Radiometric Surveys

Aerial radiometric surveys provide (Duval, 1988) a regional estimate of uranium concentrations in the surficial rocks and soils and correlate well with the amount of radon in the ground (Peake and Schumann, in press). However, it must be emphasized that the amount of radon that is available to enter a house from the ground is dependent upon many other variables. The primary source for aerial radiometric data in New Mexico is a series of reports prepared as part of the National Uranium Resource Evaluation (NURE) program. The NURE program was established in 1974 and terminated in 1984 and the main objectives were 1) to provide an assessment of the uranium resources in the United States and 2) to identify areas of uranium mineralization.

Aerial radiometric data are dependent upon a constant altitude above the ground. However, in some areas of New Mexico where there are steep mountains and deep canyons, constant altitude could not be maintained, resulting in erroneous measurements. Both airplanes and helicopters were used to collect data in New Mexico and helicopters were able to better maintain constant altitude than airplanes.

The NURE aerial radiometric data has been released in reports based on 1° x 2° topographic quadrangles and on magnetic tape. The quadrangle reports include a brief narrative and graphs of the flight line data, uranium anomaly maps, and histograms of the radioactivity data by lithology. Aerial gamma-ray contour maps of regional surface concentrations of uranium, potassium, and thorium in New Mexico has been recently published by the U.S. Geological Survey at a scale of 1:750,000 (Duval, 1988). A colored contour map of the state showing radiometric equivalent uranium (eU) concentrations was also prepared by the U.S.G.S. at a scale of 1:1,000,000 from the computerized aerial radiometric data. Copies of this map are available for inspection at the NMBM&MR and NMEID.

Several problems exist with the aerial radiometric data. Most 1° x 2° quadrangles in New Mexico were flown with east-west flight line spacings of three miles. However, parts of the Tularosa and all of the Carlsbad, Raton, and Ft. Sumner quadrangles (parts of Chaves, Colfax, De Baca, Doña Ana, Eddy, Guadalupe, Lincoln, Sierra, Taos and Torrance Counties) were flown with six mile spacings. Large unmeasured areas exist between these flight lines and localized anomalies may be overlooked. In addition, not all areas of New Mexico were flown. The largest area of no data is in the vicinity of the White Sands Missile Range north of Las Cruces and west of Alamogordo, primarily in Doña Ana and Otero Counties.

In the southwestern part of New Mexico, atmospheric inversions are known to occur frequently and may result in uncompensated U-air anomalies. Atmospheric plumes generated by copper smelters in southwestern New Mexico and southeastern Arizona also may result in uranium anomalies in the surveys. The effect of these atmospheric anomalies in predicting elevated levels of indoor radon is unknown.

The extremely high uranium anomalies in the aerial radiometric data (>5 ppm eU) near Grants, Cibola County, are a result of high values measured over mill tailings at four uranium mill sites. The computer-generated aerial radiometric maps produced by the U.S. Geological Survey exaggerate the significance of these anomalies; the actual area affected by the mill tailings is small. Surveys conducted by the NMEID and Homestake Mining Company suggest that mill tailings have not contributed to indoor radon levels in nearby houses. Capping of mill tailings and other remedial measures are in progress in this area of New Mexico.

General Geologic and Soils Information

Information on the type and distribution of the lithologic and structural units in New Mexico is important in identifying areas of radon-availability for indoor-radon generation. Published geologic maps, primarily the New Mexico Geological Society (1982) State Map and NMBMMR State Uranium Resources Map (McLemore and Chenoweth, 1988), were used in the preliminary phase of the study.

There are very few direct measurements of radon or radium concentrations in the rocks and soils of New Mexico; however, data on uranium concentrations in rocks and soils of New Mexico is more plentiful. Rocks with uranium concentrations exceeding 5 ppm U are sufficient to produce elevated levels of indoor radon (Peake and Hess, 1987). In New Mexico, most rock types could provide a source for indoor radon.

In addition to lithology, structural features also play an important role in many areas. Fault zones and other areas of highly jointed rocks are likely sites of uranium mineralization; and they also provide a pathway for radon to migrate into houses (Ogden et al., 1987). Karst (rock dissolution) features in carbonate and gypsiferous terranes may also provide pathways for migration of radon. Highly permeable and porous rocks and soils (such as pumice, poorly welded tuffs, sand and gravel, and expansive clays) are also potential source materials that need to be evaluated throughout the state.

Uranium Occurrences

Areas of uranium and thorium occurrences (as well as mine-mill sites) are well known in New Mexico (McLemore, 1983; McLemore and Chenoweth, 1989). The majority of these areas are found in relatively unpopulated parts of the state; however, there are a number of important exceptions. Uraniferous coals in the Gallup area, McKinley County, were once mined for uranium, and the host rocks are probably a good source for radon. Other areas, such as northern Santa Fe County, and White Signal in Grant County, occur at sites of uranium mineralization near or at the surface that could provide radon in nearby houses. Some indurated caliche (calcrete) horizons in soils and surficial geologic formations may also be sources of elevated uranium-radium-radon levels. More detailed studies of the correlation of known uranium and thorium occurrences, population distribution, and indoor radon levels are required.

Soil Surveys

Soil textural, permeability, and mineral data from soil surveys prepared by the U.S. Soil Conservation Service are an important data base for any assessment of radon availability. Well-drained, permeable soils, typically with hydraulic conductivity measurements exceeding 6 in/hr, provide excellent pathways for radon. Many areas of elevated radiometric- equivalent uranium (eU) concentrations shown on the aerial radiometric map are also associated with permeable soils. However, the soil permeability data used in this preliminary study is generalized and based on very few actual measurements of hydraulic conductivity. Also soil-moisture regimes vary significantly on a seasonal as well as an annual basis, and they can materially affect permeability values. Clay-rich soils with high shrink-swell potential develop wide and deep desiccation cracks when dry (a typical condition in New Mexico) and provide pathways for rapid soil-gas transfer. These soils, however, are very impermeable when moist.

Other Sources of Information

Other information sources were examined to support interpretations of aforementioned data. The NURE geochemical data consists of uranium analyses of stream sediment and ground water samples (McLemore and Chamberlin, 1986). Geochemical reconnaissance maps showing the distribution of uranium for each 1° x 2° quadrangle in New Mexico were used to identify areas of high uranium concentrations. Most of these areas correlate well with areas identified using aerial radiometric data. A few problems exist with the NURE geochemical data. Uranium concentrations in stream sediments are actually displaced and diluted values. Very little information, such as host rock and depth of the ground water samples, is available. In addition, many populated areas of New Mexico were not sampled and no data exists.

Ground water data, such as depth, flow direction, and chemical composition, provide additional information on hydrogeologic conditions which may affect the levels of indoor radon. Other data such as distribution and character of geothermal areas were also used in this assessment. In Idaho, houses built in geothermal areas have higher levels of indoor radon (Ogden et al., 1987). This relationship is being tested in New

Mexico at present (James Witcher, New Mexico State University, personal commun., Feb., 1990).

Only a limited amount of indoor radon measurements are available on a statewide basis. Much of the data from past studies (prior to 1988) are confidential, at least on a site-specific scale. However, all available published and unpublished data were reviewed during this preliminary investigation.

PRELIMINARY CLASSIFICATION OF RADON AVAILABILITY

Prior to placement of detectors in the winter of 1989 random survey, the rocks and soils in New Mexico were geographically grouped into three radon-availability categories according to interpretations of available geologic data (Tables 1, 2; Fig. 1; McLemore and Hawley, 1988). These relative radon-availability categories are specific to New Mexico and should be regarded as provisional until many more "on-site" radon investigations are completed. Because the risk of inhaling or ingesting a dangerous amount of radon is controlled by many factors besides geology and soil conditions, "risk" considerations played no part in this preliminary evaluation of "radon-availability." It should be also emphasized that any category area will contain a significant number of localities where one or both of the other two categories occur.

High Radon-Availability Category (Provisional)

The provisional high radon-availability category included areas where the rocks and soils were believed to have the greatest potential for generation of indoor radon. These areas included rocks which typically exceed 2.7 ppm eU on the areal radiometric map and, generally (but not always) included well drained, permeable soils. The limit of 2.7 ppm eU was chosen on the basis of prior experiences of EPA elsewhere in the country (T. Peake, USEPA, personal commun., Sept., 1988).

The "high category" included many outcrop areas of Proterozoic granitic rocks with average uranium concentrations of 3-17 ppm (Sterling and Malan, 1970; Brookins and Della Valle, 1977; Brookins, 1978; Condie and Brookins, 1980; McLemore, 1986; McLemore and McKee, 1988). Other lithologic units in the high-availability category include:

a. Tertiary rhyolitic and andesitic volcanic rocks in southwestern New Mexico. The rocks contain anomalously high uranium concentrations (Walton et al., 1980; Bornhorst and Elston, 1981). For example, a sample of the Alum Mountain andesite near Silver City, Grant County, contained 35.1 ppm U (Bornhorst and Elston, 1981). A sample of the Bandelier Tuff in the Jemez Mountains in north-central New Mexico contained 14.8 ppm U (Zielinski, 1981).

b. Tertiary alkalic intrusive rocks in central and eastern New Mexico (New Mexico Geological Society, 1982). Many uranium and thorium occurrences are associated with these units (McLemore and Chenoweth, 1989).

c. Sedimentary rocks. Some Paleozoic and Mesozoic sandstones, shales, and limestones locally contain high concentrations of uranium (Brookins and Della Valle, 1977; Dickson et al., 1977).

d. Coal. Some Cretaceous coals in the San Juan Basin contain 3-9 ppm U (Frank Campbell, NMBM&MR, personal commun., Oct. 3, 1988).

e. Permeable basin-fill sediments of Tertiary to Quaternary age. Although only very few analyses of these rocks are reported, they need to be (at least locally) considered as radon sources (Brookins, 1990; Brookins and Enzel, 1989).

f. Any areas of intense shearing and faulting, especially in areas of uraniferous rocks.

A few areas in New Mexico contain rocks with greater than 5 ppm eU from the aerial radiometric map. These areas typically merited a high availability ranking; but there is one exception, the Grants area. The Grants anomaly is a result of uranium mill tailings and has been assigned a moderate availability ranking.

Most of the aerial radiometric anomalies (>5 ppm eU) can be explained geologically. The Gallup anomaly is the only one near a major city. It is a result of uraniferous coals, some of which were mined for uranium. The other anomalies occur in sparsely populated areas. The Vermejo Park anomaly is associated with a uraniferous Proterozoic granite and pegmatites; epithermal uranium veins may occur in the area (McLemore, 1990; Goodknight and Dexter, 1984; Reid et al., 1980). The anomalies in the Cornudas Mountains, Otero County and at Laughlin Peak, Colfax County are associated with Tertiary alkalic intrusives; uranium and thorium veins occur in the area (McLemore and Chenoweth, 1989; Zapp, 1941; Staatz, 1982, 1985, 1986, 1987). Several anomalies occur in southern Socorro County, east of Las Cruces in Doña Ana County, west-central Hidalgo County, and in the Black Range that are associated with Tertiary rhyolitic and andesitic volcanics. Only two of these anomalies are associated with known uranium occurrences: the Nogal cauldron in Socorro County (Berry et al., 1982) and Bishop Cap in Doña Ana County (McLemore and Chenoweth, 1989; McAnulty, 1978).

One of the aerial radiometric anomalies, north of Gallup in McKinley County, cannot be readily explained by geological interpretations. It correlates with the Tertiary Chuska Sandstone, Cretaceous Menefee Formation, and associated surficial cover; no mining activity is in the area. Field examination of this area of the Navajo Reservation and indoor-radon testing is needed, but was not part of the preliminary investigation.

Moderate Radon-Availability Category (Provisional)

This provisional category included areas where preliminary evaluation of geology and soils data indicated that rocks and soils only have a moderate potential for generation of elevated indoor radon. These localities include rocks with 2.3-2.7 ppm eU on the areal radiometric map (Duval, 1988) and are dominated by areas underlain by moderately permeable soils. This category includes many outcrop areas of Proterozoic metamorphic rocks, Paleozoic and Mesozoic sedimentary rocks, and Tertiary-Quaternary sedimentary rocks. Some rocks and soils in the Pecos Valley area in eastern New Mexico are rated moderate even though they have less than 2.3 ppm eU. Numerous high uranium ground water anomalies occur in that area, suggesting that uranium is highly mobile and could result in elevated levels of indoor radon.

Low Radon-Availability Category

This category includes the remaining parts of New Mexico where the rocks and soils are believed to have low radon availability. These areas include rocks with less than 2.3 ppm eU on the aerial radiometric map (Duval, 1988) and include areas dominated by soils of low permeability. Some houses in these areas may still have elevated levels of indoor radon, but there were no obvious geologic reasons for predicting their existence in the preliminary assessment of radon availability.

PRELIMINARY CLASSIFICATION BY COUNTY

The EPA's nationwide survey of indoor radon levels in houses required that each county be ranked for radon-availability. Ranking by counties was required for two reasons: (1) Population statistics required to establish a sample allocation plan are available for each county throughout the United States. (2) It provides a way to standardize the reporting of indoor radon surveys throughout the country.

New Mexico is the fifth largest state in the United States, yet it contains only 33 counties. Some of these counties are as large or larger than some states in the eastern United States. The geology and terrain of New Mexico are quite diverse (New Mexico Geological Society, 1982), and major geologic and landform units cut across most county boundaries, creating obvious problems in ranking counties for radon-availability.

Using the procedure described in the previous section, each county in New Mexico was ranked according to the predominant availability category established for combinations of geologic and soil units in the state (high, moderate, or low). If a county was represented by more than one availability category, the county was assigned the highest classification where that category represented more than 25% of the total county area. Some exceptions are explained below. Preliminary county rankings are listed in Table 1. Similar procedures were used in evaluating counties in other states.

Since New Mexico is sparsely populated in most places and is geologically diverse, the major cities in terms of population (preliminary census data, 1984) were also assessed for radon-availability (Table 1). Some cities were rated higher than the rest of the county. In order to emphasize population distributions, counties with large urban-suburban populations were assigned the higher classification (Table 2).

Preliminary Ranking of Counties

Ten counties were assigned a high-availability rating for elevated indoor radon (Table 1). Large areas of these counties typically contain rocks and soils with greater than 2.7 ppm eU and the soils are permeable. Two counties, Doña Ana and Santa Fe Counties, were assigned a high ranking even though the majority of the rocks in the county contain 2.3-2.7 ppm eU. This was because the major cities in both counties (Las Cruces and Santa Fe) were ranked as having a high radon-availability potential. The preliminary ranking indicated that Gallup in McKinley County was the most likely area in New Mexico to encounter a large number of houses with elevated levels of indoor radon. Testing to date has not been detailed enough to test whether or not this prediction is valid.

Thirteen counties were assigned to the moderate-availability category (Table 1). Large areas of these counties contain rocks and soils with 2.3-2.7 ppm eU. Soil permeabilities and lithologies vary. Three counties, Chaves, Eddy, and Lea, were assigned a moderate rating because cities in these counties were rated moderate even though most geologic evidence suggests a low ranking. In addition, NURE ground-water data suggested that uranium in ground water is highly mobile and could contribute radon. A study of uranium and radium mobility in ground water in southeastern New Mexico indicates that uranium and radium concentrations correlate with high chloride concentrations; however, higher radium concentrations occurred in chemically reducing ground water, which is not common in New Mexico (Hecrzeg et al., 1988).

Four counties, Colfax, San Juan, Grant, and Sierra, contain large areas of rocks that exceed 2.7 ppm eU and could be assigned a high rating. A moderate rating was assigned to these counties because 1) the uranium-bearing rocks and soils of many areas are reported to be moderately permeable to impermeable, 2) the cities in these areas are rated moderate, not high, and 3) the areas containing rocks exceeding 2.7 ppm eU are in sparsely populated portions of the county.

Ten counties were assigned a low availability (Table 1). These counties are underlain by rocks with less than 2.3 ppm eU. However, the lithology and permeability of the rocks and soils vary. Undoubtedly, some houses in these counties will exceed the EPA's recommended action level, but there are no obvious geologic reasons for predicting their existence.

THE 1989 STATEWIDE SURVEY

The primary objective of this survey was to locate and identify areas within the State of New Mexico which may have homes with elevated indoor levels of radon and to characterize radon levels statewide. A secondary objective was to determine how geology affects radon levels and to determine whether or not geology can be used to predict indoor radon levels. This was a "screening" survey.

The target population in this survey was restricted to owner-occupied homes selected at random from telephone listings. This eliminated high-rise structures from the survey. Since radon concentrations tend to be low in such structures and the intent of this survey was to identify areas where radon could be a potential problem, the elimination of high-rise structures from the survey should provide the most efficient use of the sampling detectors. The type of dwellings that were excluded from the survey were mobile homes, group quarters, and apartments. The survey was restricted to owner-occupied dwellings to simplify procedures in gaining permission to sample radon. Although this type of selection essentially negates a true random sampling for statistical purposes, the study had to be structured to fit workable sampling parameters.

Radon measurements were made with charcoal canisters supplied by EPA. Measurements were made under closed-house conditions and in the lowest liveable area of the dwelling in conformance with EPA screening measurement protocols. Samples were analyzed by EPA's laboratory in Montgomery, Alabama. Alpha track detectors were utilized at 10% of the homes utilizing the charcoal canisters for radon daughter determination.

The previously defined radon-availability categories (based on geology and soils) were used by the EPA in allocation of detectors in the random sampling program.

Three thousand canister detectors for sampling radon and 562 Alpha track detectors for sampling radon daughters were available for use in this survey. Table 3 gives an account of distribution of charcoal canisters by county. Fifty of the charcoal and five of the alpha track detectors were used to conduct a pilot study of fifty homes to evaluate participant response rate and workability of survey forms. This pilot study was conducted before initiating the main part of the survey.

Allocation of radon detectors in the study phase utilizing 2,250 sampling devices was initially based on population or number of households. Sample size was then adjusted by the EPA based on evaluation of the natural (geologic and soils) conditions.

Given the final sample sizes for each district, the expected allocation to counties was proportional to number of homes in the county. Consider, for example, Socorro County in District 1. The number of detectors expected to be placed in homes in Socorro County, on the average over all possible samples, was 200.

Upon receiving a list of randomly selected homes for the survey from the EPA, each potential participant was sent a letter. This letter explained how the NMEID planned to conduct the radon survey and was accompanied by general information on the radon issue (e.g. EPA, 1986). The letter also informed the potential participant that a telephone interviewer would contact him or her in the near future to discuss the participation. These letters were mailed in batches at the District level.

Approximately one week after the notification letter was mailed out, a telephone interviewer called potential participants and discussed participation. The control/screening form, which was used in conducting the telephone interview was used to log all the calls, times of contact, whether or not the homeowner wished to participate. All pertinent information was logged on the screening form. For details of canister distribution see Table 3.

The information recorded on the field survey form was entered into the State's computer. Information from the laboratory data form was stored in EPA's computer system. The EPA provided this information to the State of New Mexico in a computer readable format. All information from the combined data base are available to both the EPA and the State of New Mexico. Summary statistics and data analyses was generated from this data base (e.g. Table 3; Fig. 2).

In the ongoing final phase of the study, the remainder of the charcoal canisters and additional alpha track sampling detectors are being used to sample in high suspect areas of counties which did not receive high priority sampling in the initial phase. These sampling detectors are also being used to establish boundaries of problem areas identified in the initial phase. This has been accomplished by concentrated sampling efforts in these problem areas. Alpha track sampling detectors not used will be returned to EPA. At the writing of this report this phase was still in progress; and the data are not available for citation. An additional 200 charcoal canisters are needed for concurrent sampling in homes being tested with alpha track detectors to determine seasonal impacts on radon concentrations in homes. The alpha track detectors would remain in place during the entire testing period while charcoal canisters will be changed during seasonal periods.

Quality assurance for the radon measurements taken in this survey were established by collecting duplicate radon samples in 5% of the homes tested. Standard estimates for the data was provided by laboratory analysis of radon samples containing known concentration of radon. Blank samples were submitted to the laboratory at a rate of 2 percent of the total number of samples collected.

For classification the State is subdivided into the four EID Districts. The New Mexico plan implemented the survey utilizing EID district as well as central office staff resources; and the survey was coordinated from district offices. EID district staff are familiar with the population centers in their Districts, as well as with isolated homes in their areas. Knowledge of home location proved to be invaluable in the sparsely populated areas of New Mexico.

TABLE 3. RESULTS OF EID SCREENING SURVEY BY COUNTY IN NEW MEXICO.

County	<4 pCi/L		>4,<10 pCi/L		>10,<20 pCi/L		>20 pCi/L		TOTAL
	no.	%	no.	%	no.	%	no.	%	
Bernalillo	267	70.6	85	22.5	22	5.8	4	1.1	378
Catron	16	94.1	1	5.9	0	0.0	0	0.0	17
Chaves	41	82.0	9	18.0	0	0.0	0	0.0	50
Cibola	8	53.3	7	46.7	0	0.0	0	0.0	15
Colfax	43	51.2	31	36.9	8	9.5	2	2.4	84
Curry	35	83.3	6	14.3	1	2.4	0	0.0	42
De Baca	12	92.3	1	7.7	0	0.0	0	0.0	13
Doña Ana	75	92.6	6	7.4	0	0.0	0	0.0	81
Eddy	39	81.3	9	18.8	0	0.0	0	0.0	48
Grant	48	87.3	6	10.9	1	1.8	0	0.0	55
Guadalupe	6	100.0	0	0.0	0	0.0	0	0.0	6
Harding	9	90.0	1	10.0	0	0.0	0	0.0	10
Hidalgo	8	53.3	6	40.0	1	6.7	0	0.0	15
Lea	47	94.0	3	6.0	0	0.0	0	0.0	50
Lincoln	16	94.1	1	5.9	0	0.0	0	0.0	17
Los Alamos	30	76.9	8	20.5	1	2.6	0	0.0	39
Luna	35	70.0	12	24.0	2	4.0	1	2.0	50
McKinley	29	63.0	15	32.6	1	2.2	1	2.2	46
Mora	11	61.1	6	33.3	1	5.6	0	0.0	18
Otero	35	79.5	8	18.2	0	0.0	1	2.3	44
Quay	5	55.6	4	44.4	0	0.0	0	0.0	9
Rio Arriba	55	78.6	9	12.9	5	7.1	1	1.4	70
Roosevelt	36	90.0	4	10.0	0	0.0	0	0.0	40
Sandoval	55	78.6	7	10.0	6	8.6	2	2.9	70
San Juan	158	88.3	20	11.2	0	0.0	1	0.6	179
San Miguel	34	54.0	22	34.9	4	6.3	3	4.8	63
Santa Fe	40	54.1	28	37.8	5	6.8	1	1.4	74
Sierra	39	100.0	0	0.0	0	0.0	0	0.0	39
Socorro	30	81.1	7	18.9	0	0.0	0	0.0	37
Taos	19	40.4	20	42.6	5	10.6	3	6.4	47
Torrance	7	58.3	5	41.7	0	0.0	0	0.0	12
Union	18	66.7	8	29.6	1	3.7	0	0.0	27
Valencia	27	100.0	0	0.0	0	0.0	0	0.0	27

DISCUSSION BASED ON PRELIMINARY DATA ANALYSIS

Figure 2 is a map showing distribution by county of major radon-level classes in percent (<4 pCi/l; 4-10 pCi/l; 10-20 pCi/l; and >20 pCi/l) determined during the 1989 random-screening survey of 1775 homes. Table 3 lists the results of the screening survey of the four major radon-level classes showing both the percentage distribution within the four classes and the number of canisters allocated per county.

In this preliminary state survey, only nine counties (Bernalillo, Colfax, Hidalgo, Los Alamos, Luna, Mora, Santa Fe, San Miguel, and Taos) had a significant percentage (>5%) of homes with indoor-radon measurements greater than 10 pCi/l. All but two of these counties (Hidalgo and Luna) are clustered in the north-central part of the state. This is the Southern Rocky Mountain region identified in earlier phases of radon research where radon-availability could be relatively high in many areas (Tables 1 and 2). The southwestern Basin and Range region, including Hidalgo and Luna Counties, is also an area where moderate to high radon-availability conditions have been predicted. Seven of these counties were predicted as having moderate to high radon availability conditions; only Mora and San Miguel Counties were predicted as having low radon-availability conditions (McLemore and Hawley, 1988).

Lower indoor-radon measurements throughout the central and southern part of New Mexico also generally fit the radon-availability projections made in early phases of this study. Radon levels above the EPA "action level" of 4 pCi/l were not detected in this preliminary survey in three counties, Guadalupe, Valencia and Sierra. Twelve other counties (Catron, Chaves, Cibola, De Baca, Doña Ana, Eddy, Harding, Lea, Lincoln, Roosevelt, Quay and Torrance) had no indoor-radon measurements above 10 pCi/l. All of these counties except Doña Ana were predicted as having low to moderate radon availability conditions (McLemore and Hawley, 1988). However, extreme caution should be used in interpreting the data summarized in this report as well as the projections of radon-availability discussed earlier (see also McLemore and Hawley, 1988). The very small number of charcoal canisters allocated to most areas of the State (Table 3), the very uneven distribution of canisters (most concentrated in small urban areas within very large county areas), and the very short-term nature (24-48 hrs) of the radon-measurement period are representative of the significant factors that contribute uncertainty to this type of investigation.

Visits made to about 50 individual homes in north-central New Mexico indicate that geologic and soil conditions were the major factors contributing to elevated indoor-radon levels (>10 pCi/L). Studies to date suggest that elevated radon levels are commonly associated with hillside building sites where floors and walls are contiguous to geologic units such as highly-fractured bedrock of varying lithology, limestones with solution enlarged joints, or thick pumice deposits. Bedrock units, associated alluvial-colluvial deposits, and ground water that contain high concentrations of uranium and thorium locally make a significant contribution and need further study. Some homes built on clay-rich expansive soils also have elevated levels of radon. Areas in the vicinity of uranium mills and mines that have been tested have relatively low levels of indoor radon (below 10 pCi/L). A better understanding of the natural factors that affect indoor radon concentrations in New Mexico will only be gained through integrated, site-specific investigations which combine more comprehensive indoor-radon measurements and home construction information with data on geology, hydrology and soils.

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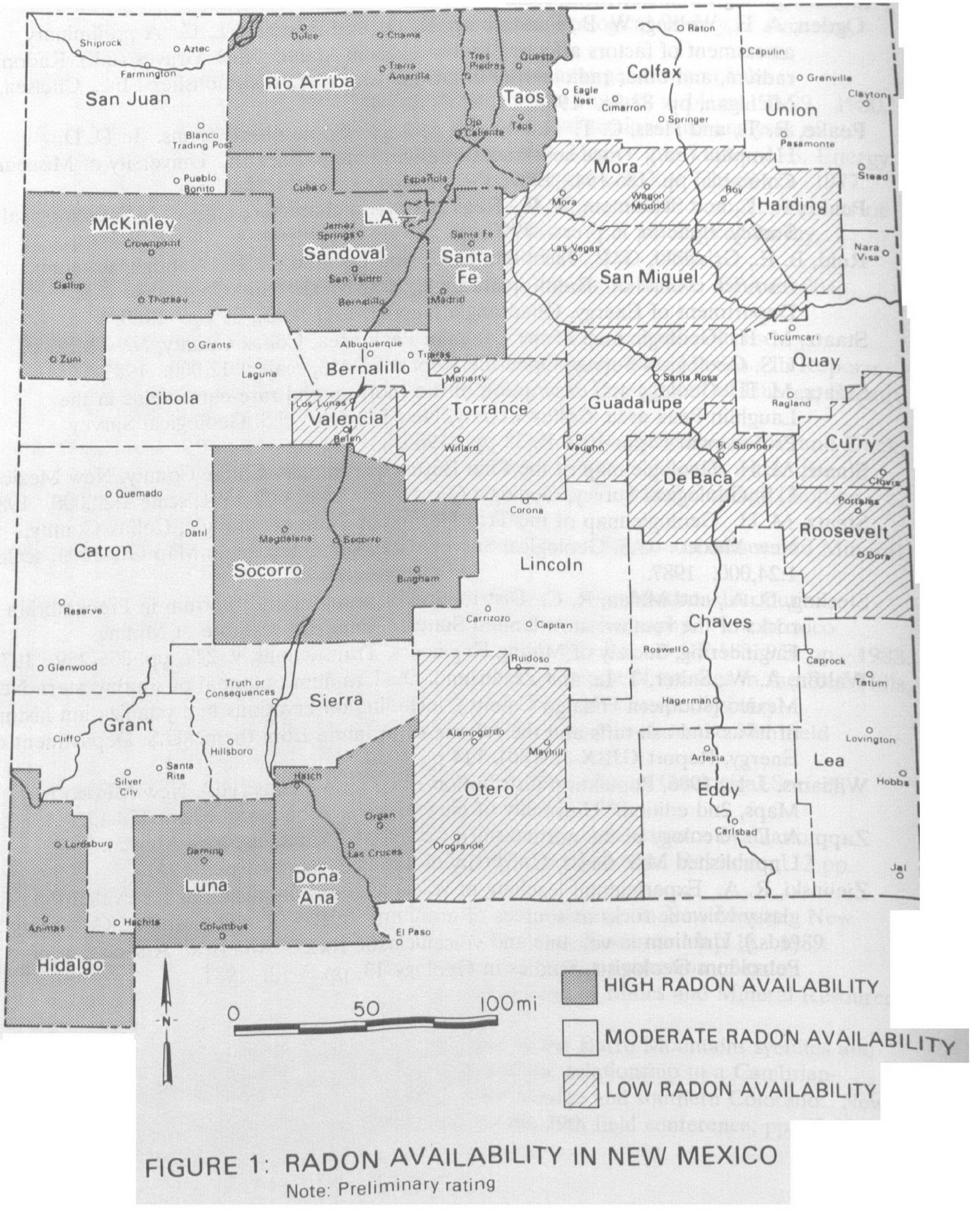

FIGURE 1: RADON AVAILABILITY IN NEW MEXICO
Note: Preliminary rating

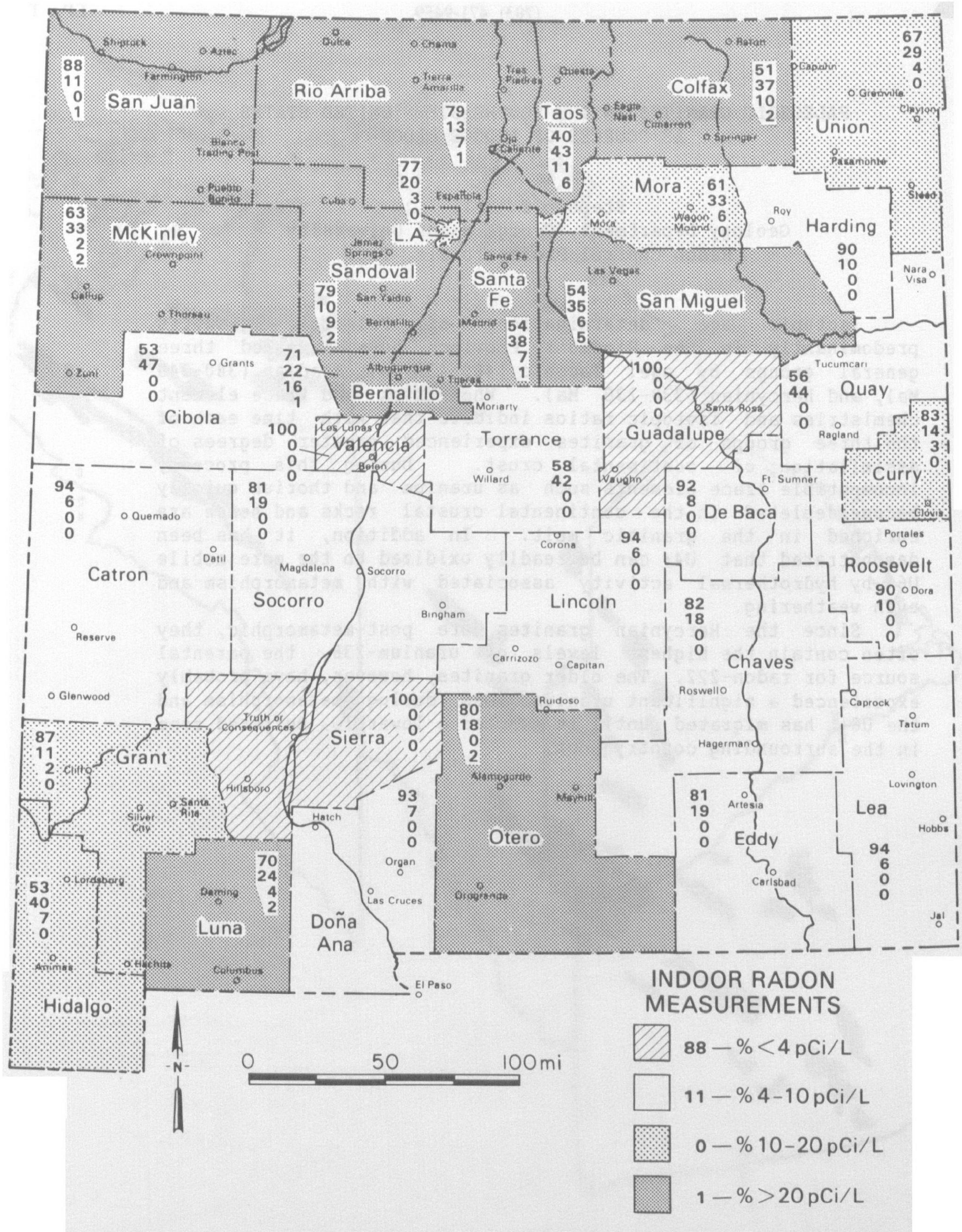

FIGURE 2: RESULTS OF EID SCREENING SURVEY BY COUNTY IN NEW MEXICO

Note on patterns: Counties where *some* measurements were >20 = dark dot pattern or 10-20 = light dot pattern. Counties where *all* measurements were <10 = white or <4 = diagonal line pattern.

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PALEOZOIC GRANITES IN THE SOUTHEASTERN UNITED STATES AS SOURCES OF INDOOR RADON

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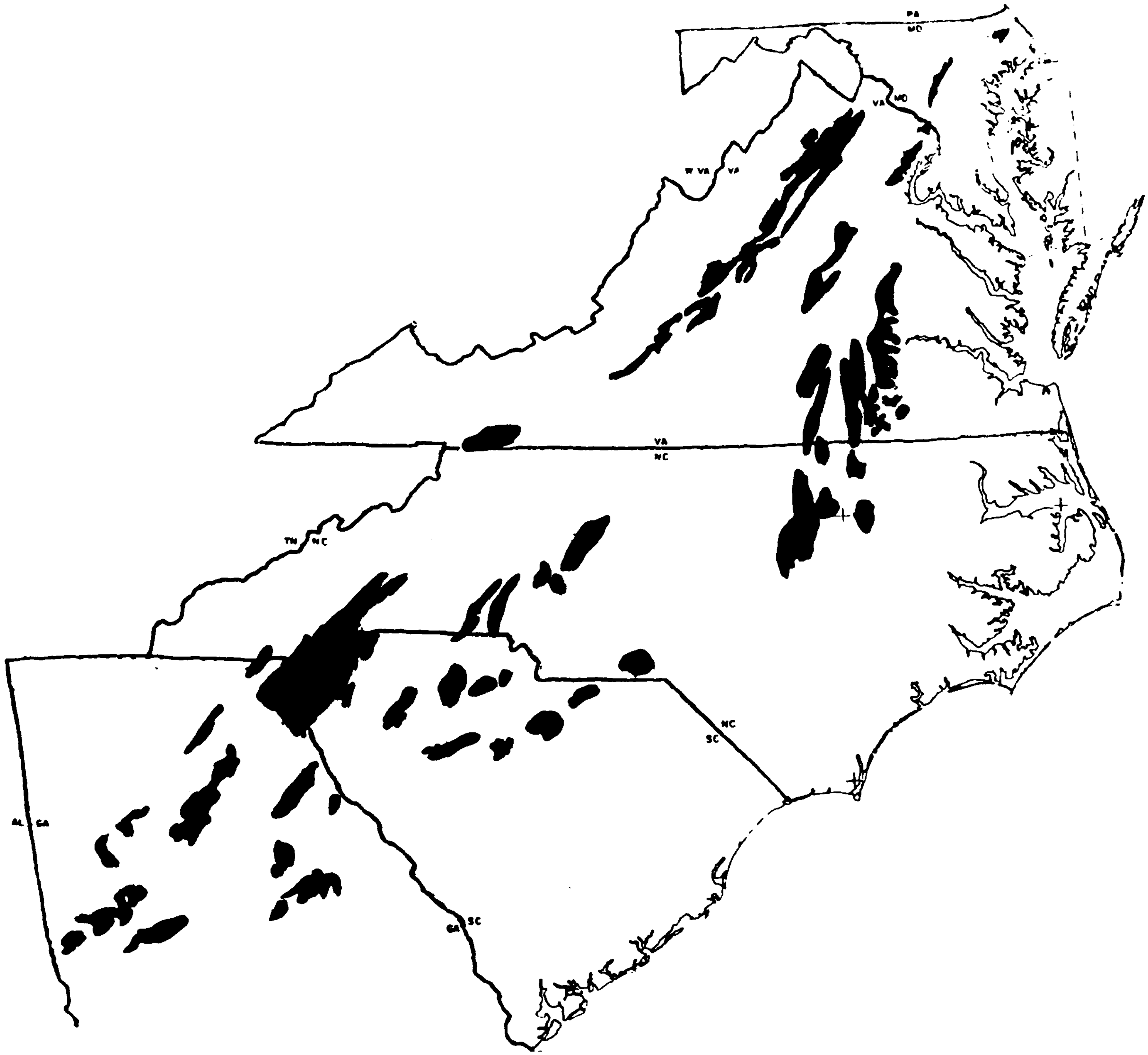
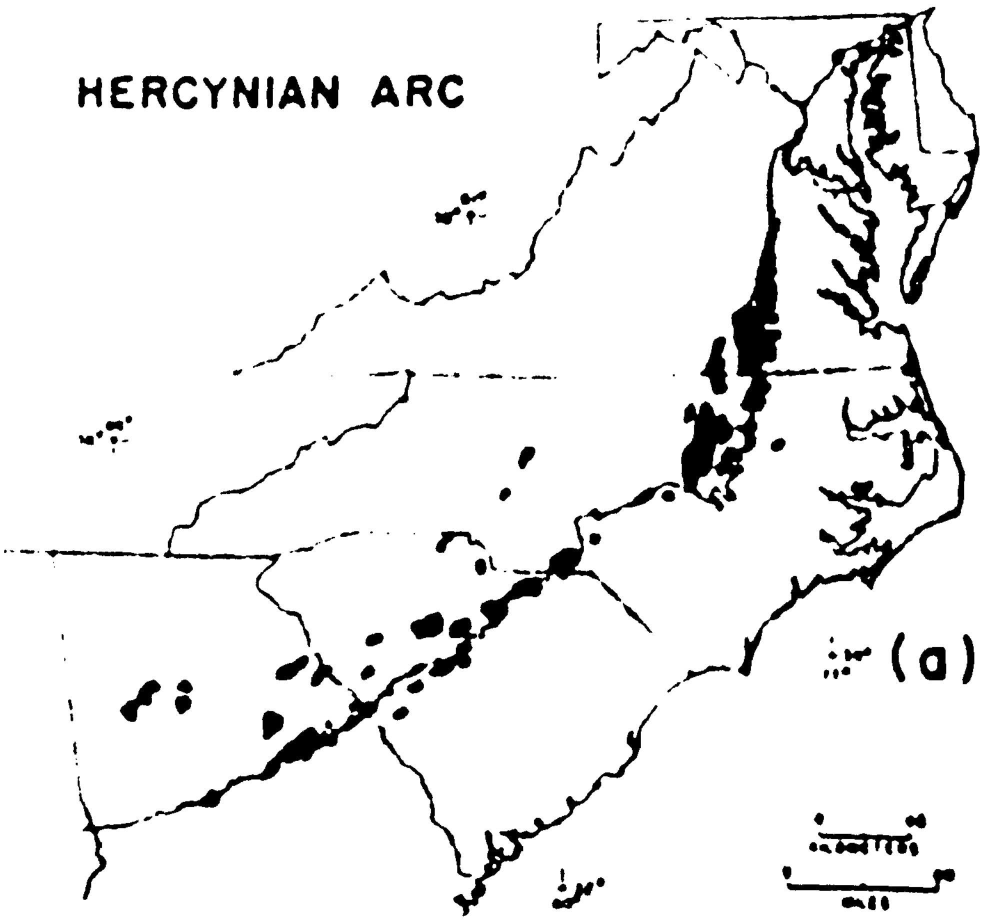
Isotopic age determinations of Paleozoic granites predominantly in the Piedmont Province have revealed three general groups by age: Taconic (480-435 Ma), Acadian (380-340 Ma), and Hercynian (330-230 Ma). Whole rock and trace element chemistries and isotopic ratios indicate that with time each of the three groups of granites experienced greater degrees of assimilation of continental crust. During this process, incompatible trace elements such as uranium and thorium quickly become depleted in the continental crustal rocks and hence are enriched in the granitic melt. In addition, it has been demonstrated that U4+ can be readily oxidized to the more mobile U6+ by hydrothermal activity associated with metamorphism and even weathering.

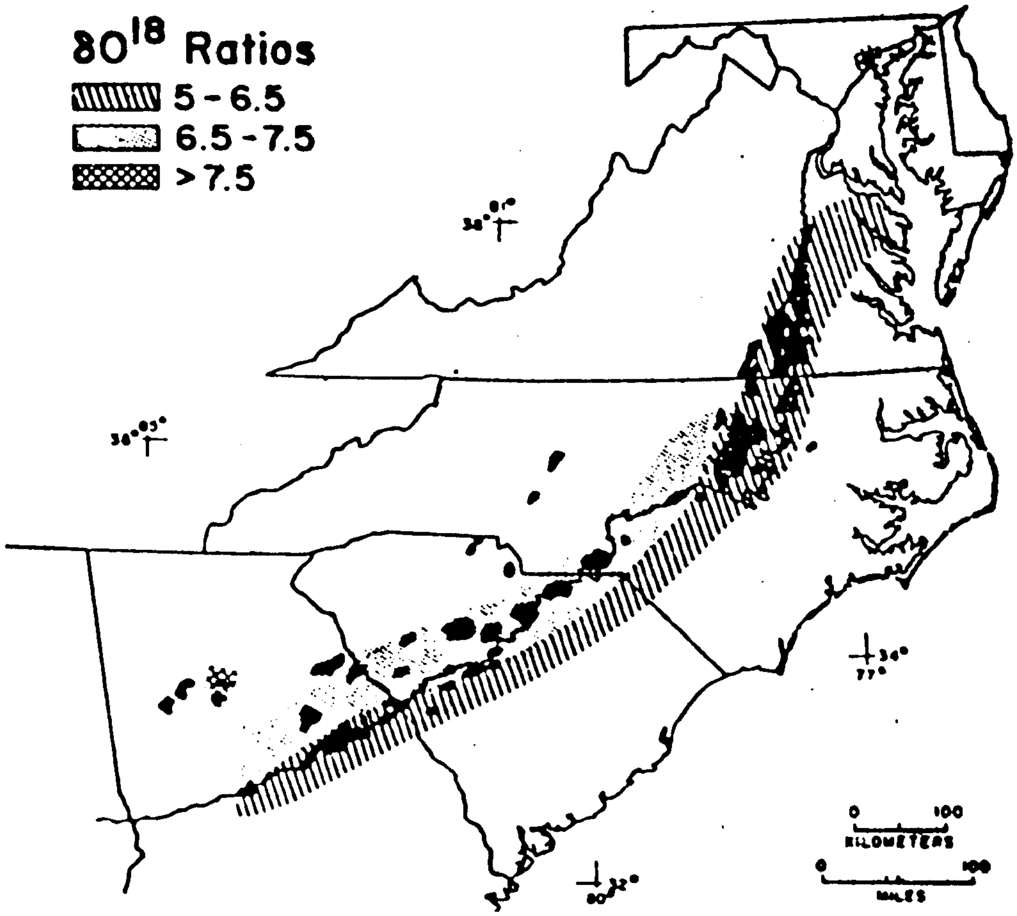
Since the Hercynian granites are post-metamorphic, they often contain the highest levels of uranium-238, the parental source for radon-222. The older granites, however, have probably experienced a significant uranium loss during metamorphism and the U6+ has migrated until it reached a lower fO_2 buffered zone in the surrounding country rock.

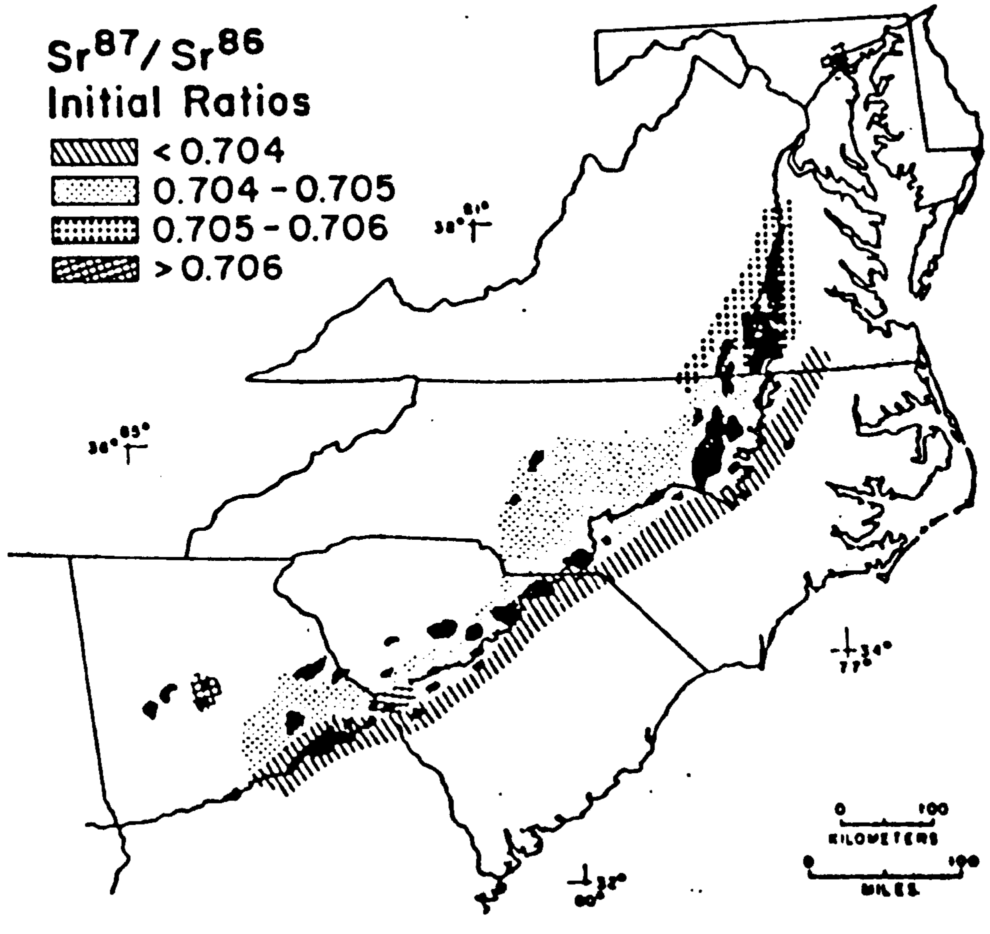


Map of the Southeastern US showing Paleozoic (480-230 million year old) granites darkened

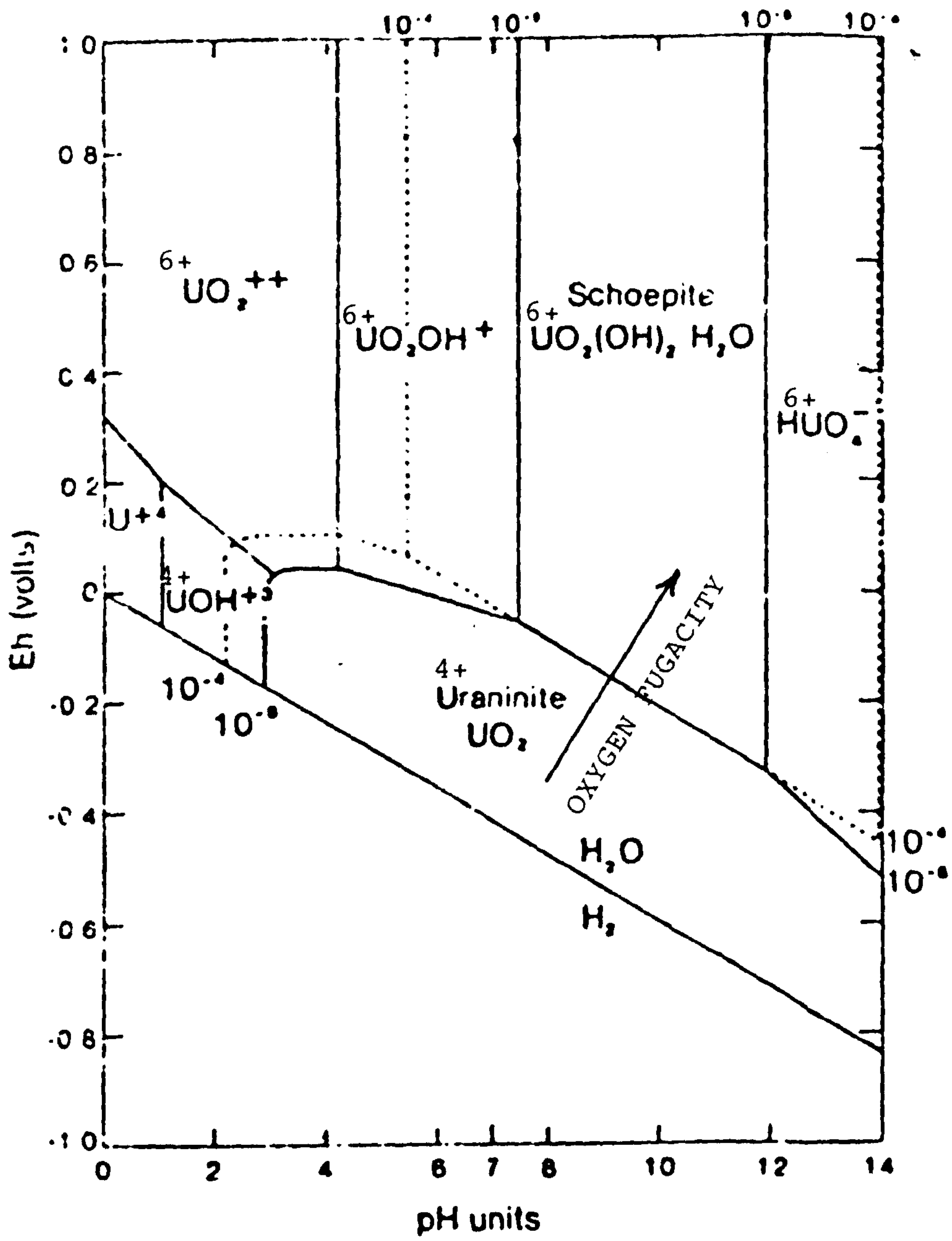


Map of the Southeastern US showing Hercynian (330-230 million year old) granites only

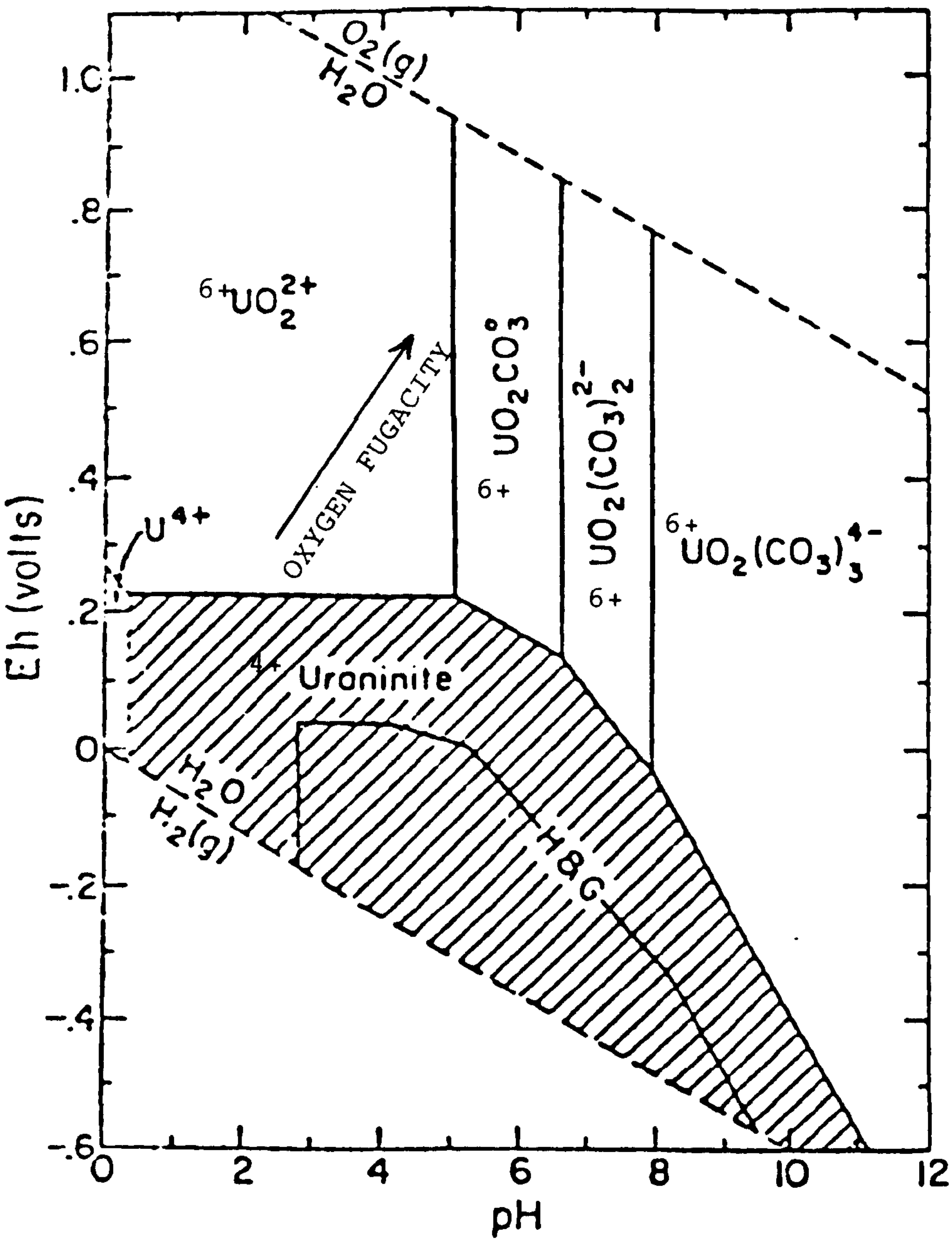




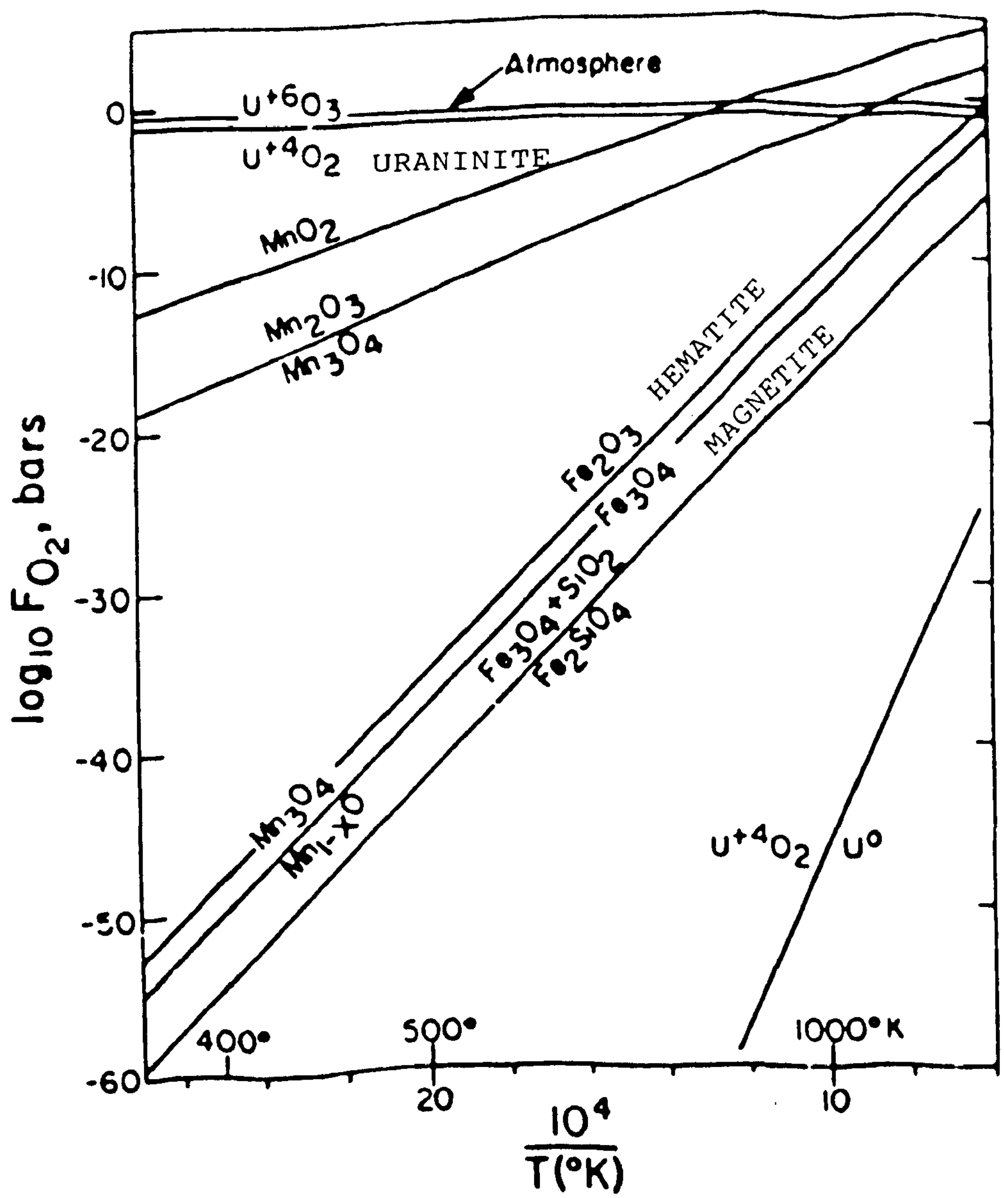
Maps of the Southeastern US showing O^{18} ratios and Sr^{87}/Sr^{86} ratios of Hercynian granites increasing inland indicating a greater involvement of continental crust and higher initial uranium content



Eh-pH diagram of the $U\text{-}O_2\text{-}H_2O$ system showing stability of U^{4+} compounds including uraninite (non-mobile uranium-bearing mineral) at lower fO_2 (oxygen fugacity)



Eh-pH diagram of the $U-O_2-H_2O-CO_2$ system showing stability of U^{4+} compounds including uraninite (non-mobile uranium-bearing mineral) at lower fO_2 (oxygen fugacity)



fO_2-temperature diagram showing magnetite stability at lower fO_2 stability than uraninite. Since many Hercynian granites contain magnetite, they have probably retained their original uraninite

Chemical compositions of some Hercynian granites indicating uranium concentrations in the 3-8 ppm range

Mean Compositions of Surface Samples

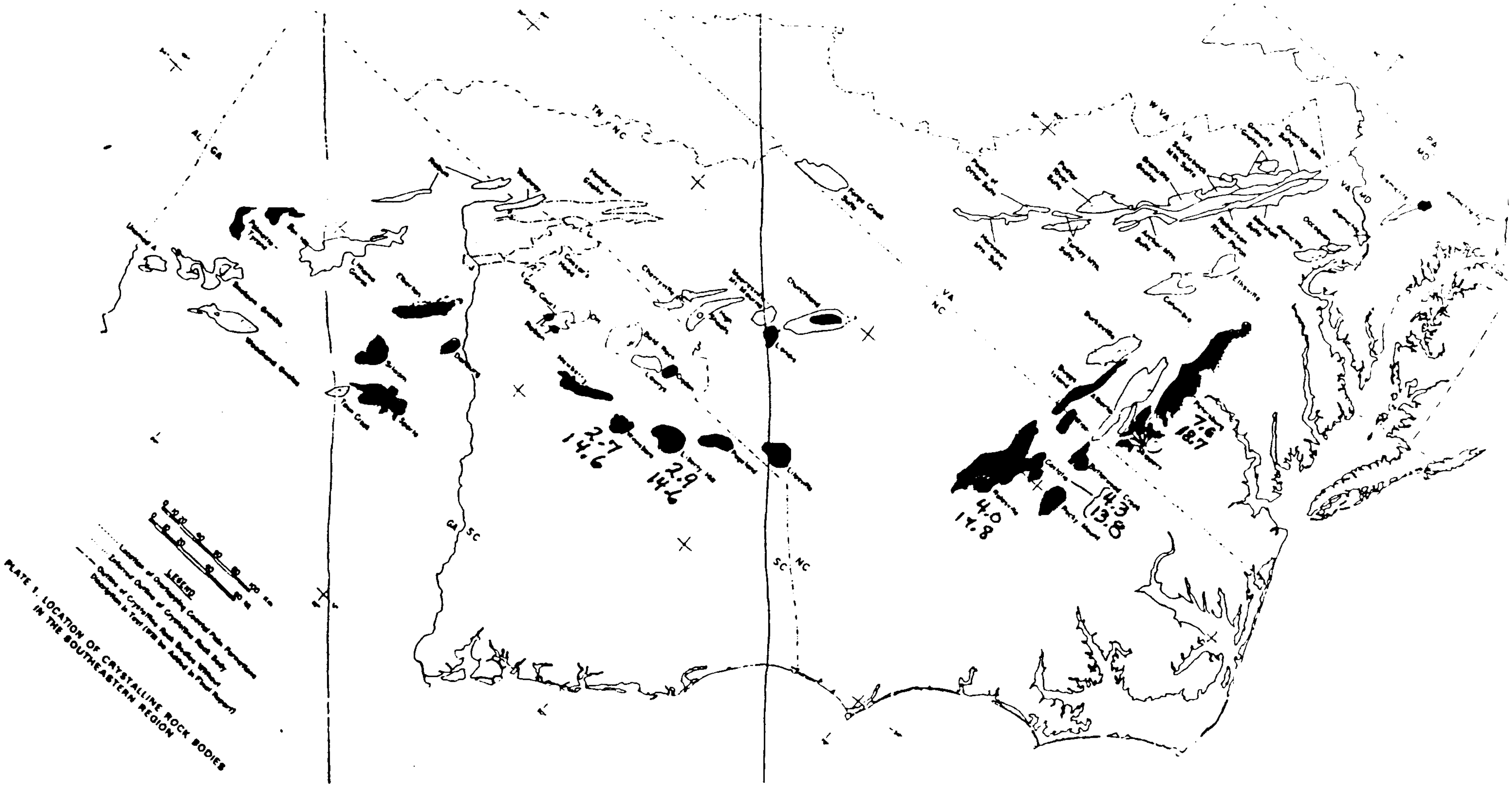
No. of Samples	Winnsboro granite (6)	Rion (16)	Liberty Hill coarse (15)	Liberty Hill fine (4)	Rolesville (18)	Castalia (3)	Louisb (1)
U ppm (st. dev.)	2.68 (0.43)	5.23 (1.58)	2.87 (0.71)	4.55 (0.67)	3.99 (1.56)	4.34 (1.74)	3.07
Th ppm (st. dev.)	14.64 (2.48)	31.55 (3.62)	14.57 (4.05)	28.7 (3.88)	17.83 (4.51)	13.76 (3.57)	30.81
SiO_2 (st. dev.)	72.91 (3.30)	72.73 (1.71)	67.25 (3.18)	71.72 (1.29)	71.18 (2.91)	75.26 (3.43)	72.53
K_2O (st. dev.)	5.47 (0.27)	5.36 (0.25)	5.66 (0.48)	5.53 (0.18)	4.52 (0.46)	4.22 (0.53)	5.11

Mean Compositions of Core Samples

No. of Samples	WIN1 Rion (17)	KER1 LH fine (1)	KER2 LH coarse (5)	KER3 LH coarse (9)	KER3 LH fine (3)
Uppm (st. dev.)	7.32 (1.90)	5.65	3.11 (0.02)	2.32 (0.08)	6.59 (4.40)
Th ppm (st. dev.)	33.58 (4.40)	21.33	14.18 (0.90)	11.64 (2.02)	29.25 (8.36)
SiO_2 (st. dev.)	72.65 (1.08)	73.82	66.31 (0.41)	67.22 (2.43)	72.12 (2.32)
K_2O (st. dev.)	5.50 (0.31)	5.27	5.02 (0.18)	5.17 (0.25)	5.41 (0.14)

AVERAGE COMPOSITIONS FROM PETERSBURG BATHOLITH

NO. SAMPLES	SURFACE (36)	PET1 CORE (11)
U ppm (st dev)	7.6 (4.1)	4.8 (0.6)
Th ppm (st dev)	18.7 (7.2)	14.9 (2.6)
SiO2 (st dev)	71.44 (3.83)	67.06 (1.47)
K2O (st dev)	5.05 (0.83)	5.38 (1.08)



Map of Paleozoic granites of the Southeastern US with Hercynian granites darkened and uranium (upper numbers) and thorium (lower numbers) contents

COMPARISON OF LONG TERM RADON DETECTORS AND THEIR CORRELATIONS WITH BEDROCK SOURCES AND FRACTURING

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ABSTRACT

Radon prospecting for mapping soil gas radon hot spots provides an additional correlation method which can be used with other geochemical tracers to support the genetic association between radon presence at the surface and bed rock sources and fracturing at depth.

Anomalous radon concentration at the surface can be caused either by proximity of shallow burial of rocks rich in uranium and radium mineralization or by migration of gases from deep sources. The working hypothesis is based on the fact that radon generated at depth can be transported by other gases or dissolved in solution and reach the surface. Areas with high densities of micro-fracturing of the rocks can enhance the migration and therefore higher than average radon concentration can be expected.

In Ohio as well as many parts of the Appalachian basin, the main source of radon has been found to be the organic rich black radioactive sections of Ohio and Olentangy shales. Other sources of radon in Ohio and other glaciated regions are the till and tillits (glacial sand and gravel deposits) which covers most of the state.

Results of studies within the intense bed rock fracturing indicated that: 1- there is a good correlation between micro-fracturing of the rocks and higher than average radon concentrations at the surface. 2- Areas closer to the regions with shallow burial of organic rich members of Ohio shale revealed anomalous radon activities in the soil. 3- Atmospheric parameters showed a measurable influences on the short term measurements. 4- Sites with high soil gas radon concentrations correlated with nearby indoor radon measurements in the study area.

INTRODUCTION

Many studies have been made to investigate the occurrences of soil gas radon concentrations within Ohio and parts of the Appalachian basin regions. Thousands of locations have been visited in Ohio alone to establish the regional background and to search for radon anomalies (Hot Spots). The working hypothesis is that natural gas yields will be optimized where natural fracturing of the bedrocks is greatest. Such fracturing would allow the gas to leak toward the ground surface at a greater rate than elsewhere, and the presence of this gas in the soil, by various geochemical mechanisms, produce conditions whereby the radon activity in the soil gas is also enhanced compared to other areas.

The case history reported herein represents a state of the art radon procedure in order to detect areas of gas leakage from bedrock or near surface sources in Ohio. Radon anomalies are caused by decay of radioactive materials such as radium and uranium transported to near surface environment by ascending hydrocarbons or the hydrocarbons affect the microgeochemistry near the surface in such a way as to enhance precipitation of radioactive substances from circulating ground-water. The exact mechanisms are poorly understood and may involve several interacting factors. Radon which is an intermediate daughter of uranium (radium) decay series, has been widely used to locate subsurface mineral deposits, geothermal monitoring, earthquake prediction and environmental studies.

METHODOLOGIES

Radiometric measurements in the soil gas were accomplished by using several short and long term techniques to monitor alpha and gamma activities in the ground. Radioactivity caused by soil or man made sources were also investigated in order to establish a correlation between deep gas migration and near surface soil gas radon anomalies.

An area of one square Kilometer was selected for this study where geological and environmental parameters related to gas movement in the ground could be evaluated. Topographic features included many east-west stream gullies, valleys, and drainages caused by bed rock fracturing. These features are intersecting a major lineament (large fracture) trending in a NW-SE direction in the study area adjacent to the N-S trend of a major river in northern Ohio (Figures 1, 2, and 3).

Figure 4 shows the location of sampling sites in the study area. A square grid was laid out with 100 stations using spacing of 100 meter outside the anomalies, reduced to 50 and 20 meter near and

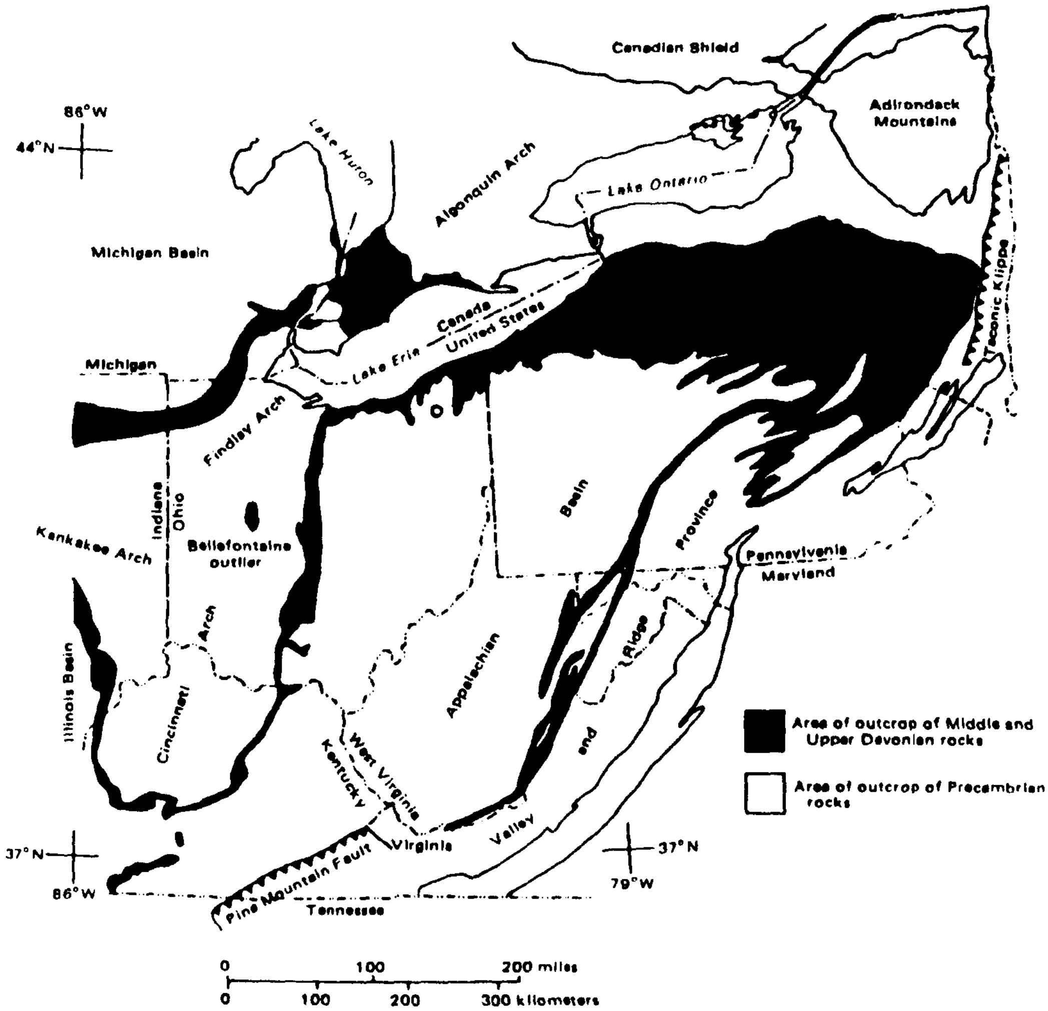

Figure 1, Structural setting and areas of Devonian shales outcrop in Ohio and Appalachian basin (Modified from Schwietering, 1979). The small dot indicates the approximate location of the study area.

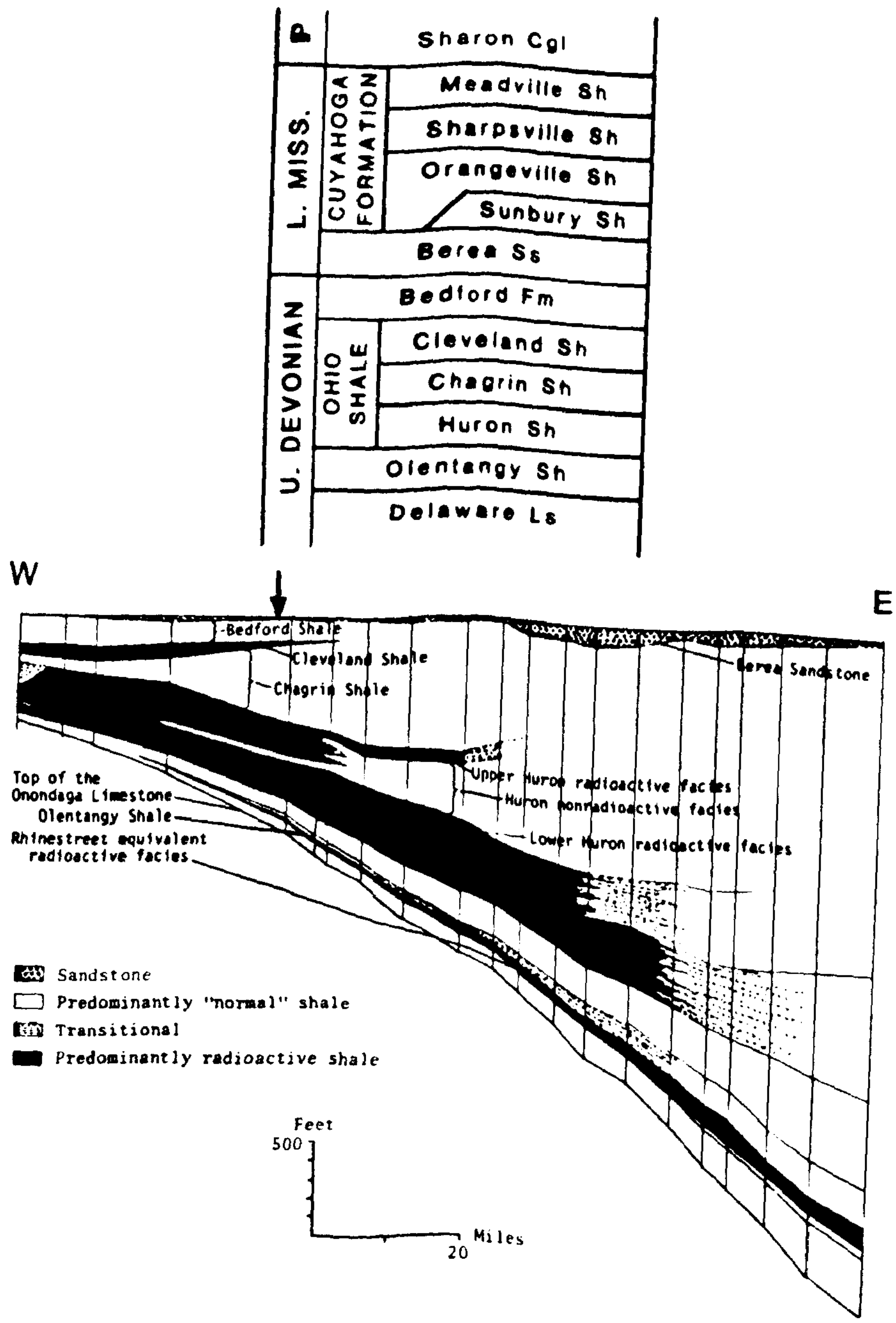

Figure 2, Generalized stratigraphic column for Devonian - Mississippian rocks and composite cross section of Devonian shale sequence in eastern Ohio. Sub-surface distribution of black radioactive shale is indicated by the black pattern. Unpatterned portions of the section represent non-radioactive gray shale and sandstone. Arrow at the top indicates the approximate part of the section that is equivalent to that underlying the study area (Adapted from Majchszak, 1977).

Figure 3, Topographic map of the study area (boxed outline) with respect to regional and local structural and topographic features. The NW-SE lineament is shown by line L-L .

above anomalies. At each sampling site marked on topographic map, long term Track Etch alpha tracks were used to cover areas of previously detected radon anomalies by short term and Kodak long term film cup detectors. a scintillometer reading of total gamma activity and a soil sample was taken. Also atmospheric parameters were recorded during the entire survey period.

RESULTS

Soil gas radon results are summarized in figure 4. Radon readings are reported in units of tracks per square millimeter and are normalized to equivalent 30-days exposure. The data ranged from 55 to 666 tracks per square millimeter with a STD of 107. Figure 4 shows readings with at least one STD above the background values.

Nearly 15% of the sites revealed values more than one STD above background mean, while 2% of the sites are identified as anomalous as represented by the larger triangle symbols in Figures 4, and 5). The actual activities at these sites are greater than 538 tracks per square millimeter as compared to the background mean of 217 track per square millimeter.

The background activity in the area was higher than other parts of the state due to several factors including: intensive bed rock fracturing, glacial coverage, and elevated radium or uranium concentrations by the action of ground water percolating in the radioactive black shales (Cleveland and Huron members of Ohio shale), a common bed rock type buried shallowly near the surface in northeast Ohio found to act as source rocks for radon mainly in eastern Ohio (Majchszak, 1977; Janssens, A. & deWitt, W.1976).

Figure 5 is a modified version of Figure 3 in which categories of anomalous, intermediate, and background values are defined as values equal to greater than mean plus 3 STD, values between mean plus one and three STD's and values within one STD respectively. Also shown symbolitically in Figure 5 are the results of the early preliminary radon surveys with long term Kodak film cups , located in the inner outlined area. The maximum values detected by each technique are slightly displaced, but the two are generally consistent in locating localized soil gas anomalies (Figure 5).

The arrangements of anomalous and intermediate values are suggestive of control by bed rock fracturing. E-W fractures are well expressed in the topography of tributary streams draining the adjacent hill slopes (Figure 3). The anomalous sites are mostly located in the vicinity of intersections between the NW-SE lineament discovered during the course of this study and numerous

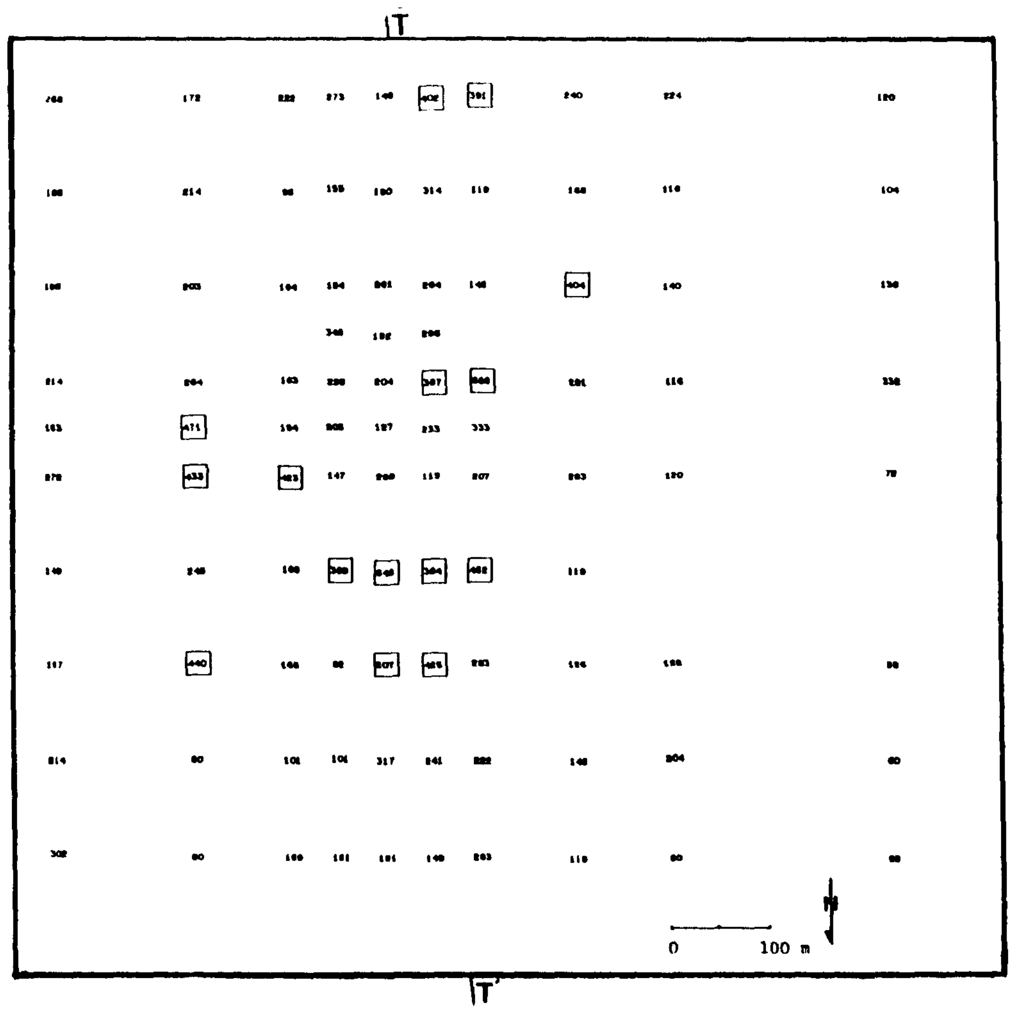

Figure 4, Map of radon activities observed at each film -cup sites in the study area. Numbers are the radon activities in tracks per square millimeter, normalized to 30-day exposure time. Higher readings (values above 363 tracks per square millimeter) are boxed. T-T'line indicates the trend of the lineament within the study area.

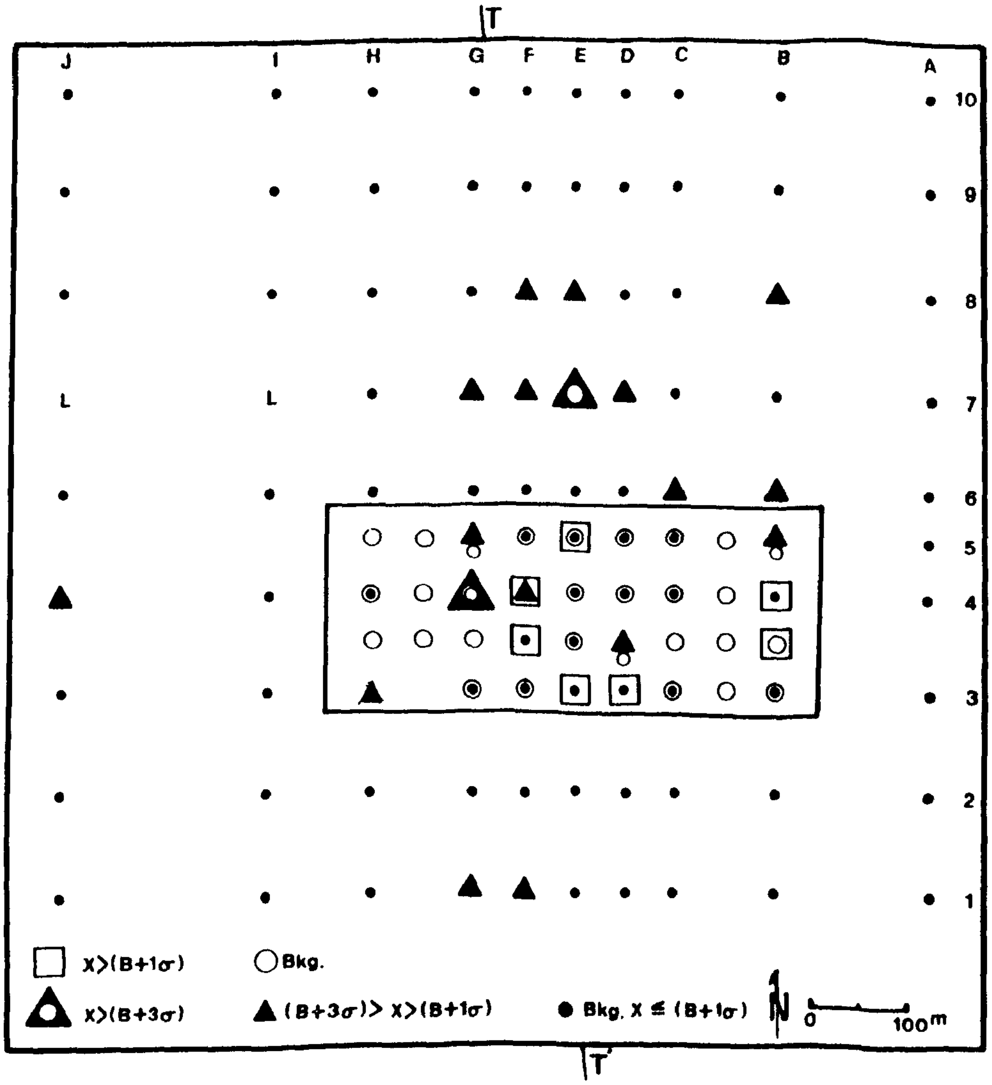

Figure 5, Map of Kodak and Track Etch results at the study area, schematically distinguished according to the categories of anomalous, intermediate, and background as defined in the text. In the legend, the symbols in the upper row refer to Kodak results whereas the symbols in the lower row refer to Trach Etch results. The inner outlined area is the site of a Kodak film-cup survey undertaken prior to the more extensive Track Etch survey. Several sampling sites are common to the two surveys. T-T' line is showing the trend of lineament in the study area.

E-W fractures. These anomalous sites are marked with large triangles for Tract Etch detectors and squared symbols for kodak film detectors located in the center of the study area and along the NW-SE lineament trend (Figures 4 and 5).

Evidence of deep gas migration compare to shallow sources of thorium or uranium mineralization included the very low correlation coefficient between radon values and scintillometers readings (Figure 6). Comparing this map to statistical criteria previously described in Figure 5, there are few differences except sites A7, A9, and A10, which have been increased from background to intermediate status, and sites D3, G5, and J4, which have been decreased from intermediate to background status.

CONCLUSIONS

Radon anomalies in the soil gases of many areas in eastern Ohio result from vertical migration of gases from subsurface sources (Figure 7). The migration pathways are primarily controlled by bed rock fracturing particularly in areas of two or more fracture intersections.

The near surface sources of radon can be differentiated from deeper sources by the compositional characteristics of liberated gases and laboratory analyses of soil or rock samples within anomalous radon concentrations. Main source rocks for radon gas detected in the study area are the black radioactive members (Cleveland and Huron) of Ohio shale underlying the entire eastern Ohio. Other sources of near surface contaminations such as glacial till (sand and gravel channels), contaminated soils or man made sources common to many industrial sites in the state were found to be insignificant in this study area.

Environmental parameters showed a measurable effect on the short term measurements compared to long term alpha tracks used in this study.

The high background level and occurrences of several anomalous sites at this study area or regions with similar geological characteristics could be considered as sites with potential environmental hazard. This hazard may be prevalent wherever radioactive black shales are present at shallow depth bellow the surface or sites in proximity of intense bedrock fracturing in Ohio and adjacent states.

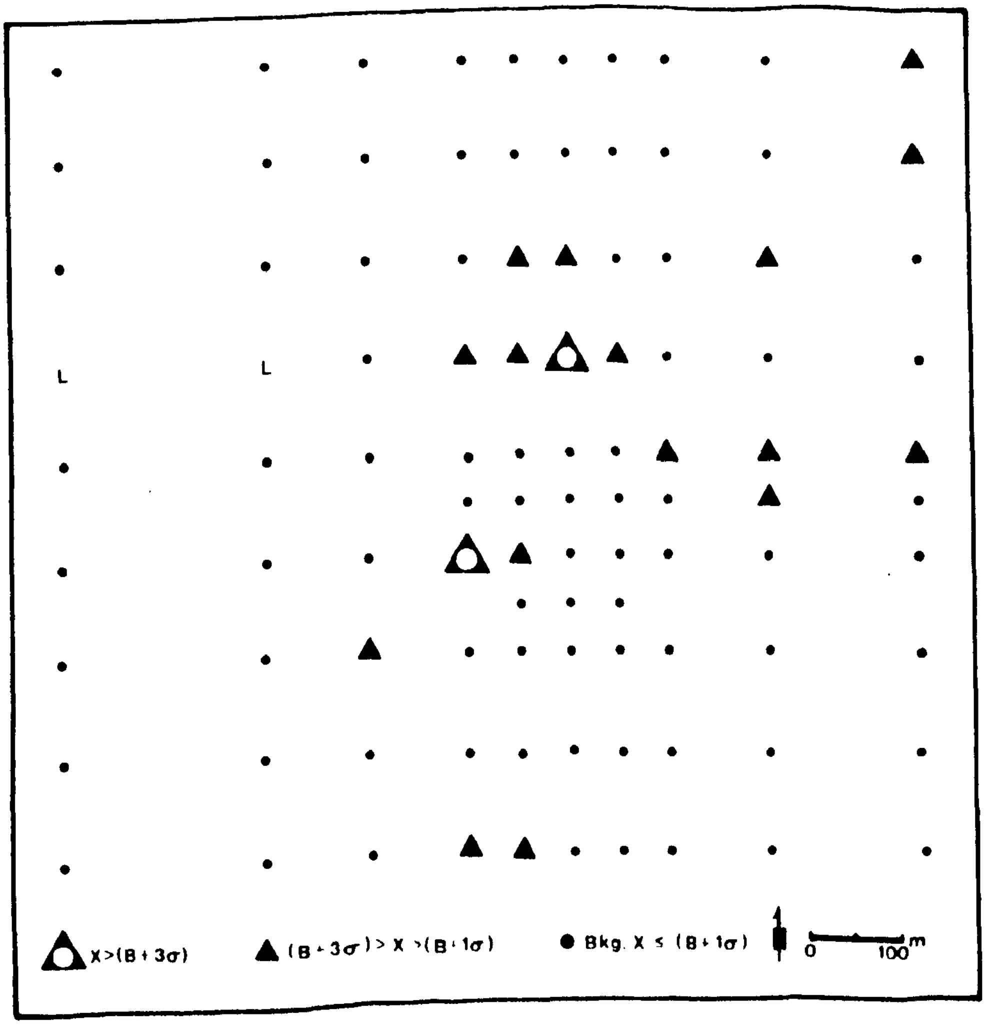

Figure 6, Map showing the ratios of TE/Scin. readings in the study area. The legend categories are the same as Figure 5.

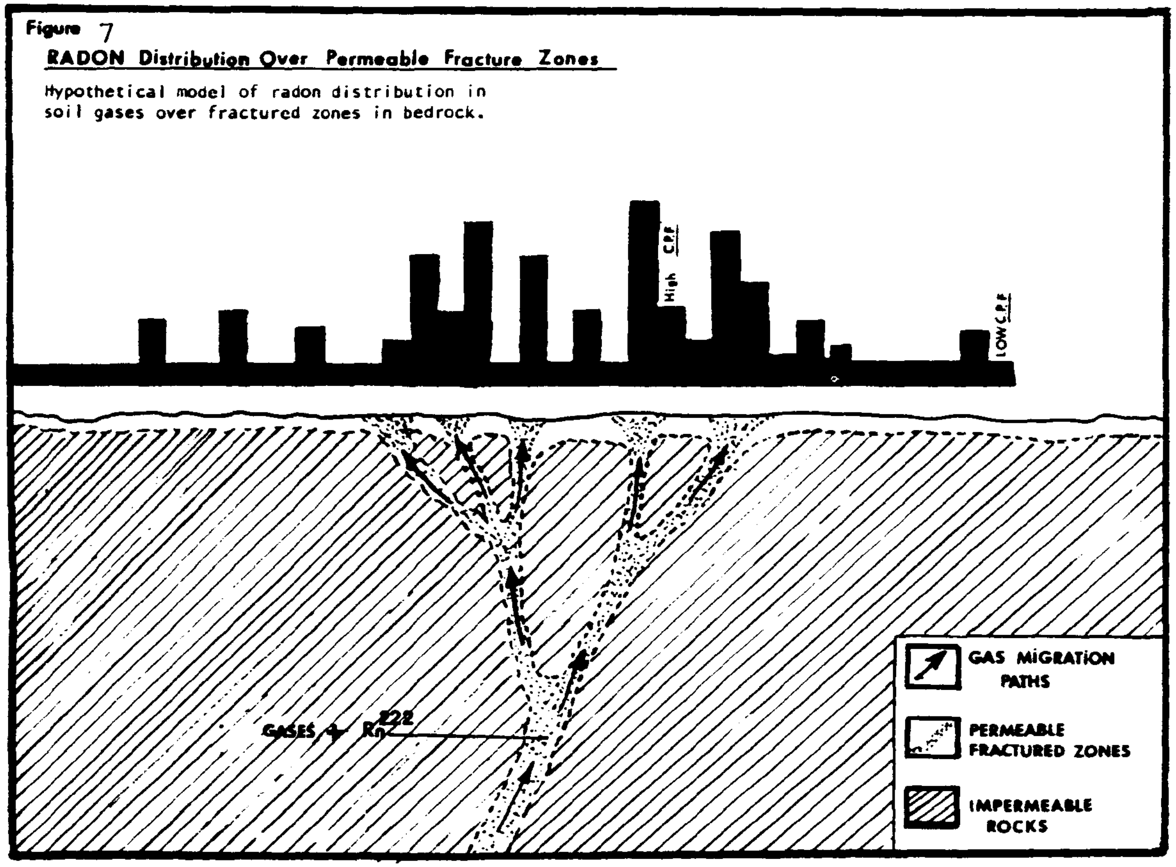

Figure 7, Radon distribution over permeable fracture zones . Hypothetical model of radon distribution in soil gases over fractured zones in bedrocks within Ohio and Appalachian basin.

ACKNOWLEDGEMENTS

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GEOLOGIC ASSESSMENT OF RADON-222 IN McLENNAN COUNTY, TEXAS

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ABSTRACT

Geologic parameters controlling the distribution and transport of radon were evaluated in McLennan County, Texas. Laboratory analysis of selected rock samples identified phosphate zones in the Austin Formation and shales and bentonites in the Lake Waco Formation as probable source rocks. Geophysical logging techniques utilizing gamma logs were supplemental in identifying the Lake Waco Formation as a source rock based on relative radioactivity between selected geologic formations. Emanation of radon from representative soil types was evaluated by using large area activated charcoal cannisters. The Houston and Houston Black clay soils had the greatest radon flux concentrations potentially resulting from increased surface area and more efficient transport of radon through desiccation cracks typical of these soils. Analysis of groundwater indicated that radon concentrations were greatest in the Austin Formation, particularly when samples were collected after rainfall events. Radon concentrations were shown to be greatly increased in wells located near stream discharge points owing to a flushing of the aquifer flow system, including the unsaturated zone, during periods of infiltration. Elevated indoor radon concentrations were found to be most commonly associated with homes overlying the Austin Formation which has been identified as a source rock and is characterized by high shrink-swell soils, abundant faulting and fracturing, and foundation failure caused by the high shrink swell soils. These characteristics allow for the production of radon and efficient transport from the subsurface to the indoor environment.

INTRODUCTION

Several localities in Texas have been identified as target areas with the potential for elevated indoor radon concentrations based on generalized geology maps and aerial gamma spectroscopy. These areas include the south Texas uranium district, Llano region, east Texas lignite belt, Panhandle shales, and Big Bend intrusives (see Figure 1)(1). However, a soil gas survey conducted by the United States Geological Survey indicated anomalous radon concentrations associated with the Austin Formation and adjoining outcrop belts, which comprise a major portion of the study area in McLennan County, Texas. Therefore, the objectives of this investigation are to examine the potential sources of radon in McLennan County, Texas; to interpret radon flux variation in soils with respect to soil type, thickness, permeability and underlying geology; to quantify the distribution of radon in shallow groundwater systems; and to analyze indoor radon concentrations on a county-wide basis.

LOCATION

The area of investigation is located in McLennan County, Texas characterized by northeast-southwest striking outcrop belts of Comanchean and Gulfian age Cretaceous deposits of limestone, chalk, shale, and marl. These units are typically shallow marine deposits, with the exception of the fluvial deltaic deposits of the Woodbine Formation and fluvial deposits of the Quaternary age alluvium. Figure 2 represents a stratigraphic column characteristic of the study area.

The study area lies within the Balcones Fault Zone, a northeast-southwest striking system characterized by normal faults, down-thrown to the east. Slickensided faults, calcite filled fractures and conjugate fractures are most commonly associated with the Austin and Ozan Formations. However, bedding plane separation and stress release fractures exist in all units.

Groundwater occurrence and flow occurs through fractured bedrock in the weathered zone and through porous sand and gravel of alluvial and terrace deposits. The aquifers are generally unconfined except where impermeable soils exist which may result in temporarily confined conditions. Regional groundwater flow systems are recharged primarily from the Austin Formation and possibly from the Lake Waco Formation, which are topographically high areas. Hydraulic communication occurs as regional flow between shallow groundwater in the Austin and Ozan Formations (2) and as local flow between the Austin and South Bosque Formations (3).

Distribution of soils within the study area relate primarily to underlying geologic influences where deep, clay-rich soils develop from shales and marls, and shallow, silty clay soils develop from limestones and chalk.

Climate within the study area is of a modified marine, sub-humid environment, characterized by hot summers and dry winters. Average annual precipitation is 33 inches and average annual lake evaporation is 65 inches (4).

METHODS

Methodology employed in this investigation involved the laboratory analysis for Radium-226 (hereafter referred to as radium) in rock and soil samples and Radon-222 (hereafter referred to as radon) in groundwater samples. Radon flux was determined by

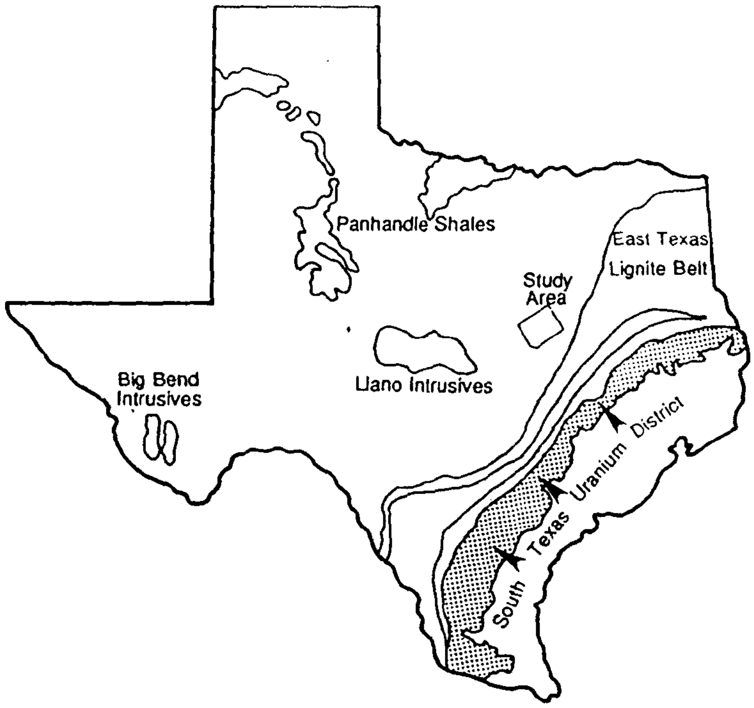

Figure 1 Areas in Texas with potential for elevated indoor radon concentrations (1).

System	Series	Group	Formation	Member	Lithology
CRETACEOUS	Gulfian	Taylor	Ozan		
		Austin	Bruceville		
			Atco		
		Eagle Ford	South Bosque		
			Lake Waco	Bouldin Cloice Bluebonnet	
		Woodbine	Woodbine Pepper *		
	Comanchean	Washita	Del Rio		
			Georgetown	Mainstreet Paw Paw Weno Denton Fort Worth Duck Creek	

*The Woodbine Formation exists in the northern study area while the Pepper Formation exists in the southern area.

Figure 2 Stratigraphy of the study area.

using large area activated charcoal cannisters (LAACC) supplied by the Environmental Protection Agency (EPA) (5). After sample collection, the charcoal was evaluated for radon by determining the concentrations of daughter products. Indoor radon concentrations were measured using charcoal cannisters supplied by an EPA proficient laboratory.

SOURCE ANALYSIS

Rock units were evaluated for source rock potential based on radium concentrations of selected rock samples and relative in-situ gamma radioactivity of boreholes completed in outcropping formations. The following sections describe the results and interpretation specific to each formation, from oldest to youngest, analyzed in this investigation.

WOODBINE GROUP

The Woodbine Group is comprised of the Woodbine Formation which forms a thin outcrop of sand and shale in the northern study area and the Pepper Formation which forms a thin outcrop of dark shale and sand stringers in the southern study area. Radium concentrations in samples obtained from the Woodbine Formation range from 1.31 pCi/g to 1.87 pCi/g for shale and sand samples, respectively (see Figure 3a and 3b). Radium concentrations in samples obtained from the Pepper Formation range from 2.06 pCi/g to 3.88 pCi/g for shale and sand samples, respectively (see Figure 3a and 3b).

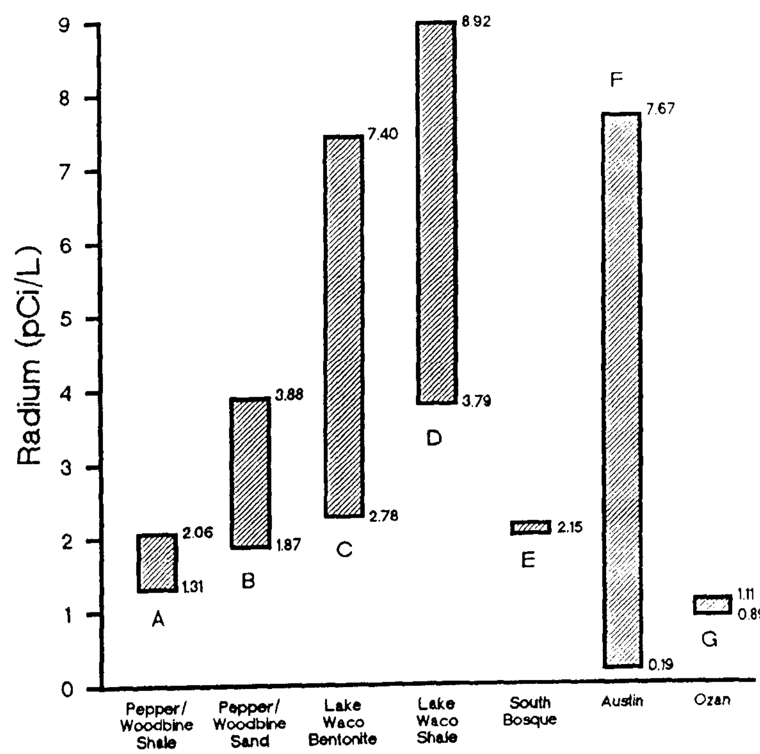

Figure 3. Ranges of radium concentrations in rock samples.

Sediment sources for the Woodbine Group include igneous, metamorphic, and sedimentary rocks from southeastern Oklahoma and southwestern Arkansas in addition to high grade metamorphics contributed by longshore currents from the Appalachians (6). Uranium present in the original source rocks was redeposited in the Woodbine sands resulting in the higher radium concentrations identified in the sand and sand stringers. The shales were deposited in a slightly reduced depositional environment with a decreased influx of sediment from the provenance described above. Therefore, slightly lower radium concentrations are characteristic of the shales.

The gamma log from a borehole completed in the Lake Waco and Pepper Formations indicates a sharp decrease in radioactivity at the Lake Waco/Pepper Formation contact (see Figure 4a). The distinct change at the contact represents a lithologic unconformity and a characteristic change in the aqueous geochemistry at the time of deposition. Radioactivity in the Pepper Formation increases slightly with depth possibly indicating that the lower units were deposited in a more restricted environment favorable for uranium precipitation.

LAKE WACO FORMATION

The rock samples were obtained from the Cloice Member of the Lake Waco Formation which consists of alternating black shale, limestone, and bentonite. Shale deposition occurred in a reduced depositional environment while limestone deposits are representative of fresh water influx (7). The bentonite unit, with radium concentrations ranging from 2.28 pCi/g to 7.40 pCi/g was deposited during periods of volcanic ash distribution and probably represent radium concentrations of the original volcanics (see Figure 3c). The black shales with radium concentrations ranging from 3.79 pCi/g to 8.92 pCi/g indicate a reduced depositional environment favorable for precipitation of uranium (see Figure 3d).

The gamma log from a borehole completed in the Lake Waco and Pepper Formations indicates that the Lake Waco Formation has relatively greater radioactivity than the Pepper Formation (see Figure 4a). This correlation coincides with the radium laboratory data indicating higher radium concentrations in samples obtained from the Lake Waco Formation. This gamma log also shows a peak associated with a bentonite unit encountered in the borehole and lesser peaks associated with shales.

The gamma log from a borehole completed in the Lake Waco Formation indicates that radioactivity increases slightly with depth (see Figure 4b). The peaks appear to correspond to bentonite or shale units and troughs represent limestone units. The upper portion of the log represents the Bouldin Member of the Lake Waco Formation which is a limestone dominated sequence having lower radioactivity. The lower portion of the log represents the Cloice Member of the Lake Waco Formation which is a shale dominated sequence with increased radioactivity.

Radium laboratory results and comparison of relative radioactivity from gamma logs indicates that shales and bentonites from the Lake Waco Formation have the greatest potential as source rocks in the study area.

SOUTH BOSQUE FORMATION

The South Bosque Formation consists of a massive dark gray shale containing sulfate deposits in the form of pyrite crystals which indicate deposition in a reduced environment (8). Radium concentrations were relatively low with 2.15 pCi/g (see Figure

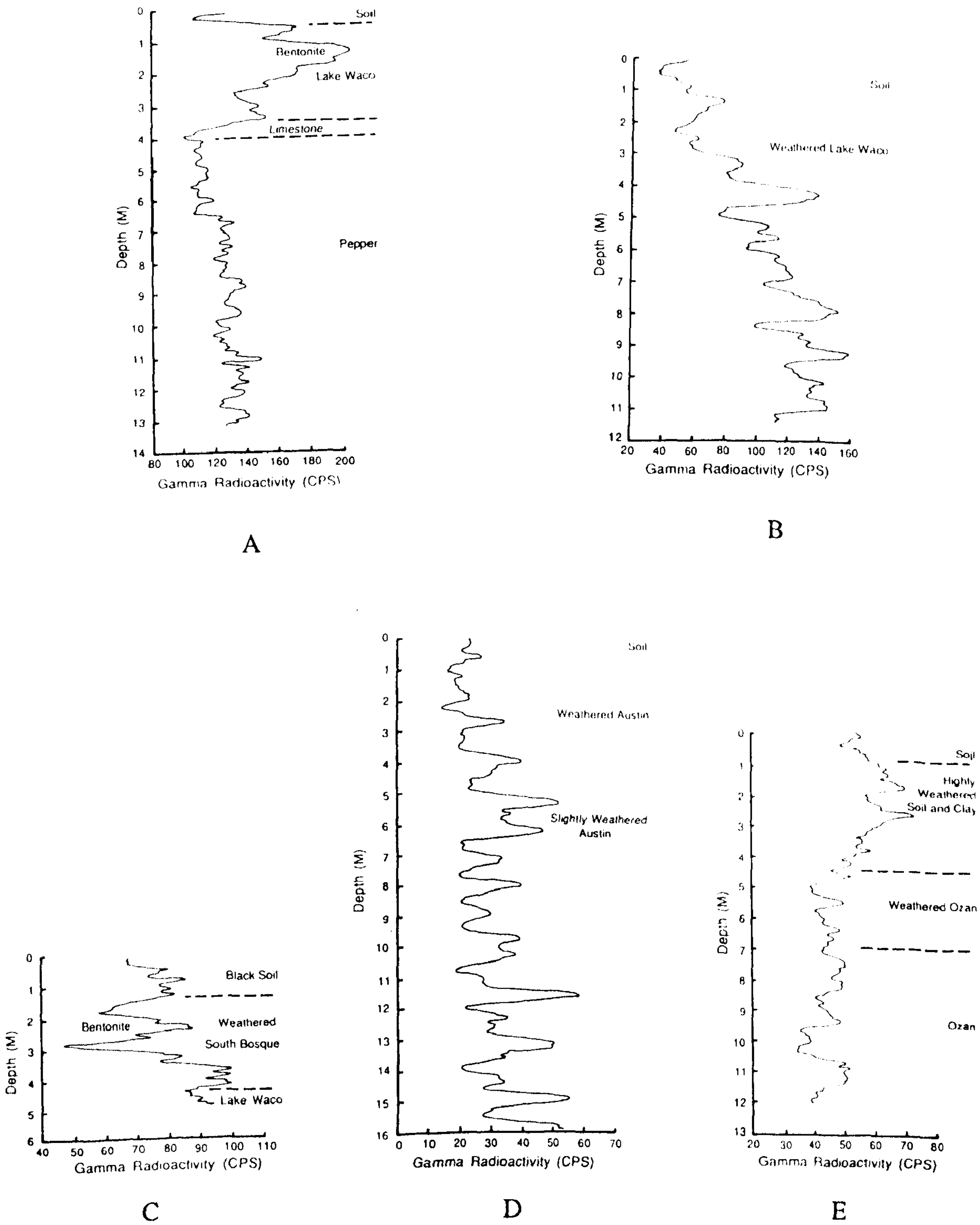

Figure 4 Representative gamma logs from wells completed in the Lake Waco/Pepper Formations (A), Lake Waco Formation (B), South Bosque/Lake Waco Formation (C), Austin Formation (D), and Ozan Formation (E).

3e). Although reduced conditions were in existence at the time of deposition, the lack of volcanics and true black shale deposition resulted in low uranium precipitation.

The gamma log of the South Bosque Formation indicates three zones of high radioactivity (see Figure 4c). The upper soil zone may represent colluvium originating from the adjacent escarpment which is known to contain phosphate nodules at the South Bosque-Austin Formation contact. These phosphate nodules sampled from the base of the Austin Formation for radium analysis contain 7.67 pCi/g which is comparable to the radium analyses from the Lake Waco shale. The middle radioactive zone is represented by a weathered bentonite unit with increased radioactivity resulting from original radionuclides present in the volcanics. The lower radioactive zone possibly represents a shale unit associated with the Lake Waco Formation.

AUSTIN FORMATION

The Austin Formation is composed of chalk with thin alternating marl units and bentonite seams (9). This unit is highly fractured due to the proximity of the Balcones Fault Zone and contains localized deposits of pyrite, calcite, and phosphate nodules. Radium concentrations ranged from 0.40 pCi/g to 1.69 pCi/g in the rock matrix and had concentrations of 0.62 in the pyritic zone, 0.13 for calcite filled fractures, 0.19 pCi/g for slickensided fractures, and 7.67 pCi/g for phosphate zones (see Figure 3f). Phosphates are located throughout the Austin Formation as a minor constituent and nodules occur at the upper and lower geologic contacts.

The gamma log of the Austin Formation indicates slightly increasing radioactivity with depth (see Figure 4d). Distinct peaks and troughs indicate lithologic changes from bentonite or marl units to chalk. The upper fractured zone shows decreased radioactivity which may indicate leaching of radionuclides by infiltrating water. Groundwater sampled from the Austin Formation maintained greater radionuclide concentrations than the remaining aquifers sampled in the study area. This may indicate that leaching and dissolution of radionuclides in the Austin Formation is more pronounced and transport through fractures more efficient.

OZAN FORMATION

The Ozan Formation consists of a massive dark gray montmorillonitic clay that is highly fractured with secondary calcite and hematite deposits along fracture faces. The samples obtained for radium analysis consist of matrix rock material and range from 0.89 pCi/g to 1.11 pCi/g (see Figure 3g). Locally higher concentrations may be present along fractures where secondary precipitation of radionuclides may have occurred.

The gamma log for the Ozan Formation indicates greater radioactivity in the upper weathered zone followed by decreasing radioactivity with depth (see Figure 4e). Previous hydrogeologic investigations show that the Austin Formation recharges the Ozan Formation through a regional groundwater flow system (2, 10). Groundwater from the Austin Formation, which contains higher radionuclide concentrations, may distribute and reprecipitate radionuclides in the Ozan Formation particularly along fracture faces. This would result in greater radioactivity in the weathered zone.

SOIL ANALYSIS

Soils were analyzed for radon flux which is defined by the EPA as the rate at which radon emanates from the soil for a given area and time interval (5). Twenty three selected sites comprise three east-west transects and represent thirteen soil types and nine geologic formations. Moisture content was analyzed for each sample to identify the relationship between radon flux and moisture. Radon flux measurements were repeated along the southern transect to identify the effects climatic variations.

RESULTS

The flux concentrations in the study area range from 0.34 pCi/m^2s to 10.40 pCi/m^2s, which are comparable to flux concentrations at an inactive phosphogypsum stack with flux concentrations ranging from 0.57 pCi/m^2s to 14.5 pCi/m^2s (11). The highest flux concentrations in the study area, ranging from 2.27 pCi/m^2s to 10.40 pCi/m^2s, are represented by Houston and Houston Black clay soils and have relatively high moisture content ranging from 5.48 percent to 20.92 percent. The Houston and Houston Black clay soils have low permeability, high moisture retention, and high shrink-swell potential owing to a fine grained montmorillonitic texture and composition. The underlying geology for the sites with the highest radon flux include the Austin, Pepper, South Bosque, and Ozan formations.

INTERPRETATION

Previous findings show that water present in intergranular spaces increase radon production by limiting the recoil range, but decreases diffusion by limiting migration (12). The clay soils represented in the study area exhibit these properties within the soil matrix. However, the residual nature and expansive property of these soils provide both a continual source and an efficient mode of transport for radon emanation. Desiccation cracks developed during dry periods are able to transport radon by initial recoil from the fissure faces, while diffusive transport occurs from interconnected pores adjacent to the fissure wall (see Figure 5). The clay matrices between desiccation cracks generate significant concentrations of radon because of higher moisture content but emanation of radon through diffusive transport is negligible because of the low permeability and the presence of water.

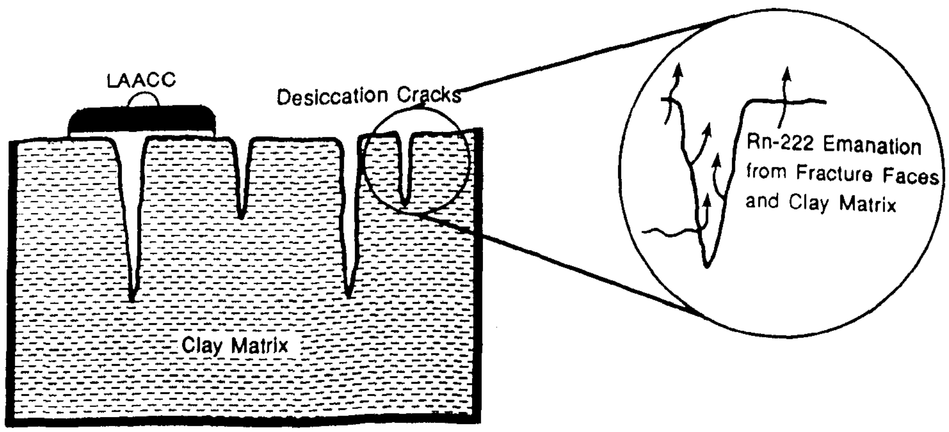

Figure 5. Diagrammatic illustration of radon emanation from the clay matrix and desiccation cracks. The presence of desiccation cracks allows for increased surface area from which radon may emanate in addition to more efficient transport of radon to the surface.

Two storm types that prevail in the study area include high intensity, short duration storms in the summer and early fall; and low intensity, long duration storms in the winter and early spring (4). During the summer and fall soils tend to be dry and desiccated. Water infiltrating into the soil matrix and desiccation cracks may force soil gas upwards causing a temporary increase in flux concentrations. Desiccation cracks will probably remain open because of the short duration of storms and a period will exist when increased flux occurs as a result of increased radon production in surface soil layers. Low intensity, long duration storms of winter, however, will reduce the size and distribution of desiccation cracks, causing infiltration to be primarily through the soil matrix. During the rainfall event, radon may be pushed upward by a rising water table and trapped by saturated clays at the surface and radon flux will be reduced except where openings exist. However, as desiccation cracks begin to form, radon flux concentrations will increase until the soil becomes dry in the area at the surface and near desiccation cracks.

Transect I in southern McLennan County was analyzed over two sampling periods for radon flux and moisture content in order to evaluate the effects of climatological differences on flux concentrations. The first sampling date represented a dry period (one month since significant rainfall) with temperatures near 100 degrees. The second sampling date represented an extremely dry period (2.5 months since significant rainfall) with temperatures near 85 degrees. Results show that a general decrease in moisture content during the second sampling period correlates with a slight reduction of radon flux, which contradicts an EPA study indicating that increased moisture correlates with decreased radon flux (5). This variation may be explained by decreased radon emanation produced from the areas near desiccation cracks during the dryer period caused by radon being recoiled more frequently into adjacent grains and less frequently into the pore space.

Sample locations representing the highest radon flux values, were evaluated for radium concentrations in the upper two to six inches of soil. The primary objective of this analysis was to determine if the source of radon flux originated from the upper soil matrix or from a deeper source.

Radium concentrations in soil samples ranged from 0.31 pCi/g to 0.89 pCi/g with a mean of 0.51 pCi/g and a median of 0.48 pCi/g. These values are low in relation to radon flux concentrations indicating a source other than the immediate soil matrix. The findings of the present investigation, therefore, identify bedrock, fissure faces in soils, and radon equilibration at the air-water interface in groundwater as potential sources contributing to radon flux and validates the significance of desiccation cracks and fractures in rock and soil as primary means of radon transport in the study area.

GROUNDWATER ANALYSIS

Groundwater from twenty-two shallow, large diameter wells and three springs was analyzed for radon concentrations. The results indicate a relationship between radon in groundwater and precipitation, temperature, aquifer efficiency, and topographic location of the well. Table 1 represents the laboratory results from each well and spring in addition to the sampling date and formation name.

The highest concentrations of radon in groundwater from the aquifers analyzed occurs in the Austin and Georgetown Formations. These are fractured chalk and limestone aquifers, respectively, which would generally be assumed to contain lower radionuclide concentrations. Four sampling periods which represent significant climatic variations were utilized in this evaluation. Precipitation, temperature, aquifer efficiency, and topographic location appear to be the major factors affecting radon concentrations in groundwater in the study area.

TABLE 1
RADON CONCENTRATIONS IN GROUNDWATER

Well or Spring* Location	Radon (pCi/L)	Date	Aquifer
1	72.4	7-06-89	Ozan
2	52.4	7-06-89	Ozan
3	39.3	7-06-89	Ozan
4 **	306.0	7-06-89	Austin
4	9.0	9-06-89	Austin
5 **	20.9	7-06-89	Austin
5	7.2	7-06-89	Austin
6	171.0	7-06-89	Austin
7	296.0	7-06-89	Austin
8	1.6	7-06-89	South Bosque
9	45.9	7-06-89	Lake Waco
10	3.9	7-06-89	Lake Waco
11	0.4	9-06-89	Del Rio
12	11.2	9-06-89	Georgetown
13	23.8	8-14-89	Ozan
14	6.3	8-14-89	Ozan
15 **	3.7	8-14-89	Ozan
15	0.0	9-06-89	Ozan
16 **	8.4	8-14-89	Austin
16	1.6	9-06-89	Austin
17	7.2	8-14-89	Austin
18 **	19.4	8-14-89	Terrace/South Bosque
18	11.9	9-06-89	Terrace/South Bosque
19	7.5	8-14-89	Terrace/Lake Waco
20	6.7	8-14-89	South Bosque
21	15.2	8-14-89	Woodbine
22	7.4	8-14-89	Terrace/Woodbine
23*	5.3	9-06-89	Austin (Proctor Spring)
24*	113.0	10-9-89	Austin (Indian Spring)
25*	211.0	10-9-89	Georgetown (Osage Spring)

** Wells sampled over two sampling periods

PRECIPITATION AND TEMPERATURE

In the two months prior to the first sampling date, 12.9 inches of rain was recorded by the National Weather Service in Waco, Texas. An additional .9 inches was recorded within three days of the first sampling date, which is characterized by higher radon concentrations. The second and third sampling dates, characterized by lower radon concentrations, were during dry periods of the year and very little precipitation was recorded prior to these dates. Double asterisks (**) on Table 2 represent wells that were sampled on two separate dates. Wells 4 and 5 had significant decreases in radon concentrations from the first sampling date to the third sampling date. Wells 15, 16, and 18 had only slight decreases in radon concentrations from the second sampling date to the third sampling date. Precipitation appears to be a significant factor in transporting radionuclides through the groundwater flow system and works in conjunction with aquifer efficiency. Samples 23 and 24, representing spring samples in the Austin Formation, indicate a significant increase in radon from the third sampling date to the fourth sampling date, which occurred the day after a precipitation event. In addition, radon variation in the spring samples may be caused by a 40 degree decrease in temperature between the third and fourth sampling dates. The agitation provided by the dispersive nature of the spring in addition to high temperatures (99 degrees) on the third sampling date resulted in greater radon loss to the atmosphere, whereas colder temperatures on the fourth sampling date assisted in increasing radon solubility factors.

AQUIFER EFFICIENCY AND TOPOGRAPHIC LOCATION

Aquifer efficiency refers to hydraulic conductivity and transmissivity of the aquifers. Based on well recovery rates observed after pumping, the Austin Formation with 98 percent recovery, appears to be the most effective at transport efficiency. The distinct and abundant interconnected fractures provide more efficient transport routes for radionuclides and supports higher radon concentrations in groundwater. The Ozan, with 65 percent recovery, and the Eagle Ford, with 59 percent recovery, appear to have tighter flow systems which would result in decreased radon in groundwater by maintaining longer residence times exceeding the half-life of radon. Therefore, radon concentrations detected in the chalk and limestone aquifers may have been sourced from areas outside the immediate well bore while radon concentrations observed in the shales are representative of an area within the near vicinity of the well bore.

The topographic location of a well may have a significant impact on the radon concentrations detected (see Figure 6) In this investigation wells located near entrenched stream valleys or discharge areas were characterized by higher radon concentrations than wells located near topographic divides. During precipitation events, water may infiltrate into the subsurface and absorb radionuclides encountered in the unsaturated zone. This infiltration will ultimately result in a water table rise and groundwater flow will temporarily be increased towards the down-gradient wells. Radionuclides in solution in the groundwater will increase in the down-gradient wells by the culmination of radionuclides obtained from the unsaturated zones and by dislodging radionuclides that are absorbed to particles. The divide wells, because of shorter flow paths from the recharge area, slower rates of groundwater flow, and thin soils, have decreased radionuclide concentrations in groundwater following precipitation events. As the water table begins to decline, radionuclides in the groundwater will begin to absorb to particles and fracture faces in what will become the unsaturated zone, and radionuclide concentrations in groundwater will decrease.

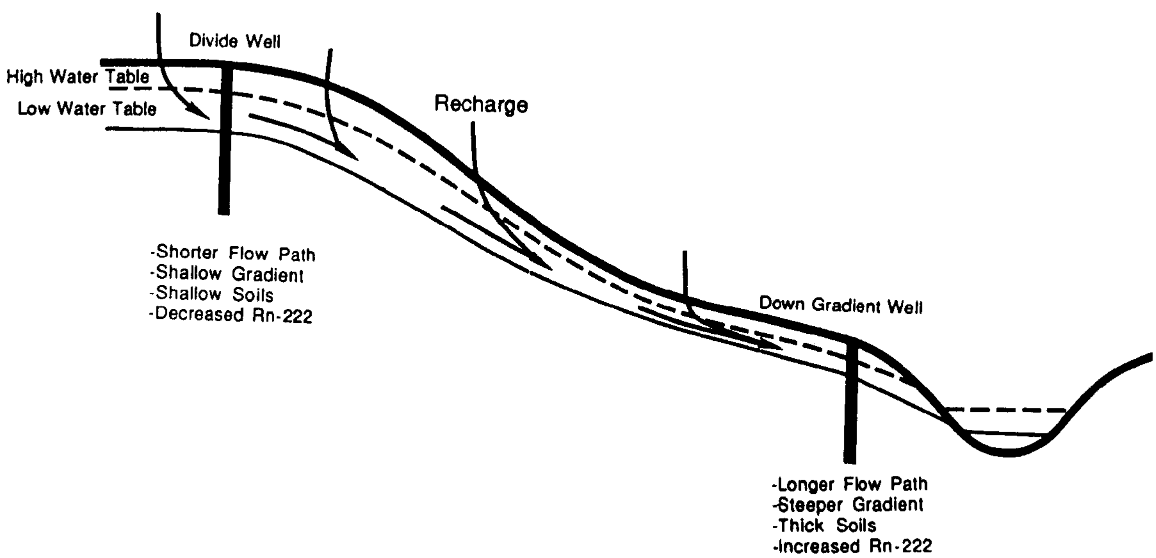

Figure 6. Diagrammatic cross section of groundwater flow showing radon variations between divide wells and down-gradient wells. The culmination of recharged water, longer flow paths, and steeper gradients transport radon from the up-gradient direction to the down-gradient well.

INDOOR ANALYSIS

Fifty homes were evaluated for indoor radon concentrations in order to determine the relationship between geological parameters and areas where homes are subject to high indoor radon concentrations. The homes tested were distributed throughout the county, with heavier concentrations in the Waco area. The resulting radon concentrations range from 0.0 pCi/l to 10.5 pCi/l. The highest indoor radon concentrations occur in homes located in Waco that overlie the Austin Formation (see Figure 7). The home with the highest indoor radon value is situated on Houston Black soils overlying the Austin Formation. The soils at this site are highly expansive and typically produce foundation failure resulting in cracked slabs through which radon may be introduced into the indoor environment. Originally the home consisted of a slab foundation but subsequent addition of pier and beam was required due to foundation failure. Cracks are visible throughout the home, particularly at door entrances, corners, windows, and between the wall and ceiling. Therefore, a pressure differential in combination with fractures in the Austin, the soil, and the home provided optimum conditions for radon transport and entry.

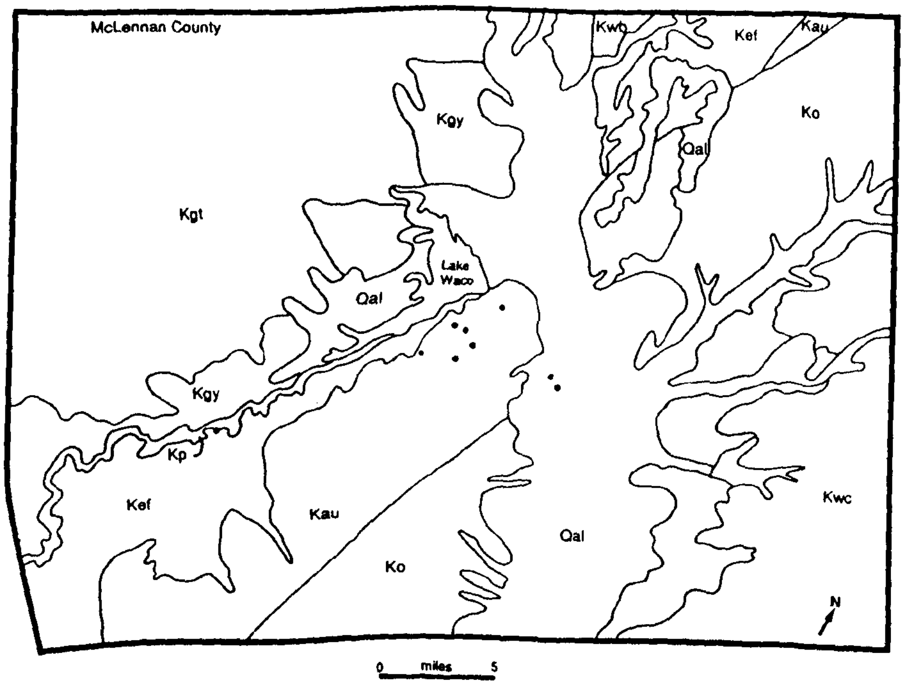

Figure 7. Distribution of indoor radon concentrations exceeding 4.0 pCi/L. The Austin Formation appears to have the greatest potential for high indoor radon concentrations.

Homes with indoor radon concentrations above the EPA recommended guideline of 4.0 pCi/l , in addition to those located over the Austin Formation, include the lower Lake Waco Formation, upper Pepper Formation, and the Woodbine Formation. High radon flux in the soils overlying the Lake Waco and Pepper Formations, and associated foundation failure due to the instability of the soil, introduced a source and mode of transport into the structures. In the Woodbine Formation, the radon flux results and source rock potential were low. However, the sandy nature of the underlying bedrock and gravelly nature of the underlying soils may have produced efficient transport mechanisms by diffusive flow resulting in a high indoor radon value.

Homes overlying the Austin Formation in the study area appear to have the greatest potential for indoor radon concentrations exceeding the EPA recommended guideline. The Austin Formation is a highly faulted and fractured formation which contains phosphatic zones identified as potential source rocks in this investigation and is associated with high shrink-swell soils causing foundation instability. These characteristics are favorable for elevated indoor radon concentrations.

CONCLUSIONS

Phosphatic zones in the Austin Formation and shales and bentonites of the Lake Waco Formation have been identified as the potential source rocks in the study area based on laboratory results from radium analysis. In-situ gamma logs indicate that the Lake Waco Formation and the South Bosque Formation contain the greatest amounts of relative gamma radioactivity.

Results from radon flux analysis in soils indicates that the greatest potential exists in relation to Houston and Houston Black clay soils. These high shrink-swell potential soils allow for increased permeability and surface area which result in increased emanation rates and high radon flux concentrations.

Radon in groundwater is greatest in the Austin Formation. A clear relationship exists between radon concentrations in groundwater and frequent precipitation events, low temperatures, lower topographic location of the well, and high aquifer efficiency.

Indoor analyses indicate anomalies associated with the Austin, Woodbine, and lower Lake Waco Formations. This is the result of high shrink-swell soils and associated foundation failure which allow for efficient transport of radon into structures. The Austin Formation has the highest potential for elevated indoor radon concentrations because of high shrink-swell soils, foundation failure, common faults and fractures, and an identified source rock.

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RADON EMANATION FROM FRACTAL SURFACES

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ABSTRACT

A fractal theory of radon emanation is developed for the precursor Ra distributed uniformly throughout the sample. The main ingredient of the theory is the α recoil from fractally rough surface. A relation between emanating power and the specific surface area is derived and discussed in detail. It is suggested that the emanating power measurements can be used to determine the fractal dimension of the surface on the scale from tens to hundreds of nanometers. The theory is in good agreement with some of the experimental data, while the discrepancy with the remaining data is attributed to radon implantation. A new process of penetrating recoil is suggested and the role of indirect recoil is modified. The need of using the median projected radon ranges rather than extrapolated ranges is discussed.

INTRODUCTION

It is well established that radon emanates from solids predominantly by α recoil at temperatures that do not substantially differ from the room temperature. The recoil effects have been shown to explain many features of radon emanation, e.g., (1,2). At temperatures much greater than normal, however, processes such as solid-state diffusion, dehydration, decomposition, structural changes, and sintering begin to contribute to radon emanation (3). Since the recoil occurs from a solid region close to the surface into the air space, the emanation is essentially a surface phenomenon. In 1923 Hahn and Müller suggested that the emanation technique could be used in surface-area determinations (4). In 1939 Flügge and Zimens published the first emanation theory; they showed that the recoil emanating power E_R from a spherical grain of radius r_0 having uniform distribution of precursor Ra is proportional to $3R/r_0$, where R is the recoil range (5). The $3/r_0$ factor is a ratio of surface to volume S/V of a sphere and it was assumed that it represents real surfaces. Thus, for sufficiently large grains one obtains (5)

$$E_R = \frac{1}{4} R \frac{S}{V} , \qquad r_0 \gg R . \tag{1}$$

While the above assumption appears quite intuitive, the formal derivation of equation 1 for realistic surfaces was made only recently (Ref. 1, eq. 23). The S/V can also be expressed as $\rho_0 A$, where ρ_0 [$\mathrm{g \cdot cm^{-3}}$] is the solid state density and A [$\mathrm{m^2 \cdot g^{-1}}$] is the specific surface area.

Several authors have studied the emanating powers of ^{220,222}Rn from various solids having uniform distribution of precursor Ra as a function of A (6–10). The specific surface areas were determined by gas adsorption (BET) technique (11). Linear relationships between E_R and S/V have been deduced from these experiments but the exact nature of this proportionality remained elusive. This is illustrated in Fig. 1 where we plot the ratio of theoretical slope from eq. 1 to the experimental slope, i.e., $R\rho_0 A/4E_R$ vs. the maximum specific surface area measured. The ranges were calculated from the semiempirical relationship by Flügge and Zimens (5). It is seen from Fig. 1 that approximately the greater the A measured the greater the discrepancy between theory and experiment, which is as high as a factor of 31 for a specific surface area of several hundreds $\mathrm{m^2 \cdot g^{-1}}$.

Other two processes that have escaped a clear understanding are Rn implantation and indirect recoil. Flügge and Zimens (5) suggested that the recoiling Rn atoms have sufficient kinetic energy to implant themselves into another grain provided the grains are sufficiently small and close to each other so that the recoils will not stop in the surrounding air. The same authors estimated that the maximum emanating power from powders is therefore ~ 0.01. This is, however, in contrast with experiments. In fact, most of the data shown in Fig. 1

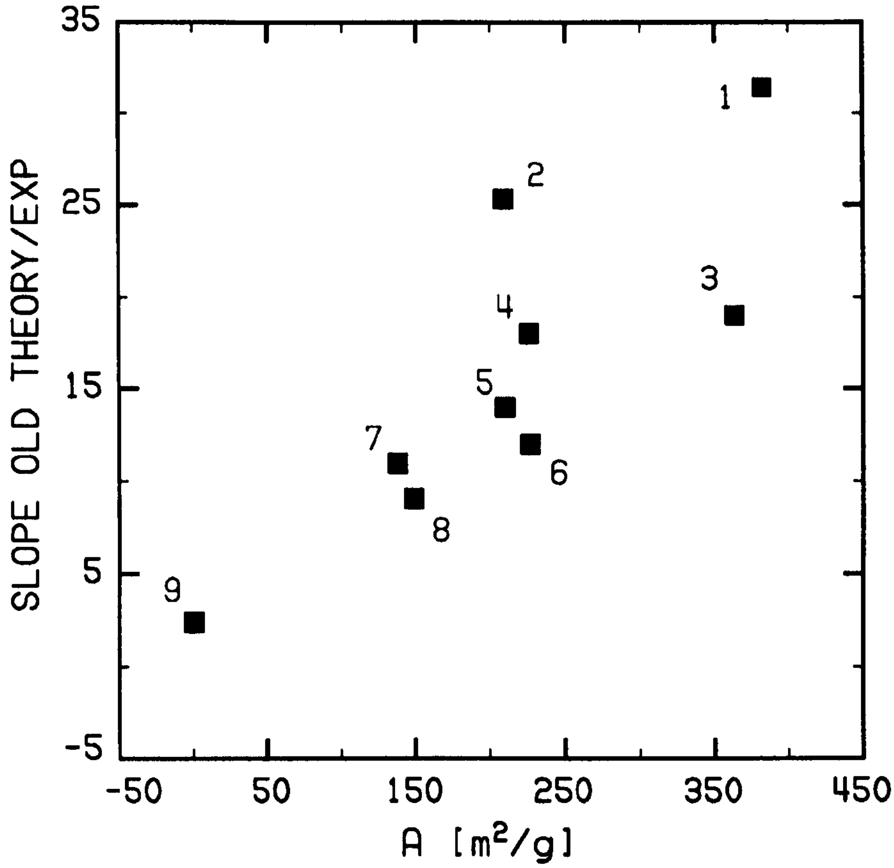

Figure 1. Ratios of the slopes of emanation curves from the old theory and from the experiments plotted vs. the maximum specific surface area A measured. Point numbers refer to the systems: 1,2 $^{220}Rn/MgO$ (6), 3 $^{220}Rn/MnO_2$ (7), 4 $^{220}Rn/ZrO_2$ (8), 5 $^{220}Rn/Al_2O_3$ (9), 6 $^{220}Rn/MgO$ (8), 7 $^{220}Rn/NiO$ (7), 8 $^{220}Rn/ThO_2$ (8), 9 ^{222}Rn/brick (10).

are for finely dispersed solids and the values of E_R often exceed 0.5. This discrepancy led Quet and Bussière to conclude: "The absolute emanating powers of the various samples are too high for a powder. We must consider the possibility for radon to escape anomalously from the solid at room temperature" (6). This situation can be helped with the concept of indirect recoil by Zimens (12): the recoils implanted into the solid may subsequently diffuse back through the region of radiation damage caused by the implantation (see also Ref. 3, p. 54). This is, however, inconsistent with ^{222}Rn implantation experiments into monocrystals and some geological samples performed by Lambert *et al.* (13) and Lambert and Bristeau (14), which indicated that the Rn recoils once implanted do not easily diffuse out. Using the authors' statement: "Simple radioactive measurements show that the diffusion of radon is very low within various monocrystals and that it cannot explain the emanating power of rocks" (14).

We have just described that, in spite of general consensus that recoil is a predominant mechanism of radon release, the exact nature of the relationship between the emanating power and the surface area as well as implantation and indirect recoil remain unclear. The purpose of this paper is to try to explain some of these discrepancies. The models of Rn emanation based on Euclidean geometry either fail to describe the emanating surface properly or express the surface with the parameters that are not sufficient. We therefore use the fractal geometry of Mandelbrot (15) to describe the emanating surface. In the subsequent sections we discuss briefly the principles of fractal geometry and use it to derive a fractal theory of Rn emanation. We then discuss the meaning of fractal dimension determined from emanation measurements in relation to the fractal dimension obtained from gas adsorption measurements. We discuss the relationship between the emanating power and specific surface area in detail. The fractal model of radon emanation leads us to suggest a new interpretation of implantation and indirect recoil. Finally, we address the question of the use of Rn recoil ranges in emanation. In this paper we are interested only in uniform distribution of Ra in the samples.

FRACTAL THEORY OF RADON EMANATION

Principles of Fractal Geometry

A concept of self-similarity is central to fractal geometry: the fractal object contains features of different sizes that are invariant under ordinary geometric scaling (Ref. 15, p. 18), i.e., they look similar at different magnifications. The number of features of size r is proportional to r^{-D}, where D is the fractal dimension (Ref. 15, p. 37). The value of D is normally a noninteger and it lies somewhere between the topological dimension D_T and the dimension of the embedding Euclidean space E: $D_T \leq D \leq E$. For lines $D_T = 1$ and $E = 2$ so $1 \leq D \leq 2$; for surfaces $D_T = 2$ and $E = 3$, so $2 \leq D \leq 3$. Another important point is that, if two sets with fractal dimensions D_a and D_b intersect, the fractal dimension of the intersection is usually $D_a + D_b - E$ (Ref. 15, p. 365). We illustrate these concepts by plotting several alternate Koch curves in Fig. 2 (Ref. 15, p. 48). The fractal dimensions are given next to each curve. If the fractal surface D is intersected with a plane, the fractal dimension of the resulting curve is $D + 2 - 3 = D - 1$. Since the curves in Fig. 2 are considered as cuts through the fractal surfaces, the dimensions of the corresponding surfaces are obtained by adding 1 to the curve dimensions and are given in parentheses in Fig. 2. A comprehensive analysis of surfaces of many materials revealed that most of them are fractals at least in the molecular range (16).

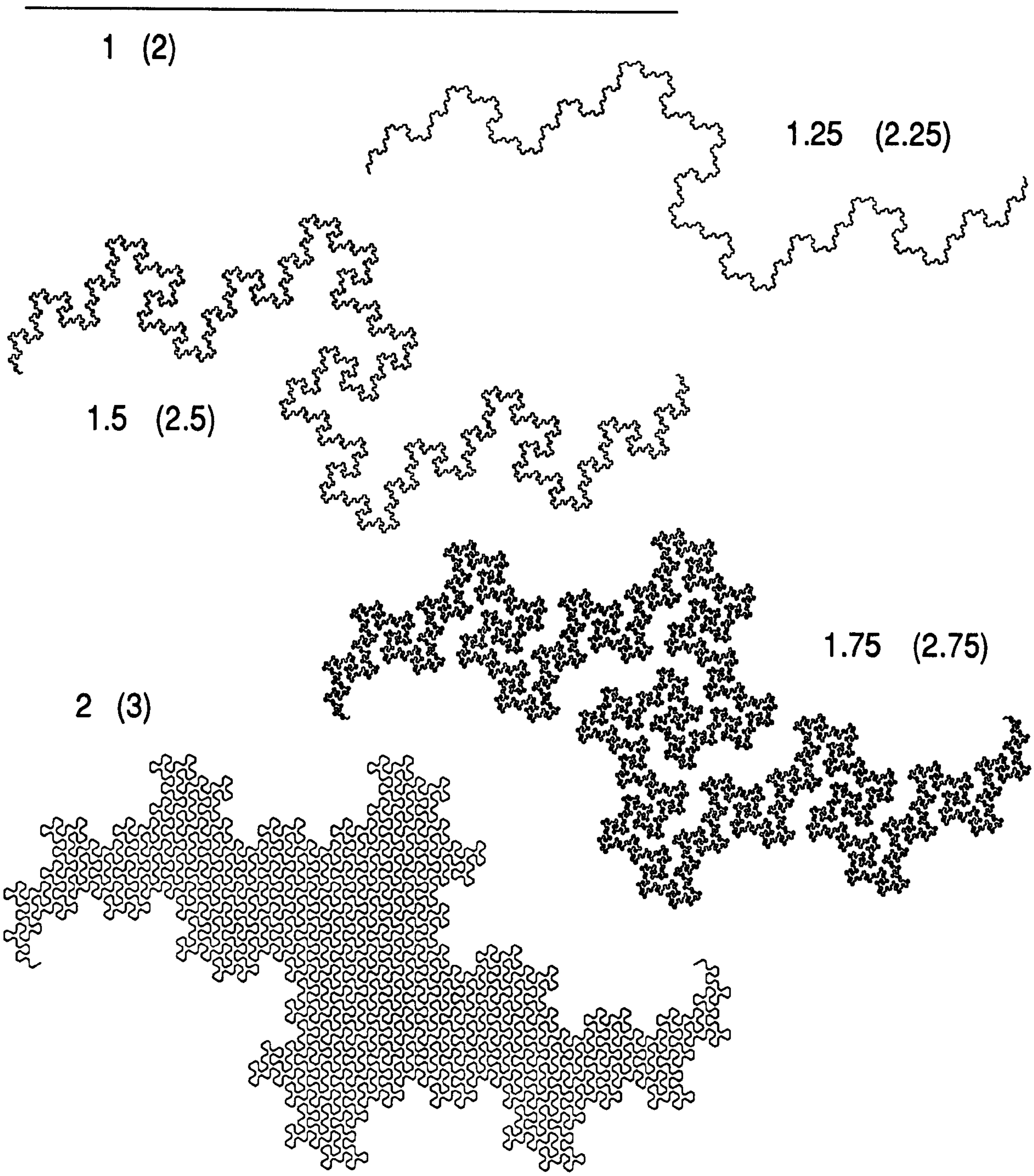

Figure 2. Alternative Koch curves describing the cuts through the fractal surfaces. The fractal dimensions are given by each curve followed by fractal dimensions of the corresponding surfaces (in parentheses).

An important concept of interest to radon emanation is the volume of points with distances $\leq r$ from a fractal. Consider a fractal object depicted in Fig. 3. At each point of a fractal center a circle of radius r. The volume enclosed by an outer envelope of the circles is given by (Ref. 15, p. 358)

$$V(r) = B\,r^{E-D}\ , \tag{2}$$

where B is a certain theoretical constant. For real fractal surfaces this constant can be eliminated by covering a surface with an adsorbate, and determining the monolayer volume $V(a)$, as suggested by Pfeifer *et al.* (17). In $V(a)$, a is a diameter of the adsorbate molecule, e.g., $a \approx 3.5$ Å for N_2 molecule. Consequently, one half of the volume from eq. 2 is given by

$$V(r) = V(a)\left(\frac{r}{a}\right)^{3-D}\ . \tag{3}$$

Equation 3 and its modifications have been used extensively in studying multilayer adsorption on fractal surfaces (17,18).

As can be seen in Fig. 2, fractal surfaces have an internal porosity that first increases and then decreases with D. Two limits are observed: for $D = 2$ and 3. For $D = 2$ we have a flat surface with no porosity. For $D = 3$ we have such an extreme roughness that the fractal surface completely fills the volume space, so the internal porosity is again zero. In fact, the pore-size distribution is proportional to $(3-D)(D-2)$ so it vanishes at both $D = 2$ and 3 (19). Note that for $D = 3$ the picture in Fig. 2 is composed of a single line where we cut the corners to illustrate the effect. It belongs to a family of Peano-type curves (Ref. 15, p. 62). This theoretical limit has to be considered as a singularity, however. For real materials, surfaces with D close to 3 such as porous silica gel with $D = 2.94 \pm 0.04$ still contain a tremendous number of micropores and have specific surface areas as high as 600 $m^2 \cdot g^{-1}$ (20).

Emanation From Fractal Surface

The precursors of fractal ideas in emanation can be found as early as in the 1941 paper of Kurbatov (21). Kurbatov figures resemble fractals in some ways. However, fractals were unknown to physical science at that time. The basic information about fractals given in the previous section will be now used to study the emanation, assuming that the emanating surface is self-similar. We refer the reader to Fig. 4 where we consider a volume of points with the distances $\leq R$ from a fractal surface $V(R)$, R being the recoil range, from which the emanation can occur. For simplicity of plotting only, we did not choose any particular fractal in Fig. 4. Four elementary processes: direct recoil, implantation, indirect recoil and penetrating recoil are depicted in Fig. 4. The emanating power E_R is proportional to the

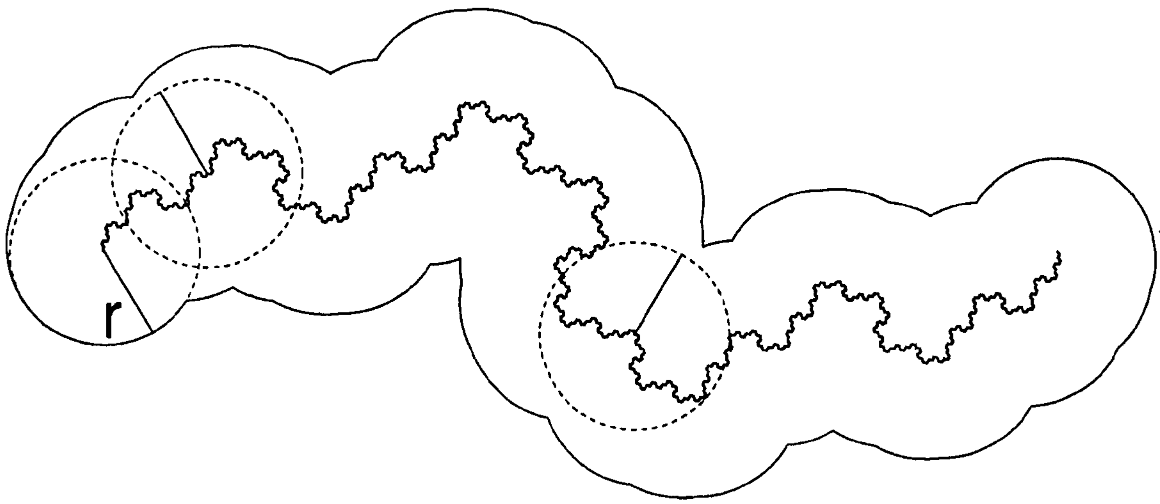

Figure 3. Volume of points with distances $\leq r$ from a fractal ($D = 1.2$).

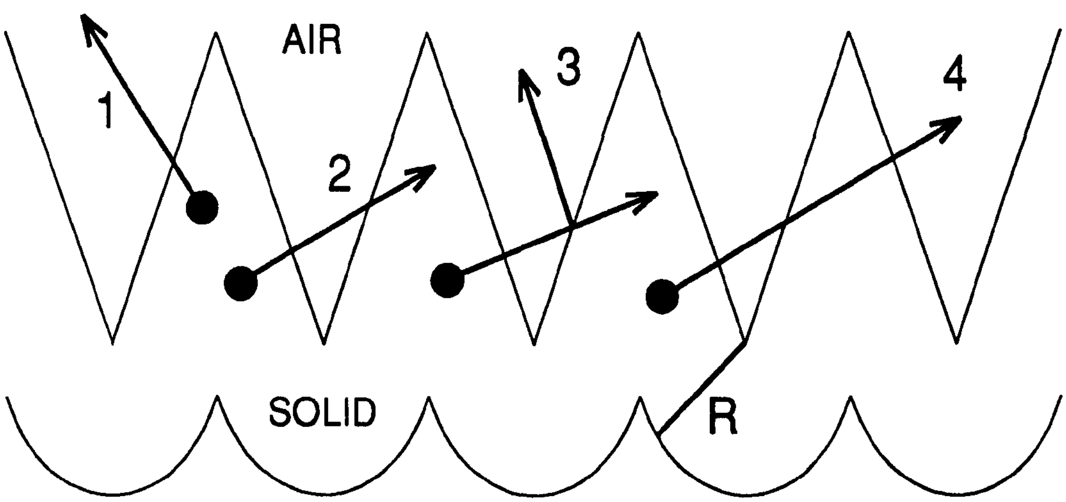

Figure 4. Volume of points with distances $\leq R$ from a surface. R is a recoil range. Arrows abbreviate the processes: 1 direct recoil, 2 implantation, 3 indirect recoil, and 4 penetrating recoil.

ratio of $V(R)$ to the total solid-state volume V. Using eq. 3 and the fact that $V(a) = Sa$, where S is the BET value of surface area we get

$$E_R \propto \frac{V(R)}{V} = \left(\frac{a}{R}\right)^{D-2} R\,\frac{S}{V}\,. \tag{4}$$

The proportionality of E_R to S/V comes naturally from considering the fractal properties of surface.

Equation 4 is modelless. However, we must consider emanation from particular shapes in order to calculate the proportionality constant in eq. 4. We have chosen emanation from plates as a specific geometric model. The reasons are manifold. The emanation from a plate is essentially a 1-dimensional problem so the integration is simple. Also, small grains can have a variety of shapes such as platelets or needles in addition to spheres. Using the formulas for emanation from a plate (22) and performing the integration over the entire fractal regime one obtains (23)

$$E_R = \frac{1}{4}\left[\frac{2^{D-1}}{4-D}\left(\frac{a}{R}\right)^{D-2}\right] R\,\frac{S}{V}\,, \qquad 2r_0 \geq R \tag{5a}$$

$$E_R = 1 - \frac{3-D}{4-D}\,\frac{2r_0}{R}\,, \qquad R > 2r_0\,, \tag{5b}$$

where r_0 is a half-thickness of a plate (or geometric radius of an object). In deriving eq. 5 we neglected the edge effects (1) and assumed cancellation of certain terms.

Equation 5a shows that for objects larger than the recoil range $E_R \propto S/V$. For objects smaller than R, E_R asymptotically approaches 1 and is independent of S/V. The surface-to-volume ratio for a fractal object can be expressed as (23)

$$\frac{S}{V} = \frac{K}{r_0}\left(\frac{r_0}{a}\right)^{D-2} \tag{6a}$$

$$K = \frac{C}{(3-D) + (D-2)\left(\frac{a}{r_0}\right)^{3-D}}\,, \tag{6b}$$

where C is a surface-to-volume ratio of an outer shape (a hull) and it is equal to 6 for a cube, 3 for a sphere, 2 for a cylinder, and 1 for a plate. Using eq. 5a,6a, the emanating power can then be expressed as a function of radius r_0

$$E_R = \frac{K}{4-D}\left(\frac{R}{2r_0}\right)^{3-D}\,, \qquad 2r_0 \geq R\,. \tag{7}$$

For $C = 1$ and $D = 2$ eq. 7,5b reduce to the familiar Euclidean formulas $R/4r_0$ and $1-r_0/R$, respectively (22). For $D = 3$ emanation is complete ($E_R = 1$). The $D = 3$ limit can be understood by recalling the discussion in the previous section. For $D = 3$ the surface has an extreme roughness and is composed of thin solid sections with well developed microporosity, so all Rn can emanate into pores. Equations 5,7 describe what fraction of Rn atoms recoil out of the surface. They do not describe the implantation processes from Fig. 4, which will be discussed later.

Recoil Ranges

In emanation studies fixed values of recoil ranges R have usually been assumed. The ranges are traditionally deduced from a semiempirical relationship by Flügge and Zimens (FZ) (5). Their approach has been questioned; we refer the reader to a work of Baulch and Duncan (24) for a detailed discussion. The point is that FZ ranges are those which one might call extrapolated. In reality the range has a distribution due to range and angle straggling of recoiling atoms penetrating the medium. The quantity that is best measured experimentally is the median projected range R_m. It is the penetration depth to stop 50% of the beam, projected on the beam direction. Here we use a theory of Lindhard, Scharff and Schiøtt (LSS) to calculate the range R_m and its variance σ_m (25,26)

$$R_m = \frac{e\,m}{\pi^2 N_0 \hbar^2} \frac{\sqrt{Z_1^{2/3} + Z_2^{2/3}}}{Z_1 Z_2} \frac{M_1 + M_2}{M_1 + \frac{1}{3} M_2} \frac{M_2}{\rho_2} E_1 \tag{8a}$$

$$\frac{\sigma_m}{R_m} = \sqrt{\frac{2}{3} \frac{M_2}{M_1}} \frac{M_1 + \frac{1}{3} M_2}{M_1 + M_2} \,. \tag{8b}$$

In eq. 8 M is the atomic mass, Z is atomic number, E is kinetic energy, ρ is the density, m is the electron mass, N_0 is the Avogadro number, $\hbar$ is the rationalized Planck constant, e is the basis of natural logarithm, and indexes 1 and 2 refer to a beam (recoil) and a target (solid), respectively. The LSS ranges are in good agreement with experimental ranges of ^{222}Rn in Al at energies of $\sim$ 100 keV (27), which, in fact, is of interest to emanation.

It is instructive to compare the R of FZ with R_m of LSS. For ^{222}Rn recoil in glass we get 37 and 26 nm, for ^{220}Rn recoil in MgO we get 37 and 21 nm, respectively. The FZ values are larger and thus they may be referred to as extrapolated. Considering the Rn emanation, we calculated the emanating power from a plate assuming a Gaussian straggling and neglecting the channeling effects. The result is (23)

$$E_{R_m} = \frac{1}{4} \frac{R_m}{r_0} \operatorname{erf}\left(\frac{R_m}{\sqrt{2}\,\sigma_m}\right) , \qquad r_0 \geq R_m , \tag{9}$$

where erf(x) is an error function. For ^{222}Rn in glass we get from eq. 8b $R_m/\sqrt{2}\,\sigma_m \approx 3$ and erf(3) $\approx$ 1. Therefore the R_m values should be used for ranges in emanation. Equation 9 is valid for features that have sizes of R_m or larger. As can be seen from eq. 5a, this is particularly important for D close to 2. For features smaller than R_m a particular value of range is less important because most of the Rn emanates anyway. This is the case for D approaching 3 and eq. 5,7 show that E_R is then only a weak function of range.

APPLICATIONS AND DISCUSSION

Equation 7 shows that the emanating power should scale as r_0^{D-3}. Therefore from a logarithmic plot of E_R vs. r_0 one should be able to deduce the fractal dimension of the emanating surface. To illustrate this we plot in Fig. 5 the data of Barretto (28) who measured E_R for sieve-separated size fractions of Lipari volcanic glass. The straight line is a least-squares fit to the data. From the Euclidean formula one would expect the slope of this line to be -1 but it is -0.83 ± 0.06, which gives the value of $D = 2.17 \pm 0.06$.

The constant C from eq. 6b can be determined to give a quantitative fit to the data. The result is $C = 9.8$, too high for any reasonable shape of the hull. We also used the LSS value of ^{222}Rn range in glass, $R_m = 26\,\mathrm{nm}$. In order to improve the fit, one has to realize that the size ranges for each fraction were quite wide and are indicated by horizontal lines in Fig. 5. The emanation will therefore depend on the (unknown) weight vs. size distribution in each size fraction. Since the emanation scales as r_0^{D-3}, the contribution to emanation is greater from smaller sizes in each size fraction. One then has to integrate eq. 7 over the appropriate distribution. We assumed a constant weight vs. size distribution in each fraction, integrated eq. 7 accordingly (23), and repeated the fit. The result is $D = 2.28 \pm 0.10$ with $C = 3.1$. The two values of D overlap within the error of the fit. The value of C is close to 3 indicating approximately spherical shapes of the particles. It is remarkable that, under a reasonable assumption, eq. 7 gave a quantitative agreement with the data with only two fit parameters: D and C. This shows that processes such as implantation were not significant, which is easy to justify on the basis of the low value of D and large r_0. Small D indicates a moderate surface irregularity so the implantation in the same grain must have been small. Implantation into neighboring grains was largely prevented by Rn stopping in the surrounding air because the intragrain distances were tens of μm or more ($R_m(\mathrm{air}) = 47\ \mu\mathrm{m}$ for ^{222}Rn).

We conclude that the Lipari volcanic glass had a fractal surface with a rather low fractal dimension in the vicinity of 2.2. It can be compared with similar geological and glassy materials with D determined by other techniques (20,29). The values of D are: 2.14 ± 0.06 for Madagascar quartz, 2.15 ± 0.06 for Snowit Belgian quartz glass, 2.21 ± 0.01 for crushed quartz, and 2.35 ± 0.11 for crushed Corning lead glass. The emanating power thus emerges as a new technique for determination of surface fractality. It is limited, however, by the prerequisite of having the precursor Ra distributed uniformly throughout the sample.

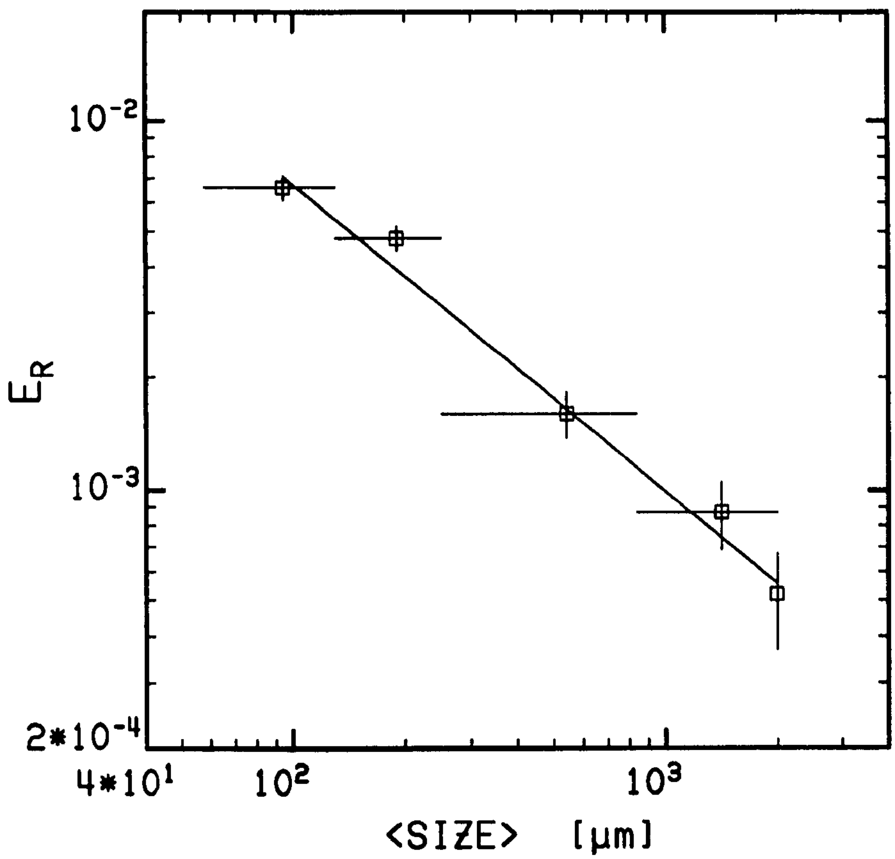

Figure 5. Emanating power E_R plotted vs. the average size of the grains. Horizontal bars are the size ranges in each fraction (not the errors). The lower rightmost point is a lower limit on size.

When implying that there is a fractal dimension D associated with a surface, we are faced with a question of a range of its self-similarity. It is instructive to compare this with gas adsorption techniques (30). In that case one covers the surface with molecules of size a and using the BET method, for instance, one can deduce a monolayer coverage. Thus the lower limit of self-similarity is a. If the fractality was determined for particle sizes between r_{min} and r_{max}, the upper limit of self-similarity is ar_{max}/r_{min}, for particles with size r_{max} (30). It does not imply that the self-similarity does not extend higher. It only says that the adsorption is not sensitive to self-similarity above the upper limit. A typical range of self-similarity determined from gas adsorption thus lies between a fraction of a nm to tens of nm.

For Rn emanation the situation is as follows. Equation 5a shows that $E_R \propto S/V$ and a value of a enters the formula. However, a more fundamental formula is given by eq. 7, which does not contain any value of a. It was just easier to derive it that way. The parameter of interest is the recoil range R_m. It is seen from eq. 7 that for $2r_0 \geq R_m$, E_R is sensitive to D. For $R_m > 2r_0$ we have to look at eq. 5b. Some sensitivity to D is still there but for plate only. For a sphere eq. 5b would give $E_R = 1$ identically, and the sensitivity to D would be lost. Hence, for realistic particles one can say that the lower limit of self-similarity is approximately $R_m/2$. Suppose a self-similarity was determined for particle radii between r_{min} and r_{max}. Using the concept of self-similarity we scale the r_{min} particle up to the r_{max} particle by a scaling factor of r_{max}/r_{min}. So if the lower limit of self-similarity is $R_m/2$, the upper limit for particle r_{max} is $R_m r_{max}/2r_{min}$. The range of self-similarity by emanation technique is thus

$$\left(\frac{1}{2}R_m\ , \frac{1}{2}R_m\frac{r_{max}}{r_{min}}\right)\ , \qquad (10)$$

for particle with radius r_{max}. Applying these concepts to the data of Barretto (28) and using $R_m = 26$ nm, $r_{min} = 94$ μm, and $r_{max} = 2000$ μm, we get a range of self-similarity between ~ 13 to ~ 280 nm. The emanation technique for D determination thus complements the adsorption technique by being sensitive between tens to hundreds of nanometers.

We now turn to a dependence of E_R on S/V and use eq. 5a to analyze the data of Quet and Bussière (6). These authors made a comprehensive investigation of ^{220}Rn emanation from MgO labelled with ^{228}Th. The samples were prepared by coprecipitation of ^{228}Th with $Mg(OH)_2$. The precipitates were then heated for several hours at different temperatures of several hundreds °C to make the final samples. The samples were composed of fine grains of MgO. Besides the E_R, specific surface areas A by BET (11) and De Boer V-t adsorption curves (31) were determined, as well as the electron-microscopy images were taken. It was also determined that the E_R was not dependent on Rn transport in the samples by showing that the measured activity of ^{220}Rn increased linearly with the sample mass.

We reproduce Quet and Bussière (6) emanating-power data in Fig. 6. The curve has a linear section, between points 8 and 16, and it deviates from linearity between points 1 and 7. The slope of the linear section is about 25 times lower than the one predicted by the Euclidean emanation theory (eq. 1). This discrepancy between theoretical and experimental slopes has been described in the Introduction and the factor of 25 for ^{220}Rn/MgO system is reproduced as point 2 in Fig. 1. Point 1 in Fig. 6 can also be assigned a "slope" which results in a discrepancy factor of 31, depicted as point 1 in Fig. 1.

In the following we focus on three points from Fig. 6: point 14 lying on the linear section, point 7 at the onset of departure from linearity, and the rightmost point number 1. Some of the experimental and theoretical parameters for these three points are reproduced in Table 1. Equation 6a shows that S/V can increase when r_0 decreases or D increases. We thus conclude from eq. 5a that the linear section in Fig. 6 has a constant D and a decreasing r_0. Each point corresponds to a distribution in r_0. In this case it does not matter, however, because the experimental S/V already takes care of that distribution. One would require $D > 3$ to fit eq. 5a to the linear part of Fig. 6. We therefore look at the Rn implantation to improve the fit. We use a concept of implantation threshold f_e introduced by Thamer

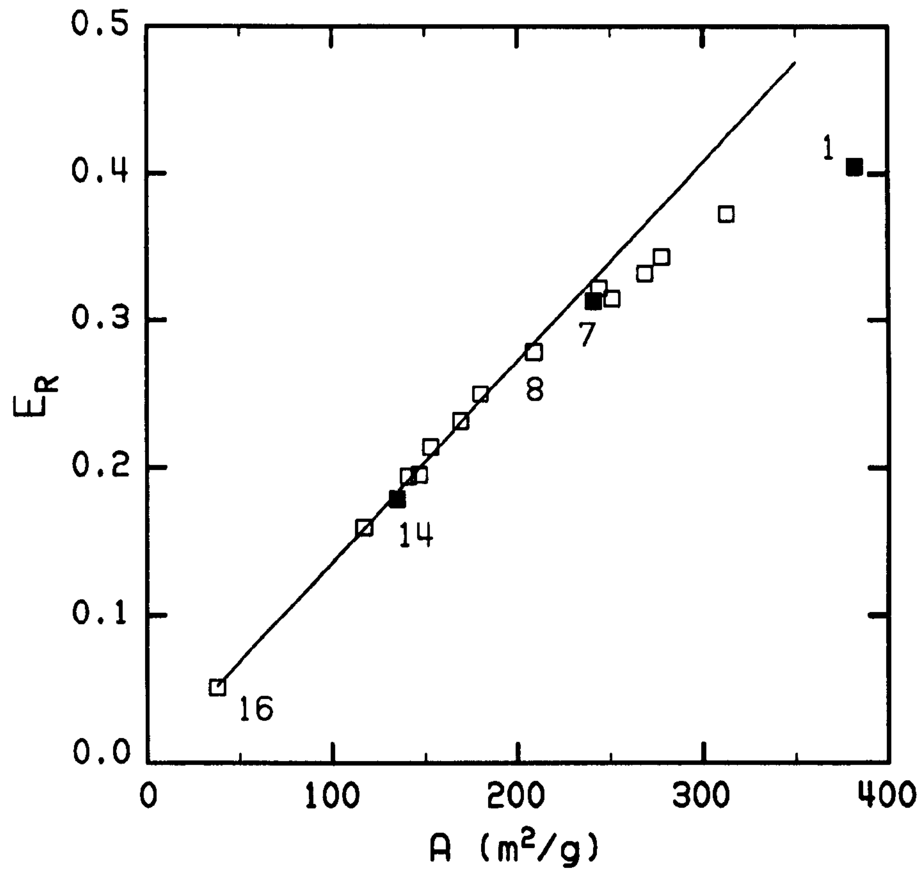

Figure 6. Emanating power E_R plotted vs. the specific surface area A for the system $^{220}Rn/MgO$ (6). Points 1, 7, 8, 14, 16 are discussed in the text.

et al. (32) and also employed in Ref. 1. By definition, f_e is a fraction of a range required for permanent implantation. Thus using

$$R_e = (1 - f_e)R_m \tag{11a}$$

the implanted fraction is E_{R_e} and the emanating power in the presence of implantation is

$$E_{R_m} - E_{R_e} \,. \tag{11b}$$

Now we have two parameters: D and f_e to determine. However, since eq. 5a,11b intersect the origin, there are many combinations of D and f_e that would fit the data. We have to look for an alternative way of finding D. It can be deduced from the V–t curves reported by Quet and Bussière (6). Using the standard V–t curve by De Boer (31), we transformed the data to isotherms, i.e., weight W of N_2 adsorbed vs. the ratio of the pressure to saturation pressure p/p_0 . Then, using the BET method (11), we determined the weight W_m for monolayer coverage. Finally, we plot the reduced isotherms, i.e., W/W_m vs. the p/p_0 in Fig. 7. This

TABLE 1. SUMMARY OF EMANATING POWER DATA[a]

Variable	Name	Value for point[b] 14	7	1	Obtained from
E_R	emanating power	0.179	0.313	0.405	experimental
A, $m^2 \cdot g^{-1}$	specific surface area	137	242	384	BET isotherm (11)
D	fractal dimension	2.4	2.6	2.9	fractal BET isotherm (18)
r_0, nm	average grain radius	35	31	23	electron micrographs
slope	theory/exp.	25.3	25.6	31.4	eq. 1[c]
slope	theory/exp.	4.5	2.7	1.5	eq. 5a[d]
f_e	implantation threshold	0.34	0.69	~ 0.99	eq. 5a,11a,b[d]

a) experimental data from Ref. 6
b) points from Fig. 6
c) $R = 37$ nm, $\rho_0 = 3.58\ g \cdot cm^{-3}$
d) $R_m = 21$ nm, $\rho_0 = 3.58\ g \cdot cm^{-3}$

analysis has been done for points number 14, 7, and 1 from Fig. 6 and Table 1. Point 14 (□) and point 7 (△) conform to the type IV isotherm having considerable mesoporosity (pore radii between 1.5–100 nm). Point 1 (◇) conforms to the type I and II isotherms with considerable microporosity (pore radii < 1.5 nm) (33). Also plotted in Fig. 7 as solid curves are the fractal BET isotherms according to a model of Pfeifer *et al.* (18). Unfortunately, the deviations from type II isotherm make it difficult to determine the values of D precisely. However, we use the parts of the data at high pressures to estimate fractal dimensions ~ 2.4 and ~ 2.6 for points 14 and 7, respectively. The diamonds lay below the $D = 3$ curve for number of adsorption layers $n = \infty$, but above $D = 3$ for $n = 20$. So we take approximately $D \approx 2.9$ for point 1.

Now we return to the discussion of the linear section of the curve from Fig. 6. Using $D = 2.4$ and eq. 5a, the ratio of theoretical slope to the experimental slope is now 4.5 for any point on the curve including point 14. This is a considerable improvement from a factor of 25, and the remaining deviation is attributed to Rn implantation. Using eq. 5a,11a,b one can fit the data exactly yielding the implantation threshold $f_e = 0.34$. It is interesting to note that the previously *assumed* value was 0.3 (32,1).

We also used the electron micrographs from Ref. 6 to estimate approximately the average sizes of the grains. As it turns out, the samples are composed of very fine grains with approximate average radii of 35, 31, and 23 nm for samples number 14, 7 and 1,

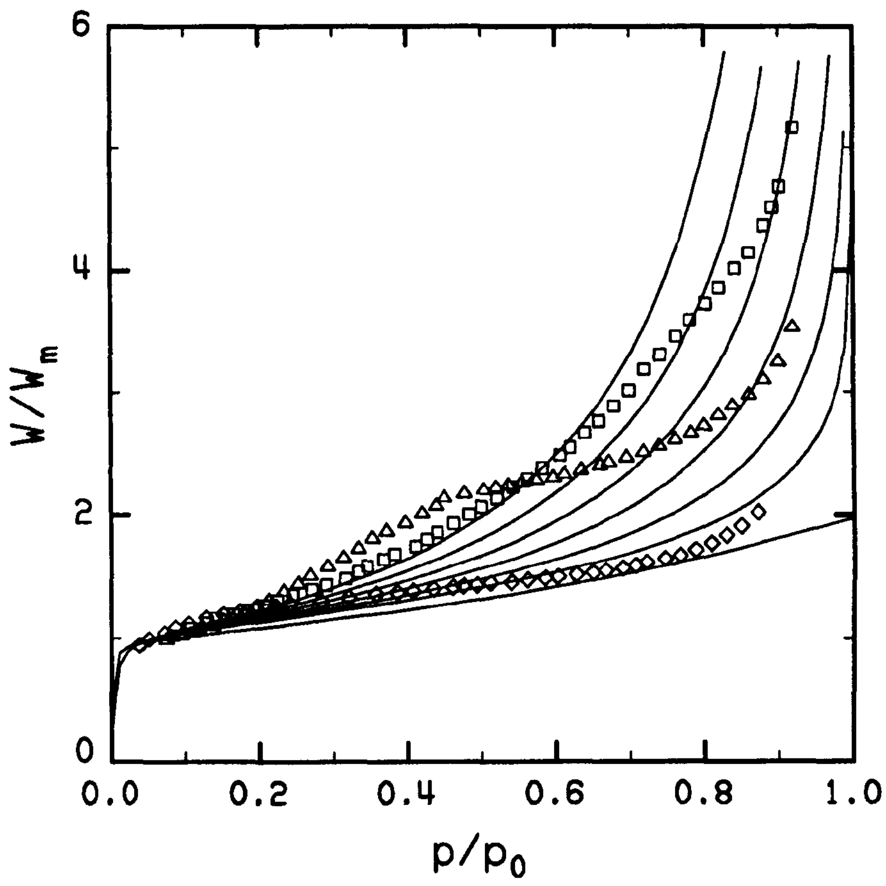

Figure 7. Reduced isotherms (adsorbed weight vs. the pressure) for N_2 adsorption on MgO (6). Point abbreviations: □ point 14, △ point 7, ◇ point 1 (point numbers from Fig. 6 and Table 1). Solid curves are for the fractal BET model (18) with D values (starting from the top): 2, 2.2, 2.4, 2.6, 2.8, 3 (all for number of layers $n = \infty$), and 3 ($n = 20$).

TABLE 2. FACTORS AFFECTING RADON IMPLANTATION AND PENETRATING RECOIL.

Case	Grain radius[a]	Water present	Fractal dimension	Implantation	Penetrating recoil
1	$\geq R_m(\text{air})$	no	low	low	low
2	$\ll R_m(\text{air})$	no	low	high	low
3	any	no	high	low	high
4	any	yes	any	low	low

a) $R_m(\text{air}) = 47\ \mu\text{m}$ is a median projected range of Rn in air respectively. According to our discussion above, the bending of the curve from **Fig. 6** is thus due to increase of D and decrease of r_0. We repeat the fits to points 7 and 1, with the values of D given in Table 1. The ratios of theoretical to experimental slopes are now 2.7 and 1.5, or, alternatively, the implantation thresholds are 0.69, and ~ 0.99 for points 7, and 1, respectively. We can say that with increasing D and decreasing r_0 the discrepancy between theory and experiment is diminishing due to decrease of implantation. The value of f_e close to 1 for point number 1 is somewhat peculiar, but for D approaching 3 eq. 5a,11b are very sensitive to D and the implantation threshold probably loses its straightforward interpretation.

The important point from this analysis is that the discrepancy between fractal theory of radon emanation and experiment is between 1.5 to 4.5. Thamer *et al.* (32) studied the water effects in Rn emanation from rocks (i.e., $E_R(\text{wet})/E_R(\text{dry})$). They found the range of water effects between 1.4 to 4.1. Because the recoils are believed to stop in water, this supports very nicely the picture of fractal theory with implantation.

We now turn to the description of implantation process. As mentioned in the Introduction, Lambert *et al.* (13) and Lambert and Bristeau (14) studied the implantation of ^{222}Rn into various materials and its diffusion back through the radiation-damaged zone (damage diffusion). They found that the damage diffusion was either small or zero. For NaCl monocrystal $1.7 \pm 0.7\%$ of Rn diffused out, for mica no diffusion was detected, for limestone $3.1 \pm 2.7\%$ diffused (at 300°C), and for basalt 0–2% diffused (at 300°C). Korselsen made a systematic study of sticking probability of inert gases in tungsten as a function of kinetic energy in the range 40 eV to 5 keV (34). He found that sticking probability ranged from $\sim 10^{-5}$ at eV energies to ~ 0.6 at 3 keV. Brown and Davies found that sticking probability of ^{131}Xe in various metals was essentially 1 for energies ≥ 5 keV, except for Ag and Au, which do not form oxides, where it was lower (35).

Let us apply these concepts to Rn emanation. Consider emanation from a plate and implantation into another plate. Since the range is proportional to kinetic energy (eq. 8a) we get (23)

$$f_e = \frac{E_t}{E_0}, \tag{12a}$$

where E_t is the threshold energy for implantation and E_0 is the recoil energy. Using eq. 6b,7,11a,b with $C = 1$ and $D = 2$ we get

$$E_{R_m} = \frac{1}{4}\frac{E_t}{E_0}\frac{R_m}{r_0}. \tag{12b}$$

Recalling the discussion above we use $E_t \approx 3$ keV and $E_0 = 86$ keV, for ^{222}Rn recoil. So the emanating power would be expected to be reduced by a factor ~ 29 due to Rn implantation. However, for Quet and Bussière data (6) we found that the loss due to implantation was between 1.5–4.5. We therefore suggest that these are the penetrating recoils from **Fig. 4** (arrow 4) rather than the indirect recoils (arrow 3) that are responsible. With an increase of D from 2.4 to 2.9 surface roughness increases and, as can be seen from Fig. 2, the surface acquires a large number of small irregularities. The recoiling Rn atoms can penetrate these irregularities through losing their energies. This process diminishes the implantation and the ratio of theoretical to experimental slopes decreases from 4.5 to 1.5.

The indirect recoil mechanism (12) is nothing else than the damage diffusion. The experiments described above showed that this damage diffusion occurs only for the smallest energies ($\leq$ 3 keV). Therefore it can occur at the very late stage of energy-loss process, after most of the energy was lost due to penetrating recoil. Then, the indirect recoil (or lowered sticking probability) prevents the implantation. For pure implantation with kinetic energies $\geq$ 3 keV there is little chance for any indirect recoil. This is especially true for ^{220}Rn whose short half life (55 s) precludes any significant damage diffusion. Some of the implanted ^{222}Rn recoils can be leached out at a slow rate with water introduced *after* the implantation (36). When water is originally present in the sample, implantation is expected to significantly decrease owing to recoils stopping in the water. The processes of implantation and penetrating recoil can occur in the same grain or into the neighboring grains depending on the sizes of the grains, average interstitial separation relative to the recoil range in air, surface roughness, and presence of water. A summary of different situations is given in Table 2.

CONCLUSIONS

1. A fractal theory of radon emanation has been developed for the case when precursor Ra is distributed uniformly throughout the sample. The emanating power was expressed either as a function of surface-to-volume ratio (eq. 5a) or an outer-shape radius (eq. 5b,7). Fractal dimension of the surface enters the equations as a parameter.
2. It has been shown how the emanating power measurements can be used to determine the fractal dimension of the emanating surface. The range of self-similarity that can be determined is between a few tens to a few hundreds of nanometers, which extends the range determined by the gas adsorption.
3. With no Rn implantation present, fractal theory gives a good agreement with emanating powers from Lipari volcanic glass. When Rn implantation is present, the theory differs from emanating powers from MgO by a factor of 1.5–4.5, which is a typical range of water effects in emanation.
4. Careful examination of our results and the implantation experiments from the literature led us to suggest that the implantation and penetrating recoil are the results of most

of the energy loss. The indirect recoil may be present at the very last stage of energy loss after most of the energy was lost due to the penetrating recoil. Consequently, the penetrating recoil may be responsible for diminished implantation in materials with rough surfaces.

5. The need of using the median projected ranges (LSS) rather than extrapolated ranges (FZ) for Rn recoil was emphasized.

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

ACKNOWLEDGMENTS

The concept of fractal geometry has been independently suggested to one of us (T.M.S.) by A.B. Tanner. Thanks are due to K. Alben for fruitful discussion.

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TITLE: National Ambient Radon Study

AUTHOR: Richard Hopper, EPA - Office of Radiation Programs

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

Session X:

Radon in Schools and Large Buildings

TITLE: The Results of EPA's School Protocol Development Study

AUTHOR: Anita L. Schmidt, EPA - Office of Radiation Programs

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

ABSTRACT

In April 1989, EPA released interim guidance, " Radon Measurements in Schools-An Interim Report (EPA520/1-89-010). This guidance was based in part on data from an intensive study of radon in a limited number (five) of schools in Fairfax County Virginia. The Radon Division of the Office of Radiation Programs subsequently conducted the School Protocol Development Study to gather additional data to update and revise as necessary the guidance and procedures for radon measurmeents in schools.

This study consisted of two phases. Phase I was a screening study of 130 schools in 16 States using 2-day, weekend charcoal canister measurements. Based on the results of these measurements, 21 schools in 7 States were selected for Phase II. This was a year-long, comprehensive study investigating short-term and long-term measurements using a variety of devices under different conditions. Various factors that influence these measurements, such as building structure and ventilation systems, will be evaluated. The final results of this study will be presented.

TITLE: Diagnostic Evaluations of Twenty-six U.S. Schools -- EPA's School Evaluation Program

AUTHOR: Gene Fisher, EPA - Office of Radiation Programs

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

As part of a coordinated radon in schools technology development effort, EPA's School Evaluation Team has performed on site evaluations of twenty six schools in eight regional locations throughout the United States. This paper presents the results and preliminary conclusions of these evaluations which represent the most schools to date diagnosed for both sub-slab and HVAC characteristics. Also reported are carbon dioxide and building shell tightness measurements which further characterize the building dynamics. In addition to these technical issues, physical and institutional problems which affect the selection and implementation of radon mitigation strategies are identified. Specific determination of soil depressurization and existing HVAC systems as radon control methods and remedial recommendations were developed for each school. Results of this two year study indicate that EPA should consider a new direction in large building radon abatement -- a holistic approach that considers total indoor air quality, comfort, cost, and energy issues.

NOTES:

This presentation will incorporate 35 mm slides (pictoral, graphic, and text types), and is expected to take a full 20 minutes.

TITLE: Extended Heating, Ventilating and Air Conditioning Diagnostics in Schools in Maine

AUTHOR: Terry Brennan, Camroden Associates

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

An extensive effort to assess the effects of HVAC system operation the indoor radon levels was conducted. Many schools in the School Evaluation Program have been found to have disabled or malfunctioning outside air on the ventilation system. The outside air in the Maine schools had been disabled. This condition was corrected using professional HVAC and control contractors. Measurements were made of radon levels, total and outside airflows, pressure differentials across the building shell and sub-slab radon levels. Exhaust ventilation, built up air handlers and unit ventilators were investigated. A heat recovery ventilator was added to a room that had leaky window sash as the outside air supply for a passive roof vent system that had been blocked off.

MITIGATION DIAGNOSTICS: THE NEED FOR UNDERSTANDING BOTH HVAC AND GEOLOGIC EFFECTS IN SCHOOLS

by: Stephen T. Hall
Radon Control Professionals, Inc.
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ABSTRACT

Experience in the remediation of schools has shown that in some, highest indoor radon levels were located near large central HVAC return ducts and were attributed to the predominance of and the proximity to negative HVAC pressure. Successful sub-slab depressurization systems were installed, however, in rooms with lower indoor but greatest sub-slab radon levels, closest to the source. This shows the inadequacy of using indoor radon levels alone as a basis for remediation. Wings of other schools with radon problems have window heating units in rooms of equal size and no central HVAC system. Highest indoor radon levels correlated well with highest sub-slab radon levels due to the equivalent effects of the window units and the predominance of geology.

Diagnostic tests in other schools have revealed: blockwall radon transport to upper floors; elevated blockwall radon adjacent to sub-slab sources; and elevated indoor radon above a crawlspace caused by HVAC-induced negative pressure.

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.

In the past three years the author has conducted radon soil analyses at approximately 20 school and numerous other construction sites in the Washington, DC area (Northern Virginia and Montgomery County, MD) to predict indoor radon potentials. Previous soil gas surveys showed correlations with indoor radon in existing buildings (1) and revealed that radon sources occur along narrow linear trends within footprint confines of a single building, correlative with geologic structures in metamorphic and sedimentary rock terrains (2). In addition, Radon Control Professionals has performed radon remedial diagnostics and remediation in 20-30 schools and other large buildings.

Our experience has shown the importance of the effects of both the location of geologic sources and HVAC-induced distribution of indoor radon. In general, elevated radon in areas of schools with evenly distributed HVAC pressures are correlated with maximum soil radon emanations. However, strong or unequal HVAC effects can redistribute indoor radon to areas away from the direct source. Effective remediation required a complete understanding of both contributions.

In some schools with central HVAC systems, highest indoor radon levels were located near large return ducts. However, highest sub-slab radon measurements were often located in neighboring rooms with lower indoor radon levels indicating that the negative pressure created by the return ducts had a more important contribution to elevated indoor radon than source strength (Figures 1, 2, and 3; In all figures, although some alpha track measurements were available, indoor radon levels, shown in the center of each room, are two-day charcoal tests performed during the same winter season for comparison. Both sub-slab radon levels, adjacent to circles, and blockwall radon levels, adjacent to semi-circles, are underlined.) Successful sub-slab depressurization systems were installed in rooms with lower indoor but greatest sub-slab radon levels, closest to the source. This shows the inadequacy of using indoor radon levels alone as a basis for remediation.

SPRINGBROOK HIGH SCHOOL

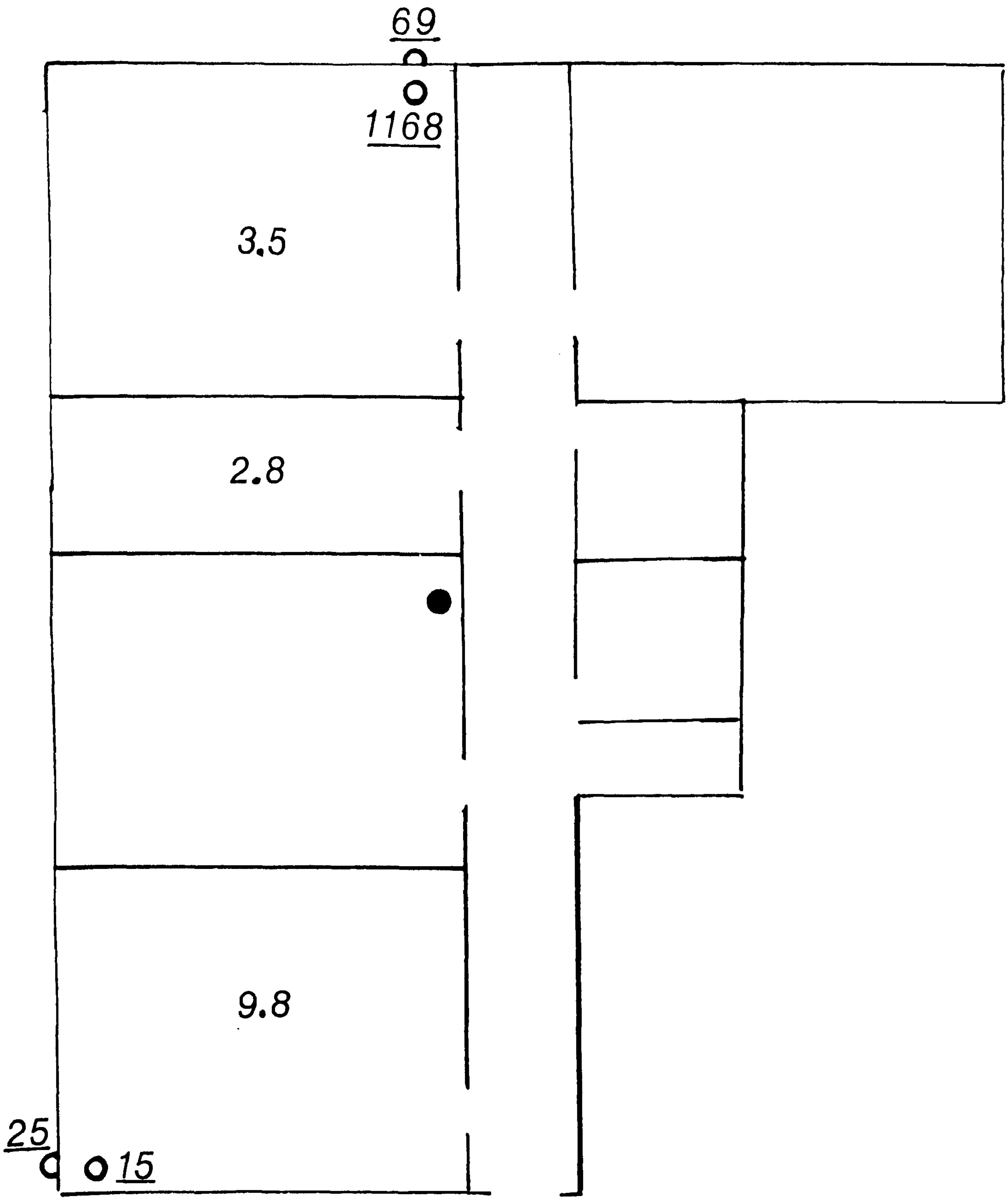

FIGURE 1. Springbrook High School - Indoor radon levels not correlated with sub-slab radon levels due to HVAC effects predominant over geologic source effects. In all Figures, indoor radon levels are in the center of each room. Both sub-slab radon levels, adjacent to circles, and blockwall radon levels, adjacent to semi-circles, are underlined.

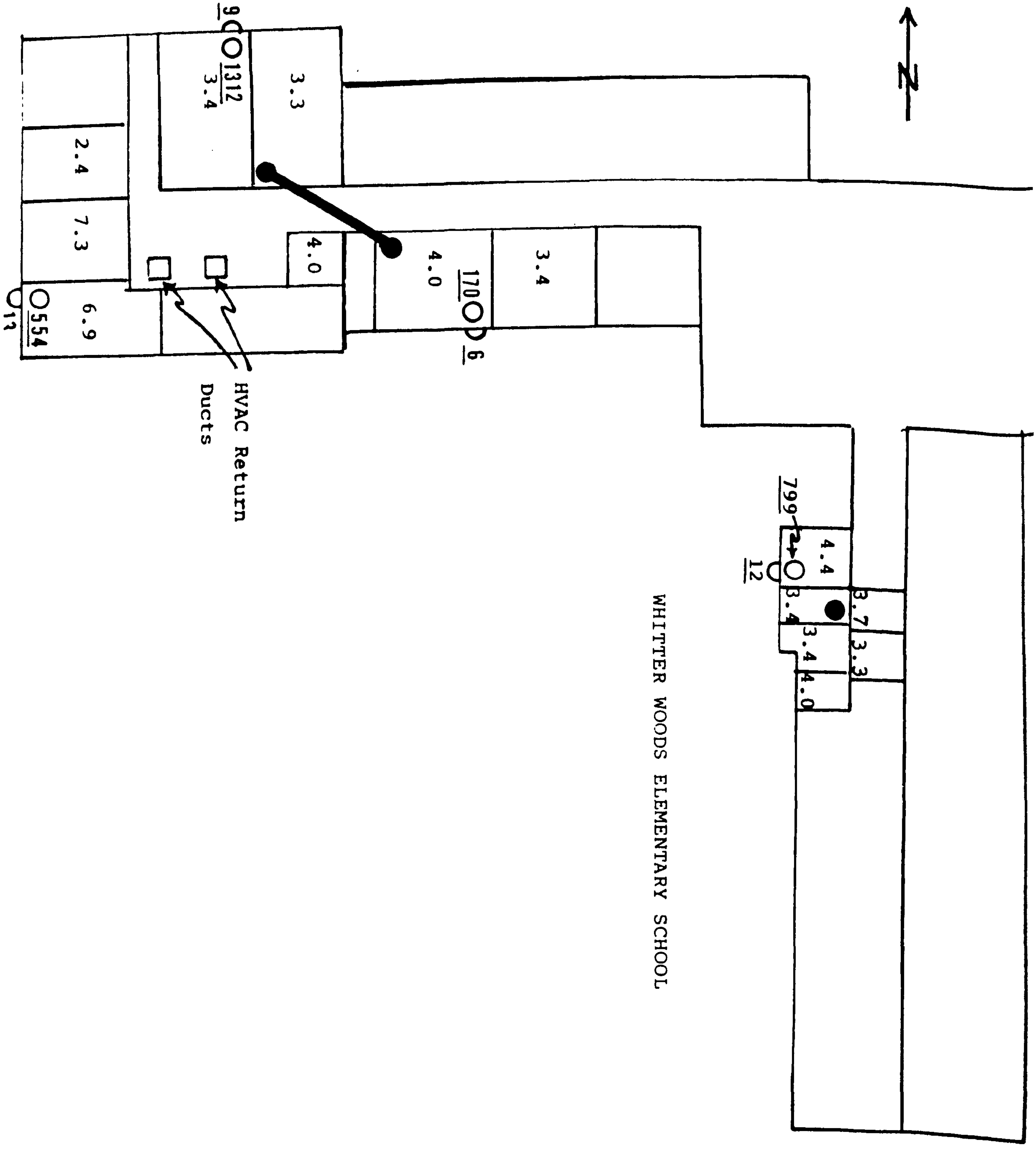

FIGURE 2. Whitter Woods Elementary School - Indoor radon levels not correlated with sub-slab radon levels due to HVAC effects predominant over geologic source effects

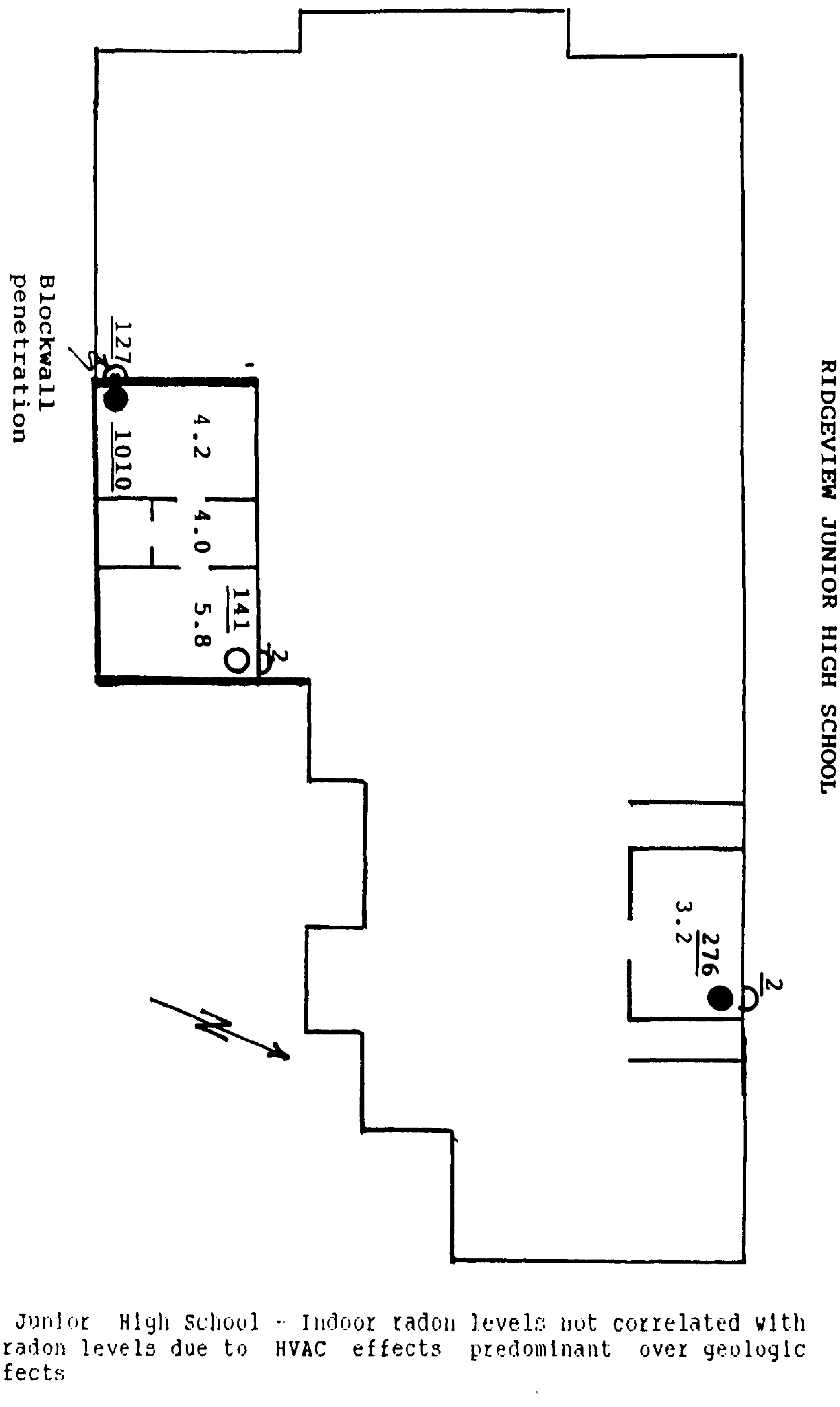

FIGURE 3. Ridgeview Junior High School - Indoor radon levels not correlated with sub-slab radon levels due to HVAC effects predominant over geologic source effects

The school shown in Figure 3 has a plenum ceiling with openings for return air. The room with 3.2 pCi/l has no windows or return openings in the plenum ceiling. Differential pressure measurements between this room with the door closed and the hallway showed no significant difference until a nearby outside door was opened and hallway air rushed outside (Table 1). We suggested sub-slab depressurization for this room because it had the potential for higher radon levels if openings were added in the return plenum ceiling or doors were opened, because both would depressurize the room.

TABLE 1. RIDGEVIEW JUNIOR HIGH SCHOOL - ΔP EFFECT FROM OPEN DOORS

ROOM 119:	TIME, SEC.	INDOOR/HALLWAY, ΔP, INCHES H_2O COLUMN
HVAC ON	30	-.001
	60	-.001
	90	-.001
	120	-.001
ADJACENT OUTSIDE DOOR OPENED-HALLWAY AIR RUSHED OUTSIDE	150	+.017
	180	+.020
	210	+.020

Wings of two other schools with radon problems have equivalent window fan coil units in rooms of equal size and no central HVAC system. Highest indoor radon levels correlated well with highest sub-slab radon levels due to the equivalent effects of the window units. (Figures 4 and 5). This was verified by an outside corner room in Francis Scott Key High School (Figure 4) with 1.0 pCi/l indoor radon and 132 pCi/l sub-slab radon, the lowest source strength found. Sub-slab/indoor radon ratios were approximately 100/1. The rooms with elevated radon are aligned along a N60°W trend, correlative with local shear fractures (2). In Cannon Road Elementary School (Figure 5), rooms with elevated radon levels are aligned along a N30°E trend, correlative with local rock layers or foliation (2). Thus in schools with equivalent HVAC effects, geologic source appears to dictate indoor radon concentrations.

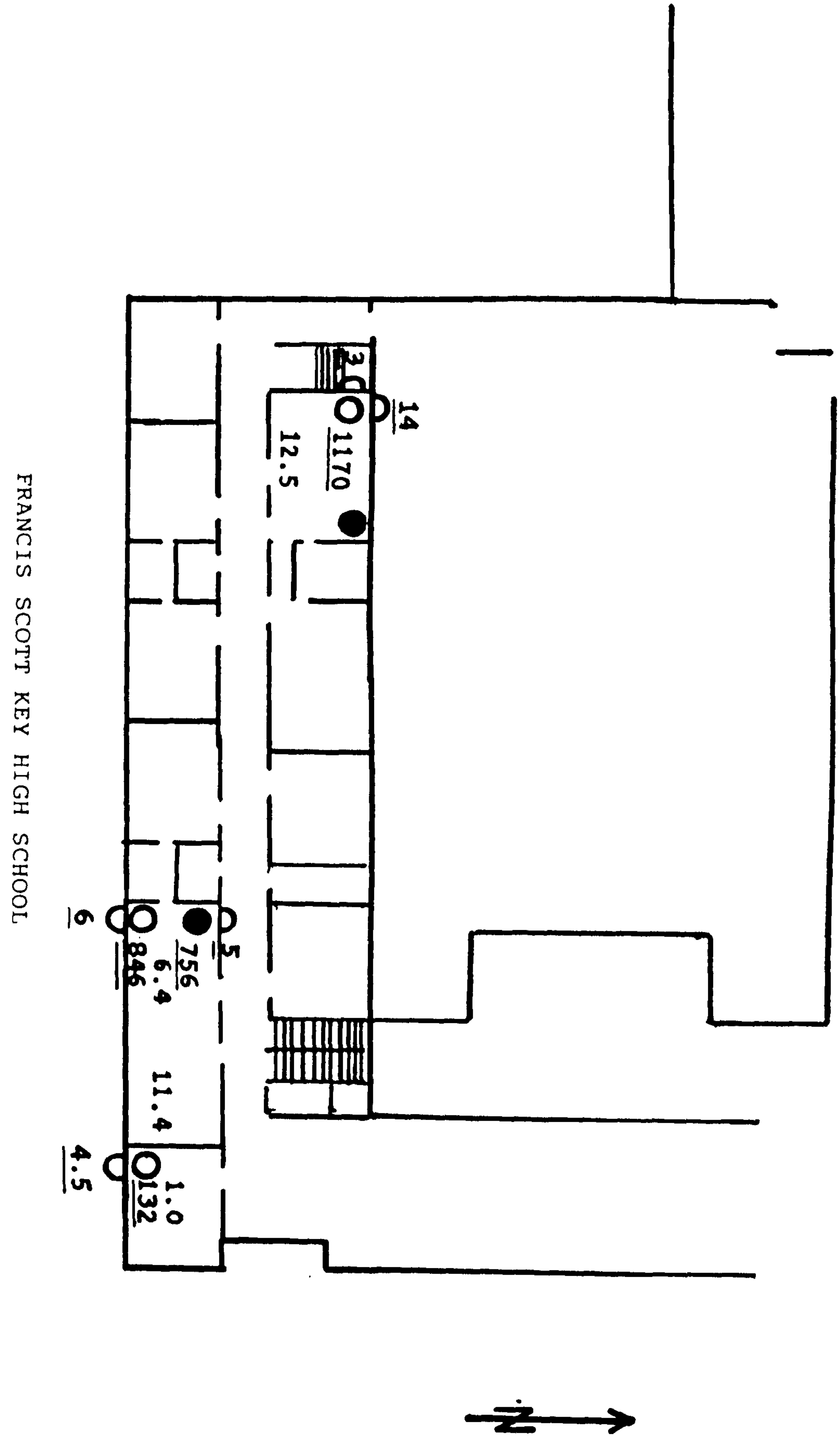

FIGURE 4. Francis Scott Key High School - Indoor radon levels proportional to sub-slab radon levels due to equivalent HVAC effects and predominant geologic control

CANNON ROAD ELEMENTARY SCHOOL

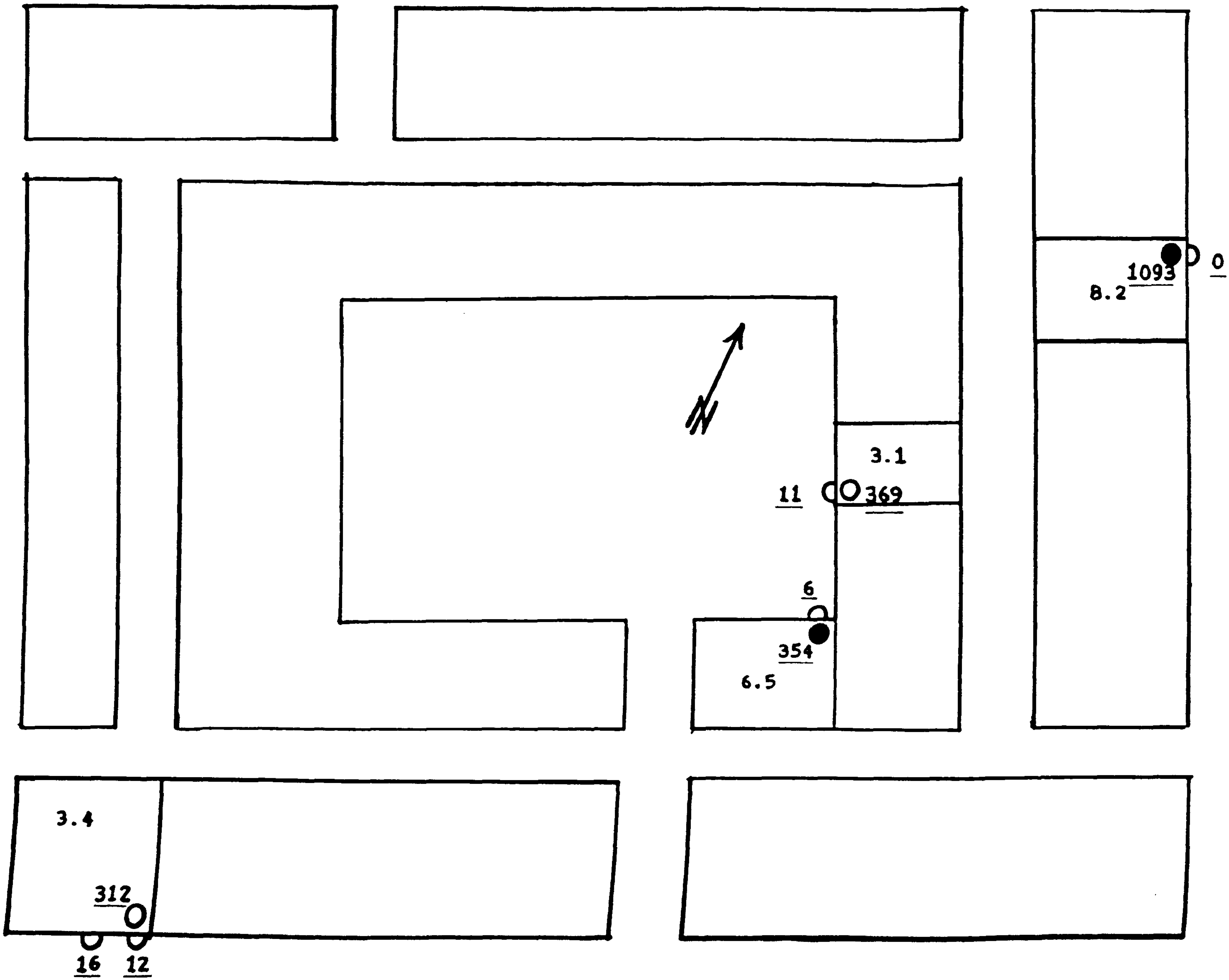

FIGURE 5. Cannon Road Elementary School - Indoor radon levels proportional to sub-slab radon levels due to equivalent HVAC effects and predominant geologic control

Martin Luther King Junior High School (Figure 6) revealed indoor radon migration through blockwalls from the first floor to the second floor. Rooms near the center of the school and in the southeast corner had both first and second floor radon levels equivalent to adjacent blockwall radon levels, showing that second floor radon problems were caused by vertical migration through blockwalls. Sub-slab depressurization with appropriately placed blockwall penetrations remediated the school.

MARTIN LUTHER KING JUNIOR HIGH

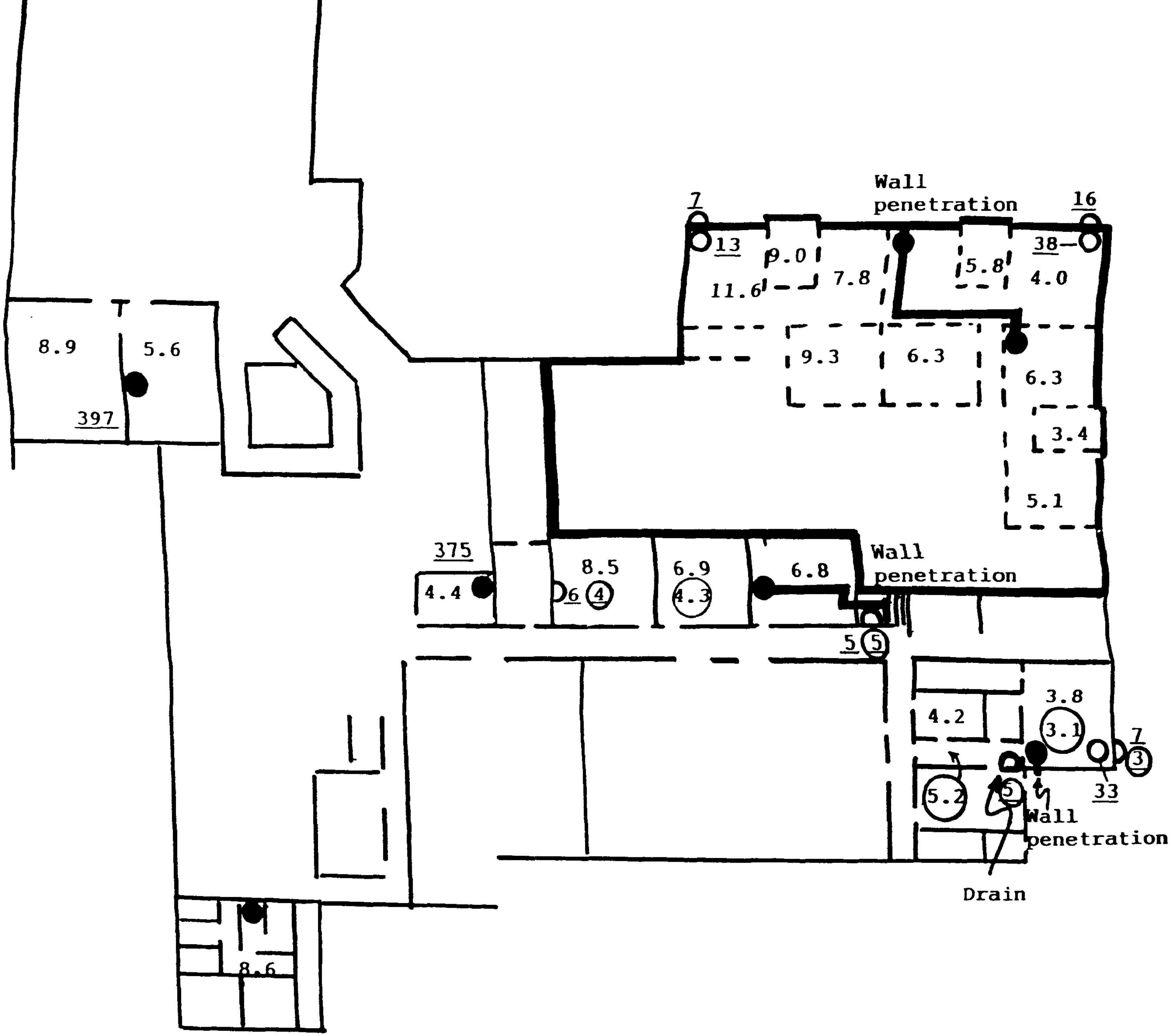

FIGURE 6. Martin Luther King Junior High School - Blockwall radon transport to second floor. Second floor slab-on-grade is outlined in bold with rooms in dashed lines. Where the second floor is above a first floor, radon levels are encircled.

Two schools (Figures 7 and 8) showed approximately equivalent blockwall/sub-slab radon concentrations revealing radon migration into blockwalls directly from the sub-slab source. This shows the need to assess blockwall radon measurements to determine when blockwall penetrations are required based upon high blockwall/sub-slab radon ratios.

SPRINGBROOK HIGH SCHOOL

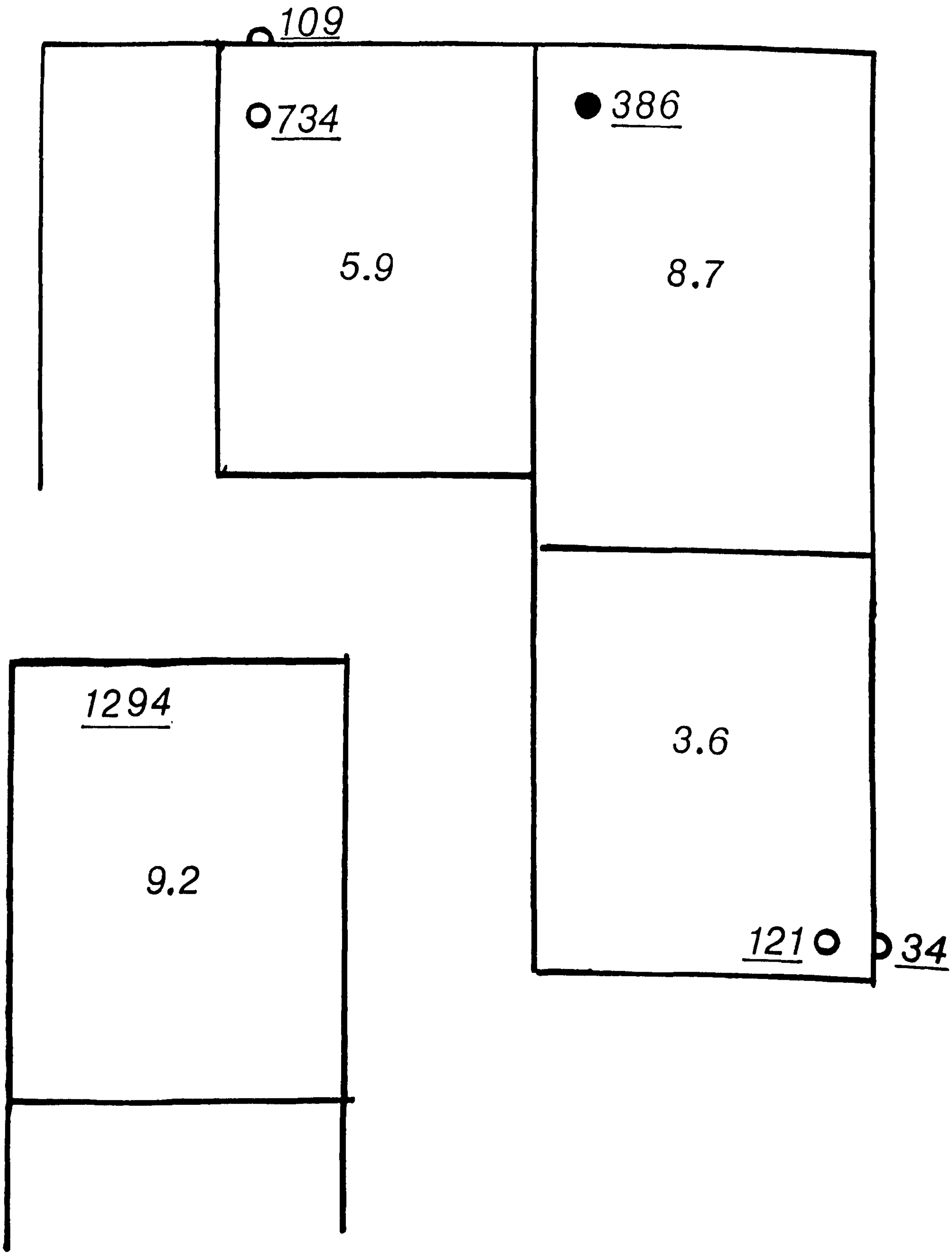

FIGURE 7. Springbrook High School - Blockwall radon concentrations correlating with adjacent sub-slab radon levels

RIDGEVIEW JUNIOR HIGH SCHOOL

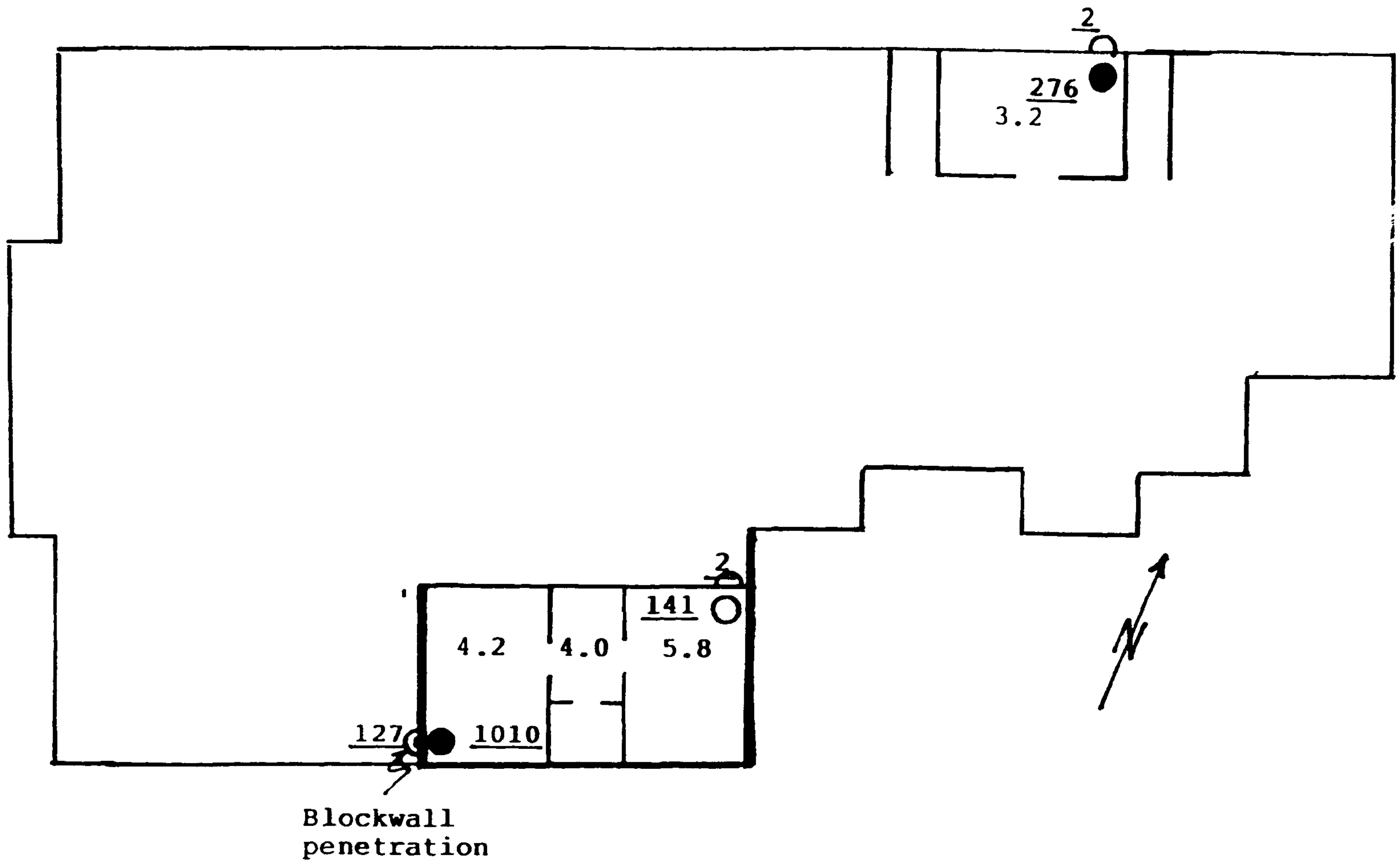

FIGURE 8. Ridgeview Junior High School - Blockwall radon concentrations correlating with adjacent sub-slab radon levels

In one school radon problems existed over one end of a room (F104) underlain by the unvented end of a crawlspace (Figure 9). Table 2 shows the results of indoor/outdoor ΔP measurements with a micromanometer. A Tygon tube was run from the high pressure port of the micromanometer to outside a window, sealed shut with tape, while the low pressure port was open to first the room and then the crawlspace. An aquarium stone was attached to the high pressure tube outside to minimize wind effects. The differential pressures were then measured in both the room and the crawlspace by turning the central HVAC system on with the exhaust fan off and then with the exhaust fan on. Results reported in Table 2 show that the HVAC system created a negative pressure in the room resulting in radon levels nearly as high as a two-day average within 60 seconds. The exhaust fan, blowing from the room into the crawlspace, diminished this effect. In the crawlspace, the HVAC system created an equal negative pressure with the exhaust off but higher radon levels. However, the exhaust fan created a positive pressure in the crawlspace greatly diminishing the radon levels. Theoretically pressurizing the crawlspace with outside air would optimally reduce crawlspace radon levels. However warm summer outside air entering the cool crawlspace causes condensation problems so remediation was achieved by adding another crawlspace vent below the problem room and running an exhaust line from a roof-mounted fan into the crawlspace, as shown in Figure 9, to draw radon from the crawlspace at a high enough rate to overcome the increase in radon levels from depressurization.

WHITE OAK MIDDLE SCHOOL

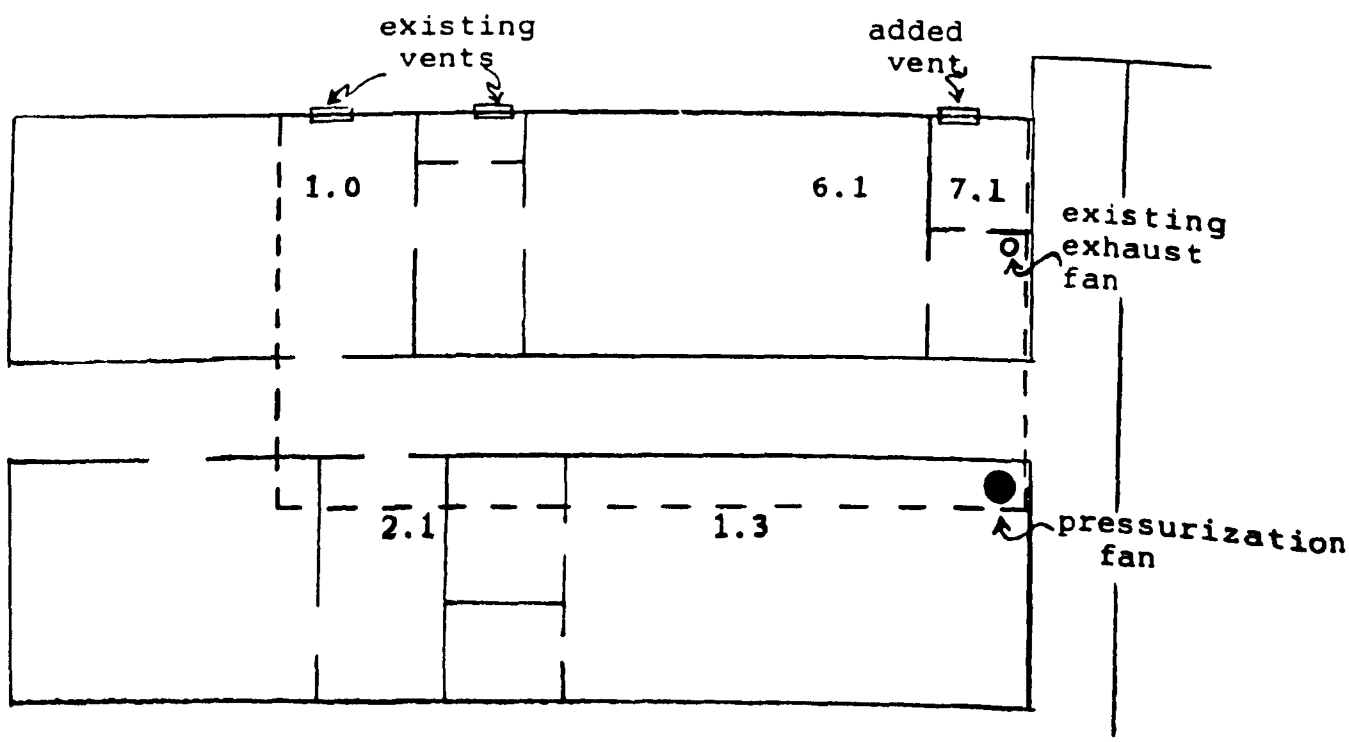

FIGURE 9. White Oak Middle School - Crawlspace area outlined with dashed line. existing exhaust fan exhausts indoor air into crawlspace.

TABLE 2. WHITE OAK MIDDLE SCHOOL - Δ P AND RADON DEPENDENCY ON HVAC AND EXHAUST FAN

	TIME, SEC.	INDOOR/OUTDOOR, Δ P, INCHES H_2O COLUMN	Rn, pCi/l
<u>ROOM F104:</u>			
HVAC ON,	15	-.005	
EXHAUST FAN	30	-.008	
OFF	60	-.010	4.5
HVAC ON,	15	0	
EXHAUST ON	30	0	
	60	-.002	
	120	-.005	<0.1
<u>CRAWLSPACE:</u>			
HVAC ON,	15	-.005	
EXHAUST OFF	30	-.008	
	60	-.010	13.0
HVAC ON,	15	+.050	1.4
EXHAUST ON	30	+.100	<0.1

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A COMPARISON OF RADON MITIGATION OPTIONS FOR CRAWL SPACE SCHOOL BUILDINGS

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ABSTRACT

School buildings that are constructed over crawl spaces can present unique challenges to radon mitigation since they are often quite large (at least 4,000 ft^2 in area) and may contain support walls with footings that extend below the soil surface. The perimeter walls in the crawl space can also be extensive (on the order of 500 to 1,000 lineal ft). In this research project, natural ventilation using the existing vents in the foundation walls, depressurization and pressurization of the crawl space, and active soil depressurization under a polyethylene liner covering the soil were compared in a wing of a school building in Nashville, Tennessee. The wing has four classrooms constructed over a crawl space area of 4,640 ft^2. The building and crawl space were monitored throughout each mitigation phase with continuous sampling devices that recorded radon levels both in the crawl space and in the rooms above, in addition to environmental conditions such as temperatures and pressure differences in the building.

Results showed that active soil depressurization was the most effective technique for reducing radon levels in both the crawl space and the rooms above. Crawl space depressurization was also very effective in reducing radon levels in the rooms above the crawl space; however, radon levels in crawl space increased during depressurization.

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

INTRODUCTION AND BACKGROUND

This 29,266 ft[2] (refer to Table 1 for metric conversion factors) Nashville school building was originally constructed in 1954, with subsequent additions in 1957 and 1964. The original building and the first addition are slab-on-grade construction, and the 1964 four-classroom addition is constructed over a crawl space connected to the slab-on-grade section by a walkway. Initial charcoal canister measurements in this school in 1989 indicated that the 18 slab-on-grade rooms measured presented the most severe radon problems, averaging 34.1 pCi/L with a standard deviation of 7.5 pCi/L. In fact, levels over 100 pCi/L were subsequently measured in some of the slab-on-grade rooms. Radon levels in the four classrooms constructed over the crawl space were relatively much lower, averaging 9.7 pCi/L with a standard deviation of 0.7 pCi/L. As a result, initial remediation efforts during the summer of 1989 focussed on reducing levels in the slab-on-grade wings with active subslab depressurization (1,2). Post-mitigation measurements during February 1990 indicated that levels in the slab-on-grade rooms averaged below 2 pCi/L, and at this time plans were initiated to research the effectiveness of various mitigation techniques in the crawl space wing.

The crawl space is approximately 4,640 ft[2] in area, and the height ranges from 46 to 80 in. with a total air volume of approximately 25,500 ft[3]. The plan view of the crawl space is shown in Figure 1. Access to the crawl space is excellent and the surface of the soil is not complex (i.e., no inaccessible areas, rock outcroppings, or large piles of soil). The floor of the classrooms over the crawl space is a suspended concrete slab poured over corrugated steel sheets supported by a network of steel trusses. There are two internal concrete block support walls in the crawl space that extend below the soil. These walls do not penetrate the slab overhead; however, the walls effectively subdivide the crawl space into three sections, as shown in Figure 1. This type of construction is quite different from that found in residential houses. In many existing houses, the floor is composed of wood decking (either 1 by 6 in. boards or plywood sheathing) supported by wooden floor joists. This type of house construction has been shown to be quite leaky and nearly impossible to seal all the openings between the crawl space and the rooms overhead (3,4). Since the crawl space does not contain any heating, ventilating, and air-conditioning (HVAC) ductwork or any asbestos, it was of interest to determine if the crawl space in this school building could be sealed well enough to permit pressurization or depressurization of the crawl space volume as a mitigation option.

The crawl space is ventilated naturally with eight block vents (four each on the east and west sides of the building). Each of these foundation wall vents has a screened opening with the same gross area as a concrete block (8 by 16 in.) or approximately 128 in.[2] Fan door leakage tests carried out on the crawl space according to ASTM E 779-87 resulted in an effective leakage area

(ELA) at 0.016 in. WC of pressure difference of 251 in.^{2} with the vents open and 83 in.^{2} with the vents sealed (using closed-cell foam board and caulking). Thus, the vents were providing approximately 168 in.^{2} of total open area, or about 21 in.^{2} per vent. This value is consistent with that measured in houses using similar techniques (5). The important point is that the leakage area independent of the block vents is very low (83 in.^{2}) compared to that measured in 15 houses in the same geographic area which ranged from 198 to 424 in.^{2} with a mean of 262 in.^{2} (5). Thus, this building was thought to be an ideal candidate to test a variety of possible mitigation techniques.

METHODOLOGY

Mitigation systems typically installed in crawl space houses include: isolation of the crawl space from the rooms above, isolation and depressurization or pressurization of the crawl space, isolation and ventilation of the crawl space (either natural or forced), and active soil depressurization either directly in the soil or under a plastic membrane (SMD) covering the exposed soil (4). Each of these mitigation techniques (with the exception of the forced ventilation and direct soil depressurization techniques) was tested in this school crawl space in an effort to compare their effectiveness when applied to a building having a larger size and a different construction type (concrete slab over the crawl space).

Initial baseline testing was carried out before any modifications were made to the building. Following the baseline measurements, the accessible openings (e.g., utility penetrations) from the crawl space to the upstairs rooms were sealed with a combination of closed-cell foam and urethane caulking. The block vents were also sealed with rigid closed-cell foam board and caulking. Following testing with the vents closed, a network of 4 in. PVC ducting was installed as shown in Figure 1. The fan installed is rated at 200 cfm at 1.5 in. WC. The fan and the air distribution network were used to test the effectiveness of crawl space pressurization and depressurization as mitigation options for the building. After the crawl space depressurization and pressurization tests were completed, two suction pits approximately 24 in. in diameter and 12 to 18 in. in depth were excavated in each of the three sections of the crawl space for a total of six suction pits as shown in Figure 1. Each suction pit was covered with a piece of 36 in. square by 1 in. thick marine grade plywood. The plywood covers were supported at the corners by four common bricks. Both the suction pits and the exposed soil were covered with two-ply high-density polyethylene sheeting. The plastic film was installed in three pieces, one in each section of the crawl space. No attempt was made to seal the plastic to the outer or inner foundation walls. The edges of the plastic were cut approximately 12 in. wider than necessary in the event that sealing to the walls was necessary. The excess material was then simply folded up the walls or allowed to fold back upon itself. The network of PVC ducting was connected to the suction pits to complete the active soil depressurization systems, as in previous house research (3).

Throughout the entire testing period, several parameters were monitored continuously using a datalogging device. The parameters monitored include: pressure differentials between Room 116 and outside the building on the east and west sides; pressure differentials between Room 116 and the crawl space interior; pressure differentials between Room 116 and the sub-poly region during the SMD testing; temperatures outdoors, in Room 116, in the crawl space, and in the soil; wind speed and direction; the outdoor relative humidity and rainfall; and the radon levels in both Room 116 and the crawl space. Each of these parameters was sampled every 6 seconds and averaged or totaled at the end of every 30 minute interval. These measurements and their locations are summarized in Table 2. The data were accumulated in the datalogging device and periodically downloaded to a personal computer and stored on magnetic disks for later analysis. Initial testing of the building began on March 1, 1990, and continued through July 20, 1990, for a total of 152 days (3648 hours). The datalogger was reinstalled from December 18, 1990, to January 17, 1991, in order to evaluate the mitigation systems during winter conditions. The most significant results are described in the following sections for both the spring/summer and winter measurements.

RESULTS OF SPRING/SUMMER MEASUREMENTS

Baseline Measurements

The baseline radon measurements made with the block vents open averaged 5.1 pCi/L in Room 116 and 10.8 pCi/L in the crawl space, as shown in Figure 2. Figure 3 shows the averaged pressure differences between the crawl space and outdoors and between Room 116 and outdoors during each phase of the mitigation. Also plotted in Figure 3 are the average temperatures outdoors, in the crawl space, and in Room 116 averaged over the testing period. Following closing and sealing of the block vents and sealing the major openings from the crawl space to the classrooms above, the average radon levels in the classroom increased by about a factor of 3.3 to 17.1 pCi/L and the crawl space levels by a factor of 8 to 87.2 pCi/L. During this time the average pressure difference in the classroom increased by a factor of 1.6 to -4.7 Pa, and the crawl space pressure increased by a factor of almost 4 to -3.9 Pa. It is obvious that closing up the crawl space greatly enhanced the depressurization produced mainly by the stack effect. Also, the temperature differences between the interior of the building and the outdoors were much larger than during the other testing periods, thus increasing the stack effect. These results clearly indicate the effect on radon when the vents of crawl spaces are closed for energy conservation purposes.

Crawl Space Pressurization

The next mitigation technique tested was crawl space pressurization using the fan installed near the roof level of the building and the network of PVC ducting to distribute the flow with the crawl space vents closed. During pressurization, the average fan flowrate was 234 cfm which was equivalent to about 0.6 air changes per hour (ACH). During this time the average crawl space pressure difference was reduced to -1.5 Pa and the average classroom pressure difference was reduced to -2.5 Pa as seen in Figure 3. The average radon levels in the classroom and crawl space were 10.6 and 29.1 pCi/L, respectively, as shown in Figure 2. It is apparent that the flowrate of outdoor air into the crawl space is not sufficient to raise the pressure in the crawl space above the outdoor pressure and could only negate about 60% of that produced by the stack effect in the crawl space and about 50% of that produced in the classroom. It is possible that by doubling the flowrate (to around 500 cfm) the crawl space and the classroom could have been pressurized above the outdoor conditions and the radon levels further reduced. However, this option did not appear as a desirable year-round solution in view of the fact that unconditioned air was being used for pressurization.

Crawl Space Depressurization

Following the crawl space pressurization testing, the fan was reversed so that air was withdrawn from the crawl space and exhausted above the roof of the building. In this configuration, the fan flowrate increased slightly to 279 cfm or about 0.7 ACH. The negative pressures in the classroom were similar. However, the pressure differential in the crawl space increased by approximately 73% (from -1.5 to -2.6 Pa). The radon levels in the classroom were reduced by about 94% (from 10.6 to 0.6 pCi/L) even though the levels in the crawl space increased by a factor 1.8 (from 29.1 to 53.6 pCi/L). Therefore, while depressurizing the crawl space lowered the levels in the classroom, it nearly doubled the levels in the crawl space. This was not unexpected since a similar technique applied to a residential house increased the levels in the crawl space by about a factor of 3 (4, 5).

Active Soil Depressurization

The third type of mitigation system implemented was active soil depressurization under a plastic membrane covering the exposed soil (SMD). The total flowrate exhausted from under the plastic liners was 260 cfm when using all six suction points shown in Figure 1. As seen in Figure 2, the radon levels in the classroom were reduced within a matter of hours to around background (0.5 pCi/L), and in the crawl space the levels decreased to 3.5 pCi/L. In an attempt to determine if fewer suction points could be used, the two suction points in the central sector of the crawl space were disconnected and the suction pipes to both the fan and the suction pits were capped. The results are shown in Figure 2. The decrease in the crawl space levels is probably not significant, and the levels in the classroom are the same within the level of uncertainty of the measurement. The results from the SMD mitigation technique are quite similar to those found when the same method is applied to residential houses (4, 5, 6), where the area of the exposed soil is typically in the range of 1,000 to 2,000 ft^2. In this building the area is much larger (4,640 ft^2); however, the resulting reduction in the radon levels using SMD is seen to be as good as that achieved in smaller crawl spaces. The next important research step is to apply the SMD technique to crawl space areas on the order 10,000 ft^2 or larger.

RESULTS OF WINTER MEASUREMENTS

The above measurements were repeated during the winter (December 18, 1990, to January 17, 1991) in order to determine if the results were consistent with the spring and summer measurements. A brief analysis of the winter data supports the results of previous measurements and the integrity of the SMD system during cold weather. These data will be fully analyzed and documented in a future report. Based upon the initial analysis of the data, the average cold weather radon levels both in Room 116 and in the crawl space are shown in Figure 2.

Baseline Measurements

No attempt was made to reproduce the open vent (natural ventilation) condition as this was felt to be an unusual operating mode for wintertime conditions. The results for the closed vent mode in winter were much the same as those obtained in the spring/summer, with the possible exception that the winter radon levels in the crawl space were not as high as the previous values (63.4 pCi/L compared to 87.2 pCi/L). The lower readings could be due in part to the fact that the winter measurements were carried out after the soil was covered with the polyethylene liners. The presence of the plastic liners covering the soil could act as a partial barrier to soil gas exhalation. The lower readings could also be due to the fact that the winter measurement period was much shorter than the spring/summer measurement period.

Crawl Space Pressurization

The wintertime crawl space pressurization levels were much the same as obtained previously. These results indicate that, with the amount of unconditioned air used, the radon reductions achieved with this mitigation technique are still less than desirable.

Crawl Space Depressurization

Using this technique during cold weather conditions gave very similar results to those obtained in the spring/summer tests. The wintertime levels in both the classroom and the crawl space were somewhat higher and could be due to an increased stack effect normally expected during cold weather. In order for this technique to be successfully applied year-round, it is obvious that the installation and testing must be done during extreme temperature conditions in order to ensure that an adequate amount of air is exhausted from the crawl space.

Active Soil Depressurization

The wintertime radon levels measured with the SMD system operative were almost identical to the levels measured previously. The average level in the classroom was within the uncertainty of the measurement techniques, and the levels in the crawl space were slightly lower than before. These results clearly indicate that the SMB technique is not only effective but stable in its ability to lower the radon levels in both the classroom and the crawl space under varying weather conditions.

CONCLUSIONS

The results of this project indicate that the SMD technique is the most effective in reducing elevated levels in both the crawl space and the classrooms. In this application, the crawl space was large but fairly simple in geometry. Access to the exposed soil areas was excellent and, with the exception of the two internal support walls, did not contain a large number of obstructions such as support piers or utility pipes lying on the soil. The topology of the soil surface in this crawl space was relatively smooth. Other crawl spaces may have some or all of the complications that were absent in this application (7). Application of the SMD technique in these more difficult crawl spaces needs further investigation.

Depressurization of the crawl space is effective in reducing levels in the classrooms; however, the levels in the crawl space will be increased by at least a factor of 2 and perhaps as much as a factor of 3. This could pose a problem in buildings that have nonsealable openings from the crawl space into the occupied rooms above (e.g., HVAC ducts in the crawl space, wooden floors over the crawl space, or doors or other entry openings from the crawl space into the rooms above) or if the crawl space is occupied on a regular basis. In this building the overhead floor was a poured concrete slab with very few openings to the classrooms above that helped to contribute to the effectiveness of crawl space depressurization.

Pressurization of the crawl space was found to be less effective in reducing the radon levels than natural ventilation. This method may be more effective if larger quantities of air are supplied to the crawl space; however, this may result in increased energy losses and perhaps could increase the risk of damage to utility lines in cold weather.

Natural ventilation of the crawl space also appears to be ineffective in reducing the radon levels to acceptable levels. Increasing the ventilation through larger or more numerous vents may increase radon reduction; however, the effectiveness of this method depends to a large extent on the wind patterns outdoors. Also, this method can easily be defeated by closing vent openings during the colder periods.

The number of school buildings constructed over crawl spaces is not quantified at the present, although EPA research in over 40 schools has shown that only 7 of the buildings contain crawl spaces (in combination with slab-on-grade substructures). There is little information available regarding crawl space characteristics, such as floor construction, number of vents, number of piers and support walls, and the presence of HVAC ductwork or asbestos in the crawl space. While the SMD technique appears to be the method of choice for reducing levels in both the crawl space and the rooms above, further investigations need to be carried out in crawl spaces that are not as simple as the one used in this study to determine if it can indeed be applied successfully in non-ideal conditions.

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TABLE 1. METRIC CONVERSION FACTORS

Non-Metric	Times	Yields Metric
cubic foot (ft^3)	28.3	liters (L)
cubic feet per minute (cfm)	0.47	liter per second (L/s)
degrees Fahrenheit (°F)	5/9 (°F-32)	degrees centrigrade (°C)
foot (ft)	0.30	meter (m)
inch (in.)	2.54	centimeters (cm)
inch of water column (in. WC)	248	pascals (Pa)
picocurie per liter (pCi/L)	37	becquerels per cubic meter (Bq/m^3)
square foot (ft^2)	0.093	square meter (m^2)
square inch ($in.^2$)	6.452	square centimeters (cm^2)

TABLE 2. SUMMARY OF MEASUREMENTS

Parameter	Location
Differential Pressure	Room 116 to Outdoors Room 116 to Crawl space Room 116 to Subpoly
Radon	Room 116 Crawl Space
Temperature	Room 116 Crawl space Soil Outdoors
Wind Speed and Direction	Outdoors
Relative Humidity	Outdoors
Rainfall	Outdoors

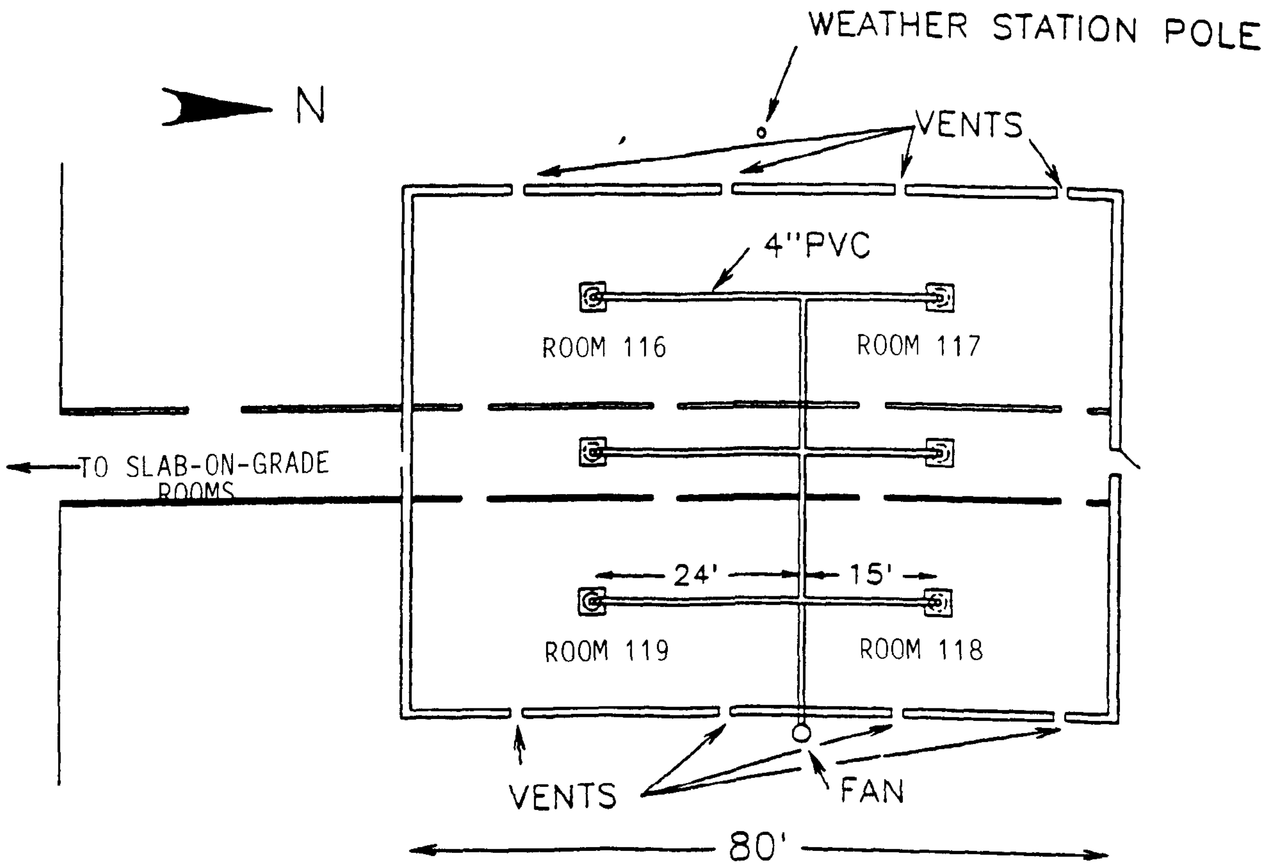

Figure 1. Plan view of the crawl space and installed ducting network.

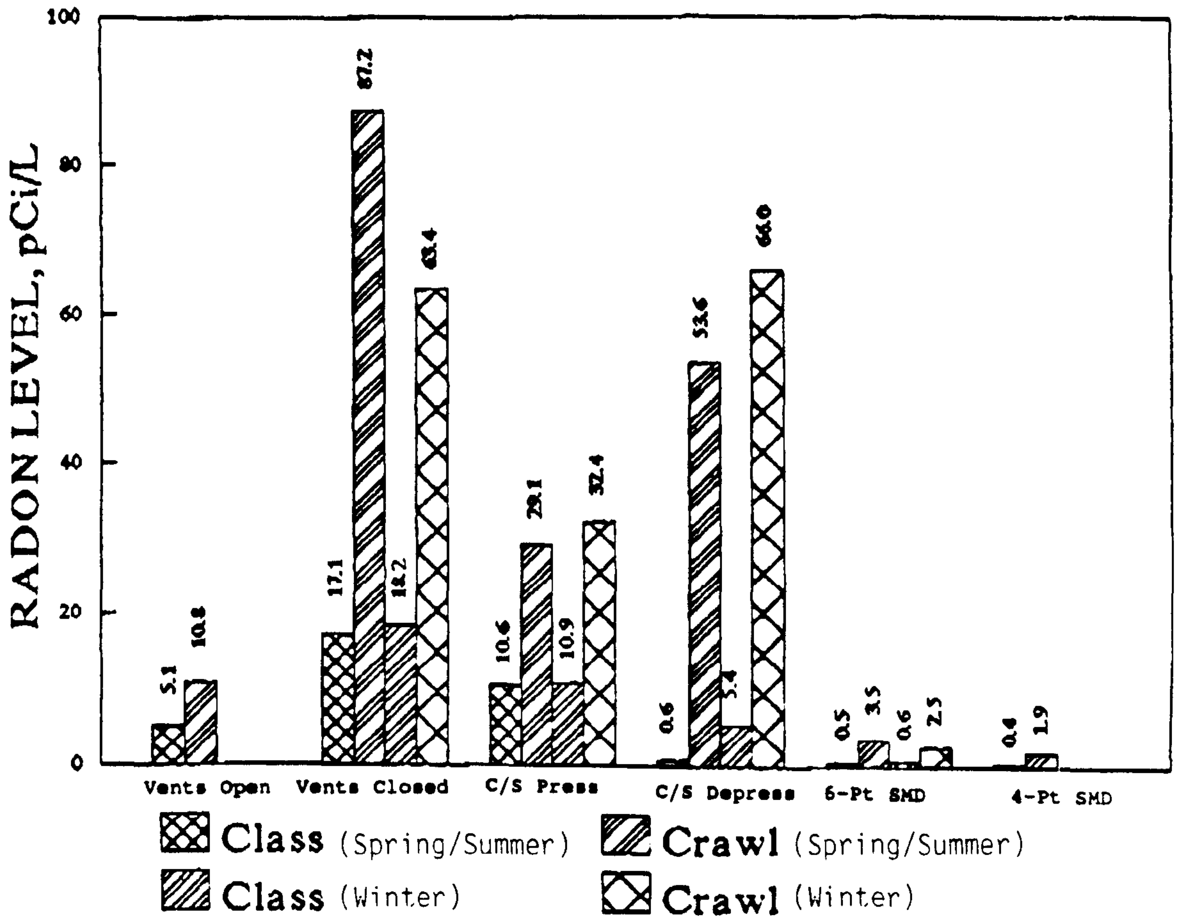

Figure 2. Average radon levels in the crawl space and in Room 116 during each of the mitigation testing periods (both spring/summer and winter).

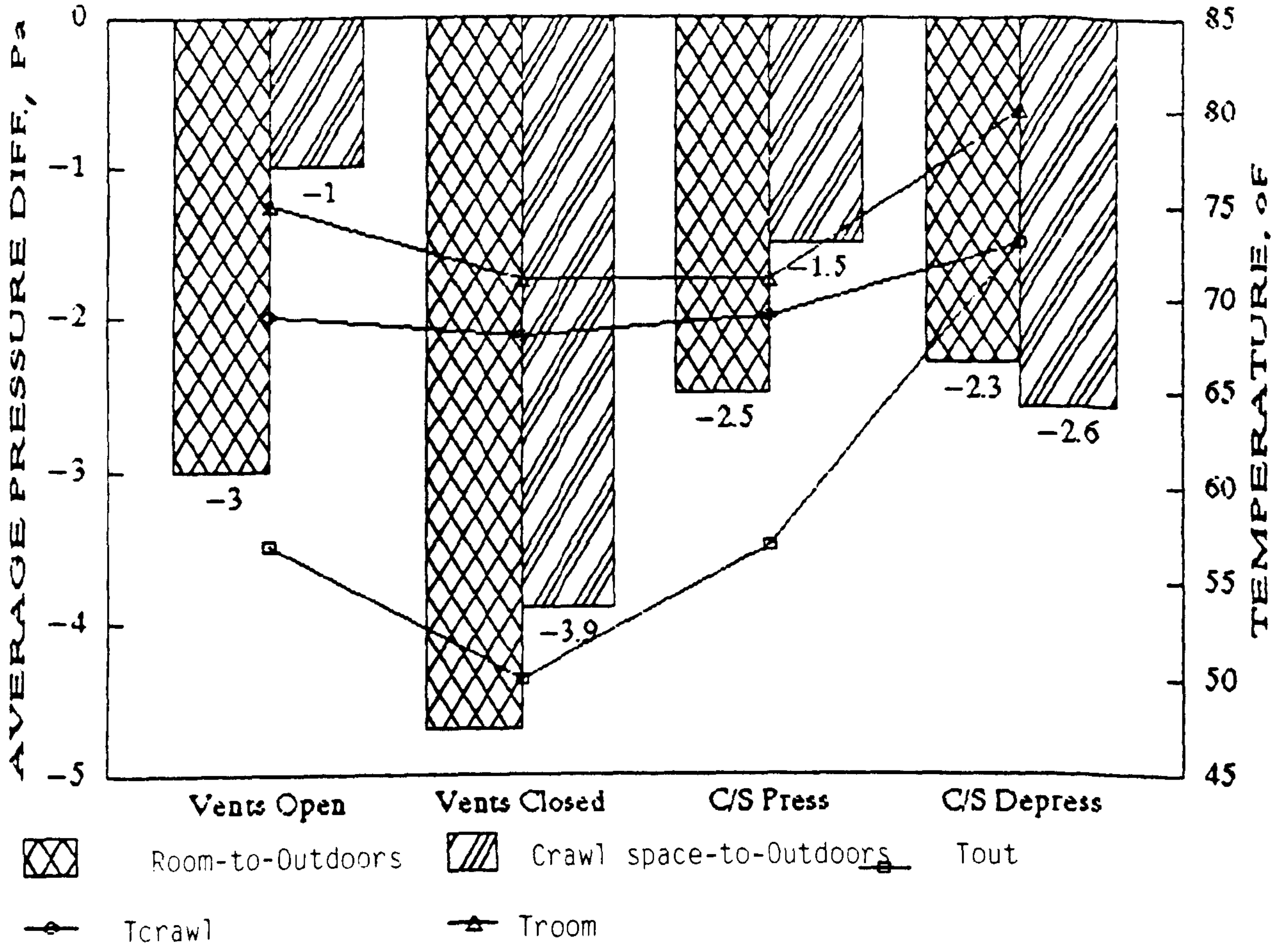

Figure 3. Average pressure differences between both the crawl space and outdoors and Room 116 and the outdoors during each of the mitigation testing periods.

HVAC SYSTEM COMPLICATIONS AND CONTROLS FOR RADON REDUCTION IN SCHOOL BUILDINGS

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ABSTRACT

School mitigation research to date has emphasized reduction of radon levels using active subslab depressurization (ASD). Although ASD has proven successful in a number of schools, it is not reasonably applicable in all school buildings since many schools do not have a layer of clean, coarse aggregate under the slab or may have many subslab barriers that would require an unreasonable number of ASD suction points. Additionally, mitigation options that have relatively low installation and operating costs need to be researched for application to schools with moderately elevated radon levels (4 to 20 picocuries per liter, pCi/L). Since many schools are designed with heating, ventilating, and air-conditioning (HVAC) systems that can provide outdoor air to the building, research has been initiated to determine the feasibility of using HVAC systems to pressurize the building interior to reduce elevated levels of radon in selected schools.

This paper discusses case studies of four schools where the U.S. Environmental Protection Agency's (EPA) Air and Energy Engineering Research Laboratory (AEERL) has recently initiated long-term research on the ability of HVAC systems to reduce elevated levels of radon. The schools are located in the states of Colorado, Maryland, Virginia, and Washington. Depending on the school building floor plan and HVAC system design, a specific wing or the entire building was selected for research. Two of the schools have unit ventilators in the rooms being researched and two have central air-handling systems. Initial results indicate that, when sufficient outdoor air is supplied by the HVAC system, radon levels can be reduced. The amount of radon reduction depends on the specific HVAC system design and operation.

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

Previous research efforts on radon reduction in schools have presented theoretical aspects and limited short-term data on radon mitigation using HVAC systems (1, 2, 3); however, long-term research on the feasibility of radon mitigation using HVAC system pressurization is limited. As a result, in the summer of 1990 AEERL's Radon Mitigation Branch initiated several projects in an effort to better understand school HVAC systems and their ability to reduce radon levels in schools while also improving overall indoor air quality.

To initiate this research on radon mitigation using HVAC systems, four schools (or wings of the schools) were selected. Two of the school wings contain wall-mounted unit ventilators in each classroom (Maryland and Washington), and two of the schools have central air-handling systems (Colorado and Virginia). The Maryland and Virginia schools had been part of previous research efforts by AEERL (1, 4), and the Colorado and Washington schools were identified during field studies in the summer of 1990. These four schools, in addition to three other schools (one in Maryland and two in Ohio), will be studied in more detail over the next year. In a few of the schools future research will also include a comparison of HVAC systems and ASD in reducing elevated levels of radon. Metric conversion factors are presented in Table 1.

CASE STUDIES

The following case studies discuss four schools located in Colorado, Maryland, Virginia, and Washington. In addition to background information on each school, each case study includes an HVAC system description, the results of initial measurements, and future research plans for the school. The summary characteristics of these schools are displayed in Table 2.

COLORADO SCHOOL

The original building was constructed in 1956 and includes seven classrooms and various other support offices and storage rooms with a total area of approximately 15,750 ft^2 of floor space as shown in Figure 1. The original building includes a 1,300 ft^2 boiler room located in a basement in the southwest corner. The boiler room is approximately 11 ft below grade and contains the HVAC system. The remainder of the building is slab-on-grade construction. In 1958 an additional six classrooms, a kitchen, several restrooms, and support rooms totaling about 9,500 ft^2 were added to the original building. In 1976, a 2,100 ft^2 media center was added to the end of the 1958 addition. The last addition to the building was in 1982 when a 200 ft^2 storage area was added to the southwest end of the multipurpose (gym) room. The total footprint of the building is approximately 29,000 ft^2 , with approximately 27,700 ft^2 in contact with the soil.

E-Perm measurements made in all classrooms from January 15 to 17, 1990, averaged 6.6 pCi/L with a minimum of 4.8 pCi/L and a maximum of 12.3 pCi/L. Most of the rooms were remeasured during followup tests from February 14 to 16, 1990. These later measurements averaged 7.6 pCi/L with a minimum value of 5.8 pCi/L and a maximum value of 10.2 pCi/L. The results of both sets of measurements are shown on the floorplans in Figures 1 and 2, respectively.

<u>HVAC System Description</u>

The building HVAC system includes a central air handler with a single fan and individual controls in each of the rooms. The HVAC system operates by time control with the system operating approximately 9 hours during the daytime and set back for approximately 15 hours at night. This schedule is apparently maintained even during the weekend when the school is not occupied. The HVAC registers are located in the floor and the supply ducts are located below the slabs and are composed of cylindrical cardboard ducts surrounded by poured concrete. In those areas where these ducts were visible, large gaps were found between the cardboard tubing and the surrounding concrete. It is highly likely that in most locations the cardboard tubing has deteriorated to the point that the supply air is in direct contact with the concrete. Since radon levels may build up in the supply ducts when the HVAC fan is not operating, these levels will be measured in future studies to determine the relative contribution to building radon levels.

The return air from each classroom exits through grilles into the hallway with the hallway of the building serving as a return air plenum. From the hallway the return air is ducted into a central subslab return-air tunnel that leads back to the air handler in the basement. The air in the gym is returned through floor grilles in the northeast and northwest corners of the room directly into the return air tunnel. The tunnel varies in size from about 3 by 3 ft up to 4 by 4 ft in cross section and can be accessed in the boiler room. The tunnel has numerous penetrations by utility lines that lead to direct soil contact and probably represent a major radon source. There is a provision for outdoor air to the air handler located at roof level with the air ducted directly into the HVAC fan chamber through a control damper. Visual observation of the outdoor air intake damper from inside the fan chamber with the fan operating indicated that the damper did not open during fan operation. Subsequent investigation by the school maintenance staff confirmed that the control rod for the fresh-air intake damper did not operate properly, and this was repaired. However, it is not clear what control system operates the damper. During the cold winter days the damper may be only partially opened depending on the outdoor temperature.

Results of Initial Measurements

Room pressure differentials were investigated primarily in the kindergarten room using an electronic micromanometer. These measurements were made before the outdoor air damper was repaired. The differential pressure in the kindergarten room relative to the subslab was measured to be -0.005 in. WC with the HVAC on and the door to the hall open. When the door was closed the differential pressure dropped to -0.003 in. WC. The differential pressure between the kindergarten room and the hallway was -0.005 in. WC with the HVAC on and the door closed. The pressure of the room relative to outdoors was -0.005 in. WC. Differential pressure was not measured with the HVAC system off. However, it appears that the HVAC system is depressurizing the classroom relative to both the subslab region and outdoors. This indicates that, even in the warm summer months when the HVAC system is used for ventilation purposes only, it causes room depressurization which results in soil gas flow from the subslab regions into the room.

Radon concentrations under the slab and at several possible entry points were measured using a Pylon AB5 in a "sniff" configuration. The subslab radon levels measured through 0.5 in. diameter holes drilled through the slab in the kindergarten room and the office in Room 6 were about 700 pCi/L. Levels of about 300 pCi/L were measured in a crack in the slab adjacent to one of the air supply registers in the kindergarten room. Sniffing in one of the supply registers in the gym showed levels of about 15 pCi/L with the air handler off and about 25 pCi/L with the fan on. Measurements in the wall cracks of the air return tunnel showed levels of between 50 and 100 pCi/L with the fan off. These levels increased to about 350 pCi/L when the fan was turned on and the tunnel depressurized. This indicates that the depressurization of the return duct can increase radon entry from the soil through the cracks and penetrations in the tunnel walls.

Examination of the air handler fan chamber identified a relatively large crack (about 0.1 in. wide) in the slab. The investigators sealed the accessible part of the crack with duct tape for a length of roughly 4 ft and sealed the hose of the Pylon under the tape. The levels were measured to be about 700 pCi/L with the fan off and about 800 pCi/L with the fan on. The AB5 was placed in the fan chamber to sniff the air in the chamber. The radon levels were about 70 pCi/L with the fan off and increased to 350 to 700 pCi/L with the fan on, indicating that the slab crack into the fan chamber is a major radon entry route. It was also observed that the crack was very clean with little or no dust filling in the crack. Apparently there is sufficient air flow out of the crack (or turbulence in the air above) to keep the crack clean. The pressure in the fan chamber relative to the boiler room was measured to be approximately -2 in. WC.

Over the 1990 Christmas break a series of E-Perm measurements were made in all classrooms of this school with the outdoor air damper for the HVAC system opened and closed. Measurements were also made in another school in the district that has the same design but has not been shown to have elevated levels of radon. In both schools the first set of measurements were made with the outdoor air dampers closed (December 21-26, 1990), and the second set were made with the damper open (December 27-31, 1990). The weather during the second measurement period was exceptionally cold and, as a result, it appears that the damper in the school with the radon problem did not open as intended. Because of this, the measurements with the damper open were repeated in this school on January 1-2, 1991. For each of the two schools, Table 3 presents the average of the radon levels in all classrooms, the levels in the boiler rooms, and the levels in the return air ducts. School 1 is the school with the known radon problem, and School 2 is the other school.

As indicated by the results in Table 3, opening the outdoor air damper reduces average classroom radon levels in School 1; however, it does not bring the average of the average classroom levels to below 4 pCi/L. The results from School 2 show only a slight decrease in average radon classroom levels with the outdoor air damper open. The radon measurements in the return air duct exceed average levels in the classrooms in both schools. These results support the theory that the return air duct is a major contributor to elevated radon levels, particularly in School 1. Opening the damper helps to dilute radon levels in the tunnel but not enough to reduce average classroom levels to below 4 pCi/L.

Future Plans

A datalogger was installed in School 1 in January 1991 to collect continuous radon levels (in Room 6, the supply, and the return ducts), differential pressure, and meteorological data. Measurements will also be made to compare the radon source strengths in Schools 1 and 2. Once a series of baseline data are collected with the outdoor air damper opened and closed, the slab crack in the fan chamber will be sealed and the measurements repeated.

MARYLAND SCHOOL

This school was mitigated with ASD in 1988 and is discussed in detail in Reference 5. Previous measurements in a four classroom addition to the school (Building B in Reference 5) indicated that the unit ventilators in the classrooms could reduce radon levels of over 20 pCi/L to below 2 pCi/L; however, school personnel had decided to install an ASD system since radon levels increased at night when the unit ventilators were off. Measurements indicate that radon levels are typically well below 1 pCi/L with the ASD system operating and, as a result, this school presents an ideal opportunity to compare ASD and unit ventilator pressurization in the same school.

HVAC System Description

The area being studied is a four classroom addition, as shown in Figure 3. Each of the classrooms has a wall-mounted unit ventilator that has the ability to provide outdoor air when the damper is open. Although there is a large exhaust fan in the school (3600 cfm), according to school officials it is never used.

Investigation of the unit ventilators revealed that, although the design drawings called for a minimum of 16% outdoor air, the outdoor air dampers for two of the four units were not opening at all. After repairs, flow hood measurements for the units in Rooms 107 and 108 indicated that about 120 cfm of outdoor air was being supplied by each unit with the outdoor air damper in minimum (roughly 10% open) position. With the restroom exhaust estimated to be 50 cfm, Classroom 107 was at a neutral pressure. With the outdoor air dampers open to 100% outdoor air, Room 107 was about +0.003 in. WC relative to the outdoors, and the air flow into the unit ventilator was 450 cfm. All doors and windows in the room were shut during the data collection.

Results of Initial Measurements

A datalogger was installed in Rooms 105 - 108 over the holiday break (December 21 to 31, 1990) in order to collect preliminary data on the unit ventilators operating with the ASD system off. Measurements were made over successive 3-day periods with the unit ventilators operated as follows:

1) setback (no outdoor air), 2) normal operation (with evening setback), and 3) continuous day operation with no setback (outdoor air provided for entire period). The fans for these units do not run during setback unless room temperatures drop below 60°F. The radon levels measured in Room 108 during these three conditions are shown in Figure 4. As seen by these data, radon levels remain well below 4 pCi/L while the unit ventilator is operated continuously but rise above 4 pCi/L during the setback modes. Note that during the day-plus-setback operation, radon levels rise at night and drop to about 4 pCi/L during the day.

Future Plans

A datalogger was re-installed in Rooms 107 and 108 to study unit ventilator operation over a longer time period while the school is occupied. Continuous data being collected include: radon levels, room to subslab differential pressure, unit ventilator damper position, and indoor/outdoor temperatures.

VIRGINIA SCHOOL

This school was constructed in 1987 in an area with a known radon problem. As a result, various steps were taken by designers to reduce the likelihood of elevated levels of indoor radon and to facilitate post-construction mitigation if needed. (The construction of this school is covered in detail in Reference 4.) Initial post-construction charcoal canister measurements were made in October 1988 in all ground floor classrooms: all measurements were below 2 pCi/L, as shown in Figure 5. These measurements were repeated in December 1990, and radon levels were consistently higher: 13 of the rooms measured 4 pCi/L or higher as shown in Figure 6. Note that levels in the east wing of the school tend to be highest. This is consistent with the higher subslab radon levels measured during construction (4).

HVAC System Description

This school has eight air-handling units serving eight zones. The units are designed to provide a total of 72,600 cfm with a minimum of 16,010 cfm outdoor air. Total building exhaust is 9,506 cfm. This design should maintain the building at a positive pressure; however, the HVAC system is Variable Air Volume (VAV), and outdoor supply is reduced if the temperature drops below a given level.

Results of Initial Measurements

Differential pressure data showed the room to be at a negative pressure relative to the subslab, thus the air-handling units were not adequately pressurizing the building as intended. A datalogger was placed in a conference room December 21, 1990, to collect continuous radon, differential pressure, and temperature data. These results, displayed in Figure 7, show that radon levels are about 5 pCi/L when the room is at a negative pressure relative to the subslab. Radon levels tend to drop slightly as the room-to-subslab differential pressure approaches zero.

Future Plans

The datalogger will remain in this school to collect additional continuous data. School personnel are also considering installation of an ASD system to reduce radon levels on a continual basis. If the ASD system is installed, its effectiveness in reducing radon levels will be compared with that of HVAC pressurization.

WASHINGTON SCHOOL

This school has 16 classrooms, a multipurpose room (gym/cafeteria), and several special purpose rooms and offices. Eight of the classrooms are built over a crawl space, and the remaining eight are slab-on-grade.

Several radon measurements were made over all four seasons (spring, summer, fall, and winter) under a number of ventilation conditions using 2-day charcoal canisters, short and long term E-perms, and alpha track detectors. The results of these measurements are to be presented at the 1991 International Symposium on Radon and Radon Reduction Technology in a paper entitled "The Results of EPA's School Protocol Development Study (6)."

Measurements indicated that the eight rooms built over the crawl space did not have elevated radon levels. As a result, research focused on four of the eight slab-on-grade classrooms that had consistently measured above 4 pCi/L. The layout of this part of the school is shown in Figure 8. These classrooms were located in the northwest wing of the school (Rooms 139-142), and the design drawings indicated the presence of aggregate under the slab. This school contained several classrooms additions, and the foundation drawings available were not particularly clear on specific subslab foundation locations. The subslab foundations included both poured concrete footings and thickened slab footings.

There was a utility tunnel located under the slab along the perimeters of the classrooms in each wing. This tunnel was approximately 4 ft wide by 4 ft high with a dirt floor. The walls of the tunnel were of poured concrete and had numerous penetrations leading to the soil. Accesses to the tunnels were in Rooms 140 and 141 in the west section and in Rooms 127 and 128 in the east section. The tunnel contained the steam pipes that connected the boiler with the unit ventilators in each of the rooms.

<u>HVAC System Description</u>

The HVAC system in this school consists of heating-only, three-speed unit ventilators located in each room. Each room had an electronic thermostat that controlled the outdoor air damper and the heating valve in the unit ventilator. Each unit had a low-limit thermostat that shuts off the outdoor air damper when the supply air temperature falls below 60° F. The units appeared to be in excellent working order in Rooms 139-142. Rooms 141 and 142 each have a wind-turbine exhaust ducted to the roof through the storage/coat closets. The turbine for Room 142 was inoperable (not turning) during the investigation, but school maintenance personnel planned to fix it promptly. A passive exhaust was located in Room 140, and there was no exhaust in Room 139 (library).

There was no automatic shutoff of the ventilators, nor was there an automatic temperature setback control. It appeared that each unit fan ran continuously and the unit cabinets and thermostats were inaccessible without special tools (a hex key); thus the fan speeds and temperature settings could not be adjusted by the teachers. The unit ventilator fans could be shut off at the electrical panelboard.

The piping was routed to each unit ventilator through tunnels under the slab, as seen in Figure 8. The return air for the unit ventilator was not isolated from the slab over the tunnel, thus any opening in the slab (e.g., a pipe sleeve, crack) would allow air from the tunnel to enter the unit ventilator and mix with the room air return and outdoor air. A high radon level in the tunnel could be the source of elevated radon levels in the room. Some openings were found around pipe penetrations, and radon levels in the tunnel averaged about 55 to 60 pCi/L.

<u>Results of Initial Measurements</u>

Air flow quantities were measured for each unit ventilator, and static pressure readings (relative to the outdoor pressure) were taken in Rooms 139-142. The readings were taken for the various operating modes of each unit ventilators: 1) unit ventilator off; 2) unit ventilator on low, medium, high fan speed; and 3) unit ventilator with outdoor air damper opened and closed. In addition to these unit ventilator modes of operation, room static pressure was measured with the hallway door opened and closed. The results of the differential pressure and flow measurements are shown in Tables 4 through 7, and the results of the differential pressure measurements are displayed graphically in Figures 9 through 12. These measurements indicate that the optimal operating mode for the reduction of soil gas infiltration would require the unit ventilator to be on (any speed) with the outdoor air damper in the open (or 100%) position, and with the hallway door closed. It appears that no other operating mode, or door position, would allow for pressurization of the room. Only Room 139 (library) could be pressurized with the outdoor air damper in the minimum (roughly 10% open) position, with the hallway door closed (probably due to the lack of any exhaust system in the room). With the unit ventilator on, the outdoor air damper open, and the hallway door closed, pressures in those rooms with wind turbine or passive exhausts (140-142) ranged from +0.020 to +0.036 in. WC. These pressures should be adequate to prevent soil gas infiltration into the rooms.

To determine the ability of the unit ventilators to reduce radon levels during normal occupancy, a datalogger was installed in this school from November 29, 1990, to January 8, 1991. Continuous radon levels were measured in Rooms 139, 140, and 141, and in the tunnel. Differential pressures, temperatures, wind speeds and directions, classroom door openings and closings, and unit ventilator operations were also monitored. These data are currently being analyzed. For a general comparison, a summary of the data is displayed in Table 8. The results shown in this table were obtained over a 2 week period (December 2 through December 15, 1990). During the first week (December 2 through 8, 1990) the classrooms were operated in a normal manner with the classroom doors into the hall closed about 75% of the time (note that the doors were usually closed after class and throughout the weekend). During the second week (December 9 through 15) the teachers were asked to keep their classroom doors closed as much as possible during class. As seen in Table 4, the percent of time the doors were closed increased to about 90%. The average radon level was reduced by approximately 50% as a result of the pressurization of the classrooms produced by the unit ventilators.

These data indicate that if the classroom-to-hall doors are kept closed, radon levels in the classrooms can be reduced. The slightly lower levels in Room 139 (the library) are probably due to a combination of factors including: a lower source strength, no exhaust (passive or turbine), and the library door is closed more frequently than the classroom doors.

Future Plans

Data collected from the datalogger are being analyzed. Depending on the need to keep the classroom-to-hall doors closed to achieve adequate mitigation with the unit ventilators, the school will make a final decision on the mitigation approach.

CONCLUSIONS

The initial data collected in these four schools confirmed that pressurization of classrooms (using the HVAC system) reduces average radon levels. Pressurization, however, did not consistently reduce the levels to below 4 pCi/L in all the classrooms studied. The schools used in this study are a small sample, but the HVAC systems found in these schools are expected to have a great deal in common with those installed in most school buildings constructed in the U. S. since the 1950s.

Those buildings with central air handling units are designed to be pressurized. It was found that modifications to the control systems by owners and deterioration of the system components have resulted in these systems no longer operating to pressurize the classrooms. These systems were contributing to depressurization of the building interiors, thus increasing the potential for the entry of radon-laden soil gas. (In one case, it appears that radon entry into the subslab return air duct is also contributing to elevated radon levels in the building.) A change in the control strategy, returning them to original operations, should allow for pressurization of the classrooms and a reduction in radon levels. However, it should be noted that most control strategies will close outdoor air dampers in cold weather to reduce the likelihood of freezing the heating coil.

Unit ventilators are designed and operated in such a manner that the outdoor air damper is modulated based on indoor and supply air temperatures. They were observed in this study to pressurize a classroom but usually only when the classroom door to the hallway was closed and the outdoor air damper was open. This may not be sufficient to reduce radon levels consistently below 4 pCi/L without additional efforts to reduce other negative pressures in the building.

Research in these schools and additional schools over the next year will focus on determining the optimal HVAC system operation for radon reduction. Limitations of HVAC pressurization will also be studied, and in some of the schools HVAC pressurization will be compared with ASD.

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TABLE 1. METRIC CONVERSION FACTORS

Non-Metric	Times	Yields Metric
cubic foot per minute (cfm)	0.47	liter per second (L/s)
degree Fahrenheit (°F)	5/9 (°F-32)	degrees Centigrade (°C)
foot (ft)	0.305	meter (m)
inch (in.)	2.54	centimeters (cm)
inch of water column (in. WC)	248	pascals (Pa)
picocurie per liter (pCi/L)	37	becquerels per cubic meter (Bq/m^3)
square foot (sq ft)	0.093	square meter (m^2)
square inch (sq in.)	0.00065	square meter (m^2)

TABLE 2. SUMMARY OF SCHOOLS*

State	Approximate Size of Area Under Study sq ft	HVAC	Initial Radon Levels pCi/L
Colorado	29,000	central	5-12
Maryland	3,500	unit ventilators	14-20
Virginia	1,200	central	2-7
Washington	5,000	unit ventilators	3-21

* Substructure of all schools is slab-on-grade.

TABLE 3. E-PERM MEASUREMENTS IN COLORADO SCHOOLS 1 AND 2

		Radon Levels, pCi/L					
		Classrooms		Boiler Room		Return Air Duct	
Dates	Outdoor Air Damper	1	2	1	2	1	2
Dec 21-26	closed	10.8	2.9	2.5	2.6	13.5	6.6
Dec 27-31	open in 2 open & closed in 1	7.0	2.5	3.5	2.0	14.6	7.8
Jan 1-2	open in 1	4.6	-	2.5	-	7.5	-

TABLE 4. DIFFERENTIAL PRESSURE AND FLOW MEASUREMENTS IN ROOM 139

DATA TAKEN: August 22, 1990

DIFFERENTIAL PRESSURE MEASUREMENTS, ROOM TO OUTDOORS (in. WC)

Room-to-Hall Door Closed

Outdoor Air Damper Position	Unit Ventilator Speed Setting: Off	Low	Medium	High
Open (100%)	-0.001	0.053	0.054	0.056
Closed (10% open)	-0.001	0.01	0.009	-0.012

Room-to-Hall Door Open

Outdoor Air Damper Position	Off	Low	Medium	High
Open (100%)	-0.001	-0.001	-0.001	0
Closed (10% open)	-0.001	-0.002	-0.003	-0.001

AIR QUANTITY MEASUREMENT (cfm)

Outdoor Air Damper Position	Low	Medium	High
Open (100%)			
Outdoor Air	460	470	500
Supply Air	1175	1306	1285
Closed (10% Open)			
Outdoor Air	30	47	109
Supply Air	N/A	N/A	N/A
Percent Outdoor Air			
Outdoor Air Damper Open	39%	36%	39%
Outdoor Air Damper Closed	3%	4%	8%
Outdoor Air Per Student (cfm - Based on 20 Students)			
Outdoor Air Damper Open	23	24	25
Outdoor Air Damper Closed	2	2	5

Avg Leak Area (in.^{2}) = 73.2

OBSERVATIONS: Room 139 (Library) could be pressurized with the unit ventilator, regardless of the outdoor air damper position, but only when the room-to-hall door was closed. It does not have an exhaust vent like the other rooms, thus it is easier to pressurize.

TABLE 5. DIFFERENTIAL PRESSURE AND FLOW MEASUREMENTS IN ROOM 140

DATA TAKEN: August 22, 1990

DIFFERENTIAL PRESSURE MEASUREMENTS, ROOM TO OUTDOORS (in. WC)

Room-to-Hall Door Closed

	Unit Ventilator Speed Setting:			
Outdoor Air Damper Position	Off	Low	Medium	High
Open (100%)	0	0.02	0.021	0.024
Closed (10% open)	0	-0.002	-0.001	-0.002
Room-to-Hall Door Open				
Open (100%)	0.001	0	-0.003	-0.001
Closed (10% open)	0.001	-0.004	-0.002	-0.008

AIR QUANTITY MEASUREMENT (cfm)

Outdoor Air Damper Position	Low	Medium	High
Open (100%)			
Outdoor Air	361	438	449
Supply Air	1200	1263	1380
Closed (10% Open)			
Outdoor Air	45	23	44
Supply Air	1090	1135	1197
Percent Outdoor Air			
Outdoor Air Damper Open	30%	35%	33%
Outdoor Air Damper Closed	4%	2%	4%
Outdoor Air Per Student (cfm - Based on 20 Students)			
Outdoor Air Damper Open	18	22	22
Outdoor Air Damper Closed	2	1	2

Avg Leak Area (in.^{2}) = 101.1

OBSERVATIONS: Room 140 could be pressurized with the unit ventilator, only with the outdoor air damper in the fully open position, and the room-to-hall door closed. This room has a passive vent and is more difficult to pressurize.

TABLE 6. DIFFERENTIAL PRESSURE AND FLOW MEASUREMENTS IN ROOM 141

DATA TAKEN: August 22, 1990

DIFFERENTIAL PRESSURE MEASUREMENTS, ROOM TO OUTDOORS (in. WC)

Room-to-Hall Door Closed

Outdoor Air Damper Position	Unit Ventilator Speed Setting: Off	Low	Medium	High
Open (100%)	0	0.03	0.034	0.036
Closed (10% open)	-0.003	-0.002	-0.002	-0.003

Room-to-Hall Door Open

Outdoor Air Damper Position	Off	Low	Medium	High
Open (100%)	-0.002	-0.005	-0.001	-0.001
Closed (10% open)	-0.002	-0.002	-0.003	-0.003

AIR QUANTITY MEASUREMENT (cfm)

Outdoor Air Damper Position	Low	Medium	High
Open (100%)			
Outdoor Air	495	580	657
Supply Air	1001	1097	1160
Closed (10% Open)			
Outdoor Air	72	87	94
Supply Air	N/A	N/A	N/A
Percent Outdoor Air			
Outdoor Air Damper Open	49%	53%	57%
Outdoor Air Damper Closed	7%	8%	8%
Outdoor Air Per Student (cfm - Based on 20 Students)			
Outdoor Air Damper Open	25	29	33
Outdoor Air Damper Closed	4	4	5

Avg Leak Area (in.^{2}) = 113.0

OBSERVATIONS: Room 141 could be pressurized with the unit ventilator, only with the outdoor air damper in the fully open position, and the room-to-hall door closed. This room has a wind turbine exhaust and is more difficult to pressurize.

TABLE 7. DIFFERENTIAL PRESSURE AND FLOW MEASUREMENTS IN ROOM 142

DATA TAKEN: August 22, 1990

DIFFERENTIAL PRESSURE MEASUREMENTS, ROOM TO OUTDOORS (in. WC)

	Unit Ventilator Speed Setting:			
Outdoor Air Damper Position	Off	Low	Medium	High
Room-to-Hall Door Closed				
Open (100%)	0	0.03	0.034	0.036
Closed (10% open)	-0.003	-0.002	-0.001	-0.003
Room-to-Hall Door Open				
Open (100%)	-0.002	-0.005	-0.001	-0.001
Closed (10% open)	-0.002	-0.002	-0.003	-0.003

AIR QUANTITY MEASUREMENT (cfm)

Outdoor Air Damper Position	Low	Medium	High
Open (100%)			
Outdoor Air	266	230	251
Supply Air	1123	1218	1362
Closed (10% Open)			
Outdoor Air	150	160	184
Supply Air	1078	1250	1306
Percent Outdoor Air			
Outdoor Air Damper Open	20%	19%	18%
Outdoor Air Damper Closed	14%	13%	14%
Outdoor Air Per Student (cfm - Based on 20 Students)			
Outdoor Air Damper Open	11	12	13
Outdoor Air Damper Closed	8	8	9
Avg Leak Area (in.^{2}) =	46.2		

OBSERVATIONS: Room 142 could be pressurized with the unit ventilator, only with the outdoor air damper in the fully open position, and the room-to-hall door closed. This room has a wind turbine exhaust vent and is more difficult to pressurize although the turbine was inoperable during these measurements. The outdoor air damper appears not to open fully.

TABLE 8. AVERAGE RADON LEVELS IN WASHINGTON SCHOOL DURING 1 WEEK OF NORMAL OPERATION AND 1 WEEK OF TESTING OPERATION

Location*	Normal Operation Average Radon (max) (pCi/L)	Normal Operation Persent Time Door Closed (%)	Test Operation Average Radon (max) (pCi/L)	Test Operation Persent Time Door Closed (%)	Subslab Radon Sniff Measurement (Aug. 1990) (pCi/L)
Room 139	2.6 (26.7)	76	1.4 (16.5)	97	400
Room 140	5.3 (29.2)	74	3.2 (7.4)	92	500
Room 141	4.5 (32.1)	75	2.2 (25.0)	88	700
Average	4.1	75	2.3	92	533
Tunnel	55.6 (202.8)		60.8 (129.2)		N/A

* Data for Room 142 not available; Pylon inadvertently "unplugged."

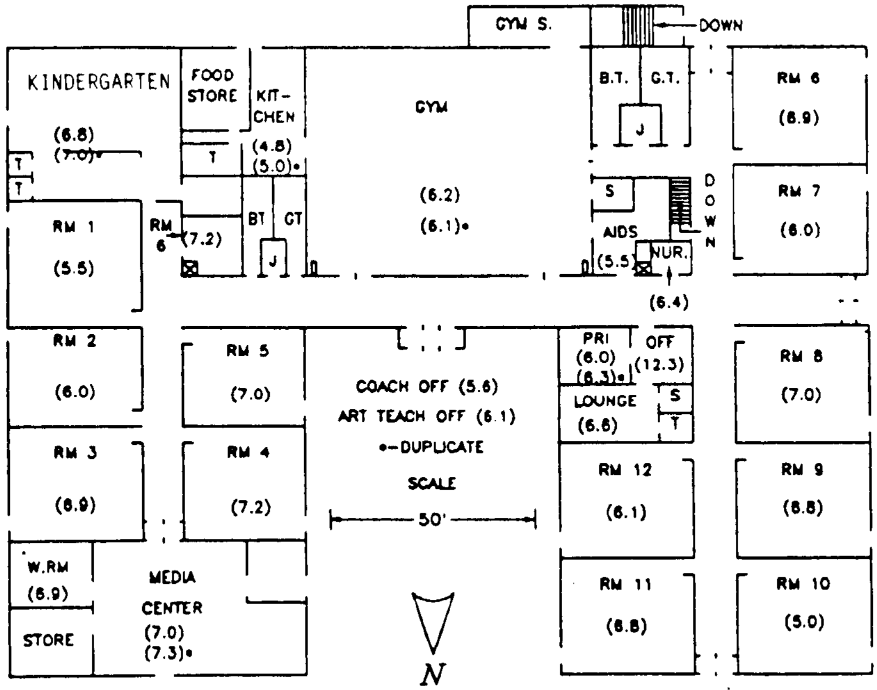

Figure 1. Results of January 1990 radon measurements in Colorado school, pCi/L.

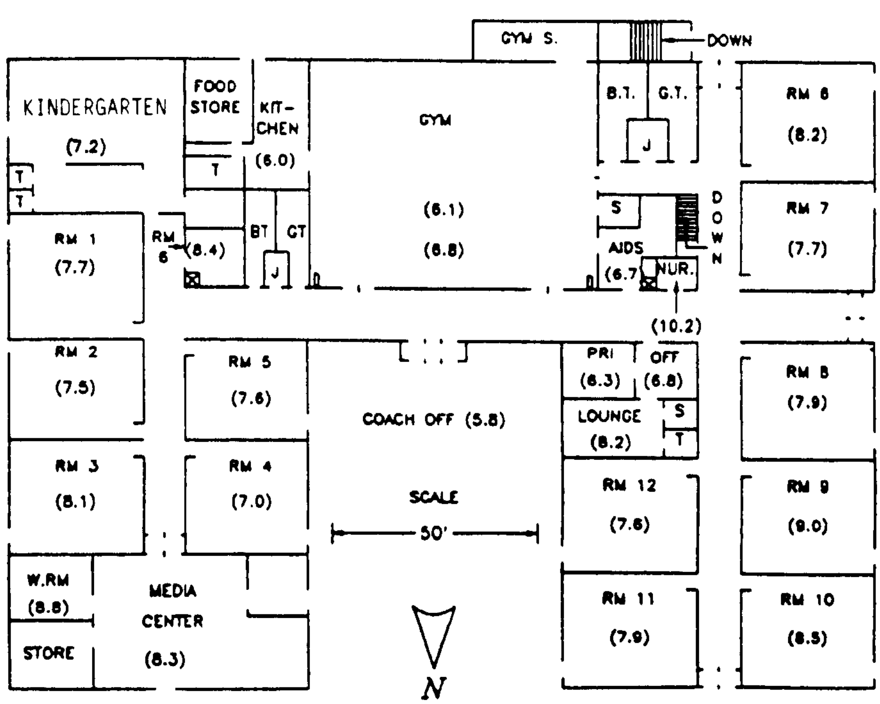

Figure 2. Results of February 1990 radon measurements in Colorado school, pCi/L

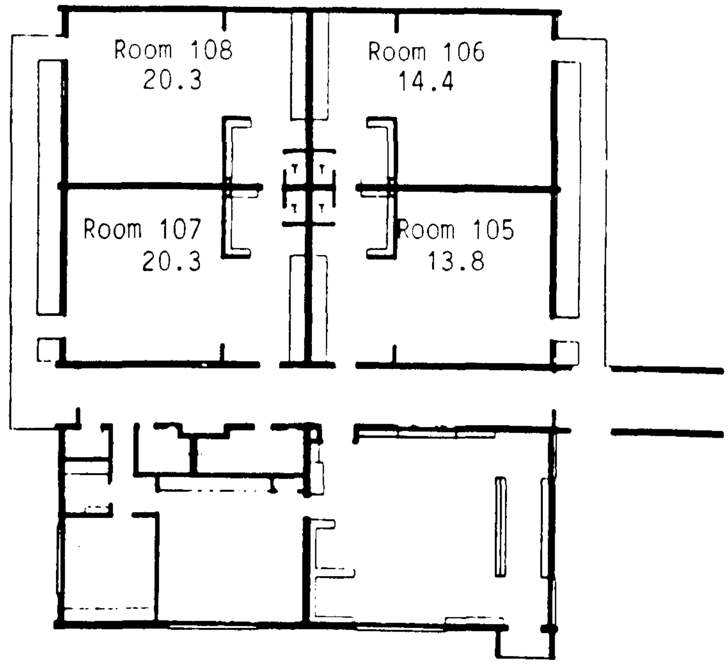

Figure 3. Results of initial radon measurements in wing of Maryland school, pCi/L.

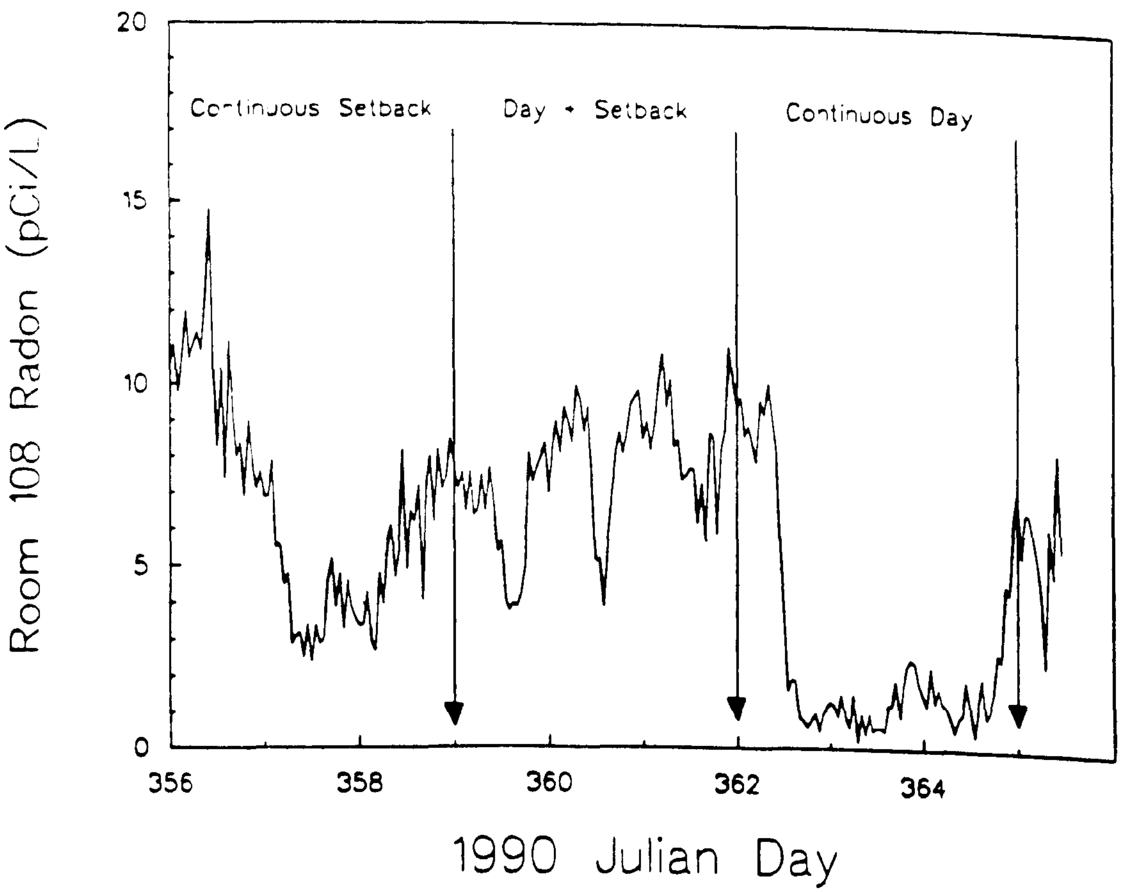

Figure 4. Continuous radon measurements in Maryland school.

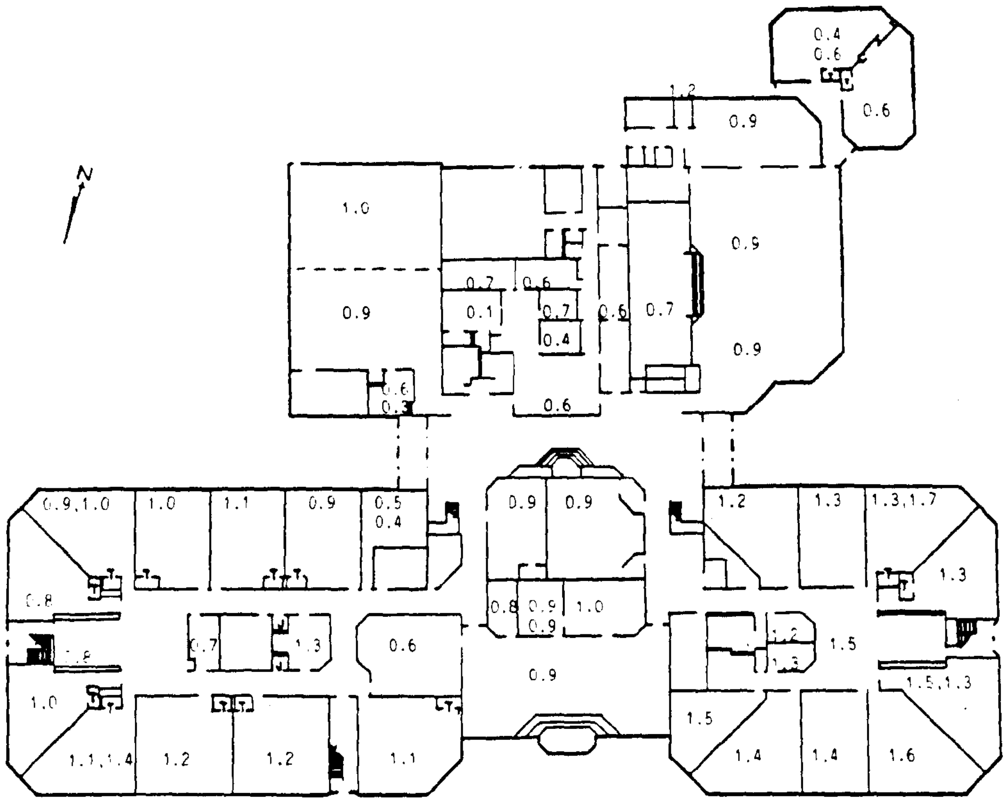

Figure 5. Results of October 1988 radon measurements in Virginia school, pCi/L

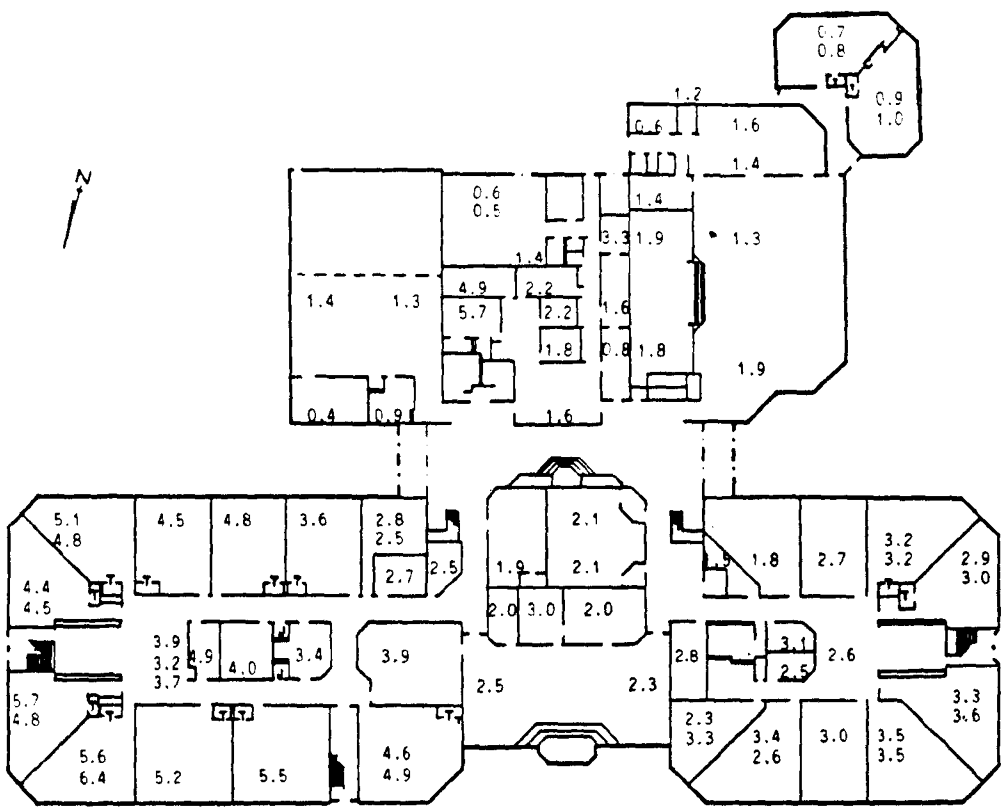

Figure 6. Results of December 1990 radon measurements in Virginia school, pCi/L.

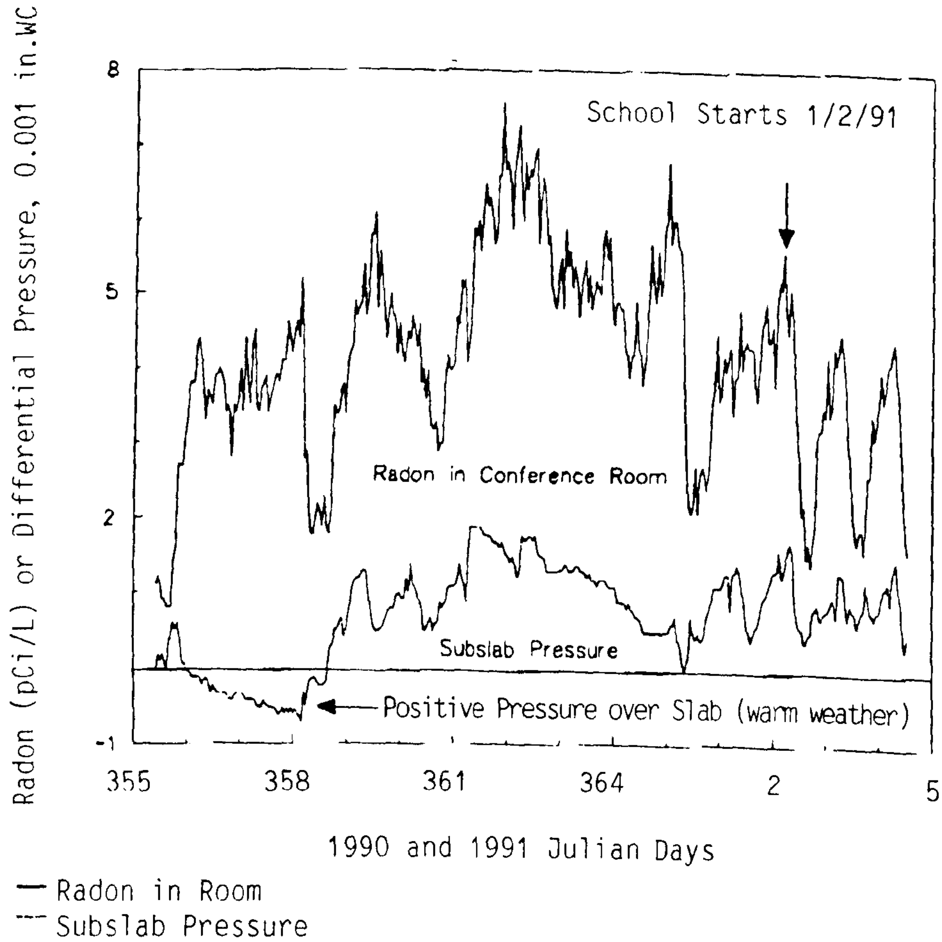

Figure 7. Continuous radon and differential pressure in Virginia school.

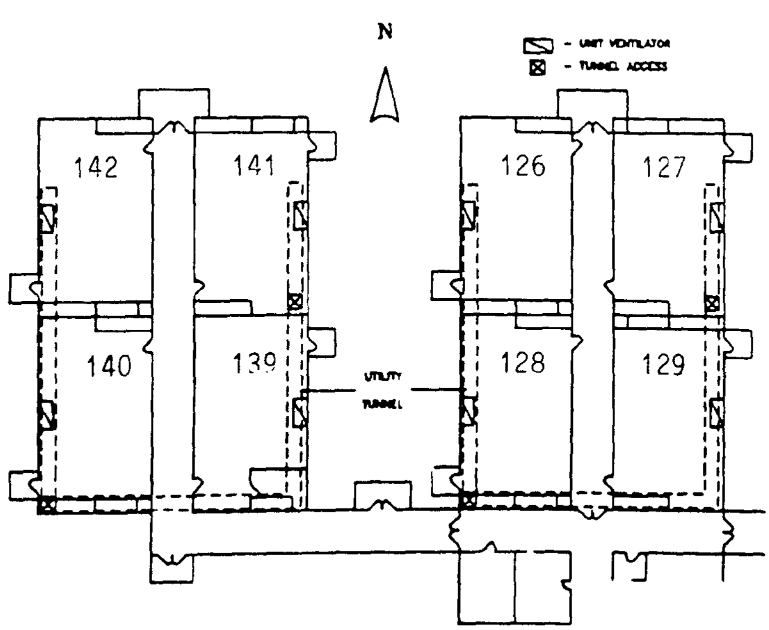

Figure 8. Partial floorplan showing utility tunnel and room locations in Washington school.

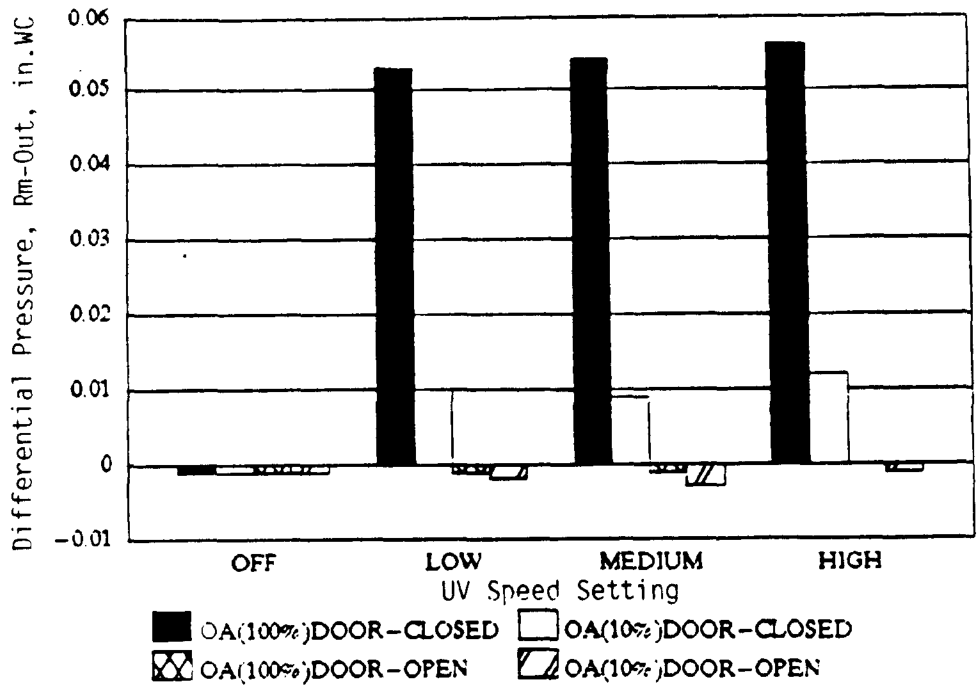

Figure 9. Differential pressure measurements in Room 139, August 1990.

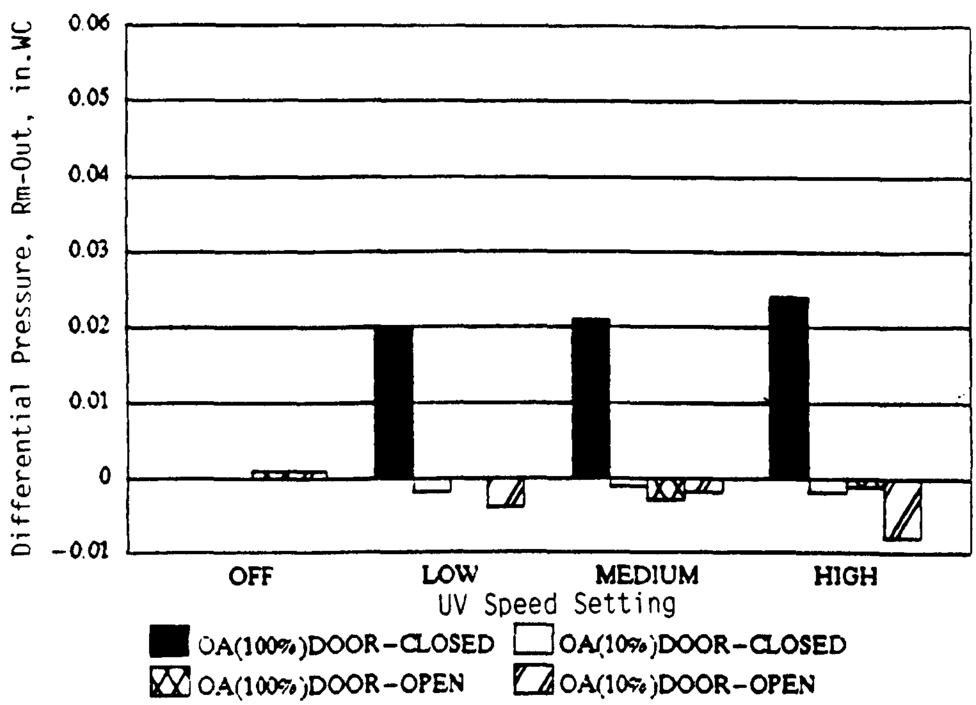

Figure 10. Differential pressure measurements in Room 140, August 1990.

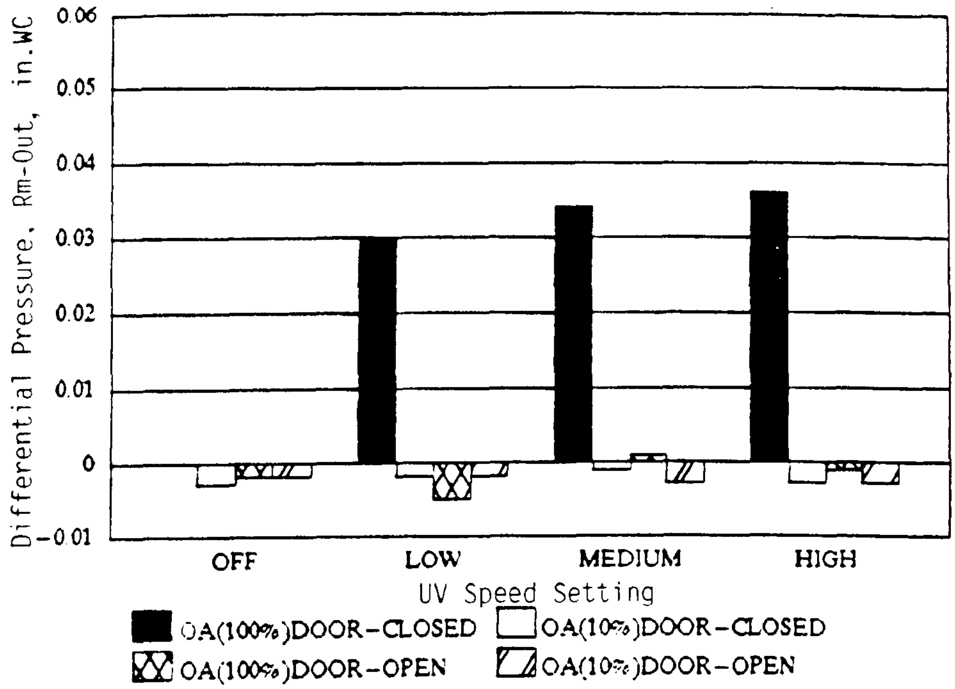

Figure 11. Differential pressure measurements in Room 141, August 1990.

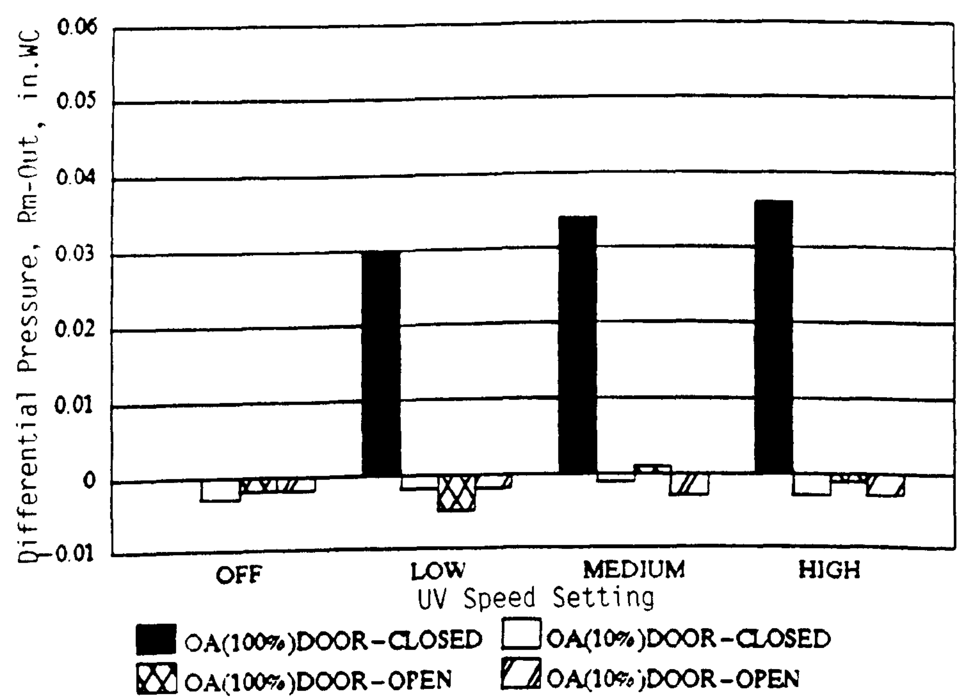

Figure 12. Differential pressure measurements in Room 142, August 1990.

RADON DIAGNOSIS IN A LARGE COMMERCIAL OFFICE BUILDING

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ABSTRACT

Large commercial office buildings present a significant challenge to the commercial radon mitigator. A radon problem in a Washington, DC area was recently analyzed with a number of diagnostic techniques in a attempt to get a quick understanding of the nature of the problem while operating within a limited budget. The building has 7 stories, is 5 years old and it has a VAV type HVAC system with 21 air handler zones. The diagnosis was carried out using and integrated approach combining: 1) multiple short term radon screening to look for hot spots, 2) continuous radon monitoring in a few sites to identify day/night radon variations, 3) pressure tests across doors to identify localized depressurization, and 4) continuous pressure in hot spots monitoring to identify building HVAC cycles. This integrated approach identified different mitigation solutions in each zone. Mitigation options have been presented to the building owners, but a final decision on mitigation has not been made at the time this paper was written.

BACKGROUND

Radon mitigators may need to use a wide variety of diagnostic tools to analyze radon problems in large office buildings. These buildings generally have sophisticated HVAC systems and complex foundation structures that are not generally found in homes or schools. For quick, cost effective radon diagnosis in large office buildings, it may b necessary to use a variety of radon and pressure measurement equipment. This paper describes an attempt to diagnose a building using: 1) multiple short term radon screening to look for hot spots, 2) continuous radon monitoring in a few sites to identify day/night radon variations, 3) pressure tests across doors to identify localized depressurization, and 4) continuous pressure monitoring in hot spots to identify building HVAC cycles.

The ground floor of this Washington, DC Metro area 7 story, 5 year old building is underground except for a loading dock area. The HVAC system is a VAV type with 3 air handlers on each floor, supplies in most rooms, and a return plenum overhead. Figure 1 shows the floor plan of the basement and each of the three HVAC zones is outlined. There are a number of areas in the basement with slab-to-slab walls that may cross the boundaries of the HVAC zones.

Previous radon tests were made with alpha-track monitors deployed for three months during the summer and winter of 1989. Rooms indicated on Figure 1 are locations of radon tests. Table 1 lists all of the radon test results. When some radon levels above 4 p/Ci/L were found, all the building VAV units were adjusted to supply a minimum airflow of 30%, and booster fans were installed in the fresh air supply ducts. All of this work was assumed to guarantee that the building would be under a positive pressure while the HVAC system was on. No further radon tests were performed after these modifications, and one of the goals of the Infiltec work was to determine if the HVAC modifications have made a change in the radon levels. Additional goals include a determination of the pressure balances inside the building and suggestions for mitigation if elevated radon levels are found.

RADON MEASUREMENTS

In order to determine if the radon levels had changed since the HVAC modifications were performed, radon tests were conducted by Infiltec over the period 9/6 to 9/14 with electret passive monitors in 23 rooms and continuous radon monitors (CRMs) in two rooms. The electrets were read out every few days to check the average radon levels and the CRMs recorded hourly data so that the short term fluctuations could be monitored. Table 1 lists the electret results and Figures 2 and 3 show the hourly radon data in 2 zones.

PERIOD 9/6-9/7

A quick 24 hour test was performed to get a snapshot of the building and to check out areas such as elevator shafts and HVAC rooms that had not been tested before. This data is shown in the first data column of Table 1. No new sources were found but the shop area which had shown the highest radon levels in previous tests was not as high as the rooms in zones B and C.

PERIOD 9/6-9/10

A longer electret test (second data column in Table 1) over the weekend was performed in more rooms with the hope of finding sources in the building when the HVAC system shut down over the weekend. Unfortunately, it was found that during the weekend the HVAC system operates with the same cycling as a weekday because of partial weekend occupancy. However, the longer tests showed continued elevated levels of radon in most rooms in zones A and B, and the shop showed the highest levels.

PERIOD 9/6-9/14

Adding 4 more days to the electret test (third data column in Table 1) resulted in a surprising lowering of radon levels in zones A and B, but the shop room stayed at about 6 pCi/L. When the electret data is analyzed for the levels between 9/10-9/14 (fourth data column in Table 1) it can be seen that the radon levels have dropped substantially in both of these zones during this period, while the levels in zone A have not changed very much.

Figure 2 shows what happened to the radon levels in one room in zone B which is expected to be representative of most of the rooms in this zone. On the evening of September 10 the radon levels fall from about 4 pCi/L to about 2.5 pCi/L and remain there. The electret data suggest that this is what happened in all the rooms in zones B and C. One possible explanation is that the onset of cooler weather on 9/10 may have changed the VAV settings to bring in more fresh air. At present the reason for this sudden change in radon levels is unknown but it seems to have only affected the radon levels in zones B and C. Since Figure 2 shows that the radon levels in zone B do not show a day/night fluctuation, it seems that radon is being constantly pulled into these zones during the day and that when the HVAC system shuts down at night there is no significant increased or decreased entry.

Figure 3 shows that the radon levels in the shop area exhibit extreme day/night fluctuations with peaks up to 30 pCi/L at night and decreasing to 1 or 2 pCi/L during the day. The shaded area on this graph shows the radon levels during occupied hours (7 am to 5 pm), and the average radon during occupied hours is not very much different from the average levels during occupied hours because the HVAC system comes on a t 7 am and it takes several hours to sweep the radon from this room. Some of this effect may be due to time lag in the CRM response. Note that Table 1 shows that radon levels in the rest of zone A rooms are quite low. There seems to be a strong radon source in the shop that is suppressed during the day by either positive pressure or ventilation, but when the HVAC system shuts down this source raises the levels in the shop very quickly.

PRESSURE MEASUREMENTS

Figure 4 shows a recording of the pressure difference between the shop and the subslab gravel layer. This data was measured through a small hole drilled through the slab in the shop. The graph shows that there is a positive pressure in the shop (relative to the subslab) during the day of 0.01 to 0.02 inches of water column ("wc) and when the HVAC system is shut down at night there is still a positive pressure of about 0.002 "wc. The pressure in the shop relative to the hall was measured at about 0.007 "wc lower than the hall during the day (Table 1) and Figure 4 suggests that zone A is generally well pressurized by the HVAC system. It is generally assumed that if there is any positive pressure in a room relative to the subslab that all radon entry will be suppressed. Therefore it is surprising that the shop appears to be at a slight positive pressure even at night when the radon is entering. This suggests that the radon source is not in the subslab and that it may be somewhere in the walls. We have been unable to locate the entry point and it may be necessary to conduct further investigations when the HVAC system is not pressurizing the room.

Subslab radon measurements were made through three drilled holes in the shop floor and levels of 130 to 280 pCi/L were found (Table 2). These radon levels are very low. From our experience we have generally seen subslab radon levels in problem buildings ranging from 500 to 80,000 pCi/L. It appears that the subslab radon may be diluted by the positive room pressurization induced flow or that there is a hot spot somewhere that we have not located.

Figure 5 shows the pressures measured through a hole drilled through the slab in room H0228A in HVAC zone B. Again we see good HVAC pressurization during the day (0.01 to 0.01 "wc) and nighttime pressure around zero, with the exception of a half hour negative period (about -0.006 "wc) just before the HVAC system comes on in the morning. Note that several days of data were recorded and each daily pressure cycle is almost identical to the one shown. Table 1 pressure measurements made under the doors in zones B and C show that the only rooms that are significantly negative are the HVAC and electrical rooms. When these rooms were investigated for possible radon sources, drains were found that had large gaps around them leading directly to the subslab. When radon measurements were taken in these drains, levels of about 250 pCi/L were found (Table 2) together with significant air flow into the HVAC rooms. It seems reasonable to believe that the negative pressure in the HVAC rooms pulls in radon during the day and distributes it around zones B and C, and that when the HVAC system goes down at night this radon does not decay enough to show any decrease in levels.

Pressure in the HVAC rooms (relative to the halls) in zones B and C were measured on 9/10 at -0.050 and -0.026 "wc respectively. The significant decrease in zone C negative pressure may be the reason that this zone had lowest radon levels during the 9/10-9/14 electret monitoring. It is assumed that this lower pressure was present during that previous time period. The lower pressure would have reduced the flow of soil gas from the drain hole in the zone C HVAC room. Zone B radon entry may not have changed but there may be some communication between the air in the two zones and the zone B radon reduction may be caused by zone C.

CONCLUSIONS AND RECOMMENDATIONS

Based on the diagnostic measurements, the following conclusions and recommendations were made:

1. The radon levels appear to be generally lower now than they were during the 1989 summer and winter alpha-track measurements. Of course, these radon measurements may not be representative of the longer term, since they only covered one week and we already have seen significant variations that appear to be due to HVAC changes resulting from weather changes. Long term (3 month) winter radon measurements are definitely recommend for confirmation.

2. The building appears to be generally under positive pressure (relative to the subslab) in most rooms while the HVAC system is on. Only a few rooms were found to be significantly negative relative to the hallway and subslab. No continuous pressure measurements were made in HVAC zone C but all other measurements suggest that it is just as positive as zones A and B.

3. At night during HVAC shutdown there appears to be very little negative pressure, but this may change as the weather gets colder and the "stack effect" becomes stronger. In order to investigate this possible effect it would be necessary to do continuous radon and pressure measurements during cold weather. If this stack effect causes significant radon entry during the night, the HVAC system might be turned on earlier in the morning (e.g. 6 am) to flush out the building. Another option is to run the basement air handlers continuously during the night to guarantee a continuous positive pressure over the slab.

3. The negative pressure in the pump room and the HVAC equipment rooms should be eliminated if possible. Since a very wide range of depressurization was measured in these rooms (from 0.8 to 0.008" wc), it is assumed that there is a balancing problem that could be corrected.

4. The radon source in the shop was not found and it might be easier to locate when the HVAC system was shut down. It is difficult to locate it during the day because the positive pressure in the shop appears to suppress the radon entry.

5. The drain openings in the HVAC equipment rooms should be sealed to prevent radon and soil gas entry. Sealing could probably be done with a non-shrink grout or with a pourable

polyurethane caulk. This may be the primary solution to the radon problem in zones B and C, but it cannot be guaranteed because radon tends to build up behind sealing and emerge at other entry points. A combination of reducing depressurization and sealing is likely to be most effective. It is not clear whether the porous block walls in the HVAC rooms are also a source and it may be necessary to seal them too.

6. The standard radon reduction technique of subslab depressurization (SSD) may not be necessary in this building if all rooms can be pressurized, the major soil gas leaks can be closed, and any radon that enters when the HVAC system is shut down can be countered by bringing up the HVAC system early enough to flush it out. The shop area might be treated with SSD if the source is located, and a small exterior exhaust fan could probably be located in the bermed area next to the shop.

DISCLAIMER

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.

Table 1 Radon and Pressure Test Results by Room

Room or zone Tested	Electret 9/6-9/7 (pCi/L)	Electret 9/6-9/10 (pCi/L)	Electret 9/6-9/14 (pcCi/L)	Electret 9/10-9/14 (pCi/L)	Alpha-Trk Summer89 (pCi/L)	Alpha-Trk Winter 89 (pCi/L)	9/10 Door Pressure (" wc)
	Test Type and Date						
HVAC ZONE A							
Shop (Pylon)	3.3	6.0	5.9	6.4	12.8	16.1	-0.007
H0001 pump	3.2	2.6	2.5	2.4		2.8	-0.098
Custodial	1.1	1.5	1.3	1.1			-0.022
H0138 Locksmith	1.7	1.6	1.3	1.0	2.0	4.0	0.002
Elect	0.7	0.5	0.5	0.5			-0.120
Kitchen elevator	0.2	0.2	0.3	0.4			-0.010
Kitchen storage	0.7	0.8	0.8	0.8		2.3	-0.003
Freight elevator	1.2	0.6	0.5	0.4			-0.010
cable chase	0.6	0.5	0.4	0.2			-0.009
H0001 storage	na	1.3	1.3	1.3			0.000
H,168 HVAC							-0.800
H0168 electrical							-0.120
HVAC ZONE B							
H0226 electrical	3.6	3.6	2.7	1.8			-0.008
H0226 HVAC	4.5	3.6	3.3	2.4			-0.050
H0256	na	4.4	3.4	2.6			0.000
H0266 (Pylon)	na	4.1	3.4	2.9	5.0	4.5	0.000
H0244	na	4.2		2.4			0.000
H0229B	n	4.0	2.2	1.5		3.7	0.000
HVAC ZONE C							
H0407 electrical	4.9	4.2	2.5	1.1			-0.005
H0407 HVAC	5.0	4.6	2.7	1.1	3.8		-0.026
H0470	5.4	4.2	2.5	0.9	2.9	6.2	0.000
H0440					3.0		na
H0450	na	4.2	2.2	0.9			0.000
H0495	na	3.9	2.0	0.7			0.000
H0308	na	3.9	2.0	0.8			0.000
H0310					2.9	6.3	na
H0318	na	4.2	2.1	0.8			0.000
H0324	na	4.3	2.7	1.6			0.000

Pylon indicates continuous monitoring available for that room

Negative pressure indicates that pressure across door is ower inside room

Table 2 Subslab Radon Test Results By Room

Room Tested	Test Date	Radon (pCi/L)	HVAC Zone
Shop hole A	9/14	200	A
Shop hole B	9/14	130	A
Shop Hole C	9/14	280	A
H0226 HVAC drain	9/18	240	B
H0407 HVAC drain	9/18	270	C

Grab sample test using Pylon AB-5 with Lucas cell

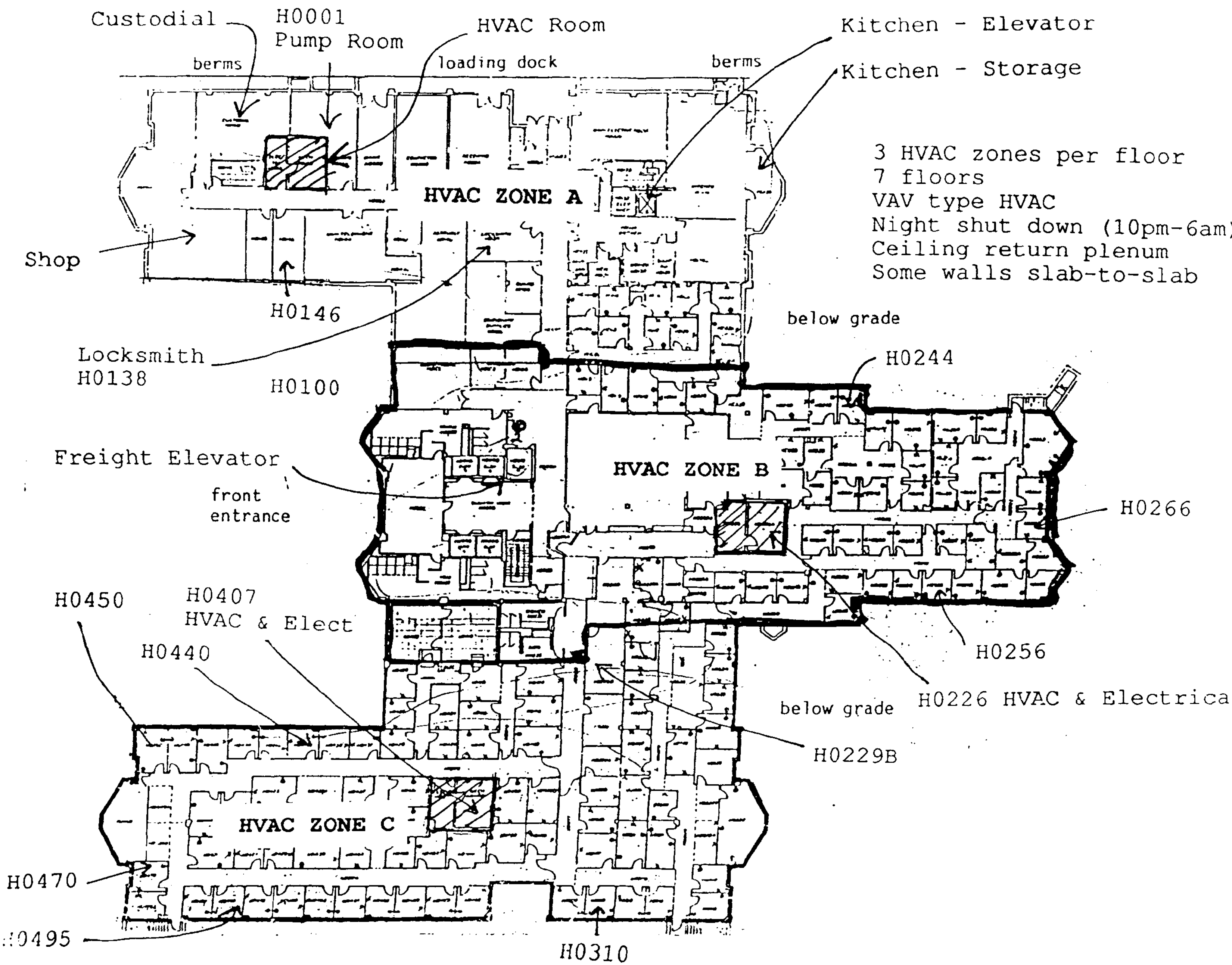

Figure 1 Basement Plan of Building

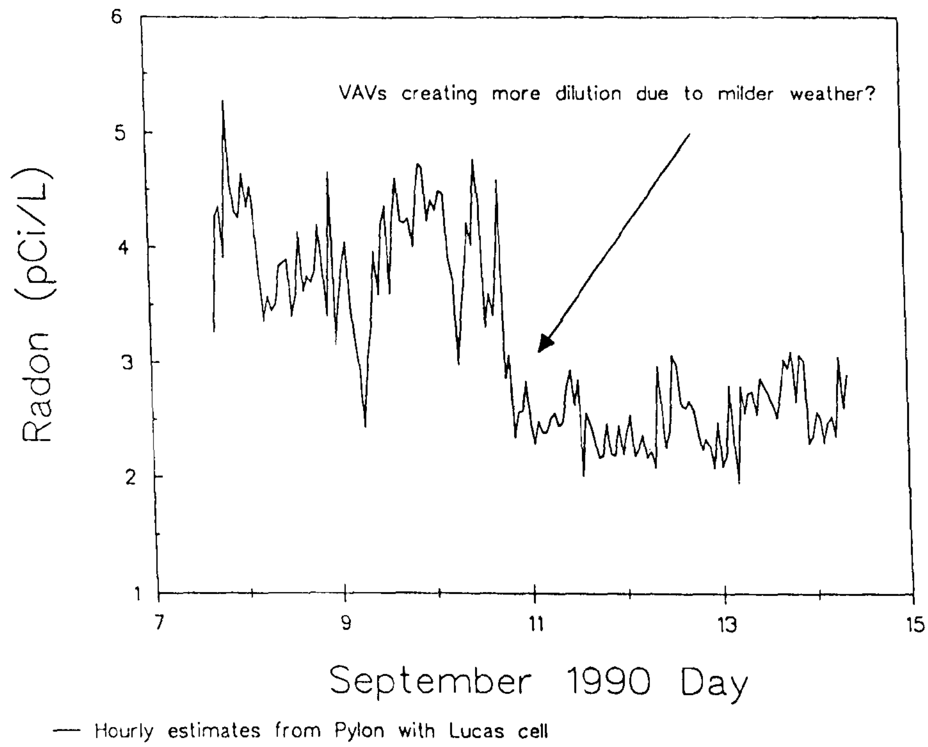

Figure 2 Continuous Radon in Zone B, Room H0226

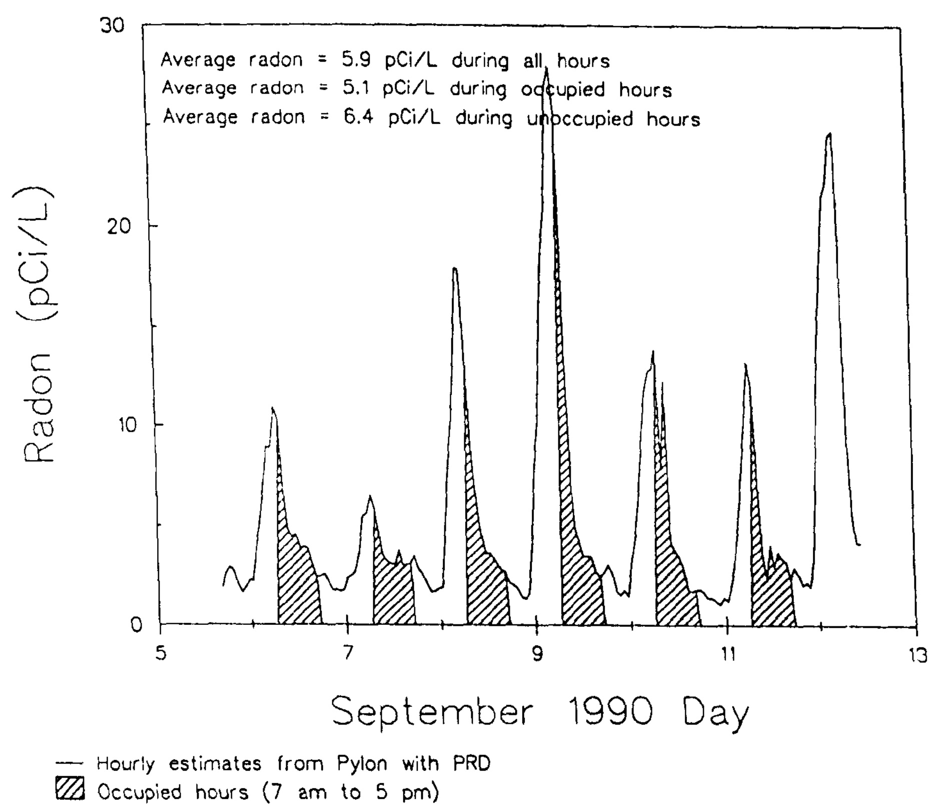

Figure 3 Continuous Radon in Zone A, Shop Room

Pressure Across Slab
(measured through drilled hole)

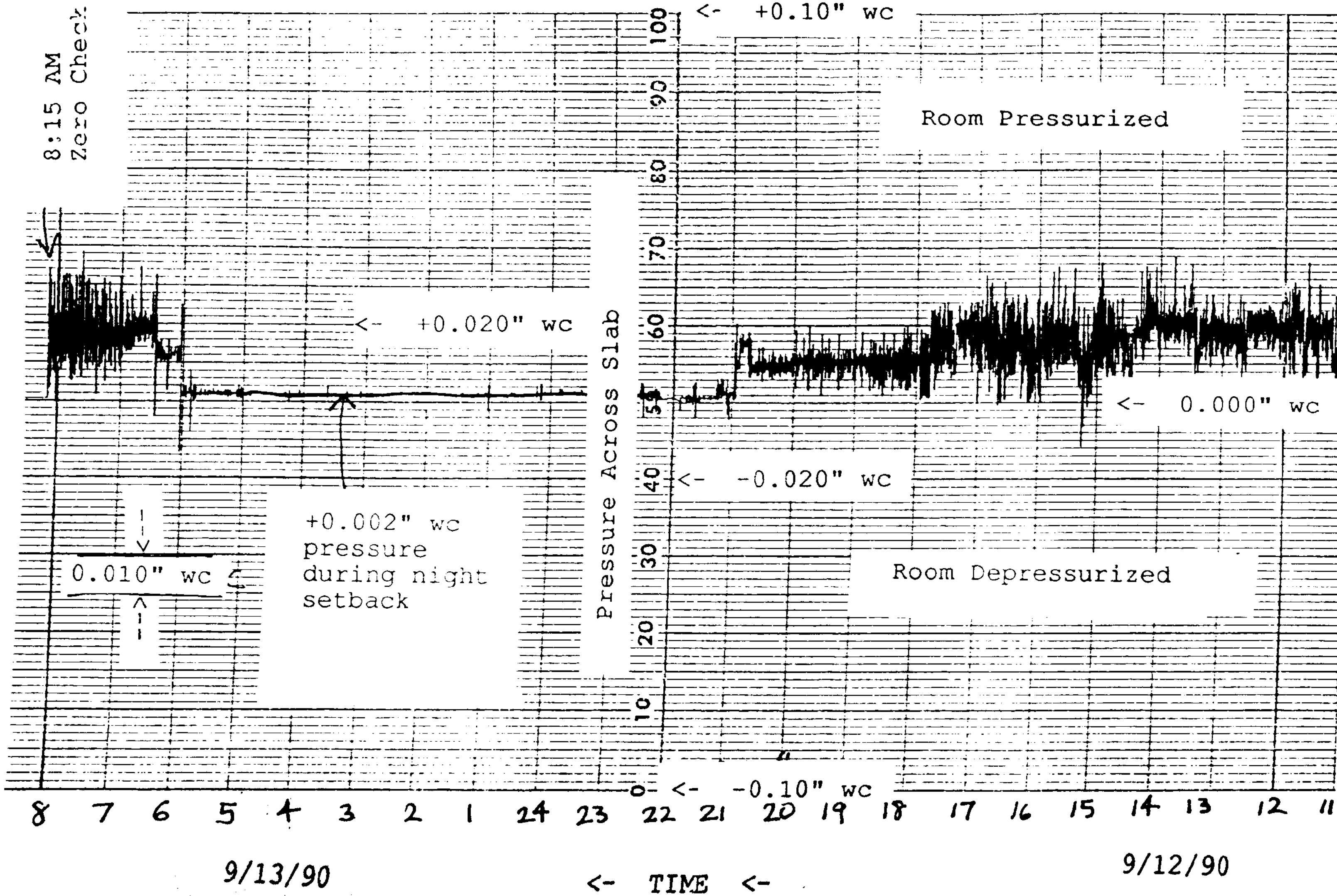

Figure 4 Continuous Pressure in Zone A, Shop Room

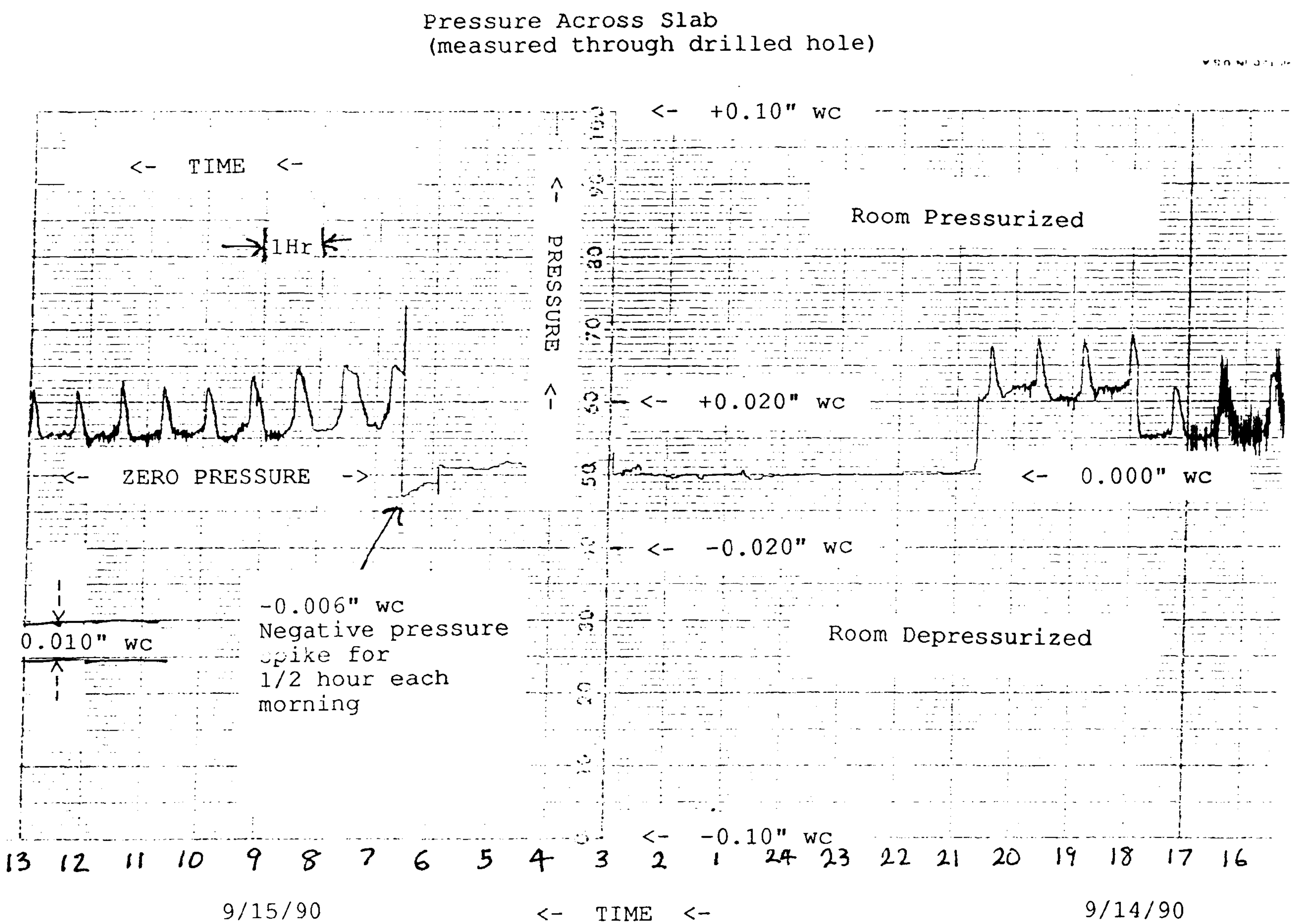

Figure 5 Continuous Pressure in Zone B, Room H0226

TITLE: New School Radon Abatement Systems

AUTHOR: Ronald F. Simon, R.F. Simon Company

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

This paper describes the methods used to develop a state-of-the-art Radon Abatement system: (1) all aspects of design and implementation from proper sizing radon ventilation ductwork (RVD) in relationship to the amount of free air available in sub-slab aggregate, (2) review of electrical systems with their monitoring devices from the very basic to the more sophisticated type of installation, (3) review abatement designs for their durability and application as well as methods and techniques.

Building codes will also be reviewed for commercial construction applications, spot-lighting the usage of specific materials and techniques and their impact on the industry.

DESIGN OF RADON RESISTANT AND EASY-TO-MITIGATE NEW SCHOOL BUILDINGS

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ABSTRACT

The Air and Energy Engineering Research Laboratory's (AEERL) radon mitigation research, development, and demonstration program was expanded in 1988 to include the mitigation of schools. Application of technology developed for house mitigation has been successful in many but not all types of school buildings. School mitigation studies carried out to date in the AEERL program have been reviewed in order to determine those architectural features which affect radon entry and ease of mitigation. This paper details those features having the most effect and recommends the design parameters which should be most cost-effective in controlling radon in new school buildings.

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

The Air and Energy Engineering Research Laboratory (AEERL) of the U.S. Environmental Protection Agency (EPA) has been developing and demonstrating radon mitigation technology in houses, both existing and new, since 1985. In 1988, the program was expanded to include radon mitigation in existing schools. In the intervening 3 years, detailed diagnostic studies have been carried out in about 40 schools in 8 states and mitigation studies in 20 of these schools. Walk-through examinations and reviews of architectural drawings have been conducted in many additional schools.

Over the past year, architectural features of the schools studied have been carefully reviewed in an attempt to identify those features which affect radon entry and ease of mitigation. Results of the studies are currently being used to develop a guide for construction of radon resistant and easy-to-mitigate schools. This new guidance document will be available later this year. The purpose of this paper is to briefly summarize some of the design and construction features which have been identified as important in this study.

Nearly all new schools being built today are slab-on-grade (SOG), and this paper is limited to this architectural substructure. However, what is stated for SOG schools normally applies to schools with basements and is applicable to them. Few, if any, new schools are being built today with crawl spaces, so they are not covered in this paper.

DESIGN FEATURES WHICH AFFECT RADON ENTRY

Two design features are known to affect the rate of radon entry into large buildings--slab cracks and penetrations and pressure differentials resulting from the building shell construction and the design and operation of the heating, ventilating, and air conditioning (HVAC) system.

SLAB CRACKS AND PENETRATIONS

Slab cracks, expansion joints, and penetrations in schools are similar to those in houses as is their control. These can be eliminated by a change of building design, or their effects can be minimized by proper sealing. Great care should be taken in slab design to minimize slab cracking.

Sealing is even more difficult in existing schools than in houses since the cracks are frequently hidden and cannot be readily found. However, this is not true in new school construction where all cracks and openings in the slab are readily accessible at some stage of construction.

Expansion joints are the largest source of cracks in SOG construction. Where codes do not require them, they should be eliminated since, in most cases, they serve no useful purpose. A slab is at its largest size during curing in the first few hours after pouring due to the heat of hydration of the cement. As a result, the only slab which can be larger at a later date (requiring an expansion joint) is one that is poured and cures in extremely cold weather. Allowance for shrinkage, the other function of an expansion joint, is better accomplished using pour joints (without expansion joints) or control saw joints, both of which are much easier to seal than are expansion joints. Where pour joints are used without expansion joints, both slabs should have a tooled edge to make possible a good polyurethane (PU) seal.

Control saw joints, pour joints, and expansion joints, where used, should be carefully sealed with a flowable PU caulk applied according to the manufacturer's specifications. With expansion joints, the top 1/2-in.* should be removed to make space for a good PU seal.

A second source of openings in the slab are utility line penetrations. These can be minimized by running all utility lines, except sanitary sewer, overhead in the area above the drop ceiling, a practice found in some existing schools visited in our mitigation studies. Overhead utility lines are recommended in radon-prone areas in order to minimize slab penetrations by utility lines. Utility penetrations, when present, must be carefully sealed. If any type of wrapping has been put around a utility pipe to protect it from the concrete, it frequently allows soil gas passage. This type of wrap must be designed so as to not allow any soil gas passage or it must be removed after the concrete is set and the resulting space filled with a PU caulking.

In some design situations, utility pipes penetrate the slab in groups to enter pipe chases. In these situations, great care should be taken to design and construct in such a way that no slab openings are left between the pipes.

HEATING, VENTILATING, AND AIR CONDITIONING SYSTEMS

Most schools being built today are air conditioned. This usually results in the use of large HVAC systems supplying many rooms. These large systems are always built with provisions for ventilation by the addition of outdoor air to the air handling system. This results in pressurization of the building as long as the circulating fan of the air handler is in operation and an adequate quantity of outdoor air is being brought into the system continuously. Pressurization by this means will significantly reduce radon-containing soil gas entry as long as the circulating fan is operating and fresh air is being brought in. When the

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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.

circulating fan goes off, as is usually the case during night or weekend temperature setback, radon-containing soil gas can enter the building and in some cases has been found to reach high levels in some classrooms. Once the circulating fan of the HVAC system starts operating continuously in the morning when heating or cooling is called for, soil gas entry is stopped and the radon in the building is diluted over some period of time by the outdoor air being brought in by the HVAC system. If the radon level reached during the night is high, this dilution process can take several hours. Studies underway, some of which are being reported at this meeting, are aimed at determining under what conditions the HVAC system can be depended upon to control radon to a satisfactory level. Viability of HVAC system design and operation as a radon mitigation approach cannot be determined until these studies are completed.

Return air ducts have been found to be an entry route for radon-containing soil gas. These should never be routed below the floor since they are always under negative pressure when the HVAC fan is running. Where the ceiling plenum is used as an unducted return air space, any block walls penetrating the slab and ending in the plenum should be capped with a solid block. Otherwise radon-containing soil gas can reach the plenum through the block wall which is very porous below the slab. Radon levels can also build up in supply ducts under the slab when the circulating fan is off and then be brought into the room when the circulating fan comes back on.

Buildings can also be heated and air conditioned using unit ventilators (UVs) supplied with hot water or steam from a boiler and with chilled water furnished from a central chiller. All UVs are designed for fresh air addition at the unit. Use of pressurization to control radon in this type of system is similar to that of a large central HVAC system.

Exhaust systems for large rooms such as kitchens, lunchrooms, gymnasiums, multipurpose rooms, and shops create special problems since they can create negative pressure and cause radon-containing soil gas to be brought in. This can be eliminated by supplying more conditioned outdoor air than is removed by the exhaust system. Although this may appear to be an expensive solution, it is the only known way to ensure no soil gas entry.

Restrooms also contain exhaust fans which frequently cause elevated radon levels in these rooms. This can be minimized by keeping the exhaust fan as small as code requirements will allow. In addition, since the amount of time per day any person spends in a restroom is presumed small, exposure in this area is relatively small.

Schools without air conditioning are frequently ventilated by the use of exhaust fans usually mounted in the plenum above the hall ceiling. The use of exhaust fans should be minimized in radon-prone areas since this will usually result in a radon problem. Rooms should always be ventilated by bringing in outdoor air rather than by exhausting room air.

DESIGN FEATURES AFFECTING EASE OF MITIGATION WITH ACTIVE SUBSLAB DEPRESSURIZATION (ASD)

The most successful mitigation technique for existing schools has been the use of ASD, the same as in existing houses. This is true as long as the school has aggregate under the slab. Since the presence of aggregate can be required in new school construction (and is, in fact, common practice), then it is logical that, until similar information for other mitigation options becomes available for performance and cost comparison, ASD should be the mitigation system of choice in new schools. Thus the rest of this paper will dwell on factors which affect the ease of application and the effectiveness of ASD in new schools.

In a paper which the authors presented at the last symposium in Atlanta(1), two schools mitigated in Nashville, TN, were compared. One required 16 suction points to mitigate 15 rooms, whereas 15 rooms were mitigated to a lower radon level in the second school with only 1 suction point. This striking difference in ASD effectiveness was the motivation for these authors' beginning to review the factors which affect the ease of mitigation in schools and has led to this paper.

In the authors' experience, pressure field extension (PFE), is the most valuable diagnostic tool in determining the ease of application of active subslab depressurization (ASD) to mitigation of houses, schools, and large buildings. PFE measurements are even more important in large buildings than in houses since much larger subslab areas are involved and subslab barriers frequently exist that are not normally found in houses. For example, PFE measurements led to the prediction of the difference in ease of application of ASD to the two previously discussed Nashville schools which was then confirmed by the results obtained. Thus PFE is used as a surrogate for ease of mitigation in the subsequent discussion in this paper.

A review of the PFE measurements that have been made on all of the schools in EPA's program, examination of their architectural drawings, and many discussions of the factors affecting flow of gases through aggregate beds with fellow scientists working on radon have led to the identification of the following factors which affect PFE:

- Aggregate
  - Bulk density (or void volume)
  - Particle size (both average size and particle size distribution)
  - Type (naturally occurring stone from moraine deposits or crushed bed rock)

Layer thickness and uniformity of thickness
- Subslab barriers
- Subslab suction pit size
- Amount of suction applied
- Size and location of openings in slabs (both planned and unplanned)

These factors are discussed in the following sections.

AGGREGATE

The four properties of aggregate listed above are known to affect the flow of a gas through stone beds. Bulk density is actually controlled by particle size distribution and type of stone (naturally occurring moraine gravel, which is rounded, packs more efficiently than crushed bedrock with its greater variation in shape).

The following tentative conclusions are postulated on the effect of aggregate properties on PFE:

1. PFE is proportional to average particle size--the smaller the particle size, the less the PFE assuming the same particle size distribution.

2. The narrower the particle size distribution range the greater the void volume and hence the greater the PFE.

3. The smoother the shape of the stone, the lower the void volume; hence moraine stone (with its rounded corners) will give lower PFE for the same average particle size and particle size distribution than crushed aggregate.

AEERL is sponsoring work at Princeton University to verify and quantify these effects. The first report of this work is being made by Kenneth Gadsby in a poster paper given at this symposium(2).

SUBSLAB BARRIERS

One of the greatest differences between mitigation of houses and schools is the presence of subslab barriers which are commonplace in schools and other large buildings and are rarely found in houses. PFE measurements made in schools have shown a very strong correlation with the presence or absence of these barriers. Their presence is determined by a review of the foundation plan in the structural drawings. Based on school plans reviewed to date, foundation designs can be divided into the four types shown schematically in Figures 1,3,5,and 6. These types determine the ease of mitigation and the number of suction points necessary assuming other factors are the same. They are presented in the order of difficulty to mitigate by ASD starting with the most difficult.

The type shown in Figure 1 (schematic) is the most common and unfortunately the most difficult to mitigate. In this type, all walls around each room extend below the slab to footings in undisturbed soil resulting in the same number of compartments under the slab as number of classrooms above the slab. A section of this type of wall is shown in Figure 2. PFE measurements made in Nashville showed that some PFE could be achieved through one subslab wall but not two. Unfortunately, installation of a suction point in every other room was not sufficient to mitigate the intervening rooms, and it is now believed that a suction point will normally be necessary in every room in this type of school. Obviously, this is not a recommended footing configuration for new schools built in radon-prone areas.

In the plan shown in Figure 3, the hall walls extend through the slab to footings, but the walls between rooms are set on the slab. The slab under these walls are normally thickened slab footings as shown in Figure 4. Aggregate continues under these thickened sections; consequently, they do not adversely affect PFE. One suction point on each side of the hall will mitigate a number of rooms in this configuration, the number depending on other variables which affect PFE (such as type of aggregate). A third suction point might be needed in the hall but it is unlikely if the rooms on each side of the hall are adequately mitigated. In this type of structure, the bar joists for the roof are placed perpendicular to the hall and rest on the hall walls. The walls between the rooms do not carry any roof load and consequently can rest satisfactorily on thickened slab footings.

Figure 5 shows a footing configuration found in three schools mitigated by EPA. In this configuration, the walls between the rooms go through the slab to footings but the hall walls set on thickened slab footings. In this case, the roof bar joists are placed parallel to the hall and rest on the walls between the rooms. The aggregate continues under the hall for the full length of the building; consequently, PFE can be achieved down the hall and into the individual rooms. With this configuration, the suction point is best put in the hall, and the number of rooms that can be mitigated will depend on other variables (such as type of aggregate).

The final configuration found to date, shown in Figure 6, was used in the Two Rivers Middle School in Nashville. In this configuration, no walls go through to footings: all sit on thickened slab footings. This is referred to architecturally as post and beam construction and is commonly used in buildings which are very wide and very long, such as supermarkets. Posts on both sides of the hall at Two Rivers go through to footings and are tied together with overhead beams which in turn carry the roof bar joists. The posts and beams can be either reinforced concrete as in Two Rivers, or more commonly steel as in supermarkets. In this configuration, the aggregate is continuous under the entire building and, consequently, PFE can reach long distances if other conditions are proper. At Two Rivers, PFE easily extended 130 ft, and one suction point mitigated 15,000 ft^2 to less than 1 picocurie per liter (pCi/L). EPA recently arranged to have a hospital building under construction install a suction point in the center of a 200 by 250 ft slab (50,000 ft^2) underlaid with carefully placed coarse crushed aggregate (ASTM #5 stone). Some time this spring, PFE of this slab will be measured, and EPA will have a better feel for just how much PFE can be achieved under a very large slab with optimum aggregate and a large suction pit.

SUBSLAB SUCTION PIT SIZE

The importance of the size and geometry of the suction system under the slab has been the subject of considerable debate and disagreement over the past 3 years. However, it has been the authors' experience that, everything else being the same, the larger the suction pit, the greater the PFE. Although this is not too important in houses, it becomes much more important in large slabs such as schools.

In an existing school, the size that can readily be dug through a hole in the slab is about 40 in. in diameter. However, in new construction, there is essentially no limit to the size of the pit which can be installed. It is believed that the controlling factor in increasing effectiveness is the size of interface between the hole and the surrounding aggregate. With this in mind, one of the authors (Craig) designed the suction pit shown in Figure 7. The pit is constructed by digging out an area of about 6 ft square where the suction pit is desired. Four concrete blocks, 8x8x8 in. in size, are placed in a square 4 ft on a side and covered with a 4x4 ft piece of 3/4-in. treated plywood. The depth of the hole is such that the top of the plywood is even with the bottom of the slab to be poured. The aggregate is filled level with the plywood, allowing it to slope into the hole. The angle of repose of the stone will be about 30° leaving most of the hole open. The 6 in. suction pipe is installed under the plywood as shown in Figure 7 and run to a convenient place for the riser. This arrangement makes it possible to separate the location of the suction pit from that of the riser.

The plywood serves only as a form for the slab over the hole. The strength of the concrete after setting is more than sufficient to span a 4 ft hole unless the slab has unusually high loading. In that case, the slab will need reinforcing.

Perforated pipe can also be used in lieu of the suction pit described above. However, calculations show that the suction pit has an air to aggregate interface equivalent to about 200 ft of perforated pipe with 10 holes of 3/4-in. diameter per lineal foot. As a result, it is believed that the PFE from either system will be about the same. Tests are planned to compare these two techniques in new construction. It is believed that the suction pit is significantly cheaper to install than the perforated pipe.

AMOUNT OF SUCTION APPLIED

The amount of PFE also depends on the level of suction applied to the suction pit. The amount of vacuum which can be applied depends on fan size and the air leakage rate from all sources into the subslab area. Theoretically, if the subslab aggregate envelope is completely airtight, very little air will need to be moved to get very large PFE. The top and sides of the envelope can be well sealed, resulting in only a small amount of air leakage. However, the bottom of the envelope, the compacted soil under the aggregate, has variable permeability depending on composition and compaction. Consequently, the air infiltration into the envelope from this source is variable. Given a choice of subaggregate conditions, the underlayment should be made as impermeable as reasonably possible. For a given subaggregate, the more the soil is compacted, the less the resultant permeability. In areas where the subaggregate fill is highly permeable, such as with sand in Florida or with near-surface moraine in many areas, it may be necessary to overlay the permeable material with a compacted layer of impermeable clay.

The size of the suction fan needed can best be determined experimentally. Table 1 lists the performance characteristics of various sizes of one commercial exhaust fan (Kanalflakt). Note that the larger fans can achieve a higher negative pressure than the smaller ones. One wing of the Two Rivers Middle School (15,000 ft^2) was mitigated by a T3B fan which had a flow of 150 cfm at 1.97 in. WC when installed in this system. In choosing a fan size, it is better to err on the high side rather than the low side.

SIZE AND LOCATION OF OPENINGS IN SLABS

Expansion joints, pour joints, control saw cracks, and pipe penetrations are discussed in an earlier section. Several other types of slab penetrations can also affect radon entry. One such source is an open sump connected to perforated pipe installed under the slab for groundwater protection. All sumps must be sealed in order to keep out soil gas which may contain radon. One good solution for this is the use of a sewage ejector pit as a sump pit since they always have vaportight lids.

Floor drains can also be a source of radon entry if connected to a septic system (which is rare in the case of schools but they do exist). In this case, care should be taken in the design to make sure that the floor drain is trapped and will always be full of water. Lines of conventional sewer systems have not been found to contain radon since they are tightly sealed.

If electrical conduit is routed under the slab, care must be taken to make sure that any conduit connections under the slab are vaporproof. The same is true for any other subslab conduit.

CONCLUSIONS

Study of the architectural features, diagnostic studies, and mitigation results for the existing schools that have been mitigated as part of the AEERL school mitigation program has resulted in identifying many factors which affect radon entry and ease of mitigation. Results of these studies have led to tentative conclusions on how to design new schools which are radon resistant and easy to mitigate. Many of these findings can be considered as sufficiently sound that they can be recommended for incorporation in new school buildings. Others need field verification in schools either currently under construction or in the design phase. Work is underway to accomplish this in the next 2 to 3 years.

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CONVERSION FACTORS

Readers more familiar with the metric system may use the following factors to convert to that system.

Nonmetric	Multiplied by	Yields Metric
cfm	0.00047	m^3s
ft	0.30	m
ft^2	0.093	m^2
HP	7.46	W
in.	0.025	m
in. WC	249	Pa

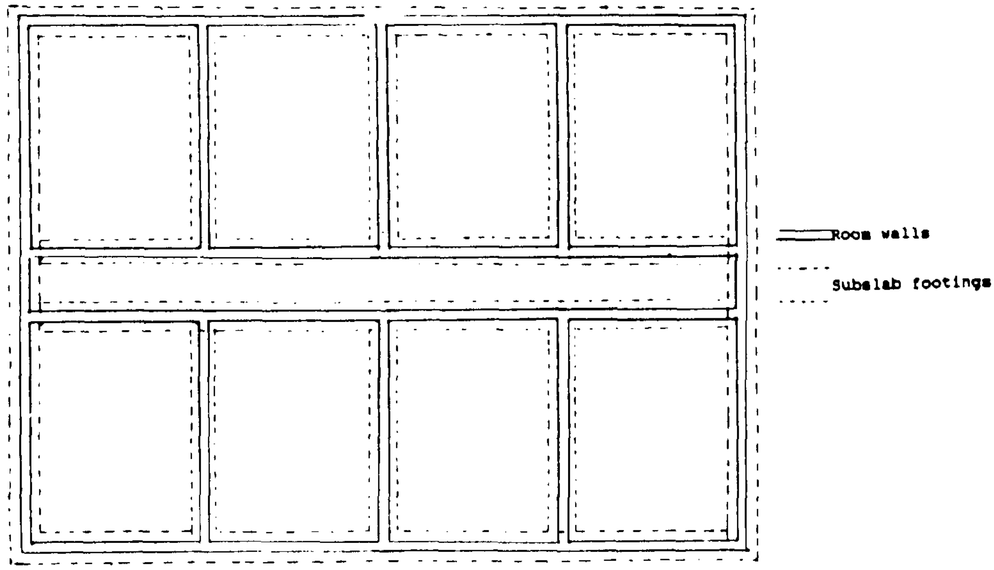

Figure 1. All walls are load-bearing.

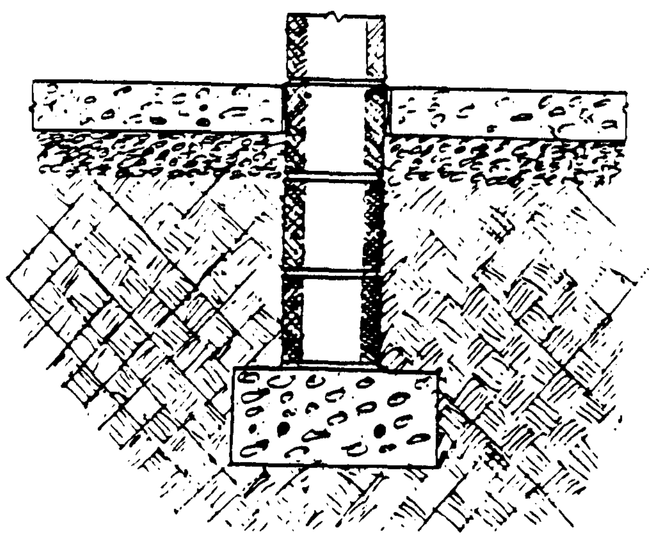

Figure 2. Section of load-bearing wall.

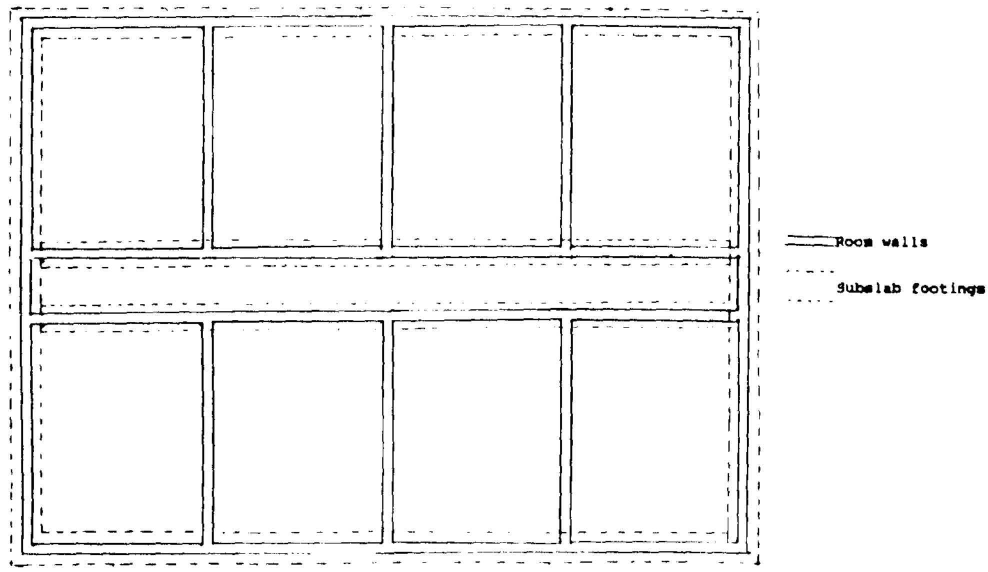

Figure 3. Hall and outside walls are load-bearing.

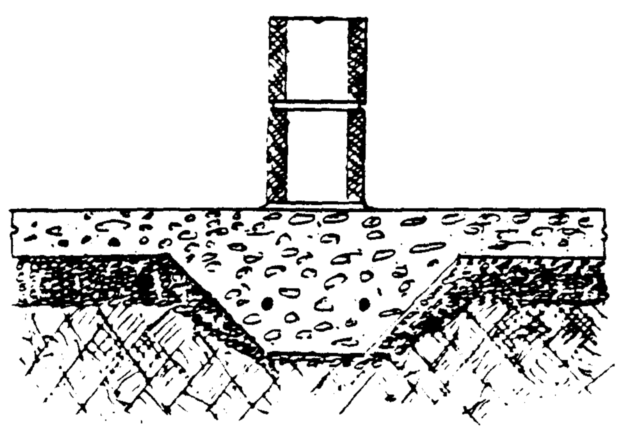

Figure 4. Section of wall resting on thickened slab footing.

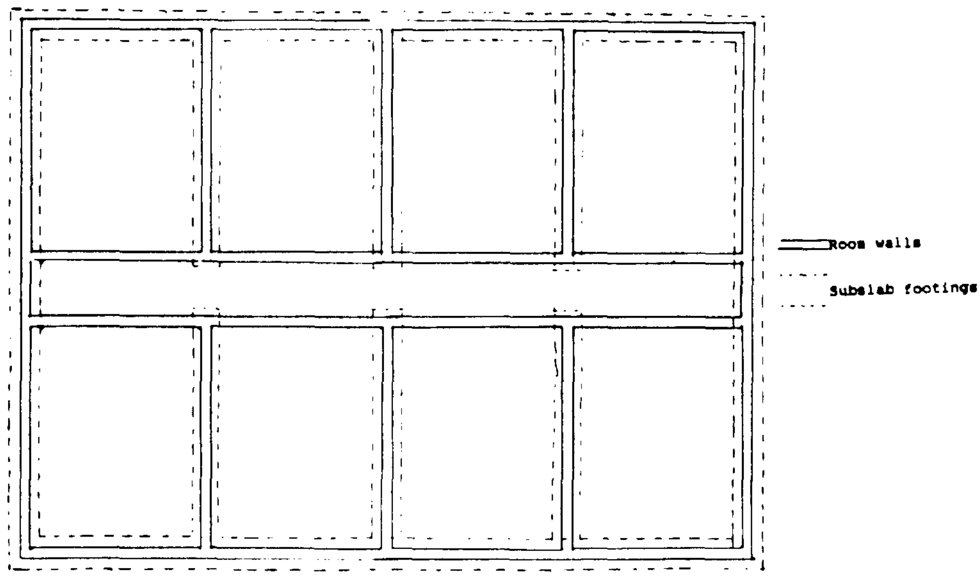

Figure 5. Walls between rooms and outside walls are load-bearing.

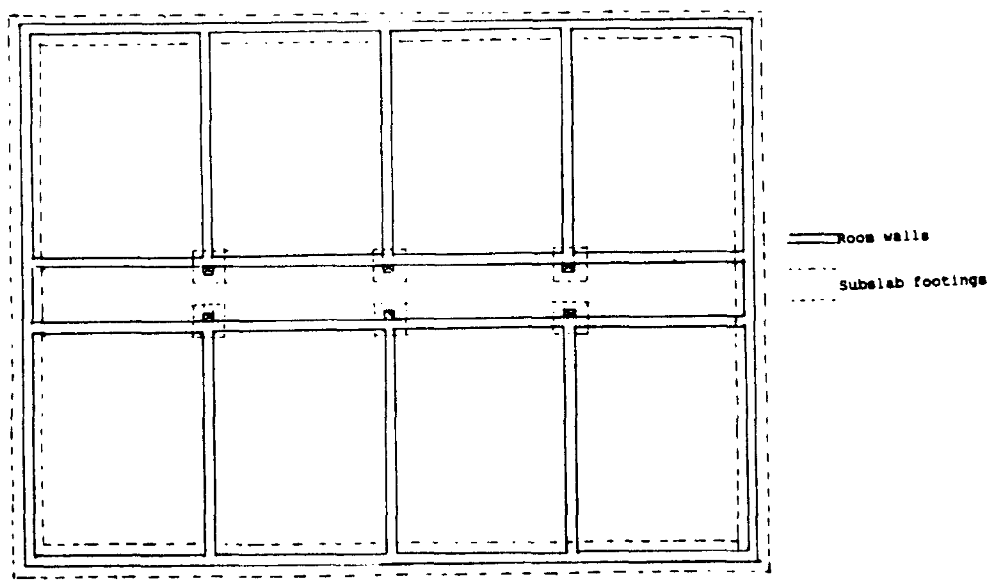

Figure 6. Outside walls and posts are load-bearing.

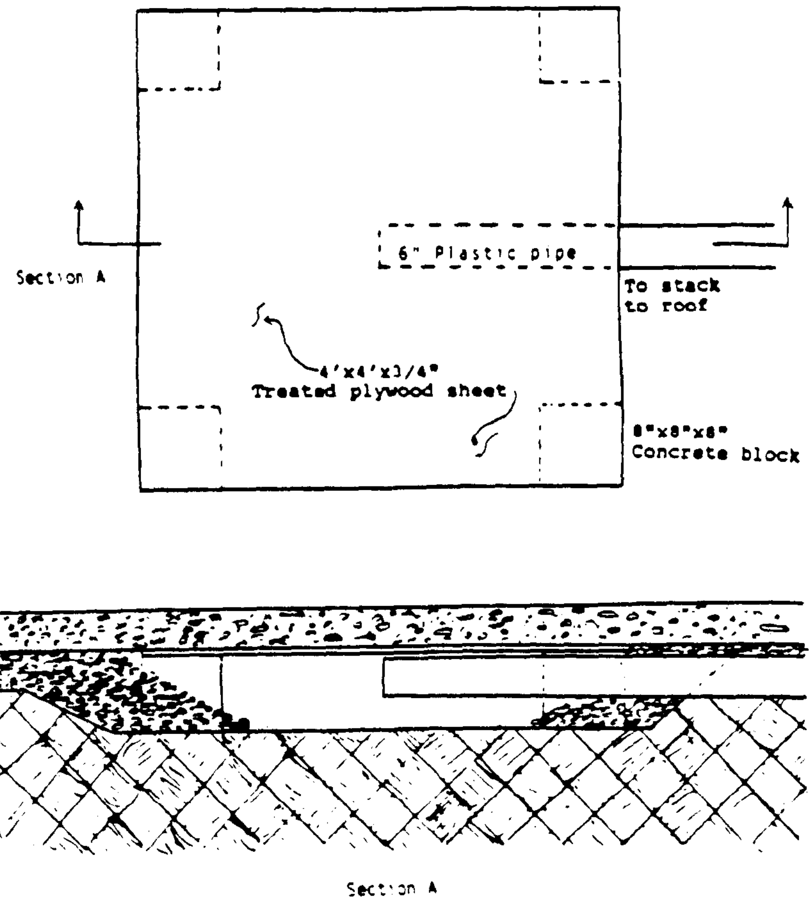

Figure 7. Design for large suction pit.

TABLE 1. KANALFLAKT FAN PERFORMANCE

MODEL	HP	FAN RPM	AIR FLOW (cfm) VS STATIC PRESSURE (in. WC) 0	1/8	1/4	3/8	1/2	3/4	1	1-1/2	2	PIPE DIA.
T1 Turbo 5	1/40	2800	158	143	125	114	90	45				5"
T2 Turbo 6	1/20	2150	270	255	235	200	180	140	110			6"
T3A Turbo 8	1/15	2150	410	375	340	285	225	180	135			8"
T3B Turbo 8	1/10	2300	520	500	470	445	415	310	230	200		8"
T4 Turbo 10	1/6	2400	700	670	640	612	582	470	410	250	115	10"
T5 Turbo 12	1/8	1250	900	801	718	624	557	456	359	254		12"

Session X:

Radon in Schools and Large Buildings -- POSTERS

DESIGN AND APPLICATION OF ACTIVE SOIL DEPRESSURIZATION (ASD) SYSTEMS IN SCHOOL BUILDINGS

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ABSTRACT

During 1990, building investigations and subslab pressure field extension (PFE) measurements were made by the U.S. Environmental Protection Agency's (EPA) Air and Energy Engineering Research Laboratory (AEERL) in several school buildings located in Colorado, Kentucky, Maine, and Washington. The recommended ASD system design for each school was based on the construction characteristics of each building including: subslab material and fan selection, subslab barriers (i.e., footings), utility tunnels, active vs. passive soil depressurization, and interior vs. exterior suction points.

These school research projects, together with previous mitigation research by the authors in nearly 40 schools over the past few years, are discussed in terms of the influences that various building construction features have on the design of the ASD system. Specific examples and data for recent or on-going research projects in Kentucky and Maine are presented.

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

INTRODUCTION

School characteristics that influence radon entry and subsequent mitigation have been discussed in previous papers on radon diagnostics and mitigation in schools (1,2,3,4,5). The purpose of this paper is to detail the effects of some of the more significant school construction characteristics and how these characteristics can influence designs of ASD systems. The ASD systems designs should be applicable for other schools with similar characteristics.

The school building construction characteristics discussed in this paper include: subslab materials and fan selection, subslab barriers (i.e., footings), utility tunnels, active vs. passive subslab depressurization systems, and interior vs. exterior suction points. Following a general discussion of how each building characteristic can affect ASD system design, specific examples and data from recent or on-going research in Kentucky and Maine schools are presented. Conversion factors are displayed in Table 1.

This paper focuses on radon mitigation with ASD systems rather than radon reduction through heating, ventilating, and air conditioning (HVAC) system pressurization and/or dilution. The authors recognize that for acceptable indoor air quality a minimum of 15 cfm of outdoor per person should be delivered to occupied classrooms according to ASHRAE guidelines (6); however, many schools are not designed and/or operated to provide adequate conditioned outdoor air for pressurization or ventilation and, as a result, reduction of radon levels using an HVAC system is not a current option without an extensive (and expensive) retrofit. Although it is strongly recommended that such schools take the necessary steps to meet minimum ASHRAE indoor air quality guidelines as soon as possible, installation of a properly designed and operated ASD system will reduce radon levels in many schools at a relatively low cost (5).

SUBSLAB MATERIAL AND FAN SELECTION

Initial experience with radon mitigation in schools has indicated that in schools with at least 4 in. of clean, coarse subslab aggregate (at least 0.75 in. in diameter with few fines) the ASD system normally requires larger fans and pipe sizes than typical ASD systems in houses because of the greater air flow through the aggregate (2). However, many schools do not have subslab aggregate and the slab may be poured over a tightly packed material such as sand or clay.

Example - Maine School

In one school currently being researched by the EPA in Maine, a multi-point ASD system was installed with both a conventional radon mitigation fan and a high vacuum fan to make direct performance evaluations between the two fans. This 1968 addition to the existing school is slab-on-grade construction with radiators for heating and an exhaust fan for ventilation. No conditioned outdoor air is provided to any classroom in this wing.

The wing being researched has seven classrooms, a library, and a multi-purpose room with a storage area. Suction points were installed in four of the seven classrooms, and two points were installed in the library. (The multi-purpose room has a separate ASD system.) All six suction points and overhead piping for the classroom and library ASD system are 4 in. diameter PVC piping and are manifolded overhead in the dropped ceiling. A suction pit (approximately 1 ft deep and 2 to 3 ft in width) was excavated at each point. The two fans were installed near an outside door. One fan is a standard radon mitigation fan (0 in. WC at 520 cfm and 1 in. WC at 230 cfm) and the other fan is a high pressure, low flow fan (30 in. WC at 0 cfm and approximately 5 in. WC at 30 cfm) being evaluated for its applicability in low permeability soils.

Data were collected from late November 1990 through mid-January 1991 while the high suction fan was in operation. The suction pressure of the fan was varied to determine the effect on radon levels. Continuous radon levels were measured in each of the seven classrooms by State of Maine Indoor Air Program employees using Honeywell Model A9000A monitors. Figure 1 displays the results of the average radon levels in each classroom under the following conditions: 1) ASD fan off, 2) fan at 1 in. WC, 3) fan at 2 in. WC, and 4) fan at 4.5 to 5 in. WC. The results show that fan suction pressures of 1 and 2 in. WC are not sufficient to reduce radon levels in these rooms. In fact, in some of the classrooms levels are slightly higher with the fan operating at 1 or 2 in. WC than with the fan off. These increases in radon levels are likely attributed to typical variations in radon rather than any detrimental effects caused by operating the fan at low suction pressures.

The data for all seven classrooms in the wing are averaged in Figure 2 for each of the four fan suctions. Radon levels averaged approximately 7 pCi/L with the ASD fan off and with the fan at 1 and 2 in. WC. indicating little, if any, change in the three conditions. Adjusting the fan to increase suction to 4.5 to 5 in. WC decreased average radon levels in the seven classrooms to below 3 pCi/L.

A datalogger was installed in this school in January 1991 to collect continuous radon, differential pressure, and temperature data for each of the fans. These data will be part of a long-term research project that will compare different mitigation techniques in all three wings of this school.

SUBSLAB BARRIERS

Subslab barriers, such as below grade footings, can increase the cost and complexity of ASD systems. PFE measurements in schools have indicated that in many instances one suction point will be required for each area surrounded by below-grade subslab footings. If the school has relatively permeable subslab material, it may be possible to reach across one subslab barrier. The PFE will need to be determined on a case by case basis for each school (or school design if more than one school is constructed from a set of plans). The different types of subslab barriers and their effects on subslab PFE are discussed thoroughly in Craig's paper to be presented at this Symposium (7).

UTILITY TUNNELS

In many slab-on-grade schools, utility lines are located below the slab in utility tunnels that typically run parallel to the corridor either down the center of the corridor or along the perimeter wall of the classrooms. These tunnels vary in size from about 1 ft wide and 0.5 ft deep to 5 ft wide and 5 ft deep (to allow entry by maintenance workers). These tunnels may or may not have poured concrete floors, and even tunnels with concrete floors typically have many openings to the soil. In many classrooms with unit ventilators or fan coil units, the piping from the utility tunnel penetrates the slab under the unit creating a radon entry route around each penetration. Limited studies have looked at utility tunnel depressurization for reducing radon levels in the classrooms above (8). Since utility tunnels are very common in slab-on-grade schools, depressurization of the tunnels could present a relatively easy and inexpensive mitigation technique if no friable asbestos is present in the tunnel (because of increased air movement), the tunnel contributes to elevated radon levels in the room, and the tunnel is not too leaky.

Example - Kentucky School

This Kentucky school is slab-on-grade construction with the utility lines in the wing under study located in a relatively small tunnel that runs along the perimeter wall on each side of the corridor. Pipes from the tunnel connect to the wall-mounted unit ventilators in each classroom. PFE across the corridor is poor since below grade footings are present along the corridor under each of the interior walls. The soil under the slab is a reddish brown clay with some rock fragments. Subslab sniffs with a Pylon AB-5 monitor showed a wide range of levels from below 1000 to over 9000 pCi/L. The subslab radon levels in the four rooms of interest averaged about 4000 pCi/L. A radon sniff measurement in one of the tunnels was about 1000 pCi/L.

During the building investigation it was noted that there was an access to the utility tunnel outdoors on one side of the corridor. It was determined that, if depressurization of this tunnel from the outdoors could reach into the four classrooms serviced by the utility lines on this side of the corridor, this would be a relatively easy and inexpensive radon mitigation technique. (No asbestos was present in tunnel.) School maintenance personnel covered the tunnel access with a sheet of plywood and attached a mitigation fan to depressurize the tunnel.

The results of the subslab to classroom pressure differentials are presented in Table 2. As seen by the negative pressures measured in the middle of three of the four rooms, this tunnel depressurization system was a very simple and effective means of creating a negative pressure under the slab.

Pre-mitigation radon levels in the four classrooms affected by the tunnel depressurization averaged 5.3 pCi/L in June 1990, and with the tunnel depressurization fan operating, levels in August 1990 averaged 1.8 pCi/L. Since data from school personnel indicate that this school tends to have higher radon levels in winter than summer, these measurements were repeated in January and February of 1991.

This school is an example of how a very simple and inexpensive approach can sometimes be effective in reducing radon levels depending on building design. The material costs for this system were approximately $300 and approximately 10 labor hours were required. A standard one-point ASD system installed in another wing of the school covered three classrooms and cost $500 in materials and required about 30 labor hours, not including diagnostics.

ACTIVE VS. PASSIVE SOIL DEPRESSURIZATION SYSTEMS

Research of passive soil depressurization (PSD) in schools is limited. Since there can be significant negative pressures to overcome from building exhausts and the stack effect, experience suggests that active systems are preferred to passive systems in existing schools.

Example - Maine School

An ASD system was installed in the basement of a three-story wing of a Maine school. Each floor of this wing is about 3000 sq ft in area, and the basement is about 4 ft below grade. No building design drawings were available to provide information on subslab fill or footings although excavation of the suction pits indicated that the material under the slab is mostly fine-grained sand. The basement contains occupied classrooms, and in the 1000 sq ft area affected by the ASD system, HVAC is provided by ceiling mounted unit ventilators. Inspection of the unit ventilators indicated that they were not operated to bring in outdoor air. A vertical ventilation shaft runs from the basement to the roof and is a likely contributor to the stack effect in this three-story building. It was thought that this building might present a good opportunity to compare PSD and ASD because of the building height.

Subslab PFE measurements made in the basement with the ASD fan on and off. Subslab pressures were measured at the 2 suction points, and at 11 test holes distributed throughout an area of about 1000 sq ft. As seen in Figure 3 and Table 3, although negative subslab pressures can be achieved at the suction points with PSD, this negative pressure does not extend to any of the test holes within the 1000 sq ft area. When the fan is activated (to pressures of about -2.5 in. WC at the suction points) the negative pressure field extends throughout the area to points that were positive with PSD.

PSD needs merit further study in new schools where it is known that the slab is underlain with a layer of clean, coarse aggregate; however, these results, together with previous experience in house mitigation, indicate that its applicably will be very limited in existing schools. Because of the reliability and effectiveness of ASD in consistently reducing elevated radon levels (even when negative pressures in the building are caused by building exhausts and the stack effect) it is recommended over PSD in existing schools.

INTERIOR VS. EXTERIOR SUCTION POINTS

Radon mitigation research in slab-on-grade houses in Ohio has shown generally comparable results for ASD points placed inside the house and exterior to the house; however, it was found that interior points were preferable in the larger houses (9). Evaluation and comparison of PFE results in schools with both interior and exterior ASD points is limited. In schools where accessibility to the classroom interior is limited (e.g., due to chalkboards), placement of exterior ASD points needs to be investigated for effectiveness.

Example - Kentucky School

In another wing of the Kentucky school discussed above (in Utility Tunnels section) suction was applied in a teachers' lounge that was located between two classrooms (Nos. 2 and 3). The results of PFE measurements in classrooms 2 and 3 are shown in Table 4. Results indicated that PFE was relatively good. To compare these PFE results with suction applied from the exterior, a hole was drilled from the exterior of Room 3 to the subslab area. With suction applied at this exterior point, no effect was apparent at the test hole located in Room 3, compared to a pressure of -0.016 in. WC when suction was applied to the interior point. As a result, school officials chose to install an interior ASD point in the teachers' lounge to mitigate Rooms 2 and 3 and the teachers' lounge.

Pre-mitigation radon levels in Rooms 2 and 3 and the teachers' lounge averaged 8.2 pCi/L in June 1990. With the ASD system operating, levels in August 1990 averaged 1.3 pCi/L in Rooms 2 and 3. (No data are available for the teachers' lounge.) These measurements were repeated in January and February 1991.

The comparison of PFE for interior and exterior suction points in this school indicates that interior suction produces a much more effective pressure field under the slab. The area of the three rooms is approximately 2100 sq ft (the size of a large house) so these results are somewhat consistent with previous house data (9).

Future research should repeat these measurements in additional school buildings, particularly in those with clean, coarse aggregate under the slab.

CONCLUSIONS

1. In the Maine school with low permeability material (sand) under the slab, a higher suction fan was required in order to adequately depressurize the subslab area and reduce radon levels.

2. Results from the Kentucky school show that utility tunnel depressurization may be an effective and relatively inexpensive technique for reducing elevated radon levels if the tunnel does not contain asbestos, is a contributor to elevated indoor radon levels, and is not too leaky.

3. Since there can be significant negative pressures to overcome from building exhausts and the stack effect, previous experience and the measurements in the Maine school suggest that active subslab depressurization systems are typically preferred to passive systems in existing schools.

4. In the Kentucky School studied, PFE was greater when suction was applied to an interior point rather than from the building exterior. Interior vs. exterior PFE should be researched in additional schools, especially those with clean, coarse subslab aggregate.

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ACKNOWLEDGMENTS

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TABLE 1. METRIC CONVERSION FACTORS

Non-Metric	Times	Yields Metric
cubic foot per minute (cfm)	0.47	liter per second (L/s)
foot (ft)	0.305	meter (m)
inch (in.)	2.54	centimeters (cm)
inch of water column (in. WC)	248	pascals (Pa)
picocurie per liter (pCi/L)	37	becquerels per cubic meter (Bq/m^3)
square foot (sq ft)	0.093	square meter (m^2)

TABLE 2. SUBSLAB PRESSURES WITH TUNNEL FAN OFF AND ON

Location,date	Distance (ft)	Fan Off (in. WC)	Fan On (in. WC)
Pit at Fan Base,6/90	0	-0.007	-0.750
Center Room 19,6/90	15	-0.001	-0.045
Center Room 17,6/90	45	0.000	-0.028
Center Room 19,7/90	15	-0.001	-0.030
Center Room 14,7/90	105	0.000	-0.003

Subslab pressures were not measured in Room 15 (located between Rooms 14 and 17).

TABLE 3. SUBSLAB PRESSURES WITH ASD FAN OFF AND ON

Location	Fan Off (in. WC)	Fan On (in. WC)
Suction Point 1	-0.010	-2.53
Suction Point 2	-0.012	-2.52
Test Point Fb	0.012	-0.010
Test Point Fc	0.009	-0.038
Test Point Fd	0.003	-0.019
Test Point Fe	0.005	-0.015
Test Point Ff	0.001	-0.005
Test Point Fg	0.002	-0.005
Test Point Fh	0.006	-0.017
Test Point Fi	0.002	-0.339
Test Point Fj	0.005	-0.016
Test Point Fk	0.003	-0.024
Test Point Fm	0.000	-0.156

TABLE 4. PFE MEASUREMENTS FROM SCHOOL INTERIOR

Location	Suction Off (in. WC)	Suction On (in. WC)*
Room 2	-0.002	-0.010
Room 3	-0.000	-0.016

* Suction applied in teachers' lounge located between Rooms 2 and 3.

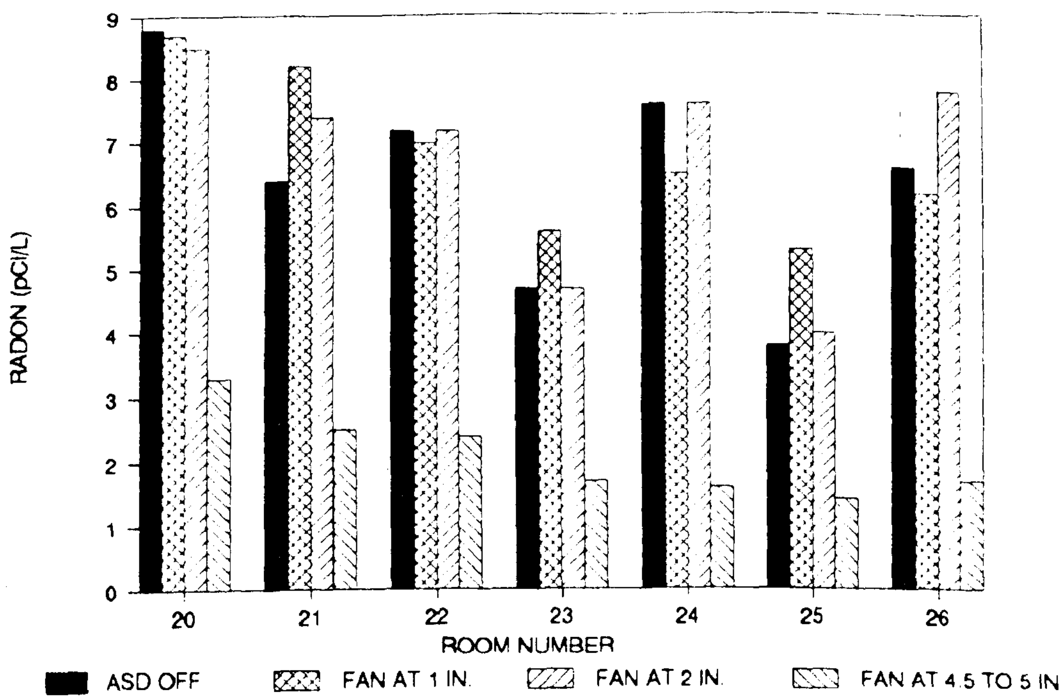

FIGURE 1. Comparison of radon levels at various fan pressures.

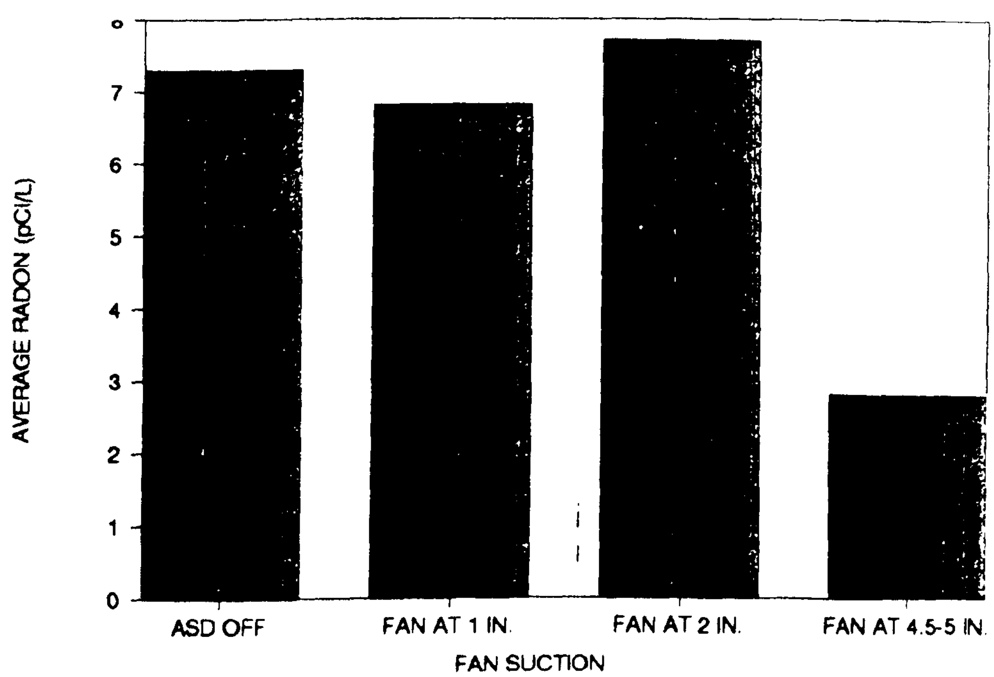

FIGURE 2. Comparison of average radon levels at various fan pressures.

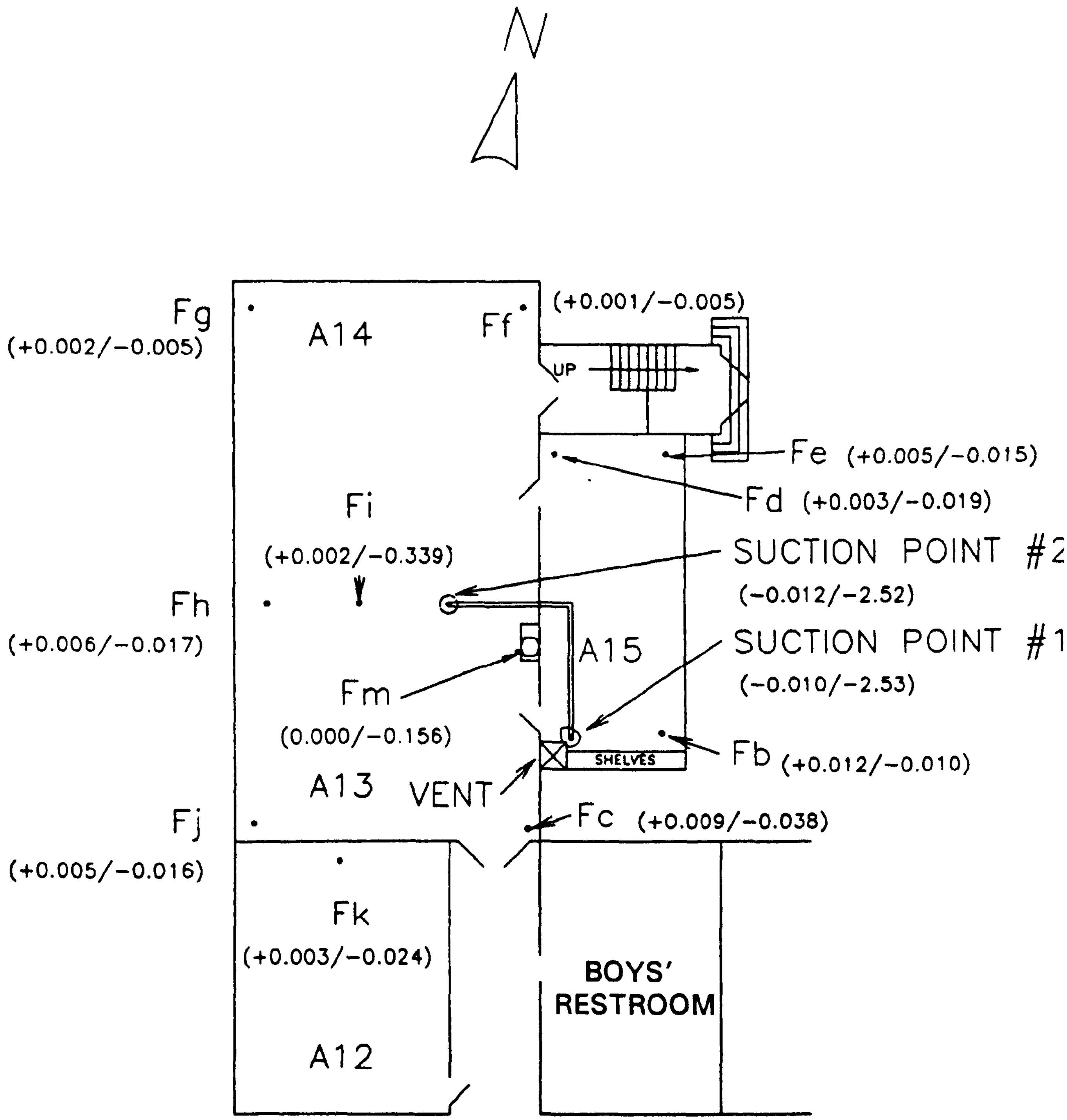

Figure 3. Results of PFE measurements in Maine school (in. WC fan off/in. WC fan on).

RADON IN LARGE BUILDINGS: PRE-CONSTRUCTION SOIL RADON SURVEYS

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ABSTRACT

Attempts to correlate individual soil radon and/or radium concentrations with the subsequent concentrations of radon measured in structures constructed on the sites of the tests have had only occasional, or perhaps even coincidental success. High concentrations in the soil may or may not result in elevated levels in buildings, and vice versa. Over the past two years the UCF Radon Project has been conducting an intensive radon screening of all buildings (>40) on the campus, a relatively compact concentration occupying about 300 acres of a 1200 acre site. Analysis of these data suggest that perhaps the earlier difficulties in obtaining correlations between soil radon/radium measurements and radon concentrations in structures has been simply a failure to measure at a sufficient number of locations for a long enough duration. A contour 'map' of average radon concentrations in the campus buildings was used as a guide for measuring soil radon for periods of several months in the areas where the construction of three large new buildings was planned. The results were used to predict the levels that to be expected an completion and to suggest appropriate radon-resistant construction measures. Two of the structures incorporating such suggestions are now under construction.

INTRODUCTION

UCF RADON PROJECT

In mid-1989 the environmental physics group at the University of Central Florida initiated a research program with objectives that included learning more about the distribution of radon concentrations in large buildings and discovering reliable methods for predicting the potential for radon diffusion into large buildings that might be constructed on particular sites. (1) The results of work directed to the first of these objectives, presented at the 1990 International Symposium on Radon and Radon Reduction Technology, revealed that radon concentrations often do not decrease nearly as rapidly as would be expected from standard diffusion theory as one moves upward in large structures, suggesting that protocols for guiding radon measurements in large buildings should call for similar sampling rates, at least through the first 5 or 6 floors.

Work on the second of these objectives was conducted throughout 1990 using the construction sites of three major buildings on the University's main campus as "laboratories". The concentration of radon in the soil gases at measured over a period of several months at several locations on each site and soil samples were collected for radium assay. All three buildings, an 87,000 ft^2 fieldhouse, a 60,000 ft^2 art complex, and a 90,000 ft^2 student center, are now under construction. In each case the final design and/or construction techniques used incorporated features and methods intended to respond to the degree of potential radon hazard at the site.

SOIL GAS RADON STUDY

SAMPLING PROCEDURES

Radon

Radon gas in the soil was collected at each measurement location using standard EPA-type charcoal canisters (F&J Specialty Products, Inc. model RA40V). At each location a sampling station was installed to hold the canisters in clean, reproducible positions. A typical installed sampling station is shown in cross-section in the Appendix.

Each canister was exposed for approximately 72 hours. Preparation and subsequent measurement of the canisters conformed to protocols established by the U. S. Environmental Protection Agency in "EERF standard operating procedures for Rn-222 measurement using charcoal canisters" (520/5-87-005). Analysis of the radon concentration of each canister was performed in the UCF Department of Physics using a research quality nuclear radiation analysis system. The system was regularly calibrated with a standard radon source whose activity is traceable to a National Institute of Standards and Technology primary standard.

Radium

Four soil samples were taken at the site of each sampling station, one each at the surface and at one foot depth intervals, as the holes for installing the stations were dug. The purpose was to analyze the soil for ^{226}Ra, the parent radioisotope of ^{222}Rn, in order to obtain information regarding the possible origin of any radon gas that might subsequently be detected at the site. Analysis of the radium in the soil samples is based on measuring the equilibrium activity of radon. The same calibrated nuclear radiation counting system is used as is employed for the analysis of the charcoal canisters. Preparation and analysis of the soil samples involves, among other things, a 20-day holding period for the sealed sample holder in order to allow time for the establishment of equilibrium between ^{226}Ra and ^{222}Rn. For that reason and because the available time on the nuclear radiation measuring system was fully taken by soil gas radon measurements, most of the soil samples have yet to be analyzed for ^{226}Ra. The long half-life of that isotope ensures that the analyses, when performed, will not be adversely affected by the several months of soil sample storage time. The very high radon concentrations measured on the east half of Pegasus Circle make radium concentration measurements of soil samples from that area very important. Radium concentrations in the soil will be the subject of a separate report.

SITES

Pegasus Circle

Six sampling stations were established and operated within Pegasus Circle, the planned location of the new student center facility. These sites are shown on the diagram below and detailed in Table 1.

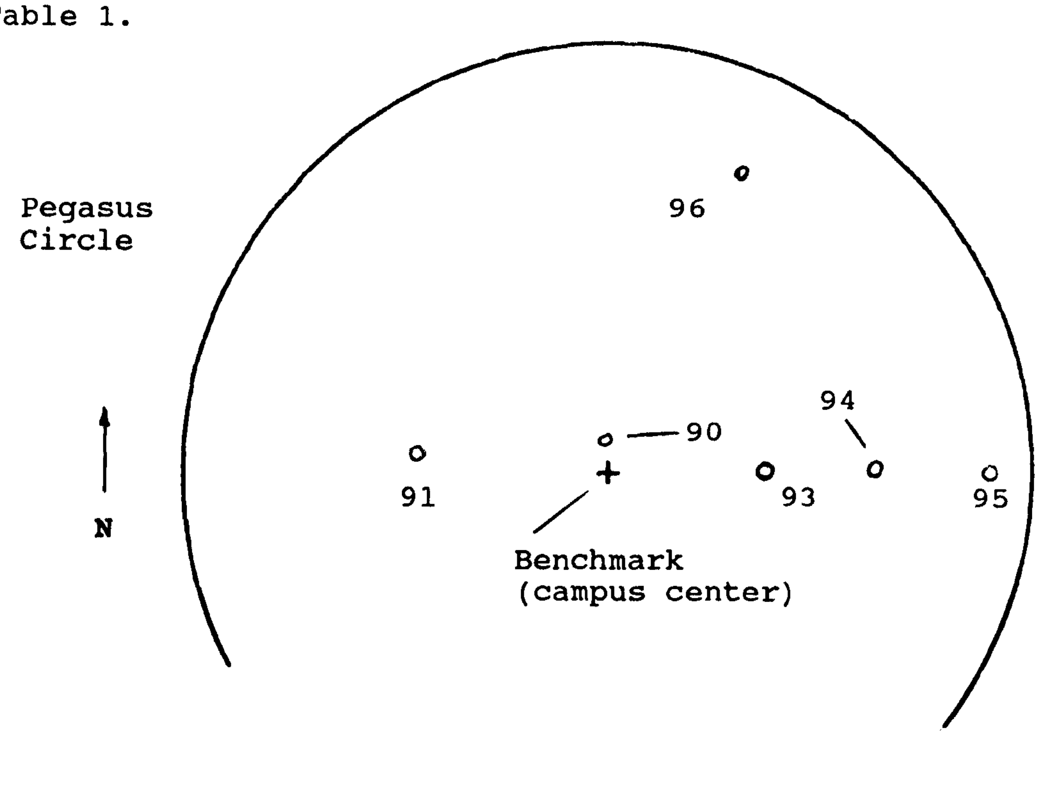

Table 1. Pegasus Circle Site

Sampling Station	Location
90	10 m north (0°) of campus center benchmark
91	30 m west (270°) of campus center benchmark
93	30 m east (90°) of campus center benchmark
94	60 m east (90°) of campus center benchmark
95	90 m east (90°) of campus center benchmark
96	92 m northeast (45°) of campus center benchmark

Fieldhouse

Three sampling stations were operated at locations adjacent to the construction pad for the fieldhouse. They are shown on the diagram below and detailed in Table 2.

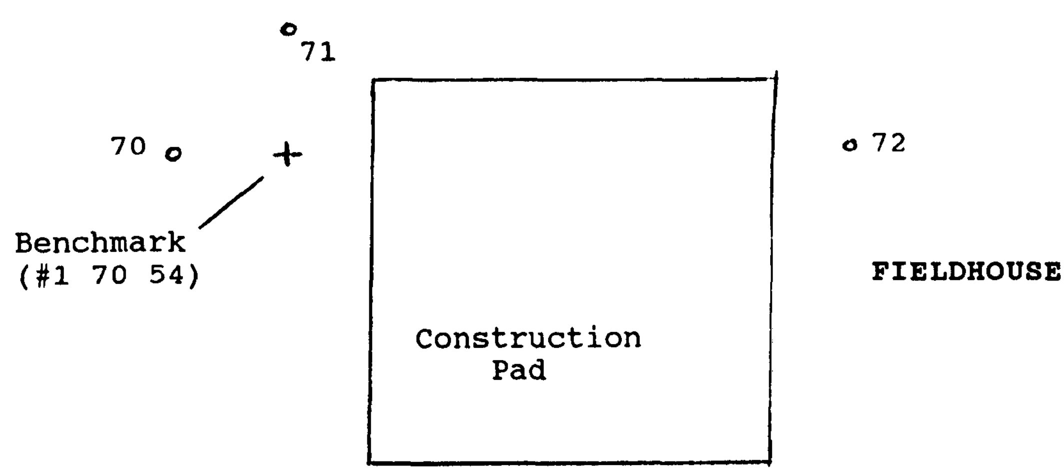

Table 2. Fieldhouse Site

Sampling Station	Location
70	6.2 m west (270°) of benchmark #1 (70 54)
71	48 m from benchmark #1 at 49.6° E of N
72	126 m from benchmark #1 at 9° S of E (99°)

Art Complex

Four sampling stations were established and operated around the construction site of the art complex. Their locations are shown in the diagram and detailed in Table 3.

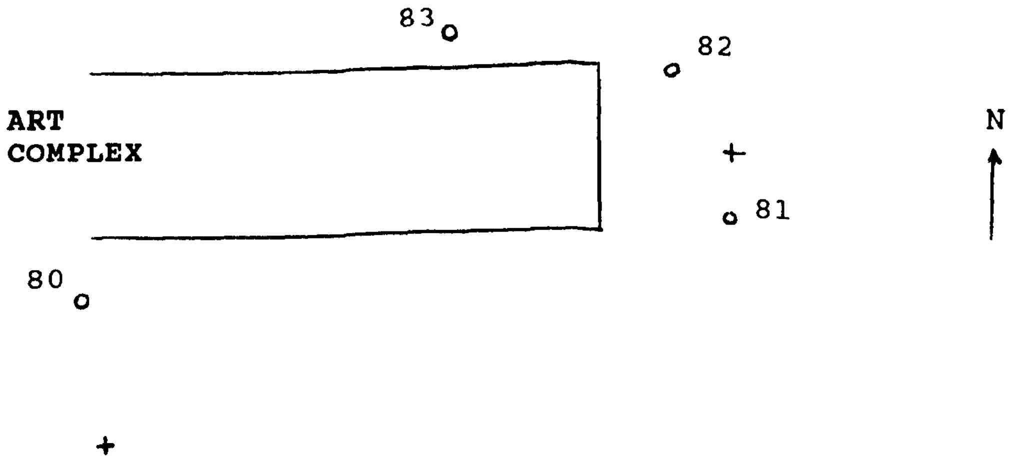

Table 3. Art Complex

Sampling Station	Location
80	125 m @ 11° W of N from benchmark (N101200,E6800)
81	120 m @ 69° E of N from site 80
82	55 m @ 48° W of N from benchmark (N101850,E7000
83	60 m @ 63° W of N from site 82

NOTE: The sampling station numbers in the diagrams and in Tables 1, 2, and 3 are identifiers used by the database UCF RADONBASE.

RESULTS

The graphs that follow record the radon concentrations measured in the soil gas since the commencement of the study until its conclusion at each of the sampling stations associated with the three construction sites identified above. (5)In reviewing the graphs, note that the EPA maximum concentration for buildings is 4 pCi/ℓ. The graphs for each construction site are grouped together in the order (1) Pegasus Circle, (2) Fieldhouse, and (3) Art Complex. Preceding the graphical radon concentration displays for each sampling station at the fieldhouse and art complex there is a composite graph of the data from all associated sampling stations that enables comparisons of the radon levels at that location. The results from the Pegasus Circle sampling stations are presented in two composite displays, one showing the data from the three stations where the higher concentrations of radon were measured and a second containing data from the stations that had the lower concentrations.

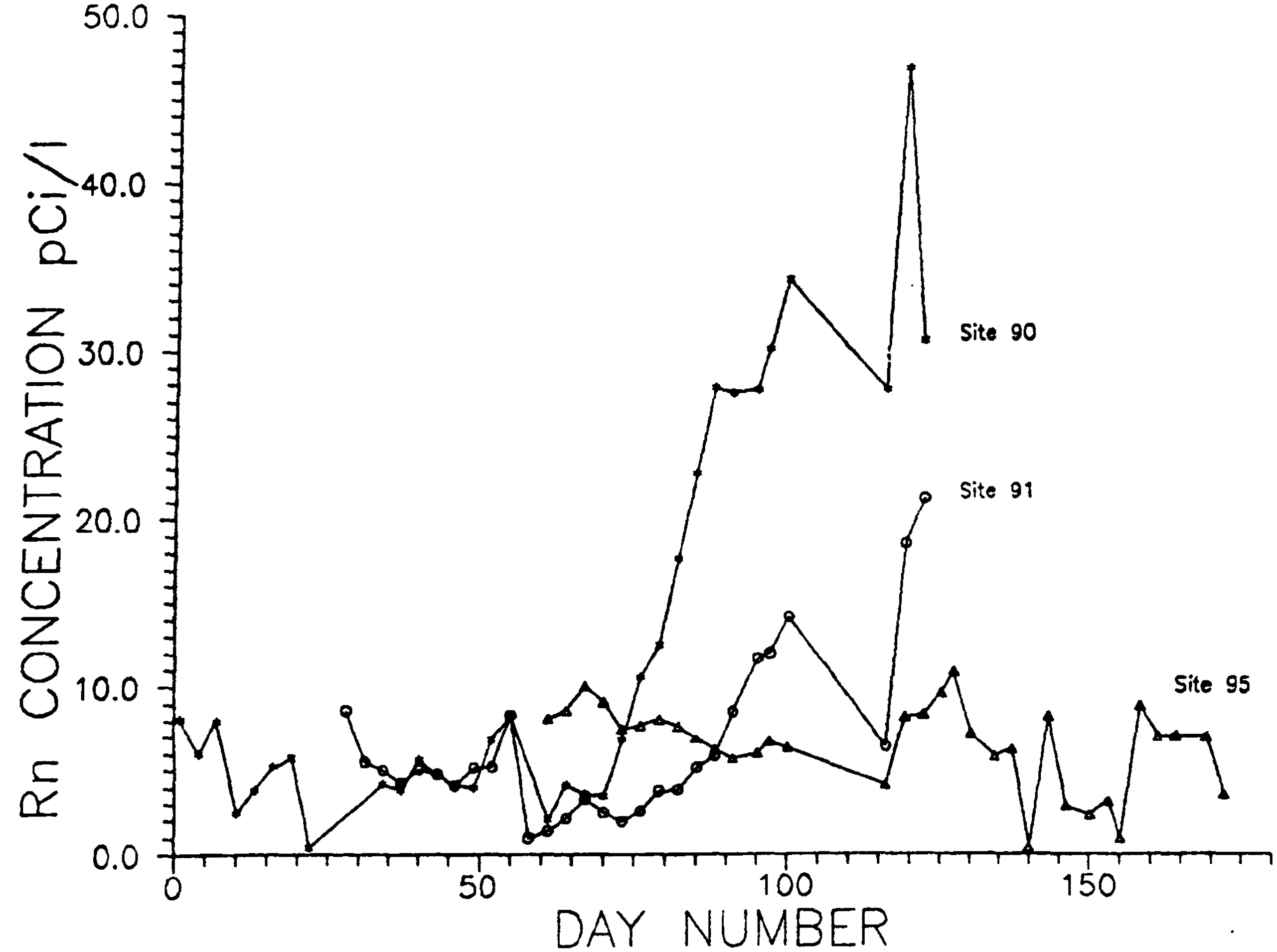

Figure 1 SOIL RADON CONCENTRATION Pegasus Circle Low Concentration Sites February 1 - July 31, 1990

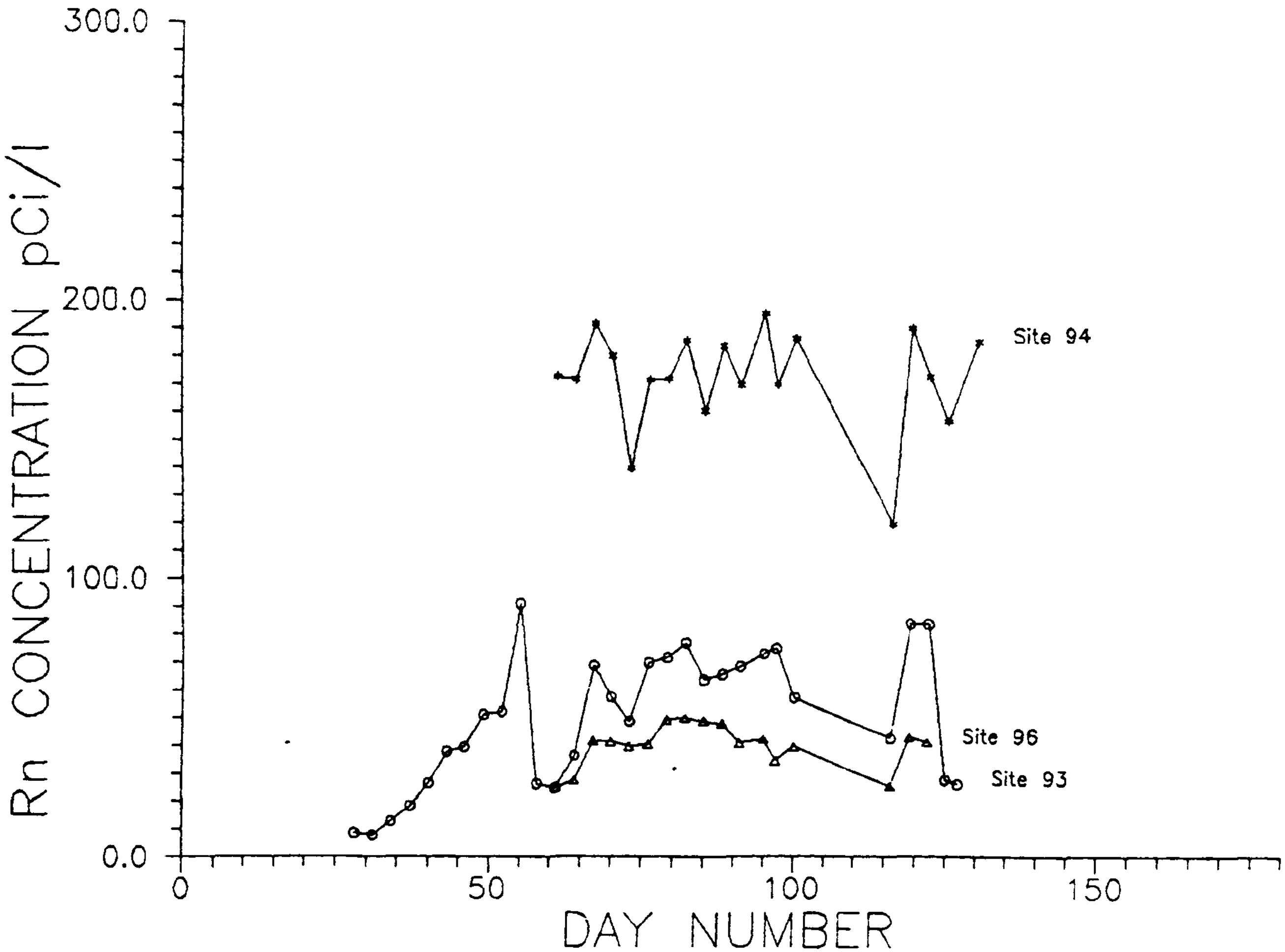

Figure 2 SOIL RADON CONCENTRATION Pegasus Circle High Concentration Sites February 1 - July 31 1990

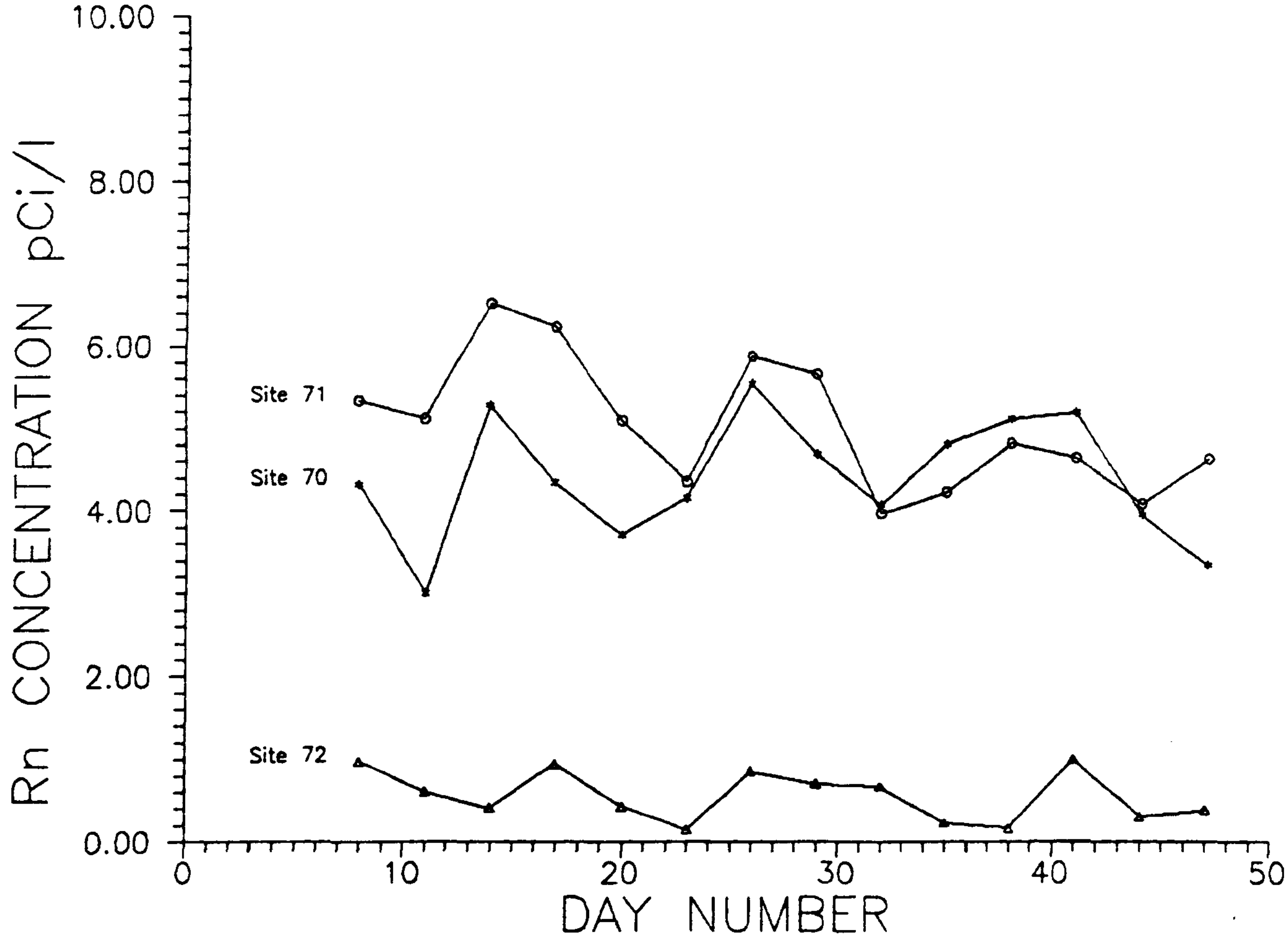

Figure 3 SOIL RADON CONCENTRATION Field House March 15 - April 30 1990

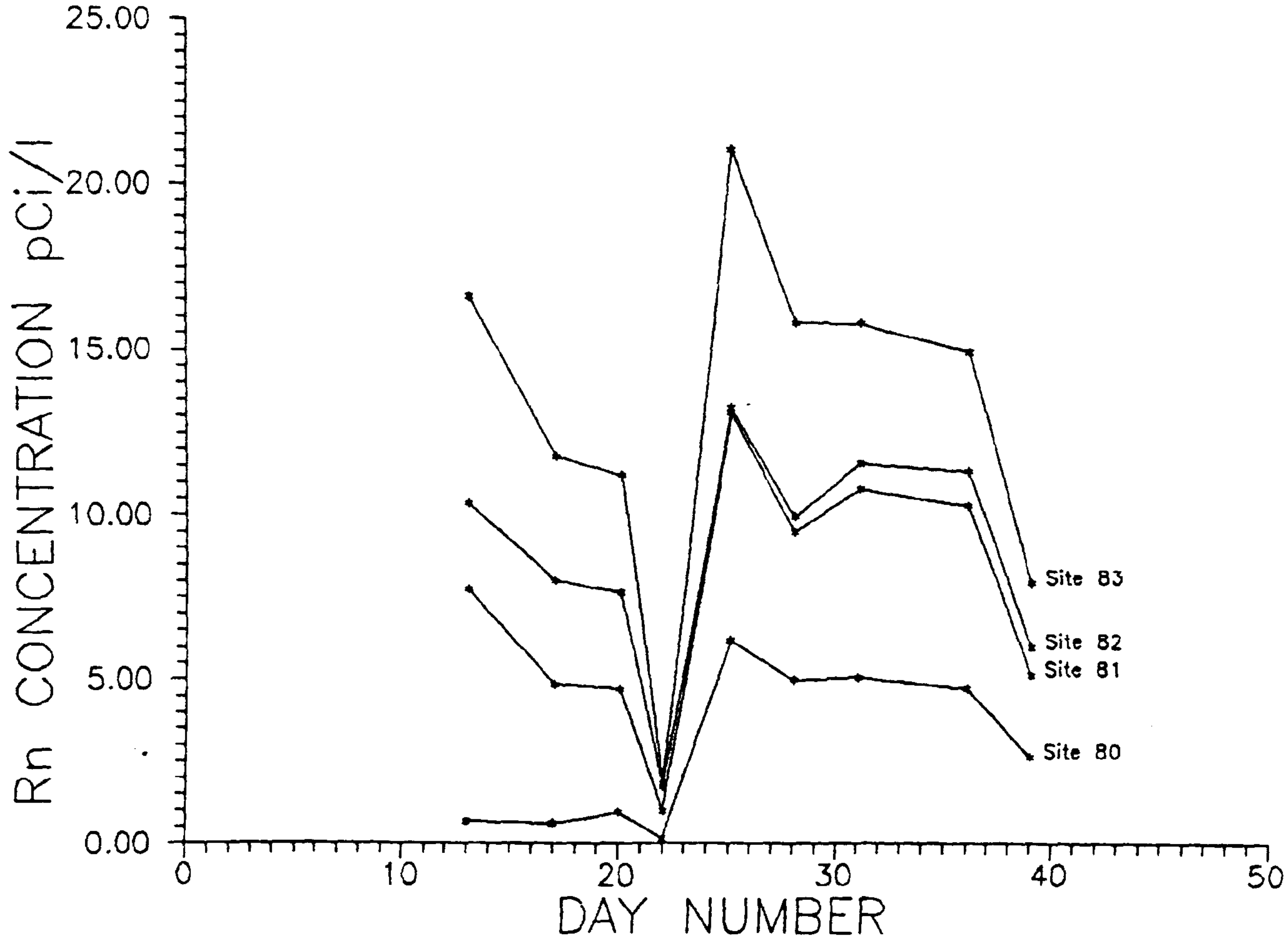

Figure 4 SOIL RADON CONCENTRATION ART COMPLEX June 15 - July 31, 1990

The radon concentration measurements at each site show both the short term effects of rainfall and the longer term effects of soil moisture. Heavy rain appears to quickly "wash" radon out of the soil, probably owing to the solubility of the gas in water and the rise of the water table following rainfall, which may partially block migration of the gas in the soil. The concentration soon returns to or even above pre-rainfall levels, however, and does so more quickly than could be accounted for by the re-establishment of secular equilibrium with radium in the soil. This effect can be seen very clearly in the composite graph of radon concentrations at the art complex site. Note, in particular, the period around Day 22.

The slow downward trend of the radon concentration at some stations may be associated with a gradual average decline in soil moisture over the 1990 spring and summer. This suggestion is based only on field observations, however, and is not the result of soil moisture measurements.

While not a part of this particular project, the Pegasus Circle area would provide an excellent region for conducting research on the transport of radon in the soil and the effects of rainfall, soil moisture, wind speed and direction, and atmospheric pressure on it. The establishment of a set of sampling stations associated with an automated weather station in Pegasus Circle for long-term study of this interaction is a goal of the UCF Radon Project.

WORK IN PROGRESS

Based on what appears to be effects on soil radon concentration arising from rainfall, changes in soil moisture, atmospheric pressure fluctuations, and surface wind speed an direction, the next phase of the project will involve searches for correlations between those parameters and radon concentration in the soil gas. The results of this work will be presented at future meetings.

CONCLUSION

The results presented above suggest that earlier difficulties in obtaining correlations between soil radon/radium measurements and radon concentrations in structures subsequently built on the sites tested may in part be due simply to a failure to measure at a sufficient number of locations for a long enough period of time. Better data should more informed radon-protection strategies in the design and construction of large buildings.

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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RADON MEASUREMENTS IN NORTH DAKOTA SCHOOLS

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ABSTRACT

Through the Environmental Protection Agency's State Indoor Radon Grant (SIRG) Program, the State of North Dakota conducted a survey for the presence of radon in schools throughout the state, from January to April of 1990.

Two main reasons for undertaking this project were:

1. Elementary and secondary school students' theoretically higher risk from exposure to radon and its progeny;

2. Results of the 1988 state-wide random survey showed 63% of the homes tested as having screening measurements greater than or equal to 4.0 pCi/l, suggesting radon's presence in other types of structures.

The results of this school survey revealed that 6.1% of the rooms tested had radon levels greater than or equal to 4.0 pCi/l, differing from the residential survey by a factor of ten.

The position is advanced that this survey is representative of schools in the upper midwest and that its data will be important in developing testing, diagnosis, and mitigation protocols in schools and larger public buildings.

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.

BACKGROUND

In the winter and spring of 1988, the North Dakota State Department of Health and Consolidated Laboratories (the Department), in conjunction with the Environmental Protection Agency (EPA), undertook a state-wide residential radon survey. 1596 homes were measured with two-day charcoal canisters. An average concentration of 7.0 picocuries of radon per liter of interior atmosphere (pCi/l) was recorded, with 59% of these homes having concentrations in the 4.0 - 20.0 pCi/l range, and 4% having 20.0 pCi/l or greater.

These results indicated a potential for high radon levels throughout the state, with 51 of 53 counties reporting 25% or greater of home screening measurements at or above the EPA action level of 4.0 pCi/l (Figure 1).

These screening measurements were confirmed by analysis of year-long alpha-track detectors placed in addition to the charcoal canisters in 175 of the above homes. 47.4% of these homes had at least one alpha-track result above 4.0 pCi/l.

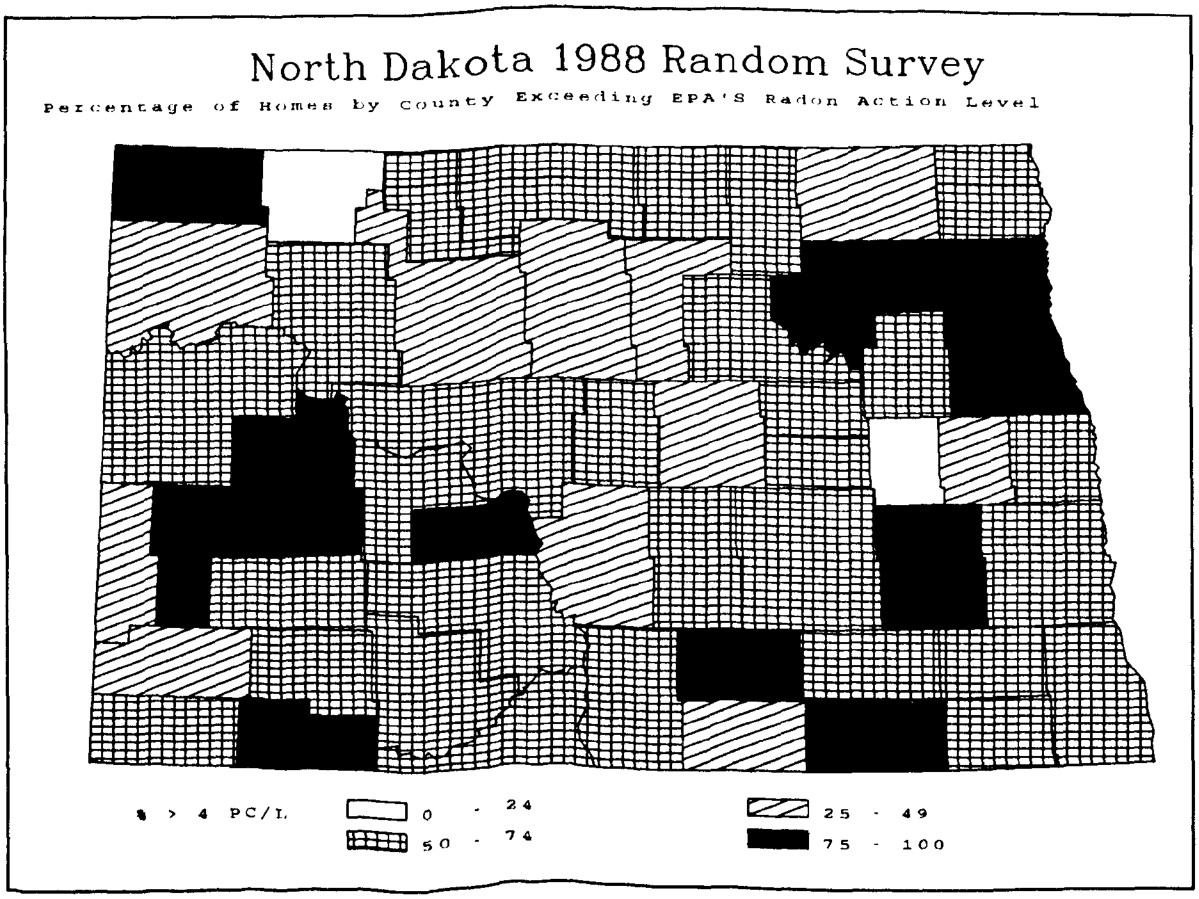

Figure 1.

Given these results, and the potentially more harmful effects of radiation from radon and it's progeny on younger people, it was decided to explore cumulative exposures to children based on where the majority of their time was spent in addition to that spent in their homes, notably their schools. A grant deviation was applied for and approved by EPA to enable screening measurements to be performed this past testing season rather than delay the study another year. This led to the Department conducting a state-wide radon in schools survey in the winter/spring of 1990 under an EPA State Indoor Radon Grant (SIRG).

STUDY DESIGN

Since the residential state-wide survey was conducted using 48-72 hour charcoal canister screening measurements, it was decided to be consistent with this approach for the initial testing in schools. The canisters were to be EPA style, cylindrical open-faced of the same testing window duration. For consistency, one vendor to supply and analyze the canisters was to be chosen. Other criteria for a vendor included: being listed in the EPA Radon Measurement Proficiency Program (RMP) and having the capacity to analyze up to thousands of canisters within a meaningful amount of time.

Bids were submitted by approximately 20 prospective vendors. The contract was eventually awarded to Home Radon Detection, Inc. (HRDI), whose bid allowed the purchase and analysis of over 7,000 canisters by funds allocated under the SIRG. Terms of the contract called for the solicitation of schools for participation in the survey by the Department. The Department was to analyze the testing plan submission by the schools for correct room placement, number, control and duplicate canisters, etc. An approved plan would then be returned to the school showing approved test room locations. The vendor was then notified as to the address of the school and the number to be sent to that address. After testing, the canisters would be returned postage-paid directly to the vendor for analysis. Results of this analysis were to be furnished to both the school and the Department.

Since the clientele to be solicited for this survey do not normally fall exclusively under the jurisdiction of a health agency, the State Department of Public Instruction was notified and informed of the proposed project and given the opportunity to be the lead agency, as a matter of professional courtesy. They declined this, and provided the Department with all school district contact individuals and mailing addresses. At that time, December 1989, the number of public and private school districts numbered approximately 350 for the entire state.

It was decided to contact school districts and make the district responsible for the individual schools within that district, rather than us contacting each individual school. This was a far more efficient method, as many districts had a considerable number of school buildings, and worked within the normal educational chain of informational flow.

METHODOLOGY

SOLICITATION

All 350 school districts within the state were contacted by mail and offered the opportunity to participate in the survey. There was no cost to the districts for this program as it was under the SIRG, 75% federal and 25% state-matching funded. However, since school testing was and is not mandated under North Dakota or federal regulation, only 130 districts submitted applications for testing under the 1990 grant year.

In September 1989, at a school administrator's conference, the Department made a radon presentation and included a copy of the EPA publication "Radon Measurements in Schools - An Interim Report" in the informational packet for each attender.

This publication was referenced in the application packet sent to each school district; pertinent sections related to testing were duplicated and included as part of the packet. Other enclosures were:

Individual school information sheets (Form 1).

Summary district application form to be dated and signed by a district official (Form 2).

Instructions on completing the above two forms.

A sample completed application.

As part of the application, floor plans of all levels of all school buildings to be tested showing proposed test locations were requested.

REVIEW

Current EPA school testing protocols call for testing in all frequently used rooms at or below ground level. Ten percent of these rooms were to be tested with duplicate canisters; an additional five percent of canisters were to be set aside as controls. To maximize the radon levels obtained under screening measurements, it is also suggested the testing be performed during periods of relative inactivity, such as over a weekend. The Department followed these protocols with the following exceptions:

Testing in rooms or areas of high humidity such as bath or locker rooms was strongly discouraged due to the effects of moisture on canister analysis accuracy;

To maximize the number of tests to be performed under the grant, not all support rooms, such as offices, conference rooms, etc., were tested, but a representative sampling thereof - virtually all classrooms were tested, however - this was felt to be a more critical area of concern;

These protocols call for placement of a canister for every 2,000 square feet of area in an "open-classroom" school or gymnasium. In this survey, canister placement in gymnasiums was often for areas of greater than 2,000 square feet.

A two stage, primary and secondary, review process was performed on each application. If more information or clarification was needed, the district official was contacted by mail or phone. Upon approval, written notification to the district was provided along with approved floor plan showing test locations and room summary enclosures. At this time, the vendor (HRDI) was also notified and given the district contact, mailing address, and total number of canisters to be delivered.

Care had to be exercised so as to time the approval of schools so that the number of canisters to be analyzed would not exceed the capacity of the vendor. This technique was negated to some degree by the school districts not testing as soon as possible after receipt, but waiting until the "perfect" testing weekend. Canisters were therefore delayed in being sent to some schools until "outstanding" ones were returned for analysis.

RECORD MANAGEMENT

To maintain a quality assurance program, the vendor was not informed as to which canisters were duplicates and controls until after analysis. The Department sent separate quality assurance forms to each district for each school, to be returned to the Department upon completion of testing, listing canister numbers and locations of controls and duplicates. This procedure established an accounting redundancy between the Department, the schools, and the vendor.

Upon receipt of results from the vendor, data was input to personal computers utilizing a dBASEIV software system. Rationale for database structure was one main district record; multiple schools per district; and multiple results per school.

Radon results were further broken down by the type of room use category and organized in such a manner that results for a particular category could be split and analyzed separately. This was done to allow for the theoretically variable harmful effects of radon based on age of incidence of exposure. It is, therefore, beneficial to know whether a particular classroom was in a primary or secondary school.

RESULTS

Due to widely variant climatic extremes within North Dakota, all buildings, including schools, are well insulated, well sealed, and generally energy efficient. Some of the schools tested during this survey were constructed around the time of admission to statehood, in 1889, while others were built within the past year. A wide range of construction styles and techniques are, therefore, encompassed. The majority of existing school structures appear to be slab-on-grade or "ranch" style, primarily to achieve lower construction costs and to allow for handicapped accessibility.

130 out of the 350 school districts participated in the 1990 school survey; however, virtually all of the larger districts did so. It is estimated that radon exposures to 50% of the state's students were analyzed. In these 130 districts, 273 buildings were tested. Out of 7,011 approved test locations in these 273 buildings, 6,983 canisters were placed and analyzed - a rate of 99.60 %.

Results showed mean levels to be considerably less than those discovered for residences - less than 2.0 pCi/l for any room use category - resulting in a extremely skewed distribution to the lower end of the scale. These results are further delineated in Tables 1, 2, and 3.

Table 1. Canister Use

Control canisters		323	(323/6052 = 5.34%)
Duplicate canisters		608	(608/6052 = 10.05%)
Room canisters*		6,052	
Basement	156		
1st Floor	5,896		
Total		6,983	

* Definitive rooms or 2,000 square feet of floor area.

Table 2. Placement and Results by Room Category

Room category	Number	% of 6052	Number ≥ 4.0 pCi/l	% of room cat. ≥ 4.0 pCi/l
Classrooms:				
Elementary	1,981	32.7	137	6.9
Secondary	1,856	30.7	94	5.1
	3,837		231	
Support rooms:				
General*	426	7.0	22	5.2
Physical Ed	32	0.5	4	12.5
Kitchen	204	3.4	12	5.9
Lunchroom	128	2.1	6	4.7
Lounge	185	3.1	12	6.5
Library	192	3.2	11	5.7
Office	581	9.6	43	7.4
Multi-purpose	119	2.0	8	6.7
Gymnasium	348	5.8	20	5.7
	2,215		138	
Totals	6,052	100.1	369**	

* General support rooms include: conference, counselor, bath, auditorium, locker, apartment, custodial, storage, etc.

** Results (x) of 6,052 rooms in pCi/l

$x < 4.0$	:	5,683	93.90%
$4.0 \leq x < 20.0$	:	363	6.00%
$x \geq 20.0$	:	6	0.10%

66.2 pCi/l was the highest measurement.

74 districts (74/130 = 56.9%) had at least one test result ≥ 4.0 pCi/l.

102 buildings (102/273 = 37.4%) had at least one test result ≥ 4.0 pCi/l.

Table 3. Statistical Analysis

Room Category	Number*	Arith Mean pCi/l	Arith Std Dev pCi/l	Geom Mean pCi/l
Total	6,660	1.53	1.95	0.98
Elem class	2,206	1.61	1.56	1.04
Sec class	2,068	1.40	1.96	0.87
Support	2,386	1.58	2.24	1.01

* Including duplicate canisters, but not controls.

School districts were sent results by the vendor soon after project completion. Confirmatory correspondence was also sent to each district, listing the schools, and the rooms within the schools that had screening measurement results $\geq$ 4.0 pCi/l. Procedures were referenced from "Radon Measurements in Schools"; additionally, the Department recommended retesting at 5 - 10 year intervals and following school building remodeling or additions. No mitigation was recommended at this stage, but rather confirmatory testing for rooms with screening measurements $\geq$ 4.0 pCi/l. Suppliers of alpha-track detectors were listed in the Department's letter along with the statement that there was currently no funding anticipated for this follow-up testing under future state grants.

EVALUATION

RESULTS

In participatory studies such as this, a great deal of trust must be placed in the personnel on site to properly place canisters, record data, and maintain qualitatively and quantitatively effective sampling techniques. Placement of the canisters in this study was performed by administrators, building superintendents, selected educators, and school science clubs.

The Department was available to answer questions from the project inception until its conclusion, greatly reducing the number of errors that inevitably occur. The high analysis percentage (99.6) is indicative of this effort.

METHODOLOGY

The following are ways in which it is thought the survey could have been run more effectively:

1. In addition to the sample completed application forms, it would have been illustrative to include a sample floor plan showing correct canister placement.

2. Consistency between the approved test locations and their identity on the vendor analysis forms should have been stressed. Oftentimes a room was identified by number (101, 102, etc.) or use (Math, English, etc.) and then reported by educator (Ms. Smythe, Mr. Johnson, etc.).

3. Some extraneous information was asked for on Form 1. The total number of classrooms in a school was requested, not just those at or below ground level. This was asked to get an idea of the construction style of a building, but this could be inferred from the floor plans we requested. This data was also thought to have informational value in the event a school chose to conduct optional testing. While this would have been useful, this Form would not appear to be the appropriate place to bring up the point of optional testing. Questions 3, 5, and 7 on Form 1 could therefore have been eliminated.

4. A split on Form 1 between class and support rooms was asked for without a great deal of delineating criteria. Some additional definition would have been helpful.

5. Some school officials took the protocols for testing in all frequently occupied rooms literally, and submitted plans showing placement in all areas, including closets, storage, boiler rooms, etc. A list of types of rooms not to test would have been helpful.

6. Testing of some schools did extend into April, which even in North Dakota is at or beyond the end of the heating season. This was brought about by the earlier noted tendency by some school officials to wait for the "perfect" weekend, delaying the entire queue, and by the timing of the grant approval after the first of the year, so that the survey began somewhat advanced into the testing season. Starting the SIRG programs at the beginning of the Federal fiscal year (October 1) would help to increase the length of the testing season as opposed to delaying a study until the beginning of the next school year.

7. Some school officials were reluctant to sign the summary application Form 2 as they were unsure as to what they were committing to by signing. Form 2 should have stated that they were agreeing to follow the protocols for screening measurements only.

8. North Dakota has an open records law; the results of any school would be open to examination by anyone, compromising the implied confidentiality between the Department and the school district. The policy was to refer questions on results to the district, but if pressed, the Department would have had to release them. A statement on the application summary form to this effect would have explicitly stated this position and avoided future misunderstandings.

CONCLUSIONS

There would appear to be an anomaly between the results of the residential state survey and the radon in schools survey. The initial assumption was that much higher levels of radon would be found in the schools and that more rooms would have been identified as being above the action level. A variety of reasons may have an effect on this situation:

1. School rooms generally have a larger volume than residential rooms.

2. School rooms are generally better ventilated as a result of increased traffic and more effective HVAC (Heating, Ventilating, and Air Conditioning) systems.

3. Whereas it is estimated that 95% of all homes in North Dakota have basements[1], the majority of schools in the state appear to be of slab-on-grade construction. Only 156 tested rooms (156/6052 = 2.6%) were basement rooms. Of these 156, 16 (10.3%) had levels greater than or equal to 4.0 pCi/l.

In May 1990, an EPA diagnostic/mitigation team headed by Mr. Gene Fisher, Washington D.C., examined three Minot, North Dakota area schools where elevated levels had been indicated by the SIRG screening measurements. Diagnostic work was linked to a possible correlation between elevated radon levels and elevated CO_2 levels within the rooms in question. Mitigation recommendations were made to the individual schools by this team. HVAC supply-exhaust air flow adjustments were recommendations common to all schools.

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[1] U.S. Environmental Protection Agency, Radon-Resistant Residential New Construction (EPA/600/8-88/087 July 1988), p. 4.

FUTURE ACTIONS

To continue the logic behind the impetus for school testing, future grant applications will be directed toward completion of screening measurements in schools and licensed day care centers across the state. Confirmatory measurements were recommended to schools prior to potential mitigation. These results will be illustrative in determining the actual exposure to students and young people from radon gas.

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5. Fisher, Gene, U.S. Environmental Protection Agency, Office of Radiation Programs, on-site, Minot, ND area school investigations.

Form 1.

RADON IN SCHOOLS TESTING QUESTIONNAIRE/APPLICATION

1. Name of School District and Address/Location (including City and County):

____

____

2. Name of School building and Address/Location (including City and County):

____

____

3. Total number of classrooms in building: ________

4. Total number of classrooms on or below the ground level: ________

5. Total number of support rooms:
   (e.g. library, cafeteria, administrative, etc.): ________

6. Total number of support rooms on or below the ground level: ________

7. Total number of classrooms/support rooms (add Items 3 & 5 above): ________

8. Total number of classrooms/support rooms on or below the ground level:
   (Add Items 4 and 6 above): ________

9. Subtotal number of test devices required for this building
   (minimum-1 classroom in contact with the ground): ________

10. Number of control test devices required
    (5% of total shown in Item 9): ________

11. Number of duplicate test devices required
    (10% of total shown in in Item 9): ________

12. Total number of test devices required for testing this
    school building (Items 9 + 10 + 11): ________

13. Attach sketches/drawings of the school buildings showing proposed placement
    of test devices for radon testing.

Please refer to pages A-1 to A-5 when planning the placement of your test devices.

14. School district contact for radon in schools testing program:

________________________ ________________________
(Contact Person) (Contact Telephone No)

Form 2.

SCHOOL DISTRICT SUMMARY OF RADON TESTING REQUIREMENTS

School Building/ Location (City and County)	Subtotal Devices Required (Item 9)	Controls Required (Item 10)	Duplicates Required (Item 11)	Total Devices Required For School
TOTALS				

CERTIFICATION

I ______________________ hereby certify that the ______________________ School District will follow the EPA protocols, referenced in "Radon Measurements in Schools - Interim Report."

Typed Name of School District Official	County
Signature of School District Official	Date

MAJOR RENOVATION OF PUBLIC SCHOOLS THAT INCLUDES RADON PREVENTION: A Case Study of Approach, System Design and Installation; and, Problems Encountered

By: Thomas Meehan

An increasing number of schools had been identified by 1989 with radon concentrations in excess of U.S. EPA guidelines. As some data suggests that children may be more susceptible to radiation induced cancer than adults. The State of Connecticut Department of Health Services recommended in April 1989 that all local education agencies and districts test their schools for radon. One school district that followed these recommendations identified high levels in an elementary school that was scheduled for major renovations. The local education agency agreed to mitigate existing building and utilize radon-resistant new construction techniques for the additional buildings planned. Many problems were encountered while attempting to install these systems, and utilize techniques recommended by the EPA for installation of radon reduction systems. An outline of this experience with recommendations for avoiding similar problems is presented.

After initial testing identified high radon levels in the school, maintenance workers attempted to lower the levels by sealing openings and cracks in the slab and foundation, isolating an open dirt tunnel, yet not allowing for release of any trapped gases, and putting a fan in the boiler room window to bring outside air in. More testing was performed and the levels were still high.

Since major renovations were slated, the school district asked architects to design systems to address the existing building and utilize radon resistant techniques for new buildings planned.

We were invited to submit a bid to install systems to the architects specifications and secured the job.

In reviewing the prints and specifications of the mitigation systems, it was evident that, although the systems were superbly designed, knowledge of EPA protocols were lacking.

The most prevalent was the fan location. The architect chose to mount in-line duct fans horizontally above the ceiling within the building.

We discussed this matter with the general contractor and the architect, pointing out the potential problems of condensation build-up in a horizontally mounted fan. Also discussed, were EPA protocols suggesting the mounting of fans outside the occupied envelope to avoid potential release of radon gas inside the building on the positive pressure end of the exhaust.

After the general contractor and architect discussed the matter among themselves, the decision to mount the fans vertically was agreed upon, but that the fans were to remain inside, stating the change would cost too much.

As a sub-contractor, we could not push the subject without alienating ourselves.

Another aspect of the job discussed was the decision to use Schedule 80 for all above ground pipe on a system that would have relatively low pressure. They decided to stay with the larger and more costly pipe for reasons not explained.

Although work on the existing building has not begun, another potential problem we feel that might arise is in reference to the lack of diagnostics.

When we are invited to bid to do work on existing schools and large buildings, mitigation systems are designed in conjunction with thorough diagnostics of the building consisting of:

1. Communication testing with micromometer
2. Sniffing with Pylon AB-5 to identify hot spots
3. Use of blower door to identify air balancing affects.

A follow-up paper we will be writing will cover these areas in more detail.

What we have learned to date, in reference to doing work on State funded School Radon Mitigation, might assist you on your next project.

In the decision to engage your company in large scale radon mitigations, there are many things that must be taken into consideration. These can be broken down into three categories.

1. Bid process
2. Job Orientation and Familiarization
3. Actual Work

There are many things to consider in each of these areas. The following are what we feel are important factors that must be addressed.

1. Bid Process - Pre bid on site inspection is strongly advised. There are always characteristics unique to each construction site that are not explained on the blueprint or in the specifications.

When putting a bid together, always verify any State or Federal wage rate requirements. If there are, obtain the classification of your workers in writing from the State Labor Department.

Another important aspect is the insurance and bonding requirements. These can vary depending upon the project. Generally, a $1,000,000 liability and workman's compensation coverage is required.

One of the most important factors to consider, are the payment schedules. Most government and State jobs give no money up front and will make payments on a scheduled basis, a minimum of 30 days from the date of requisition. This also involves elaborate paperwork that is required for each payment. It is very important to have the proper funding in place prior to acceptance of large scale jobs. Be sure to check on performance penalties.

2. Job Orientation & Familiarization - Once a job has been secured and contracts signed, it is key to the sucess of the job that you spend time with the following:

Materials - Obtain a locked in price, purchase materials and get them stored on site. This will allow you to submit bills for materials purchased, and avoid any future price increases. Also, request specification sheets on all materials purchased and retain for job file. When possible, locate supply houses near the job site and obtain an account to avoid costly delays.

The most important person related to your work, other than employees, is the job superintendent. It is important to establish a working relationship with him. Be sure to let him know your capabilties and possible short comings related to the job. Review the entire job with him, if possible. Going over potential problems you might see that he does not realize (EPA Protocols).

It is very important to go through this entire process with another key employee in case you are unavailable.

3. Actual work - It is important to have two people very familiar with blueprint reading. The need will also arise to coordinate your work along with other contractors on the job.

Some potential problems that can occur are: pouring foundation prior to placement of piping. Be sure to coordinate with concrete workers so the appropriate steps can be taken to insure access through foundation in the appropriate place. (Core bore drilling is expensive).

Check all foundation prints on the interior of the building for footings. The prints might not show this, but a dip in the piping may be required where footings are present.

Exact measurements are a necessity. Do not rely on one measurement. Measure pipe placement from two locations. Where piping comes through a slab, measure from four points. (Concrete cutters are expensive).

In reviewing the prints throughout the course of the job, if you see anything that might create future problems, discuss this with the superintendent or architect.

The State of Maine School Radon Project: The Design Study

by: Henry E. Warren, Director
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ABSTRACT

The State of Maine, with a population of 1,222,000, has a public school enrollment of 212,000 students (K through 12) in 14,500+ rooms in about 800 buildings in some 160 public school systems. A proposal to study the radon in the school systems was requested by the state. An advisory team was formed, expert on schools, HVAC systems, geology, radon testing and radon mitigation. This group, meeting with experts from NITON Corporation, the chosen testing firm, formulated a comprehensive program to provide thorough testing and, where necessary, retesting, within the constraints of a frugal budget. A quality control program was initiated. So too were plans for informing the public. This paper will describe the major choices and decisions on such questions as: Should the program be spread over several years? Is a statistical sampling of rooms sufficient? Should one test in the summer? Who should set out the tests? How should the tests be monitored?

INTRODUCTION

The State of Maine, with a population of 1,222,000, has a public school enrollment of 212,000 students (K through 12) in some 160 public school systems. A proposal and bid was requested by the state to test for radon in the entire Maine school system. NITON Corporation was chosen as the testing firm.

Henry E. Warren, Director of the Division of Safety & Environmental Services of the Bureau of Public Improvement for the State of Maine formed an advisory team: Expert in schools— Roy Nesbitt, Director of Maine School Facilities; HVAC systems— William A. Turner, PE; geology —Ted Bradstreet, geologist; radon in Maine —Eugene Moreau, Manager of Indoor Air Quality, Department of Human Services. This group met with experts from NITON Corporation, who have much experience in testing schools and other large buildings, and formulated a comprehensive program to provide thorough testing and, where necessary, retesting, within the constrains of a frugal budget. A quality control program was initiated. So, too, were plans for informing the public. This paper discusses the many choices and decisions made by the group.

Many questions had to be decided. The two critical questions were: How many tests should be made and who should place and retrieve them? The answers to these determined the costs, and thus the extent of the testing.

PLANNING

FUNDAMENTAL DECISIONS

How Many Tests?

Determining the number of radon tests required for large buildings is counter-intuitive. It would seem reasonable to expect that testing the four corner rooms of a school will reveal any high levels that may exist. Maine had thus first proposed "4000 tests for approximately 900 buildings."

In the view of NITON and the experts consulted, a program with this proportion is very nearly a waste of money. Four tests that read less than 4 pCi/L do not mean the building itself is below the EPA's action level, only that those four rooms are below the action level. Any other room nearby or any cluster of rooms may be higher and only testing them all reveals which ones.

The location of high radon in large buildings cannot, unfortunately, be predicted, so that every occupied room on the ground or over crawl space must be tested. To uncover radioactivity, the EPA protocol is one's best assurance.

The group recommended: A short-term screening test done over a week-end in (a) every (b) frequently occupied (c) room (d) on the ground or (e) over crawl space. If the budget was limited, use the 4000 tests to do fewer buildings correctly, rather then do them all badly.

The State of Maine chose to follow the EPA protocol and do each building properly to the limit of its budget.

Who should place and retrieve the tests?

To the extent that school personnel could do this task, the costs would drop dramatically and more tests could be done. Travel costs alone, for example, can be prohibitive in a state as large, rural, and winter-bound as Maine, 303 miles from North to South.

Most experts would agree that in many, perhaps most, situations, a professional radon tester is always to be desired. For example, in real estate transfers of homes and commercial property, there are too many questions of placing the test at proper height, in which areas, how the heating system affects numbers and locations, how stone foundations and fireplaces affect placement, and how to maintain closed building conditions, not to mention matters of tampering.

A school, however, poses none of these problems, whose solution requires training and experience. The question of placement, for instance, is minor. Every classroom or school office has a desk, which is exactly the height EPA calls for, 30".

NITON had already had substantial experience in helping public schools to test. Although its products are used almost exclusively by professionals—environmental firms, inspectors, and the like—the company had earlier been approached by a number of Massachusetts public school systems to devise a low-cost system. The schools of Massachusetts had very little money but wanted to test. Without in-school testers, they could not have tested at all.

The program NITON had developed for non-professionals was further refined for Maine. It involved reading and marking all floor plans, an 800 Number Help Line, continuous follow-through, etc. These are described elsewhere in this program under Protocols and Procedures (1).

Because school personnel placed and harvested the tests, the State of Maine was able to afford a test for every designated schoolroom in the state within one year.

Why were short-term charcoal canisters chosen?

The EPA's Interim Protocol for Schools recommends both short-term screening tests (two days or over a week-end) and Alpha Tracks (three months) (2). There are three reasons why the short-term charcoal screening test was chosen for Maine schools:

1. The cost of an Alpha Track is typically about twice that of a charcoal canister.

2. In buildings where people work or go to school, the HV and HVAC systems typically have a set-back cycle during the evenings, week-ends, holidays, and school vacations, making Alpha Tracks inappropriate for long-term testing in these structures. With a 168-hour week, and the systems set back 120 to 136 or more of those hours, ATs will generally give a false high or a false low, and take many months to do it. That is, ATs are skewed in these buildings from 3 to 1 to 7 to 1 or more in the direction of the radon values of the off or set-back cycle. These concentrations may be very much higher or very much lower than during hours of occupation. The problem is aggravated since during the week-ends and vacations, radon can build up to values that may be 10 times the mid-week evening set-back value.

3. More importantly, a short-term test will efficiently find high radon levels in a short time. In addition, tests are less likely to be misplaced or forgotten. Any tests that are lost or mishandled can be quickly and inexpensively replaced and the test promptly redone, again over a weekend. If an AT is lost, the three months of testing is lost and the next three-month test has to start again. If the air handling equipment is on its regular mid-week cycle, the set-back cycle dominates by a

factor of only 2 to 1 (16 hours set back, 8 hours on). If the system is kept on continuously as this Maine protocol calls for, the occupied conditions are more nearly met.

One should not have to wait many months to learn of occupied rooms with high radon levels. In Maine, 8.7% of rooms were found to be more than 4 pCi/L, 1.9% were more than 10, and 0.7% were more than 20 pCi/L, and results were available within a week, including the testing.

OPERATIONS ORGANIZATION

Where should the tests go?

NITON read and marked the plans of every school building. For details, see Protocols and Procedures (1).

When should the tests be done?

Schools were tested from late Friday afternoon to early Monday morning, a time period recommended by the EPA that is becoming standard practice for testing schools (3). NITON vials are calibrated from 24-72 hours for screening.

This week-end period assures that outside windows and doors will be kept shut to maximize the radon potential. It is also felt that students will not tamper with the tests.

Heating and ventilation cycles on?

When there are sufficient funds, one would ideally screen test all rooms with all systems down, to learn how much radon is entering the building; then one would retest, with HV or HVAC systems on, to learn the effectiveness of these systems at clearing away radon gas or creating negative pressure and sucking it in. Given an extremely limited budget, the group felt it was most important to learn what the radon levels were when students and adults were actually occupying the building. It was decided to request that the Heating and Ventilating be on continuously. The instructions were made part of the Data Entry Sheet.

Test in spring and fall, or continue through summer?

With testing scheduled to begin at the end of February, the question of continuing the testing through the summer or waiting until fall to recommence the testing came up.

Based on preliminary evidence, the EPA Interim School Protocol calls for testing in the wintertime only (4). Warren checked with Maria Van der Werff, Radon Coordinator, EPA, Region #1 and William Turner, PE, who agreed with NITON that mounting evidence was showing that summer testing was valid.

For example, NITON had done comparison testing of 89 rooms in 5 schools in Massachusetts six months apart and found slightly higher readings in the summer; 80% of the rooms were within 1 pCi/L (5). Summer is, in fact, an excellent time for two-day screen testing. The custodians have more time, there are fewer distractions, and it costs very little to put the HVAC onto continuous cycle for the short test period.

MANAGEMENT OF NON-PROFESSIONALS

HOW TO KEEP THE PROGRAM ON SCHEDULE?

Even with professionals, schedules need to be set up. With non-professionals, schedules have to be far more detailed, and people need to be monitored very closely and continuously. Maine had previously provided free radon tests to several schools, most of whom had never returned their tests to the lab, or had returned them months after exposure. Maine was particularly concerned with this point. The system devised worked for 98.5% of the tests.

NITON was given the name, principal's name, and phone number of every school in the State of Maine. Many schools were in towns and cities, with facilities maintenance staffs. Some were out on islands or Indian reservations with no staffs. Some were one-room schoolhouses, with no principal and no custodian. NITON devised a checking system that kept track of all of them at every stage in the program, from sending in floor plans to returning tests.

RE-TESTING: WHERE AND HOW

It was already known that some areas of Maine were high in radon; 60 pCi/L in basements was not so rare in those parts. When the first very high readings showed up in schools there, the EPA was called in and mitigation begun.

The decision was made to retest every room with a reading over 3 pCi/L. Ideally, one would want a sensitive electronic continuous radon monitor to give hour-by-hour results in every such room, but the cost is high.

A cost-effective way to retest is the use of NITON vials to learn day and night readings. The NITON vial is calibrated to 8 hours, and is extremely sensitive as well as accurate at low levels (a liquid scintillation counter counts virtually 100% of 5 decaying particles). At 1 pCi/L, the Standard Deviation is 10%; in retests, all tests are counted to a Standard Deviation of 2% at 3 pCi/L. Thus, a reading may be taken during the school day, when the building is occupied, and another in the same room at night, when the systems are set back. Rooms confirmed to be high would then be candidates for careful diagnosis of all conditions, beginning with the HVAC.

QUALITY CONTROL

QUALITY ASSURANCE FOR TESTING VIALS

To test the tests, two procedures were used. Side-by-side NITON vials were set out in some 150 rooms. In addition, 50 of the 4" charcoal canisters (75 gr) were supplied by the State of Maine and analyzed in the Maine Radon Lab. More information on this is given in the presentation on Results in the State of Maine School Radon Project (6).

DATA REPORTING

It was decided that test results would be sent to Henry Warren's office within two business days of the arrival of the tests at the lab. In addition, NITON would make the data available on discs for further analysis.

PUBLIC RELATIONS

The decision was made to tell the public of results as they were learned. Disclosure of even high radon values can be made without arousing undue alarm provided it is done early. This has been proven again and again in towns and school systems where such information was provided to the public early, instead of being withheld and then "revealed" by an outside source.

Note: The wisdom of this policy was demonstrated in the towns in the Sebago Lake region, where the radon was in excess of occupational levels for uranium mines, yet there was no hue and cry to close the schools, as there has been in areas where high results have been kept secret for too long.

ACKNOWLEDGEMENTS

H.W.and E.R. wish to acknowledge with gratitude the contributions of the following to the success of this study: William Bell, Maria Van der Werff, Roy Nesbitt, William Turner, and the planners from NITON, who include Lee Grodzins and Anne McGuineas.

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TITLE: Design for the National Schools Survey

AUTHOR: Lisa Ratcliff, EPA - Office of Radiation Programs

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

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