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# PROCEEDINGS: THE 1991 INTERNATIONAL SYMPOSIUM ON RADON AND RADON REDUCTION TECHNOLOGY

Volume 2: Symposium Oral Papers
Technical Sessions VI through X

Symposium Co-chairpersons:

Timothy M. Dyess
U.S. EPA
Air and Energy Engineering Research Laboratory

Susan M. Conrath
U.S. EPA
Office of Radiation Programs

Charles M. Hardin
Director
Conference of Radiation Control Program Directors
(CRCPD), Inc.

S. Cohen and Associates
1311 Dolley Madison Blvd.
McLean, VA 22101

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EPA Task Officer:
Timothy M. Dyess

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

Prepared for:

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16. ABSTRACT The proceedings, in four volumes, document the 1991 International Symposium on Radon and Radon Reduction Technology, held in Philadelphia, PA, April 2-5, 1991. In all, 65 oral papers (including the welcome address, the lead address, and the keynote address), 14 panel session papers, and 40 poster papers were presented. The papers addressed a wide range of radon-related topics: government programs and policies, health studies, health risk communication, measurement methods, radon reduction methods in existing houses, radon transport and entry dynamics, survey results, geological data, radon-resistant new construction methods, and radon measurement and mitigation in schools and other large buildings. The symposium speakers included EPA personnel, representatives from federal and state environmental/health agencies, research and development groups, academic and medical personnel, manufacturers of testing equipment, and those in the construction and real estate industries. Attendees represented 14 countries other than the U.S. The international papers provided updates on government policies, results of surveys, and technological developments in radon and radon reduction technology.

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# ABSTRACT

The 1991 International Symposium on Radon and Radon Reduction Technology was jointly sponsored by the U.S. Environmental Protection Agency (EPA) Air and Energy Engineering Research Laboratory (AEERL), EPA Office of Radiation Programs (ORP), and the Conference of Radiation Control Program Directors (CRCPD), Inc. The symposium was held in Philadelphia, Pennsylvania on April 2-5, 1991. The objective of the symposium was to provide an international forum for the exchange of technical information on radon and radon reduction technology in the indoor environment. Oral papers and poster presentations conveyed recent advances in radon research and radon reduction methods in the following fields: the assessment of radon derived health impacts, government programs and policy, the measurement of radon and radon progeny, soil/geology and radon source potential, and diagnostics and application of radon reduction and radon resistant construction techniques. The Symposium Proceedings, published in four volumes, include 65 oral papers (including the welcome address, the lead address, and the keynote address), 14 panel session papers, and 40 poster session presentations.

## PREFACE

The 1991 International Symposium on Radon and Radon Reduction Technology was held on April 2-5, 1991, in Philadelphia, Pennsylvania. Sponsored jointly by the U.S. Environmental Protection Agency (EPA) Air and Energy Engineering Research Laboratory (AEERL), EPA Office of Radiation Programs (ORP), and the Conference of Radiation Control Program Directors (CRCPD), Inc., the symposium was devoted to the exchange of current research developments in radon and radon reduction technology in the indoor environment. Education in radon research and the dissemination of technical information were the primary objectives of the meeting.

The co-chairpersons of the symposium were Timothy M. Dyess of EPA-AEERL, Susan M. Conrath of EPA-ORP, and Charles M. Hardin of CRCPD. The opening address was given by Charles M. Hardin, Executive Director of CRCPD, who briefed the audience on the objectives of that organization. The welcome address was given by Edwin B. Erickson, Administrator of EPA Region 3. The lead address, entitled "Comparative Dosimetry of Radon in Mines and Homes: An overview of the NAS Report", was presented by Jonathan M. Samet of the New Mexico Tumor Registry at the University of New Mexico. This paper addressed the results of recent risk estimate calculations. The keynote address, given by John R. Garrison, Managing Director of the American Lung Association, focused on ways to promote public respect for the health hazard which indoor radon presents.

In all, 62 oral papers, 14 panel session papers, and 40 poster papers were presented. The papers addressed a wide range of radon topics: government programs and policies, health studies, health risk communication, measurement methods, radon reduction methods in existing houses, radon transport and entry dynamics, survey results, geological data, radon resistant new construction methods, and radon measurement and mitigation in schools and large buildings.

The symposium speakers included EPA personnel, as well as representatives from federal and state environmental/health agencies, research and development groups conducting radon testing, academic and medical personnel, manufacturers of testing equipment, and those in the construction and real estate industries. Attendees represented 14 countries (other than the U.S.), most of which were European. The international papers provided updates on government policies, results of surveys, and technological developments in radon and radon reduction technology issues.

The symposium has been published in four volumes:

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# Session VI

# Oral Presentations

# Radon Surveys

# FACTORS ASSOCIATED WITH HOME RADON CONCENTRATIONS IN ILLINOIS

Thomas J. Bierma and Jennifer O'Neill
Environmental Health Program
Department of Health Sciences
Illinois State University
Normal, Illinois 61761

ABSTRACT

The Illinois Department of Nuclear Safety has performed short-term alpha-track radon testing in over 3000 homes throughout Illinois. Data were also collected on a wide array of household characteristics and test conditions. Analysis of these data revealed a number of interesting patterns.

Contrary to many investigations, the highest average concentrations were not obtained in homes monitored in winter. Though a number of models were explored in the analysis, few could explain more than 10% of the variation in radon concentrations and no model could explain more than 20%. This suggests that other factors, such as local geology, may be largely responsible for inter-house variations.

Among houses with a crawlspace elevated radon was associated with having an indoor entrance and not ventilating or insulating the crawlspace. In houses with basements, the foundation construction materials were important explanatory variables. Surprisingly, common entry routes, such as sump pits, cracks, drains, and exposed earth, were not associated with radon concentration. Also contrary to other studies, energy efficiency was positively associated with radon concentration.

Results suggest that factors governing radon concentrations in the Midwest are poorly understood.

## INTRODUCTION

The primary factors governing the entrance of radon into the home are well known: 1) the soil radon gas concentration and soil permeability, 2) the existence of entry routes between soil and home interior, and 3) a pressure difference between home and soil to provide a driving force for radon entry. However, specific conditions that influence these factors are not well understood, and other factors, such as the distribution of radon in the home and the infiltration of outside air, can influence the concentration of radon in various parts of a home.

Though a number of studies have been performed to examine the relationships between local conditions and indoor radon concentrations, considerable uncertainty remains. In addition, relatively little work has been conducted on factors influencing home radon concentration in the Midwest.

This study was performed using data collected on approximately 3,000 homes in Illinois that were tested for radon as a part of the Illinois Department of Nuclear Safety's Radon Program. In addition to radon testing, data were collected on a number of household and monitoring conditions. The purpose of this analysis is to build a predictive model for indoor radon concentrations in Illinois. Such a model could not only help identify homes with a higher risk of elevated radon, but could also assist in directing mitigation efforts.

## *A PRIORI* MODEL SPECIFICATION

Data on a number of household and monitoring variables were collected during monitoring (see the following section for details). An *a priori* model was developed to guide analysis of these variables and their relationships to indoor radon. The model is also useful in identifying gaps in the array of variables included on the questionnaire.

Table 1 presents the household and monitoring variables evaluated in this analysis. Indicated in the table expected relationships between each variable and monitored radon concentration. These expectations are based upon relationships reported by others in the literature and on the authors' own field experience. Table 1 lists the basic references used in creating the table. A detailed discussion of the current literature and *a priori* model is not presented here due to space limitations. The reader is referred to reviews such as references (1-3). However, a few comments should be made to clarify subsequent modeling.

Air infiltration may b associated with an increase or decrease home radon concentrations. Increases may occur if infiltration occurs due to house depressurization, which can increase infiltration of soil gas. Similarly, the mixing of air within a house can increase or decrease monitored radon depending upon the location of the monitor. For example, basement radon levels may decrease and first floor radon levels may increase as basement air is distributed through a forced-air heating system. Therefore, variables related to air infiltration and air distribution may demonstrate either a positive or negative relationship to radon in modeling results.

No information on local geology, weather conditions, or other radon sources (other than basement wall construction material and exterior brick) was collected. Thus, the contribution of these factors to radon concentrations cannot be assessed with this data.

## METHODS

In the Fall of 1986, the Illinois Department of Nuclear Safety began a systematic radon testing program for houses in Illinois. Testing was performed on a county-by-county basis using local assistance from county health departments, Cooperative Extension Service personnel, or other organizations. The program continued through the Spring of 1990, though no testing was performed from the Summer of 1988 to the Fall of 1989.

An alpha-track detector was typically placed in the lowest livable area of the home. After approximately one month of exposure, detectors were returned to the contract laboratory (Tech/Ops Landaur, Inc.) for evaluation.

In addition to placement of detectors, surveyors completed a questionnaire with the assistance of a head-of-household. The questionnaire included a number of questions on house characteristics and on the household occupants.

Though houses were not selected randomly, selection procedures, typically involving identification of houses from county highway maps, were intended to avoid any systematic bias. Due to the complex interaction of factors influencing radon concentrations, such selection processes may be relatively free of bias (1). At least 20 houses were tested in each county. The number of houses tested in a county increased with increasing population. The 3,021 monitored houses analyzed in this study were drawn from 73 of 102 Illinois counties. These 73 counties contain approximately 88% of the Illinois population.

All data were evaluated for distributional characteristics and coding errors or ambiguities. For many quantitative variables demonstrating non-normal distributions, transformations were performed to enhance normality. In most cases, natural logarithm transformations were sufficient. For other non-normal quantitative variables, however, no useful distributions could be derived from transformation. Many variables demonstrated bi- or tri-modal distributions. Such variables were typically transformed to artificial categorical variables using either theoretically or empirically based cut-points. All final variables and their coding schemes are presented in Table 1. For quantitative variables, scatter plots were assessed for evidence of hereroskidasticity and non-linearity. No problems were identified.

Multiple linear regression was used to explore models of monitored radon concentration. A series of theory and non-theory based models were explored. These are explained in more detail in the following section.

# RESULTS

## OVERALL

Radon concentrations were approximately log-normally distributed with a geometric mean of 2.84 pCi/l and a standard geometric deviation of 2.30. All subsequent modeling and statistical analysis used the natural log transform of radon concentration.

It was anticipated, prior to analysis, that substructure type, monitor location, and season of monitoring would be the primary explanatory variables across all types of homes, but that the effects of monitor location and season of monitoring could vary by substructure type. Table 2 presents the ANOVA results for radon concentration across the four basic substructure types encountered. Results confirm that substructure is a critical explanatory variable, with crawlspace/no basement producing the lowest concentrations and basement/crawlspace combination producing the highest concentration.

Some of the difference in means, however, may be due to monitor location rather than a direct effect of substructure type. A small percentage of houses with basements were monitored on the first floor, presumably because the basements were not considered "livable". Table 2 presents ANOVA results using first floor measurements only. Though significant differences are still noted, slab-on-grade, rather than basement/crawlspace combination represents the substructure associated with the highest average monitored concentrations

No analysis was conducted on the joint effect of monitor location and substructure type since interaction is an artifact of the survey method: a monitor was placed in the basement only if the home had a basement. The joint effect of substructure and season are presented in Table 3. Both independent variables are significantly associated with the dependent variable, and there appears to be an interaction effect. In basement homes without a crawlspace, fall monitoring produced the highest concentrations. For slab-on-grade homes, fall monitoring produced the lowest concentrations.

Due to the apparent interaction between substructure type and monitoring location and season, as well as probable interactions with other explanatory variables, subsequent analyses were conducted separately for each of the four substructure types.

Before leaving Table 3, however, it is important to note that, contrary to many research findings, winter was not the season of highest radon concentrations. Summer produced the highest or second highest concentrations in each substructure type.

A number of regression models were explored for each substructure type. These are presented in Tables 4 through 7. Model A in all tables represents the results from a series of simple linear regressions using the variable listed as the only independent variable. Interpretation of statistical significance under multiple comparisons is an obvious problem. Consistency with theory and the findings of other studies, as well as consistency across substructure types, should be used in evaluating the results. This point will be explored further in the discussion section.

Models B and C reflect models built upon theory and the results of other models. In Model B, only the monitor location variables were used. In Model C included the addition of monitoring location.

Models D through F represent non-theoretical modeling. Model D includes all variables simultaneously in the model. Because many of the independent variables are correlated, multicolinearity is a significant problem in Model E. However, by comparing the regression coefficients and p-values to those obtained in other models, one can use Model D to identify those variable that are relatively sensitive or relatively insensitive to the inclusion of other variables in the model. Model E uses Model C plus a forward selection procedure, and Model F used a stepwise selection procedure without any forced variables. Variables included through such non-theoretic methods should only be considered curious possibilities as true explanatory factors for indoor radon. Considerable support from other studies would be needed to enhance the reliability of such models.

Model G represents the best attempt at a complete, theory-based model. Beginning with a base of Model C, additional variables were added for which a good theoretic foundation exists, and which demonstrated results consistent with theory in Models A and D. Model G should be considered the best model for prediction in Illinois houses.

The most immediate observation from the regression analyses is the relatively low explanatory power of the models. The percentage of variation in radon explained by the models was generally under 10%. Only for homes with both a basement and crawlspace does theoretical modeling achieve an r-square greater than 0.2. (Note: although Model D can produce a greater R-square, non-theoretic models are likely to have far less predictive power than explanatory power.)

Specific variables of interest include monitoring location and season. For homes with basements, knowing whether the monitor had been located in the basement or not was an important predictor of monitored radon in all models. Knowing whether the monitor was located in a first-floor bedroom or elsewhere on the first was not, generally, a good explanatory variable. This changed in the non-theoretic models for homes with basement/ no crawlspace, possibly due to the addition of the energy efficiency or central air conditioning variables. For homes without basements, bedroom location was important only for homes with a crawlspace, and then, only when monitoring season was included in the model.

Monitoring season was important in nearly all models though the effects were not consistent across substructure types (supporting the previous ANOVA results). Only for slab-on-grade homes, where sample size was small, did the season variables generally have p-values greater than 0.1 and not produce a significant r-square change from Model B to Model C.

BASEMENT/CRAWLSPACE SUBSTRUCTURE

For homes with a basement/crawlspace combination, an entrance from the interior of the home (most likely the basement) to the crawlspace produced a consistent increase in monitored radon. Because the dependent variable is logarithmic, coefficients represent the multiplicative effects of an independent variable on the radon concentration. The coefficient of 0.26 in Model G indicates that a crawlspace entrance increases home radon about 30%. Similarly, venting a crawlspace demonstrated a consistent decrease in radon, with Model G indicating approximately 20% higher radon levels for homes with unvented crawlspaces. Coefficients for crawlspace insulation and the presence of exposed earth in the crawlspace were both in the correct direction but did not demonstrate consistent statistical significance.

Basement foundation construction material also appeared to be important. Construction materials, from lowest to highest in their apparent contribution to home radon levels are poured concrete, block, "other material", stone and mortar, and brick. From Model G, brick is associated with an average increase in radon levels of greater than 50% over poured concrete. (It is interesting to note that brick reverses signs in Model D. This is apparently an artifact due to multicollinearity.)

Energy efficiency demonstrated a consistent positive relationship with radon. The greater the occupant-assessed energy efficiency, the greater the radon. Perhaps for similar reasons, the number of people in the house was negatively related to radon. Both variables may be related to the amount of air exchange and the size of the house.

Among the most significant findings is that the standard entry routes in a basement (cracks, sump pit, exposed earth, etc.) were not important explanatory variables. Some even had coefficients with a sign opposite that predicted by theory. Also contrary to theory, the presence of a woodstove or fireplace had a negative coefficient and large p-value.

There are a number of interesting curiosities in the regressions of houses with basement/crawlspace combinations. In Model A having room air conditioning or an electric space heater were associated with lower radon concentrations. These did not retain their significance in Model D and may reflect the effects of energy efficiency. Another interesting point is the importance of a brick exterior appearing only in the non-theoretic models. Having an interior entrance to the basement was associated with higher radon levels in Model A, though this association lessened dramatically in Model D. A test for an interaction effect between basement monitor location and basement entry was negative (results not presented here).

BASEMENT/NO CRAWLSPACE SUBSTRUCTURE

For basement homes without a crawlspace, a similar pattern appears. Basement construction materials, in the order of their apparent contribution to radon, are: poured concrete, block, brick, and stone and mortar. This order, and magnitude of effect, are roughly consistent with the findings of basement/crawlspace homes.

Standard basement entry routes were, again, not significant, though the presence of cracks had a marginal p-value and correctly signed coefficient in Model A. The presence of a woodstove or fireplace also was not an important explanatory factor.

An interaction term between basement monitor location and B-FINISH (using the basement as a bedroom or living area) was found to be significant in a separate test. The inclusion of this term in Model G resulted in a dramatic change in the effect of B_FINISH. Together, these variables would appear to have a substantial effect on radon. For a home with a basement used as a bedroom of living area, basement levels averaged nearly 5 times higher than in homes without finished basements.

Energy efficiency demonstrated the same relationship with radon as in basement/crawlspace homes.

Among the curiosities, the presence of central air conditioning or central forced-air heat, which may be inversely related to energy efficiency, demonstrated significance in Model A. Brick exterior was negatively related to radon, the opposite effect of that in basement/crawlspace homes.

CRAWLSPACE/NO BASEMENT SUBSTRUCTURE

In homes with a crawlspace but no basement, having an entrance to the crawlspace from the home interior was an important predictor of radon in all models. Insulation and ventilation of crawlspace were directionally consistent with theory, through p-values were marginal.

A number of curious associations were found. Having an attic fan was consistently an important explanatory variable, though in the opposite direction generally expected from theory. Other variables, such as having hot water heat, gravity feed furnace, and "other" fuel type, had low or marginally low p-values in at least one model. Having a gravity feed furnace, for example, produced an average 75% increase in home radon level. Explanations for such associations are unclear.

SLAB-ON-GRADE SUBSTRUCTURE

For slab-on-grade homes, age of house and energy efficiency (which may be related to age of house) were consistently important explanatory factors, indicating that the older and less energy-efficient the home, the lower the radon.

A curiosity was the very strong inverse relationship between central air conditioning and radon. Having central air was associated with an average decrease in radon of about 50%. Having a fireplace or woodstove was associated with a decrease in radon, though p-values were relatively large.

Because of the relatively small sample size for slab-on-grade homes, caution should be used in assessing the importance of variables based on p-value alone.

## DISCUSSION

A number of limitations should be recognized when drawing conclusions from this study. The methods used to select homes for testing produce a greater likelihood of bias than more rigorous, pseudo-random selection methods. Though reasonable steps were taken to assure quality and consistency in data collection, the use of local personnel and home occupants is likely to introduce some error.

Because sampling was conducted by independent local agencies as time permitted, a correlation between local factors (such as housing or geology) and time-variant factors (such as weather) may have been introduced. In addition, lack of local geological data means that correlations between geology and household conditions cannot be identified. Thus, some results may be due to the confounding effects of geology and time-variant factors.

Finally, due to the high degree of correlation between variables, modeling is prone to error. Model results should be considered suggestive, not confirmatory, evidence of the actual underlying relationships.

It appears that the vast majority of radon variation is due to factors other than the common household factors considered in this analysis. Such factors may include differences in regional or local geology, housing construction types, weather conditions at the time of monitoring, or household factors not considered (such as the existence of thermal bypasses or vented appliances). This does **not** indicate, however, that the factors considered in this survey are not important determinants of radon (for example having a brick foundation may increase radon readings an average of 50%) but only that other factors appear to be more important in explaining the **variation** between houses. Household factors may not be consistent in their effects. This supports policy recommendations that all homes be tested for radon, despite the apparent presence or absence of known risk factors.

Location of the monitor in the basement produced, as expected, a significant increase in radon concentration. Location of the monitor in the bedroom, as opposed to elsewhere on the first floor, was generally unimportant. For research primarily intended to evaluate determinants of home radon concentrations, first floor monitoring in all homes is desirable to allow direct comparisons across all house types.

Season of monitoring was an important explanatory factor. However, the relationship between season and home radon concentration was not consistent with other investigations nor was it consistent across housing substructures. The finding that summer radon concentrations could be as high or higher than other seasons suggests that current guidelines for winter monitoring be reevaluated. However, since these data reflect the measurement of different homes in different seasons, they should be interpreted with caution. Additional research on seasonal effects in the Midwest and elsewhere in the country are needed.

Basement foundation construction material was a relatively consistent predictor of radon. Brick and stone foundations were consistently higher than poured concrete, even after adjustment for age of house. Block foundations were slightly elevated compared to poured concrete. This suggests opportunities for low cost mitigative strategies if foundation walls are accessible, and if a suitable radon barrier can be found.

An entrance to a crawlspace was consistently associated with increased radon. Insulation, exposed earth, and lack of ventilation in the crawlspace were also associated with increased radon, though less consistently. These findings suggest that the common weatherization practices of sealing crawlspace entries, insulating floors, and installing vapor barriers not only save energy, but may reduce radon (through vapor barriers may need to be sealed and vented). Limiting crawlspace ventilation as an energy-saving measure, however, does not appear advisable.

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TABLE 1. VARIABLE NAMES, EXPLANATIONS, CODING, AND THEORETICAL RELATIONSHIP TO INDOOR RADON CONCENTRATION

| Variable name | Description | Coding[a] | Relationship to indoor radon[b,c] |
|---|---|---|---|
| Substructure[d] | | | |
| BMTCRL | Basement and crawlspace | | + |
| BMTNCC | Basement but no crawlspace | | |
| CRLNOB | Crawlspace but no basement | | |
| SLAB | Slab-on-grade only | | - |
| Season | | | |
| WINTER | Monitoring done during the winter | | ++ |
| SPRING | Monitoring done during the spring | | |
| SUMMER | Monitoring done during the summer | | -- |
| FALL | Monitoring done during the fall | | |
| Monitor | | | |
| LOCBMT | Monitor located in the basement | | ++ |
| LOCBDR | Monitor located in the bedroom | | -- |
| OTHER | Monitor located somewhere else on first floor | | -- |
| N_PEOPLE | How many people will be living in the house for the next month? | count | - |
| LNAGEHS | What is the age of the house? | natural log of years | +/- |
| N_SMOKER | Is there at least one smoker in the house? | | - |
| ADJ_SLAB | Does the house have any attached asphalt or concrete slabs(attached garage, carport slab, patio, driveway, etc.)? | | + |
| PC_BRICK | What percent of the outside of the house is covered with brick? | 0%=0, >0%=1 | + |
| ENER_EFF | Sum of occupant ratings on five energy efficiency characteristic. Each characteristic rated on scale of 1 to 5. | A scale of 5=least to 25=most energy efficient | +/- |
| CENT_AC | Do you use central air-conditioning during warm weather? | | +/- |
| ROOM_AC | Do you use a room air_conditioner during warm weather? | | ? |
| FAN_ATIC | Do you use a whole house and/or attic fan during warm weather? | | + |

TABLE 1. VARIABLE NAMES, EXPLANATIONS, CODING, AND THEORETICAL RELATIONSHIP TO INDOOR RADON CONCENTRATION (CONTINUED)

| Variable name | Description | Coding[a] | Relationship to indoor radon[b,c] |
|---|---|---|---|
| CENT_FA | Do you use a forced air central heating system during cold weather? | | +/- |
| W_BASE | Do you use a hot water baseboard or radiator system during cold weather? | | +/- |
| CENT_GF | Do you use a gravity flow central heating system during cold weather? | | +/- |
| ELEC_SPA | Do you use an electric space heater during cold weather? | | ? |
| WOOD | Do you use a fireplace or wood burning stove during cold weather? | | +/- |
| KEROHEAT | Do you use a kerosene space heater during cold weather? | | ? |
| GAS_STOV | Do you use a gas stove during cold weather? | | + |
| HEAT_OTHER | Do you use some other kind of heating system during cold weather that was not mentioned on this questionnaire? If so, specify. | | ? |
| B_FINISH | Is all or a portion of the basement frequently used as a bedroom or living area? (If so, speci | | ? |
| Foundation | The outside basement walls are primarily composed | | |
| BLOCK | Concrete or cinder block | | + |
| CRET | Poured concrete | | - |
| MORT | Stone and mortar | | + |
| BRK | Brick | | + |
| OTHER | Other and tile | | ? |
| ENT_BASE | Can you enter the basement from inside the house? | | +/- |
| CRACKS | Does the basement floor(or sub-surface floor in a split-level home) have large cracks or holes? | | + |
| DRAINS | Does the basement floor(or sub_surface floor in a split-level home) have drains? | | + |
| SUMP | Does the basement floor(or sub-surface floor in a split-level home) have sump pumps? | | + |

TABLE 1. VARIABLE NAMES, EXPLANATIONS, CODING, AND THEORETICAL RELATIONSHIP TO INDOOR RADON CONCENTRATION (CONTINUED)

| Variable name | Description | Coding[a] | Relationship to indoor radon[b,c] |
|---|---|---|---|
| EARTH | Does the basement floor(or sub-surface floor in a split-level home) have exposed earth? | | + |
| CSP_ENTR | Can you enter the crawl space from inside the house(from basement, for example)? | | + |
| CSP_INSL | Is the floor above the crawl space insulated? | | - |
| CSP_VENT | Will the crawl space be vented to the outside during the monitoring period? | | - |
| CSP_EXP | Does the crawl space have exposed earth? | | + |

a. All Yes/No variables codes as 0=no, 1=yes

b. ++ = strongly and positively related
 + = positively related
 - = negatively related
 -- = strongly and negatively related
 +/- = both positive and negative relationships may be expected
 ? = too little information to predict a relationship

c. Based largely upon references 1 through 11

d. These variables were used to define datasets and do not appear explicitly in later tables.

TABLE 2: ANALYSIS OF VARIANCE RESULTS FOR RADON CONCENTRATION BY SUBSTRUCTURE TYPE.

| Monitor Location | Substructure type | Geometric mean concentration (pCi/l) | Geometric Standard Dev. | N |
|---|---|---|---|---|
| All(a) | All types | 2.84 | 2.30 | 3,021 |
| | Basement and crawlspace | 3.56 | 2.21 | 752 |
| | Crawlspace, no basement | 1.67 | 2.11 | 572 |
| | Basement, no crawlspace | 3.16 | 2.21 | 1,548 |
| | Slab-on-grade only | 2.32 | 2.33 | 134 |
| First floor(b) | All types | 1.79 | 2.14 | 853 |
| | Basement and crawlspace | 1.95 | 1.88 | 78 |
| | Crawlspace, no basement | 1.67 | 2.11 | 572 |
| | Basement, no crawlspace | 1.81 | 2.07 | 69 |
| | Slab-on-grade only | 2.32 | 2.33 | 134 |

(a) p-value = <.001 for at least two means differing by substructure type.
(b) p-value = <.001 for at least two means differing by substructure type.

TABLE 3: GEOMETRIC MEAN CONCENTRATION IN pCi/l (AND SAMPLE SIZE) BY SEASON OF MONITORING AND SUBSTRUCTURE TYPE[a]

| | BASEMENT CRAWLSPACE | BASEMENT NO CRAWLSPACE | NO BASEMENT CRAWLSPACE | NO BASEMENT NO CRAWLSPACE |
|---|---|---|---|---|
| SEASON | | | | |
| WINTER | 3.74 (509) | 3.22 (1137) | 1.68 (354) | 2.27 (97) |
| SPRING | 2.34 (122) | 2.51 (218) | 1.39 (103) | 2.83 (17) |
| SUMMER | 4.76 (65) | 3.74 (118) | 1.67 (45) | 2.34 (14) |
| FALL | 3.94 (56) | 3.78 ( 75) | 2.03 (70) | 1.70 (6) |

a. p-values = <.001 for both main effects and interaction

TABLE 4: MULTIPLE REGRESSION RESULTS FOR MODELS OF HOME RADON CONCENTRATION: HOMES BUILT OVER BASEMENT AND CRAWLSPACE

| VARIABLE | MODEL A | MODEL B | MODEL C | MODEL D | MODEL E | MODEL F | MODEL G |
|---|---|---|---|---|---|---|---|
| INTERCEPT | - | .62447 | .90441 | .63720 | .13636 | -.06271 | .42381 |
| | - | (<.01) | (<.01) | (<.01) | (<.01) | (.79) | (.20) |
| WINTER | -.13391 | | -.11985 | -.13353 | -.19473 | | -.17511 |
| | (.34) | | (.38) | (.34) | (.14) | | (.19) |
| SPRING | -.60418 | | -.54158 | -.62871 | -.66264 | -.48379 | -.64939 |
| | (<.01) | | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) |
| SUMMER | .15321 | | .10257 | .05199 | -.03172 | | -.08679 |
| | (.74) | | (.82) | (.91) | (.94) | | (.84) |
| LOCBMT | .66483 | .66483 | .57401 | .55822 | .58134 | .63876 | .57936 |
| | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) |
| LOCBDR | -.02230 | -.02230 | -.08867 | -.22949 | -.11436 | | -.11565 |
| | (.91) | (.91) | (.65) | (.24) | (.55) | | (.54) |
| N_PEOPLE | -.05905 | | | -.05277 | | | -.04495 |
| | (.03) | | | (.05) | | | (.07) |
| ADJ_SLAB | .10375 | | | .08877 | | | |
| | (.17) | | | (.26) | | | |
| N_SMOKER | .09009 | | | .10630 | | | |
| | (.21) | | | (.13) | | | |
| LNAGEHS | -.04625 | | | -.05477 | | | -.06157 |
| | (.18) | | | (.20) | | | (.13) |
| ENER_EFF | .02528 | | | .01958 | .02655 | .02516 | .02513 |
| | (.01) | | | (.04) | (<.01) | (<.01) | (<.01) |
| PC_BRICK | -.07020 | | | .50320 | | .34598 | |
| | (.45) | | | (<.01) | | (<.01) | |
| CENT_AC | .09944 | | | .08401 | | | |
| | (.17) | | | (.33) | | | |
| ROOM_AC | -.14919 | | | -.06130 | | | |
| | (.06) | | | (.49) | | | |
| FAN_ATIC | .05429 | | | .10389 | | | |
| | (.60) | | | (.30) | | | |
| CENT_FA | .05843 | | | -.03392 | | | |
| | (.52) | | | (.81) | | | |
| W_BASE | -.05531 | | | .01585 | | | |
| | (.62) | | | (.92) | | | |
| CENT_GF | -.30802 | | | -.27069 | | | |
| | (.19) | | | (.26) | | | |
| ELEC_SPA | -.22500 | | | -.02960 | | | |
| | (.06) | | | (.80) | | | |
| FP_WS_HE | -.03622 | | | -.10073 | | | |
| | (.63) | | | (.16) | | | |
| KEROHEAT | -.09649 | | | .00570 | | | |
| | (.47) | | | (.96) | | | |
| GAS_STOV | -.31293 | | | -.24238 | | | |
| | (.14) | | | (.24) | | | |
| HEAT_OTHER | .12606 | | | .31080 | | | |
| | (.35) | | | (.03) | | | |

TABLE 4: MULTIPLE REGRESSION RESULTS FOR MODELS OF HOME RADON CONCENTRATION:
HOMES BUILT OVER BASEMENT AND CRAWLSPACE (CONTINUE)

| VARIABLE | MODEL A | MODEL B | MODEL C | MODEL D | MODEL E | MODEL F | MODEL G |
|---|---|---|---|---|---|---|---|
| BLOCK | .09408 | | | .10501 | | | .13430 |
| | (.27) | | | (.23) | | | (.10) |
| MORT | .13457 | | | .41139 | | | .39434 |
| | (.32) | | | (<.01) | | | (<.01) |
| BRK | .33532 | | | -.13263 | .34835 | | .50465 |
| | (<.01) | | | (.15) | (<.01) | | (<.01) |
| OTHERBMT | .18767 | | | .32299 | | | .34548 |
| | (.21) | | | (.03) | | | (.02) |
| B_FINISH | .01927 | | | .02686 | | | |
| | (.81) | | | (.75) | | | |
| ENT_BASE | .26429 | | | .05568 | | | |
| | (.02) | | | (.61) | | | |
| CRACKS | -.05275 | | | -.03644 | | | |
| | (.47) | | | (.61) | | | |
| DRAINS | -.04133 | | | -.11459 | | | |
| | (.66) | | | (.20) | | | |
| SUMP | -.03177 | | | -.00855 | | | |
| | (.66) | | | (.26) | | | |
| EARTH | .06191 | | | .08333 | | | |
| | (.45) | | | (.32) | | | |
| CSP_ENTR | .30078 | | | .21091 | .23927 | .22295 | .25269 |
| | (<.01) | | | (.03) | (.01) | (.01) | (<.01) |
| CSP_INSL | -.03825 | | | -.06228 | | | |
| | (.62) | | | (.40) | | | |
| CSP_VENT | -.13419 | | | -.20053 | -.18782 | -.18901 | -.19699 |
| | (.07) | | | (<.01) | (.01) | (.01) | (.01) |
| CSP_EXP | .06678 | | | .09223 | .19421 | .20200 | .14370 |
| | (.47) | | | (.34) | (.03) | (.02) | (.13) |
| Multiple $R^2$ | | .07481 | .12360 | .25315 | .19353 | .18892 | .21718 |
| (p-value) | | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) |
| $R^2$-Change | | | .04879 | .12955 | | | |
| (p-value) | | | (<.01) | (<.01) | | | |

TABLE 5: MULTIPLE REGRESSION RESULTS FOR MODELS OF HOME RADON CONCENTRATION:
HOMES BUILT OVER BASEMENT BUT NO CRAWLSPACE

| VARIABLE | MODEL A | MODEL B | MODEL C | MODEL D | MODEL E | MODEL F | MODEL G |
|---|---|---|---|---|---|---|---|
| INTERCEPT | - | .68446 | .96252 | .73018 | .84825 | .50784 | .78389 |
| | - | (<.01) | (<.01) | (.02) | (<.01) | (.02) | (<.01) |
| WINTER | -.18722 | | -.16864 | -.20245 | -.17015 | | -.17590 |
| | (.13) | | (.17) | (.10) | (.16) | | (.14) |
| SPRING | -.46281 | | -.41092 | -.42518 | -.40259 | -.23534 | -.41147 |
| | (<.01) | | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) |
| SUMMER | -.09921 | | -.09921 | -.11711 | -.07166 | | -.09674 |
| | (.76) | | (.76) | (.71) | (.82) | | (.76) |
| LOCBMT | .47646 | .47646 | .39752 | .40905 | .39413 | .57138 | .39319 |
| | (<.01) | (<.01) | (.01) | (<.01) | (.01) | (<.01) | (<.01) |
| LOCBDR | -.29852 | -.29852 | -.33525 | -.47366 | -.43520 | -.47317 | -.36979 |
| | (.19) | (.19) | (.14) | (.04) | (.05) | (.04) | (.11) |
| N_PEOPLE | .02780 | | | .03166 | | | |
| | (.12) | | | (.08) | | | |
| ADJ_SLAB | .07140 | | | .11599 | | | |
| | (.16) | | | (.04) | | | |
| N_SMOKER | .02038 | | | -.00685 | | | |
| | (.67) | | | (.89) | | | |
| LNAGEHS | -.02615 | | | -.08970 | | -.08629 | -.09404 |
| | (.29) | | | (<.01) | | (<.01) | (<.01) |
| ENER_EFF | .01519 | | | .02134 | .01692 | .01666 | .01699 |
| | (.02) | | | (<.01) | (.01) | (.02) | (.01) |
| PC_BRICK | -.11062 | | | -.07839 | | | |
| | (.04) | | | (.15) | | | |
| CENT_AC | -.11208 | | | -.12129 | -.12048 | -.12346 | |
| | (.02) | | | (.05) | (.02) | (.02) | |
| ROOM_AC | .04593 | | | -.08926 | | | |
| | (.43) | | | (.21) | | | |
| FAN_ATIC | -.11001 | | | -.09317 | | | |
| | (.13) | | | (.20) | | | |
| CENT_FA | -.11838 | | | -.13650 | | | -.11611 |
| | (.05) | | | (.24) | | | (.04) |
| W_BASE | .10301 | | | -.03680 | | | |
| | (.15) | | | (.77) | | | |
| CENT_GF | .01615 | | | -.14266 | | | |
| | (.92) | | | (.47) | | | |
| ELEC_SPA | -.02207 | | | -.02826 | | | |
| | (.80) | | | (.75) | | | |
| FP_WS_HE | .02871 | | | .01815 | | | |
| | (.57) | | | (.72) | | | |
| KEROHEAT | .11347 | | | .12184 | | | |
| | (.29) | | | (.25) | | | |
| GAS_STOV | -.01028 | | | .02939 | | | |
| | (.94) | | | (.83) | | | |
| HEAT_OTHER | .06506 | | | -.03535 | | | |
| | (.52) | | | (.77) | | | |
| BLOCK | .21535 | | | .28573 | .27904 | .26975 | .27563 |
| | (<.01) | | | (<.01) | (<.01) | (<.01) | (<.01) |

TABLE 5: MULTIPLE REGRESSION RESULTS FOR MODELS OF HOME RADON CONCENTRATION: HOMES BUILT OVER BASEMENT BUT NO CRAWLSPACE (CONTINUED)

| VARIABLE | MODEL A | MODEL B | MODEL C | MODEL D | MODEL E | MODEL F | MODEL G |
|---|---|---|---|---|---|---|---|
| MORT | .35438 | | | .46092 | .48845 | .48387 | |
| | (<.01) | | | (<.01) | (<.01) | (<.01) | |
| BRK | .26990 | | | .38522 | .40233 | .40290 | .49618 |
| | (<.01) | | | (<.01) | (<.01) | (<.01) | (<.01) |
| OTHERBMT | -.04626 | | | .07880 | | | .39319 |
| | (.72) | | | (.55) | | | (<.01) |
| B_FINISH | -.06937 | | | -.10759 | | -.11224 | .08526 |
| | (.15) | | | (.03) | | (.02) | (.51) |
| LOCFIN (a) | | | | | | | .64436 |
| | | | | | | | (.12) |
| ENT_BASE | .02046 | | | -.01569 | | | -.74116 |
| | (.85) | | | (.89) | | | (.08) |
| CRACKS | .08293 | | | .05840 | | | |
| | (.09) | | | (.25) | | | |
| DRAINS | .04636 | | | .06675 | | | |
| | (.52) | | | (.35) | | | |
| SUMP | -.02555 | | | -.04301 | | | |
| | (.59) | | | (.39) | | | |
| EARTH | .09408 | | | .13934 | | | .15700 |
| | (.31) | | | (.15) | | | (.10) |
| Multiple $R^2$ | | .02426 | .03894 | .10581 | .08507 | .08036 | .09169 |
| (p-value) | | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) | (<.01) |
| $R^2$-Change | | | .01468 | .06687 | | | |
| (p-value) | | | (<.01) | (<.01) | | | |

TABLE 6: MULTIPLE REGRESSION RESULTS FOR MODELS OF HOME RADON CONCENTRATION: HOMES BUILT OVER CRAWLSPACE BUT NO BASEMENT

| VARIABLE | MODEL A | MODEL B | MODEL C | MODEL D | MODEL E | MODEL F | MODEL G |
|---|---|---|---|---|---|---|---|
| INTERCEPT | - | .43901 | .63841 | .28924 | .60853 | .50219 | .74458 |
| | - | (<.01) | (<.01) | (.42) | (<.01) | (<.01) | (<.01) |
| WINTER | -.16455 | | -.19250 | -.23470 | -.26874 | | -.29359 |
| | (.14) | | (.09) | (.07) | (.02) | | (.01) |
| SPRING | -.38879 | | -.42165 | -.40197 | -.44044 | -.19195 | -.50885 |
| | (<.01) | | (<.01) | (.01) | (<.01) | (.03) | (<.01) |
| SUMMER | -.21478 | | -.27490 | -.32321 | -.41428 | | -.39123 |
| | (.24) | | (.14) | (.11) | (.03) | | (.04) |
| LOCBMT | | | | | | | |
| LOCBDR | .11316 | .11316 | .14463 | .15581 | .17344 | | .15547 |
| | (.13) | (.13) | (.05) | (.04) | (.02) | | (.04) |
| N_PEOPLE | .00389 | | | .01128 | | | |
| | (.89) | | | (.70) | | | |
| ADJ_SLAB | .04341 | | | .10461 | | | |
| | (.58) | | | (.20) | | | |
| N_SMOKER | .11543 | | | .06467 | | | |
| | (.11) | | | (.38) | | | |
| LNAGEHS | .04566 | | | .03790 | | | |
| | (.24) | | | (.41) | | | |
| ENER_EFF | .00355 | | | .01355 | | | |
| | (.72) | | | (.21) | | | |
| PC_BRICK | .02862 | | | .03722 | | | |
| | (.77) | | | (.71) | | | |
| CENT_AC | -.02534 | | | .06893 | | | |
| | (.72) | | | (.51) | | | |
| ROOM_AC | .01281 | | | .02986 | | | |
| | (.87) | | | (.77) | | | |
| FAN_ATIC | -.29695 | | | -.25446 | -.24573 | -.26775 | |
| | (<.01) | | | (.02) | (.02) | (.01) | |
| CENT_FA | -.05006 | | | -.17104 | | | |
| | (.52) | | | (.22) | | | |
| W_BASE | .30619 | | | .22883 | .36088 | .32856 | |
| | (.03) | | | (.21) | (.01) | (.02) | |
| CENT_GF | -.57371 | | | -.56661 | | | |
| | (.07) | | | (.09) | | | |
| ELEC_SPA | -.16027 | | | -.11494 | | | |
| | (.18) | | | (.35) | | | |
| FP_WS_HE | -.07852 | | | -.06947 | | | |
| | (.34) | | | (.40) | | | |
| KEROHEAT | -.06352 | | | -.00899 | | | |
| | (.71) | | | (.96) | | | |
| GAS_STOV | .19141 | | | .07700 | | | |
| | (.17) | | | (.64) | | | |
| HEAT_OTHER | -.19467 | | | -.24163 | | | |
| | (.09) | | | (.12) | | | |
| CSP_ENTR | .22661 | | | .28046 | .26974 | .21505 | .28106 |
| | (<.01) | | | (<.01) | (<.01) | (.01) | (<.01) |

TABLE 6: MULTIPLE REGRESSION RESULTS FOR MODELS OF HOME RADON CONCENTRATION: HOMES BUILT OVER CRAWLSPACE BUT NO BASEMENT (CONTINUED)

| VARIABLE | MODEL A | MODEL B | MODEL C | MODEL D | MODEL E | MODEL F | MODEL G |
|---|---|---|---|---|---|---|---|
| CSP_INSL | -.12095 | | | -.11359 | | | -.10899 |
| | (.12) | | | (.16) | | | (.14) |
| CSP_VENT | -.08019 | | | -.13048 | | | -.12354 |
| | (.26) | | | (.08) | | | (.09) |
| CSP_EXP | .03655 | | | .01987 | | | |
| | (.69) | | | (.83) | | | |
| Multiple $R^2$ | | .00492 | .02936 | .11306 | .07685 | .05571 | .06398 |
| (p-value) | | (.13) | (.01) | (<.01) | (<.01) | (.00) | (<.01) |
| $R^2$-Change | | | .02444 | .08370 | | | |
| (p-value) | | | (.01) | (.01) | | | |

TABLE 7: MULTIPLE REGRESSION RESULTS FOR MODELS OF HOME RADON CONCENTRATION: HOMES BUILT OVER SLAB-ON-GRADE ONLY

| VARIABLE | MODEL A | MODEL B | MODEL C | MODEL D | MODEL E | MODEL F | MODEL G |
|---|---|---|---|---|---|---|---|
| INTERCEPT | - | .72577 | .30640 | -1.88722 | .47208 | 1.07722 | -1.47057 |
| | - | (<.01) | (.44) | (.08) | (.23) | (<.01) | (.05) |
| WINTER | .44310 | | .43118 | .55750 | .49918 | | .40731 |
| | (.27) | | (.28) | (.18) | (21) | | (.30) |
| SPRING | .70936 | | .63447 | .79930 | .63153 | | .63846 |
| | (.11) | | (.16) | (.09) | (.15) | | (.15) |
| SUMMER | .45747 | | .38257 | .59130 | .56041 | | .36715 |
| | (.32) | | (.41) | (.22) | (.23) | | (.42) |
| LOCBDR | .24511 | .24511 | .21398 | .11732 | .19420 | | .19473 |
| | (.14) | (.14) | (.21) | (.52) | (.25) | | (.24) |
| N_PEOPLE | -.06949 | | | -.04225 | | | |
| | (.31) | | | (.59) | | | |
| N_SMOKER | .25388 | | | .26591 | | | |
| | (.13) | | | (.13) | | | |
| LNAGEHS | .13552 | | | .23415 | | | .23172 |
| | (.14) | | | (.03) | | | (.02) |
| ENER_EFF | .03208 | | | .08430 | | | .05745 |
| | (.17) | | | (<.01) | | | (.03) |
| PC_BRICK | -.09390 | | | -.23546 | | | |
| | (.65) | | | (.28) | | | |
| CENT_AC | -.39525 | | | -.54079 | -.39441 | -.39525 | |
| | (.02) | | | (.01) | (.02) | (.02) | |
| ROOM_AC | .10428 | | | -.41429 | | | |
| | (.60) | | | (.13) | | | |
| FAN_ATIC | .26593 | | | .57891 | | | |
| | (.43) | | | (.10) | | | |
| CENT_FA | -.16207 | | | .20092 | | | |
| | (.39) | | | (.54) | | | |
| W_BASE | .13815 | | | .38537 | | | |
| | (.63) | | | (.31) | | | |
| CENT_GF | .11750 | | | .32170 | | | |
| | (.82) | | | (.58) | | | |
| ELEC_SPA | -.03449 | | | .13368 | | | |
| | (.92) | | | (.71) | | | |
| FP_WS_HE | -.21622 | | | -.25058 | | | |
| | (.24) | | | (.19) | | | |
| KEROHEAT | .73459 | | | .91013 | | | |
| | (.24) | | | (.17) | | | |
| GAS_STOV | -.20941 | | | .20125 | | | |
| | (.64) | | | (.70) | | | |
| HEAT_OTHER | .09399 | | | .01911 | | | |
| | (.72) | | | (.95) | | | |
| Multiple $R^2$ | | .03009 | .03912 | .24870 | .08740 | .05156 | .10304 |
| (p-value) | | (.14) | (.37) | (.10) | (.08) | (.02) | (.07) |
| $R^2$-Change | | | .01904 | .20958 | | | |
| (p-value) | | | (.55) | (.09) | | | |

# RADON IN FEDERAL BUILDINGS

Michael Boyd
U.S. Environmental Protection Agency
Office of Radiation Programs
Washington, DC 20460

Terry Inge
Sandy Cohen and Associates
McLean, VA 22101

## ABSTRACT

The Environmental Protection Agency (EPA) has provided guidance to Federal agencies in response to requirements of the Indoor Radon Abatement Act (IRAA) for testing Federal buildings for radon. Twenty-two agencies have reported complete or partial results to EPA. These data are included in the first report to Congress on radon in Federal buildings which is now in preparation. Initial analysis indicates that the percentage of Federal buildings tested with screening levels above 4 picocuries per liter (pCi/L) may be somewhat lower than that routinely cited for houses. However, given the large number of such buildings in the U.S., this percentage indicates there are many Federal buildings with elevated radon levels. Except for the Armed Services, most of the Federal studies have focused on office buildings. The data collected thus far does clearly demonstrate that office buildings are not immune to radon problems. Because of the large number of people that work in a typical multistory office building, and the ease with which radon can be transported through a building's ventilation system, the Federal Building Survey results have already demonstrated the prudence of testing the workplace for radon.

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 Indoor Radon Abatement Act (IRAA) was passed by Congress in October, 1988. Among its provisions was a requirement in Section 309 for all Federal departments and agencies that own buildings to test a representative sample of those buildings for radon. The Environmental Protection Agency (EPA) reviewed the radon study designs submitted by each affected agency and provided information available on high risk areas, testing protocols, and other technical guidance. EPA also provided direct support (measurement devices, device analysis, quality control activities) to interested agencies through interagency agreements (IAGs).

EPA established contact with 48 Federal departments and agencies and notified them of the provisions of IRAA. It was determined that 23 of these agencies owned at least some of their own buildings and were responsible for conducting radon surveys. Many of the remaining agencies had their buildings tested by the General Services Administration (GSA).

The first report to Congress on the results of radon testing has been drafted and includes at least some results from 22 of the 23 affected agencies. The reporting agencies primarily used passive detectors (typically alpha track detectors or activated charcoal devices) to make screening measurements of radon in ground contact rooms, stairwells, and on upper floors near elevator shafts and ventilation ducts. The duration of the radon tests ranged from 2 - 7 days for the charcoal devices to 3 months for the alpha track detectors. Some agencies, such as GSA, chose to sample all of their buildings, while others sampled only a portion. The EPA shared with other Federal agencies existing information on surface uranium deposits in the U.S. as well as the results of State radon surveys. Some agencies used this information to select regions to include in their sampling strategy.

The testing plans of the agencies differed in certain aspects including the type of detector used, the sampling strategy, the length of time the detector was deployed, and the season during which the test was conducted. Nevertheless, there is remarkable similarity between the surveys. Initial analysis indicates that the percentage of Federal buildings tested with screening levels above 4 picocuries per liter (pCi/L) may be somewhat lower than that routinely cited for houses (see Tables 1 & 2). Because many buildings operate under steady-state conditions and because seasonal differences may not be as important a factor in determining radon entry in big buildings as it is for houses, the results reported in this paper may not differ greatly from the annual averages. Most agencies have already begun performing long term tests in areas that screened above 4 pCi/L. Results from these tests will be useful in determining how much variability in radon levels occurs as a result of seasonal changes.

The types of buildings owned by a particular agency have a significant effect on the measurement results. For example, laboratories with one-pass air handling systems and large office buildings with significant outside air intake tend to have fewer radon problems than smaller buildings or houses. In addition to larger buildings, the Army, Navy, and Air Force also conducted residential testing. Because of the large number of test results reported by the Army, the distribution of radon levels by Army building type is presented later in this paper.

## MATERIALS AND METHOD

EPA reviewed and ultimately approved the radon survey designs submitted by Federal agencies. Approval of the plans was often contingent on an agency agreeing to modifications suggested by EPA. Many of the agencies chose to perform 3-month measurements using alpha track detectors. The next most popular device was the diffusion barrier charcoal canister which was typically deployed for 5 to 7 days. Electret ion chambers and continuous monitors were also used in some cases. EPA's policy is that any measurement device listed in the Indoor Radon and Radon Decay Product Measurement Protocols (EPA 520/1-89-033, March 1989) is acceptable for making short-term measurements, except that grab sampling may not be used alone. Grab sampling can be a useful confirmatory measurement made in conjunction with a measurement from some other approved device.

In responding to the survey designs, EPA recommended that all occupiable rooms in ground contact be tested. Open areas in ground contact were recommended to be tested at a density of one detector every 2000 square feet. In addition, it was recommended to place at least one detector on every floor. Placement of detectors in stairwells, near elevator shafts, and in the vicinity of each vertical service shaft was encouraged.

Agencies were advised to test during the winter heating season when possible. The reporting constraints imposed by IRAA did result in extensive testing during other seasons, however. EPA is currently investigating the effect of climate on indoor radon concentrations in big buildings. Preliminary indications are that seasonal differences do not have as marked an effect in big buildings as they do in houses.

IRAA also required private water supplies to be tested for radon. Since most Federal buildings are on public water supplies, very little water testing was performed.

## RESULTS

Many of the Federal agencies are still conducting radon surveys. This is particularly true for the Armed Services where world-wide testing and large property holdings are involved. The results reported to EPA as of February, 1991 are given in Table 1 for the total number of reported measurements and Table 2 for the total number of measured buildings. Each building represented in Table 2 is characterized by its highest single reading. It is not statistically valid to lump together surveys that have different sample selection strategies, differing measurement devices and techniques, and differing periods of measurement. Nevertheless, the results do provide a qualitative indication of the extent of radon contamination in big buildings.

Table 1. Preliminary Federal Agency Radon Survey Data
Summary Data for 84,642 Measurements

| Radon Concentration | Number of Measurements | Percent of Total |
|---|---|---|
| 0-2 pCi/L | 71,346 | 84.3 |
| 2-4 pCi/L | 8,851 | 10.5 |
| 4-10 pCi/L | 3,511 | 4.1 |
| 10-20 pCi/L | 812 | 1.0 |
| 20-200 pCi/L | 115 | 0.1 |
| > 200 pCi/L | 7 | <0.1 |

Table 2. Preliminary Federal Agency Radon Survey Data
Summary Data for 52,031 Buildings
(Includes 29,671 Army Housing Units)

| Radon Concentration | Number of Buildings | Percent of Total |
|---|---|---|
| 0-2 pCi/L | 42,864 | 82.4 |
| 2-4 pCi/L | 5,948 | 11.4 |
| 4-10 pCi/L | 2,469 | 4.7 |
| 10-20 pCi/L | 649 | 1.2 |
| 20-200 pCi/L | 94 | 0.2 |
| > 200 pCi/L | 7 | <0.1 |

The effect of combining measurement data from houses, schools, daycare centers, and hospitals with office building data has implications for the extent to which these surveys can be used to indicate radon contamination in big buildings. Fortunately, the data from the Army was coded so that building types could be analyzed separately. The Army survey uses alpha track detectors deployed for 90 days. Using the Army as an example, Figures 1 & 2 represent the format used for reporting data in the report to Congress. Figure 1 represents the total number of measurements by concentration range and Figure 2 represents the number of affected buildings, using the highest reading in each building to characterize it. Figures 3 - 5 represent the measurement data separated by building type. As these figures indicate, there is not a great difference between the radon distribution for these 3 categories. With the exception of the Army, Navy, and Air Force, most of the remaining agencies reported primarily the results of testing in the workplace.

Most agencies reported that their buildings were served by municipal water systems and so they were not required to test their water for radon. Radon concentrations in surface water and water that has been aerated are typically very low. A few agencies did report results for buildings served by private water supplies. Of the 163 water supplies tested, 46 were above 300 pCi/L.

Some agencies have offices that are located on the upper floors of multistory office buildings. If the Federal government does not occupy the entire building, then generally the Federal tenant may only legally test for radon on the floors that it occupies. Sharing space in large office buildings is common for EPA, with its 10 regional locations. EPA also has a significant number of field stations and laboratories that have one-pass air handling systems. For these reasons, EPA did not expect to find many instances of elevated radon levels in its buildings. This expectation proved correct as can be seen from the graphs of EPA's data (Figures 6 & 7). EPA's measurements were made with diffusion barrier charcoal canisters which were, in most cases, deployed from Monday morning until Friday afternoon. The canisters were then returned for analysis to one of the EPA Office of Radiation Programs (ORP) laboratories located in Montgomery, Alabama and Las Vegas, Nevada.

In general terms, distance from the source (usually the soil) and extent of dilution flow (degree of outside air intake and air exchange rate) have a major effect on radon concentrations on upper floors of buildings. EPA has not yet found an example where radon levels were above 4 pCi/L on upper floors of a building and below 4 pCi/L in the basement or ground-contact floor (the recommended screening location). For the usual case, where the source of radon is soil gas, simple diffusion will result in radon concentrations decreasing on upper floors of the building. Depending on the ventilation pattern, radon levels may not decrease in a linear fashion, floor by floor, as predicted by diffusion alone. In fact, the configuration of the air handling system may result in the second highest radon level in a building being found on the top floor. This case has been observed where the supply air was being pumped from the basement directly to the top floor to assist in cooling the building during the summer. In some cases, radon may enter a building through a conduit that penetrates the foundation. For this reason, telephone rooms and electrical cabinets are likely places to find radon on upper floors.

EPA's recommendations to Federal agencies to sample extensively in ground contact areas during periods of minimal outside air intake appears to be sound. The importance of testing big buildings during the winter is being examined in tests that will be completed this year. Based on these findings, an interim protocol for testing big buildings for radon will be issued. The Federal building surveys that have been completed to date indicate the need for increased testing of the workplace. A big building protocol will be especially useful for the expected increase in radon testing in this area.

For most Federal landlords, the minor costs associated with testing will be followed by the good news that their building does not have a radon problem. For those buildings that indicate elevated radon concentrations, a significant health threat will have been identified which can then be corrected. EPA is actively investigating diagnostic and mitigation tools for application in big buildings. It is anticipated that EPA will continue to provide support to agencies in addressing the mitigation of problem buildings and that the lessons learned and technologies developed from these efforts will be transferred to the private sector.

## CONCLUSIONS

Since the individual agency results have yet to be transmitted to the Congress, it would be premature to list them here. The results reported for EPA and the Army are by permission. Several conclusions from the Federal building study may be drawn.

1. Soil gas is the primary source of radon in Federal buildings, as it is for other building types.

2. The effect of seasonal differences on radon levels in big buildings has not yet been confirmed, but appears to be less significant than for houses and other small buildings. EPA still advises testing during the winter or during periods of minimal outside air intake.

3. The highest radon levels are most likely to be found in ground contact areas. Radon levels in other parts of a

building will be determined by the distribution pattern of air handling systems, by diffusion, and by the availability of direct paths to the sub-slab environment such as telephone and electrical conduits.

4. From the data received thus far, the percentage of Federal buildings with radon screening measurements above 4 pCi/L appears to be somewhat less than the corresponding percentage of houses. Because of the steady state conditions maintained in many big buildings, the difference between screening and annual measurements in big buildings may be less than for houses.

5. The sampling strategy presented by EPA, namely to test extensively in ground contact areas, in stairwells, outside elevator shafts, and near vertical service shafts, appears to be effective for locating buildings with potential radon problems.

6. Most Federal buildings are connected to municipal water supplies and are not expected to have significant radon in their water. For buildings that do use private water supplies, a significant percentage are likely to be above 300 pCi/L.

7. The prudence of testing workplaces for radon is confirmed by the results of this study.

# RADON IN SWITZERLAND

H.Surbeck and H.Völkle
Federal Office of Public Health
c/o Physics Institute, University
Pérolles
CH-1700 Fribourg, Switzerland

W.Zeller
Federal Office of Public Health
Bollwerk 27
CH-3001 Bern, Switzerland

## ABSTRACT

Based on measurements in nearly 1600 homes, representing 0.15% of the housing stock, we estimate that the Swiss live on the average in rooms with a radon concentration of 80 $Bq/m^3$ and that 5% of them are exposed to concentrations exceeding 200 $Bq/m^3$.

Radon research in Switzerland started nearly a decade ago and shows that building materials and household water use present no serious radon problems, the soil being the main radon source. The highest values are found in homes on highly permeable building grounds (Karst terrains, rockslides).

We discuss the results of the radon surveys and explain how we try to get a representative exposure estimate from biased data. We also present geological aspects of the radon situation in our country and outline the policy for the new decade that will see surveys concentrated on the search for hot spots.

Several mitigation techniques have been tested successfully but few homeowners are interested to take remedial actions. There is no great public concern on radon in Switzerland; radon is natural.

## INTRODUCTION

As early as in 1908 Gockel (1) reported on radon ("Radiumemanation") measurements in Switzerland. He already knew that the radon concentration in the soil gas depends on various geological factors, meteorological conditions like wind speed and on the soil moisture content !

Well seven decades later one started to realize that exposure to radon may present a serious health problem and small scale radon surveys were carried out in Switzerland in the early 1980s.

Alarmed by high values (up to 5 $kBq/m^3$ in living rooms) found in homes in a city in the Western Swiss Jura Mountains (2,3) a task force was set up to study the radon situation in Switzerland. This eventually has led to a nationwide 5-year research program (RAPROS) that started in 1987.

It took some time to correct the then widely accepted but unproven "facts" like : "high radon concentrations are mainly due to building materials", "granitic bedrock shows a high uranium concentration and therefore homes in the Alps have high radon levels", "there can't be high radon concentrations in homes on Jurassic limestone".

Building materials and domestic water use showed to be a negligible radon source in Switzerland (4,5), the main source being the soil. Enhanced $^{226}Ra$ have been found in various soils not of granitic origin and the highest activity (880 Bq/kg dry weight) has been measured in a soil covering Jurassic limestone.

We show the general radon situation in Switzerland and how we try to gain representative exposure estimates from biased data. Geological aspects of the radon problem are discussed. Mitigation techniques tested in Swiss homes are presented and the policy for the new decade is outlined. This policy is characterized by a concentrated search for radon hot-spots.

## GENERAL RADON SITUATION

### FREQUENCY DISTRIBUTION AND AVERAGE RADON EXPOSURE

The frequency distribution of the radon concentrations in about 5000 rooms, corresponding to nearly 1600 buildings, representing 0.15% of the

Swiss residential housing stock, is shown in figure 1. The radon levels have been determined by exposing passive (etched-track) detectors for at least two months. In general two detectors are placed per building, one in the basement and one in an inhabited room at or above ground floor. We ask people to use the rooms as usual in order to get radon concentrations under realistic conditions. About 80% of the measurements have been carried out during the winter. Few homes are represented by both summer- and winter-values. These measurements show that summer levels are on the average 1/3 lower than the winter levels.

The raw data in figure 1 are not representative for the radon exposure of the Swiss for the following reasons :

1) Mainly in early surveys single family homes are overrepresented.

2) Certain regions are overrepresented due to particular research programs like the search for radon sources in the Jura Mountains (6) or because of the initiative of local authorities.

3) Most measurements have been carried out during the winter and thus don't give the annual mean.

To correct for bias 1) we sort the room data into building classes like single family homes, blocks of flats, farms and "others". For multistory buildings different stories (up to the forth floor) form separate classes. For every class the number of radon values falling into a concentration interval (subclass) is then multiplied by the percentage of the population living in the respective class (1980 census data). Summing up the weighted subclass contents over all classes leads to the new frequency distribution. This first weighting is carried out for every canton (State of the Swiss Confederation) or in the case of small cantons for a group of cantons.

To correct for bias 2) the numbers in the subclasses of each canton are multiplied by the percentage of the Swiss population living in this canton. This frequency distribution having an arithmetic mean of 80 Bq/m3 is more representative for the radon concentration to which the Swiss are exposed in their homes than the arithmetic mean of 140 $Bq/m^3$ from the raw data in figure 1.

The mean of 80 $Bq/m^3$ still lacks the correction for bias 3) and for the fact that few people stay at home 24 hours a day. We estimate that these two factors lower the above 80 $Bq/m^3$ to an annual mean of about 70 $Bq/m^3$.

The Swiss map in figure 2 shows the geographical terms used.

## REGIONAL DISTRIBUTION

In figure 3 we show the regional distribution of the 1540 buildings that have at least one inhabited room at or above ground floor measured.

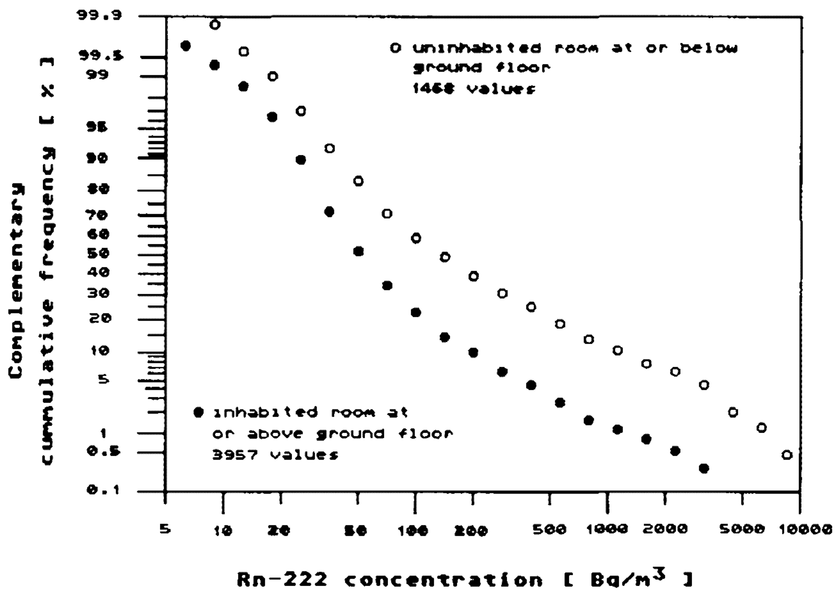



Figure 1. Frequency distribution of radon measurement results

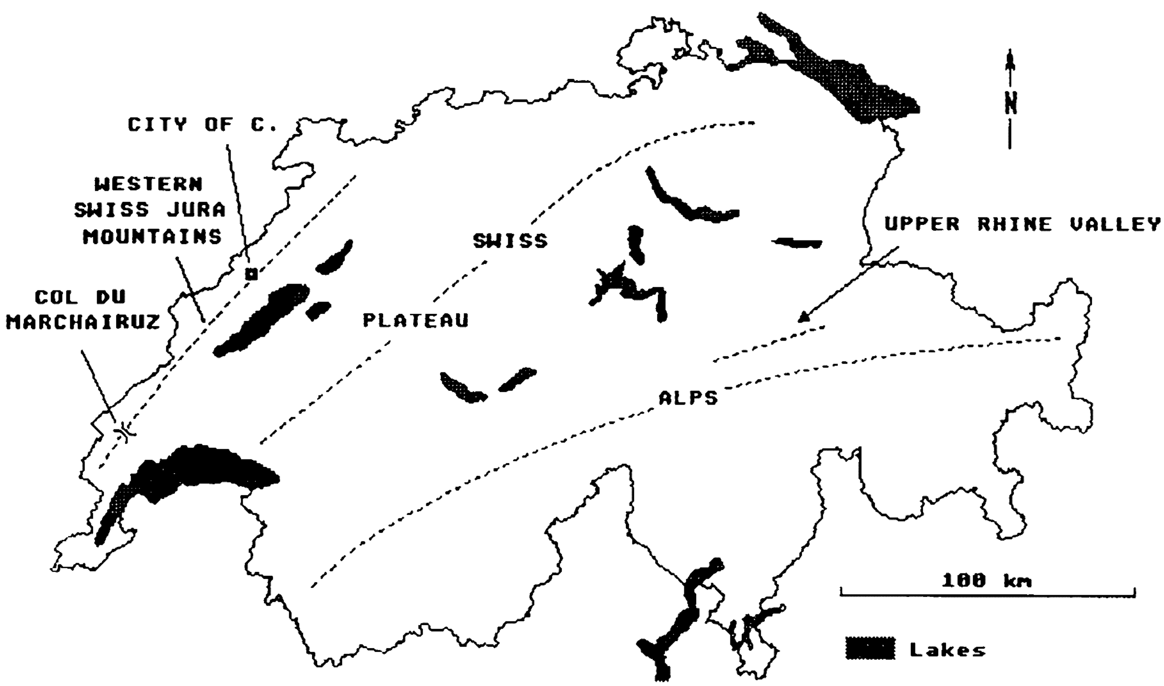



Figure 2. Swiss map. The dashed lines roughly represent the axis of the respective geographic unit.

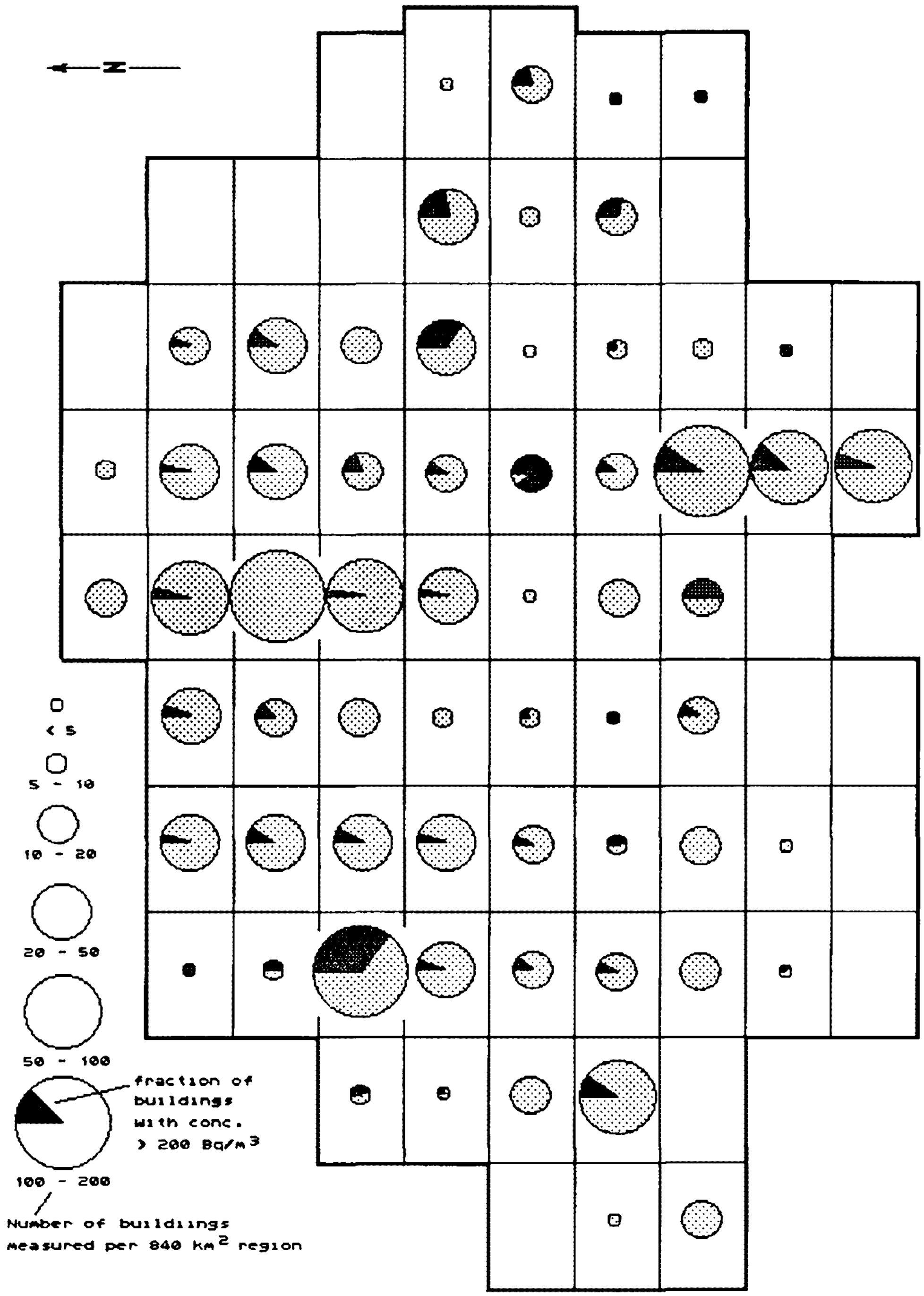



Figure 3. Regional distribution of radon measurement results

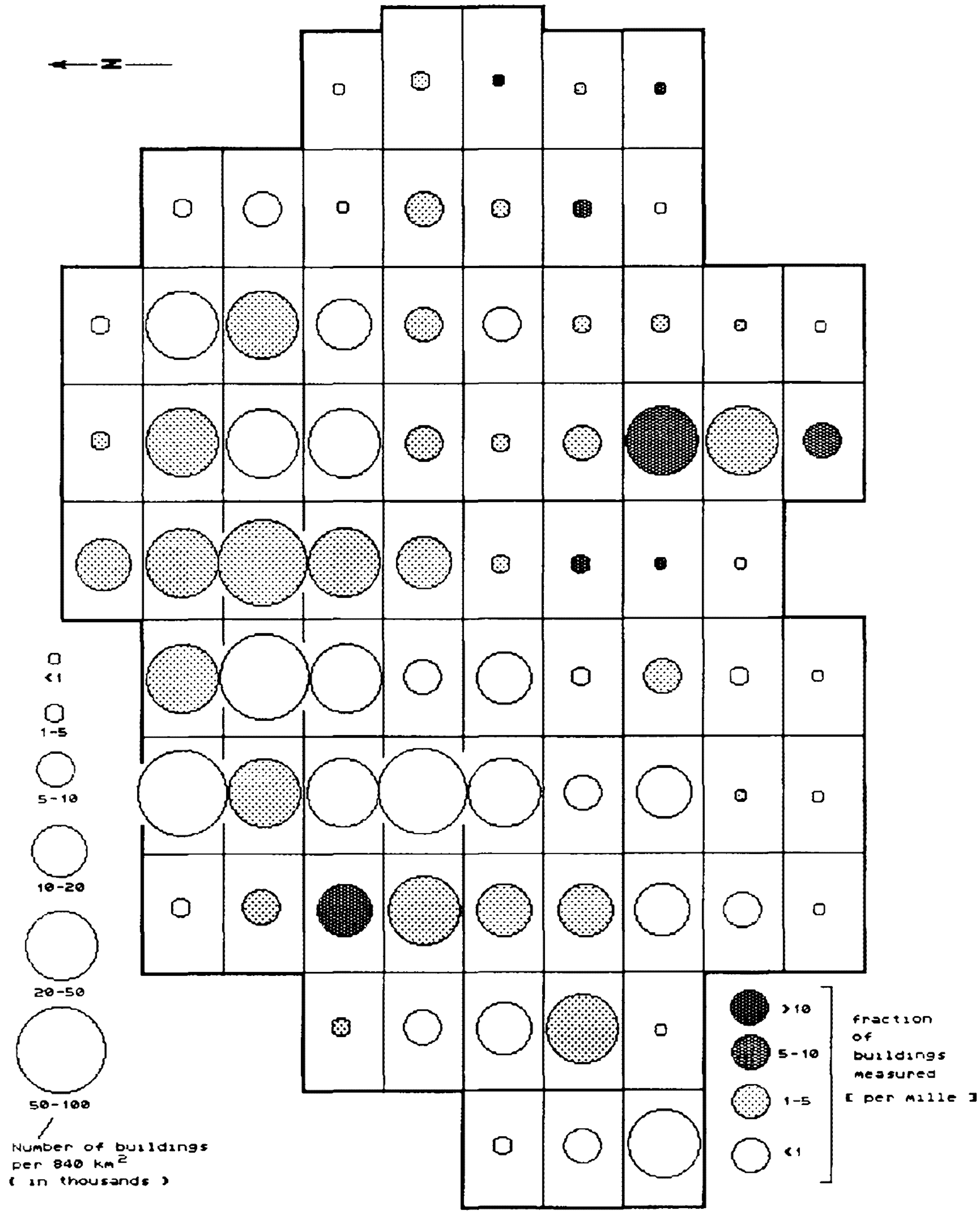



**Figure 4. Fraction of buildings measured**

We consider radon levels exceeding 200 Bq/m$^3$ in this type of rooms as an indicator for a possible radon problem. The fraction of homes with at least one room exceeding this level is shown in this figure for each of the regions. The division into regions is the one used for the 1:50000-scale maps. Each rectangle measures 24 km times 35 km (840 km$^2$).

There are at least two regions in Switzerland with clearly enhanced radon concentrations : the Jura Mountains in the west and the Upper Rhine Valley in the east. Geological aspects of the radon problem in these two regions are discussed below. Enhanced levels are present in the south-eastern part of Switzerland too. The Swiss Plateau where most of the Swiss live is essentially free from radon problems.

The more than 1500 homes measured so far represent 0.15 % of the residential housing stock in Switzerland. This may be sufficient to calculate a Swiss average but as can be seen from figure 4 many regions are not well represented. We don't really know what "well represented" means. What percentage of homes has to be measured per 840 km$^2$ unit until one can declare it as "affected" or "safe" ? A hint comes from a recent survey in the southern part of Switzerland (Ticino) that nearly doubled the number of homes measured in this region. From a comparison of the frequency distributions of the radon values before and after this survey we conclude that a representative sample has to contain at least 1 % of the residential buildings. Another hint comes from the now best covered region ( 3.5 % of the 6000 homes are sampled) where we have been measuring for more than 8 years. The frequency distribution changed slightly over the years and now has become quite stable. We don't expect any surprise from further measurements. We therefore recommend to sample 1 to 3 % of the housing stock before any region can be declared as safe or affected.

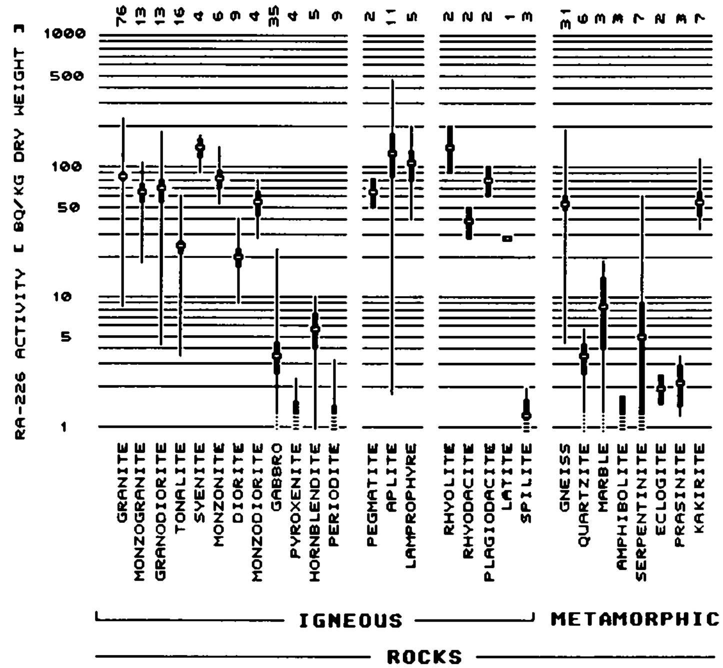
## GEOLOGICAL ASPECTS OF THE RADON SITUATION IN SWITZERLAND

There are mainly three factors that determine the radon risk of a building ground : 1) $^{226}$Ra activity concentration in the soil, 2) Fraction of the $^{222}$Rn produced that is available for transport (emanation) and 3) Gas permeability of the soil.

We will show the range of values found in Switzerland for these three factors and discuss geological aspects of two high risk sites.

## RA-226 ACTIVITIES IN ROCKS AND SOILS

Uranium data for Swiss rocks, taken from a recent compilation by Schärli (7) are shown in figure 5. The term "Uranium" used by Schärli is somewhat misleading for the quantity measured has been the $^{222}$Rn daughter concentration. He neglects any disequilibrium in the $^{238}$U series down to the $^{222}$Rn daughters. We therefore call his "Uranium" values $^{226}$Ra taking a conversion factor of 12.3 Bq/kg per ppm U. From this figure it is obvious



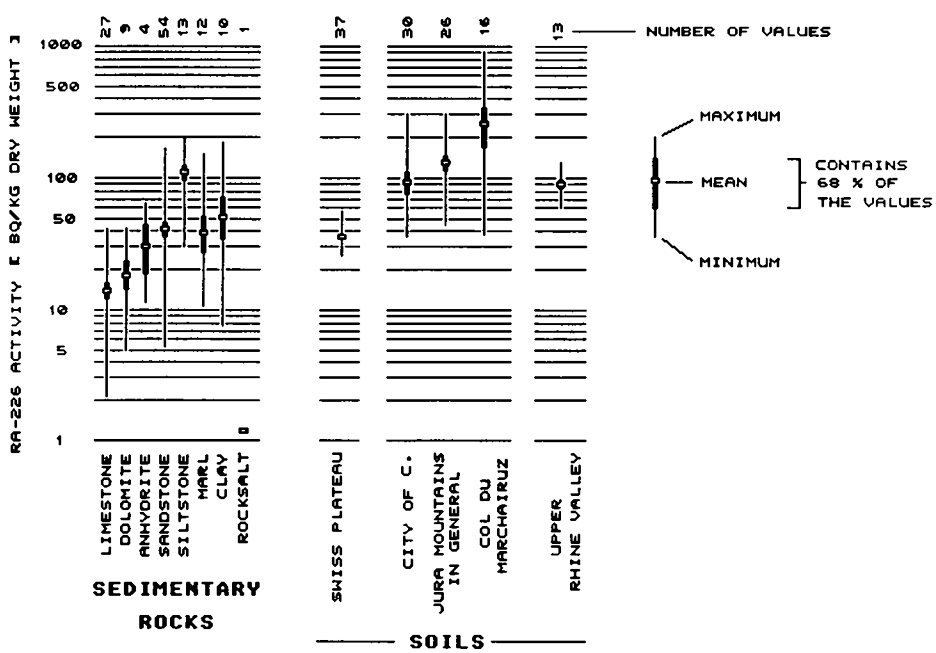




Figure 5. Ra-226 activities in Swiss rocks and soils

that "granite" is not synonymous with "high activity".

Activities in Swiss soils are shown in the figures 5 and 6. The $^{226}Ra$ concentrations in figure 5 have been determined by high resolution gamma spectrometry on dried soil samples. The data given in figure 6 are from in situ gamma spectrometry measurements (8). Contrary to the laboratory measurements the poor statistics for in situ measurements exclude a precise determination of the $^{235}U$ or the $^{234}Th$ concentrations. The $^{235}U$ contribution to the 186 keV $^{226}Ra$ line has thus to be calculated assuming perfect equilibrium down the $^{238}U$ series. This leads to an underestimation of the $^{226}Ra$ activity in soils with a $^{230}Th$ ( and thus $^{226}Ra$) excess. A $^{230}Th$ excess is present in Jura Mountains soils. When comparing activities in figures 5 and 6 one has also to take into account that the laboratory data are for dried samples whereas the in situ values refer to the undisturbed wet soil.

The complex nature of the Swiss geology and the important impact that Quaternary had on our country makes it very difficult to find any correlation between the regional activity distribution in figure 6 and geological or tectonic maps. Soils in many parts of Switzerland are not derived from the underlying bedrock. The most striking example is found in the Western Swiss Jura Mountains where $^{226}Ra$ activities of up to 880 Bq/kg dry weight are present in soils covering Jurassic or Cretaceous limestone having only about 20 Bq/kg of $^{226}Ra$.

A peculiarity of these soils is that $^{230}Th$ and $^{226}Ra$ are largely in excess of $^{238}U$ (determined quantity is $^{234}U$), the latter being present in "normal" quantities (30-50 Bq/kg dry weight). There is still no explanation for this widespread anomaly. The watch industry, being very prominent in the Jura Mountains has used large quantities of radium-activated luminous paint but we can hardly blame them for this "contamination". The $^{226}Ra$ and it's natural precursor $^{230}Th$ are nearly at equilibrium even in soil samples taken close to a former radium processing workshop. In samples of luminous paint from this workshop the $^{230}Th$ activity is orders of magnitude lower than the $^{226}Ra$ activity.

A hint for the origin of the enhanced activities may come from the regional distribution of the $^{226}Ra$ activity and it's dependence on the altitude. There is a general trend for higher activities towards the southwest (the main wind direction). Enhanced ( > 100 Bq/kg dry weight) $^{226}Ra$ activities are abundant at high altitudes (figure 7) and no Ra anomaly has been found so far below about 900 m above sea level. This altitude roughly corresponds to the upper ice margin of the Rhone glacier during the latest glacial period. These two observation are consistent with the idea by Pochon (9) of an aeolian origin of an important part of the Jura Mountains' soils.

## RADON EMANATION

The few emanation measurements on Swiss Plateau soils (mainly glacial till) show that for these soils about 30% of the radon produced can escape

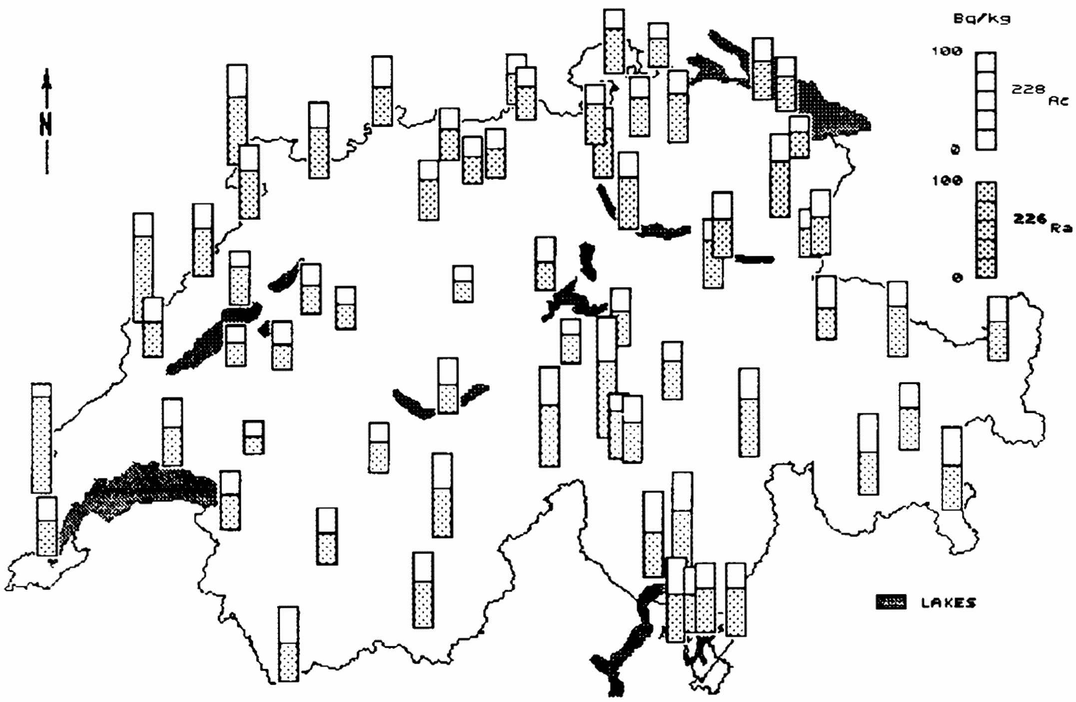



Figure 6. Ra-226 and Ac-228 in Swiss soils.
Determined by in situ gamma spectrometry

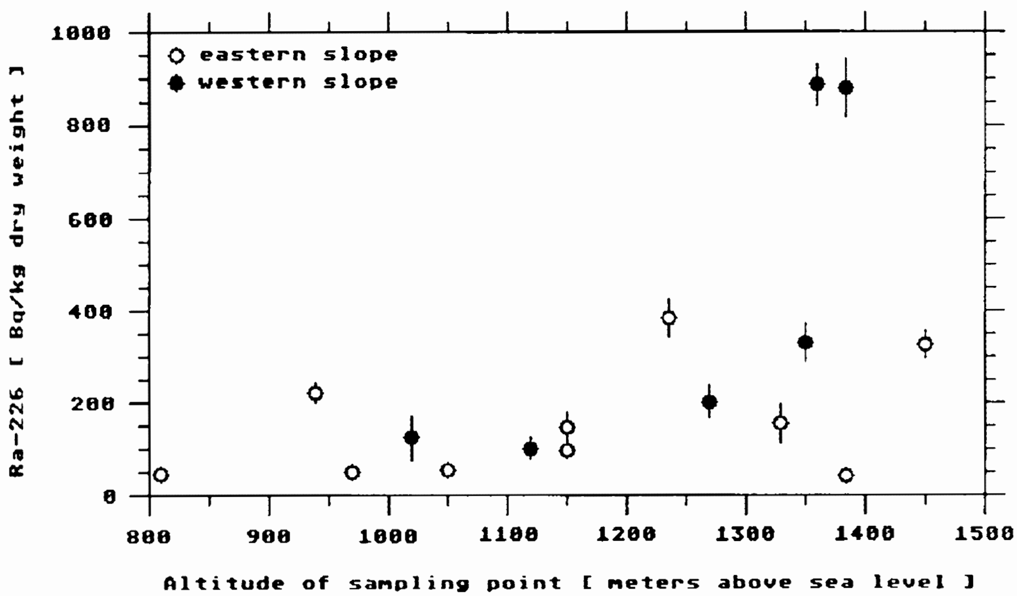



Figure 7. Soil samples Col du Marchairuz

to the pore space and is thus available for transport. This fraction is far higher (about 70%) for "high radium" soil samples from the Jura Mountains. An example is shown in figure 8. The $^{226}Ra$ values given in this figure have been determined using the 186 keV gamma line. The $^{235}U$ contribution to this line is calculated from the measured $^{234}Th$ activity assuming equilibrium between $^{238}U$ and $^{234}Th$ and taking the "universal" $^{235}U/^{238}U$ activity ratio of 0.046.

## GAS PERMEABILITY OF THE SOIL

Our soil gas sampling apparatus (figure 9 and (6)) allows for the simultaneous measurement of the gas permeability. Values from $10^{-14}m^2$ to $>10^{-10}m^2$ i.e. variations of at least four orders of magnitude have been found in Swiss soils. The highest values show badly consolidated rockslides.

High radon concentrations in the soil gas only present a radon risk if the permeability of the soil is sufficiently large to allow for an efficient radon transport to the foundation of a house. Even "normal" radon levels in the soil gas may lead to a considerable radon risk if the gas permeability of the soil is very high.

Therefore the product of the radon concentration in the soil gas times the soil's gas permeability may be a better measure of the radon risk than the bare radon concentration. This "radon availability" is plotted in figure 10 for several regions in Switzerland. The envelopes have been generously drawn around the respective data sets. Individual data points are not shown in this figure. In the regions TI and FR we could not find homes with high indoor radon concentrations whereas the regions RA and SI are characterized by high indoor levels. Measurements in the region SI include gas samples taken in unconsolidated rocks. Despite the large scatter of the data points there is some evidence that building grounds with radon availabilities larger than $10^{-7}$Bq/m to $10^{-6}$Bq/m present a radon risk.

## GEOLOGICAL ASPECTS OF TWO HIGH RISK REGIONS

### Western Jura Mountains, a Limestone Karst Region

As can be seen from the figures 5 and 6 $^{226}$ Ra concentrations in the soils of the Western Jura Mountains are on the average well above the values for soils from the Swiss Plateau. At first sight this seems to correspond well to the high percentage of increased indoor radon levels found in this region (figure 3). But a closer look at the houses with high concentrations shows that they are built directly onto the bare limestone bedrock. The contact with the soil is limited to a less than 30 cm high zone round the walls. More important than the soil $^{226}Ra$ concentration seems to be the fact that most of the homes affected in the city of C. are close to karst features like caves and sinkholes. In the basement of one

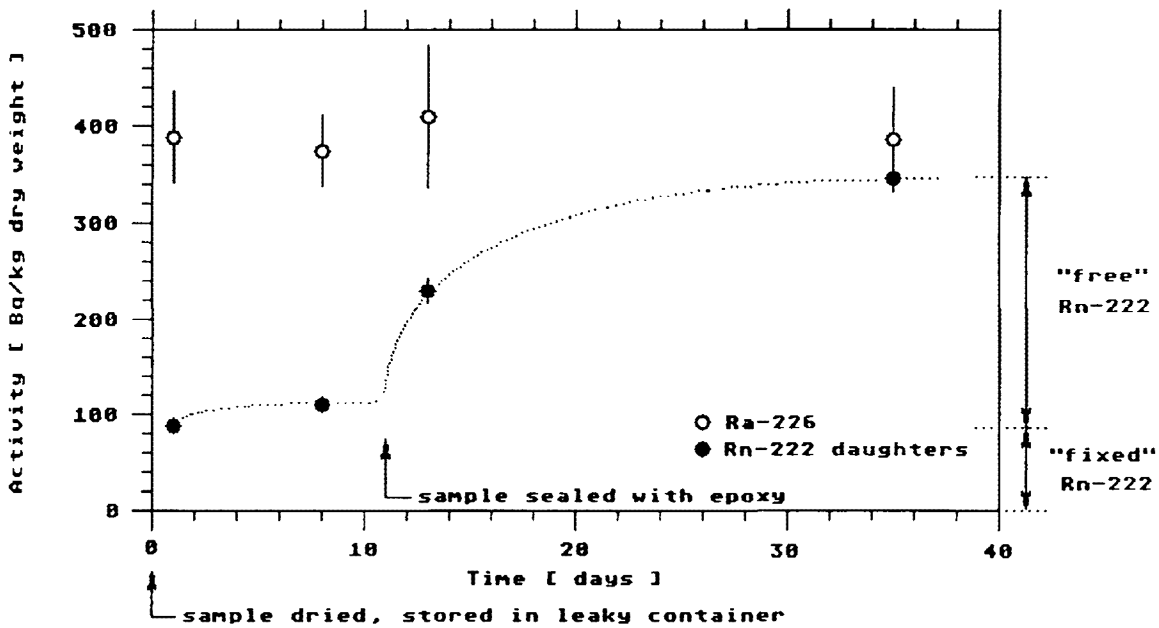



Figure 8. Radon buildup in a Jura Mountains soil sample

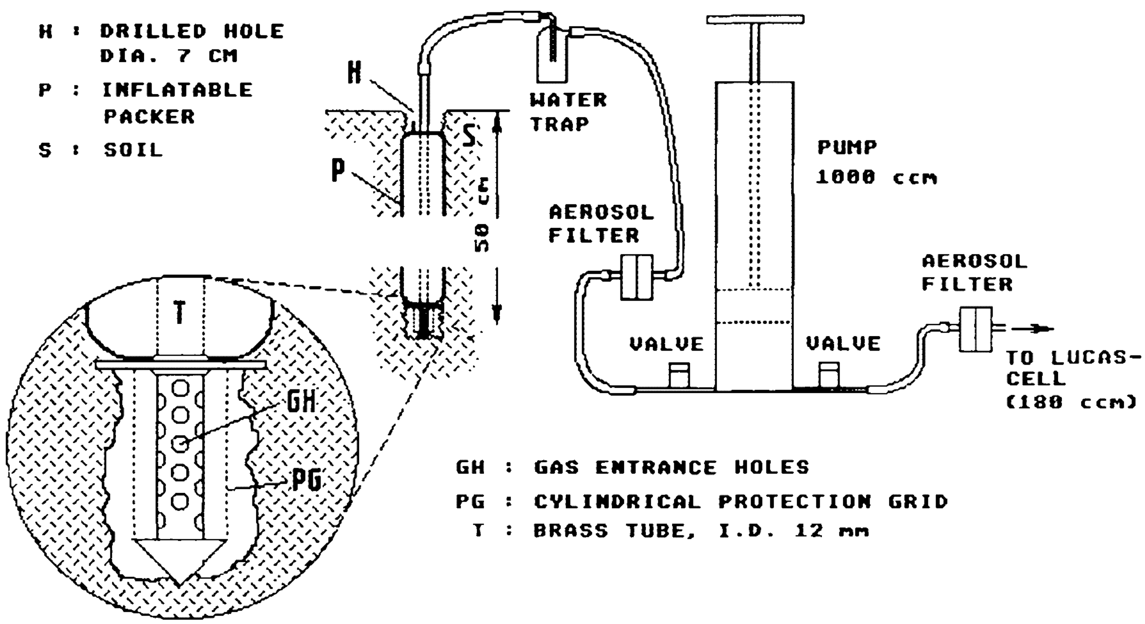



Figure 9. Soil gas sampling equipment. To determine soil permeability we measure the time it takes to pump 1000 ccm at constant pressure into the borehole. Constant pressure is produced by the pump piston's own weight.

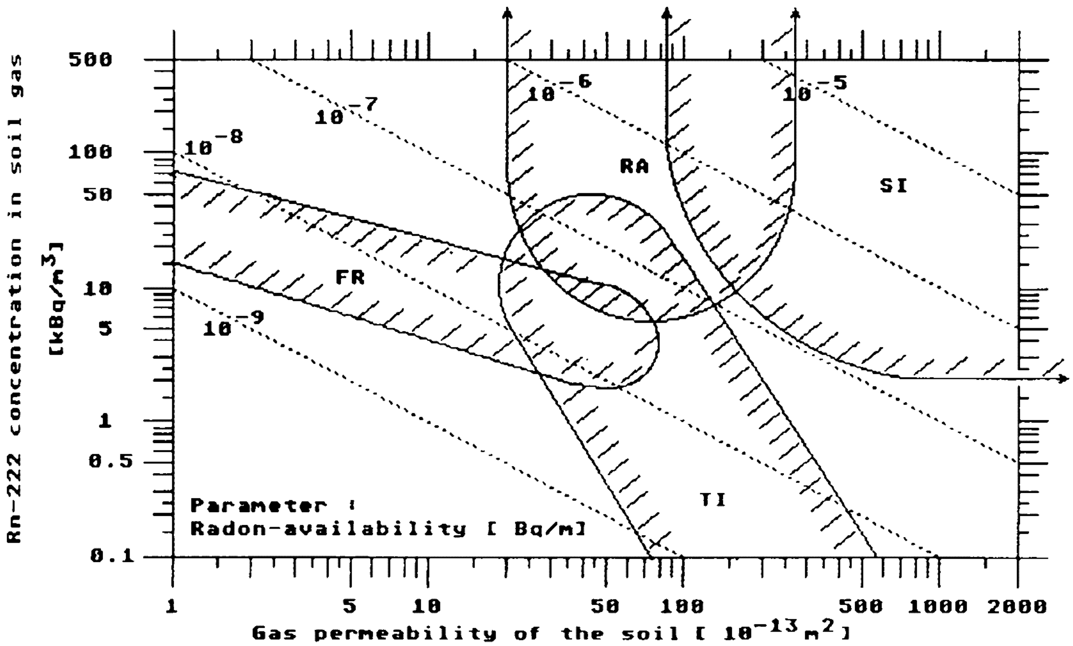



Figure 10. Radon availability in Swiss soils

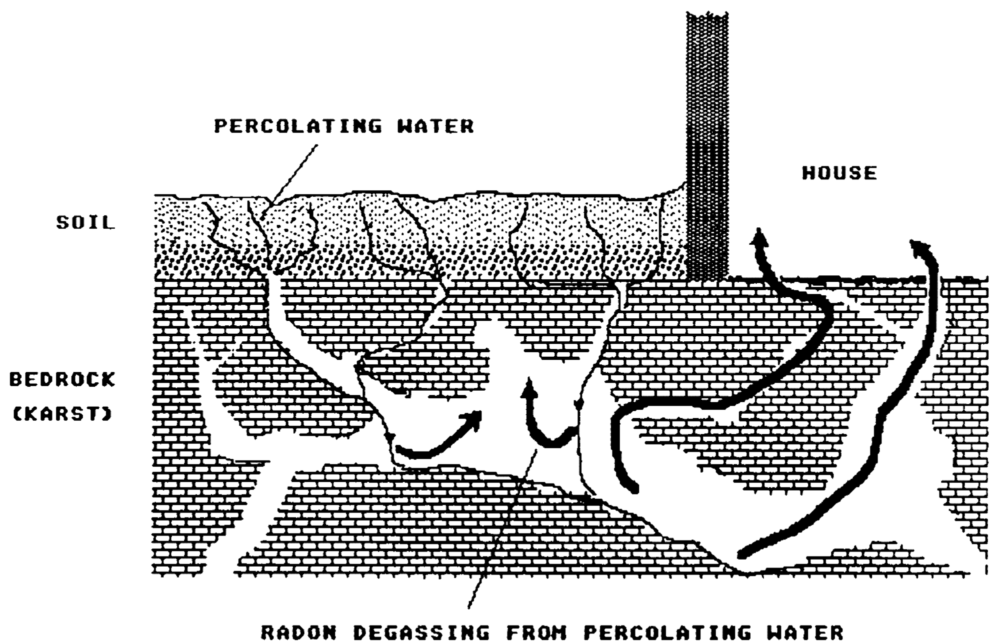



Figure 11. Proposed radon transport in a karst system

of the buildings there is even a visible connection to the karst system.

The radon concentrations in caves below this city are very high (up to 40 $kBq/m^3$ (10,11)). In combination with the high gas permeability this karst system represents a very powerful radon source. Even small connections to this source are sufficient to supply large quantities of radon to the basement of a house.

There remains to explain the high radon levels in the air of the karst system. The Jurassic limestone contains only about 20 Bq $^{226}Ra$/kg, by far not enough to sustain 30 to 40 $kBq/m^3$ $^{222}Rn$ in the cave air. We have therefore proposed (12) that percolating water is transporting large quantities of radon from the (high $^{226}Ra$) soil to the caves (figure 11).

## Rockslides in the Alps

There are many villages in the Swiss Alps built onto badly consolidated rockslide debris. In the Upper Rhine Valley these rockslides contain "Verrucano". In Switzerland the term "Verrucano" means an old clastic sediment frequently showing enhanced $^{226}Ra$ concentrations. $^{226}Ra$ values in soils from the Upper Rhine Valley are shown in figure 5. The combination of relatively high $^{226}Ra$ activities with the extremely high gas permeabilities in these rockslides seems to be the reason for high indoor radon concentrations. Contrary to the situation in the Jura Mountains the homes are built onto the "high $^{226}Ra$" material.

# MITIGATION

Remedial actions are still in a test phase. Homeowners willing to participate in pilot projects have been offered a substantial financial support by the Federal Office of Public Health that also plans and supervises the work.

Pilot projects carried out so far have shown that passive methods like sealing floors are insufficient. Combining sealing with subfloor suction has lead to the successful mitigation of several homes at still reasonable costs.

The most dramatic reduction (to nearly outdoor radon levels) has been achieved by an air conditioning system that allows for the control of air flow and pressure in the basement. A heat exchanger keeps the energy consumption low. This installation is for research only. It is too expensive for a general use but a scaled down version may give comparable results at reasonable costs.

In a high risk area a future homeowner could be convinced to install a subslab suction system. We hope that he will have considerably lower radon levels in his new home than his neighbour living with the highest radon concentration ever measured in Switzerland (45 $kBq/m^3$ in winter).

In Switzerland the mitigation technique has not yet passed to the private sector. There is no "radon business" in our country for there is no real public concern about radon. This may be partly due to the lack of limits or recommendations for indoor radon levels but distinctly more important is the general feeling that something natural like radon can't be harmful.

## THE NEW DECADE

In the 1980s we have gathered enough data to make a reasonable estimate for the average radon exposure of the Swiss. This average will change only slightly even if we could double the number of buildings measured. What we need more is to find the homes with extreme values, homes really worth remedial actions. Therefore any new survey will concentrate on the search for high risk regions. This search will be guided by the knowledge gained on the correlation between geology and radon concentration. A survey started in November 1990 in the eastern part of Switzerland has already been planned according to this new concept. Etched-track detectors are placed in villages on high permeability grounds (rockslides, karst, clean coarse gravel with low lying water table, important fault zones) and/or close to known or suspected uranium mineralizations.

The new decade will also see recommendations or even limits for safe indoor radon concentrations and an increased engagement and responsibility of local authorities. The federal government will concentrate on research, the search for high concentrations, scientific support and quality control.

We will plead for sensible radon concentration limits. Radon is only one of the many carcinogenic substances present in our environment.

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

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# A CROSS-SECTIONAL SURVEY OF INDOOR RADON CONCENTRATIONS IN 966 HOUSING UNITS AT THE CANADIAN FORCES BASE IN WINNIPEG, MANITOBA

D.A. Figley & J.T. Makohon
Saskatchewan Research Council
Building Science Division
Saskatoon, SK S7N 0W9
CANADA

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## ABSTRACT

This paper summarizes the results of a cross-sectional survey of indoor radon concentrations in a total group of 966 housing units at the Canadian Forces Base (CFB) in Winnipeg, Manitoba. The major objective of the study was to characterize the distribution of indoor radon levels in the housing group as the first step in developing a radon control strategy. Subsequent investigations on sub-groups of these houses (not reported here) were conducted to examine the building factors associated with the indoor concentrations and the efficacy of post-construction control measures.

Measurements were obtained from 670 of the 966 housing units (69% participation). The study group was composed of large numbers of nominally identical housing units of several different building styles. The two-day average measurements were taken using charcoal canisters during extremely cold weather, -28°C to -35°C. A short questionnaire administered to the occupants by the field workers who installed and removed the canisters recorded basic data on occupant activities and building factors.

For the entire group, the geometric mean concentration was 112 Bq/m$^3$ (3.0 pCi/L), approximately twice as high as the geometric mean obtained by an earlier summertime study of 563 Winnipeg houses. Data was subgrouped based on geographic location within the city, and the subgroup geometric mean concentrations varied between 25 and 206 Bq/m$^2$ (0.7 and 5.6 pCi/L). Individual house measurements ranged from <10 Bq/m$^3$ to >5400 Bq/m$^3$ (<0.3 pCi/L to >146.0 pCi/L). No building or occupant factors were initially identified as being associated with the variation in levels.

## INTRODUCTION

In the fall of 1989, the Department of National Defence (DND) retained the authors to design and conduct a study to investigate the indoor radon levels in the residences occupied by DND personnel at the Canadian Forces Base (CFB) Winnipeg, MB. These residences included housing units (PMQ's) owned by DND, bulk leased (BL) housing units rented by DND, and barracks units (BU). Radon levels were also surveyed in 46 areas of the officers' and non-commissioned members' messes and other occupied areas on both north and south areas of CFB Winnipeg.

Radon has been identified as a naturally occurring pollutant that is broadly distributed throughout Canada. In 1977 to 1980, Health and Welfare Canada conducted a study to survey indoor radon levels in 14000 homes in 19 cities across Canada (1). These data are frequently referred to in discussions regarding the radon situation in Canada and are used to rank cities with respect to their radon risk potential. In this study, Winnipeg was identified as the Canadian city having the highest geometric mean indoor radon level (57 $Bq/m^3$) based on a sample of 563 houses. For the purposes of this paper, the conversion 37 $Bq/m^3$ = 1 pCi/L can be used.

Many studies of indoor radon levels have been conducted and while a more complete understanding of the factors that influence indoor levels is emerging, at present, the only reliable method of estimating the radon concentration in a specific building is to measure it (2).

The study design included three parts to be conducted consecutively:

Part 1. Cross-Sectional Survey of Indoor Radon Concentrations.

The focus of this part of the project was to provide an overview screening of the radon concentrations occurring in the homes. The data would also provide a statistical database for future studies. DND requested that all of the occupants of both the owned and leased housing units be given the opportunity to participate in the study. In an attempt to obtain the highest indoor readings, measurements were taken in the lowest levels of the houses during calm, cold weather.

Part 2. Detailed Engineering Study of a Selected Sub-group of Houses.

This work focused on identifying the building factors that influence indoor radon concentrations and provided information for the development of mitigation techniques. It included a more intensive study on a sub-group of approximately 40 houses identified in the part 1 work as having the highest and lowest indoor radon concentrations.

Part 3. Mitigation Study on a Small Group of Houses.

The focus of this work was to select five houses with high indoor radon concentrations, make building modifications and evaluate the impact of the modifications on the indoor radon concentrations.

All houses having part 1 screening levels >150 $Bq/m^3$ had alpha track monitors installed for the period from October 90 to March 91.

This paper deals with the results of the cross-sectional survey (part 1) of the study.

For the purposes of data presentation and discussion, the current Manitoba Government interim guidelines (3) are referred to in the report. In summary, these are:

1) If the screening measurement is about 150 $Bq/m^3$ or lower and was taken during cold weather with the house closed up, there is little chance that the home will have an annual average concentration greater than 150 $Bq/m^3$. Follow-up measurements are probably not required.

2) If the screening measurement is about 150 - 800 $Bq/m^3$, consider performing follow-up measurements.

3) If the screening measurement is about 800 $Bq/m^3$ or greater, perform long term (minimum three months) measurement as soon as possible.

## OBJECTIVES

Part 1 of the study had two major objectives:

1) Measurement of indoor radon levels in all CFB Winnipeg residences (PMQ, BL and BU) and selected other buildings to give DND an accurate assessment of the current indoor radon levels. These data would be used to determine if additional measurements or mitigation work were required to ensure indoor radon levels were maintained below levels established by DND.

2) Characterization of the distribution of radon levels and analysis of the levels in conjunction with selected building and occupant factors. The analysis would identify factors that are statistically associated with the radon concentration and will be used in subsequent phases of work.

## STUDY DESIGN

The initial phase of the study was a cross-sectional survey to measure the two day average concentration in (nominally) all of the 966 residential units potentially inhabited by base personnel. CFB Winnipeg engineering staff also prepared a list of 17 buildings to be monitored. A total of 46 monitors were placed in various locations in the lowest levels of these buildings.

Prior to conducting the study, the base command prepared an information package containing basic information about radon and a brief overview of the proposed study which was mailed to all occupants of homes in the study. Only homes that were occupied during the test period were monitored since gaining access to homes where the occupants were not present was not permitted. Participation in the study was at the discretion of the occupant.

The study consisted of an initial home visit to install the radon monitor and a follow-up visit 48 hours later to remove the monitor and complete (with the homeowner's assistance) a short questionnaire concerning the building construction and occupant activities. If the homeowner indicated that they would not be home when the monitor was to be removed, they were carefully instructed as to the protocol for repackaging the monitor. The homeowner would leave the monitor in the mailbox for pick-up.

Twenty-three temporary contract employees were used over a four day period to install and remove the monitors. They were all paid on an hourly basis and instructed to take as much time as necessary to complete each house visit (average 15 minutes). On the day before the monitoring began, a two hour seminar was held to train all of the personnel assisting with the study. A phone-in help line was manned at all times so that workers could phone in for assistance. Only five calls requesting minor information were received during the study.

The field work was conducted from 10-14 December, 1989. During the test period, the weather was clear and relatively calm with the outdoor air temperature varying between -28°C to -35°C.

Additional monitors and questionnaires were available at the base engineering office for persons who phoned in to say they were in the city but would not be home when the visits were being made. These people were invited to come to the engineering office to pick up the materials for self administration. These data are not included in this report.

For this survey, the sample population and the target population were identical since all residences were included in the survey. Considerations as to sample size, representativeness of sample and estimation of the distribution of indoor radon levels are eliminated in a total sampling program. This is an important point in designing radon research projects since the nature of radon concentration distributions varies widely depending upon local circumstances.

The following potential biases may affect the study, however, they are not considered significant in the analysis.

Although all of the residences occupied by base personnel were included in the survey population, some houses were not monitored. For most cases, the reason for not being included was that the occupants were not home at the time the house was initially visited (between the hours 8:00 to 21:00 Monday or Tuesday). Several attempts were made at various times of the day over the two day period.

The non-participants may bias the selection of the data group towards residences where a co-operative individual was home, however, there does not appear to be any systematic reason why this would affect the validity or interpretation of the study results. The demographic and building data obtained from the questionnaire would correctly account for these occupant differences. Of the 966 potential residences, 670 measurements were obtained.

The questionnaire contained primarily descriptive and quantitative questions concerning the building and the occupant activities during the two day monitoring period. A section for general homeowner comments was also included.

## METHODOLOGY

The indoor radon concentration was measured using RADPAC TM activated charcoal canisters. The nominal exposure time suggested by the supplier was two days, however, as long as the exposure time was accurately recorded, exposures in the range of 45 to 72 hours were acceptable.

The canisters were installed approximately 0.6 m above the floor in the lowest level of the residence, centrally located away from drafts and in accordance with the manufacturer's instructions.

All of the canisters were received by the supplier for analysis within 48 hours of removal from the house.

The monitor supplier was listed as a registered participant in both the US EPA and Health and Welfare Canada quality assurance programs. In 10 locations, duplicate canisters were installed as an internal check of the measurements.

## QUESTIONNAIRE DESIGN

The questionnaire was designed to be either self-administered or filled in by the survey employee with assistance from the homeowner. It consisted of 36 questions requiring;

1) a yes or no response about building characteristics.

2) basic physical information about the building such as the number of windows, main floor area or type of space heating system.

3) selection of a ranked descriptor to rate the condition of the foundation walls and floor.

4) estimation of hours spent doing specific household activities or frequency of door/window openings.

The purpose of the questionnaire was to obtain information on building and occupant factors that would influence the indoor radon concentration either directly or indirectly.

## ANALYSIS

The survey yield for the entire housing group was 670 measurements from a total population of 966 (69%). Since the geographic location was considered to be an important factor associated with the indoor radon concentration, the data were sub-grouped 1 to 8 (somewhat arbitrarily) based on location.

The sub-groups used in the initial analysis were combinations of streets based on a common geographic area. For the sub-groupings used, the smallest yield was 62% of all possible houses so all of the areas were considered to be adequately sampled.

Information from the questionnaire can be used to group the houses into different categories. Most of the questionnaire information can not be directly assigned a quantitative value that could be used in a mathematical analysis, but will be useful in identifying houses that can be grouped together on the basis of some common characteristics and compared with respect to other factors.

## RESULTS

The authors or project manager should be contacted for information on the detailed survey results.

A frequency distribution of all of the indoor concentration data is presented in Figure 1 and replotted with the logarithm of the concentration in Figure 1a. All logarithms are taken to the base 10. The distribution in Figure 1a follows the log-normal distribution and therefore, the geometric mean (GM) rather than the arithmetic mean is used to describe the central tendency of the data. For the entire group, the geometric mean indoor radon concentration was 111.8 $Bq/m^3$ (123.1 $Bq/m^3$ for the housing units only) which was well above the 57 $Bq/m^3$ geometric mean for Winnipeg given by the Cross-Canada study.

The class intervals for the histograms were selected to allow group frequencies corresponding to the Manitoba guideline values to be calculated.

A second set of frequency distributions were prepared by breaking the population into six geographic areas (somewhat arbitrarily) based on the physical proximity of groups of streets Figure 2. Also included are the separate data from the north and south base building areas. The data are presented in Table 1.

The geometric means, arithmetic means and standard deviations for the geographic sub-group of data are given in Table 1. These values show the wide variation in mean radon concentrations both within the groups and based on location. It is important to note that the grouping based on location is, in some cases, a surrogate grouping based on other building factors such as house style or ventilation system type. The sub-groups also include buildings owned and maintained by DND and bulk leased housing that is owned and maintained by the leasing company.

In future analysis (beyond the scope of this report) the data for the individual geographic locations (where applicable) may be further sub-grouped based on the general retrofit status of the detached and semi-detached houses. Over the past years, different levels of improvements have been made to the DND housing stock. The present housing stock falls into one of the following categories:

1) original construction as built in the 1940's.

2) replacement of windows and doors with more modern units.

3) replacement of windows and doors along with reinsulation and siding of the exterior walls above grade.

Other possible analysis include examination of the effect of house style, heating/ventilating system type, foundation type and foundation condition.

## DISCUSSION

The initial screening survey indicated that there is a wide variation in radon levels in the buildings occupied by CFB Winnipeg personnel.

Overall, the indoor radon concentrations are much higher than the 57 $Bq/m^3$ geometric mean level obtained in the Cross-Canada study by Health and Welfare Canada. To a large extent, this may be related to the test conditions under which the measurements were taken. The Cross-Canada study used short term (<10 minute) measurements conducted in the summer. For this study, two day averages during sealed house conditions in very cold weather were taken. While detailed modelling is beyond the scope of this study, several building science principles support these results:

1) The cold outdoor temperatures would result in high sustained negative pressures at the lower level of the buildings. This would maximize the pressure potential driving radon into the buildings.

2) Although the high negative pressures should result in an increase in the air exchange rate for the houses, a concerted effort on the part of the homeowners to keep all windows and doors closed (as compared to summer when children are home from school and window/door opening may provide the only cooling ventilation) may have offset the pressure effect and resulted in lower overall outdoor air exchange rates. Many of the homeowners reported taking special care to keep their homes "sealed up" during the winter to minimize drafts and reduce heating costs.

The groups with the lowest geometric mean indoor radon levels (25-30 $Bq/m^3$) were the south and north base buildings - groups 7 & 8 and the two storey six/eight family units in group 5 located adjacent to the north base. All of these buildings had hot water heating systems and no mechanical ventilation systems.

All of the other groups were single or double family residences. While a detailed analysis is not provided, there is a general tendency for the north base areas to have higher geometric mean indoor radon levels (group 1 - 206.5 $Bq/m^3$, group 2 - 173.4 $Bq/m^3$, group 4 - 147.0 $Bq/m^3$) than the south base areas (group 3 - 110.2 $Bq/m^3$, group 6 - 156 $Bq/m^3$).

Table 2 lists the values for the replicate measurement tests. For the ten locations, two charcoal monitors were placed side by side and exposed for the same time period. In nine cases, the agreement was within a maximum range of 16.7% and typically much smaller. For the test at Location E, the monitor results varied by a factor of six. There are no procedural differences that would account for this anomalous result. Using a paired t-test analysis, the differences between the measured values (excluding Location E) were not significant at the 5% level of significance.

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.

Although this project was funded by the Canadian Department of National Defense, DND does not endorse the products or techniques used by the authors.

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2. "Radon Reduction Techniques for Detached Houses - Technical Guidance, Second Edition", United States Environmental Protection Agency, Washington, DC., January, 1988.

3. "RADON - An Interim Guide for Manitoba Homeowners", Manitoba Energy and Mines Information Center, Winnipeg, MB., 1989.

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TABLE 1. INDOOR RADON CONCENTRATION DATA FOR GEOGRAPHICAL SUB-GROUPS

| GROUP | NO. OF HOMES | NO. OF MEAS. | GEO. MEAN Rn ($Bq/m^3$) | ARITHMETIC MEAN ($Bq/m^3$) | NO. > 150 ($Bq/m^3$) | NO. > 800 ($Bq/m^3$) |
|---|---|---|---|---|---|---|
| 1 | 214 | 145 | 206.5 | 319.1 | 88 | 10 |
| 2 | 180 | 111 | 173.4 | 206.3 | 68 | 1 |
| 3 | 243 | 181 | 108.2 | 183.0 | 47 | 6 |
| 4 | 106 | 65 | 147.0 | 200.8 | 34 | 1 |
| 5 | 105 | 77 | 25.7 | 29.2 | 0 | 0 |
| 6 | 118 | 91 | 152.1 | 266.7 | 40 | 4 |
| 7 | - | 35 | 27.2 | 47.0 | 2 | 0 |
| 8 | - | 11 | 27.8 | 35.0 | 0 | 0 |

TABLE 2. COMPARISON OF REPLICATE MEASUREMENTS

| Location | RADPAC Bq/m3 | % Diff. |
|---|---|---|
| Location A | 125.8<br>125.8 | 0 |
| Location B | 88.8<br>88.8 | 0 |
| Location C | 103.6<br>99.9 | 3.6 |
| Location D | 55.5<br>66.6 | 16.7 |
| Location E | 140.6<br>806.6 | 82.6 |
| Location F | 388.5<br>388.5 | 0 |
| Location G | 299.7<br>299.7 | 0 |
| Location H | 629.0<br>629.0 | 0 |
| Location I | 510.6<br>503.2 | 1.4 |
| Location J | 92.5<br>88.8 | 4.0 |

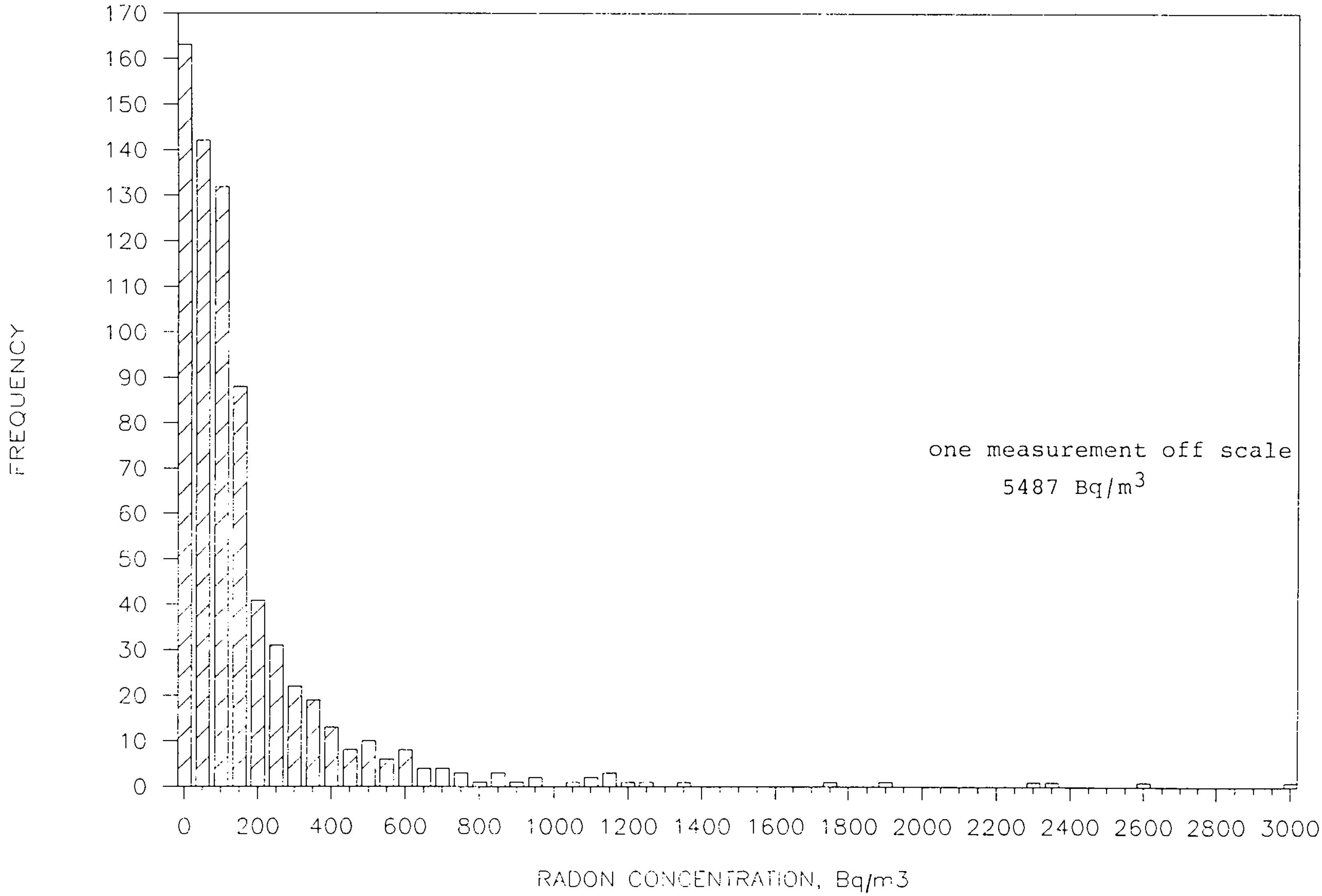


FIGURE 1. FREQUENCY DISTRIBUTION OF ALL INDOOR MEASUREMENTS

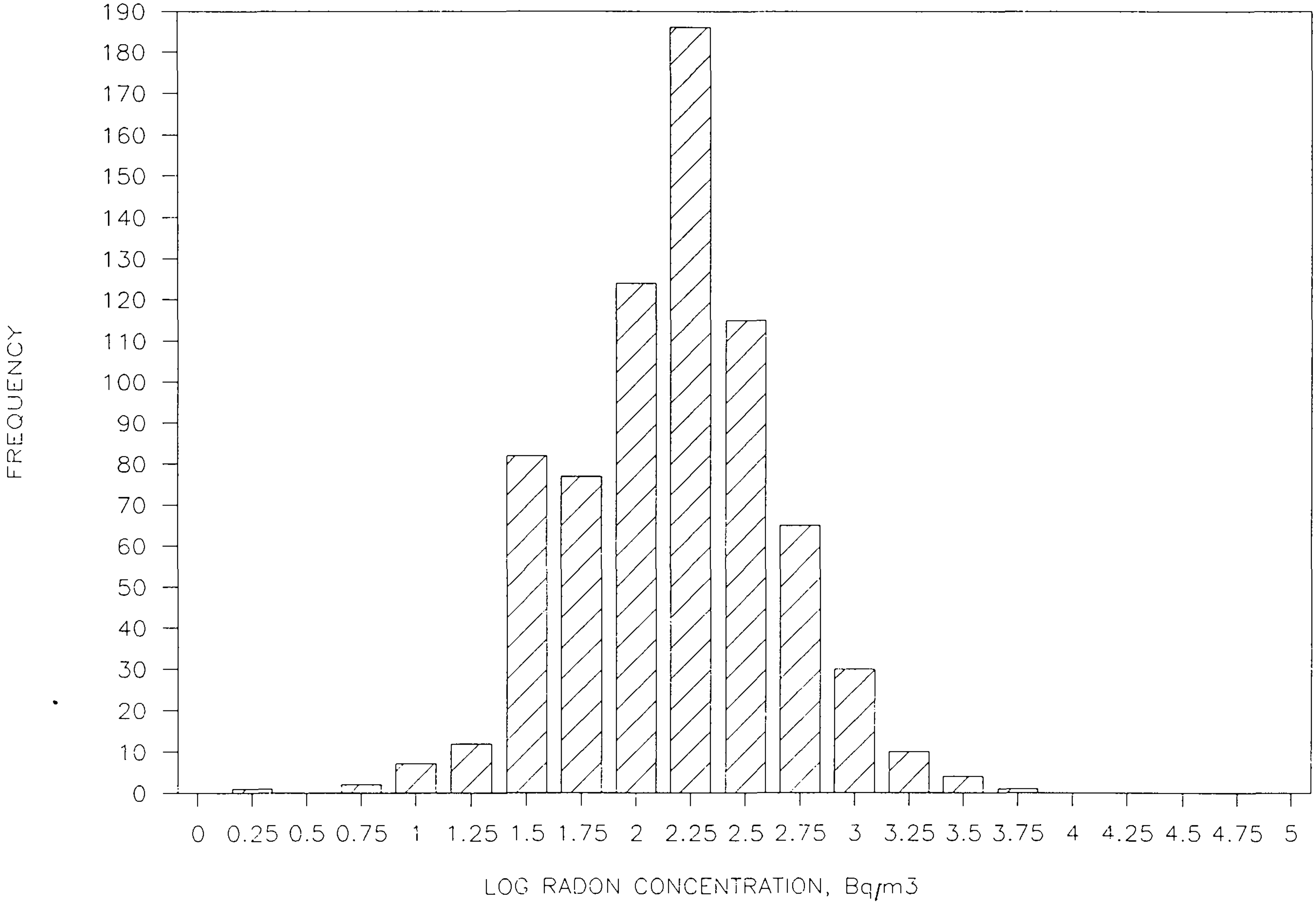


FIGURE 1A. FREQUENCY DISTRIBUTION OF ALL INDOOR MEASUREMENTS (LOGARITHM)


FIGURE 2. MAP OF WINNIPEG SHOWING EIGHT SAMPLING GROUP LOCATIONS

# RADON STUDIES IN BRITISH COLUMBIA, CANADA

D.R. Morley[1], M.M. Ghomshei[2], C. Van Netten[3] and B.G. Phillips[1]

1 - Province of British Columbia. Ministry of Health, Radiation Protection Service, 200 - 307 West Broadway, Vancouver, B.C. V5Y 1P9, Canada.

2 - Orchard Geothermal Inc. 500 - 342 Water Street, Vancouver, B.C. V6B 1B6, Canada.

3 - Faculty of Medicine. The University of British Columbia, 5804 Fairview Avenue, Vancouver, B.C. V6T 1V5, Canada.

## ABSTRACT

Three radon studies, involving 150 background gamma measurements and long-term alpha track tests in a total of 400 homes have been conducted in three geologically distinct areas of the province of British Columbia. A positive correlation between the background gamma radiation and the measured radon level can be depicted only at the regional scale.

In the Coastal Area where the terrestrial gamma radiation is low, no homes were found to exceed 4 pCi/l on the main floor. In the Kootenays, where the background gamma is relatively high, considerably higher radon levels were encountered. The highest radon levels were encountered in the West Kootenay where the terrestrial gamma level is comparatively higher than East Kootenay. In West Kootenay about 45% of the homes demonstrate radon levels above 4 pCi/l and 7% above 20 pCi/l on the main floor. In the same area more than 60% of the homes demonstrate radon levels above 4 pCi/l in the basement. In the East Kootenay, where the radon levels were found to be lower than in West Kootenay, the terrestrial gamma levels are generally lower.

In some areas, the age of the house and the combustion air supply system seem to correlate with the radon level. In West Kootenay, where the highest radon levels were encountered, a positive correlation was observed between the radon level in the basement and the age of the house. The correlation was negative for the main floor (possibly due to air circulation between main floor and the basement in the new houses). In both Kootenay areas, the homes with combustion air supply from outside demonstrated reduced radon levels on the main floor (most probably due to increased inside pressure).

## INTRODUCTION

Surveys of radon gas in homes have been carried out in Canada since 1977(1). These early studies, although they covered over 14,000 homes, were based upon single grab measurements normally in the basement of the house during summer and therefore gave poor indications of the annual exposure(2) and the correlation between annual exposure and construction parameters. The British Columbia (B.C.) Ministry of Health began making terrestrial gamma ray measurements in 1980 using both Thermoluminescent Dosimeters (T.L.D.s) in 25 locations(3), and a portable high pressure ionization chamber (Reuter Stoke RSS-111) in 150 locations. The areas of higher gamma activity generally corresponded with rock structures where uranium is likely to occur(4). We found the province could be divided into three gamma background areas. The coastal region of the province has very low gamma background, a moderate or normal gamma background regions that is located in the interior of the province: and an elevated gamma radiation area of the province which is scattered about the interior and associated with areas favourable for uranium deposits. Figure 1 shows the province of British Columbia and the three areas where our long-term radon surveys were carried out during 1988 - 89.


Figure 1 - British Columbia with the locations of 3 radon surveys

The first long-term radon study was carried out in the town of Castlegar, the West Kootenay region of the province. A previous radon grab sample study indicated elevated radon levels in many basements there(5). The region has an elevated gamma background and there has been uranium exploration in the area. The second study was carried out in the East Kootenay (Cranbrook) region of the province. Moderate gamma radiation levels had been detected in the region. However just south of the region, moderately elevated radon levels had been measured in Montana(6). The third study was conducted in the Greater Vancouver Region of the coastal British Columbia low gamma background region. In a previous grab sample study(1) by Health and Welfare Canada in this area, only low radon concentrations were found.

This paper will compare the data obtained in these three long-term radon surveys, the terrestrial gamma surveys, other geological and construction data available. This is the first step in developing a good potential radon risk model for homes in this province.

## METHODOLOGY

### RADON SURVEYS

The first survey was conducted in Castlegar, in the West Kootenay area of B.C. The homes are located on glacial terraces created by the Columbia River. The soil is dry gravelly and permeable. The monitors were installed in July of 1987 and removed in March of 1988. This period was representative of the observed annual weather pattern. 74 homes were monitored (73 homes returned monitors). All but one home had an upstairs and a downstairs (or basement) monitor. The monitors were mounted 4 - 7 feet above the ground, away from drafts and placed in an area where the family commonly resided. Measurement of the terrestrial gamma were made at each house, usually outside on the front yard.

The second survey was conducted in the East Kootenays where 157 of the 160 monitors were recovered. The monitors were placed one per house. In this study, the owner decided if the monitor should be placed in the basement or upstairs. The monitors were again placed 4 - 7 feet above the ground, away from draft and in a central living area. They were installed in January 1988 and removed in July 1988. It was our observation that this period represented an average annual weather conditions. Most of the monitors were placed in Cranbrook, the principal community in the area but some were placed in the nearby communities of Fernie, Invermere, Kimberley, Creston and Golden. These communities are located in valley bottoms at the foot of the Rocky Mountains.

The third set of 140 monitors was distributed in Greater Vancouver area. 135 monitors were recovered. Although the terrestrial gamma background is consistently low the geology varies from the Fraser River delta (rich farming land) to the North Shore mountains and includes bed rock and glacial out-wash. One monitor was placed in the main living area of each home 4 - 7 feet above the floor and away from drafts and corners. No terrestrial gamma measurements were made in Greater Vancouver in this study since previous studies had detected no significant difference from one home to another in this area. The radon monitors were placed in January 1988 and removed in August 1988. This period was observed as representative of the average annual weather pattern. Similar weather patterns have been observed in previous years by Ghomshei et al(8) during their radon studies.

At the time of monitor placement, a questionnaire was completed by the surveyor. Information was collected on the location of the monitor(s), house construction, age of home, home occupancy, basement or slab construction, possible radon pathways, heating and ventilating systems and the geological environment. Surveyors were instructed on required procedures prior to going out so that survey consistency would be maintained.

**ANALYTICAL PROCEDURES**

Terradex alpha tract radon detectors were obtained from Landauer Inc. They were type DRN and had a detection limit of about (.4 pCi/l) - month. Terrestrial gamma measurements were made using a Reuter-Stokes RSS-111 Environmental Radiation Monitor. The monitor's gamma ray response extends from .060 MeV to above 8 MeV. Correction for cosmic rays was made by recording the barometric pressure and subtracting the corresponding cosmic ray component, as specified in the operators manual for the Reuter Stokes instrument.

## RESULTS AND DISCUSSION

**TERRESTRIAL GAMMA MEASUREMENT**

Terrestrial gamma radiation levels were determined in 150 areas of the province (2 to 100 measurements/area). The province (Figure 1) can be divided into 3 regions of terrestional radiation intensity. The first or low background area is the coastal strip composed of the two tectonic belts which were most recently rafted into North America to build the province. The second, moderate terrestrial radiation area, composes much of the interior area of the province. Within this interior area are large areas of high terrestrial background. These areas correspond to the areas identified by the British Columbia Ministry of Mines as being favourable environments for uranium deposits(7).

There is a good correlation between average terrestrial gamma background and average radon concentration (see Figure 2). This however does not follow through to the individual homes. There was no correlation between the individual homes terrestrial gamma intensity and the radon levels found in the basement or upstairs. The elevated terrestrial gamma was not the only indicator of potential radon problems in communities. In the Castlegar, West Kootenay area the soil was dry, gravelly, and permeable while in the East Kootenay area a number of communities (Cranbrook and Creston) were underlain with clay which appears to retard radon migration.

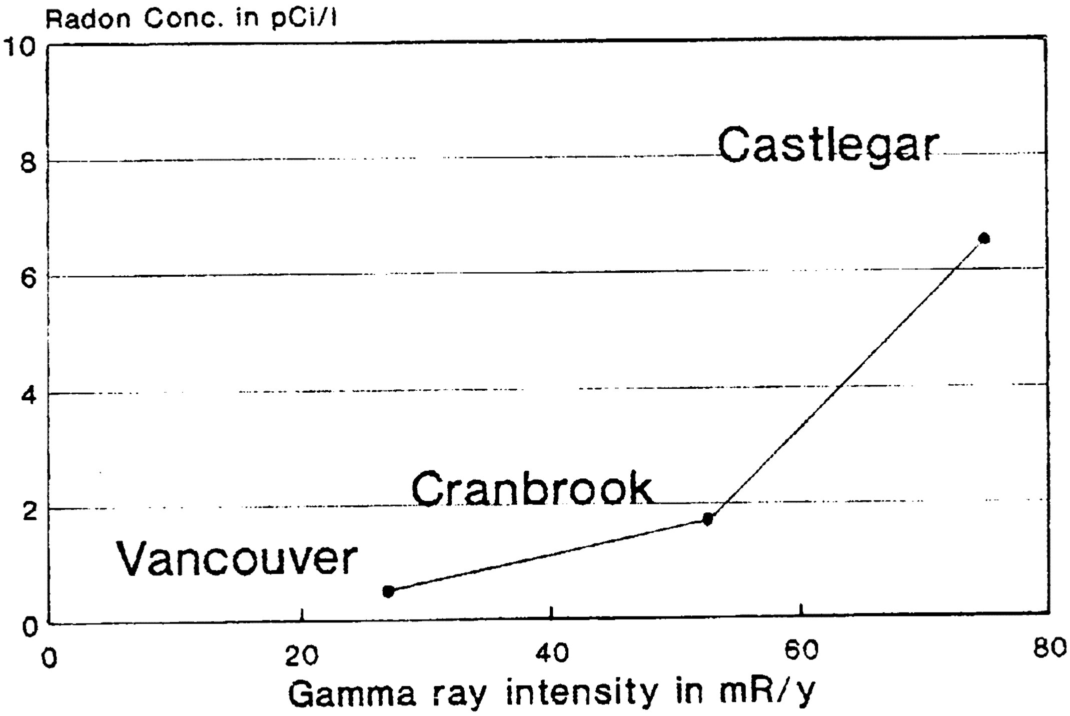


Figure 2 - Main Floor Radon Levels as a Function of Terrestrial Gamma Radiation

**CASTLEGAR, WEST KOOTENAY AREA**

All but one of the homes surveyed in Castlegar had two levels. The land was strongly sloped and the lower levels were sunk into the ground on at least 3 sides of the home. Most of the second level was located above ground. The average main radon level was 6.5 pCi/l and the average basement level was 10.6 pCi/l. A low pass filter was applied to smooth out some of the fluctuation in the data (figure 3). As can be seen from figure 3, about 45% of the homes demonstrated radon levels above 4 pCi/l and 7% were above 20 pCi/l on the main floor. More than 60% of the homes had radon levels above 4 pCi/l in the basement. Approximately 15% of the homes had higher radon concentrations upstairs. In these homes fresh air entering at the basement level was probably diluting the radon in the vicinity of the monitor. The age of the home had a marked influence on the radon concentration (Figure 4). Older homes can be characterized as having poorly constructed basement foundations with a doorway sealing them off from a leaky upstairs. New homes, although they have better constructed basements, have open stairways, an occupied basement, a central heating system, and a better sealed housing envelop. Although less radon enters the newer building, it gets distributed over both floors and is retained there. There was no direct correlation between upstairs and downstairs radon levels. If a home was supplied with make up combustion air the average radon level was downstairs 10.8 +/- 10.5 and 5.4 +/- 6.0 pCi/l upstairs. If no combustion air was supplied the average radon level downstairs was 10.2 +/- 12.0 pCi/l and upstairs was 8.2 +/- 10.5 pCi/l. Although the evidence is not strong it appears that the combustion air supply may reduce the negative pressure in the home reducing radon infiltration.

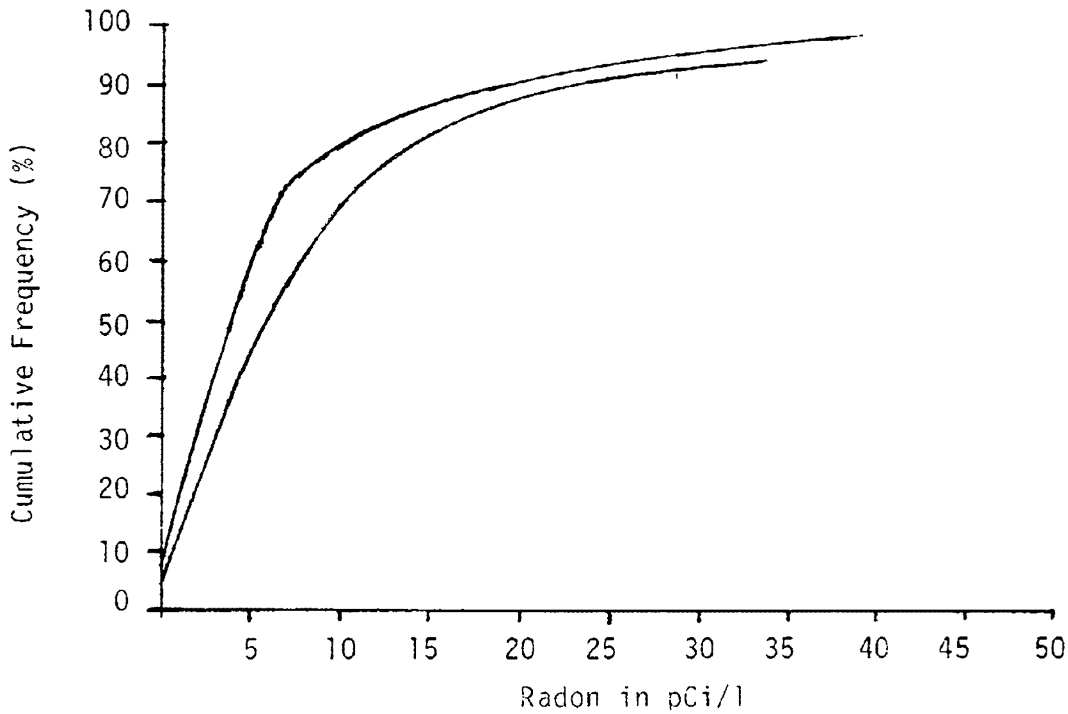


Figure 3 - Distribution of Main Floor and Basement Radon Values (Castlegar, B.C.)

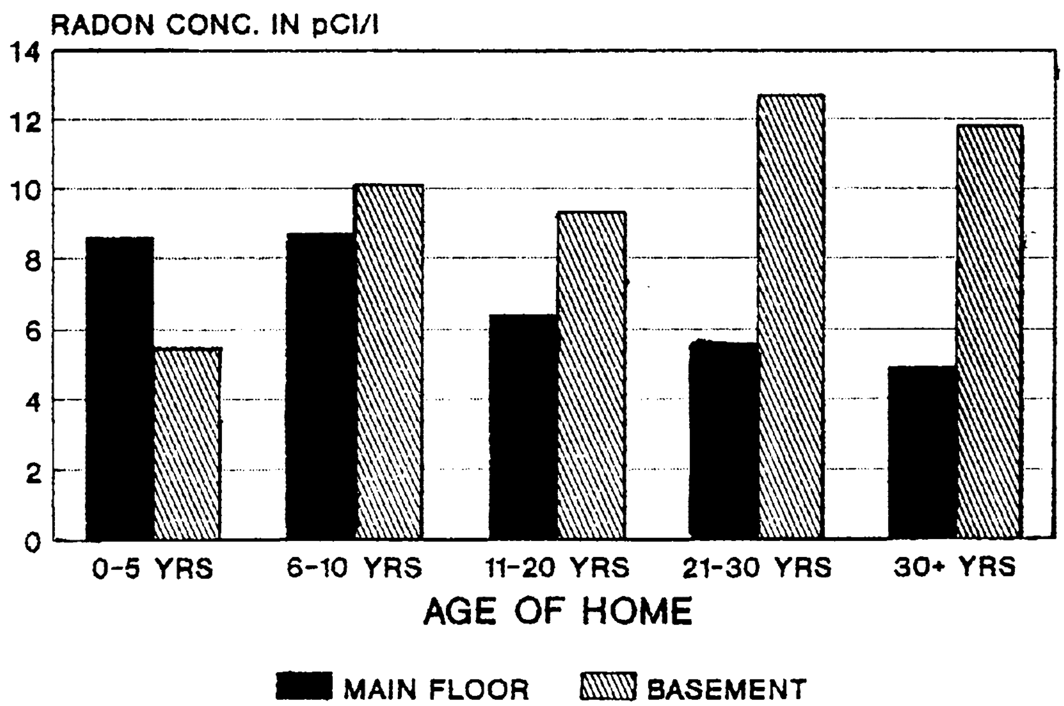


Figure 4 - Radon in Castlegar Homes as Function of Age

**EAST KOOTENAY DATA (CRANBROOK AND VICINITY)**

The East Kootenay area had, unlike the West Kootenay, a wide variety of housing types. Table 1 gives the average radon values found in the region. Terrestrial gamma levels are relatively constant throughout the region. It is interesting to note that Creston and Cranbrook are underlain with clay. This clay is not permeable and presents problems when septic fields are constructed. The other nearby communities are located on rocky and coarse soil which is much more permeable. These communities have higher radon levels. No clear trend was detected when comparing the age of the houses with radon concentration. This may be because both upstairs and downstairs measurements were not conducted in each home. Combustion air intake however does appear to have some impact on radon levels. If combustion air is supplied the average radon concentration was 1.56 +/- 2.90 pCi/l on the main floor and 1.87 +/- 1.82 pCi/l in the basement. If combustion air was not supplied the average radon concentration was 2.29 +/-2.75 pCi/l on the main floor and 2.29 +/- 3.36 pCi/l in the basement. 10% of the main floor radon levels exceeded 4 pCi/l and 1% exceeded 20 pCi/l.

**Table 1 Radon Concentrations in the East Kootenay Area (Cranbrook and Vicinity)**

| Area | Number of Homes | Average Conc. in pCi/l | Standard Deviation |
|---|---|---|---|
| All Survey Sites | | | |
| Main Floor | 90 | 1.7 | 2.8 |
| Basement | 67 | 2.0 | 1.9 |
| Fernie | | | |
| Main Floor | 3 | 3.2 | 2.9 |
| Basement | 7 | 1.7 | .6 |
| Cranbrook | | | |
| Main Floor | 47 | .9 | .7 |
| Basement | 41 | 1.7 | 1.7 |
| Kimberley | | | |
| Main Floor | 15 | 2.1 | 2.3 |
| Basement | 10 | 3.4 | 2.8 |
| Invermere | | | |
| Main Floor | 6 | 7.1 | 8.5 |
| Basement | 4 | 1.6 | .9 |
| Golden | | | |
| Main Floor | 4 | 1.7 | 1.8 |
| Basement | 5 | 3.1 | 1.7 |
| Creston | | | |
| Main Floor | 14 | 1.4 | 1.0 |
| Basement | 1 | .9 | - |

## GREATER VANCOUVER AREA

Radon concentrations in the Vancouver region were very low (average of 0.49 +/- 0.23 pCi/l and ranged between .2 and 1.6 pCi/l in the 135 homes measured. There is no significant difference from one area of the city to another despite a large variation in geological environments. The three factors that are common to the city which may explain the low radon levels are the low terrestrial gamma, an abundance of "hard pan" clay that deters radon infiltration and higher than average rainfall.

## CONCLUDING REMARKS

Terrestrial gamma measurements can be used in British Columbia to predict a community radon potential. They however cannot be used to predict an individual home's concentration of radon. Soil structure particularly permeability appears to have a marked impact on radon potential (9). The province can be divided into three radon risk areas. There is a wide coastal strip where the risk of radon exposure is very low compared to other areas of North America. However the majority of the province lies in an interior belt where the radon risk is typical of other areas of North America. There are patches within that belt where both the terrestrial gamma and radon risk are relatively high. Further study is required to delineate these areas and all homeowners in these areas should make it a priority to test their homes. Modern changes to house construction have been reported to increase radon concentration in the living area(10). Although we have also seen this in the Castlegar study, some construction techniques such as supplying combustion area and well built basements are tending to mitigate this trend. There is some concern that annual variations in household radon levels may also have to be investigated(10). At this time, fifteen additional regional radon surveys are being carried out. These additional surveys should allow us to more accurately delineate the geological, meterological, and construction parameters that impact on radon levels in the province of British Columbia.

**ACKNOWLEDGEMENTS**

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# The State of Maine Schools Radon Project: Results

L. Grodzins, Professor of Physics
Massachusetts Institute of Technology
and Founder & Chairman of the Board of
NITON Corporation, Bedford, MA 01730

T. Bradstreet, Director of Information and Education
Division of Safety and Environmental Services
Augusta, ME 04333

E. Moreau, Manager of Indoor Air Quality Program
Division of Health Engineering
Department of Human Services
Augusta, ME 04333

## ABSTRACT

A comprehensive study has been made of the radon concentrations in every frequently occupied room on or below grade in every public school in the State of Maine. 32% of the 653 school buildings covered in this report had at least one room with a radon level exceeding the EPA guideline of 4 picoCuries of radon per Liter of air (4 pCi/L). 8.7% of the 13,353 rooms had a radon level ≥ 4 pCi/L; 1.9% of the rooms had radon concentrations ≥ 10 pCi/L; 0.7% of the rooms had radon concentrations ≥ 20 pCi/L. The radon concentrations were not distributed uniformly among the schools; a building tended to have a radon problem or it was essentially free of radon. The radon concentrations were not uniformly distributed throughout the state. The schools in the counties contiguous to New Hampshire were far more likely to have a serious radon problem than were schools in the central part of the state, especially along the coast. And we note a strong correlation between the geographical results of this state-wide school survey and the previous state-wide results of radon in homes.

## INTRODUCTION

This is a report on the findings of the comprehensive survey of radon carried out in 1990 in more than 13,000 classrooms in more than 650 school buildings in the state of Maine. Overall, 33% of the school buildings had radon levels exceeding the EPA action level of 4 pCi/L. Schools with elevated radon values were not, however, uniformly located in the state. The western counties tended to have considerably higher radon levels than elsewhere. Some schools in these counties had mean concentrations exceeding 4 pCi/L and several had mean concentrations greater than 20 pCi/L. Most striking is the strong correlation between the radon levels in the schools of a county with the radon levels in the homes in that county.

This study is unique in several ways. It is, to our knowledge, the first complete state-wide school survey in which every regularly occupied room on or below grade in every school was measured; nearly 50% of all school rooms in Maine were tested. It is the first to survey all the schools using a single radon detection method analyzed by a single company. Without this unified approach, the present study would not have been practical. It is the first survey in which the placement and retrieval of the radon detectors were carried out by the school custodians, with all scientific and technical decisions handled in advance by the testing firm, NITON Corporation; the 98.5% success rate of this procedure has important economic implications for future surveys.

The design of the study is described elsewhere in this meeting (1). So, too, are the protocols and procedures of the testing program (2). For completeness, a summary follows. The next section presents the results, first in overview, then in greater detail. The last section correlates the school results with other information, particularly the radon survey of homes in the state and summarizes our conclusions.

## PROCEDURES

The radon tests were carried out using NITON's patented liquid scintillation charcoal detectors. These small, 1" diameter by 2" long, detectors contain a cartridge holding about 1.5 grams of charcoal mixed with desiccant. For each school, NITON made up individual packages containing the test vials, data sheets, and a copy of the school floor plans marked with locations for placing the test vials. Most important, the package included a set of simple, comprehensive, step-by-step, check-off instructions.

Every regularly occupied room on or below grade was tested over a week-end under closed building conditions. The air-handling systems were generally operated continuously. School custodians set out and retrieved the tests and returned them to the NITON Laboratory in Massachusetts, using next-day UPS service. This protocol worked exceptionally well even for remote one-room school houses, including those on islands off the coast and those in Indian reservations; only 1.5% of the rooms had to be resurveyed because of faulty procedures.

The NITON LS vials were set out on Friday afternoons, retrieved Monday morning, generally arrived at the laboratory in Massachusetts and were counted in the automated LS counters on Tuesday. The NITON "2-day" diffusion barrier is most sensitive to the last 48 hours of testing so the first evening of the test effectively established the base line of closed conditions.

All test vials were counted for 5 minutes each. Prompt return of the test vials meant that the radon decayed by only 25% to 35% between the time the vials were closed and the time they were counted. As a consequence, the 5-minute count in the automated scintillation counter resulted in a standard deviation $\sigma$ <5 % at a concentration level of 4 pCi/L; $\sigma$ ~10% at 1 pCi/L; and $\sigma$ ~20% at 0.4 pCi/L. All vials with radon concentrations exceeding 3 pCi/L were rerun for 20 minutes each ( $\sigma \leq 2\%$). Results, quoted to the nearest 0.1 pCi/L, were sent to the State of Maine the following day.

## RESULTS

### QUALITY OF THE DATA

The results from NITON vials were compared with themselves and with independent tests. Over the course of the study, side-by-side tests were run in a total of 33 buildings. The results were excellent. The mean of the absolute differences between the side-by-sides was 0.2 ± 0.16 pCi/L. The mean of the absolute differences for results exceeding 2 pCi/L was 0.25 ± 0.17 pCi/L. Only 2% of the absolute differences were as great as 0.6 pCi/L; none were higher. The precision of the results was <5% at 4 pCi/L, about the same as the statistical uncertainty of the initial liquid scintillation test.

Quality control of the NITON vials is carried out routinely with in-house radon standards, and checked periodically using independent radon quality control laboratories. We followed three additional procedures to establish the quality control for the Maine survey: 1) The NITON liquid scintillation vials were specially tested at the Environmental Measurements Laboratory of the Department of Energy; 2) 100 NITON LS detectors, in pairs, were compared with 50 Charcoal Canisters; i.e. 3 detectors (2 NITON LS and 1 CC) were run side-by-side. The Charcoal Canisters were tested by the State of Maine Indoor Air Quality group. Most of the compared results were within 0.1 pCi/L. Two comparison tests differed widely: In one test, the LS values were 3.3 and 3.0 pCi/L, the CC result was 1.2 pCi/L; in another, the LS values were 5.5 and 5.3 pCi/L while the CC result was 3.0 pCi/L.

3) 30 NITON LS detectors were compared by the State of Maine with continuous monitors. Half the tests lasted 8 hours, half lasted 16 hours; NITON detectors are calibrated from 8 to 72 hours. The mean radon concentrations ranged from 4.4 pCi/L to 67 pCi/L, with short-term variations ranging from 0.6 pCi/L to 74.5 pCi/L, according to the continuous monitor. The mean of the 30 NITON results was 10% higher than the mean of the means of the 30 results from the continuous monitor. These comparisons give considerable confidence in the results for the individual schools and for the overall survey.

### STATE-WIDE RESULTS

#### <u>School Rooms</u>

The results for 13,353 school rooms are presented in Table I and Figures 1 and 2. The frequency distribution of radon in the school rooms of Maine had a most probable value of <1 pCi/L, a median value of 1.1 pCi/L and a geometric mean of 1.05 pCi/L. These values are not much different from those obtained by NITON in a survey of 5,000 school rooms in Massachusetts. 8.7% of the school rooms in Maine had radon values of 4 pCi/L and above (the corresponding number in Massachusetts was 6%); 1.9% of the Maine school rooms had radon values of 10 pCi/L and above (Massachusetts was 1.1%); 0.7% of the Maine school rooms had radon values of 20 pCi/L and above (Massachusetts also had 0.7%).

TABLE 1. THE FREQUENCY DISTRIBUTION OF RADON IN SCHOOL ROOMS AND SCHOOL BUILDINGS IN MAINE

| Concentration, pCi/L | Rooms with ≥ Concentration | Column 2 as % of 13,353 Rooms | Buildings with 1 or more rooms ≥ Concentration | Column 4 as % of 653 Buildings |
|---|---|---|---|---|
| 0.4 | 11,550 | 86.5 | 644 | 98.6 |
| 1.0 | 7,322 | 54.8 | 587 | 89.9 |
| 1.5 | 4,884 | 36.6 | 520 | 79.6 |
| 2.0 | 3,365 | 25.2 | 445 | 68.1 |
| 2.5 | 2,429 | 18.2 | 373 | 57.1 |
| 3.0 | 1,828 | 13.7 | 308 | 47.2 |
| 3.5 | 1,420 | 10.6 | 248 | 38.0 |
| 4.0 | 1,164 | 8.7 | 213 | 32.6 |
| 5.0 | 808 | 6.1 | 167 | 25.6 |
| 6.0 | 601 | 4.5 | 126 | 19.3 |
| 7.0 | 454 | 3.4 | 93 | 14.2 |
| 8.0 | 370 | 2.8 | 77 | 11.8 |
| 9.0 | 312 | 2.3 | 70 | 10.7 |
| 10.0 | 255 | 1.9 | 54 | 8.3 |
| 11.0 | 222 | 1.7 | 49 | 7.5 |
| 12.0 | 197 | 1.5 | 44 | 6.7 |
| 13.0 | 172 | 1.3 | 38 | 5.8 |
| 14.0 | 155 | 1.2 | 35 | 5.4 |
| 15.0 | 144 | 1.1 | 33 | 5.1 |
| 16.0 | 131 | .9 | 31 | 4.7 |
| 17.0 | 118 | .8 | 28 | 4.3 |
| 18.0 | 109 | .8 | 24 | 3.7 |
| 19.0 | 102 | .7 | 21 | 3.2 |
| 20.0 | 98 | .7 | 21 | 3.2 |
| 25.0 | 68 | .5 | 14 | 2.1 |
| 30.0 | 48 | .35 | 11 | 1.7 |
| 40.0 | 16 | .11 | 7 | 1.1 |
| 50.0 | 2 | .01 | 2 | .3 |

The distribution is plotted in Figure 2 as a lognormal probability graph. The data exhibit the fact, now familiar in most radon surveys, that the radon distributions follow a normal probability distribution up to about 4 to 5 pCi/L. The probability of observing elevated radon concentrations is higher than would be predicted on the basis of a normal distribution. This study found twice as many school rooms with radon concentrations above 10 pCi/L, and ten times as many above 20 pCi/L, as would be inferred from a normal distribution.

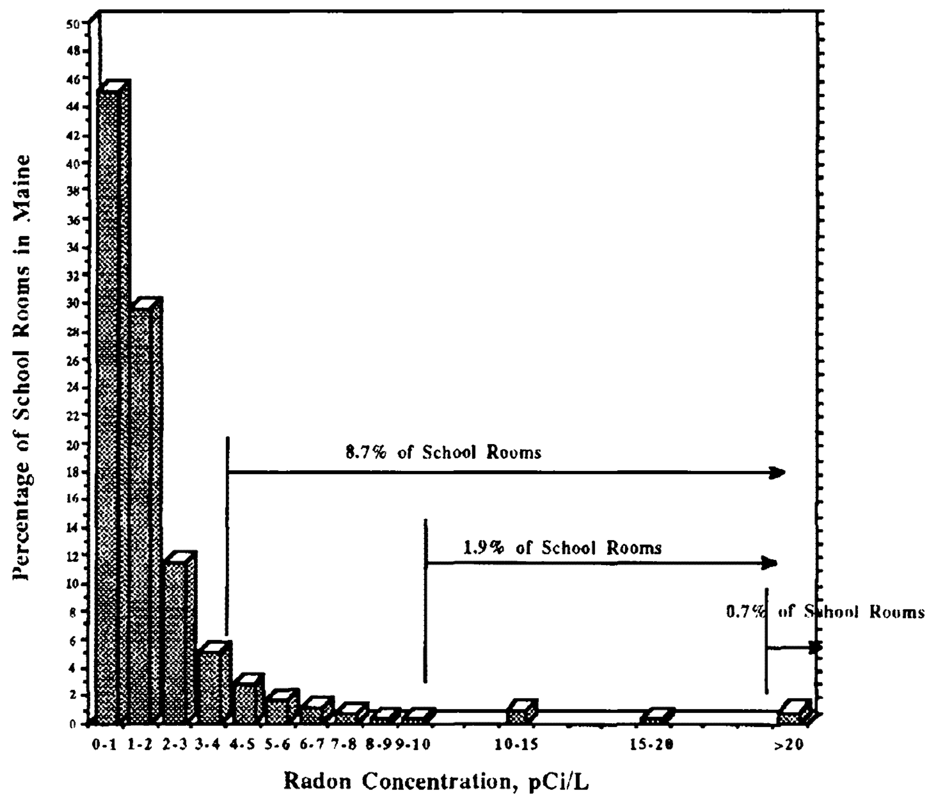



Figure 1. The distribution of radon in the school rooms of Maine

N.B. The uncertainties in these statistical values, and those given later in the paper, are due almost entirely to the uncertainty in the accuracy of the test results, which we assume to be ~10% on the basis of NITON's overall accuracy in several EPA Quality Assurance rounds. A 10% uncertainty in the absolute accuracy results in a corresponding 10% uncertainty to the median, arithmetic and geometric means, as well as to the percentage of school rooms exceeding 10 pCi/L and 20 pCi/L. The percentage of school rooms above 4 pCi/L depends more strongly on the absolute accuracy because of the steepness of the distribution at 4 pCi/L. For example, if NITON's absolute calibrations have a systematic error such that all results are 10% too high (and recall that the EPA accepts a 25% absolute uncertainty) then only 7% of the school rooms are above 4 pCi/L. If NITON's values are 10% low then 10.5 % of the school rooms are above 4 pCi/L. The sensitivity of the results to the absolute accuracy in the tests is a compelling reason why surveys should be carried out using a single method and, wherever possible, by a single group using the same calibration standards. In practice it is very difficult to accurately compare surveys carried out by different methods or by different laboratories.

The distribution is plotted in Figure 2 as a lognormal probability graph. The data exhibit the fact, now familiar in most radon surveys, that the radon distributions follow a normal probability distribution up to about 4 to 5 pCi/L. The probability of observing elevated radon concentrations is higher than would be predicted on the basis of a normal distribution. This study found twice as many school rooms with radon concentrations above 10 pCi/L, and ten times as many above 20 pCi/L, as would be inferred from a normal distribution.

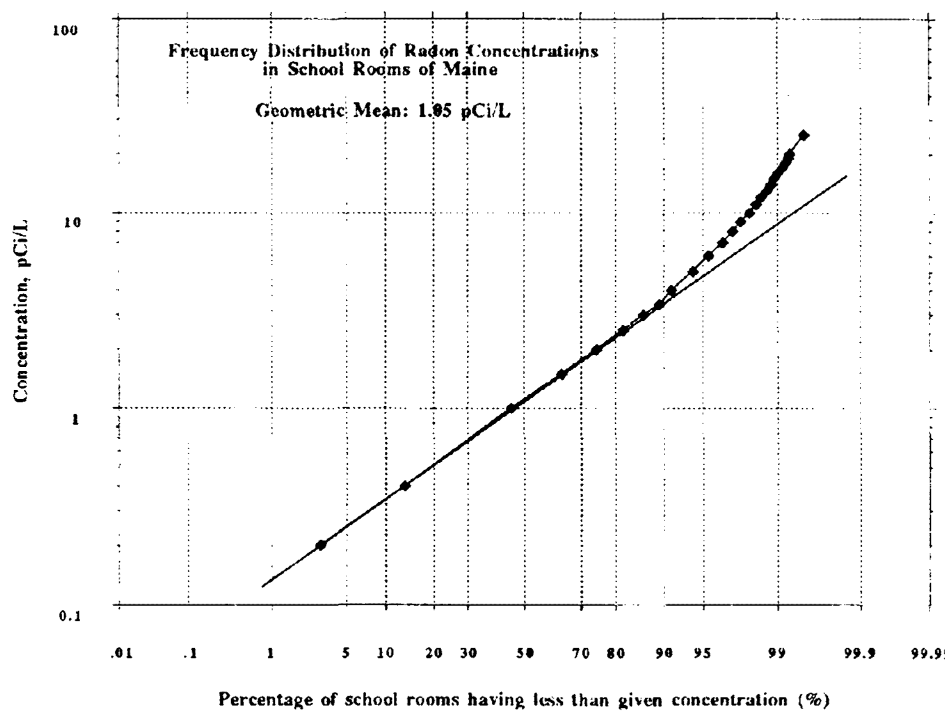



Figure 2. Lognormal plot of the distribution of radon in the school rooms of Maine.

School Buildings

The data for the 653 school buildings examined in this survey are presented in Table I. Columns 4 and 5 give, as a function of radon concentration shown in column 1, the number and percentage of school buildings that have at least one room with a concentration greater than that level. 32.6% of the buildings had at least one room with a radon level o≥ 4 pCi/L. Stated the other way, 67.4% of the buildings had no room with a radon concentration exceeding the EPA action level. 8.3% of the buildings had at least one room with a concentration of 10 pCi/L or greater, and 3.2% of the buildings had at least one room with a radon concentration of 20 pCi/L. These state-wide percentages tell an incomplete story since both the geographic location and the size of the school are critical variables.

School Size

Table II shows the distribution of the number of rooms per school building. The typical school in Maine has fewer than 20 rooms, 151 schools have fewer than 10 rooms. The third row of Table II gives the number of school buildings that have at least one room with ≥ 4 pCi/L of radon. The bottom row of the table gives the percentages of buildings that have at least one elevated radon reading. The percentages vary from 21% to 50% but, within statistical uncertainties, the percentages are essentially constant. This is a most surprising finding since one would expect, a priori, that the larger the school the greater the probability of finding an elevated radon level.

TABLE II: SOME DISTRIBUTIONS IN SCHOOL BUILDINGS IN MAINE

| Number of Rooms per Building | <10 | 10-19 | 20-29 | 30-39 | 40-49 | ≥ 50 |
|---|---|---|---|---|---|---|
| Total number of buildings | 151 | 184 | 141 | 90 | 40 | 42 |
| Total number of buildings with at least one room ≥ 4 pCi/L | 40 | 65 | 41 | 36 | 20 | 9 |
| % of "High-Radon" Buildings | 27% | 35% | 29% | 40% | 50% | 21% |

The explanation is that radon is not randomly distributed in the schools. School rooms, in a building that has a common architecture and air-handling system, show very similar radon concentrations. To emphasize the lack of randomness, consider the larger buildings with more than 50 rooms. If radon were distributed randomly we would find 8.7% of the rooms of each school with elevated radon concentrations. The probability that a school with 50 rooms would have no elevated radon room is $(0.913)^{50}$ = 1.1%; the actual probability is 79%.

The "one-room" school houses do not follow a random pattern either, though one expects, on the basis of the state-wide data, to find about 30% of the buildings with a radon problem. The lack of randomness is demonstrated in Table III, which breaks out the data of the third row of Table II to give, as a function of the size of the school, the number of buildings that have a given percentage of the school rooms with ≥ 4 pCi/L. Thus, of the schools that have at least one radon problem, there were 5 large school buildings (>50 rooms) in which fewer than 10% of the rooms had elevated radon. There was, however, one large school building in which more than 80% of the rooms had an elevated radon problem.

TABLE III: THE NUMBER OF BUILDINGS AS A FUNCTION OF THE NUMBER OF ROOMS AND THE PERCENTAGE OF ROOMS WITH ELEVATED RADON LEVELS

| Number of Rooms per Building | <10 | 10-19 | 20-29 | 30-39 | 40-49 | ≥ 50 |
|---|---|---|---|---|---|---|
| <10% of the rooms | 0 | 14 | 20 | 19 | 9 | 5 |
| 10% - 39% of the rooms | 22 | 37 | 12 | 11 | 7 | 1 |
| 40% - 59% of the rooms | 1 | 5 | 5 | 3 | 0 | 1 |
| 60% - 79% of the rooms | 5 | 6 | 3 | 2 | 3 | 1 |
| >80% of the rooms | 12 | 3 | 1 | 1 | 1 | 1 |
| Total number of buildings | 40 | 65 | 41 | 36 | 20 | 9 |

A number of school buildings (bottom row of Table III) were saturated with radon. There is negligible probability that any of these saturations could occur by chance. Every one of the 48 rooms in one school building was far above the EPA guidelines; the median value was 25 pCi/L. All of the buildings in the lower part of the table support the general observation that high radon levels tend to cluster; there are relatively few buildings that have isolated rooms with elevated radon levels.

The school buildings in the second row of Table III have, typically, only 1 or 2 high-radon level rooms. Unfortunately, the odd high radon value can be very high indeed. For example, in one school of 23 rooms, having a median radon level of 1 pCi/L, there was one classroom with 27 pCi/L; in a 4-room school house where 3 of the rooms were under 4 pCi/L, there was one room with 38 pCi/L. In the next section we examine a few of the radon distributions in individual school buildings.

Results of Individual Schools

The present study involved more than 650 school buildings and NITON has surveyed more than 500 other school buildings during the past two years. The buildings have different ages, architectures, geological sites, air-handling systems, etc. From the mitigator's point of view, each building is unique. From the radon surveyor's point of view, there are definite patterns of radon distributions that can be useful guides to understanding the origins of the radon problem.

Figure 3 shows three radon distributions found in schools in Maine. Distribution A is a "radon-free" building; the median value is well below 1 pCi/L and no concentration is greater than 2 pCi/L. There is no correlation between the radon levels and the room location. The most probable value is similar to the radon level found outdoors.

Distribution C is a "radon-infested" building in which the radon levels are about the same in every room. The distribution is nearly Gaussian; the mean of 24.9 pCi/L is same as the median value.

Distribution B is very similar to C, though the mean and the median are both below 4 pCi/L. Every room in the school has a potential radon problem as the levels fluctuate with changes in the weather and the air-handling.

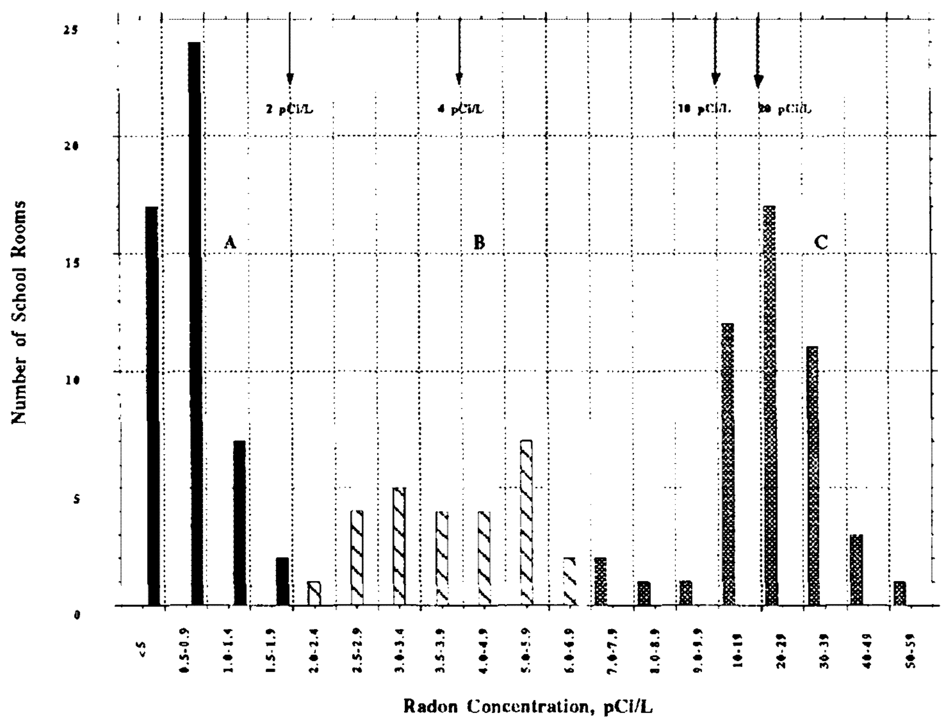



Figure 3. Radon distributions in three schools in Maine.

Figure 4 shows three distributions observed in school buildings of Maine. These are rather typical of the broad distributions that almost always show a correlation between the radon concentration and the room location. Contiguous rooms show similar radon values; changes in concentration take place over several to many rooms..

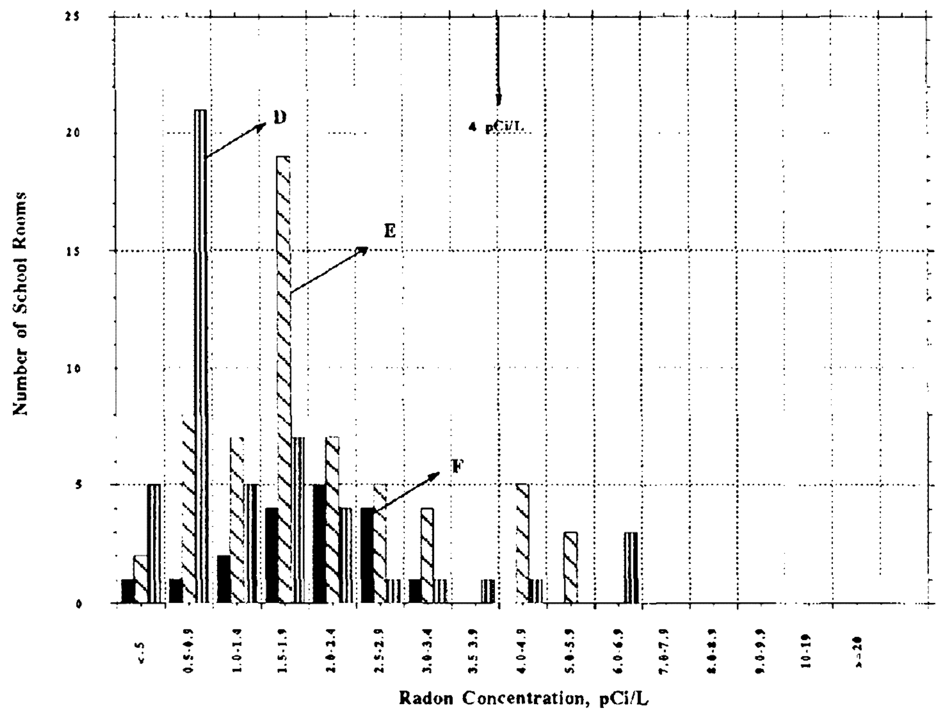



Figure 4. Radon distributions in three schools in Maine

The most probable radon concentration of distribution D is below 1 pCi/L and most of the rooms are radon-free. Nevertheless, a few rooms have values well above the EPA guidelines; it is our experience that these rooms are generally localized to the same area of the school.

Distribution E is also sharply peaked at a low radon value, but the median value is close to 2 pCi/L, indicating a radon problem. We again anticipate a strong correlation between the radon concentration and the geography of the room.

Distribution F has no reading above 3.5 pCi/L. But the median value of 2.5 is high. This building should be carefully monitored over time since it is likely that there will be periods during the year when the radon levels will rise by at least a factor of two and most of the rooms will have concentrations exceeding EPA guidelines.

Only distributions similar to those of A in Figure 3 can give us reasonable assurance of a school without a real or potential radon problem. The assurance is not, however, a guarantee. We have several examples of schools in this survey in which there is one or at most two elevated radon concentrations in an otherwise radon-free school. To find such rooms, one must survey every room on or below grade.

Survey Results by Maine County

Table 4 presents the results by county. The last 3 columns give the results of the Maine survey of radon in homes.

TABLE 4: RADON IN THE SCHOOLS AND HOMES OF MAINE, BY COUNTY

| County | Total School Rooms | Median pCi/L | Maximum pCi/L | % ≥4 pCi/L | Total Houses | Maximum pCi/L | % ≥ 4 pCi/L |
|---|---|---|---|---|---|---|---|
| Androscoggin | 1,065 | 1.3 | 21.8 | 5.34 | 39 | 17.7 | 18 |
| Aroostock | 1,493 | 1.5 | 18.7 | 11.25 | 95 | 25.2 | 43 |
| Cumberland | 2,222 | 1.4 | 59.2 | 16.42 | 120 | 82.7 | 41 |
| Franklin | 345 | .5 | 15.8 | 6.66 | 19 | 9.7 | 16 |
| Hancock | 654 | 1.2 | 21.4 | 5.5 | 49 | 19.4 | 27 |
| Kennebec | 1,062 | 1 | 43.5 | 5.83 | 57 | 19.4 | 26 |
| Knox | 151 | .6 | 4.5 | .66 | 24 | 9.7 | 29 |
| Lincoln | 116 | .6 | 13.8 | 4.31 | 12 | 5.9 | 8 |
| Oxford | 580 | 1.5 | 37.7 | 14.47 | 37 | 30.2 | 51 |
| Penobscot | 1,783 | .7 | 17.9 | 3.64 | 72 | 5.7 | 17 |
| Piscataquis | 384 | .6 | 5.7 | 0.26 | 37 | 22.5 | 32 |
| Sagadahoc | 499 | .9 | 5.3 | 1.4 | 32 | 8 | 19 |
| Somerset | 746 | .8 | 26.4 | 4.28 | 27 | 5.8 | 19 |
| Waldo | 223 | 1 | 7.6 | 6.27 | 26 | 13 | 19 |
| Washington | 539 | 1 | 12.6 | 1.66 | 36 | 12.2 | 14 |
| York | 1,491 | 1.4 | 41.6 | 15.75 | 73 | 33 | 38 |
| Total Tests | 13,353 | | | | 755 | | |

The counties vary widely in population and, therefore, in the number of schools and school rooms. There are large variances in the measures of radon concentration in the homes of several of the counties, particularly, Lincoln, Knox and Waldo. The school measurements are much more secure. Even the smallest county had more than 100 school tests and the median value is measured to an uncertainty of less than 0.2 pCi/L.

Table 4 gives three indicators of the radon concentration in the schools of the different counties. The maximum radon value, column 4, can be a statistical outrider and is not a useful measure of the radon problem in the county. The percentage of rooms that exceed 4 pCi/L, column 5, is a much more useful indicator since it focuses on that part of the distribution which demands action. The median radon values, column 3, while not giving the full description that would be obtained from the geometrical moments of each distribution, does give an easily understood measure of the radon problem and is, in our view, the best single number to quote. If half the rooms have a radon concentration below 0.7 pCi/L, which is the case in 5 counties, one can be quite sure that fewer than 10% of the school rooms will have elevated values. On the other hand, if half the rooms have a radon concentration greater than 1.4 pCi/L, which is the case in 4 counties, one can be quite sure that more than 10% of the rooms will have concentrations greater than 4 pCi/L.

The four counties with the highest radon concentrations in the schools also have the four highest radon concentrations found in homes. The correlation between the percentage of school rooms in a county that are ≥ 4 pCi/L (column 5) and the median radon concentration found in the county (column 3) is $r^2 = 0.58$. The correlation between the values in column 5 and the highest radon value found in any school room in the county (column 4) is $r^2 = 0.65$. There is little correlation between the median and the maximum values in a county.

Figure 5 shows, by county, the percentage of school rooms and homes that exceed the EPA action level. The values for homes have been divided by a factor of 3. (These home readings are generally basement readings. The first floor level in New England is, as a rule of thumb, about one-third of the basement level.)

There is a striking correspondence between the results for schools and those for homes in the same counties. There are several exceptions to the obvious correlation, but most have large uncertainties in the individual values due to the small sample sizes.

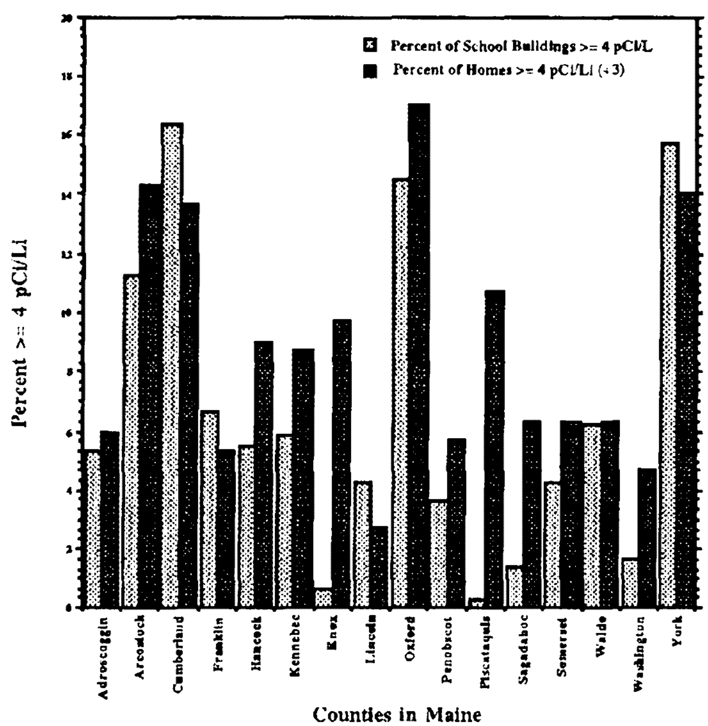
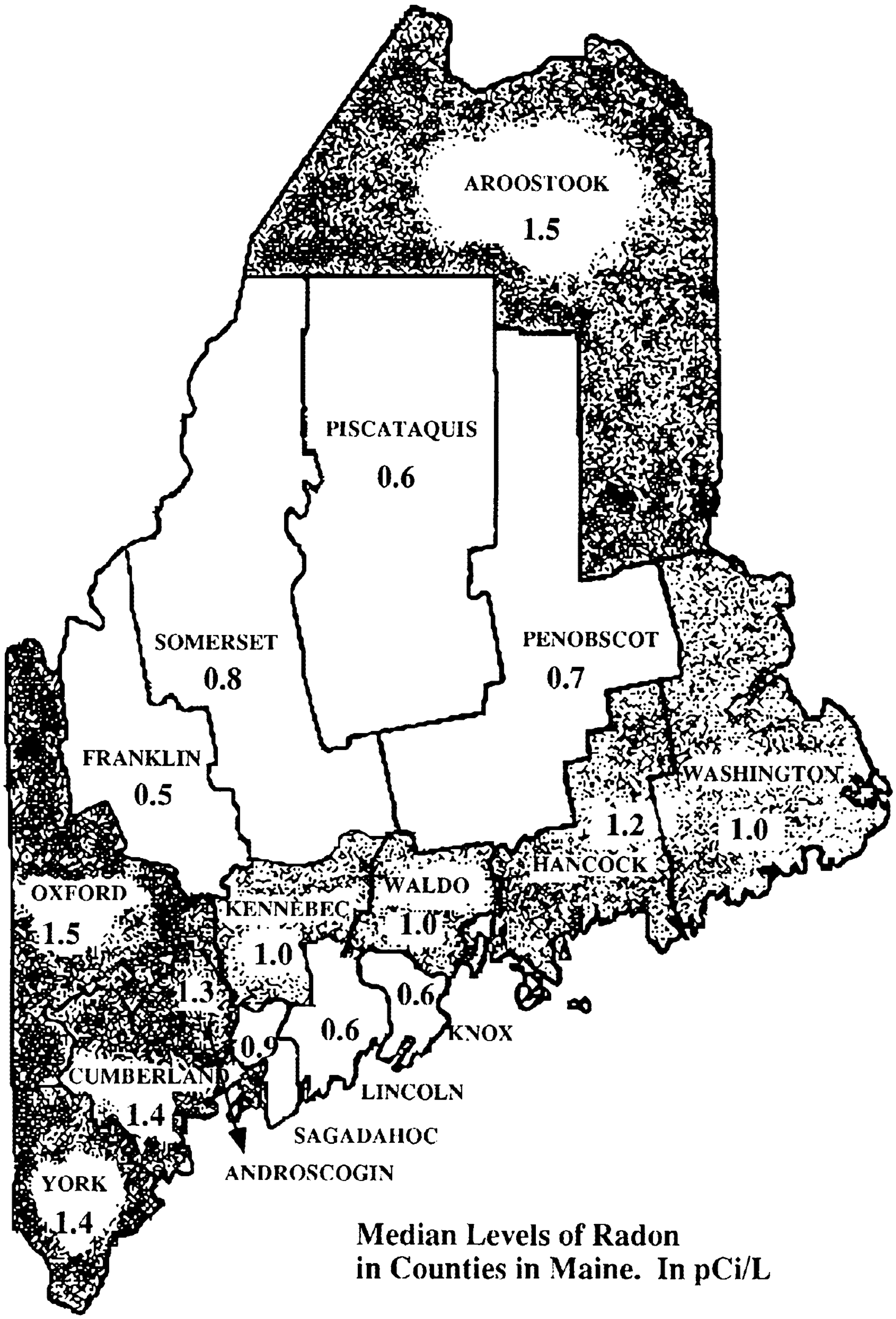



Figure 5. Radon Concentrations in School Rooms and Homes by County in Maine




Median Levels of Radon
in Counties in Maine. In pCi/L

The final figure shows a map of Maine divided into its 16 counties. The median radon concentration for each county is given in pCi/L. The map has been shaded to show the strengths of the radon values; the darker the shading the higher the median value. Radon is obviously correlated with the geography of Maine. The four southwestern counties, York, Cumberland, Androscogin and Oxford have uniformly high mean radon values. There is then a band of moderate radon concentrations extending from Kennebec through Waldo, Hancock and Washington. The central coastal counties of Sagadahoc, Lincoln and Knox have low radon concentrations, as do the Maine-woods counties of Franklin, Somerset and Piscataquis. Aroostook county, with towns and schools bordering New Brunswick, Canada, is another area of high radon concentration. As we noted above, the areas bordering New Hampshire and New Brunswick have the highest radon concentrations in both school rooms and homes.

## SUMMARY

The principal aim of this comprehensive survey of radon in the schools of Maine was to find those schools that should be mitigated immediately, as well as those schools that have potential problems that must be monitored over time. That aim has been well met. A second aim was to obtain a data base of the radon concentrations in every school, which would serve as the bench mark and guide for spot checks and sample surveys that might be conducted in future years either as part of a general "due diligence" program or because of changes in construction or air handling. That aim, too, has been well met. A third aim was to find generalities and correlations that might aid in understanding the radon problems in the state. This paper presents the sum of those findings.

The frequency distribution of radon in school rooms in Maine is similar to that found in surveys of school rooms elsewhere; for example, in Massachusetts. The distribution follows a lognormal curve up to radon concentrations of about 5 pCi/L. The occurrence rate at the higher concentrations is greater than would be predicted by the normal curve.

8.7% of the school rooms tested over weekends under closed building conditions were found to have radon concentrations greater than the EPA action level of 4 pCi/L; 1.9% of the rooms were above 10 pCi/L; 0.7% were ≥ 20 pCi/L. The elevated radon concentrations were not randomly distributed. A school that had one room with > 4 pCi/L, had, on the average, 5 such rooms. The odds that a school building had at least one room with > 4 pCi/L, was about one in three. The odds were almost independent of the size of school.

The patterns of radon distributions in the schools can be conveniently divided into three broad groups: 1) those radon-free schools with median (or geometric mean) values well below 1 pCi/L, no concentration greater than 2 pCi/L, and no correlation between the radon values and the position of the school room; 2) those radon-infested schools with median and mean values above ~3 pCi/L, and with a majority of the values exceeding the EPA guidelines; 3) schools that have median (or geometric mean) values in the 1-2 pCi/L range, have broad distributions (large standard deviations of the geometric means), and generally a strong correlation between the position of the room in the building and its radon concentration. The first group is the only one with a strong probability of being radon-free under all circumstances of weather and air handling; the second group must be mitigated early; the last group encompasses a wide variety of situations with few common denominators other than the need for close examination and monitoring.

The radon concentrations showed a strong correlation with geography. The median radon concentrations in the western counties — Oxford, York, Cumberland and Androscogin — and the northernmost county, Aroostock, were more than twice the values in the coastal counties of Knox and Lincoln and the Maine woods counties of Franklin, Somerset, Piscataquis and Penobscot.

The counties with highest (lowest) radon concentration in the schools generally had the highest (lowest) average concentration in the homes. This strong correlation between radon levels in school rooms and homes in the same geographical area implies that the underlying geological factors are the determinants for the average or median radon concentrations in county-size areas. We anticipate that this is a general conclusion that will be observed throughout the country.

The correlation between radon levels in homes and in schools is strengthened by comparing the Maine results with those obtained by NITON Corporation tests of more than 5,000 school rooms in Massachusetts. The EPA state-wide studies of homes found that 25% of the "lowest-livable" rooms in Massachusetts had values > 4 pCi/L, compared to 30% for Maine. Massachusetts has only 6% of its school rooms exceeding the EPA guideline, compared to 8.7% for Maine. Thus there are fewer school rooms with high readings in Massachusetts to about the same degree that there are fewer homes with high radon readings.

We also consider it worth noting that the percentage of school rooms with > 4 pCi/L of radon is, for both Maine and Massachusetts, about one-third the percentage of homes with basements with radon concentrations > 4 pCi/L. This correlation implies that the average radon values in schools is not much different from the radon concentrations found on the first floors (the living areas) of homes in the same geographical area.


## ACKNOWLEDGEMENTS

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# RADON IN BELGIUM : THE CURRENT SITUATION AND PLANS FOR THE FUTURE

A. Poffijn[1], J.M. Charlet[2], E. Cottens[3], S. Hallez[3], H. Vanmarcke[4], P. Wouters[5]

[1] Nuclear Physics Lab, RUG, B-9000 Gent, Belgium
[2] Polytechnical Faculty Mons, B-7000 Mons, Belgium
[3] Ministry of Public Health, B-1000 Brussels, Belgium
[4] Radiation Protection, SCK/CEN, B-2400 Mol Belgium
[5] BBRI, B-1342 Limelette, Belgium

## ABSTRACT

An overview is given of the current knowledge about radon in Belgium. The results and experience obtained from regional and local surveys are presented .
The indications about the risk of indoor radon are discussed.
The general outline and main purposes of the national action program, as prepared for presentation to the competent authorities, are also dealt with.

## INTRODUCTION

In Belgium, the yearly average population dose from natural ionising radiation is estimated to be of the order of 3.5 mSv (1). This value is about three times higher than what was generally accepted some 15 years ago. This increase is a major consequence of the introduction of the notion effective dose-equivalent and of a better knowledge of the respiratory track dosimetry.
As a matter of fact, radon progeny alone is responsible for some 50% of the total annual effective dose.
From the point of view of policy the range of variation of exposures is an even much more important quantity. Radon concentrations are found to vary over more than three decades, being at least one order of magnitude greater than the range for other natural sources of ionising radiation.
Based-upon the avaiable radon data, some hundred of houses are expected to exist, where the inhabitants are exposed to levels giving rise to doses higher than the limits for radiation workers.
Infiltration of radon bearing soil gas is the major source of radon in dwellings. As a lot of uranium anomalies occur in Belgium, the study of the geological parameters is an essential tool for the evaluation and reduction of this infiltration. The specific construction characteristics of Belgian dwellings should of course also be taken into account.

## RISK ESTIMATIONS AND REGULATIONS

According to the results of a national survey (1) the average indoor radon concentration in Belgium is 48 Bq/m3, with a net distinction between the two major geological zones wherein the country may roughly be divided (Fig.1).

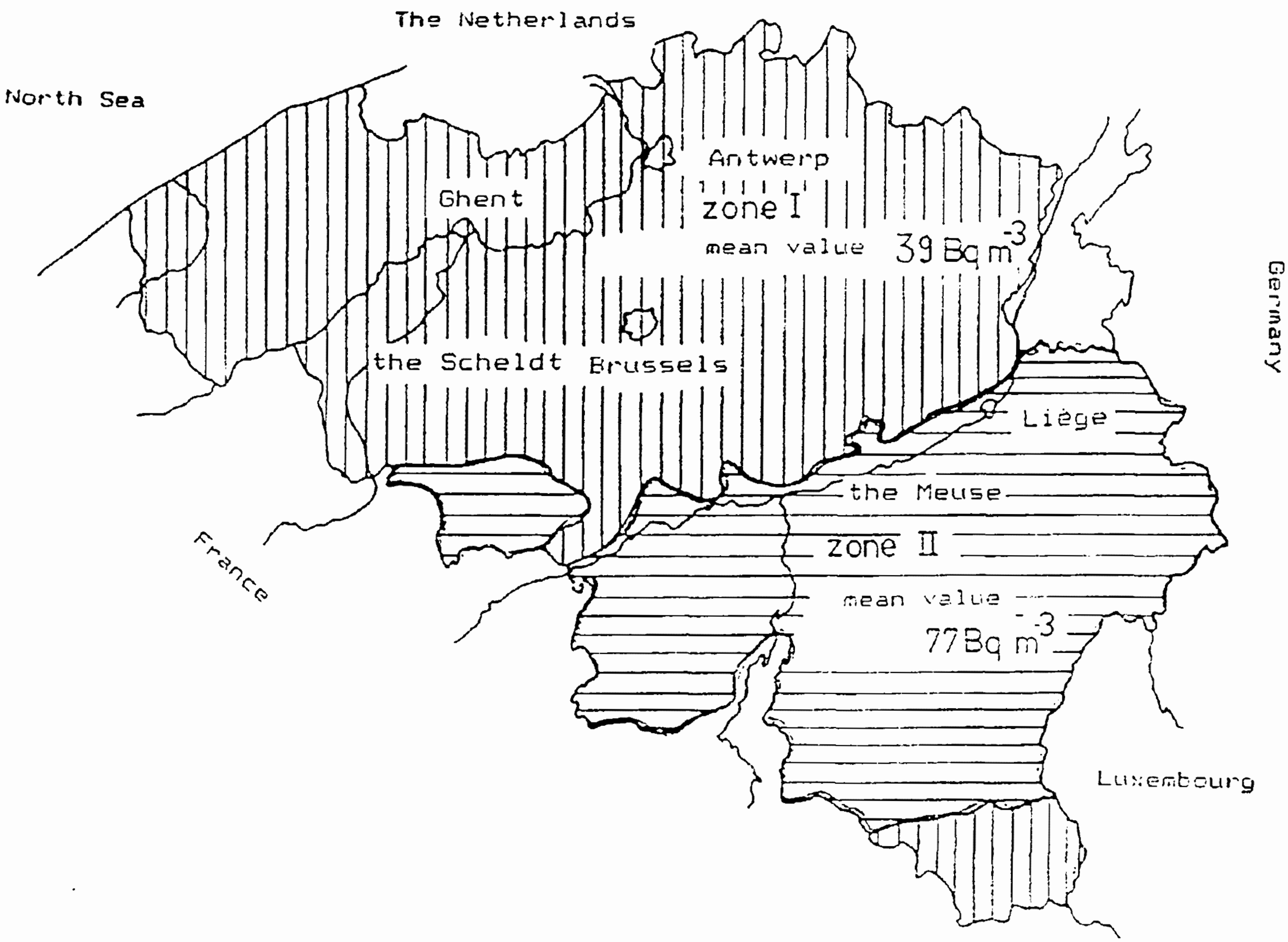


Figure 1 : Mean radon concentration in the two major geological zones of Belgium

Using a dose conversion factor of $50\mu Sv$ per $Bq/m^3$ and a mean time spent indoors of about 0.8, an average effective dose equivalent of 1.9 mSv per year may be put forward as reference value for a member of the Belgian population, corresponding to a collective dose of 19000 Sv.
Up to now, near all risk estimations for radon are extrapolations of the results of epidemiological studies among workers (2). From these data, an overall (absolute) risk of the order $(3 \pm 1.5)*10^{-2}$ per Sv can be expected to hold for the general population (3). This value agrees well with the ICRP risk factor of 1.65/Sv for radiation of artificial origin. Using this risk factor, some 250 up to 750 of the total number of lung cases per year in Belgium (6000) may be associated with radon. The corresponding life-time risk is of the order of 0.3% and is of the same order as the risk for a mortal accident at work.
Due to the increasing awareness of the significance of indoor radon, many national and international authorities have drawn up dose-control policies. The proposed reference levels vary between 150 and 800 $Bq/m^3$ for existing buildings and between 140 and 250 $Bq/m^3$ for future constructions (Table 1).

TABLE 1 : RECOMMENDATIONS FOR RADON LIMITATION

| Radiological Authority | Existing Homes ($Bq/m^3$) | Future Homes ($Bq/m^3$) |
|---|---|---|
| ICRP | 400 | 200 |
| CEC | 400 | 200 |
| WHO | 200 | 200 |
| Germany | 250 | 250 |
| Sweden | 800 | 140 |
| UK | 200 | 200 |
| USA | 150 | 150 |

In Belgium the highest values have been reported in the province of Luxemburg (Fig.2). Based upon the avaiable data some 10000 dwellings are expected to have radon concentrations of more than 400 Bq/m$^3$, with an exceptional high proportion being situated in the province of Luxemburg (Table 2).

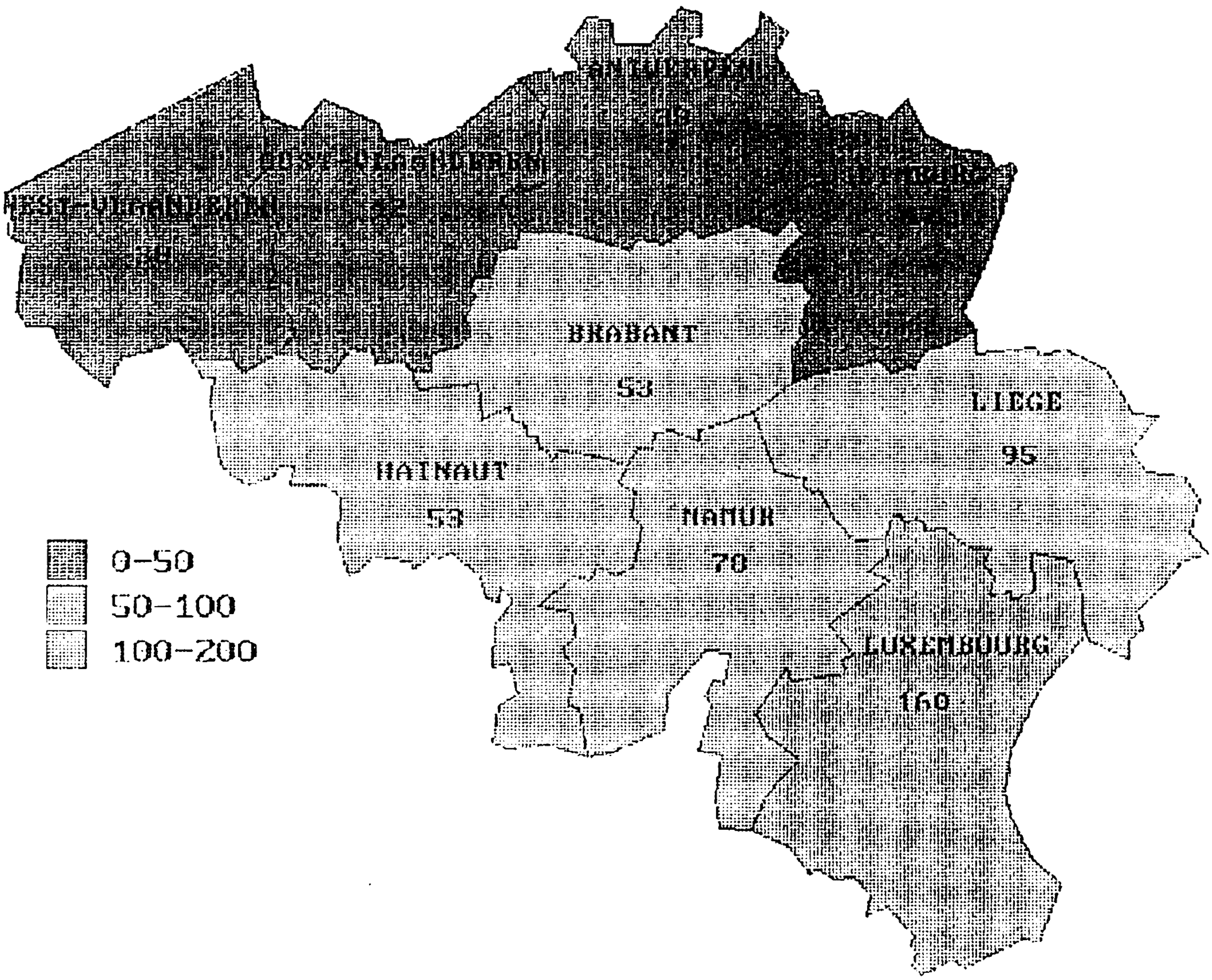


Figure 2 : Indoor radon concentrations in Belgium

TABLE 2 : DISTRIBUTION OF PROBLEM DWELLINGS IN BELGIUM

| Province | Number(percent) of dwellings >400 Bq/m3 |
|---|---|
| Antwerp | - |
| Brabant | 680 (0.08) |
| Hainault | - |
| Limburg | - |
| Liège | 1500 (0.4) |
| Luxemburg | 7400 (9.0) |
| Namur | 800 (0.5) |
| East-Flanders | - |
| West-Flanders | - |
| TOTAL | 10380 (0.3) |

## RADON SOURCES

For most house the soil and the building materials form the major sources of radon indoors. As part of a general study on building materials, the exhalation rate of some 120 commonly used materials in Belgium was measured. From the obtained results ranging from $10^{-3}$ Bq/kg*s for bricks up to $10^{-1}$ Bq/kg*s for materials made of phosphogypsum, it can be concluded that building materials in Belgium contribute only for a minor part to indoor radon (max. 20 to 30 Bq/$m^3$) .
On the other hand the infiltration of radon bearing soil gas can easily give rise to very high indoor levels.
Evidence of this statement was obtained by means of a case-control study in two neighbouring villages.
Referring to the results of a survey for uranium exploration in the Belgian Paleozoic (4), a case-village was selected, where the uranium content of the soil reaches locally 70 up to 80 ppm. In some 50 houses built-on on close to this anomaly the radon concentration was monitored for one year through 4 seasonal measuring campaigns. The same was done in a comparable neighbouring control-village.

From the best log-normal fits (Fig.3) it can be concluded that the radon concentrations in the case-village (with an average of 117 Bq/m$^3$ and a median value of 77 Bq/m$^3$) are significantly higher than the values obtained in the control-village (average and median resp. 80 and 54 Bq/m$^3$). In about 3% of the houses in the case-village the radon concentration exceeds 400 Bq/m$^3$. As the results of the national survey indicate that in only some 0.3% of the total house stock this value is expected to be exceeded, the zone around the anomaly should be classified as high risk area. Special prevention and migitation actions should be taken there without any delay.

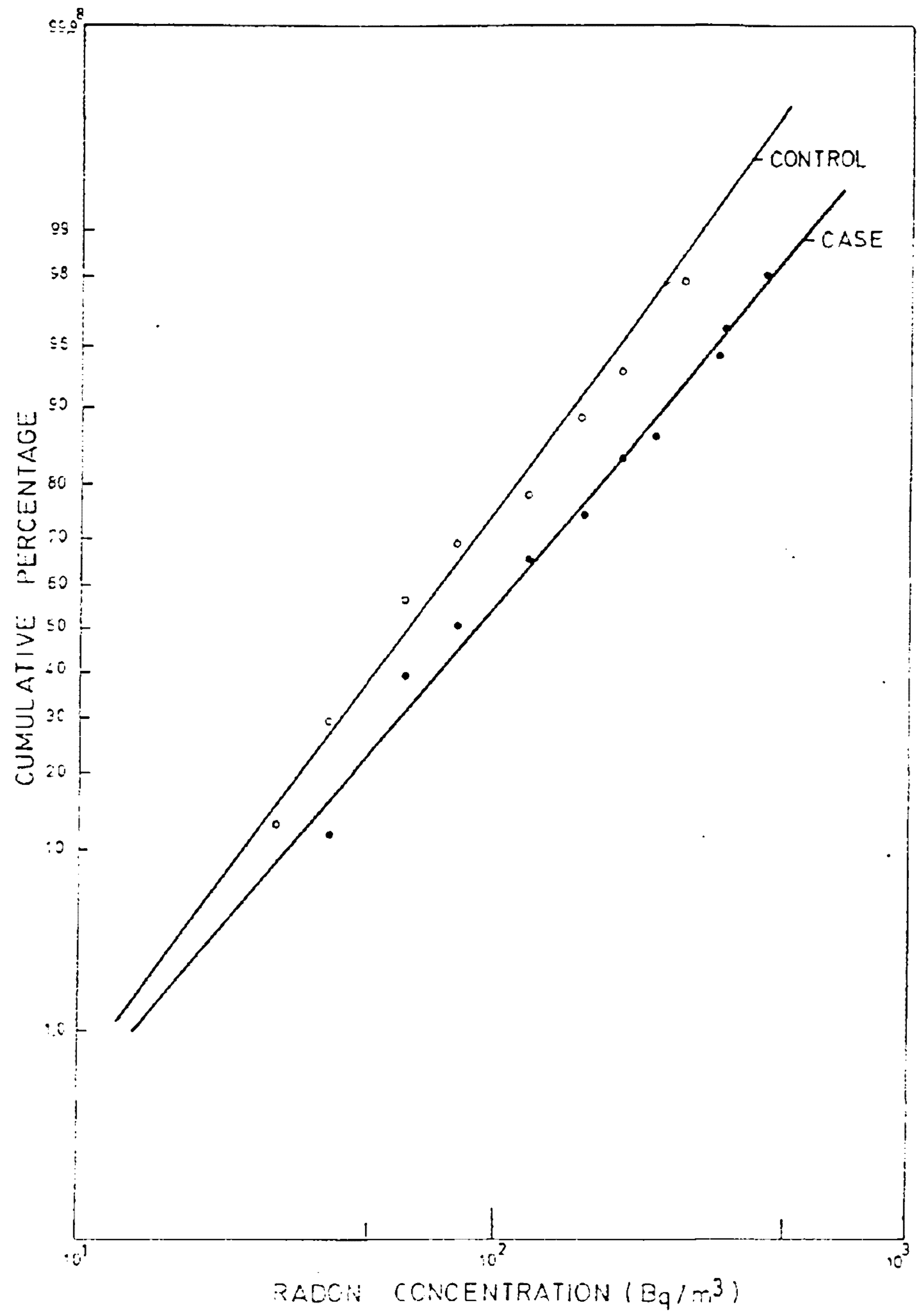


Figure 3 : Cumulative radon distributions in the case & control village

## RADON PLAN(S) FOR THE FUTURE

The growing uneasiness among the population about radon and the lack of any guideline or strategy nessecitated a coordinated action plan covering topics as mapping, prevention, mitigation and information of the public.
Therefore, in close collaboration with governmental responsibles and different concerned research groups a national radon research project was worked-out and agreed upon.
It primarely focusses on the province of Luxemburg and on two smaller areas - coinciding more or less with the territory of the town of Visé and the village of Bièvre - where alarming high radon levels (>4000 $Bq/m^3$) were registrated.
In this project attention is given to the following points :

- Databank for all radon measurements in Belgium
- Detailed radon risk map of the province of Luxemburg and of the area around Visé and Bièvre
- Detailed inventory of a selected number of risk areas
- Effectiveness of mitigation techniques
- Quality control exercices
- Information of the public.


## ACKOWLEGMENT

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# A RADIOLOGICAL STUDY OF THE GREEK RADON SPAS

P. Kritidis
Environmental Radioactivity Laboratory
Institute of Nuclear Technology - Radiation Protection
15310 Aghia Paraskevi, Athens, Greece

## ABSTRACT

A number of balneological units located in four regions of Greece and using thermal spring waters of high $^{222}Rn$ concentrations (0.1-6 MBq $m^{-3}$) have been investigated. The concentrations of $^{222}Rn$ and $^{226}Ra$ in the water used, as well as those of the short-lived decay products of $^{222}Rn$ (RnD) in the indoor air have been determined. The annual doses to the personnel and the patients have been evaluated. The results are discussed in the frame of the Justification and ALARA principles. The main problem concerns the absence of scientific statements relating the benefit from the procedures applied (or certain part of it) to the exposure to $^{222}Rn$ and RnD.

*Keywords: natural radioactivity, radon spas, balneotherapy, inhalation doses*

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

## INTRODUCTION

The water is known to be, generally, a minor source of indoor radon. This is not always the case in the balneological (water-physiotherapy) units using thermal spring waters. The balneotherapy is an ancient (Greek, Roman) practice which has survived until our days in many parts of Europe. After the discovery of radioactivity, it was found that certain spa waters are characterised by high concentrations of $^{222}Rn$. In Greece, the first studies of this kind were carried out by Pertesis during the 20s and 30s (1-3). In four regions of thermal springs the concentrations of $^{222}Rn$ in the water exceeded 100 kBq $m^{-3}$ (originally expressed in the old Mache units, where 1 Mache = 13.5 kBq $m^{-3}$). These regions are shown in Fig.1. The maximum radon concentrations were measured in the Artemis and Apollon springs of the Ikaria island and equaled 10 and 7.5 MBq $m^{-3}$ respectively. The major radon spas have been investigated later by other authors (4,5) and the early values of Pertesis have been, generally, confirmed. Nevertheless, we could not find, during 1983, any study with radiation protection goals, i.e. study considering the critical pathway of man's exposure - the inhalation of RnD related to the radon released from the thermal waters. During the period 1984-88 we have visited repeatedly the balneological premises in the 4 spa regions mentioned, measuring the concentrations of $^{222}Rn$ and $^{226}Ra$ in the waters used, the concentrations of RnD in the air of the main and auxiliary indoor spaces, collecting information about the existing practices, occupancy factors etc. The results of these studies, together with the related dose estimations, are given in the present paper.

## THE GREEK RADON SPAS: GENERAL DATA

The major Greek radon spas are located in four regions (Fig.1): Ikaria island in the Eastern Aegean Sea (9 springs, 3 units), Kamena Vourla (1 common source and 4 units) and Edypsos (5 springs and 5 units) in the Northern Evoikos gulf and Loutraki in the Eastern Korinthiakos gulf (5 springs and 5 units).

In all cases the spas are located right on the coast and, also, in the mild climate central latitudes of Greece. This allowed their establishing, throughout the centuries, as attractive places of the so-called "therapeutical tourism", where certain physiotherapy practices are combined with usual by-sea vacation, swimming, fishing etc. In most cases, the high temperature of the water allows its use for bathing procedures, typically in separate individual baths, but also in common pools (Kamena Vourla). In one case the water has to be warmed before use. The water is collected, usually, in some basic reservoirs and directed further to the points of use. This results in certain losses of radon gas, of the order of 10-30 %.

During the typical individual bath procedure the patient enters a tub filled with warm spa water (or mixture with cold spa water) and spends about 20 min in it. The total time spent in the bath, including undressing and dressing, is about 30 min. The personnel has to prepare the bath (clean and fill the tub with new water) and often, also, to help the patients before and/or during the procedure. In most cases there are at least 5 baths per member of the personnel and their in-the-bath occupancy exceeds 50%.

There are various architecture designs of bath premises. In some cases the baths are isolated, from the ventilation point of view, from the common spaces (corridors, halls), but communicate one with another through big holes (0.5 to 4 m) in the top parts of the common walls. This construction leads to higher ventilation of the bath, but also to dependence of the average radon concentration in the bath air on the current working occupancy of the whole premise. In other cases the baths are totally isolated one from another, but there is some air exchange with the common spaces. This leads to higher average concentrations of radon in the bath air, but also in the air of the common spaces, especially under "stack effect" conditions in the building.

The significant dispersion of the water during the tub filling, its enhanced temperature and the duration of the procedure lead to the release of practically 100% of the radon in the air. The use of 1 $m^3$ spa water per procedure in a bath of 25 $m^3$ air volume will result in a transfer coefficient of 0.04 between the water and air concentrations of radon under the absence of ventilation. In the extreme case of the 6 MBq $m^{-3}$ Apollon spring water it would correspond to average concentration of $^{222}Rn$ in the bath air equal to 240 kBq $m^{-3}$.

The drinking therapy is another use of certain spa waters. In this case the patients exposure to inhaled radon is significantly lower, with the exception of cases like LU3, where certain patients combine the drinking with a sort of inhalation therapy, by staying 10-15 min inside the hall built around the twin thermal spring. In all cases, the intake of $^{226}Ra$ is a pathway to be considered as well. The water consumed per season is about 20 l.

## INSTRUMENTS AND METHODS

The concentrations of $^{222}Rn$ and $^{226}Ra$ in the spa waters have been determined by use of the total alpha-counting method (Lucas cell instrument) in a closed loop air circulation system (6). The glass sampler is designed to be used for radon extraction as well, which avoids any sample transfer and the related losses. The concentration of $^{222}Rn$ is measured soon after sampling to ensure maximum counting statistics. Temperature and volume corrections are applied. After the "in situ" determination of $^{222}Rn$, the 0.25 l water sample is fully de-emanated and sealed for about 30 days, to allow the radioactive equilibrium between $^{226}Ra$ and $^{222}Rn$. Then a second measurement of $^{222}Rn$ is made to determine $^{226}Ra$. The LLD ($2\sigma$ of bckg) of the method is 25 Bq $m^{-3}$, which is quite adequate for $^{222}Rn$, and acceptable for $^{226}Ra$ (where it corresponds to 6.3 μSv per year for a standard 0.8 $m^3$ water consumption and to 0.16 μSv for the 20 l average patient consumption of spa water per season.

The concentrations of RnD have been determined separately by use of an express variant of the 3-interval total alpha-counting filter method (6). The time of air sampling is 1 min and the counting intervals - (1-5), (6-10) and (11-15) min after the end of sampling. The sampling flow rate is 100 l $min^{-1}$ and the active filter area - 7 $cm^2$. The LLD ($2\sigma$ of bckg) is 30 Bq $m^{-3}$ equilibrium equivalent concentration (EEC) of $^{222}Rn$ - a value adequate for the levels observed in the radon spas studied. It was also possible to determine a "quasi-equilibrium factor", as the ratio of EEC to the concentration of $^{218}Po$.

## RESULTS AND DISCUSSION

The concentrations of $^{222}Rn$ and $^{226}Ra$ in the waters examined, as well as the range of concentrations of RnD measured in the air of the premises using these waters (if any) are given in Table 1. Note that the water sampling has been done *at the point of use* (if any) and not at the source spring. Therefore, in most cases the values for $^{222}Rn$ are slightly lower than those in the source point. The waters of the Ikaria springs I3-I7 are not used for any curative procedures indoors. The concentrations of RnD in the outdoor air close to these springs are measurable, but insignificant from the radiological point of view, so they are not given in Table 1. Note also, that only the waters of the units L2 and L4 are used for drinking therapy.

The balneological premises in Kamena Vourla use a common water reservoir, while the other premises have separate reservoirs, in certain cases - even two, one for hot water and a second, where the water is cooled before use.

The maximum concentrations of RnD in air have been measured, in all cases, at the place of the water use (bath, pool etc.). The minimum values have been measured at the auxiliary spaces used by the personnel and/or the patients (during waiting). The occupancy factors of the various spaces for the patients and the personnel have been estimated both by observations and from the information provided by the staff.

The "maximum transfer factor" is the ratio of the maximum RnD concentration measured in air to the $^{222}Rn$ concentration in the water used. It can be seen that these factors vary significantly from premise to premise by more than two orders of magnitude: minimum value 0.00032, maximum value 0.085 and average value 0.012. One must note that both extreme values have been measured in the air of personal bathrooms. It is also interesting, that the highest values of RnD in air (K3, K4) are related to water concentrations of $^{222}Rn$ significantly lower that the maximum observed (I1, I2). We do not consider here the case I1R, which is a reservoir of radon water, not visited by patients. It is interesting, nevertheless, to note that certain individuals, attracted by the idea of the "primary curative source", have been seen to apply a sort of "private inhalation therapy" in the entry of the reservoir, inhaling several minutes its 120 kBq $m^{-3}$ RnD air!

TABLE 1. CONCENTRATIONS OF NATURAL RADIONUCLIDES MEASURED IN THE WATER AND THE AIR OF VARIOUS GREEK RADON SPAS (Bq $m^{-3}$).

| Region, premise | | $^{222}Rn$ in water | $^{226}Ra$ in water | RnD in air | Maximum transfer factor |
|---|---|---|---|---|---|
| | L1 | 450000 | | 18-400 | 0.0009 |
| | L2 | 175000 | 103 | 20-200 | 0.0011 |
| Loutraki | L3 | 170000 | | 150-3500 | 0.021 |
| | L4 | 140000 | 55 | 180-440 | 0.0031 |
| | L5 | 90000 | | 15-40 | 0.0004 |
| Kamena | K1 | 850000 | 1500 | 20-3700 | 0.0044 |
| Vourla | K2 | " | " | 90-1400 | 0.0016 |
| | K3 | " | " | 110-15000 | 0.018 |
| | K4 | " | " | 11-18000 | 0.021 |
| Ikaria | I1 | 5700000 | 950 | 1300-6900 | 0.0012 |
| | I1R | 5700000 | 950 | 120000 | 0.021 |
| | I2 | 5700000 | 1200 | 500-1800 | 0.00032 |
| | I3 | 3000000 | 200 | - | - |
| | I4 | 625000 | 360 | - | - |
| | I5 | 480000 | 200 | - | - |
| | I6 | 270000 | 3400 | - | - |
| | I7 | 200000 | 4700 | - | - |
| | I8 | 160000 | 3500 | 70 | 0.00044 |
| | I9 | <100 | 3400 | <20 | - |
| Edypsos | E1 | 200000 | 3400 | 150-1750 | 0.0088 |
| | E2 | 72000 | 1600 | 200 | 0.0028 |
| | E3 | 10000 | 1100 | 400-850 | 0.085 |
| | E4 | 9300 | 2700 | 30-130 | 0.014 |
| | E5 | 1000 | 5000 | <20 | - |

The differences in the transfer factors observed reflect, mainly, the variability of ventilation rates, but also the differences in the water temperatures and the "typical" dispersion of the water during its use. This variability leads to insignificant correlation between the water and air concentrations of radon (CC=0.2). It is interesting to note, that an weak *negative* correlation (CC=-0.3) is observed between the concentrations of $^{226}Ra$

and $^{222}Rn$ in the waters examined. The discussion of this point is beyond the scopes of the present study.

The estimations of the annual effective dose equivalents (EDE) for the personnel and the patients of the radon therapy centers examined are given in Table 2. The occupancy of the personnel is 5 months per season and, in most cases, 50% of the working time is supposed to be spent in the areas of highest radon concentrations in air. The patients are advised, typically, for 20 bath procedures of 30 min each per season. The intake of radon water for the drinking therapy patients is, typically, 20 l per season.

TABLE 2. ESTIMATIONS OF ANNUAL EFFECTIVE DOSE EQUIVALENTS FOR THE PERSONNEL AND THE PATIENTS OF VARIOUS GREEK RADON SPAS (mSv).

| Region, premise | | Personnel inhalation of RnD | Patients inhalation of RnD | Patients ingestion of $^{226}Ra$ |
|---|---|---|---|---|
| | L1 | 1.9 | 0.05 | - |
| | L2 | 0.9 | 0.01 | 0.001 |
| Loutraki | L3 | 16 | 0.4 | - |
| | L4 | 4.0 | 0.03 | 0.0005 |
| | L5 | 0.2 | 0.005 | - |
| Kamena | K1 | 17 | 0.4 | (0.01)+ |
| Vourla | K2 | 6.6 | 0.15 | " |
| | K3 | 70 | 1.7 | " |
| | K4 | 85 | 2.0 | " |
| Ikaria | I1 | 32 | 0.8 | (0.006) |
| | I1R | - | (1.3)* | - |
| | I2 | 8.5 | 0.2 | (0.008) |
| | I8 | 0.35 | 0.01 | (0.02) |
| | I9 | 0.1 | 0.002 | (0.02) |
| Edypsos | E1 | 8.2 | 0.2 | (0.02) |
| | E2 | 1.0 | 0.02 | (0.01) |
| | E3 | 4.0 | 0.09 | (0.01) |
| | E4 | 0.6 | 0.015 | (0.015) |
| | E5 | 0.1 | 0.002 | (0.03) |

* Based on 3 min per day "private inhalation therapy" (see text).
+ The values in parentheses are hypothetical. These waters are not used for drinking therapy.

It can be seen, that the estimated yearly EDE for the personnel exceed, in 2 cases, the current 50 mSv $a^{-1}$ dose limit, in 5 cases - 30% of this limit (controlled area conditions) and in *other* 4 cases lay between 10% and 30% of this limit (supervised area conditions). If we apply the new 0.04 per Sv fatal cancer risk coefficient recommended by ICRP (7), then risks of the order of 10% could be attributed to the personnel of the units K3 and K4 after 30 years of work and risks between 1% and 5% - in other 6 cases.

The dose estimations for the patients vary 3 orders of magnitude, with maximum values not exceeding 2 mSv $a^{-1}$. These doses are mainly due to the inhalation of RnD, while the ingestion of water (where applied) has an insignificant contribution.

## CONCLUSIONS

Two different radiation protection problems arise from the results presented above.

1. The members of the personnel of certain radon therapy premises are exposed to doses which not only exceed the 10% and/or 30% of the current dose limit, but, in 2 cases, the limit itself. Nevertheless, these working areas are not classified as supervised or controlled and no radiation protection measures are applied. We have, in all cases, a violation of the Justification and ALARA principles and in 2 cases - also of the Dose Limitation principle.

2. The patients are exposed to doses similar to those reported for other cases of medical use of ionising radiations. Nevertheless, we could not find any scientific material dealing with the dose-benefit relation of the radon therapy procedures and, therefor, no risk-to-benefit analysis and no optimisation can be applied.

It seems necessary to draw further the attention of the international radiation protection community to the problem of the radon balneology practice, in order to achieve, gradually, the conformity of this practice (whatever it could mean) with the basic radiation protection principles.

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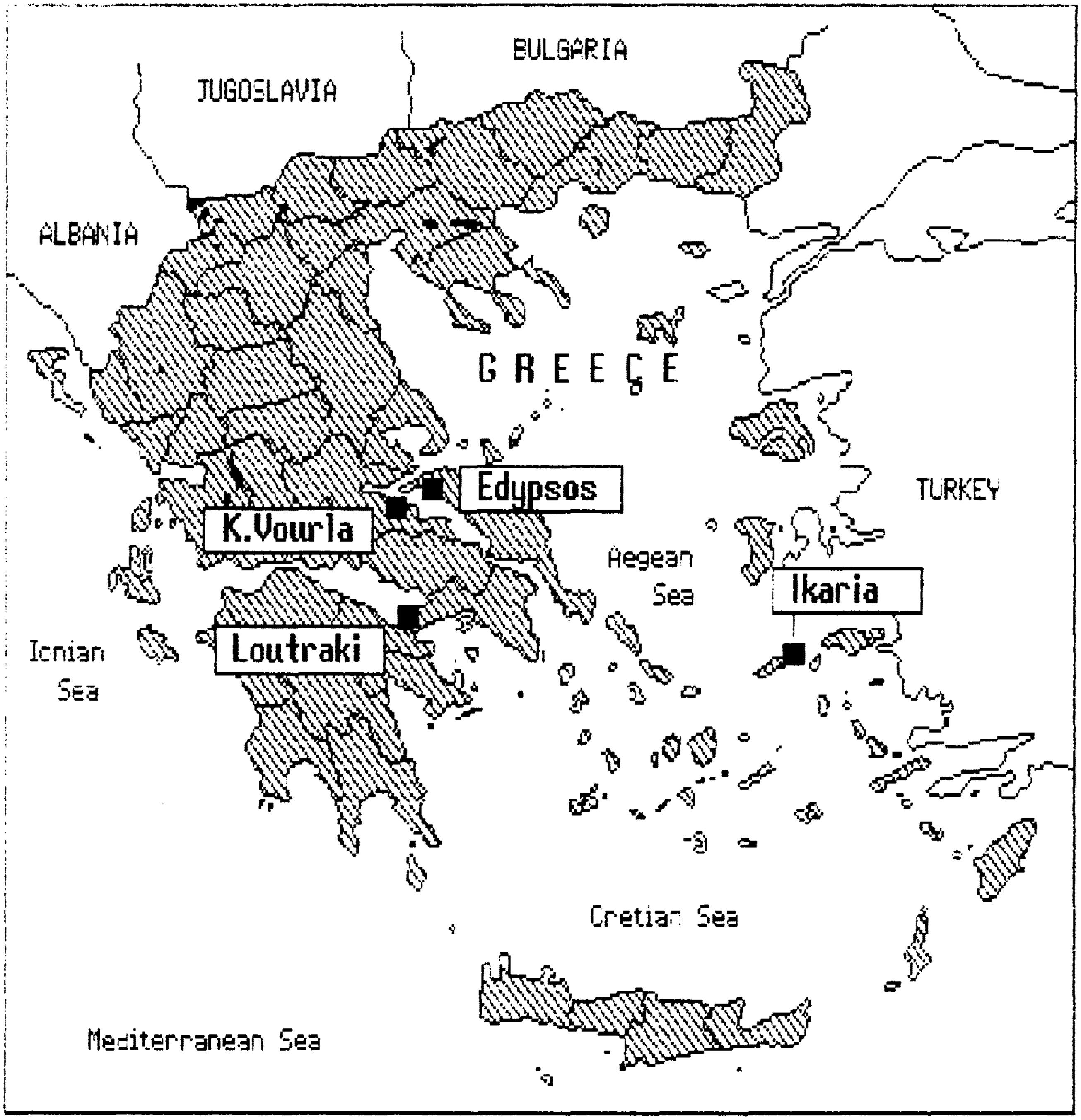


Fig.1. Locations of the regions of the major Greek radon spas.

# Session VII

## Oral Presentations

## State Programs and Policies Relating to Radon

# WASHINGTON STATE'S INNOVATIVE GRANT: COMMUNITY SUPPORT RADON ACTION TEAM FOR SCHOOLS

Patricia A. McLachlan
Department of Health
Olympia, Washington 98504

## ABSTRACT

In February, 1990, the Environmental Protection Agency awarded the Washington State Department of Health $100,000 from the State Indoor Radon Grants Program to fund an innovative project titled, "Community Support Radon Action Team for Schools." The Department of Health contributed an additional $34,000 to the project and organized a team of public and private sector experts. The goal of the team was to write a manual of cooperative and cost-effective approaches school administrators could use to assess and mitigate radon exposure in schools.

The team of federal, state and local experts from the fields of health, education, energy, building science and codes, safety, administration, communication, and radon testing, diagnostics and mitigation, chose to write and evaluate the manual with the cooperation of a school district in northeastern Washington.

The manual includes chapters on administrator's overview, radon facts, radon awareness, radon and liability, strategic planning, public informational materials, school radon testing, building inspection and radon diagnostics, radon mitigation, long-term radon management, and case studies. These chapters and the experience gained in their application in the school district will be discussed.

## INTRODUCTION

Despite the identification of elevated radon exposure levels (100 pCi/L) in some buildings in Washington State's five northeastern counties, very few residences, schools or public and commercial buildings have been tested or mitigated. Within the Core Radon Program, the Department of Health (DOH), the State's lead agency responsible for a radon program, has insufficient resources to help school districts that want to tackle their radon problems but lack the funds and technical expertise.

DOH with its State Radon Task Force encourages state agencies, local governing bodies and other organizations to work cooperatively to reduce the public health risk from radon. In discussions with personnel in the school community, government agencies and the private radon industry, DOH found a manual was needed to help schools resolve radon issues. Since a variety of relevant expertise was present in Washington State, a team approach to developing the manual had merit. EPA agreed and awarded funding for DOH's innovative project, "Community Support Radon Action Team."

## THE RADON ACTION TEAM

The Community Support Radon Action Team, a group of public and private sector experts, met ten times from March, 1990 to February, 1991 and numerous times in small working groups to develop the **School Radon Action Manual.** The team was composed of health, radon and building science experts from DOH, Region 10 EPA, the Washington Energy Extension Service (WEES), the Spokane County Health District (SCHD) and the City of Spokane Building Services Department (SBSD). Also, Faytek, Inc., Quality Conservation and Thomas J. Gerard & Associates, Inc. from the private sector provided expertise on radon testing, diagnostics and mitigation, and HVAC (heating, ventilation and air conditioning) systems, respectively.

In addition, the school community was represented on the team by a manager of state school facilities from the Office of the State Superintendent of Public Instruction (OSPI); a writer and a safety coordinator from the Education Service District 101 (ESD 101, one of nine regional agencies in Washington providing administrative and instructional support to local school districts); an administrator experienced in school radon testing from Spokane School District 81 (SSD); and an administrator, a public information officer, a supervisor of school maintenance and an HVAC specialist from Central Valley School District 356 (CVSD). The Northwest Regional Foundation (NRF, a private, non-profit corporation committed to facilitating change in communities) provided a facilitator to help this group of people work as a team to write the manual and evaluate its application in the CVSD. Finally, as a legal consultant, a Washington State Assistant Attorney General (OAG) contributed his expertise about liability.

## THE TEAM PROCESS

In initial meetings, team members discussed the project goal, participants' self-interests, the process of radon problem solving in a school community, manual contents, working group assignments and site selections for the case studies in CVSD. The major goal of the team was to compile educational, problem solving and organizational resources in the **School Radon Action Manual.** The manual was designed to help school personnel communicate with their school community about radon and use internal resources as well as the private sector to cost-effectively assess and remediate for radon in their schools.

Radon Action Team members represented a wide variety of expertise and self-interests. Health professionals focussed on the need to communicate the health effects of radon exposure accurately and effectively to the public. School administrators desired to test, diagnose and mitigate for radon in a cost-effective manner while informing and involving their communities. Radon testing professionals demanded a scientific approach that complied with EPA interim protocols. Building science professionals viewed each building as an integrated system that demanded careful, logical problem solving techniques to tackle radon and other indoor air quality problems. Team members decided to pool their knowledge and concerns in the manual development realizing they had differences in perspectives and opinions which would be debated during the writing process.

In fact, many vigorous discussions did take place over the course of the year. One often debated question was: How much testing, diagnostics and mitigation work should school personnel attempt before they call in the private sector? A second question was: How should a school district communicate about radon to its community which often wants problems solved immediately? It has to be pointed out that the district needs to train its staff, hire consultants, request bids, raise funding and plan to remediate radon problems as they are discovered over several years of testing and diagnostics A third question was: How can schools achieve cost-effectiveness? Team members decided they could provide accurate and concise guidance on such things as radon testing options, building inspection and radon diagnostics, and public informational materials. They concluded, however, that ultimately it would be school administrators with an intimate knowledge of their communities and resources who with the help of the manual would answer these questions.

The **School Radon Action Manual** contains sections designed for school district administrators, public information officers, building managers and maintenance personnel. The manual organization follows a school radon action process (illustrated in Figure 1) recommended by the team. A list of the sections with a summary of their contents follows:

The "Administrators' Overview" includes what radon is, where radon is found, what the health risks are and when radon was recognized as a health hazard. Other topics are how radon enters a building, how it is measured, how radon concentrations are reduced and who can perform the radon testing and mitigation. In this section, the team recommends that school district staff involved in radon testing, building diagnostics or mitigation attend an EPA endorsed training course. Also, it is recommended that school district consultants show that they have successfully participated in EPA's Radon Measurement Proficiency Program, or employ individuals who have passed EPA's National Radon Contractor Proficiency Program.

"Radon Facts" gives greater detail on radon discovery, radon and radon progeny, the health effects of radon, the health risk to children and comparisons of school to home exposures.

"Risk Awareness" deals with assessing risk, the nature of radon risk, 4 pCi/L as an action level, the Indoor Radon Abatement Act, the health risk to children and smokers, challenges to EPA's risk estimates, getting to ALARA (As-Low-As-Reasonably-Achievable), managing and communicating radon risk and the risk awareness process.

"Radon and Liability" concludes that health hazards presented by radon and indoor pollution in schools and public buildings may be substantially reduced by technical analysis of the problem and a careful administrative response from management. Failure to initiate the analysis and respond to the problem presents the risk of liability for any school or public institution. Suggestions for a program that schools can develop to deal with radon and other indoor air quality problems are given.

"Strategic Planning" deals with how a school district may develop a plan for dealing with radon in its buildings. Topics covered include prerequisites for planning, action steps, timelines and financing. Formulation of a radon action team is recommended.

"Public Informational Materials" includes internal and external communications strategies utilized by the Central Valley School District as it dealt with radon in its schools. It includes

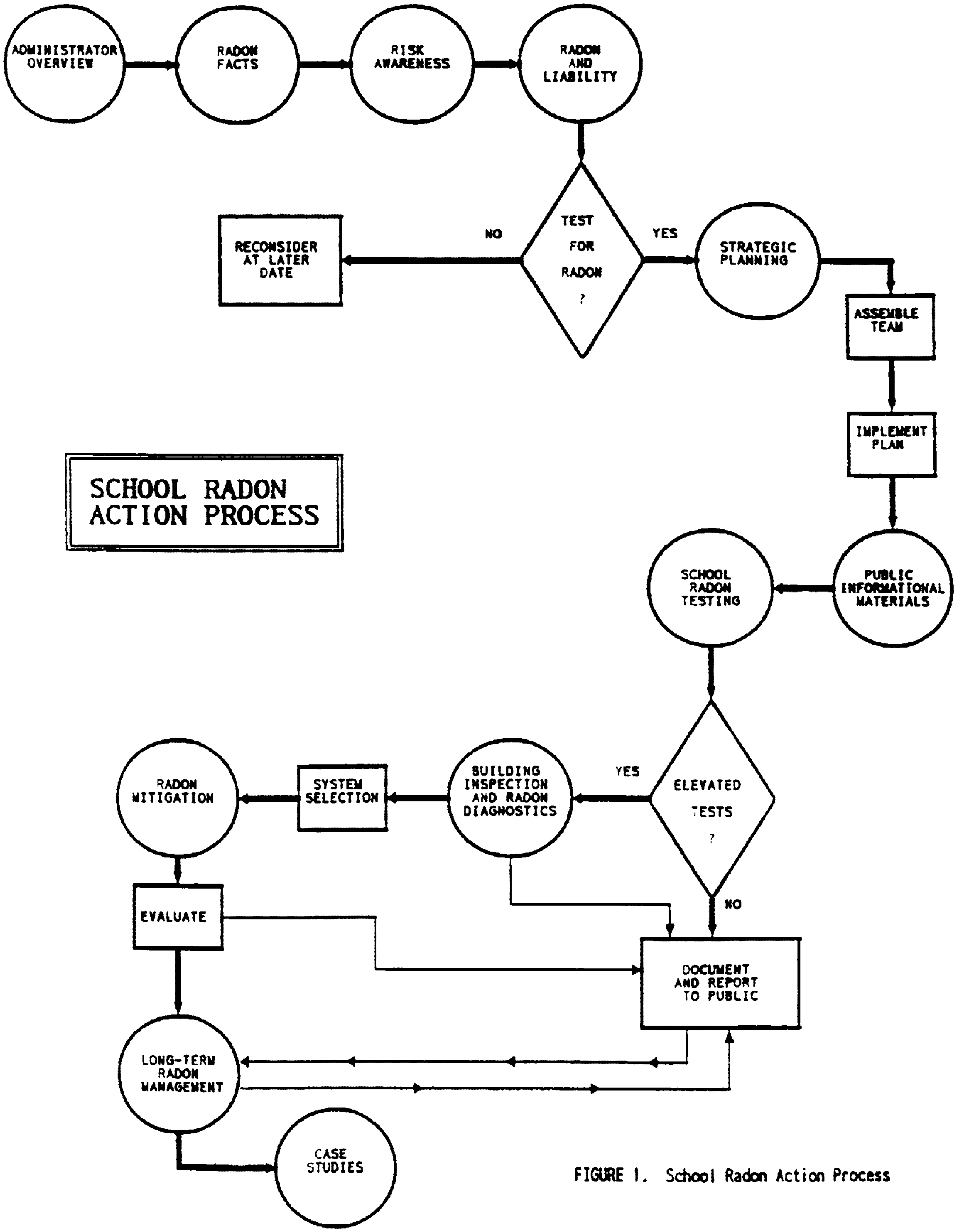


FIGURE 1. School Radon Action Process

strategies for communicating with staff, administrators, students, parents and the news media. Sample press releases and letters are included in this section.

"School Radon Testing" deals with testing school buildings for radon. It provides information on qualifications necessary to perform testing, school district requirements, testing procedures and forms, testing methods with advantages and disadvantages, and evaluation of testing results.

"Building Inspection and Radon Diagnostics" describes how to inspect buildings and perform or oversee diagnostic testing for radon entry locations. It includes checklists for review of testing data and for mechanical and structural inspections.

"Radon Mitigation" provides strategies for mitigation if elevated levels of radon are found in a building. Topics include radon entry, causes of pressure differentials, variations in radon concentrations between rooms, mitigation techniques and dealing with contractors.

"Long-term Radon Management" provides the basics for continual monitoring of indoor air quality, including radon, for the district. Topics include team design, program design, public policy guidelines and documentation.

"Case Studies" documents the application of the manual in six schools in the Central Valley School District (CVSD). This section describes the radon action process that CVSD employed with the manual and team members' expertise. Based on this limited application of the manual in one school district, the team offers suggestions to other school districts.

The "Glossary" defines key terms school district personnel must understand to communicate meaningfully about radon as a public health issue. The "Bibliography," a "Team Members' List" and "Federal and State Contacts" complete the manual.

## CASE STUDIES

During this project, part of the manual's school radon action process (see Figure 1) was evaluated using six buildings in the Central Valley School District of Spokane County, Washington. The school community (including school board, faculty and staff, parents and students) was informed of the project and the radon action process by Radon Action Team members through the use of the sections: "Radon Facts," "Risk Awareness," and "Public Informational Materials." School personnel were trained by team professionals using parts of the sections: "School Radon Testing" and "Building Inspection and Radon Diagnostics." The manual sections, "Administrator's Overview," "Radon and Liability," "Strategic Planning," "Radon Mitigation," and "Long-Term Radon Management" were still being developed during this time so they were not evaluated in this school district.

Selected for evaluation of the educational, communications, testing and diagnostics processes were three elementary schools, a junior high school, a high school and an administration building. Team members made presentations about the project and the school radon action process at meetings of the school board, administrators, faculty, staff, Parent Teacher Association (PTA) and press. Four junior high science instructors wrote model radon awareness curriculum which they taught and are refining for distribution next summer. Literature on radon was displayed and made available to staff and the public in the building reception areas. Letters were sent home to parents, and articles published in the newspapers. A spirit of openness and cooperation was encouraged by the radon action team and the school administrators.

The team decided to employ charcoal canisters to test the administration building and the high school and electrets to test the other four schools. In both cases, school maintenance personnel were given training from the manual in placing the detectors, retrieving them, and keeping records. Charcoal devices were sent to the manufacturer's lab for analysis while electrets were read by school personnel. Faytek, a private EPA proficient testing company, provided training and oversight throughout the whole testing process.

Elevated radon levels were found in the administration building, high school, and three elementary schools. Building inspection and radon diagnostics were performed by both team members and school personnel. School personnel provided information about building histories and basic building operation. They completed some initial mitigation involving sealing cracks and adjusting HVAC systems. Most of the detailed diagnostics was performed by radon professionals from Quality Conservation, EPA proficient contractors, and a mechanical engineer from Gerard and Associates, all team members. Quality Conservation developed remediation plans for two elementary schools and the high school. Due to time and funding limitations, the team's efforts ended after the three remediation plans were given to the Central Valley School District.

## SUGGESTIONS FOR SCHOOL PERSONNEL

Some suggestions emerged from the Radon Action Team's work on the Central Valley School District case studies. This school district is to be applauded for its progressive approach to radon problem solving and its offer to share lessons learned from this project with other school districts.

Suggestions are as follows:

As a part of strategic planning, the team recommends that schools assemble a Radon Action Team which incorporates relevant expertise from both the public and private sectors. The team organized for this project provides a model for team member selection (although smaller teams are appropriate for individual school districts). It is important that regular meetings of this team be held and that progress reports be shared with and decisions supported by upper level administrators (school board members, superintendents, district level administrators, and principals) in the school district. As part of the school district's operations strategy, it is recommended that EPA testing protocols should be followed. Decision points and procedures for immediate risk interventions should be developed. Thought should be given to scheduling, and minimizing class disruptions and loss of detectors.

During the public informational process, we suggest that a public information officer or a superintendent be the primary contact for all information requests. This contact person should be a team member, well-informed about radon issues, activities in the schools and the district's strategic plan. Requests for information should be answered accurately, openly and quickly, with a timeline given for the radon action process (eg. when test results will be reported, when buildings will be fixed). A good relationship should be established with the press at the outset of the process. The contact person needs to be flexible, calm and ready to handle "incidents" with concerned individuals and groups. Staff in buildings with preexisting indoor air quality problems may show a heightened interest or sensitivity to radon testing. More communication may be needed. PTA meetings work well to inform parents and faculty. The public information officer should be accompanied by other team members who have expertise in radon health effects, testing, diagnostics and mitigation, to gain public credibility through answering a broad range of questions.

Before a school district begins the radon testing process, school personnel should evaluate the various options for testing, considering cost-effectiveness, available internal and external resources, liability issues and time constraints. These options include use of private testing firms, use of school personnel or a combination of the two. If school personnel will be involved in performing school radon testing, the team suggests that school personnel (perhaps one or two maintenance personnel) receive EPA approved training. Also, a private, EPA proficient testing company should be employed as a consultant to oversee placement, retrieval, and recording of test results. Quality control procedures must be performed for both charcoal canisters and electrets. If school personnel read electrets, they must have training in appropriate analytical techniques. Clear procedures should be used from the outset to ensure accurate and complete record keeping of data. Building maps should show radon levels for each room and be color coded to make radon hotspots evident. Originals of all data should be kept in one file.

During testing, building inspection and radon diagnostics, plans and maps are required. Team members found that both architectural drawings and AHERA (asbestos) plans were sometimes inaccurate, inadequate or missing altogether. Also, the district public information officer needs to be prepared to answer concerns from school community members who want immediate action to lower radon levels. Radon diagnostics and mitigation take time and money to perform. Scheduling testing before a holiday such as winter break may give the district more time to perform this process.

## SECOND YEAR PLANS FOR THE SCHOOL RADON ACTION MANUAL

The Washington State Department of Health (DOH) was awarded second year EPA funding to complete the review process for the draft **School Radon Action Manual** and publish the **Manual**. Also, the Radon Action Team will design training curriculum and materials for state and national presentations on the **School Radon Action Manual.** Trained instructors from the Radon Action Team will be available for presentations to regional and national conferences of school administrators, teachers, facilities maintenance personnel, public relations staff, public health officials, and radon program and industry representatives. Finally, evaluation of the **Manual's** use in one Demonstration School District will result in a revised edition, if appropriate.

## ACKNOWLEDGEMENTS

The author wishes to acknowledge the contributions made to the **School Radon Action Manual** by the following Radon Action Team members: Jerry Leitch and Misha Vakoc (Region 10 EPA); Mike Nuess and Rich Prill (WEES); Michael F. LaScuola (SCHD); Robert L. Stilger (NRF); Bob Eugene and Steve Belzak (SBSD); Mike Roberts (OSPI); Jim Kerns and Dick Moody (ESD 101); Dave Jackman, Karl Speltz and Skip Bonnucelli (CVSD); Jody Schmitz (SSD); Ray Tekverk and Jan Fay (Faytek); John Anderson and Jack Bartholomew (Quality Conservation); and Tom Gerard (Gerard and Associates). Other important contributions were made by T.R. Strong, Robert R. Mooney, Kate Coleman and Ed Scherieble (DOH); Dick Sovde (CVSD); and Larry Watters (OAG).

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.

# KENTUCKY INNOVATIVE GRANT
# RADON IN SCHOOLS' TELECOMMUNICATION PROJECT

M. Jeana Phelps
Radon Program, Radiation Control Branch
Division of Community Safety
Kentucky Cabinet for Human Resources
Frankfort, Kentucky
and
Carolyn Rude-Parkins
Occupational Training and Development
University of Louisville
Louisville, Kentucky

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

## ABSTRACT

One of the many challenges facing the U.S. Environmental Protection Agency and individual state radiation control programs is to provide decision-making information and technical support to school administrators about radon testing and mitigation in school buildings.

This paper provides information on the development, delivery and overall implementation of a model radon telecommunication outreach program to school administrators in Kentucky and to the following states: Alabama, Arkansas, Georgia, Louisiana, Michigan, Missouri, Mississippi, North Dakota, Nebraska, New Jersey, Ohio, Pennsylvania, Texas, South Carolina, Wisconsin, and West Virginia, Virginia, and Florida.(Figure 1)

The two hour interactive broadcast will be delivered by satellite to all locations through the Kentucky Educational Television Network (KET).

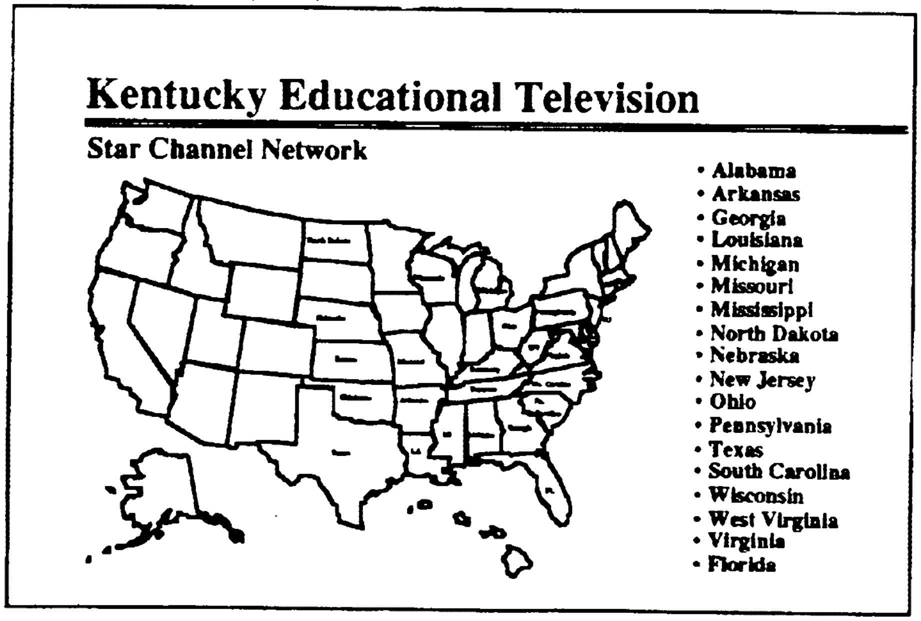


Figure 1: KET Star Channel Network
State Contacts

In schools around the world, students are "talking" to other students they may never see; teachers are instructing students who are not in the room; professionals are meeting with far away colleagues without leaving their desks. Distance learning concepts and technologies make these interactions possible.

Distance learning is defined as the application of telecommunications and electronic devices which enable students to receive instruction that originates from some distant location. It involves four major concepts:

1. students are seperated from one another and from the teacher;
2. interactive two-way technologies are used to unite them;
3. the learning is planned, delivered, and evaluated by an institution;
4. students organize themselves and collaborate around a goal which may be theirs or the teacher's (1,2).

SEPARATED

Virtually any subject can be taught via distance learning. During 1989-1990, the National University Teleconference Network (NUTU) offered 94 programs, both fee-based and free. The greatest percentage (41%) of these programs were directed to Engineers with the remaining being delivered to: Education (38.6%), Medical and Allied Health (27.3%), and general interest (34.1%) (3). Distance learning provides a connecting network to learners who may be in the next building, another city or in a different country. Distance learning also allows the learners to "tune-in" at a time and location convenient to their schedule.

UNITED

The key to distance learning is two-way interactive technology. In the past, print technology and the U.S. Postal Service delivered correspondence courses to students in dispersed locations. Radio and telephone added an audio component and the possibility for two-way interaction. Later, education television broadcasts, cable programs, and video cassettes offered other ways of distributing course materials. Interactivity was added via telephone and then computer.

Today, computers, satellites and telecommunications technologies such as fiber optics expand the power of older distance learning technologies. Computers make it possible to access electronic mail, bulletin boards, interactive computer conferences, data bases of information and computer assisted instructional lessons and courses. Microwave dishes and satellite links enable the computer to reach across the street and around the world. Telephones, fiber optics and satellites permit one-way and two-way interactive video conferencing.

Distance learning technologies fall into the categories of video, voice and data communications. Video is the primary means of delivery. It is the most attractive, complex and expensive. Audio telephone delivery provides one-on-one interaction or handles groups of three or more in different locations via an audio bridge. Audiographic teleconferencing permits the transmission of still images and audio signals over telephone lines. Electronic blackboards and tablets, FAX, slow scan, and compressed video also use telecommunications technologies.

Video, voice, and data communications can reach learners at any time and in any place. But the real power of distance learning lies in two-way interactive technologies (2). The reason for this is the capability for interpersonal communication. One-way systems leave the learners passive, uninvolved and isolated. Two-way systems let them actively exchange ideas, information and feelings. It puts high touch into high technology. They can reach out and touch a real someone.(2)

KENTUCKY EDUCATIONAL NETWORK (KET)

Kentucky is the first state in the nation to fund and construct a statewide telecommunications delivery system. KET was established by the Legislature in 1968 to provide instructional services to teachers. The Satellite uplink costs $500,000 and $2,000 for each school downlink. It is the largest system in the nation. The KET Star channel system consists of a transmitting and receiving site at the KET Network Center in Lexington, Kentucky and has more than 1,300 receiving sites (down links) located throughout Kentucky at public schools. The KET satellite can uplink programs not only to Kentucky schools but also to schools throughout the nation (Figure 1 and Figure 2).

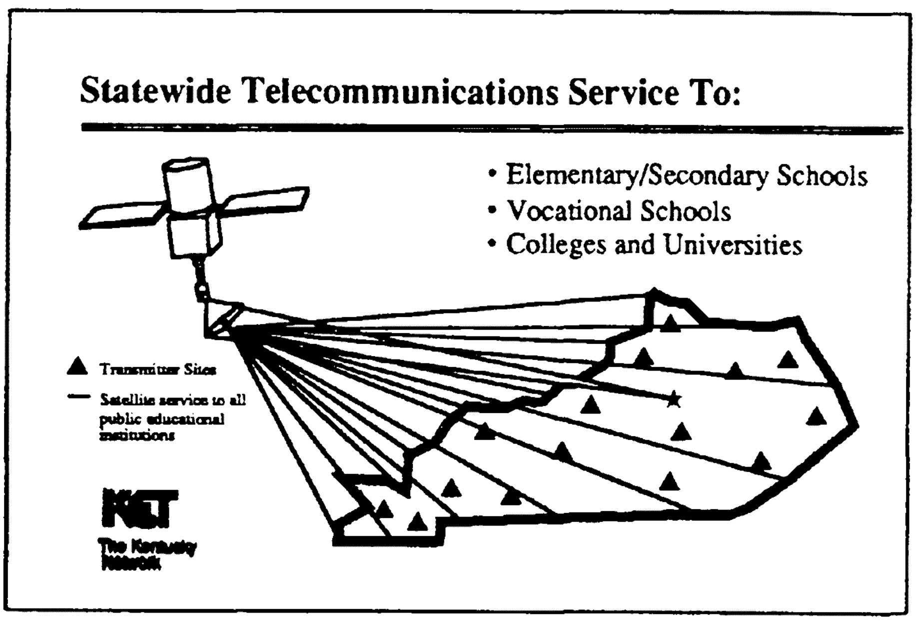


**Figure 2: KET Reaches all Public Schools in the State**

This potential nationwide KET linkage will allow the Kentucky radon program to offer the "Radon in Schools" broadcasts to radiation control offices and education departments in the following states.

| | |
|---|---|
| Alabama | Arkansas |
| Georgia | Louisiana |
| Michigan | Missouri |
| Mississippi | North Dakota |
| Nebraska | New Jersey |
| Ohio | Pennsylvania |
| Texas | South Carolina |
| Wisconsin | West Virginia |
| Virginia | Florida |

Kansas, Oklahoma, Tennessee, and North Carolina are not currently KET STAR Channel participants, but linkage to these states can be arranged.

TARGET AUDIENCE

The radon program, funded through the U.S. Environmental Protection Agency, State Indoor Radon Innovative Grant, will apply KET's high technology approach to providing radon information to school administrators, school building managers, daycare operators, and others engaged in managing buildings where citizens learn and work.(Figure 3)

Once the broadcast dates have been scheduled and pre-broadcast materials developed, all state radiation control offices, radon programs, state departments' of education and other target participants will be invited to link up and take part in this project.

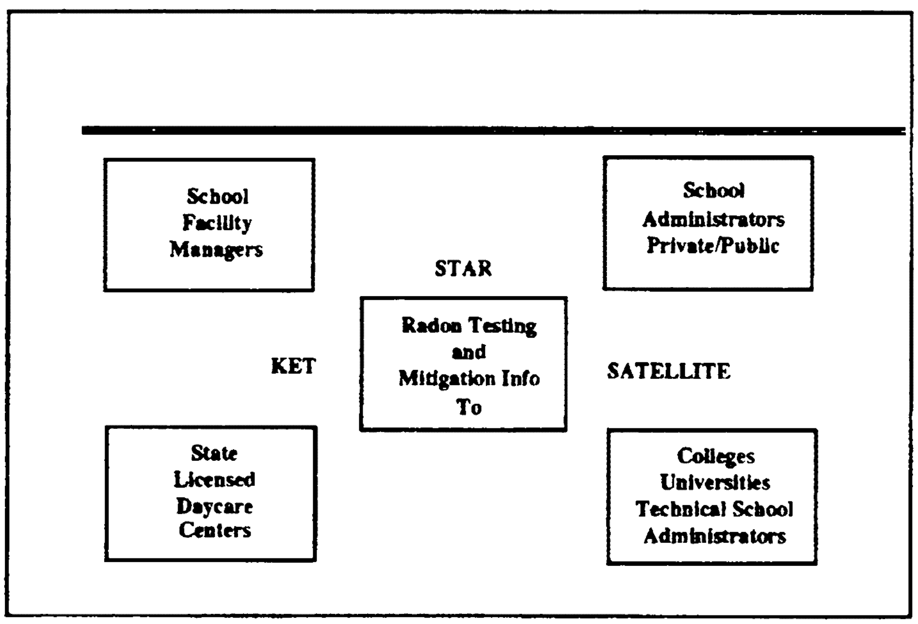


Figure 3: KET/Radon Target Audience

For Kentucky public school officials, the radon in schools broadcast will arrive soon after they receive confirmatory radon measurements for their building(s). For others such as daycare and nursing home operators, the information will arrive as they begin to consider how to go about testing and mitigating their buildings.

By using the Star Channel satellite and distance learning concepts, the radon program staff can reduce the need to travel statewide to disseminate radon information to these groups. An additional benefit of this communication media is that the audience is exposed to a consistent message with minimal presenter bias.

KET-RADON PROJECT GOALS

The second KET/Radon Innovative grant goal will go beyond the initial broadcasts to research the potential for using telecommunications to deliver information about radon. To do this, the KET project staff will investigate existing telecommunication networks and apply this knowledge to the delivery of radon information and technical training. Another aspect to be investigated will be the possibility of linking the USEPA Regional Radon Training Centers, through a central training delivery system with on-site training center faculty in designated locations (Table 1).

TABLE 1: KET/RADON INNOVATIVE GRANT GOALS

**KET - Radon Project Goals**

- **Design and Deliver two Radon Programs utilizing the Star Satellite and telecommunications.**
- **Investigate the potential for using KET Network to deliver Radon information, Training, and Continuing Education.**

SCHEDULED BROADCASTS

The Spring broadcast date is expected to be scheduled prior to the time school officials finalize their 1991-1992 budget requests. Hopefully, the timing of the broadcast and the technical information provided, will be sufficient to allow school officials to request funding for radon testing and mitigation projects (Table 2).

TABLE 2: BROADCAST SCHEDULE

**Radon Broadcasts**

- **Spring 1991 - Testing**
- **Fall 1991 - Mitigating**

The Spring broadcast will emphasize radon testing protocols for schools and illustrate ways to communicate radon risk information to parents, staff, children and the public (Table 3).

TABLE 3: SPRING BROADCAST DESIGN

**Spring 1991**

**Broadcast Design**

- **Testing for Radon in Schools**
- **Decision steps based on**
  - **Initial Screening Measurements**
  - **Confirmatory Measurements**
- **Risk Communication Suggestions**
- **Resources Available**
- **Live Panel of Radon Experts for Teleconference**

Kentucky school representatives, experienced in radon testing and mitigation in their own school building(s), will share insights and lessons learned. These segments will be pre-taped in the actual school setting. Also, the radon school based outreach program being implemented by the Jefferson County Public School District and Jefferson County Parent-Teacher's Association will be highlighted (Table 4).

TABLE 4: FALL BROADCAST DESIGN

## Fall 1991

**Broadcast Design**

- **Mitigating for Radon in Schools**
- **Decision Steps**
- **Risk communication suggestions**
- **Resources Available**
- **Live Panel of Radon Experts for Teleconference panel**

The Fall Radon in Schools broadcast will provide school mitigation information. Again, Kentucky school representatives will share their experiences in an attempt to communicate the message that radon issues are manageable within a school setting and that there are others who have survived the process (Table 4).

Each two hour broadcast will feature a "live" interactive question and answer period for the last 30-40 minutes of the program. A panel consisting of radon experts from U.S. EPA and other agencies will respond "on air" to participants' questions. The audience will be provided with an 800 telephone number to the KET studio and encouraged to call in with their questions. The 800 call-in number will remain active for one hour after the broadcast. Trained radon staff will answer the incoming calls, write out the questions and route them to a panel member.

A panel member will read the question aloud and provide an answer or refer the caller to additional resources. Any caller who does not have their question addressed on live broadcast will receive a written answer by mail following the program. Callers will not be identified by name or school and their voices will not be aired.

The entire broadcast plus the live panel call-in segment will be taped for future broadcast schedules. Individual tapes will be made available through a loan program (Figure 4).

BROADCAST PRODUCTION

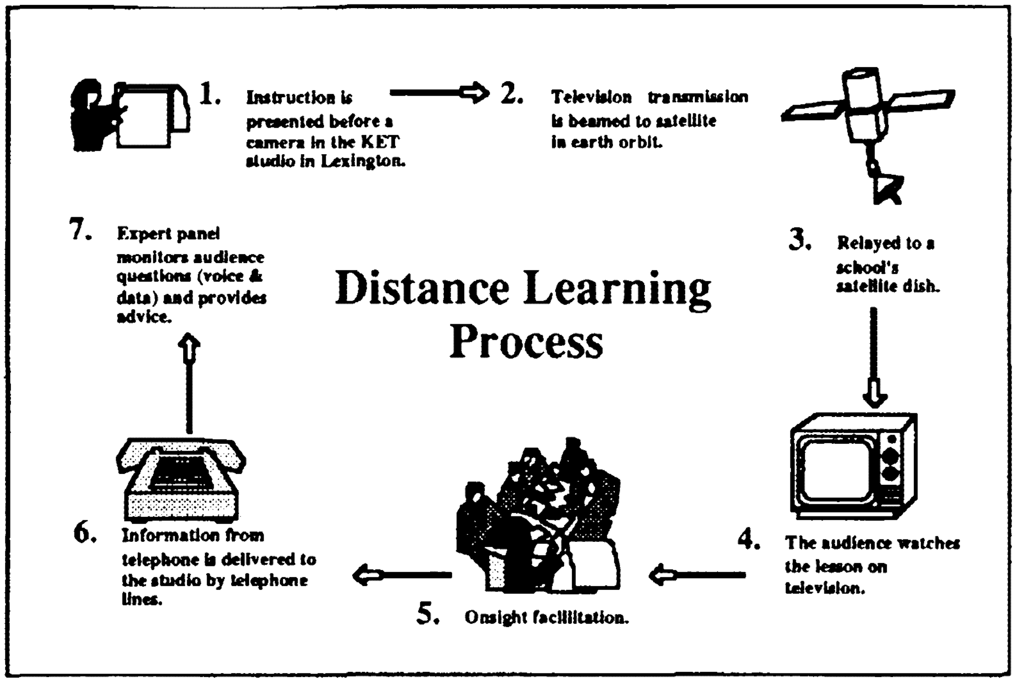


Figure 4: Distance Learning Process

Pre-broadcast activities can be divided into two major steps; audience preparation and broadcast production processes. In regard to the participants, the State Department of Education, Human Resources Licensing and Regulation Department, and KET will assist by providing mailing labels for the target audiences. The project staff person, in coordination, with the USEPA and KET and others, will prepare the broadcast design. KET staff will take the lead in taping and editing broadcast visuals. Field taping of actual school settings is planned as part of a pre-production activity. Existing video productions may also be integrated.

Other pre-broadcast activities include sending a radon resource literature package along with each invitation. In each school district, a KET receiving school will be identified as a radon resource broadcast center. These resource centers will provide on-site facilitation during and after the broadcast by a "radon trained" resource person. County Extension Agents, school representatives, local health officials, and others with demonstrated knowledge of radon testing and mitigation will be designated to serve as on-site facilitators. The facilitators will receive a pre-broadcast orientation to ensure statewide consistency of information. For security reasons, all non-school related participants (daycare operators, etc.) will be assigned to a resource center. Closest to their home/work.

## EVALUATION

The nature of this project requires an extensive system of checks and balances at each phase of development. This will be provided by the KET staff assigned to the project, as well as the project designated radon staff person. USEPA Region IV staff, and Regional Radon Training Center staff will provide ongoing assistance and review. An in-state work group will also be assigned to on-going evaluation. Members of this group will include, staff from the radon program, State Department of Education; Jefferson, Fayette, and Warren County School Districts; University of Kentucky Cooperative Extension Service, Kentucky Parent-Teachers Association, and others.

An immediate post-broadcast evaluation questionnaire and a six week follow-up will be administered to all participants. The results from the immediate and delayed evaluation will serve to measure the degree of change in participant attitude regarding radon.

## ACKNOWLEDGEMENTS

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# JEFFERSON COUNTY SCHOOL DISTRICT AND RADON PROGRAM

1. Work cooperatively to establish a radon comunication outreach program through the school to parents, staff, and students.

2. Promote the Jefferson County School District radon testing project and the communication outreach program as a model for other school districts in the state and the nation.

## MODEL COMMUNICATION OUTREACH

<u>Audience</u>

| | |
|---|---|
| School Administrators | Building Maintenance Personnel |
| Teachers | Ancillary School Staff |
| Parents | Parent-Teachers Association |
| Students | |

<u>Message</u>

Long-term exposure to elevated levels of rdon gas is associated with increased risk of developing lung cancer.

Testing for radon gas is easy and mitigation methods are effective.

All homeowners should test their homes. Schools, daycares, public and commerical buildings should also be tested.

If elevated levels are discovered, action should be taken to reduce the levels.

## RADON COMMUNICATION OUTREACH PROGRAM THROUGH SCHOOLS

| Audience | Type of Communication | Message | Method |
|---|---|---|---|
| School Administrators<br>Building Maintenance Personnel | Technical/Support and Motivational | - Testing Protocols<br>- Decision process after testing<br>- Mitigation strategies<br>- Technical assistance<br>- Public disclosure<br>- Encourage them to test their homes | Kentucky Educational Television-Radon in Schools Broadcast Spring/Fall 1991 |
| Teachers<br>Ancillary School Staff | Informational and Motivational | -Levels of radon in school, by room<br>- Mitigation strategy<br>- Encourage them to test their homes | - Dissemination of informational literature<br>-Presentations through the Kentucky Education Association |
| Parent-Teacher's Association | Informational and Motivational | - Levels of radon in school, by room<br>- Mitigation strategy<br>- PTA can help school administrators to reach parents with radon information<br>- Encourage them to test their homes | - Presentation at State and District Meetings and Workshops<br>- Assistance to individual schools/districts<br>- PTA host Radon Awareness Program<br>-PTA distribute radon info to parents<br>- Host testing campaigns |
| Parents | Informational and Motivational | -Levels of radon in school, by room<br>-Mitigation strategy<br>- Encourage them to test their homes | - District/School/PTA sponsored radon awareness programs<br>- Distribution of radon literature through PTA/ District office |
| Students | Informational and Motivational | - Facts about radon and indoor air quality<br>- How to improve air quality | - American Lung Association lesson on radon in "Growing Healthy" curriculum<br>-Weekly Reader Poster contest |

*Risk Communication Information Provided for each Group

# REGULATION OF RADON PROFESSIONALS BY STATES: THE CONNECTICUT EXPERIENCE AND POLICY ISSUES

Alan J. Siniscalchi, M.S., M.P.H. (1); Zygmunt F. Dembek, M.S. (1), Nicholas Macelletti, M.S. (1); Laurie Gokey, M.P.H. (1); Paul Schur, M.P.H. (1); Susan Nichols, B.S. (2); and Jessie Stratton, B.S. (3)

(1) State of Connecticut Department of Health Services
(2) State of Connecticut Department of Consumer Protection
(3) State Representative, Connecticut General Assembly

## ABSTRACT

The desire of state governments to provide information on proficient radon professionals to their citizens has resulted in a variety of informational and regulatory programs. The State of Connecticut has developed a new registration program for radon professionals, pursuant to Connecticut Public Act 90-321, that combines requirements for successful completion of both state registration and federal proficiency programs in order to be listed. Under this program, radon testers and testing companies are required to successfully participate in the current round of the EPA Radon Measurement Proficiency (RMP) Program. Radon mitigation contractors must successfully participate in the Radon Contractor Proficiency (RCP) Program and register with the Department of Consumer Protection. Radon Diagnosticians are required to successfully participate in both the RMP and RCP Programs. The process by which Connecticut developed this program and recommendations for EPA policy changes are discussed.

## INTRODUCTION

The State of Connecticut Department of Health Services (DHS) began receiving inquiries on radon and requests for information on radon professionals soon after high levels of radon were discovered in a home in Pennsylvania. Many of the callers requested our recommendations for radon testing companies and mitigation contractors. Most callers wanted information on what types of testing services were available, what prices were reasonable, which companies had the most experience and whether they could conduct the test themselves. Callers who had already tested asked for information on mitigation systems and lists of "approved" mitigation contractors. Some of the better informed callers also asked about whether it is appropriate for the same company that conducted the radon test to also conduct the mitigation operation. In time, other consumers also reported problems with the radon testing and mitigation companies.

The DHS response to these requests has evolved through a number of changes. These changes have included both the information provided on radon assessment and control and the means by which we regulate radon professionals. Our ultimate goal is to provide sufficient information to Connecticut consumers to enable them to make informed choices on testing and mitigation services.

This paper will outline the evolution of radon professional regulation in Connecticut, provide recommendations for other state programs, and propose changes for the EPA proficiency programs.

## EARLY GUIDANCE ON RADON PROFESSIONALS

The DHS first attempt at providing guidance to Connecticut consumers on radon professionals was the development, in 1985, of a list of radon testing companies. The information was obtained from results of an early round of the EPA's Radon Measurement Proficiency (RMP) Program. The DHS determined that additional information on both the types of testing services offered by each company and the price of each testing service would also be beneficial. Information on DHS recommendations regarding screening devices and procedures was also included.

During 1986 the DHS provided the public with a list of mitigation contractors used by the EPA in the northeast since little information was available on Connecticut mitigation companies. As mitigation companies became established in Connecticut, the DHS expanded the list to include information on mitigation company services. Since this list of contractors was not derived from a state or federal proficiency program, disclaimers were added to warn the public that the DHS could not be responsible for a company's performance.

During 1986-88 the DHS prepared additional informational material on radon exposure in Connecticut that was mailed in response to telephone inquiries on radon testing. This material included fact sheets summarizing the results of the various statewide radon surveys, and the two EPA radon pamphlets (1,2).

In August 1987, the DHS held a news conference to announce the results of our second statewide survey. At this conference the Department recommended that all Connecticut citizens test their homes for radon regardless of the geographic area of their residence, since our surveys to date had revealed the potential for high levels of radon in all areas of the state. The DHS formally organized a Radon Program in December 1987 to publicize these recommendations and conduct additional surveys. A third survey revealed consistent results in the percentage of homes (20%) with radon levels in excess of the U.S. EPA guideline of 4 picocuries (pCi/L) per liter (3,4,5). These results further emphasized our recommendation that all Connecticut residents test their homes for radon (3,4,5).

During 1989, a second state agency became increasingly involved in assisting Connecticut consumers in evaluating radon professionals. This agency, the Department of Consumer Protection (DCP), recommended that individuals offering mitigation services register as "home improvement contractors." This existing DCP registration program provided consumers with additional protection in the form of the "Home Improvement Guaranty Fund" with monies that can be used to correct poorly installed or unfinished mitigation systems.

During this time, the Radon Program greatly revised the format of how information on radon is provided to Connecticut residents. This new approach included the development of two information packets. Information packet "A" included a list of testing companies, a fact sheet and the EPA pamphlet "A Citizen's Guide to Radon" (1). Information packet "B" included the EPA pamphlet "Radon Reduction Methods A Homeowners Guide" (2), and the list of diagnostic services and mitigation contractors. Although the DCP registration procedures for mitigation contractors was not mandatory at this time, the DHS added a notice to the contractor list advising consumers of the benefits of this program. Table 1 summarizes the other registration requirements and recommendations. It should be noted that while the DHS Bureau of Laboratory Services had existing regulatory authority to require registration of testing laboratories, the DHS could not require mitigation contractor registration. During early 1990 the Radon Program also recommended that consumers select mitigation contractors that had successfully participated in the EPA Radon Contractor Proficiency (RCP) examination.

## REGISTRATION REQUIREMENTS AFTER OCTOBER 1990

Many consumers were not satisfied with the status of our radon professional lists since these lists did not require contractors to demonstrate competency by completing a proficiency examination or program.

A number of Connecticut State Representatives and agency staff began to independently suggest alternative approaches toward a more formal regulation of radon professionals. Many of these alternative approaches called for mandatory certification or registration programs. A proposed bill was submitted by the Conecticut General Assembly's General Law Committee that asked for a mandatory licensure program for all radon professionals. This proposed program would have required individuals offering radon testing, diagnostic or mitigation services to obtain a license from the DHS, that would be renewable on an annual basis. While the bill would have offered consumers better protection against fraudulant radon professionals than a registration program, it would have required additional agency staff to implement. The DHS testified against the bill, pointing out that due to fiscal constraints and a lack of staff it would not be possible to implement the legislation if it was enacted.

TABLE 1. REQUIREMENTS FOR LISTING OF RADON PROFESSIONALS IN CONNECTICUT PRIOR TO OCTOBER 1990

| Requirement | Professional Class<br>Testing primary and secondary | Diagnostics | Mitigation |
|---|---|---|---|
| Department of Health Services (DHS) Registration | Yes | Yes | Yes |
| EPA Radon Measurement Proficiency (RMP) Program | Yes | No | No |
| EPA Radon Contractor Proficiency (RCP) Program | No | Rec.* | Rec. |
| Education | Rec. | Rec. | Rec. |
| Department of Consumer Protection (DCP) Registration | No | No | Rec. |

*recommended

One of the authors (Representative Jessie Stratton) began work on an alternative proposal that would increase the Department's ability to regulate radon professionals at little cost to the agency. After meeting with the representatives of appropriate state agencies (including the other authors) a bill was proposed to accomplish these goals using a more formal registration program. This proposed bill survived various committee meetings and hearings and was signed into

law by Governor William A. O'Neill on May 3, 1990. The requirements of Public Act 90-321 "AN ACT CONCERNING PERSONS WHO TEST FOR OR MAKE HOME REPAIRS TO ELIMINATE THE PRESENCE OF RADON GAS AND DIRECTING THE DEPARTMENT OF HEALTH SERVICES TO ADOPT REGULATIONS ESTABLISHING SAFE LEVELS OF RADON IN POTABLE WATER AND PAYMENTS FROM THE HOME IMPROVEMENT GUARANTY FUND" became law on October 1, 1990. This bill stated that "the Department of Health Services shall publish a list from time to time of: companies that perform radon mitigation or diagnosis; primary testing companies and secondary testing companies."
Table 2 summarizes these new requirements.

TABLE 2. REQUIREMENTS* FOR LISTING OF RADON PROFESSIONALS IN CONNECTICUT AFTER OCTOBER 1990

| Requirement | Professional Class: Testing primary and secondary | Diagnostics | Mitigation |
|---|---|---|---|
| Department of Health Services (DHS) Registration | Yes | Yes | Yes |
| EPA Radon Measurement Proficiency (RMP) Program | Yes | Yes | No |
| EPA Radon Contractor Proficiency (RCP) Program | No | Yes | Yes |
| Education | EPA Measurement** | "EPA Approved" | "EPA Approved" |
| Department of Consumer Protection (DCP) Registration | No | No | Yes |

* Under Connecticut Public Act 90-321
** Required by the DHS Bureau of Laboratory Services only

One should note the most significant changes relate to the registration process for radon professionals. Diagnosticians and mitigation contractors are now <u>required</u> to fulfill federal proficiency requirements by successfully participating in the RCP Program in order to be listed by DHS. This requirement of successful participation in the RCP Program established a minimum level of proficiency for radon contractors.

Individuals offering both radon testing and diagnostic services are specifically required to successfully participate in the federal RMP Program to be listed by the DHS under PA 90-321.

Both diagnosticians and mitigation contractors are required to fulfill an educational requirement specified in the bill. This requirement states that diagnostic specialists and the on-site supervisor must have "attended a program approved by the United States Environmental Protection Agency."

Finally, mitigation contractors are required to register with the DCP as "home improvement contractors." This requirement was added to the legislation to ensure that Connecticut residents retaining the services of radon mitigation contractors will be afforded the same protection available to consumers using the services of any other home improvement contractor. This protection can include receiving funding to complete unfinished installations or correct problem systems.

PROBLEMS ENCOUNTERED WITH THE IMPLEMENTATION OF PUBLIC ACT 99-321

The authors have documented the following problems in the implementation of PA 90-321. The first problem relates to the bill's reference to "EPA-approved" courses in outlining the educational requirements for the three radon professional groups. This term, suggested by EPA staff and others, referred to courses offered by EPA contractors including the newly organized Regional Radon Training Centers. It was chosen to avoid the resource intensive problem of state agency approval of source providers.

A number of radon professionals who wished to be listed by the state asked if courses they had taken from private vendors were considered "EPA- approved". Inquiries to the EPA revealed that they did not "approve" any radon courses at that time, although they did endorse the courses offered by the Regional Radon Training Centers.

A second problem relates to the infrequent review periods or "rounds" offered by the EPA Radon Measurement Proficiency (RMP) Program. Public Act 90-321 now requires both primary and secondary testing companies and diagnosticians to have "successfully completed" the RMP program in order to be listed. Therefore, newly organized companies must wait up to a year or more for the next test round prior to being listed.

A third problem relates to the requirement of individuals who wish to be listed as offering services as a radon diagnostician participate in both the EPA RMP Program and the Radon Contractor Proficiency (RCP) Program. The final language of the bill allowed any RMP participant including secondary companies to be listed as a diagnostician. The authors have found that only those companies with instruments capable of performing real-time radon measurements and successfully participating in the RMP Program with these instruments can conduct accurate diagnostic evaluations.

A forth major problem relates to the program's design as a listing rather than a registration program. While the program places little demand on the Department, it allows radon professionals to conduct business without requiring proof of proficiency and training.

## SUGGESTED CHANGES IN EPA POLICY TO ASSIST STATES IN THE REGULATION OF RADON PROFESSIONALS

The Department's preliminary experience with PA 90-321 has already modified the author's thoughts on the definition of the model radon professional registration program. The following changes are suggested to aid states in the development of their radon programs. These suggestions include both changes in EPA policy and recommendations for states in their interpretation of EPA policy.

Most changes are related to the educational requirements. Table 3 lists recommended educational requirements which call for "EPA-equivalent" radon training courses specifically designed for radon testers and mitigators. EPA-equivalent being defined as having a course content based on courses offered by the EPA or by the EPA Regional Radon Training Centers.

The change in language from "EPA-approved" to EPA-equivalent will more accurately reflect the current EPA policy on approval of training providers. At this time the EPA only approves providers of the "hands-on" mitigation training course (see below).

TABLE 3. RECOMMENDED REGISTRATION REQUIREMENTS OF RADON PROFESSIONALS BY STATE AND LOCAL GOVERNMENTS

| | Professional Class | | |
|---|---|---|---|
| Requirement | Testing primary and secondary | Diagnostics | Mitigation |
| Health Agency Registration | Yes | Yes | Yes |
| EPA Radon Measurement Proficiency (RMP) Program | Yes | Yes | No |
| EPA Radon Contractor Proficiency (RCP) Program | No | Yes | Yes |
| Education | EPA-Equivalent Measurement | EPA-Equivalent Measurement & Mitigation | EPA Equivalent Mitigation |
| Consumer Agency Registration | No | No | Yes |

Ideally the EPA would determine if a course provider is offering an EPA-equivalent course. EPA staff would review new course offerings submitted by the providers and make a determination of "equivalency". The EPA could also develop a model accreditation program for radon course providers. State agencies could determine if a course is considered EPA-equivalent by comparing the course outline to the EPA accreditation model. States with limited resources devoted to radon issues can make this determination by simple comparison of the course outline.

The measurement course should consist of a one day program while the mitigation course would include a "hands on" training component. A list of approved courses that include this "hands on" component will be maintained by the EPA. This course will include actual practice in assembling radon mitigation systems. Diagnosticians would be required to complete both courses, since they must be both proficient with testing methods and knowledgeable about mitigation systems.

A second proposed change would require diagnosticians to participate in the RMP Program as a primary company using a radon testing device capable of obtaining real-time pinpoint radon measurements. This type of device is needed to conduct accurate diagnostic evaluations of homes and other buildings. This requirement would ensure that diagnosticians will not try to conduct diagnostic radon measurements with passive radon detection devices.

Perhaps the most significant changes would have these requirements mandated not only for professionals who wish to be listed, but for all professionals conducting business in a state.

## SUGGESTIONS FOR THE EPA RADON MEASUREMENT PROFICIENCY (RMP) PROGRAM

The EPA's Radon Measurement Proficiency Program has proven extremely useful for states such as Connecticut in providing information on competent radon professionals. The authors have identified a few minor changes that would improve the RMP's Program's ability to provide useful information to states. These changes are summarized on Table 4.

The most significant changes again relate to educational requirements. The authors recommend both prerequisite and continuing education requirements for all radon testing company personnel involved with placement and retrieval of radon measurement devices. This requirement will help to ensure that accurate testing procedures are followed by professional radon testers. In addition, laboratory directors will be required to complete a course on techniques and procedures used in radon analysis. This requirement will ensure that accurate analysis will be conducted by using appropriate quality assurance techniques. Both a continuous RMP Program application process and a continuous randomly selected blind testing are also recommended. A continuous testing round policy will allow newly-formed companies to immediately participate in the RMP program. The current system of periodic "test rounds" has resulted in waiting periods of up to one year. The continuous blind testing plan will ensure that laboratories maintain a high level of proficiency throughout the year.

TABLE 4. CURRENT AND RECOMMENDED REQUIREMENTS FOR RADON TESTING COMPANIES PARTICIPATING IN THE U.S. ENVIRONMENTAL PROTECTION AGENCY (EPA) RADON MEASUREMENT PROFICIENCY (RMP) PROGRAM

| Company Type & Requirements | Current | Recommended |
|---|---|---|
| PRIMARY COMPANY: | | |
| Education | None | EPA Lab. Analysis*, EPA Measurement** or Equivalent |
| QA Program (Analysis) | Yes | Yes |
| Chamber Testing (Submitted) | Yes | Yes |
| Chamber Testing (Blind) | Selected (test round period only) | Random (year-long) |
| SECONDARY COMPANY: | | |
| Documentation of Approval by the Primary Co. | Listing Only | Yes |
| Education | None | EPA Measurement** or Equivalent |
| QA Program (Sampling) | No | Yes |
| Chamber Testing (Blind) | No | Random (year-long) |

* Prerequisite and continuing educational requirement for laboratory director only

** Educational requirement for all staff involved with testing device placement
and retrieval

RECOMMENDATIONS FOR THE EPA RADON CONTRACTOR (RCP) PROFICIENCY PROGRAM

The authors have found the EPA Radon Contractor Proficiency Program (RCP) to be a useful addition to the RMP Program. We have some minor recommendations for improving this program's value in providing information to consumers who wish to contract for installation of mitigation systems. Table 5 summarizes these changes which again emphasize prerequisite and continuous educational requirements. The authors have recommended that the EPA emphasize the separation of the radon diagnostician and mitigation contractor services. This separation should be used in both the registration requirements of the RCP Program, where the Radon Program would recommend a separate listing, and within the text of EPA literature on radon reduction techniques (6,7).

An example of a document where a text change is needed can be seen in Section 4.1 of the EPA booklet "Application of Radon Reduction Methods" (7). This section, entitled "Choice of Diagnostician/Mitigator," describes the diagnostician but does not emphasize the distinction:

> "The person primarily responsible for the diagnosis of the problem is called the "diagnostician." The person who will be primarily responsible for the design, installation, and post-installation evaluation of the radon reduction system is referred to here as the "mitigator." These may or may not be the same person (7)."

The authors also recommend that participants in the RCP Program must agree to follow the "RCP Program Guidelines" in all their mitigation activities. These guidelines are designed to insure that only well-designed, efficient systems are installed in homes and only when needed.

## CONCLUSIONS

The authors are of the opinion that adoption of these changes would increase the value of EPA's Proficiency Programs by providing useful information which would enable our nation's consumers to make informed decisions regarding the selection of radon professionals. By requiring participating in the EPA proficiency programs and following the recommendations listed on Table 3, states can offer better protection to their residents. Consumers in those states will know that all listed professionals possess a minimum level of knowledge and training in proper testing diagnostic and mitigation procedures. It is our belief that such information and consumer protection safeguards contribute to reducing radon exposure and decreased mortality among our nation's citizens.

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TABLE 5. CURRENT AND RECOMMENDED REQUIREMENTS FOR RADON DIAGNOSTICIAN SPECIALISTS AND MITIGATION CONTRACTORS PARTICIPATING IN THE U.S. ENVIRONMENTAL PROTECTION AGENCY (EPA) RADON CONTRACTOR PROFICIENCY (RCP) PROGRAM

| Professional Class and Requirements | Current | Recommended |
|---|---|---|
| <u>Diagnostician</u>: | | |
| Prerequisite Education | No* | EPA Measurement and Mitigation Courses or Equivalent |
| Participation in the EPA Radon Measurement Proficiency (RMP) Program | No* | Yes |
| Participation in the EPA Radon Contractor Proficiency (RCP) Program | No* | Yes |
| Continuing Education | No* | Yes |
| <u>Mitigation Contractor</u>: | | |
| Prerequisite Education | Rec.** | EPA Mitigation Course*** or Equivalent |
| Participation in the EPA Radon Contractor Proficiency (RCP) Program including use of | Yes | yes |
| the RCP Guidelines (see text) | Rec. | Yes |
| Continuing Education | Rec.** | Yes |

* Current EPA proficiency programs do not recognize diagnostic specialists as a separate professional class
** Will be required after July 1991
*** Required for on-site supervisor only, recommended for all staff
Rec. = Recommended

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# NEW JERSEY'S RADON PROGRAM - 1991

Jill A. Lapoti
New Jersey Department of Environmental Protection

# NEW JERSEY RADON PROGRAM, 1991

## Background

Early in 1985, the Pennsylvania Department of Environmental Resources contacted the New Jersey Department of Environmental Protection (NJDEP) and described finding high indoor radon levels in homes along the geologic formation known as the Reading Prong. Since the Reading Prong extends from Pennsylvania, through northern New Jersey, and into southern New York State, it was likely that a similar hazard existed in homes in New Jersey. A few months after this initial notification, a greater sense of urgency was added to the situation as a result of an article about radon and the Reading Prong which appeared in the New York Times. As a result of the article, the State received a large number of phone calls from concerned citizens.

Early on the NJDEP identified two major issues: 1) there was a potential indoor radon exposure problem in the State which required testing and remediation whenever necessary, and 2) the extent of the problem needed to be identified. It would not have been enough to assume that only the Reading Prong area was affected, but that was the natural starting place to begin studying and testing.

A review of available geologic data showed that uranium, of which radon is a natural decay product, was commonly present in a greater geographic area of the State than the Reading Prong. Based on this data, the NJDEP estimated that 1.6 million homes could potentially be affected. That meant as many as 4 million people or more might be affected, greater than one half of New Jersey's population. Two facts were apparent; indoor radon posed an extremely large potential environmental hazard and no single state agency had the resources to deal with a problem of such magnitude. In late 1985, planning began on what actions to take and how to involve all levels of government, as well as the private sector wherever possible.

The New Jersey Legislature also recognized the magnitude of the situation and enacted two separate pieces of legislation providing $4.2 million and mandating specific activities. The NJDEP was designated the lead agency and required to develop an information outreach program to educate New Jersey residents about the problem and methods of testing and remediation. Additionally the NJDEP was to institute a program of confirmatory monitoring for residents whose initial radon tests showed 4 picoCuries per liter (4 pCi/l) or higher and to also conduct a statewide scientific study to identify areas at risk for residential exposure to high levels of radon. Finally the legislation required the NJDEP to develop a certification program for companies offering radon testing and mitigation services. The New Jersey Department of Health (NJDOH) was required to conduct an epidemiologic study to identify potential risk of lung cancer associated with residential exposure and also to develop a voluntary registry of residents with a radon exposure history.

Activities

The information outreach program that the NJDEP developed, centers around a toll-free "800" number that is open to callers every work day from 8:00 a.m. to 5:00 p.m. Since July of 1985 when the information phone line was first set up, more than 125,000 calls have been logged. Many callers want information about testing and remediation, so brochures were prepared and a standard information packet is sent to callers upon request. To date over 60,000 of these packets have been sent out. More than 350 presentations by Radon Program staff have been made to audiences including homeowners and local officials, realtors, health professionals, educators and students, testers and mitigators, and a number of professional groups at conferences convened for the purpose of information exchange. Other public awareness and education outreach activities include production of a radon slide show, which was also converted to a video. Three billboards were put up along roadways in high exposure areas in an attempt to generate more awareness about radon testing. Radon Program staff worked with representatives from New Jersey Transit on a project to put placards in buses, so as people rode to work or went shopping they would repeatedly see the radon testing message. A mass mailing to almost a half million households in the Tier 1 area, resulted in about 40,000 inquiries about radon, its health effects, and testing and mitigation programs. More recently, an insert was included in energy bills, which the participating utility company estimates goes to about 2,000,000 customers. It generated over 1,000 telephone inquiries, which is a small percentage, but calls are still coming in and the mailing was at no cost to the NJDEP. An article about radon, its identification, hazards, and control was prepared by Radon Program staff and is scheduled to appear in a real estate magazine and also in a New Jersey Transit publication which is available to commuters.

As important as it was and is to promote public awareness about the hazard of radon and the importance of testing, the NJDEP knew it could not offer every potentially affected homeowner a free test kit. Some communities, where an initial few high readings were found, did make radon test canisters available for free or at greatly reduced prices. Instead, the NJDEP established a program offering free confirmatory testing to any homeowner who requests it because their initial test results are equal to or above 8 pCi/l. Up to and including October 1988, the confirming test was offered if the initial result was equal to or above 4 pCi/l. This program has now been expanded to include followup measurements on homes which have been mitigated. The confirmatory and followup programs were an effective means to monitor the growing industry providing radon testing services and home mitigation services.

From October 1985 through October 1988, when confirmatory testing was offered for a test result equal to or greater than 4 pCi/l, 7,223 tests were conducted. Since the level was raised to 8 pCi/l in November 1988, an additional 1,909 tests have been performed, making a total of 9,132 confirmatory tests conducted through December 1990. From October 1985 through December 1990, 2,389 followup remediation tests have been conducted.

Perhaps the most significant undertaking in the beginning of the New Jersey Radon Program was determining the extent of the potential radon exposure problem.

To start, the NJDEP delineated the geographic area of the Reading Prong that ran through the State in order to make an initial evaluation of the number of potentially affected homes. The number exceeded 250,000. Then a review of available geologic data for the State was conducted. It showed uranium deposits extended beyond the Reading Prong formation. Additionally, an examination of a New Jersey Geological Survey literature review showed that "radioactive mineralizations" were present throughout northern New Jersey. This meant the potential geographic area was any part of the State north of Trenton, and that approximately 1.6 million homes were affected. Further the number of homes was increasing in that area as more people were building in the northwestern portion of the State during the 1980's. This initial review of available geologic data gave New Jersey officials a sense of the magnitude of the radon problem in the State. However officials were aware that an extensive statewide radon study needed to be conducted to determine where elevated radon levels were most likely to be found and to better understand how environmental and structural factors contribute to radon entry in homes.

Work on the legislatively mandated Statewide Study of Radon was begun in the summer of 1986 when a contractor for the project was selected. The study was to prepare a risk assessment of contracting lung cancer as a result of exposure to indoor radon and radon progeny. Almost 6,000 homes were tested in different geologic areas of the State over the course of the study. In order to estimate an annual exposure rate, the contractor took the average of radon readings based on a six month heating season and a six month non-heating season. Residency periods and smoking history were major factors in the risk assessment. Statistics showing risk of contracting lung cancer were compiled on both county and selected municipal levels. The findings confirmed, and further defined, the initial areas of concern identified by the State.

In the autumn of 1987, using information from both the initial NJDEP geologic data review and data already collected during the statewide study, the voluntary certification program, and the Cluster Study Program, the NJDEP released the first "Tier" map entitled, "Preliminary Recommendations for Radon Testing". The map outlined three tiers: Tier 1 was "test as soon as practical", Tier 2 was "test within one year", and Tier 3 was "test if concerned". Municipalities were categorized as Tier 1, 2, or 3 based on the percentage of homes measured with radon levels greater than or equal to 4 pCi/l. Data on 25 homes was required to classify a municipality into a particular tier. If there was insufficient data, then classification of the municipality was based on the geological province data in which the municipality was located. The tiers are drawn on municipal boundaries because these were considered the smallest workable political and geographic subdivisions on which to identify radon potential.

Both a press release and a direct mailing to every homeowner in Tier 1 were done in conjunction with the map release. The mailing was sent to almost a half million home and resulted in approximately 40,000 inquiries about the radon issue and testing recommendations.

The Tier map continues to be periodically updated based on data submitted to the NJDEP by radon testing firms currently participating in the "Interim Voluntary Certification Program". Over the past four years the Tier boundaries have altered. The reported test results have shown that although the initial designated areas were on track further identification and definition are possible and necessary. Recently the tiers ceased to be defined as recommendations for testing. Instead, they are defined as radon potential. The current criteria used to classify municipalities into a particular Tier are outlined in Table 1.

TABLE 1

Criteria for Tier Designation

| **Tier** | **Municipality*** | **Geologic Province**** |
|---|---|---|
| Tier 1 - High Radon Potential | ≥25% of homes tested have radon levels ≥4.0 pCi/l | ≥25% of homes tested have radon levels ≥4.0 pCi/l |
| Tier 2 - Moderate Radon Potential | 5-24% of homes tested have radon levels ≥4.0 pCi/l | 5-24% of homes tested have radon levels ≥4.0 pCi/l |
| Tier 3 - Low Radon Potential | 0-4% of homes tested have radon levels ≥4.0 pCi/l | 0-4% of homes tested have radon levels ≥4.0 pCi/l |

* Criteria used if there are at least 25 homes that have been tested in the municipality.

** Criteria used only when municipality data is insufficient (less than 25 homes tested for radon) and at least 100 homes have been tested in the province.

The New Jersey Legislature had also mandated requirements for the NJDOH. An epidemiological study of radon and lung cancer based on actual radon measurements in homes and detailed smoking histories for individual subjects was conducted by the NJDOH. It was an extension of a previously conducted lung cancer study among New Jersey women. Residence criterion was established and both year-long alpha track detector measurements for estimating subject exposure as well as four-day canister quick screening for current residents were done. The entire study group, cases and controls combined, was 835 women. Detailed smoking histories were taken for the subjects. The findings reported by the NJDOH suggested "the trend for increasing risk with increasing radon exposure was statistically significant". Consequently, "the study suggests that the findings of radon-related lung cancer in miners can be applied to the residential setting. Excess radon exposures typical of homes may increase risk of lung cancer; extremely high residential exposures would be associated with very serious lung cancer risks." The NJDOH reported that the study findings supported the State's initiatives for technical information and services, citizen education, and research studies, and that smoking avoidance education for the public should also be included and emphasized in any radon reduction program.

The NJDOH was also charged with establishing and operating a Voluntary Radon Exposure Registry. Residents who were found to have high indoor radon levels which they had been exposed to for some time, could be listed on the registry. They are to receive follow-up information about hazard reduction, risk, and medical treatments. The registry is also a source for background information about exposures and exposure areas.

Current Program Activities

Two major programs are currently underway which should improve radon protection efforts in New Jersey. The first is the legislatively required certification program for testers and mitigators. The second is the federal State Indoor Radon Grant program.

The New Jersey Legislature enacted a law requiring that the NJDEP develop a mandatory certification program for all radon testers and mitigators who want to operate in the State. Initially, the NJDEP established a voluntary program in which testers and mitigators voluntarily submitted proof to the NJDEP that they met certain requirements. These companies were included on an "Interim Voluntary Certification" list. These companies have been the major source of information about home testing done in the State. To date they have supplied data for more than 140,000 tests conducted statewide.

Final regulations have been adopted, and as of May 13, 1991, no tester or mitigator may continue to operate in New Jersey, if he or she has not applied for and met the State's certification requirements. The certification process begins with a tester or mitigator taking a training course that is given by the NJDEP or that is NJDEP-approved. Then the applicant must take an examination. There are four exams, each given for a particular title, and they are Radon Measurement Specialist, Radon Measurement Technician, Radon Mitigation Specialist, and Radon Mitigation Technician. Finally, there is an application form on which the applicant reports his or her qualifications and experience, and this form must be submitted to and reviewed by Radon Program staff. Applicants may choose to submit their certification forms for review prior to taking the examination.

However, it is not sufficient to simply await data that is supplied by testers and mitigators. There remain large portions of the homeowning population who know about radon and its associated risk but still do not test. And there is also a large population group that may be unaware of radon problems although they might very well be at risk. With funds from the United States Environmental Protection Agency's State Indoor Radon Grant program, the NJDEP is working to increase awareness and educate the public about radon issues.

One project is the development of school activities to teach children about radon and also about the concept of risk, using radon as an example. The intent is that these children will grow up being more aware of potential hazards in life and how to make rational risk based decisions regarding them. It is also hoped that the children will carry the message home to their parents. Somehow, adults find it hard to ignore information that is presented to them by a child who has just learned a new and interesting lesson in school. Especially, when that lesson has direct bearing on all their lives.

Another project that received funding is training local health officials to evaluate elevated radon areas. This creates a valuable working resource, lessening the burden on Radon Program staff in conducting labor intensive radon evaluation studies. Evaluations of elevated radon areas are needed when a home test result is at or above 200 pCi/l because it has been found in a number of communities that as many as three quarters of the surrounding homes will have readings exceeding 4pCi/l. A protocol was developed for State employees to conduct area evaluations and recently, with grant funding, local health officers are being trained in the protocol. It consists of confirmatory testing, public meetings to explain the situation and plan of action, selection of candidate homes for radon testing based on geologic data, house structure and a gamma survey, radon canister placement and pickup by evaluating staff, and a public report of findings and recommendations. In the first year of the project, 28 local health officers were trained and others have expressed interest.

Contacting and communicating with low income residents and residents of metropolitan areas (urban environments) about radon presents a unique challenge. Currently, two grant projects are being funded to identify and assess the radon exposure, testing, and remediation needs of low income and disabled persons, and also urban populations especially focusing on multifamily dwellings. Many of the standard means for informing and educating the public are not applicable to these population groups. Additionally, questions such as testing and remediation expenses and building owner responsibility and liability must be dealt with.

A fifth grant project is to survey real estate transactions in New Jersey. This project has four objectives: 1) to assess the current radon knowledge and information needs of buyers, realtors, bankers, and real estate attorneys; 2) to assess the assistance and notification that current home buyers are receiving about radon; 3) to develop additional information pieces for all of these groups; and 4) to develop guidelines and policies on radon testing and real estate transactions.

Since the New Jersey Radon Program began work in the spring of 1985, the direction of the program has been identifying the extent of the radon problem in the State, educating the public about radon, and assuring that the latest and most effective means for control and mitigation are available. The NJDEP believes that residential exposure to radon is the most serious environmental health threat facing New Jersey citizens today. The NJDEP has taken steps to make each State resident aware of the hazards of radon exposure by providing information about potential radon occurrence in local areas via the Tier map, advertising the toll-free Radon hotline number, and preparing and distributing informational materials.

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

# Session VIII

# Oral Presentations

# Radon Prevention in New Construction

# A COMPARISON OF INDOOR RADON CONCENTRATIONS BETWEEN PRECONSTRUCTION AND POST-CONSTRUCTION MITIGATED SINGLE FAMILY DWELLINGS

**James F. Burkhart, Physics Department,**
**University of Colorado at Colorado Springs**
**Colorado Springs, CO 80933**

**Douglas L. Kladder, Residential Service**
**Network, Inc.,**
**525 E. Fountain**
**Colorado Springs, CO 80903**

ABSTRACT

We have done a detailed study comparing indoor radon concentrations among single family dwellings in Colorado Springs that were mitigated prior to the completion of construction and similar buildings that were mitigated after construction. There appears to be evidence which indicates that "preconstruction" mitigation is more effective at lowering indoor radon concentrations than "post-construction" mitigation.

A total of 102 owners of single family dwellings, in two different areas within the city, agreed to participate in the study. Thirty-nine homes formed the preconstruction mitigation category (with 14 of these homes having only passive systems), 24 had been mitigated after construction and the final 39, chosen as a control group, had never been mitigated but shared similar soil and surficial geological features with the mitigated homes (including distance to nearby faults). Eighty nine homeowners successfully completed the test. All of theses houses were tested over the same 48-hour period, under closed-house conditions, thereby controlling the variables of weather and, to some extent, occupants' usage.

By analyzing the data obtained, we can conclude that there is a statistically significant difference in post-mitigation indoor radon concentrations (as measured by simultaneous charcoal screening tests) between the preconstruction and the post-construction mitigated homes. The preconstruction category exhibited the lower radon average, although both mitigation categories had averages below 4.0 pCi/L. Such a conclusion could have an impact on current mitigation practices, especially as they pertain to new housing construction.

Esthetics, installation costs and operating costs of the two mitigation techniques (pre and post-construction) are also discussed herein.

## INTRODUCTION

The purpose of this study is to assess the relative effectiveness of radon reduction methods in residential structures when they are utilized after the home is constructed as opposed to when the home is mitigated prior to the completion of construction. It is hoped that the results discussed herein will provide information for the building industry and those agencies which assist it in developing approaches to mitigating new and existing homes.

This study was conceived by the authors when it was noted that data collected from post-mitigation testing over the last three years were giving the indication that post-construction mitigation provided similar results to mitigations performed prior to the completion of construction. However, such a conclusion was difficult to make due to varying environmental conditions which affected test results. Consequently, this study was designed to remove many of the typical testing variables by testing all subject homes simultaneously and on the same floor. As will be seen later, the hypothesis that active mitigation, whether performed during or after construction, had essentially the same results proved to be <u>incorrect</u> based upon the total data obtained.

The study was conducted concurrently within two different areas of Colorado Springs, Colorado, which we refer to as Area 1 and Area 2. The two study areas offer a unique opportunity for comparison since they are both infill subdivisions where a significant number of homes have no radon mitigation system at all (Category 1). These unmitigated homes serve as a basis for reference as to what a mitigated home might have been if no radon reduction techniques had been used. Furthermore, these same areas had a relatively large number of homes that had been mitigated with active systems (i.e.; operating fans installed) after construction (Category 2) and prior to the completion of construction (Category 3). A fourth category was necessary to distinguish between these homes mitigated during construction using active systems and homes using only caulking, membranes or sub-slab ventilation without fans. In this region, these latter homes are called "radon ready" by the authors. We designated these radon ready houses as category 4.

Homeowner participation was voluntary and solicited on a neighborhood-wide basis through the two appropriate homeowner's associations, therefore no preselection of mitigation techniques occurred. However, subsequent interviews with participants indicated that all mitigated homes with active systems (Categories 2 and 3) employed sub-slab or sub-membrane depressurization techniques as the primary mitigation method. No attempt has been made to determine relative ventilation rates within test homes.

Homes in Area 1 were all within a half mile radius while homes in Area 2 were within a one-quarter mile radius. The homes in both areas were custom homes, ranging in size from 3,000 to 4,000 square feet of livable area. Most homes had finished walk-out basements.

The number of homes initially participating in this study fell into the four categories as noted in Table 1 below. The numbers in the brackets, on this same chart, show the number of participants who conducted the charcoal canister test correctly and who were subsequently used as our data base.

TABLE 1. NUMBER OF HOMES PARTICIPATING IN THE STUDY

| Category | Area 1 | Area 2 | Total |
|---|---|---|---|
| 1 Homes never mitigated | 26 (22) | 13 (13) | 39 (35) |
| 2 Homes mitigated after construction | 12 (12) | 12 (11) | 24 (23) |
| 3 Homes mitigated during construction | 19 (15) | 6 ( 4) | 25 (19) |
| 4 Homes made "radon-ready" for future mitigation | 10 ( 8) | 4 ( 4) | 14 (12) |

## GEOLOGY OF THE TEST AREAS

A previous study (1) had already shown correlations between certain characteristics of the soils and geology of these two areas and the indoor radon concentrations as measured by screening tests. Specifically, elevated radon concentrations are predicted for these two areas because of low shrink-swell potential (indicating very little clays) and relatively high permeability of the soil as determined from the Soil Conservation Service County Soil Surveys (2). The surficial geology of both areas is made up of rock derived from the Pikes Peak batholith (3) which is known to contain 5.0 ppm of uranium (4). Finally, Area 2 is known to be relatively close to a major fault system. This fact is believed to contribute to enhanced radon transport.

A more precise breakdown of the above characteristics for each of the two areas is as follows:

Area 1 soil has a low shrink-swell potential with a permeability of 2 to 6 inches of water per hour. The surficial geology is a Dawson Arkose with some Verdos alluvium (both dervived from the Pikes Peak granite). The average distance of these homes to a major fault is 2.8 km.

Area 2 soil has a low shrink-swell potential, also, with a permeability of 6 to 20 inches of water per hour. The surficial geology is Rocky Flats alluvium (which is also derived from the Pikes Peak granite). The average distance of these houses from a major fault is .75 km.

Ignoring house construction details completely, the above characteristics would lead one to predict elevated radon in homes in both areas and the higher permeability and closer distance to a fault in Area 2 would suggest even higher radon levels in those homes. These predictions will be seen to be verified when the actual measurements are discussed in the Statistics section, below.

## TESTING METHODOLOGY

Radon Measurements Laboratory, housed at the University of Colorado-Colorado Springs, is a primary lab for the evaluation of radon concentrations using the 48 hour, four-inch, open faced charcoal canister. These canisters are of typical design with approximately 70 grams of 8 X 16 mesh Calgon charcoal encased in a four-inch diameter canister, one-and-five-sixteenths inches high, covered with a 30-50 % open-mesh retainer screen. The laboratory has analyzed over 8,000 canisters over the last three years.

Canisters are read using a three inch by three inch NaI(Tl) crystal housed within a commercial lead shield. A 1,024 channel MCA is used to look at the three most intense lead-214 and one bismuth-214 photopeak lying between 220 and 692 KeV. The minimum detectable activity (MDA) at the 3 $\sigma$ level was calculated to be 0.13 pCi/l for canisters measured 3 hours after closing and slightly higher for the balance of the canisters.

The usual quality assurance procedures were in place during this testing period with 100 % of the blanks being identified and duplicates above 4.0 pCi/l all within the 10 % precision expected. The 2 $\sigma$ error was 0.17 pCi/l at 1.0 pCi/l and 0.4 pCi/l at 30 pCi/l. This low error was maintained by measuring all the canisters (after equilibrating) the same day the test concluded.

The canisters were delivered to the participants by the authors along with a detailed instruction sheet. The instruction sheet augmented prior phone conversations and further oral instructions at the time the canisters were delivered. The tests were all to begin on the morning of December 17th and conclude on the morning of December 19th, 1990. The canisters were placed in an open area in the basement (in most cases, the family room), 30 inches off of the floor in the center of the room. The canisters were sealed by the homeowner and placed outside for pick-up by the authors. Non-compliance with the instructions, or failure to perform the test, led to 13 of the original 102 participants being dropped from the subsequent data base. This gave us an 87 % compliance with the fairly stringent test requirements.

## THE WEATHER DURING THE TESTING PERIOD

Since all of the homes were tested during the same time period and the distance between the two test areas is only a few kilometers, the weather was identical for all houses. It is probably safe to assume, therefore, that pressure differentials brought on by outside temperatures, wind, surface conditions (i.e.; frozen soils) and atmospheric disturbances were also similar.

Nonetheless, it is instructive to review the climatological data for that 48 hour period because the weather conditions were clearly such as to promote an honest screening test by discouraging surreptitious ventilation. Table 2 below shows the weather data from the morning of December 17th through the morning of December 19th. Not shown on this table is the fact that the winds were gusty for a short time on the morning of the 18th, with a peak gust of 48 mph from the northwest.

TABLE 2. CLIMATALOGICAL DATA FOR THE TEST PERIOD

| Date | temp (high and low) | | pressure | winds | precipitation |
|---|---|---|---|---|---|
| Dec 17 | 30°F | 17°F | 29.78 ↓ | 8.2mph | light snow |
| Dec 18 | 49°F | 17°F | 29.62 → | 10.8mph | none |
| Dec 19 | 27°F | 21°F | 29.60 → | 8.0mph | light snow |

## STATISTICS

This section is in two parts. First, the raw data will be presented in histogram form for each area separately and then both areas combined. Second, the results of the t-tests (testing the means of two populations to see if the populations are the same or different) will be given after each histogram.

### RAW DATA IN HISTOGRAM FORM

Figure 1 below compares the indoor radon concentrations as measured during the testing period in Area 1 with the number of houses having a particular radon concentration. The black bars refer to those houses which were never mitigated (Category 1) and the bars with hash marks within them refer to houses which have passive systems only (Category 4), the so-called "radon ready" homes.

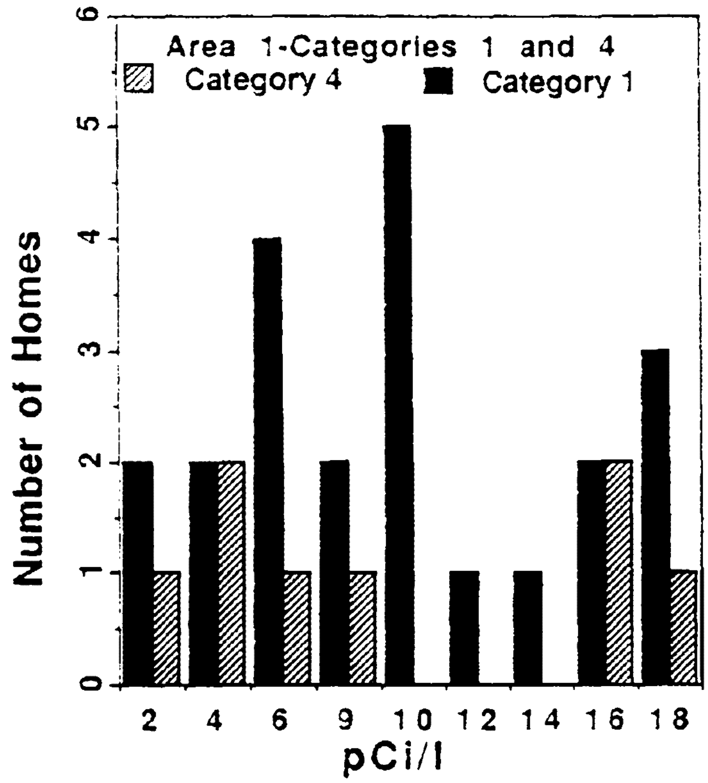


Figure 1. Radon in homes in Area 1, Categories 1 and 4

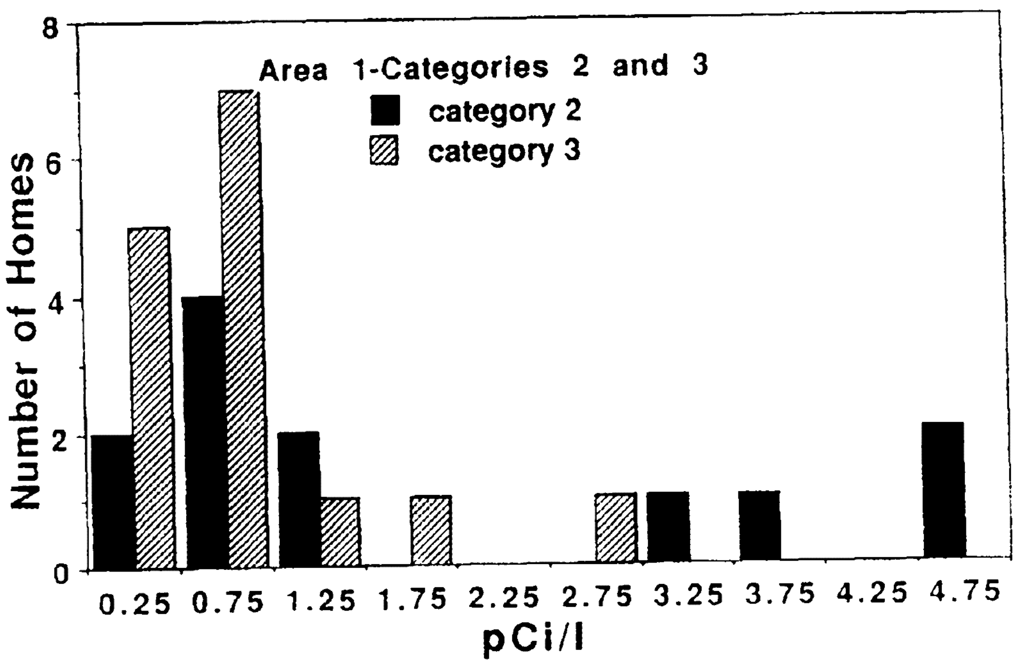


Figure 2. Radon in homes in Area 1, Categories 2 and 3

Figure 2 above makes the same comparison between number of houses and radon concentrations in Area 1 only using houses mitigated after construction (Category 2) and houses mitigated during construction (Category 3).

Comparing Category 1 and Category 4, in Area 1, and using the null hypothesis that the two categories represented the same population, a t-test was performed. The t-test, with a t value of .017, tells us that the two categories are indistinguishable. It would appear that "radon ready" houses have the same radon as unmitigated houses. The statistics are given in Table 3.

Comparing Category 2 and Category 3, in Area 1, and using the null hypothesis that the two categories represented the same population, a single tailed t-test, with a t value of 2.416 indicates that the two populations are indeed different at the 95% confidence level with the houses mitigated during construction (category 3) having the lower radon mean. The statistics are summarized in Table 3

Figure 3 below compares the indoor radon concentrations as measured during the testing period in Area 2 with the number of houses having a particular radon concentration. The black bars refer to those houses which were never mitigated (Category 1) while the bars with hash marks within them refer to houses which have passive systems only (Category 4).

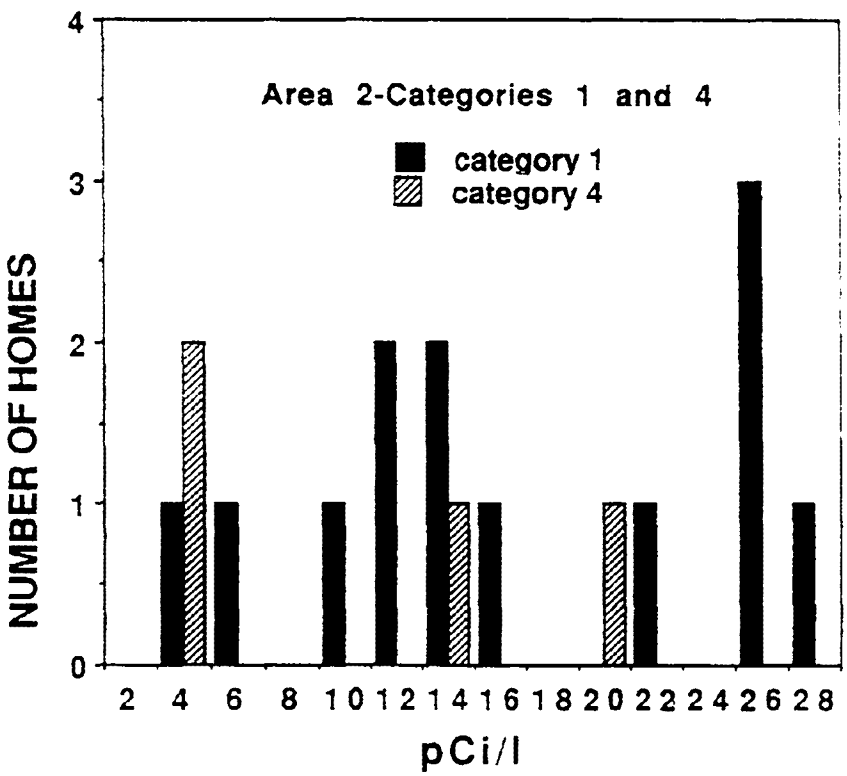


Figure 3. Radon in homes in Area 2, Categories 1 and 4

Figure 4 compares the indoor radon concentrations in Area 2 with the number of homes at a particular radon concentration. Here, the black bars refer to homes mitigated after construction (Category 2) while the hash mark bars refer to homes mitigated during construction (category 3).

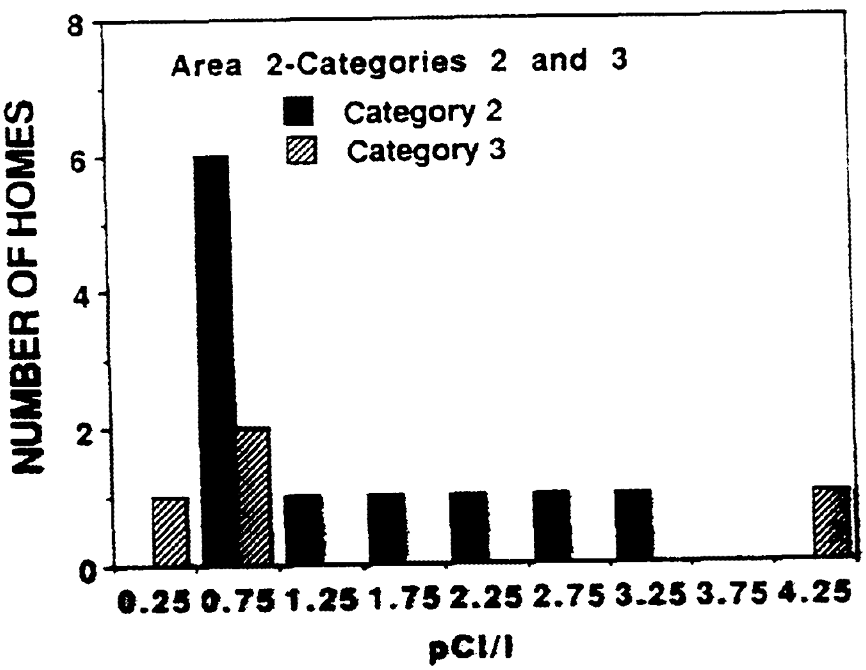


Figure 4. Radon in homes in Area 2, Categories 2 and 3

Comparing Category 1 and Category 4, in Area 2, and using the null hypothesis that the two categories represented the same population, a one-tail t-distribution, with a t value of 1.304, seems to confirm the null hypothesis. That is, as in Area 1, "radon ready" homes have the same average radon as do unmitigated homes. The statistics are shown later in Table 4.

Comparing Category 2 and Category 3, in Area 2, and using the null hypothesis that the two categories represented the same population, a one-tail t-test, with a t value of .091, seems to confirm the null hypothesis. That is, homes mitigated during construction have the same average radon as do homes mitigated after construction. It should be mentioned that the small number of homes (only 4) in category 3 make this conclusion far from certain, although statistically justified. The statistics are shown later in Table 4.

Finally, the data from the two areas is combined, thereby making any conclusions more general and, because of the larger numbers involved, more convincing. We begin by showing a histogram of the combined data, Categories 1 and 4 in figure 5.

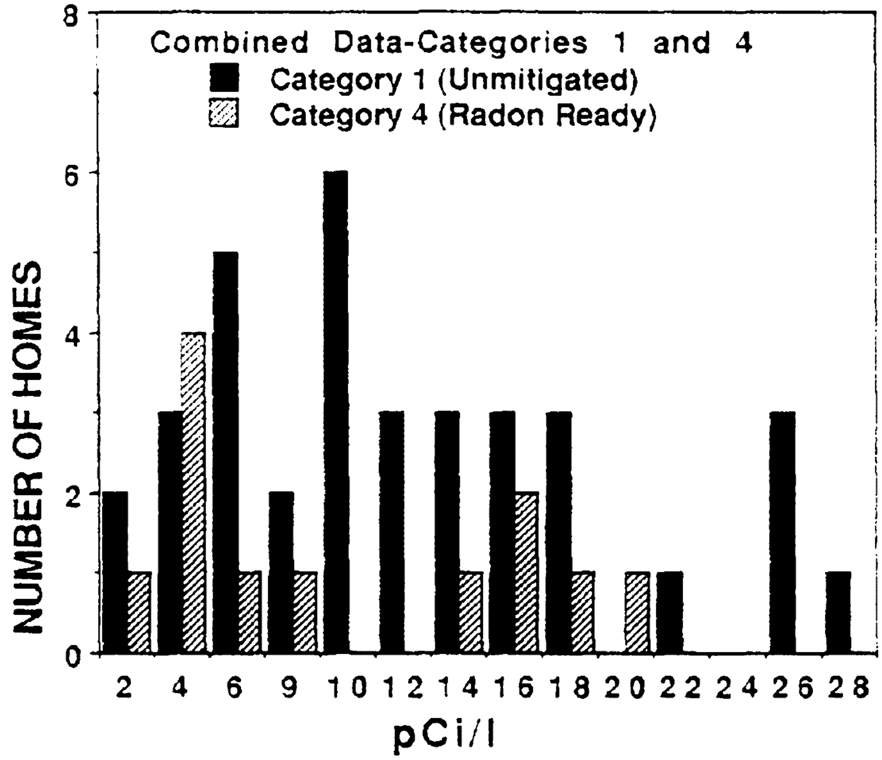


Figure 5. Radon in all the homes combined, Categories 1 and 4

When we combine all the data from both areas, we can also compare radon levels in homes which were mitigated during construction (Category 3) and homes mitigated after construction (Category 2). This comparison is given below in figure 6.

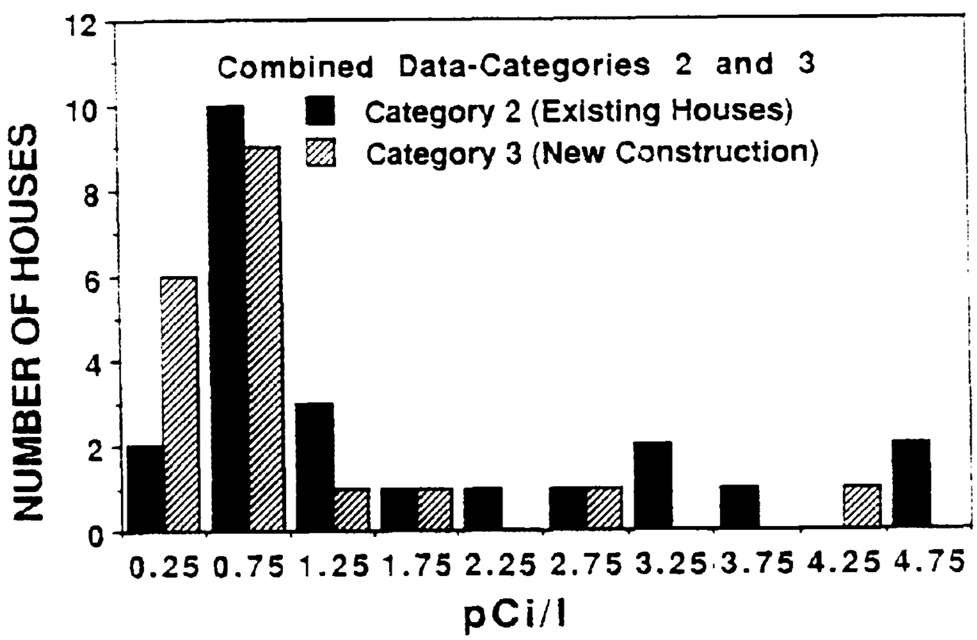


Figure 6. Radon in all the homes combined, Categories 2 and 3

Comparing unmitigated homes (Category 1) with "radon ready" homes (Category 4) in the combined data, and using the null hypothesis that the two categories really represent the same population, a single tailed t-test with a t value of .987 seems to confirm the null hypothesis. At this point, it seems safe to say that "radon ready" homes are no better at reducing radon concentrations than are unmitigated homes. The statistics are shown in Table 5.

A last comparison is now made. This is comparing houses mitigated during construction (Category 3) with houses mitigated after construction (Category 2) with all data combined. Again, the null hypothesis is that the two categories will represent populations with similar averages and standard deviations, i.e.; that it makes no difference in indoor radon levels if a house is mitigated during or after construction. This time, it is probably safe to reject the null hypothesis because a single tailed t-test indicates that the two are separate populations at the 98% confidence level, with a t value of 2.059. The statistics are shown in Table 5.

To show the effectiveness of the radon prevention measures in the three mitigation categories, a final histogram is presented. Figure 7 compares the average of each of the categories when all of the data is combined.

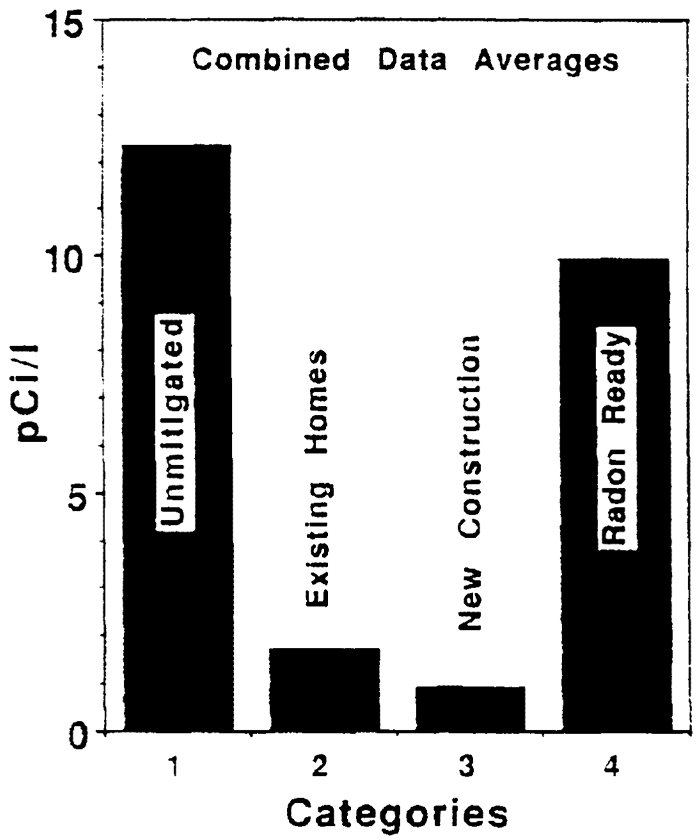


Figure 7. Average radon in all homes combined, broken down by category

## DATA REVIEW

After receiving the questionnaires and the exposed canisters, the authors found several conflicting comments regarding descriptions of the type of system installed. Consequently, a combination of participant interviews, site visits and construction files were reviewed to verify which category each house really belonged within. All mitigated houses were reviewed in this manner which yielded some additional insights for this study:

1) Several new home owners were under the impression that adequate systems had been installed in their homes by the builders. Some of these systems turned out to be only barrier techniques (sealing or sub-concrete polyethylene). Perhaps more notable were homes that had sub-slab perforate piping systems that were stubbed up in the basement (most were sealed and one was open into the home). As an interesting note, this survey was the first time some of the homes were tested after occupation. For the purpose of the study, these homes were moved into Category 4 with Category 3 retaining only active sub-structure depressurization systems.

2) Two homes had utilized a sub-concrete mesh system where all of the rest of the survey utilized foundation drains or a combination of foundation drain and interior piping approaches for negative field propagation. These two homes were more than twice the mean of the other existing homes. Inspection of these homes indicated that the problem was not necessarily with the membrane, but rather with the installation. Fans were installed inside with extensive positive side piping. Non-standard fittings were utilized, which discharged beneath windows and near dryer vent openings. As the purpose of the study was to distinguish between during- and post-construction techniques as they are actually being installed, these two houses were maintained in the Area 2 data pool. The balance of the mitigated properties were carried out by the same RCPP listed contractor. Although it is not the purpose of this paper to distinguish between installers, it reinforces the need for proper training of those involved in radon mitigation.

3) Some homes which had active mitigation systems installed, after construction, had inoperable fans. These homes were moved to Category 4 since the authors felt that they represented a passively vented system as in a "radon ready" approach. At this time, no attempt has been made to distinguish between barrier versus passive systems. As an interesting side light, one homeowner insisted that her system was operating because it was not unplugged. She was only convinced when she inspected the fan. This system was installed three years ago before the present EPA mitigation guidelines requiring certain operating indicators for the homeowners were developed (5).

## RESULTS OF THE STUDY

What follows is a discussion of each area separately, culminating in a discussion of both areas combined. However, it should be kept in mind that because of the smaller data base of Area 2, conclusions based upon this smaller data base may prove to be less convincing.

## RESULTS FROM AREA 1

A comparison of the mean radon levels listed in Table 3 clearly indicates that mitigation during or after construction had beneficial effects. In fact, the means of both Categories 2 and 3 were well below the current EPA guideline of 4.0 pCi/L. As these were screening measurements taken at the lowest living area, current approaches would recommend no further action by the homeowner (6).

TABLE 3. RADON LEVEL MEANS AND STANDARD DEVIATIONS FROM AREA 1

| Category | Description | Number | Mean | Standard Deviation |
|---|---|---|---|---|
| 1 | Unmitigated | 22 | 9.8 | 5.26 |
| 2 | Post-construction mitigation | 12 | 1.94 | 1.72 |
| 3 | During construction mitigation | 15 | 0.78 | 0.64 |
| 4 | Radon ready | 8 | 9.77 | 6.63 |

Homes that were mitigated during construction with active sub-slab systems (Category 3) outperformed those active systems that were installed after construction (Category 2). This conclusion is based on a one-tail t-distribution at the 95% confidence level.

Homes that were built with radon ready systems or had passively vented systems showed statistically no benefit over homes that had no mitigation work done.

## RESULTS FROM AREA 2

As was seen in Area 1 using unmitigated houses as reference (Category 1), mitigation which occurred during or after construction showed significant beneficial reductions. Additionally, both the mean of Categories 2 and 3 were well below the current screen action level of 4.0 pCi/L (Table 4).

TABLE 4. RADON LEVEL MEANS AND STANDARD DEVIATIONS FROM AREA 2

| Category | Description | Number | Mean | Standard Deviation |
|---|---|---|---|---|
| 1 | Unmitigated | 13 | 16.57 | ± 8.39 |
| 2 | Post-construction mitigation | 11 | 1.43 | 0.86 |
| 3 | During construction mitigation | 4 | 1.49 | 1.74 |
| 4 | Radon ready | 4 | 10.27 | 8.71 |

Homes that were mitigated during construction with active systems (Category 3) did not show a statistical difference from those homes that were mitigated after construction (Category 2). This result is certainly different from that obtained in Area 1. This may be due to the smaller sample volume and the effect of the non-mitigation guideline homes. One might also speculate that the higher soil porosity in Area 2 allows equal propagation of a sub-slab negative pressure field regardless of the use of a perimeter drain system (Category 2) or a perimeter drain system plus a sub-slab pipe network (Category 3).

Although the mean of radon ready homes (Category 4) in Area 2 was lower than non-mitigated homes (Category 1), no statistical difference can be demonstrated. Therefore, the conclusion for Area 2 is the same as for Area 1 in that no reduction benefit was seen on radon ready installations.

RESULTS FROM BOTH AREAS COMBINED

In order to better answer the question that served as the hypothesis for this paper, both data sets were combined. This approach can be justified due to similarity of home construction, unmitigated levels and soil type. The only difference noted, however, was slightly different soil porosity. The comments made above regarding unmitigated homes (Category 1) with respect to mitigated homes (Categories 2, 3 and 4) remain the same when the data is combined. That is, any active mitigation system is beneficial and no benefit was derived from radon ready homes (See Table 5 below).

TABLE 5. RADON LEVEL MEANS AND STANDARD DEVIATIONS FROM BOTH AREAS

| Category | Description | Number | Mean | Standard Deviation |
|---|---|---|---|---|
| 1 | Unmitigated | 35 | 12.32 | ± 7.28 |
| 2 | Post-construction mitigation | 23 | 1.70 | 1.37 |
| 3 | During construction mitigation | 19 | 0.93 | 0.96 |
| 4 | Radon ready | 12 | 9.94 | 6.98 |

When all data is combined, including the anomalies mentioned earlier, one can determine statistically that systems installed during construction (Category 3) outperformed systems installed after construction (Category 2). Categories 2 and 3 are two distinctly different populations as verified by the one-tail t-test at the 98% confidence level.

## IMPLICATIONS OF RESULTS

It is interesting to note that the existing homes that were mitigated after construction (Category 2) had a mean screening result of 1.70 pCi/L ± 1.40. Although this is at a level below the current EPA action level of 4.0 pCi/L, it is right at contemplated values for the new proposed guideline of 2.0 pCi/L. (Ref 7). Although it is reasonable to assume upper floors of these homes would be at lower concentrations of radon, it should be noted that due to terrain and architectural plans, many of these lower level floors contain family rooms and bedrooms. The adoption of 2.0 pCi/L guideline for living areas may be difficult to consistently achieve with mitigation techniques observed in this study.

Similarly, the homes that had active mitigation system installed during construction exhibited a mean result of 0.93 pCi/L ± 0.96. Within one standard deviation all of these Category 3 homes would exhibit screening levels beneath both the existing guideline of 4.0 pCi/L and the proposed guideline of 2.0 pCi/L.

The overall mean of new homes constructed with active systems (Category 3, mean 0.93) would lend partial credence to the (Option 1) prescriptive approach proposed in the draft model standards for new buildings. (Ref 8). However, the approach of not requiring, or not emphasizing post-occupancy testing may result in not identifying improper installations, as this study did. This may, on the other hand, speak to proper education of installers and the extension of the RCPP program to home builders as well as specialty radon mitigation sub-constractors.

The inability to distinguish between "radon ready" systems (Category 4) and non-mitigated homes reinforces the need for testing within 30 days of occupancy for a non-activated radon ready home. This is referred to as Option 2 of the Draft Model Standards for New Buildings. Furthermore, the results of Category 3 indicate the ability to reduce levels to below 2.0 pCi/L once the radon ready system is made active by addition of a fan. It would be prudent to emphasize testing after actuation of the system fan for the same reasons as indicated above.

Homeowners' understanding of proper system operation was inadequate in some cases. Interviews with participants indicated little information was passed on from previous homeowners or building contractors. This comment is more pertinent with respect to homes which were constructed with radon ready systems. In this case, some homeowners felt that a complete system had been installed. This can be dealt with either in a regulatory manner or perhaps a greater emphasis can be placed on the present Radon Contractor's Proficiency Program and particularly the Mitigation Guidelines (5).

The data made available from this study will, with further evaluation, offer opportunities to assess differences between finer points of mitigation installations. A more detailed review of homes in Categories 2 and 3 that fell outside the standard deviation of the mean can be made to assess these installation differences. A comparison of individual results to soil porosity and soil gas measurements can also be made in order to assist in developing a predictive model, at least for this geological area.

Furthermore, a more detailed review of Category 4 homes needs to be made to determine which radon ready approaches may offer the most cost effective benefit.

**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 REDUCTION IN NEW CONSTRUCTION: DOUBLE-BARRIER APPROACH

C. Kunz
Wadsworth Center for Laboratories and Research
New York State Department of Health
Albany, New York 12201-0509

## ABSTRACT

A double-barrier design with the space between the barriers having little resistance to gas flow is described for those parts of homes and buildings that interface with the soil or surficial rock to reduce soil-gas (radon) entry into structures. The outside or soil-side barrier interfaces with the soil. A barrier placed on the soil under the subslab aggregate is an important element in this design. This forms the outer barrier for the floor. The subslab aggregate forms a permeable layer, while a plastic membrane above the aggregate, the slab, and caulking form the inner barrier. If hollow block are used, barrier coatings can be placed on both the soil side and interior wall of the blocks, while the hollow space in the blocks forms the permeable space. The hollow-block walls are connected to the subslab aggregate to form a small interconnected permeable volume that can be managed in the following ways to reduce soil-gas entry into the structure.

1. Sealed.
2. Passively vented to outdoor air.
3. Passively depressurized using an internal stack.
4. Actively depressurized.
5. Actively pressurized.

In addition to basements with hollow-block walls, the double-barrier technique can be adapted to solid wall, crawl space and slab-on-grade construction including various combinations.

## INTRODUCTION

In the long term, substantial reduction in radon exposure can result from improved new home and building construction techniques that reduce radon entry. In addressing this approach to reducing radon exposure, the EPA has published a report "Radon-Resistant Residential New Construction" (1) in which construction techniques to minimize radon entry in new structures and to facilitate its removal after construction are described. This report is the first edition of technical guidance for constructing radon-resistant structures to be issued by the EPA, and they anticipate future editions as additional experience and approaches become available. The EPA report includes a section on barriers to reduce radon entry including wall coatings, sub-slab membranes, caulking, sealing and prevention of slab cracking. Another section discusses designs for post-construction active or passive sub-slab ventilation. A primary element in these designs is a minimum of 4 in. of aggregate under the slab. The preferred material is crushed aggregate with a minimum of 80% of the aggregate at least 3/4 in. in diameter. This highly permeable bed under the slab is necessary for good communication in the event that sub-slab ventilation is needed. The aggregate is placed directly on the soil and represents a large permeable volume into which radon can diffuse or flow from the soil and rock under and around the foundation. The radon that accumulates in the permeable aggregate can then flow with little resistance to any penetrations in the barriers above the aggregate. These barriers include the membrane placed over the aggregate, the slab and any caulking and sealing of the wall floor joint, cracks and penetrations. Having a permeable volume between the soil and the barriers reduces the effectiveness of the barriers. Barriers are most effective when interfacing with the soil. A similar situation occurs when hollow blocks are used to construct the foundation walls. Radon that infiltrates through the outer wall and into the hollow cavity of the block walls can then flow with little resistance to any penetrations of the inside wall barriers. Again, barriers to radon entry are most effective on the outside or soil-side of the wall.

An indication that aggregate under the slab increases radon entry into structures was obtained in a survey of over 6,000 homes in New Jersey (2). The data collected in this study show a definite relationship between age and radon concentration. On average, houses built since World War II tend to have higher indoor radon concentrations than houses built between 1900 and about 1945. Initially, it was suspected that newer houses had higher indoor radon concentrations because newer houses tend to be tighter and have lower air exchange rates. However, closer examination of the data indicated that the differences in radon concentrations associated with tightness did not fully account for the decline in radon concentration with increasing age in 20th-century houses. The authors speculated that the use of sub-slab aggregate, which increased in the post-World War II era, could also contribute to the higher indoor radon observed in newer homes.

It is difficult to determine the effectiveness of the barriers to radon entry suggested by the EPA, when used in the passive mode, since it is not possible to know what the indoor radon concentrations would be for a house if the radon-resistant techniques were not employed. The initial results, however, have led the EPA to conclude "that in the presence of a moderate-to-high radon source, radon prevention techniques that are passive only may not produce indoor radon levels consistently below 4 pCi/l." In a study of 15 full-basement homes in New York State which were built employing radon-resistant techniques in an area with above-average levels of indoor radon, most of the homes required active sub-slab ventilation systems (3). The results from the New Jersey survey and the initial results of the homes built with radon-resistant construction indicate that sub-slab aggregate interfacing directly with the soil or rock under a home can increase radon entry into the home and decrease the effectiveness of barriers placed above the aggregate.

## DOUBLE-BARRIER CONSTRUCTION

It is the purpose of this paper to suggest a design for new home construction that is more effective in reducing radon entry in the passive mode but one that can be readily adapted to active mitigation systems if needed. The design proposes to reduce soil-gas entry by using double-barrier construction for the sub-grade structure of homes and buildings. A primary element in this approach is to have a radon barrier under the subslab aggregate at the soil interface.

The double-barrier approach is illustrated in Figure 1 for a basement with block walls and a sump. The hollow space in the block walls is connected to the subslab aggregate via weeping holes or some other low resistance pathway for air flow, to form an interconnected permeable space that surrounds the entire subgrade structure. Barriers to radon transport such as membranes, coatings, caulking, sealing, etc., are placed on both the soil side and inside of the permeable space. Since radon barriers are most effective at the soil interface, most of the barrier effort should be concentrated on the sub-aggregate and outside wall barriers. The barrier below the aggregate may be a composite of materials such as cement, tar, plastic film, fine sand, and clay. Barriers at the soil interface should be resistant to both diffusive and convective flow. A special effort should be made to seal the outside wall barrier at the wall-footing joint and the barrier below the aggregate at the footing-aggregate and aggregate-sump joints.

The double-barrier subgrade construction creates a reasonably small volume between the inside and outside barriers that can be managed in several ways to reduce radon entry. Without a barrier below the aggregate, the soil and rock under and around the house will be directly connected to any mitigation system used to reduce radon entry. The double-barrier approach works toward decoupling this direct connection. For the double-barrier system shown in Figure 1, passively venting the hollow-block walls to outdoor air will allow outdoor air to flow with little resistance into the permeable space. As gas from the permeable space is drawn through any penetrations in the interior or upper barriers into the basement by indoor-outdoor pressure differentials, outdoor air can flow into the permeable space with little resistance. The outside air flow reduces the draw on soil-gas at any penetration in the outer or below barriers and thereby reduces the flow of soil-gas radon into the permeable space. Alternatively, the permeable space could be treated by depressurization (passive or active) or pressurization (active). For these approaches it would be best to not vent the block walls to outside air. Radon entry reduction can then be accomplished by creating either a reduced pressure or increased pressure in the permeable space. Having created a reasonably small interconnected permeable space with sealing

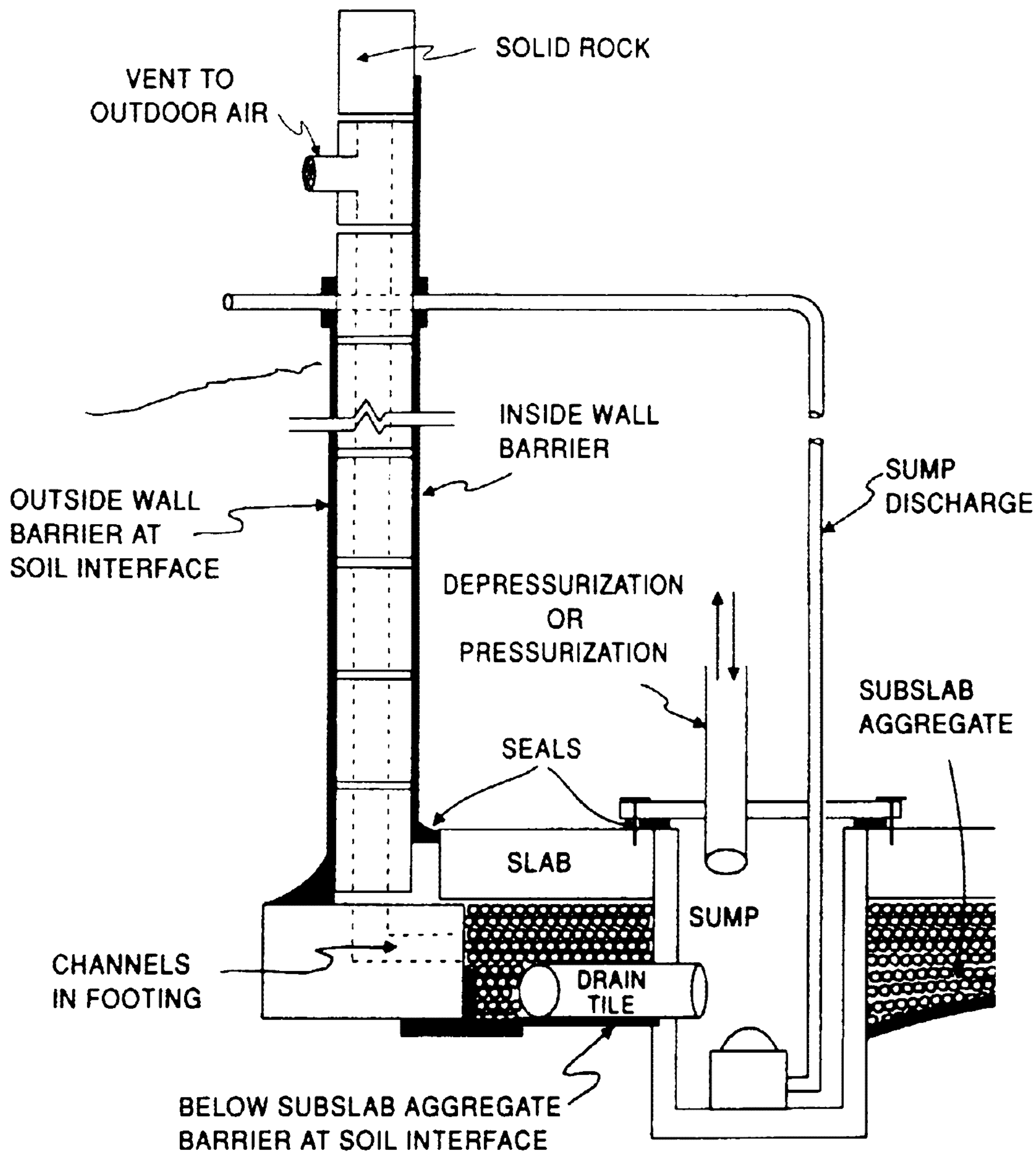


Figure 1. Double-barrier construction for a basement with sump.

on both the soil side and inside, it is expected that, if passive venting (using a stack through the house interior), active suction, or positive pressure flow is necessary to reduce indoor radon to acceptable concentrations, then relatively low flow rates would be successful.

An example for an active pressurization system would be to draw air from ceiling vents in the highest level of the house and blow this air into the permeable space between the double barriers (Figure 2). The fan could be located in the basement and relatively low flow rates (~20 cfm) should suffice. In this manner, heated air from the highest interior level of the house would be used to pressurize the double-barrier system heating the floor and walls of the basement while reducing heat loss via exfiltration from the higher levels of the house.

It is of primary importance to ensure that water effectively drains from the permeable substructure space between the double barriers. This can be accomplished with a sump as shown in Figure 1. It may be necessary to grade the soil forming the base of the subslab aggregate toward the drain tiles and the sump to aid in preventing the accumulation of water in the subslab aggregate. If it is possible to drain the subslab aggregate to grade or to a sewer, then this drainage option could be used instead of or with a sump. Solid pipe should be used and it should be sealed at the outside or soil-side barrier.

Exterior footing drainage of gravel and/or perforated piping is used by many builders and presents a problem to the double-barrier design approach. The gravel and/or perforated piping of the exterior drainage system runs around the outside perimeter of the wall-footing joint. It represents a permeable volume in which radon can accumulate and flow to any penetrations in the wall and wall-footing joint. To minimize radon entry, the exterior drainage system should be drained to daylight or to a sewer and not connected to the subslab aggregate and sump via weeping holes or other methods. Connecting the exterior drainage system to the subslab aggregate would provide a pathway for soil-gas radon to enter the permeable zone of the double-barrier system. Exterior perimeter drainage systems increase the need for careful sealing at the exterior wall-footing joint.

The double-barrier approach is illustrated for slab-on-grade and crawl space construction in Figure 3. Drainage of water that might accumulate in the sub-slab-on-grade aggregate can be accomplished using a sealed sump as shown in Figure 1 or by drainage to grade or a sewer using solid pipe. If the double-barrier system is not effective in the passive mode (sealed, vented to outdoor air, or passively depressurized using stack ventilation), then active pressurization or depressurization can be employed. When a barrier is placed directly on the soil of a crawl space and the floor of the house is sealed, one obtains a double-barrier system with the space between the soil barrier and the floor being the permeable space. The crawl space can then be vented to outdoor air or the crawl space can be sealed and passively depressurized, or actively pressurized or depressurized. To reduce the volume of air to be pressurized or depressurized, a permeable layer of aggregate or other construction to form a permeable space with barriers on both the soil side and house side can be used as shown in Figure 3. Sealing the floor and using a double barrier at the soil surface results in a triple-barrier system where the two permeable spaces could be treated independently.

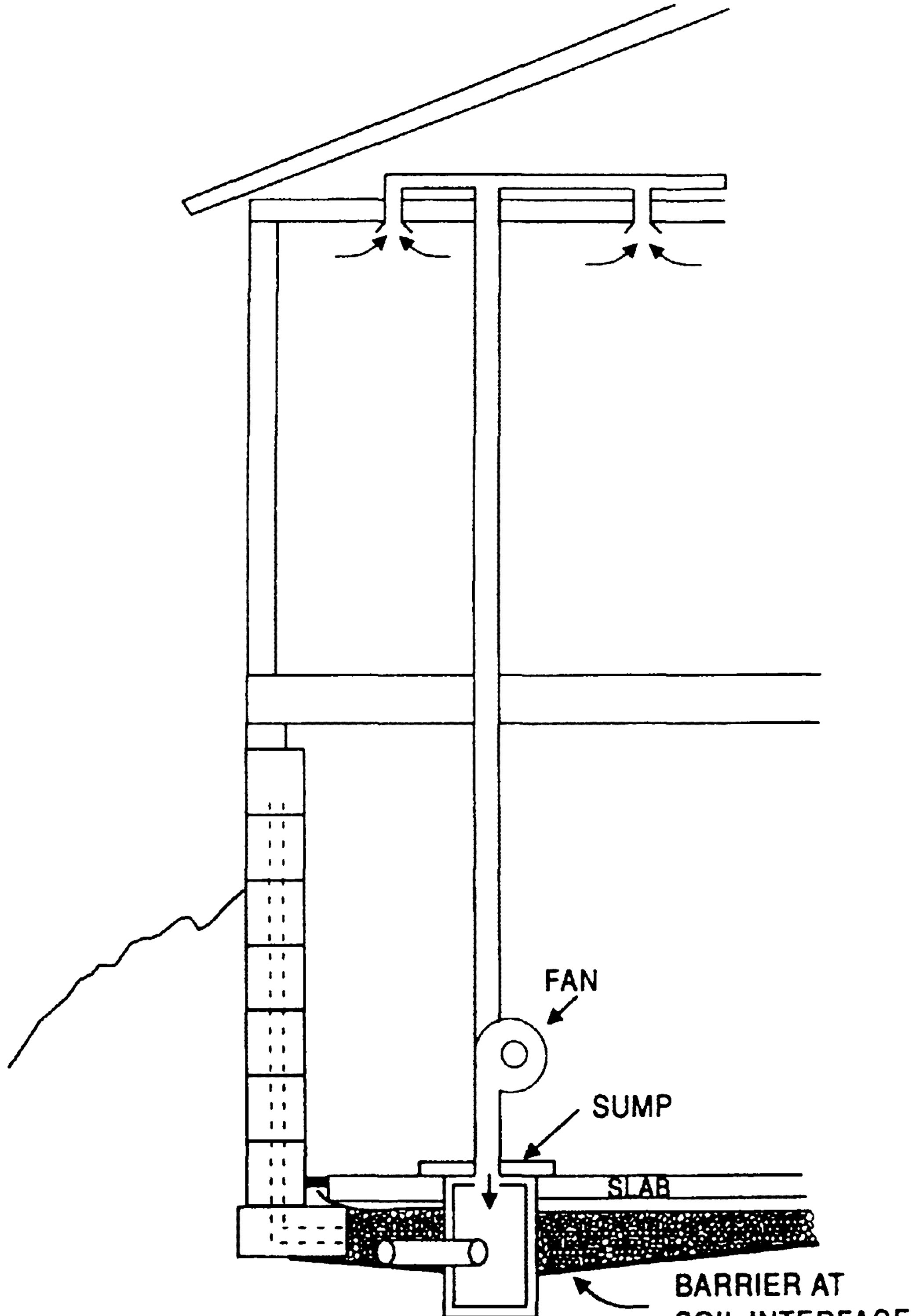


Figure 2. Double-barrier pressurization using interior air.

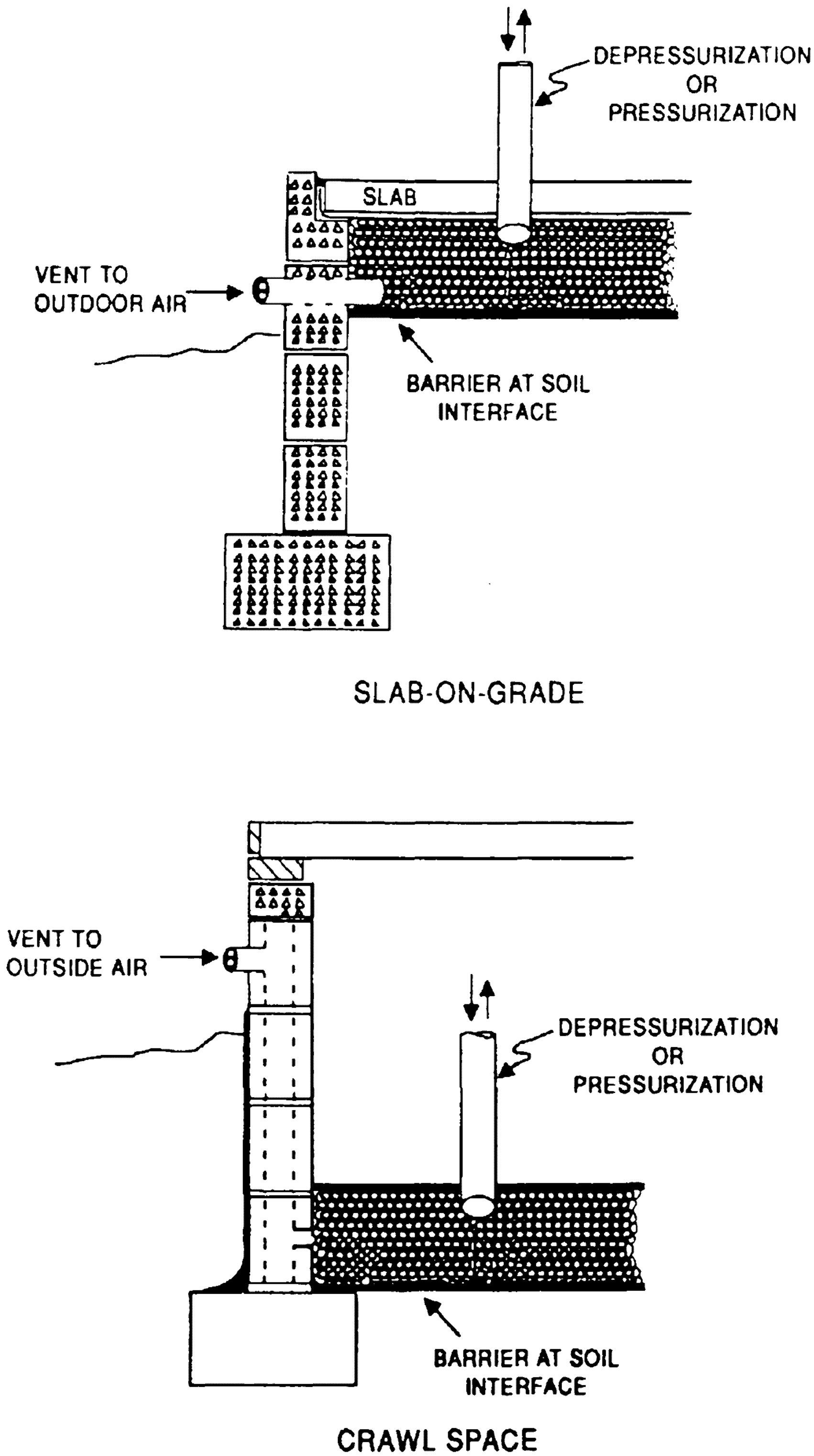


Figure 3. Double-barrier systems for slab-on-grade and crawl space construction.

For example, the aggregate could be passively depressurized and the space below the floor could be vented to outdoor air.

## SUMMARY

Radon-resistant construction designed to decouple houses from the soil has been suggested and used in various forms. The EPA refers to constructing a pressure break between the foundation and the soil. Brennan and Osborne (4) suggested that a drainage mat be used to form an air curtain around the foundation. A Denver builder excavates to a depth of 10 ft. and constructs a crawl space under a wood basement floor (1). The crawl space is then actively ventilated. Walkinshaw (5) constructs a shell inside the basement and then ventilates the space between the interior shell and the basement floor and walls.

The double-barrier approach described in this paper attempts to modify normal building practices to be more radon-resistant at moderate cost. Barriers under the aggregate and on the outside of hollow-block walls interfacing with the soil and rock will be the most effective barriers in reducing radon entry. The double-barrier construction creates a relatively small permeable volume between the inside and outside barriers that can be managed in several ways, either passively or actively, to reduce radon entry. A key element in this design is to maintain water drainage from the permeable space between the barriers and from around the foundation. There are many types and variations of house and foundation construction. Very often these variations are dictated by the local and regional surficial geology. It is not possible to describe a radon-resistant design readily applicable to all types of construction and water drainage conditions. However, a better understanding of how water drainage systems around foundations can increase the potential for radon entry will enable builders to make water drainage and radon-resistant construction more compatible. Double-barrier construction is such an attempt to make water drainage and radon resistance work together.

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 CONTROL - TOWARDS A SYSTEMS APPROACH

Nuess, R. M. and Prill R. J.
Washington State Energy Office
Energy Extension Service
N 1212 Washington, Suite 106
Spokane WA 99201

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## ABSTRACT

The normal operation of a continuous mechanical ventilation system, incorporated into a relatively airtight house, and designed to control pressure-differences, has been demonstrated to provide sufficient control of radon entry in a two story residential building.

This was accomplished via a "two-cell barrier-enhanced pressure-difference control system."

Ventilation rates, energy usage, moisture levels, pressure-differences, and radon concentrations were monitored. Changes in radon concentrations in several building locations, as a function of distinct pressure-difference configurations, have been measured.

Indications are that this design offers the new residential construction industry an opportunity to realize affordable control of radon entry, while simultaneously optimizing potentials for moisture control, energy efficiency, and control of other indoor air pollutants.

## INTRODUCTION

This project explores the use of an airtight building envelope (and separately isolated airtight crawlspace) integrated with a continuously operating mechanical ventilation system, to enhance pressure-difference control strategies for minimizing soil-air entry into the indoor air.

This approach seeks to obtain robust control of radon entry, while concurrently optimizing potentials for several building design goals including: moisture control, energy efficiency, control of other indoor air pollutants.

## CONTEXTING ASSUMPTIONS

There are several primary design goals for the environment control system "house:" safety, comfort, durability, healthy indoor air, and energy efficiency. These goals are not only increasingly achievable, but can be mutually advantaged in a manner that can reduce net system cost.

A systems approach that seeks to optimize a building's performance with regard to several desirable performance qualities might well include several very successful radon solutions.

The radon source of concern is soil-air. The primary goal with regard to control of indoor radon is the prevention of soil-air entry into the indoor air. Radon is a given component of soil-air though its concentration both varies from one site to another and is not readily predictable. In one case, measurements of soil radon within a distance of 9 meters varied by a factor of 250 (1). Hence, the degree of soil-air entry control required is neither constant nor predictable.

Two conditions are necessary for soil-air entry:

- There must be openings in the building envelope that couple the soil-air to the indoor air.
- There must be a driving force, a pressure-difference that results in a flow from the soil-air zone into the indoor air zone.

While significant reduction of all coupling pathways from the soil zone is reasonably achievable, elimination of them is not. It has been observed that even very small openings are sufficient to allow unacceptable radon levels (2). Control of pressure-differences may be the practical key to adequately limiting the entry of soil-air pollutants, including radon. Envelope tightness may be most important for its role in enabling and enhancing pressure-difference control.

The tight building envelope, coupled with a properly designed mechanical ventilation system, can play a central role in a systems approach that incorporates pressure-difference control to limit soil gas entry. The tighter the air barriers of the system, the more effective the pressure-difference control for a given amount of fan power. This dovetails nicely with the desirable advantages of a tight building envelope for several other building performance purposes, including:

- Comfort - fewer drafts; minimal temperature stratification; reduced noise, dust, pollen, insects.
- Energy efficiency - large net reduction in heating/cooling loads.

- Moisture control - structural durability and reduced maintenance costs.
- Enhanced dilution/removal of pollutants generated indoors - via improved ventilation effectiveness, control and capability.

Several of the design elements serve to advantage multiple design goals. This should be recognized when attempting to allocate costs. For example, soil-air may also contain other pollutants of concern, such as garbage gasses (methane), herbicides, fungicides, pesticides, spores of soil fungi, etc. (3). The cost of preventing soil-air entry should be life-cycled against the delivery of several health benefits. Also, in this particular project, the cost of mechanical ventilation and the tight envelope must be apportioned to comfort, energy performance, radon control, moisture control, and control of other pollutants.

## SPECIFIC HYPOTHESIS

The normal operation of a commercially available continuous mechanical ventilation system incorporated into a tight house, and designed to control pressure-differences, can provide sufficient day-to-day control of those pressure-differences (induced by weather, internal household activities, and mechanical systems) to prevent entry of radon and other soil-air pollutants. This can be reasonably accomplished by developing a "two-cell, barrier-enhanced pressure-difference control system." (4).

## BUILDING DESCRIPTION

In 1988, a tightly sealed and energy efficient two-story residential building was constructed with the intent to exceed any energy performance standards currently in place in the U.S. The building was among those instrumented and continuously monitored for one year as part of the Residential Construction Demonstration Program (RCDP), a multipurpose research and development effort of the Bonneville Power Administration and the Washington State Energy Office. As an RCDP Cycle II Future House, the expected energy performance of the building was designed to exceed that required by the Northwest Power Planning Council's Model Conservation Standards by 30%.

The building was constructed in Spokane, WA. Spokane has a winter outdoor design temperature of 4°F (-15°C), 6882 normal heating degree days, and 411 normal cooling degree days. Spokane weather has the characteristics of a mild arid climate in the summer and a cold coastal climate in winter. Winter solar potentials are limited by both the climate and the site. The building was calculated to have an annual need of 2.5 kWh/ft$^2$ (97 MJ/m$^2$) for space heating.

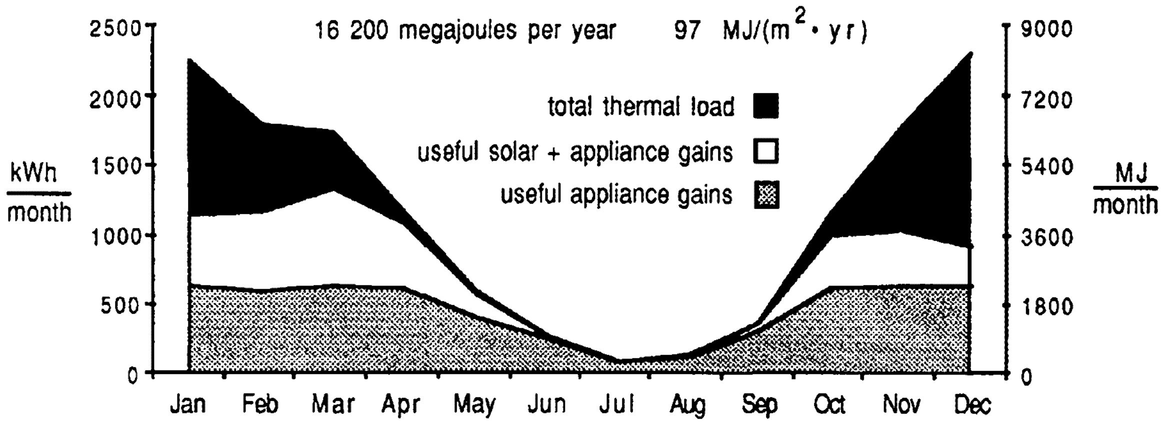


Figure 1. Predicted space heating profile.

The building is of double-wall construction and the wall thermal resistance is approximately R45 (.126 W/[$m^2$•K] ). This insulation level extends from the ceiling to the concrete footing, except as interrupted by doors and glazing (Figure 2). The glazing area is 328 $ft^2$ (30.5 $m^2$) and is 18% of the conditioned floor area 1780 $ft^2$ (166 $m^2$). Fifty-five percent of the glazing faces south. The glazing thermal resistance is approximately R4 (1.5 W/[$m^2$•K] ). The ceiling is insulated to R60 (0.095 W/[$m^2$•K] ). The continuous thermal envelope is completed by R25 ( 0.227 W[($m^2$•K]) fiberglass batt insulation laid directly upon the ground (over a gravel capillary break).

A continuous air barrier was established with the interior drywall by gasketing the drywall to the wood framing and sealing any penetrations through the drywall. Upon completion of construction, the building had a tested air leakage rate of 1.2 air changes per hour (ACH) at an induced indoor/outdoor pressure-difference of 50 pascals. One year later it was tested at 1.4 ACH at 50 pascals. The measured Pacific Northwest average is 9.3 ACH at 50 pascals (5). The vapor retarder was established on the interior surface of the drywall with a rated paint. The glue in the laminated subflooring provided the floor vapor retarder.

The building is divided into two distinct cells, that are atmospherically decoupled from both each other and the outdoor air (Figure 2). The tightness and isolation of these two "cells" enables pressure-difference control with the mechanical ventilation system (and prevents contamination of air in cell 1 by air in cell 2. Cell 1 contains all occupied space, so that the breathable indoor air is contained in cell 1. The volume of cell 1 is 16,500 $ft^3$ (467 $m^3$). Cell 2 is a plenum by which stale air from cell 1 is removed. Though atmospherically decoupled, it is thermally coupled to cell 1, so it provides warm floors. Cell 2 adds another 3000 $ft^3$ (85 $m^3$) to the conditioned volume.

The first floor subfloor was the selected air barrier between cell 1 and cell 2. All joints in the tongue and groove exterior grade plywood were sealed with urethane sealant during installation. Special care was taken to identify and seal any holes created in this barrier by the construction process (eg; temporary nailing for wall bracing, sawhorses, measuring and cutting tables). A tracer gas was injected into cell 2 prior to carpet installation and two small air leaks were located using a detection instrument.

## HVAC SYSTEM

A small (5000 to 7000 btuh) commercially available integrated residential heat recovery ventilation system (HPV) provides continuous ventilation, partial space heating, space cooling, water heating, as well as the desired pressure-differences (6). The unit consists of a water heating tank and a space conditioning module (SCM). The SCM contains 2 constant speed fans, 2 coils, and utilizes a reversible refrigeration cycle to provide heating or cooling via the same ductwork. During the winter heating cycle, heat is extracted from stale exhaust air and delivered to either the domentic hot water tank or the mixed air supply. In summer, heat is extracted from the mixed air supply and either exhausted outside or used to heat domestic water.

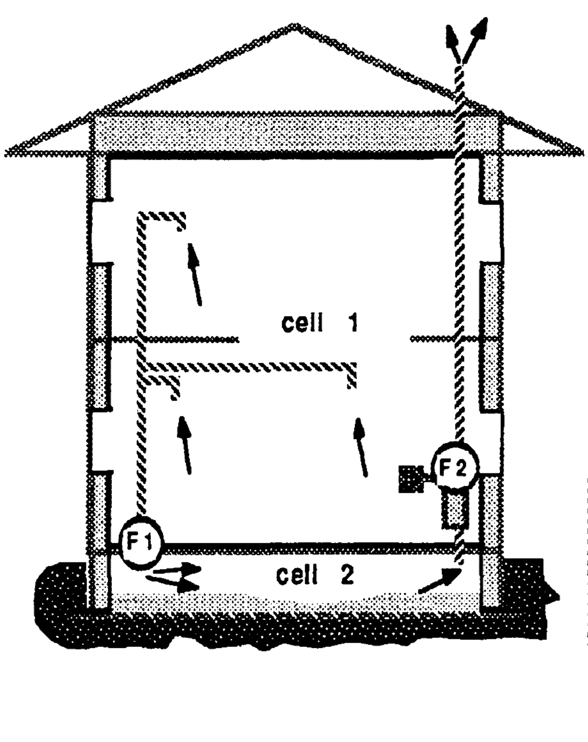


Figure 2. Exhaust Air Side.

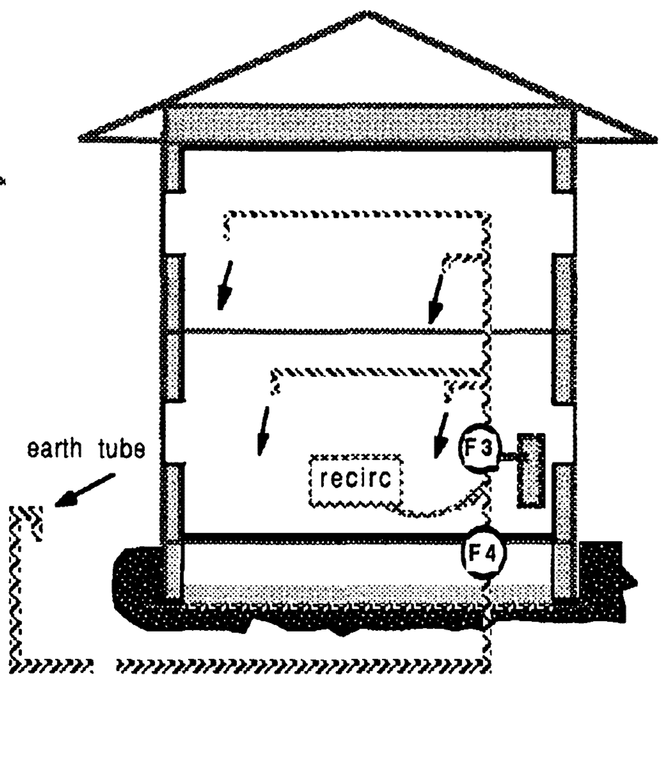


Figure 3. Supply Air Side.

On the supply air side, two 60 ft (18 m) long by 4 in (10 cm) diameter PVC earth tubes provide filtered outdoor air which is mixed with recirculating air before it passes over the supply-side coil and is distributed to individual living areas by fan F3 (Figure 3). The earth tubes are buried approximately 4 ft (1.2 m) below grade and serve to temper both winter and summer air.

On the exhaust air side, stale indoor air is removed from kitchen and bathrooms by fan F1 and ducted to cell 2. From this point it remains isolated from cell 1. The stale air travels across cell 2, then exits via a sealed duct which leads to the SCM. Continuous operation of fan F2 (SCM exhaust fan) is necessary to maintain a lower pressure inside the SCM than in the mechanical room, so that no leakage back into the indoor air occurs. After passing through the SCM the air is exhausted above the roof line.

## TWO-CELL, BARRIER ENHANCED PRESSURE-DIFFERENCE CONTROL

Cells 1 and 2 are isolated from each other, from the outdoor air, and from the indoor air; by accessible and maintainable air barriers. Sealed ducts allow controlled air passage. Continuous mechanical ventilation removes stale air from cell 1 and delivers it outside via cell 2. Depending on which fans are selected to operate, cell 2 can be either pressurized or depressurized relative to cell 1 and/or the soil-air. This project incorporated four fans in the ventilation system in order to enable comparison between these two approaches, as well as other possible ventilation and pressure-difference configurations:

• Continuously pressurize and flush cell 2: This is the baseline operating condition. Fan F1 removes stale indoor air from cell 1, depressurizing cell 1 relative to outside and pressurizing cell 2. Fans F2 and F3 are part of the commercial unit and operate at a constant speed. Fan F1 must produce a greater flow than fan F2 in order to maintain cell 2 at a greater pressure than cell 1. A solid state speed control allows adjustment of fan F1. Dampers allow adjustment of the flows through the SCM, but adjustment is limited to the range of flows required by the SCM.

• Continuously depressurize and flush cell 2: Fan F1 does not operate, so fan F2 depressurizes both cell 1 and cell 2. Cell 2 is at a lower pressure than cell 1.

• Continuously pressurize cell 2: Fan F1 operates but no flushing of cell 2 occurs. Cell 2 is decoupled from the exhaust loop, and stale air is removed directly from cell 1.

• Mimic typical housing leakage and ventilate: Increase the envelope equivalent leakage area of cell 1 to typical levels by introducing deliberate openings in floor and ceiling (The northwest average is 125 $in^2$ (806 $cm^2$). The measured cell 1 leakage area is 16-20 $in^2$ (100-130 $cm^2$). The ventilation system operates (decoupled from cell 2). Leakage distribution can also be adjusted. Typical outside vents can be installed in the crawlspace.

• Mimic typical housing leakage and do not ventilate: Increase the envelope equivalent leakage area of cell 1 to typical levels by introducing deliberate openings in floor and ceiling. Typical outside vents can be installed in the crawlspace.

## ENERGY PERFORMANCE

Limited data is available at this time and results should be considered preliminary. The building was completed and occupied during January of 1989. Shortly thereafter extensive energy performance monitoring was begun by the Washington State Energy Office, via a subcontract with W.S. Fleming Inc. Selected air and water temperatures, air and water flows, relative humidities, and electrical energy usage have been monitored and recorded (six second averages) on a multi-channel datalogger. Data collection for the first year has been completed. Once the data are analysed a more complete energy performance profile will become available.

Zoned electric resistance heaters were separately submetered. The integrated heat recovery ventilation system, which provides continuous ventilation, partial space heating, space cooling and water heating was also submetered. Electrical main and submeter data were recorded by the author. For the one year period between March 4, 1989 and March 3, 1990, electric resistance heating used 1.4 kWh/$ft^2$ (54 MJ/$m^2$). The HPV unit used 3.5 kWh/$ft^2$ (135 MJ/$m^2$) for continuous ventilation, space heating and cooling, water heating, and pressure-difference control. The HPV system is estimated to provide 44% of the space heating load. This brings the total cost of space heating to $216/year. The measured average Kwh consumption for heating conventional electrically heated homes in the Pacific Northwest is 12,420 Kwh, which amounts to $596 (5).

## MOISTURE PERFORMANCE

Humidity sensors (7) were calibrated and placed inside structural wood framing in six locations prior to completion of construction. Two sensors were placed in the attic, two in the walls, and two in the floor of cell 1. An attempt was made to select locations with the greatest moisture potential; generally downwind from the prevailing wind direction, shaded areas on the north side, and (for walls) high in the building:

- Attic top chord - north side near center of building.
- Attic bottom chord - north side near center of building.
- East wall exterior framing stud - north side on upper level.

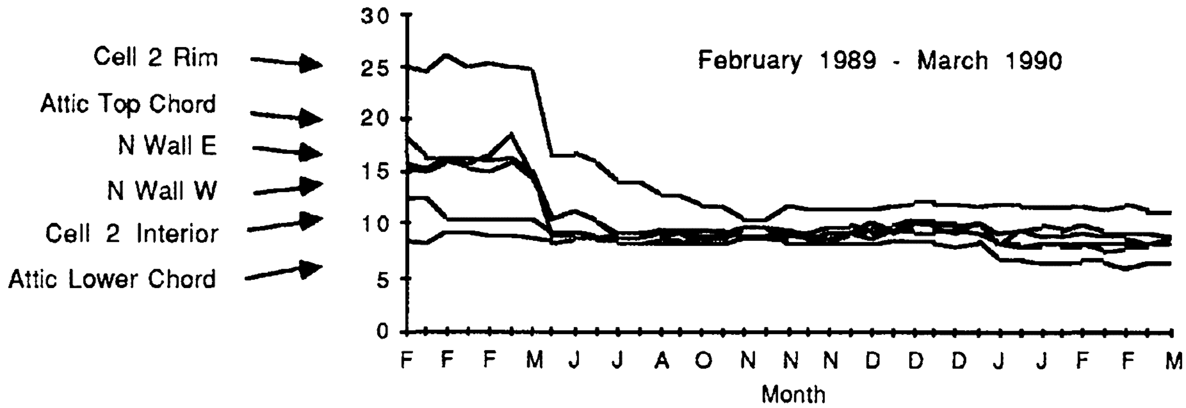


Figure 4. Percent wood moisture content in six locations.

- West wall exterior framing stud - north side on upper level and near electrical outlet.
- Warm joist in cell 2 - center of building.
- Cold joist cell 2 - next to north rim joist and on cold side of air-vapor barrier and insulation.

Thirty-seven intermittent readings were recorded (approximately weekly during the heating season) and corrected for temperature. Monitored moisture levels in all locations dropped by the end of the summer following completion of construction, and remained approximately constant through the following winter (Figure 4). Moisture levels remained constant during the second winter as well.

## VENTILATION PERFORMANCE DYNAMICS

The clock timer on the HPV unit is set to provide continuous exhaust ventilation, so the unit's exhaust fan (F2) drawing stale air from cell 2 is always activated. If there is a demand for water heating the compressor also operates. If there is a demand for space heat or cooling the supply fan (F3) also activates. Both fans operate at a constant speed and flows must be adjusted by dampers.

The baseline mode of operation has been to adjust fan F1 to maintain a slightly lower pressure at the ceiling of cell 1 than that outside (thus also pressurizing cell 2). This typically resulted in a 2-13 Pa lower pressure at the ceiling of cell 1 relative to outdoors during space heating. The neutral pressure plane was maintained above the ceiling of cell 1, there was no exfiltration, and therefore all air exchange was induced by the HPV unit. The resultant pressure in cell 2 was generally 3 to 7 pascals greater than the pressure in cell 1, during space heating mode of operation. The supply air fan (F3) operates during space heating and cooling, and tends to pressuize the building, by increasing the flow of outside air through the earth tubes.

However, when it is off (during periods of ventilation and water heating), fans F1 and F2 remain on, so the cell 1/cell 2 pressure-difference increases (10 to 20 Pa). Additionally, a manual timer switch in the bathrooms enables short pulses of greatly increased ventilation by boosting fan F1 to full power, and the cell 1/cell 2 pressure-differences become even larger (45 to 60 Pa).

Intermittent measurements by the author indicate that the mechanically induced air exchange rate for the first year has been roughly .6 ACH, or equivalent outdoor air supply for 11 persons at 15 cfm (7 L/s) per person. Since the pressure in cell 1 was lower than the pressure outside (therefore no exfiltration), all the air leaving cell 1 had to pass through fan F1. A Kurz Model 435 Linear Air Velocity Transducer was used to measure the mass flow of air in the duct downstream of fan F1.

The purpose of fan F4 is to pull outdoor air through the earth tubes and provide adequate outdoor air supply. It was found to be unecessary and was not operated. The negative pressure of cell 1 induced sufficient flow in the earth tubes. When the unit's supply fan (F3) did not operate (ventilation and water heating modes) the earth tube flow averaged 27 cfm (13 L/s). When the supply fan operated the average earth tube flow was 57 cfm (27 L/s). Approximately one third of the outside air supply was via the earth tube. Envelope infiltration, due to the induced negative pressure of cell 1, provided the remaining outside air.

The pressure-difference control under these conditions appears to have been very robust. Though pressure-differences were not continuously monitored, they were frequently observed during cold and windy periods. No reversals of the desired pressure-difference directions were observed.

## CONTROL OF RADON

### RADON PHASE ONE

Five continuous radon monitors (CRMs) were placed in the same location for five days to establish a comparison baseline. The monitors were then placed in five different locations in the building for a thirteen day period between November 11, 1989 and November 23, 1989. Fan F1 was off during the first part of of this period, so that fan F2 depressurized both cell 1 and cell 2 relative to outside.

After the first 112 hours, Fan F1 was activated and adjusted to maintain a slightly lower pressure at the ceiling of cell 1 relative to outside during the space heating mode. This resulted in a 10 to 60 Pa greater pressure in cell 2 (depending on the HPV system's operating mode at time of read).

Cumulative CRM data were recorded intermittently and averaged over each elapsed time period. Thirty-two readings were recorded. Average radon levels in cell 2 decreased dramatically when fan F2 was activated; average radon levels in cell 1 also showed a tendency to decrease (Figure 5).

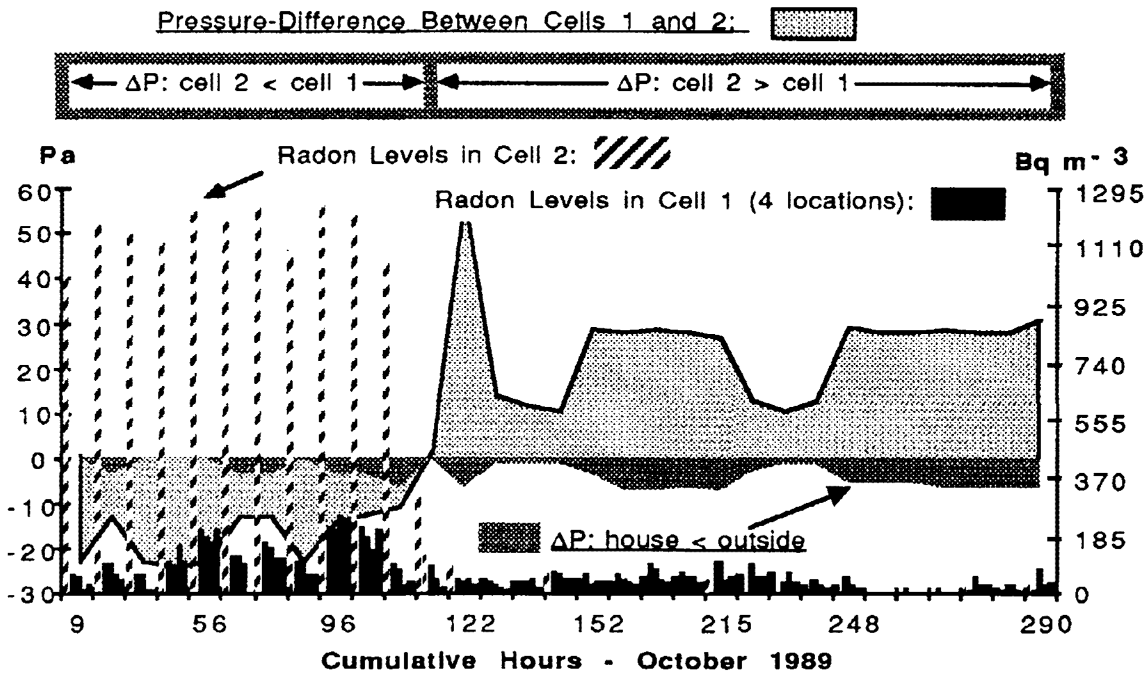


Figure 5. Radon levels in five locations.

## RADON PHASE TWO

Two CRMs were placed in separate locations within cell 1 (CRMs 1a and 1b) and two CRMs were placed in separate locations within cell 2 (CRMs 2a and 2b). Hourly radon averages were recorded for the three month period between 17 February and 21 May 1990. During this period, the baseline system configuration (continuously pressurize and flush cell 2 while depressurizing cell 1) was held constant for the first 23 days. Then 9 deliberate alterations in system configuration were made. After each alteration the system was returned to the baseline configuration, before the next alteration was initiated. Upon completion of the 9 alterations the system was returned to the baseline configuration for 22 days.

The alterations had powerful effects upon Cell 2 radon levels, and clear effects upon radon levels in Cell 1. Effects of wind, rainfall, and temperature did not appear to have noticeable influence on radon levels, except that Cell 2 radon levels may have showed some indication of response to temperature. Nonetheless the effect was subtle relative to the effects of system operation.

The baseline system configuration and the alterations to it are discussed below, and referenced in the following graphs.

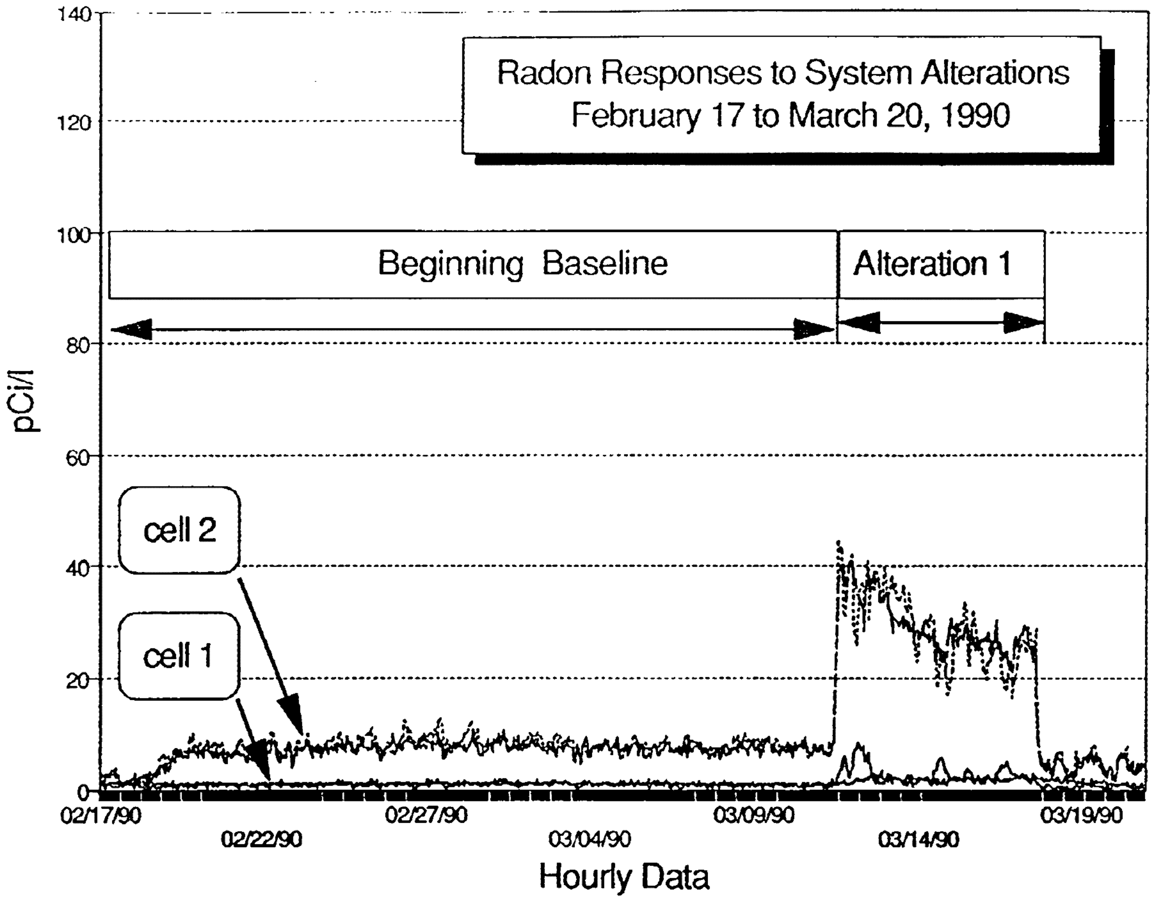


Figure 6. Baseline and Alteration 1.

<u>Baseline.</u> The baseline operating condition was established for 23 days, from 2/17 to 3/11. During this period the average radon concentration in cell 1 was on the order of 1 pCi/l. The average radon concentration in cell 2 was 7 pCi/l. Intermittently recorded cell 2 pressures ranged from 1 to 7 pascals greater than those of cell 1. The average was 3 pascals. Cell 1 was 7 to 15 pascals lower in pressure than outside. The average was 9 pascals.

<u>Alteration 1.</u> Fan F1 was turned off on 3/11 at 10:20 am. The pressure in cell 2 had been greater than the pressure in cell 1, but now shifted to about 30 pascals lower than cell 1, since F2 now pulled air through the cell 2 plenum. In two hours radon levels in cell 2 had increased by a factor of three. Radon levels in cell 2 averaged 29 pCi/l. Radon levels in cell 1 increased also to an average of about 2.5 pCi/l. On 3/17, six days later, fan F1 was turned back on. Pressure in cell 2 returned to 3-4 pascals greater than cell 1. Radon levels in cell 2 dropped by a factor of three in three hours and returned to baseline levels.

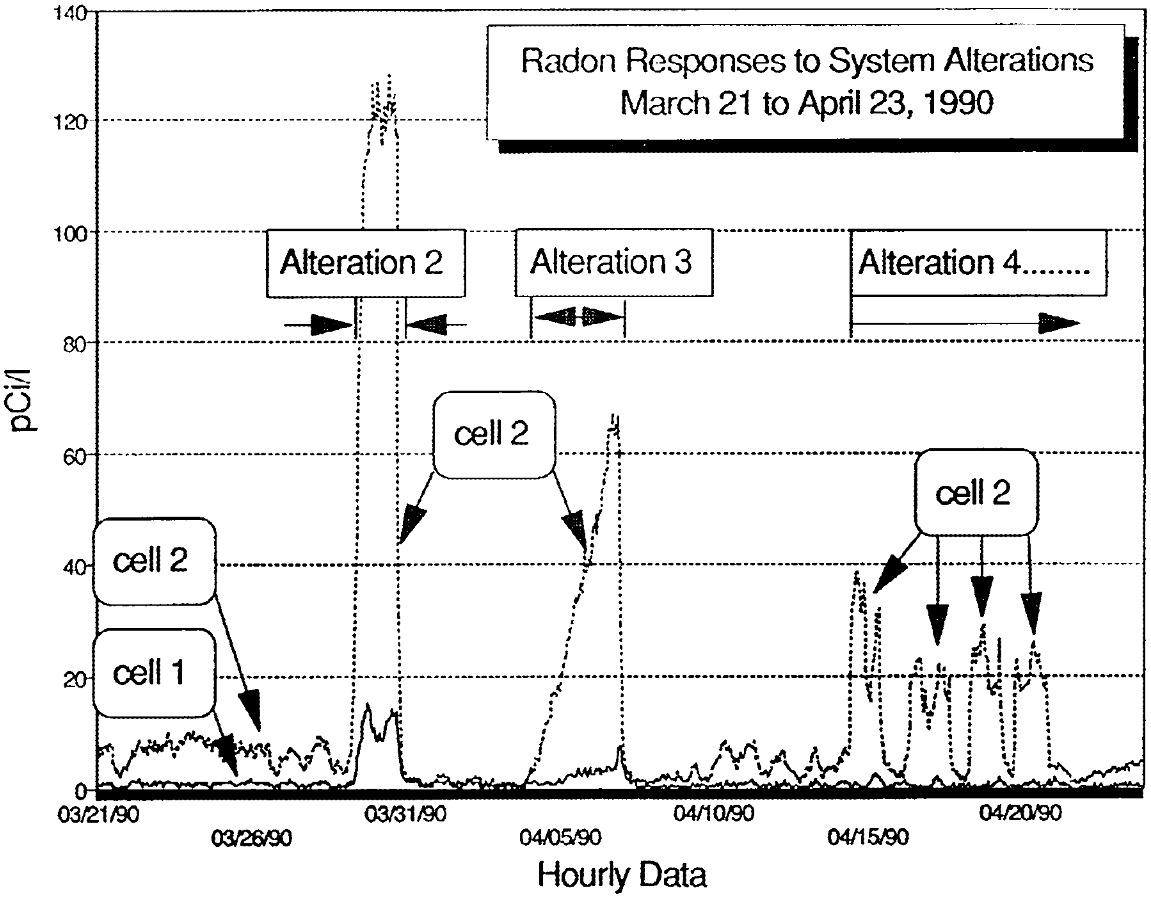


Figure 7. Alterations 2,3, and 4.

<u>Alteration 2.</u> On 3/29 fan F1 was turned off again for approximately 34 hours. F2 continued to operate, but the duct connection from F2 to cell 2 was disconnected and exhaust air taken from cell 1 instead. The ductwork joining the two cells remained open. Cell 2 was atmospherically coupled to cell 1, but was decoupled from the ventilation loop. During this condition the cell 1 pressure was 10 pascals lower than the outdoor pressure and cell 2 was about 7 pascal lower than than the outdoor pressure. Hence, both cells sucked on the ground, but only cell 1 recieved ventilation. Cell 1 radon levels increased by a factor of 12 to an average peak of 12 pCi/l. Cell 2 radon levels increased by roughly a factor of 20 to an average peak of 120 pCi/l. When the system configuration was returned to the baseline, radon levels quickly returned to baseline levels.

<u>Alteration 3.</u> On 4/4 fan F1 was turned off for 62 hours. Also F2 and F3 were turned off. There was no ventilation. The ductwork joining the two cells was sealed to atmospherically decouple the cells from each other. Radon levels in cell 2 rose gradually (whereas in the previous alterations they had risen abruptly) to a peak of

66 pCi/l. Then F1, F2, and F3 were reactivated and radon levels in both cells returned abruptly to baseline levels. The pattern of a more gradual rise in radon levels also seemed to occur in the cell 1 radon levels which rose to over 5 pCi/l. The gradual rise is assumed to be attributed to soil recharging and the slower response related to the lesser stack pressures.

The three fans were activated 62 hours after the initial alteration. However, cell 2 remained atmospherically decoupled from the ventilation cycle (F2 drew exhaust air from cell 1), as well as isolated from cell 1 by the sealed ductwork. The condition was that cell 2 was pressurized by fan F1 but there was no flushing of the air in cell 2. The resultant pressure in cell 2 was 45 pascals greater than that in cell 1. Radon levels returned to baseline in about 6 hours, hence were already at baseline levels when the ductwork was reconnected and the system configuration returned to baseline.

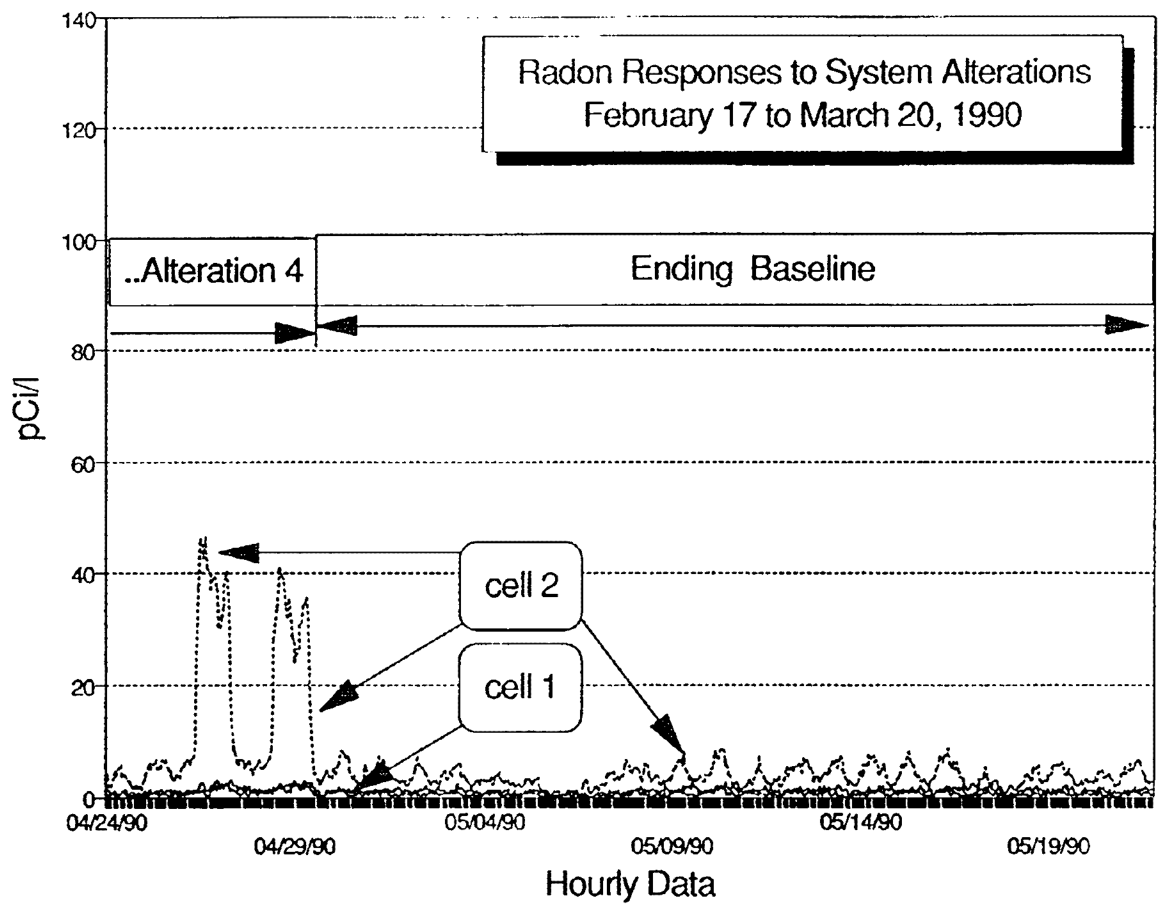


Figure 8. Alteration 4 and Baseline.

<u>Alteration 4.</u>. Fan F1 was turned off. The system was altered as described in alteration #2 for roughly 24 to 30 hours, then returned to the baseline configuration. This process was repeated six times. In each case cell 2 radon levels responded as they had in alteration #2.

**Baseline.** The baseline operating condition was restablished for 22 days, from 4/29 to 5/21. During this period the average radon concentration in cell 1 was less than one pCi/l. The average radon concentration in cell 2 was about 2.5 pCi/l.

There is some uncertainty associated with the radon measurements. The CRMs were research instruments that were not calibrated immediately prior to these measurements. However, they were compared to each other by operating them in the same location for six days at the beginning of this project. All 4 CRMs tracked radon levels consistently (Figure 9).

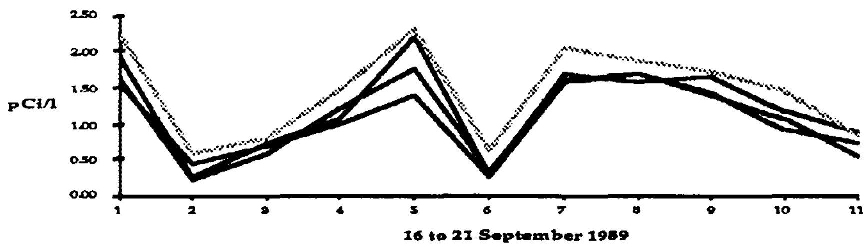


Figure 9. Radon instrument comparisons.

Several months after the project they were again compared to each other, and it was discovered that only CRM 1a had a correctly operating air pump. This CRM was then compared for about 30 hours to a Pylon AB5 with a PRD, which had been recently calibrated with a Pylon Calibration Standard. The two monitors tracked radon fluctuations consistently. When the data from this project was later reviewed*, it was discovered that CRMs 1b and 2b had diverged widely (radon levels declined) from their respective matched pairs and never recovered. These were suspected to be the points of pump failure. Data from these units was removed from the data set for the time periods after their responses suggested pump failures.

CRMs 1a and 2a did respond in a consistent manner throughout the entire measurement period. Fortunately one was located in cell 1 and the other in cell 2. It was also fortunate that CRM 1a -- which was recording the lowest and least variable radon levels -- was also the CRM that continued to have a correctly operating pump and was compared to the calibrated Pylon instrument after the study. Both the consistent response of these two remaining CRMs to the repetitive nature of alteration #4, and the similarity of their ending baseline responses to their starting baseline responses, suggest that these two CRMs responded with acceptable accuracy to radon fluctuations throughout the study.

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* This study was not funded and was conducted as time allowed.

It is not known when the the pump on CRM 2a began to fail. The data set suggests that CRM 2a was operating correctly during the study period and likely failed after the study period.

## COST

It is very difficult to assign costs to the radon prevention and mitigation features of this building, since virtually all the features that control radon also enhance energy performance, durability, comfort, and the control of other pollutants. The simple energy-only payback for these features is 10 to 20 years. The building's useful life has also been extended due to such features as the vented rain screen designed to extend siding life, and the elimination of air transported moisture into the exterior walls. Since these features primarily address energy, and there is a clear energy payback for them, it can be argued that there is no incremental cost for the control of radon entry. The building cost $80,824, approximately $45 to $48 per square foot.

## INDICATIONS

1. Control of soil-air entry with pressure-differences using a continuous mechanical ventilation system incorporated into a tight house is readily achievable.
2. The initial radon experiment indicates that the radon source at this building location may be sufficient to allow the demonstration of radon control, as well as the comparison and evaluation of the impact of different pressure-difference configurations on radon entry.
3. Airflows through the HPVAC-80 can be reduced by installation and adjustment of dampers so that the flows necessary to maintain required pressure-differences can be reduced (within the limits of the range of flows required by the HPV). The target goal of maintaining soil gas entry control with a mechanical system operating at .35 ACH may be achievable at this level of envelope tightness.
4. Careful attention to air-vapor barrier installation can enable sufficient control of moisture levels in the Spokane climate, even under conditions of constant and relatively large pressurization.

## FUTURE DIRECTIONS

- Evaluate this concept at sites where the known soil radon source is high.

- Evaluate the degree of pressure-difference necessary to control radon and determine the associated air exchange rates, climatic conditions, and energy costs.

- Compare different pressure-difference scenarios and their impact on radon levels.

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1. U.S. EPA & New York State Energy Office, Reducing Radon in Structures/Training Manual, unit 2, page 4.

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# MINI FAN FOR SSD RADON MITIGATION IN NEW CONSTRUCTION

David W. Saum
Infiltec
Falls Church, VA 22041

## ABSTRACT

Subslab depressurization (SSD) systems in new houses constructed with well sealed slabs and good aggregate beds will probably achieve excellent radon mitigation performance with fans that are considerably smaller than the 80 Watt fans that are currently recommended. This paper describes the development, testing, and evaluation of a low power radon mitigation fan for installation in new houses. This "mini SSD fan" uses only 10 Watts of power, and its radon mitigation performance is shown to be almost as good as the larger fans. Since the EPA plans to recommend the installation of SSD systems in hundreds of thousands of houses that are constructed each year in high radon areas, the long term energy savings involved in reducing fan power could involve billions of dollars. In addition, the mini SSD fan lowers the installation cost of the radon mitigation system, and this might encourage more builders to follow with the EPA recommendations.

## BACKGROUND

One strategy for radon mitigation in new construction is for builders in areas with high radon levels to install SSD systems in all the houses that they build. Experience with SSD in new construction suggests that when houses are constructed with SSD combined with a well sealed foundation and a porous aggregate layer, then the performance of SSD radon mitigation has been shown to be excellent. Although many houses with these systems would not have had a radon problem above the EPA action level of 4 pCi/L, even the lower level houses would probably experience some radon mitigation. Since most radon exposure occurs in these lower level houses (due to their large numbers), the net result of installing SSD in all houses in high radon areas is a substantial decrease in radon exposure for occupants of these houses.

A primary objection to installing SSD systems in all houses would be the costs, both for initial installation and for energy and eventual replacement. This objection could be reduced by using the lowest cost components consistent with good radon mitigation performance, long life, and low energy costs. This paper describes the development, test, and life cycle cost evaluation of a low power SSD radon mitigation fan for installation in new houses. This "mini SSD fan" uses 10 Watts of electric power compared to the 80 Watts of the standard fan, and its performance is shown to be almost as good as the larger fans. Since the EPA plans to recommend the installation of SSD systems in hundreds of thousands of houses that are constructed each year in high radon areas, the long term energy savings involved in reducing fan power could involve billions of dollars, and these energy savings might provide some assistance in solutions to problems such as global warming and U.S. energy independence. In addition, the mini SSD fan lowers the installation cost of the radon mitigation system, and this might encourage more builders to follow the EPA recommendations.

## PREVIOUS EXPERIENCE

Although SSD is by far the most common radon mitigation technique, the details of its operation are not entirely clear and the size of the fan that is necessary for effective mitigation is not well understood. As a result, most mitigators use 80 Watt fans for most of their mitigation jobs, and most of the industry experience is based on the use of these fans. For new house construction, it seems that smaller fans might be successful if the builder provides a good site preparation by installing at least a 4" depth of large diameter aggregate under the slab, and by sealing all slab penetrations. Several documents have been written about construction details for radon resistant new construction, including: a new ASTM standard[1], a Bonneville Power Administration report[2], and the EPA new construction guide[3]. Unfortunately, these documents do not contain much discussion of fan performance versus size or of life cycle costs. The EPA will soon issue recommendations on model code language for radon resistant new construction, and there will be a technical support document with life cycle cost calculations.

However, there is one study that suggests that very small fans might provide good performance: the February 1990 EPA Symposium Paper

*Radon Mitigation Performance of Passive Stacks in Residential New Construction*[4] by Saum and Osborne. This research showed that one builder's passive stacks (SSD systems without any fans) offered significant radon mitigation performance in both summer and winter. Table 1 shows a summary of the radon mitigation results for this study. The passive stacks reduced the radon levels by about 66%, and 45 Watt SSD fans reduced radon levels by an average of 98% of the pre mitigation levels. Most performance reductions in these passive stack houses are thought to be due poor installation of the stacks, or to depressurization of the basement by leaky forced air return ducts which reversed the passive stack pressures. This suggests that a small SSD fan would boost the passive stack pressures enough to overcome most of these residual mitigation problems.

## MINI FAN DESIGN

The first step in this project was to design a low power and low cost fan that could be used in a conventional new home SSD system. It was assumed that the builder would install a 4 inches of coarse aggregate under the slab, seal all slab penetrations, and run a stack pipe (3" or 4" PVC) up through the slab and exiting though the roof. In order to take advantage of the passive stack effect, the stack should run through the heated part of the house. The desirable fan characteristics were considered to be low power, long life, and low cost. Conventional radon fans use about 80 Watts, have an estimated 100,000 hour life, require 2 pipe couplings to connect to the stack pipe, and the total cost of fan and couplings is about $150.

The final mini SSD fan design is shown in Figure 1. The conventional radon fan system consists of a fan motor, fan housing, and two pipe couplings. To reduce noise, the conventional 45 or 90 Watt radon fans use a backward inclined blade, but 10 Watt fans are so quiet that a conventional low-cost axial fan blade can be used. For simplicity and lower cost, the mini fan is built into one pipe coupling which serves as a combined fan housing and pipe coupling. The final mini fan design consists of a high quality 10 Watt, 3" diameter, axial fan mounted in a 3" diameter PVC ring, and enclosed in a 3" flexible pipe coupling. When a 3" stack pipe is used, the fan housing serves as the pipe coupling. If a 4" stack pipe is used, then two 4" to 3" pipe couplings can be used to couple the fan to the 4" stack. The use of 3" stacks would be recommended because of the low air flows, the reduced costs, and the consistency with the use of 3" plumbing stacks already installed in houses. To complete the radon control system, a pressure gauge capable of monitoring the low expected stack pressures was developed from the commercially available "Fancheck" type pressure indicator. The Fancheck is a modified Dwyer air flow meter that consists of a small ball in a tapered clear-plastic tube. The conventional Fancheck indicates pressures greater than about 0.2" wc, but this device was modified for use with the mini SSD fan by using a much lighter ball so that it indicates pressures of only a few hundredths " wc.

## COST ESTIMATES

### FAN PARTS COSTS

The parts cost of the mini SSD fan is less than $20, and the modified pressure gauge is about the same cost (about $10) as the Fancheck gauge. Therefore the mini SSD fan could be sold to builders for considerably less than a standard radon mitigation fan system consists of an 80 Watt fan with 2 pipe couplings (about $150), and a pressure indicator ($10). It is anticipated that the mini SSD fan system could be sold to builders for about $75, half the cost of the standard 80 Watt fan system.

### LIFE CYCLE COSTS

The largest cost savings are in the life-cycle costs, not the initial installation costs. Table 2 shows a comparison of life cycle costs between a 10 Watt SSD fan and a standard 80 Watt SSD fan. Three types of recurring costs are assumed: electric cost for running the fan continuously, wasted heat costs for warming house air that is exhausted through the fan, and fan replacement costs. These calculations show that the mini SSD fan would cost about $29 per average year, while the standard 80 Watt fan would cost about $135 per year to operate continuously.

If builders follow the forthcoming EPA recommendations that all houses in radon prone areas have radon resistant features built into them, then it is reasonable to assume that at least 100,000 of the 1,000,000 new home built every year will have SSD fans installed. Under these assumptions, the estimated savings for installing a 10 Watt fan, rather than an 80 Watt fan, are shown to be $11 million in the first year, $476 million in 10 years, and $4.6 billion in 30 years.

## RADON MITIGATION PERFORMANCE

Ideally we would like to know the performance trade-off between fan power and radon mitigation performance under a wide variety of conditions: geology, climate zones, building practices, heating/cooling system variations, contractor variables, failure modes, etc. With this type of data, we could begin to make a calculation of the cost per life saved with different SSD fan systems. Unfortunately, this type of study is far beyond the scope of this project.

### PASSIVE STACK PERFORMANCE

The passive stack experiment data shown in Table 1 suggests that the mini SSD fan radon reductions in new houses should be somewhere between the performance of the passive stack systems (about 66% reduction) and the performance of the 45 Watt fan systems (about 98% reductions). It seems likely that if the performance of the passive stacks is based on the extremely weak forces of stack effect, then the performance of 10 Watt fan systems will be much closer to the 45 Watt fan systems than to the passive stack systems. We believe that is not unreasonable to assume that the mini SSD fan will give at least a 90% average reduction of elevated radon levels in new construction, assuming the recommendation on the subslab aggregate layer and sealing is followed.

## MINI FAN PERFORMANCE IN ONE HOUSE

Only one prototype fan was available for experiments until last month when an additional half dozen prototype units were received from the fan manufacturer. The original prototype has been tested for several months under worst case conditions: an older house with no slab sealing and a poor subslab aggregate bed. These conditions were expected to be much worse than would be found in new houses built for radon resistance. The data from these tests is shown in Figures 2-5. These Figures show that even in an older house with no sealing of cracks and an uneven subslab aggregate bed, the 10 Watt mini SSD fan lowers the radon level from 10 pCi/L to 2.1 pCi/L (a 79% reduction), versus a reduction to 0.8 pCi/L (a 92% reduction) for a 45 Watt fan. Figures 2 and 3 show the performance of the two fans over a month as the fans are being cycled off and on every 3.5 days. Figures 4 and 5 show the averages of 4 on/off cycles so that the variations are smoothed out. Note that both fans reduce radon levels within a few hours after the fans are turned on, but the larger fan seems to have depleted the radon under the slab more extensively than the smaller fan, and it takes longer for the radon levels to build up in the house after the larger fan is turned off.

## PERFORMANCE LIMITATIONS

Some general limitations of SSD fans that may apply to the mini SSD fan have not been fully investigated yet: 1) problems with large slabs, 2) problems when sand or other low porosity aggregates are used below slabs, and 3) problems when the soil below the slab is very porous. These situations are not well understood for even the standard SSD radon mitigation systems. It seems likely that this type of problem could be addressed by written guidance that would be included with the mini SSD fan systems.

## FUTURE DEVELOPMENT PLANS

The future plans for development of the mini SSD fan call for more field tests of the prototype, refinement of the design, field tests with cooperative builders, certification (UL or equivalent), volume purchase agreements, and eventual sale to builders and mitigators.

## 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.

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3. Osborne, M.C., Radon-Resistant Residential New Construction, EPA/600/8-88/087, July 1988.

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Table 1 Radon Mitigation Performance Data from Passive Stack Study

***HOUSES WITH PASSIVE STACKS, NO FANS***

| Test House No. | Stack Open (pCi/L) | Stack Sealed (pCi/L) | Radon Reduction (%) | Comment | Comment |
|---|---|---|---|---|---|
| 126 | 0.3 | 6.1 | 95% | summer data | |
| 126 | 0.1 | 13.6 | 99% | winter data | |
| 162 | 4.7 | 8.5 | 45% | duct leaks, poor communication | |
| 40 | 8.8 | 12.8 | 31% | duct leaks, poor communication | |
| 53 | 1.1 | 2.7 | 59% | | |
| 209 | 1.2 | 6.5 | 82% | | |
| 105 | 0.6 | 1.8 | 67% | | |
| 42 | 1.9 | 9.4 | 80% | duct leakage | |
| 84 | 4.9 | 5.8 | 16% | duct leaks, poor communication | |
| 206 | 2.9 | 19.9 | 85% | winter - duct leakage | |
| 206 | 0.6 | 2.4 | 75% | summer - duct leakage fixed | |
| AVERAGE: | 2.5 | 8.1 | 70% | | |

***HOUSES WITH FANS IN PASSIVE STACKS, FANS OFF***

| Test House No. | Stack Open (pCi/L) | Stack Sealed (pCi/L) | Radon Reduction (%) | Comment |
|---|---|---|---|---|
| 383 | 1.8 | 13.0 | 86% | winter |
| 308 | 4.5 na | na | na | summer, duct leakage |
| 308 | 8.0 | 33.5 | 76% | winter, duct leakage |
| 221 | 1.5 | 12.0 | 88% | winter, duct leakage |
| 181 | 6.7 | 7.4 | 9% | stack in unheated garage |
| 233 | na | 18 na | 1.9 na | not used, fan inside basement |
| 237 | 7.4 | 13.7 | 46% | stack in unheated garage |
| 184 | 12.7 | 26.4 | 52% | duct leakage |
| AVERAGE: | 6.3 | 17.7 | 64% | |

***HOUSES WITH FANS IN PASSIVE STACKS, FANS ON***

| Test House No. | Fan On (pCi/L) | Stack Sealed (pCi/L) | Radon Reduction (%) | Comment |
|---|---|---|---|---|
| 383 | 0.1 | 13.0 | 99% | winter |
| 308 | 0.4 | na | na | summer, duct leakage |
| 308 | 0.2 | 33.5 | 99% | winter, duct leakage |
| 221 | 0.3 | 12.0 | 98% | winter, duct leakage |
| 181 | 0.1 | 7.4 | 99% | stack in unheated garage |
| 233 | na | 18 na | na | not used, fan inside basement |
| 237 | 0.6 | 13.7 | 96% | stack in unheated garage |
| 184 | 0.8 | 26.4 | 97% | duct leakage |
| AVERAGE: | 0.4 | 15.1 | 98% | |

***COMMENTS AND CONCLUSIONS***

1. This data was collected by an EPA Office of Research & Development funded study conducted in 1989-90 and performed by Infiltec and Ryan Homes.
2. All radon measurements are averages of one or more weeks of hourly continuous radon data collected with Pylon or Femtotech monitors.
3. Passive stacks lowered radon by about 1/3, fan systems by about 1/40
4. Passive stacks provided mitigation in summer as well as winter.
5. Passive stack performace appeared to be reduced by duct leaks and poor subslab communication causing blocked pipes.
6. Passive stacks provided some mitigation in all cases.
7. A low power fan to assist the passive stack might overcome many of the the problems caused by house pressures or poor communication.
8. Limitations of study: one builder (Ryan Homes), one region (D.C. Metro), small number of houses (16), one HVAC type (heat pump).
9. All radon control systems were installed by the builder without supervision by a radon mitigation expert.
10. Houses with summer and winter data are included twice in averages.

Table 2 Life Cycle Costs of the Mini SSD Fan and Standard SSD Fan

***CALCULATION ASSUMPTIONS:***

| GENERAL ASSUMPTIONS: | VALUE | COMMENT |
|---|---|---|
| Electric rate | $0.08 per kwh | approximate U.S. electric rate |
| Gas rate | $0.60 per therm | approximate U.S. gas rate |
| Oil rate | $1.00 per gallon | approximate U.S. oil rate |
| Fuel cost escalation | 0.00% | to simplify long term calc. |
| Inflation rate | 0.00% | to simplify long term calc. |
| New houses built | 1 million/yr | approximate U.S. average |
| House lifetime | 30 years | used as long term limit |
| New houses with SSD | 10.00% of total | SSD = SubSlab Depres. system |
| New houses with SSD | 0.1 million/yr | this is a guess |

| HEATING ASSUMPTIONS: | VALUE | COMMENT |
|---|---|---|
| Heating degree day | 5000 deg F days | approximate U.S. degree days |
| Gas efficiency | 70% | gas furnace and ducts |
| Gas heat for 1 cfm | $1.12 per year | gas cost/yr/cfm of exhaust |
| Oil efficiency | 70% | oil furnace and distribution |
| Oil heat for 1 cfm | $1.36 per year | oil cost/yr/cfm of exhaust |
| Elec. efficiency | 90% | elec. furnace & ducts |
| Elec. heat for 1 cfm | $4.60 per year | electric cost/yr/cfm exhaust |
| Heat pump efficiency | 200% | heat pump and distribution |
| Heat pump for 1 cfm | $2.08 per year | heat pump cost/yr/cfm exhaust |
| Avg fuel for 1 cfm | $2.29 per yN / | average cost/yr/cfm exhaust |

| FAN ASSUMPTIONS: | STANDARD FAN | MINI FAN | COMMENT |
|---|---|---|---|
| Fan power | 80 watts | 10 watts | continuous electric |
| Exhausted house air | 25 cfm | 3.125 cfm | this is a guess |
| Exhaust heat cost | $57 /yr | $7 | avg oil, gas & elec. |
| Fan life | 11.42 yrs | 11.42 yrs | rated @ 100,000 hrs |
| Fan & gauge cost | $150 | $75 | cost to builder |
| Fan replacement cost | $250 | $175 | fan plus install |

***ECONOMICS FOR SINGLE HOUSE:***

| | STANDARD FAN | MINI FAN | **$ SAVING** | **% SAVING** |
|---|---|---|---|---|
| electricity (/yr) | $56 | $7 | **$49** | **88%** |
| heat loss (/yr) | $57 | $7 | **$50** | **88%** |
| replacement (/yr) | $22 | $15 | **$7** | **30%** |
| Cost (/yr) | $135 | $29 | **$106** | **78%** |
| Cost (/house life) | $4,056 | $885 | **$3,172** | **78%** |

***ECONOMICS FOR U.S.:***

| | STANDARD FAN | MINI FAN | **$ SAVING** |
|---|---|---|---|
| Costs (1st year) | $14 million | $3 million | **$11 million** |
| Costs (10 years) | $608 million | $133 million | **$476 million** |
| Costs (30 years) | $5,882 million | $1,283 milllion | **$4,599 million** |

NOTE:
1. Costs of pipe installation and slab sealing ignored since they are common to both SSD fan systems.
2. Exhaust air leakage of 25 cfm for 80 Watt fan is a guess.
3. The estimate of 10% of new home builders installing SSD systems assumes the EPA will recommend new home SSD in radon prone areas.

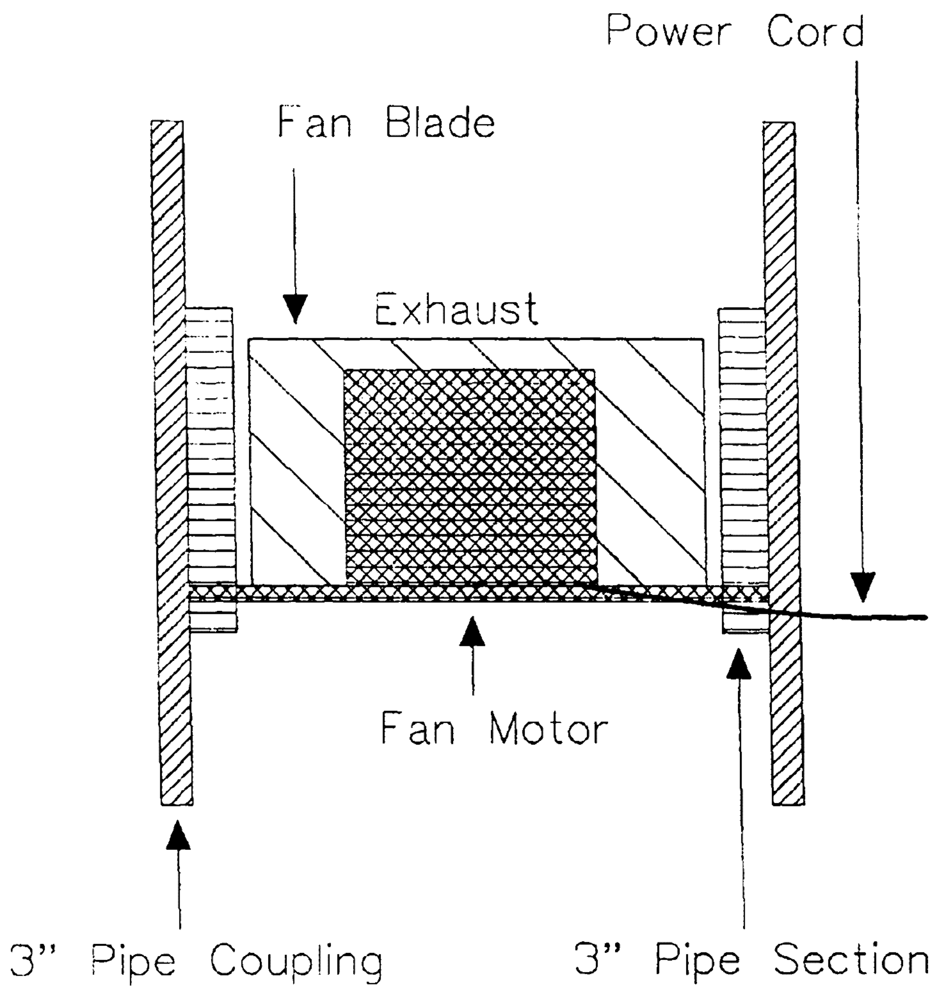


Figure 1 Vertical Cross-Section Schematic of Mini Fan

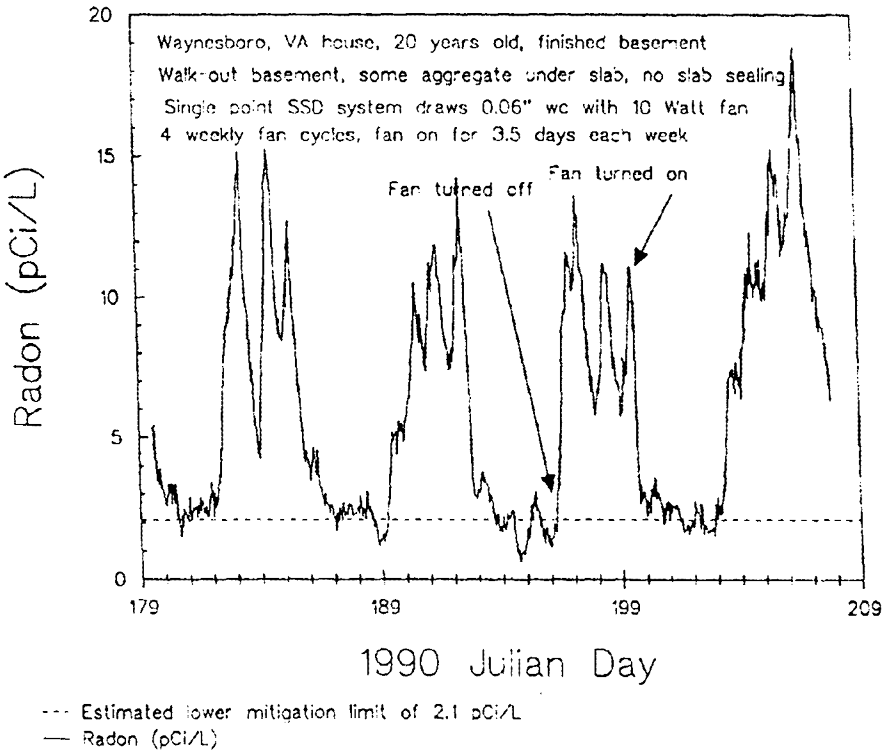


Figure 2 - Mitigation Performance of 10 Watt Fan

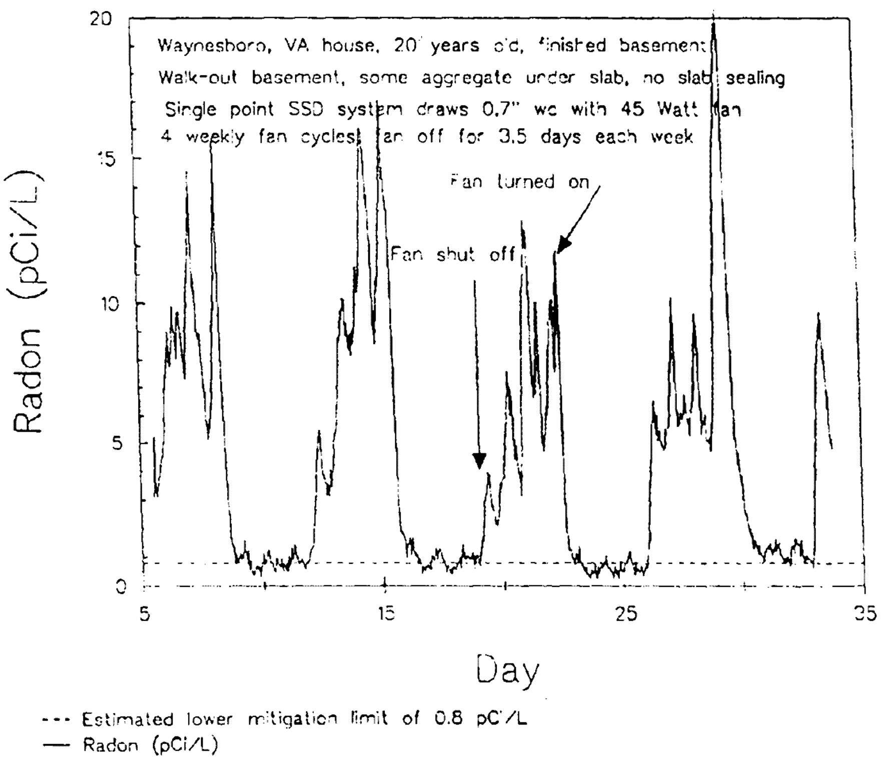


Figure 3 - Mitigation Performance of 45 Watt Fan

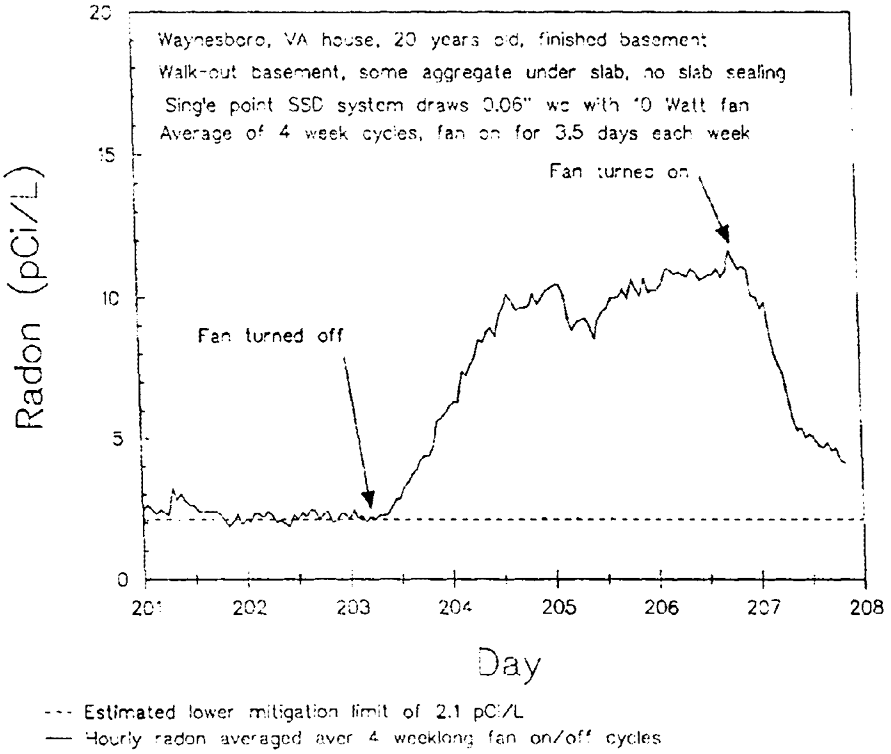


Figure 4 Average Mitigation Performance of 10 Watt Fan

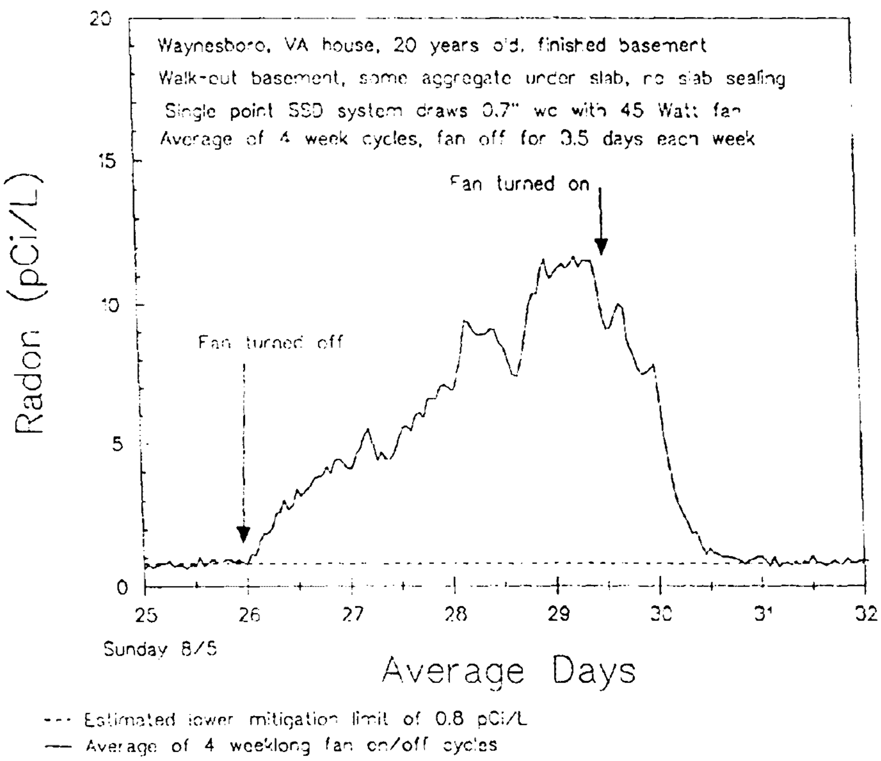


Figure 5 Average Mitigation Performance of 45 Watt Fan

# BUILDING RADON MITIGATION INTO INACCESSIBLE CRAWLSPACE NEW RESIDENTIAL CONSTRUCTION

D. Bruce Harris and A. B. Craig
U. S. EPA
Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

and

Jerry Haynes
Hunt Building Corporation
El Paso, TX 79984

ABSTRACT Specifications for new residential housing units for base personnel at Ellsworth Air Force Base, Rapid City, SD, called for demonstrated radon levels below 4 picocuries per liter (pCi/L) before they would be accepted by the Air Force. Hunt Building Corporation decided that it would be cheaper to build radon control systems into all the units than to have to retrofit some later. The Radon Mitigation Branch of EPA's Air and Energy Engineering Reasearch Laboratory assisted during the design and installation of the active soil depressurization (ASD) systems and followup measurements. The buildings utilized below grade wood floor construction over an inaccessible crawlspace because of the highly expansive soils. The initial installations demonstrated the need for complete sealing of the floor system. An effective quality control scheme was instituted which tested the negative pressure field established under every building and required additional sealing until each corner of the floor was under at least 2.5 pascals (Pa). Early data indicate that moderate levels of radon (100 pCi/L) exist in the crawlspace when the mitigation fan is off for several days and virtually none when it is on. Results from several buildings 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.

## BACKGROUND

A major housing project which will be leased by the Air Force at Ellsworth Air Force Base, Rapid City, SD, is being built by the Hunt Building Corporation. The housing project has 828 residential units in 251 buildings, consisting of singles, duplexes, and quadruplexes. The area where the houses are being built is known to be radon-prone. The Air Force had tested 30 of their 2500 houses and found about 60% of them above 4 pCi/L. As a result of this high radon incidence, the Air Force's initial Request for Proposal (RFP) contained a radon performance clause requiring the builder to test the houses before occupancy to guarantee that they were below 4 pCi/L. A unit testing below 4 pCi/L is accepted by the Air Force for occupancy and a 1-year alpha track test is commenced. If radon levels in the living area test below 4 pCi/L for the first year, then Hunt has met its performance requirement and no longer has any responsibility. If the house initially tests above 4 pCi/L, then Hunt must bring the level below 4 pCi/L before occupancy. When the 1 year test increases above 4 pCi/L, then the Air Force will stop payment until the level has been brought below 4 pCi/L.

With limited radon control experience, Hunt Building Corporation contacted EPA to seek advice on the best way to construct these multifamily housing units to ensure radon levels of below 4 pCi/L or to mitigate them to this level if they are found to contain higher levels when tested. The decision was made by Hunt to install a radon mitigation system in all units since retrofit into an inaccessible crawlspace would be very difficult and potentially expensive.

## MITIGATION SYSTEM DESIGN

Most of the units are two-story quadruplexes with the lower level built approximately 3 ft (1 m) below grade (Figure 1). The individual units are separated by a double wall for sound deadening, but no firewall. Because the units are built on expansive soils the Air Force is requiring that the lower floors be treated plywood over joists with a crawlspace below. The units are built with a 6 in. (15 cm) crawlspace between the bottom of the joists and the clay under the units. The building site is being excavated to a depth of 5 ft (1.5 m) and backfilled with compacted glacial aggregate in an effort to stabilize the ground and minimize movement. This is moraine till which is quarried on site consisting of a moraine stone with a great deal of fine sand and some soil in it.

After reviewing the various techniques which AEERL has tested on the mitigation of radon in crawlspace houses, it was recommended that the most cost-effective way to mitigate the house with a high level of assurance of lowering levels to below 4 pCi/L was to use either suction under a polyethylene sheet in the crawlspace or suction on the crawlspace itself. It was decided that there was an excellent chance of making suction on the crawlspace satisfactory by doing a thorough job of sealing the plywood subfloor. The plywood is tongue and groove along the 8 ft (2.4 m) edge, and all 4 ft (1.2 m) edges are on joists. The plywood is screwed to the joists. No outside vents are in the crawlspace, and every effort is made to make the crawlspace as airtight as possible. Moisture should be controlled by the active mitigation system. The joint between the floor and the concrete wall is sealed with polyurethane caulk. Any cuts through the polyethylene and plywood for pipes are carefully sealed around the pipe with polyurethane foam. Hunt has built a box in the joists under the bathtub so the bathtub trap does not penetrate into the crawlspace and provide a possible radon entry route.

One suction pipe per unit is used. This 6 in. pipe, in the wall between the two middle units of each quadruplex, extends straight up to the fan in the attic and exits the roof immediately above.

TESTING FIRST UNITS

Since the building season is short in South Dakota, testing began as soon as the first crawlspace floor was installed. AEERL sent a team to Ellsworth Air Force Base to install a temporary fan on the system and to measure pressure reduction at the various points of the crawlspace below the plywood floor. When negative pressures can be achieved throughout the crawlspace as measured in all four of the corners, the greatest distances from the suction point, then no soil gas should be sucked into the house. A 6 in. pipe was installed through the deck of a quadruplex at the intersection of the central "party" wall and the central beam which ran the full length of the unit. An axial aligned centrifugal fan was mounted on the pipe with power provided through a speed controller. An electronic manometer measured the pressure under the deck at several locations. Once a few small leaks had been sealed, at least -0.010 in. WC (-2.5 Pa) was obtained at each corner of the building and more than 1.0 in. WC (248.8 Pa) fan suction was recorded.

A duplex was the second unit tested. No perimeter or penetration sealing had been done so this provided an excellent opportunity to test the effect the extra sealing had on the suction obtained. No suction was detected at the corners and only

0.2 in. WC (49.8 Pa) of fan suction was measured which was the pressure drop through the floor opening. The fan suction was monitored while the sealing crew proceeded to close the openings. Little change was noticed until most of the wall joint and the pipe penetrations were closed. As the final openings were closed, dramatic increases in the fan suction were seen. The installation crew understood the need for carefully sealing all openings as a result of this test. This effort also provided the basis for the strict quality control and quality assurance program instituted by Hunt.

Every deck was tested when it was sealed and all plumbing activity was finished. A separate crew performed the tests and repaired breaks in the seal. A temporary fan depressurized the crawlspace and the sub-floor suction was measured. Any unit that failed to draw at least 0.010 in. WC in the corners was checked for leaks and resealed before additional construction activities were allowed to proceed. All buildings completed so far have exceeded the requirements when the seal was completed and a 6 in. fan installed. It may be possible to reduce the power consumption further by adding a speed control to the fans.

## RESULTS

As the first units were finished, an AB-5 Pylon radon monitor was used to check for radon in three units: a finished one with an operating mitigation system, a unit with a finished floor which had been sealed for 1 week, and a third with a just-completed floor without final sealing. No radon was found under the floor in the finished unit nor in the mitigation system duct.

Likewise, the completed but not sealed unit had no measurable radon in the crawlspace. The crawlspace under the sealed floor did yield levels of 100 pCi/L. This is a moderate source strength, but could be enough to elevate unmitigated units above the EPA action level of 4 pCi/L because the shell of each house is very tight and low dilution could be expected.

Acceptance testing of the first 130 unit section yielded levels between 0.8 and 2.4 pCi/L except for a single unit which had a carbon cannister reading of 16.0 pCi/L. A check of the system in this house found that the circuit breaker had been turned off; consequently, the reading was really an indication of the level that could have been expected if no mitigation system had been installed. A retest with the fan operating showed the levels reduced to 2.5 pCi/L. This fan inoperation showed that the effort and commitment of Hunt to install the mitigation systems and insist on an effective quality assurance program was well worth the investment. Retrofitting mitigation systems into these units would have been much more costly than doing it during the building phase.

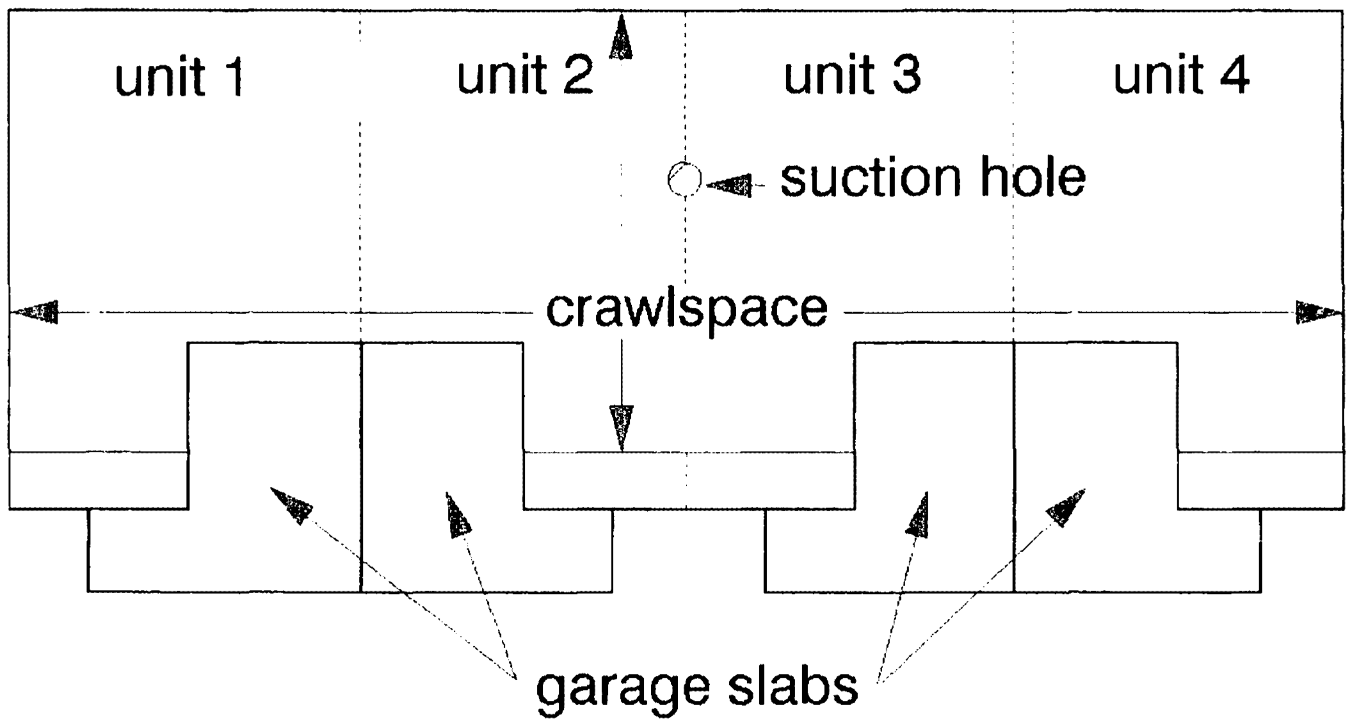


Figure 1. Quadruplex foundation plan

# THE EFFECT OF SUBSLAB AGGREGATE SIZE ON PRESSURE FIELD EXTENSION

K.J. Gadsby, T. Agami Reddy,
D.F. Anderson, and R. Gafgen
Center for Energy and Environmental Studies
Princeton University
Princeton, NJ 08544

Alfred B. Craig
Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

## ABSTRACT

Four sizes of commercially available crushed blue gravel aggregate (3/8, 1/2, 3/4, and 1 in. nominal diameter) were tested in a laboratory apparatus designed to experimentally determine the aerodynamic pressure drop coefficients of porous material such as soil and gravel. Permeability values for crushed stone of 1/2 and 3/4 in. nominal diameter were found to be 10-20 times higher than those reported in a previous study for river-run gravel of the same nominal diameter. Pressure field extension of this aggregate, when suction is applied to a single central suction hole (a practice widely used for mitigating buildings with elevated radon levels by the subslab depressurization technique), is also generated based on a disc flow model previously studied by the authors. Application of the disc flow model to residences with both basements and slab-on-grade construction is also described. Theoretical computations indicate that the permeability of soil around the foundation walls and periphery of the residence is a more crucial parameter affecting the pressure field extension than the permeability of the subslab gravel bed. The laboratory studies will be field verified in new construction of schools and houses in the future.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.[1]

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

## PROBLEM STATEMENT

Subslab air flow dynamics provide important diagnostic information for designing optimal radon mitigation systems based on the subslab depressurization (SSD) technique. An earlier study (Refs. 1 and 2) showed that subslab air flow induced by a central suction point can be mathematically treated as radial air flow through a porous bed contained between two impermeable discs. Subsequently, it was suggested that subslab material commonly found under residential buildings be categorized and tested in the laboratory in order to deduce their aerodynamic pressure drop coefficients. This would then permit the pressure field extensions to be inferred which would be of practical and realistic importance to radon mitigators. To this end, a laboratory apparatus was designed and built which is described fully in Ref. 3.

The scope of this study was limited to four aggregate mixes -- No. 600, 601, 602, and 603 -- provided by Vulcan Materials from their Manassas Quarry. The physical specifications provided by Vulcan Materials are given in Table 1. The aggregate is crushed blue gravel, a material commonly used as subslab material for residential and commercial housing.

This paper first reports aerodynamic flow coefficients of the four aggregate mixes obtained from EPA's laboratory apparatus. Subsequently, it describes how the disc flow model can be applied to residences with both basement and slab-on-grade construction. Finally, it shows generated pressure field extension plots for each aggregate in the framework of the above model and discusses the practical implications of these plots in the design of SSD systems.

## EXPERIMENTAL RESULTS

The laboratory apparatus, described fully in Ref. (3), is shown in Fig. 1. It consists of a straight length of 8 in.* PVC pipe approximately 5 ft long to the bottom of which a 1/4 in. aluminum removable screen is fitted. The screen, which slides in and out along a groove machined into the PVC pipe, is perforated with a pattern of 1/4 in. diameter holes to permit air flow. The porous material is loaded into the test column from the top after which another sleeve, containing flow straighteners and the air supply inlet tube, is placed on top of the column. Air is supplied to the system from the top and several pressure taps provide information on the pressure drop in the porous bed as air flows down through the porous bed in the test column. The total air flow rate is accurately measured. The experimental procedure involves

* For readers more familiar with metric units, 1 in. = 2.54 cm and 1 ft = 30.48 cm.

measuring the pressure drop ($\Delta P$) through a known and predetermined bed length ($\Delta L$) for a specific value of total flow rate (q). Several such tests are carried out over a range of q values for each sample of aggregate and for different samples of the same aggregate. A least-square regression finally provides estimates of the permeability (k) and the flow exponent (b) of the aggregate.

Table 2 assembles results of the porosity experiments, three different samples of each aggregate tested at least twice. This involved choosing a volume of the aggregate material and then finding the porosity by measuring the volume of water needed to completely saturate each sample (Ref. 4). The values of porosity ($\phi$) specified by the supplier and those obtained from the tests are shown in Table 2. Note that, in general, standard deviation values are less than 2% of the mean value, thereby indicating reproducibility. As for the mean values of porosity, note that those of aggregates No. 602 and 603 are close (within 10%) to those quoted by the suppliers while those of No. 601 and 602 deviate by as much as 20% from the quoted values. This relatively large difference in porosity values has not been explained.

Table 3 presents the various experiments performed as well as the values of k and b obtained by regression. The third column presents values of ($d_v/\phi$) which are needed to estimate the Reynolds number which gives an indication of the nature of the flow regime (whether laminar or turbulent) (Ref. 4). The value of gravel nominal size was assumed to be the diameter $d_v$ and was taken from the supplier's specifications (simply the mean value), while the corresponding values of porosity $\phi$ were taken from the experiments (Table 2). Two or three samples of each aggregate mix were tested and 10-20 runs were performed for each mix. This duplication was to ensure that experimental results obtained were representative and robust.

The range of air flow rates at which the experiments were performed for each aggregate and the corresponding range of resulting Reynolds numbers are also shown in Table 3. Generally, the flow is turbulent when Reynolds numbers are greater than about 10 (Ref. 4). In the experiments, the Reynolds numbers were higher than 10 but less than 50, a range of Reynold numbers which is expected for SSD air flow in gravel beds of residential buildings (Refs. 1 and 2). A further advantage of the Reynolds number range chosen is that the statistical determination of the parameters k and b is likely to be more accurate. Other than for aggregate No. 603, the $R^2$ values of the regression model are very good ($R^2 > 0.9$). This is an indirect indication that the experimental design was satisfactory. The relatively lower $R^2$ values for mix No. 603, which is the largest gravel, could be a result of the fact that, in order to keep Reynolds numbers low, the pressure drop was measured close to the sensitivity of the instruments (which was 0.25 Pa or 0.001 in. WC).

The mean and the coefficient of variation (CV) in percentage values for k and b are also given in Table 3. Permeability values of mix No. 600 are around $10^{-7}$ $m^2$, gradually increasing to about 7 x $10^{-7}$ $m^2$ for mix No. 603. It is worth pointing out that mixes No. 601 and 602 (1/2 and 3/4 in., respectively) have k values which are 10-20 times larger than those of river-run gravel of the same nominal diameter, as reported in a previous study (Refs. 1 and 2). A possible explanation for this is that river-run gravel beds have lower porosity; i.e., they tend to pack more closely (Refs. 1 and 2). This important finding suggests that crushed aggregate is more suitable as a subslab material fill than river-run gravel for buildings to be mitigated using the SSD system since the former is likely to have a larger pressure field extension from the suction hole. The flow exponent b does not vary too much with mix. The relatively higher value for mix No. 602 does seem surprising since both No. 601 and 603 have lower values for b. A possible reason for the low b value for mix No. 603 is that it had relatively more fines in the aggregate. CV values for k are low (less than 3%), while those for b are high, as much as 12% for mix No. 603.

## PRESSURE FIELD EXTENSION

This section gives results of computing the pressure field extension under the slab when the four crushed gravel sizes are used as subslab fill material, using the disc flow model described in Ref. 1. Consequently, the following conditions are assumed:

- only one suction hole is used,
- the suction hole is located at the center of the slab,
- the slab is circular, and
- the edges of the slab communicate uniformly with the ambient air.

Figure 2 illustrates how flow conditions in an actual house with a basement can be visualized in the framework of the disc model. The square basement is approximated as a circle of radius $r_0$ while the extra flow path H through the soil around the house is accounted for by effectively increasing the circle radius to R. Thus the flow is assumed to occur between two impermeable discs, the upper end being the underside of the basement slab and the lower end being the soil beneath the gravel bed. Since the material under the slab is gravel while the extra flow path around the sides of the house is through soil of different permeability than that of the gravel, this model was modified to represent a disc made up of two materials of different permeabilities: soil between radii $r_0$ and R, and gravel between $r_0$ and the central mitigation pipe. As pointed out in Ref. 1, the flow regime would likely be turbulent through the gravel bed and laminar through the soil.

Consequently the total pressure drop $\Delta P$ (in head of water) across the two-material bed is equal to the pressure drop through the gravel plus the pressure drop through the soil. From equations derived in Refs. 1 and 2:

$$\Delta P = \frac{1}{k_g}\cdot\frac{\nu_a}{g}\cdot\frac{\rho_a}{\rho_w}\cdot\left(\frac{q}{2\pi h}\right)^b\cdot\frac{1}{(1-b)}\cdot\left(r_o^{1-b}-r_s^{1-b}\right)$$
$$+\frac{1}{k_s}\cdot\frac{\nu_a}{g}\cdot\frac{\rho_a}{\rho_w}\cdot\frac{q}{2\pi h}\cdot\ln\left(\frac{r_o}{R}\right)$$

| | | | |
|---|---|---|---|
| where | $k_g$ | - | permeability of the gravel bed, |
| | $\nu$ | - | kinematic viscosity, |
| | g | - | gravity |
| | $\rho$ | - | density, |
| | q | - | total air flow rate, |
| | h | - | thickness of the gravel bed, |
| | b | - | flow exponent, |
| | $r_o$ | - | radius of the basement |
| | $r_s$ | - | radius of the suction pipe, |
| | $k_s$ | - | permeability of the soil surrounding the house, |
| | R | - | total radius of flow (equal to that of the basement and of the extra flow path through the soil). |

Note that the pressure drop given by Equation (1) is not the entire pressure drop to be overcome by the mitigation fan. The pressure drop due to entrance effects into the mitigation pipe and that due to the straight pipe, fittings, and bends could account for as much as 50% of the entire pressure drop in the mitigation system.

Two types of construction were studied: slab-on-grade and basement houses. In the framework of the disc model, the difference between the two is solely in terms of the extra flow path through the soil. Basement houses will tend to have higher H values (see Fig. 1) than slab-on-grade houses; consequently the ($R-r_o$) value will be correspondingly different. The following values, deemed representative, have been chosen in all calculations that follow:

slab-on-grade: $R = r_o + 1$ m

basement house: $R = r_o + 3$ m

Also selected were $r_s = 5$ cm (i.e., a 4 in. diameter suction pipe for the mitigation system) and a value of h = 0.05 m (which is based on experience and supported by tests in an actual house described in Ref. 1). Equation 1 cannot be directly used to compute the required suction pressure for different values of basement radius $r_o$, since the total air flow rate q is not an independent variable. It is determined by the practical criterion, which is that the pressure below the actual slab (i.e., up to a radius $r_0$) should be lower than the ambient pressure $P_a$ by an amount larger than the depressurization of the house arising from natural causes (e.g., wind, stack effect, heating, ventilation, and air conditioning system (HVAC) depressurization). A realistic range for this depressurization is 3-10 Pa (Ref. 5). Consequently, the flow rate q should be such that a pressure drop equal to this depressurization occurs in the outer portion of the disc containing soil; i.e., between R and $r_o$. Since the flow is laminar in this region, q is computed from:

$$q = (\Delta P) \cdot k_g \cdot \frac{g}{\nu_a} \cdot \frac{\rho_w}{\rho_a} \cdot \frac{2\pi h}{\ln\left(\frac{r_o}{R}\right)} \tag{2}$$

where ΔP is the prespecified minimum depressurization below all points of the slab expressed in head of water.

The value of q is then used in Equation (1) to calculate the required suction pressure at different values of slab radius $r_o$. Note that the numerical value of $k_s$, soil permeability, greatly influences q and consequently the pressure field extension. Hence the two following cases were chosen in order to study the sensitivity of the pressure field extension on the type of boundary fill material (Ref. 6):

(i) $k_s = 10^{-8}\ m^2$, corresponding to sand and gravel mixtures,

(ii) $k_s = 10^{-10}\ m^2$, corresponding to fine sands.

Additionally, a value of 10 Pa has been selected as the required pressure drop through the soil between radii R and $r_o$ due to reasons discussed above.

Figures 3 and 4 present the computed suction pressures for cases (i) and (ii), respectively, for the four gravel sizes tested and for both basement and slab-on-grade type construction. Note that differences in field extension between gravel sizes for the subslab bed material, especially mixes No. 602 and 603, are much less important than those resulting from soil type selection. Figures 3 and 4 show that there is an order of magnitude difference in pressure requirements between the two construction types; it is lower for case (ii), lower permeability soil. This fact highlights the importance of having a ring of low permeability soil around the foundation walls and the periphery of the building. There is an important difference in suction pressures between basement and slab-on-grade construction for case (i), but this is so for the tighter soil (Fig. 4). This is because most of the pressure drop occurs across the outer ring of soil, with practically no drop through the gravel bed itself. Thus theoretically, for fine soils (case ii), the pressure field extension is very large (radius greater than 50 m). However, in practice, looseness in packing of the soil, short-circuiting of flow paths, or small holes or cracks in the slab will drastically decrease this value.

Finally, Fig. 5 presents the total air flow rate for case (i) for slab-on-grade and basement construction. These flows are independent of the gravel size since they have been computed from Equation (2) following the condition that the pressure drop in the outer ring consisting of soil is equal to a prespecified minimum amount taken as 10 Pa in this study. Note that the air flow rates between the slab-on-grade and basement cases differs by almost a factor of three.

## FUTURE WORK

This study was undertaken to experimentally determine the aerodynamic flow coefficients (permeability and flow exponent) of four crushed aggregate mixes of commercially available stone. The sizes, ranging from 3/8 to 1 in. nominal diameter, are gravel sizes often used as subslab fill for residences and large buildings. An important finding of this study is that permeability values of 1/2 and 3/4 in. crushed gravel were 10-20 times higher that those reported in a previous study for river-run gravel of the same nominal diameter. Field validation of the computed pressure field extension using laboratory test results is important and such tests are currently being planned in newly constructed schools, commerical buildings, and houses. The results presented here should be used with caution until such time that the apparatus and experimental design are more fully validated.

## ACKNOWLEDGEMENTS

D. Harrje and R. de Silva contributed generously during the design and construction of the laboratory column. Useful discussions with A. Cavallo and R. Sextro are also acknowledged.

## NOMENCLATURE

| | |
|---|---|
| $b$ | flow exponent |
| $d_v$ | equivalent diameter of gravel |
| CV | coefficient of variation |
| $g$ | acceleration due to gravity |
| $h$ | thickness of the porous bed |
| $k$ | permeability of gravel |
| $\Delta L$ | length of porous bed in flow direction |
| $\Delta P$ | pressure drop |
| $P$ | pressure |
| $q$ | total volume air flow rate |
| $R^2$ | coefficient of determination of regression |
| Re | Reynolds number |
| $R$ | total radius of air flow path |
| $r_o$ | effective radius of basement |
| $r_s$ | radius of suction pipe |
| $\rho$ | density |
| $\nu$ | kinematic viscosity |
| $\phi$ | porosity of porous bed |

Suffix

| | |
|---|---|
| a | ambient, air |
| g | gravel |
| s | suction pipe, soil |
| w | water |

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TABLE 1. QC ANALYSIS OF VULCAN MATERIALS CRUSHED AGGREGATE AS SUPPLIED BY THE COMPANY

| Vulcan | | % Passing Screen Size | | | | | | | Loose | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | Description | 1-1/2 | 1 | 3/4 | 1/2 | 3/8 | 3/16 | 3/32 | Bulk Density | Void Volume |
| 600 | 3/8 in. clean | | | | 100 | 90 | 23 | 5 | 91.8 | 49.3 |
| 601 | 1/2 in. clean | | | 100 | 83 | 27 | 3 | 1 | 89.4 | 50.6 |
| 602 | 3/4 in. clean | | 100 | 93 | 27 | 7 | 2 | | 95.1 | 47.5 |
| 603 | 1 in. clean | 100 | 94 | 40 | 6 | 2 | 1 | | 93.0 | 48.6 |

TABLE 2. COMPARATIVE RESULTS OF POROSITY TESTS

| Vulcan No. | Nominal Size (in.) | Porosity From Supplier | Porosity Present Tests |
|---|---|---|---|
| 600 | 3/8 | 0.493 | 0.403 (0.006)* |
| 601 | 1/2 | 0.506 | 0.419 (0.011) |
| 602 | 3/4 | 0.475 | 0.436 (0.015) |
| 603 | 1 | 0.486 | 0.452 (0.009) |

*Values in parentheses are standard deviation values.

TABLE 3. SUMMARY OF EXPERIMENTAL DATA

| Vulcan No. | Nominal Size (in.) | $d_v$ $\phi$ (mm) | Number of Samples Tested | Flow Range (l/min) | Range of Reynolds Numbers | Number of Observations | Regression Model $R^2$ | Permeability $k \times 10^9$ ($m^2$) | Exponent b |
|---|---|---|---|---|---|---|---|---|---|
| 600 | 3/8 | 2.36 | 3 | 6 - 21 | 5 - 18 | 20 | 0.91 | 104.4 (2.5)* | 1.14 (7.0) |
| 601 | 1/2 | 3.03 | 2 | 19 - 28 | 20 - 30 | 11 | 0.99 | 193.6 (0.4) | 1.15 (3.5) |
| 602 | 3/4 | 4.37 | 2 | 19 - 28 | 29 - 42 | 10 | 0.92 | 336.3 (1.2) | 1.29 (10.9) |
| 603 | 1 | 5.62 | 3 | 19 - 30 | 37 - 58 | 16 | 0.84 | 683.9 (1.2) | 1.17 (12.0) |

* Values in parentheses are coefficient of variation (CV) values where CV = (Mean value/Standard error of the mean) x 100

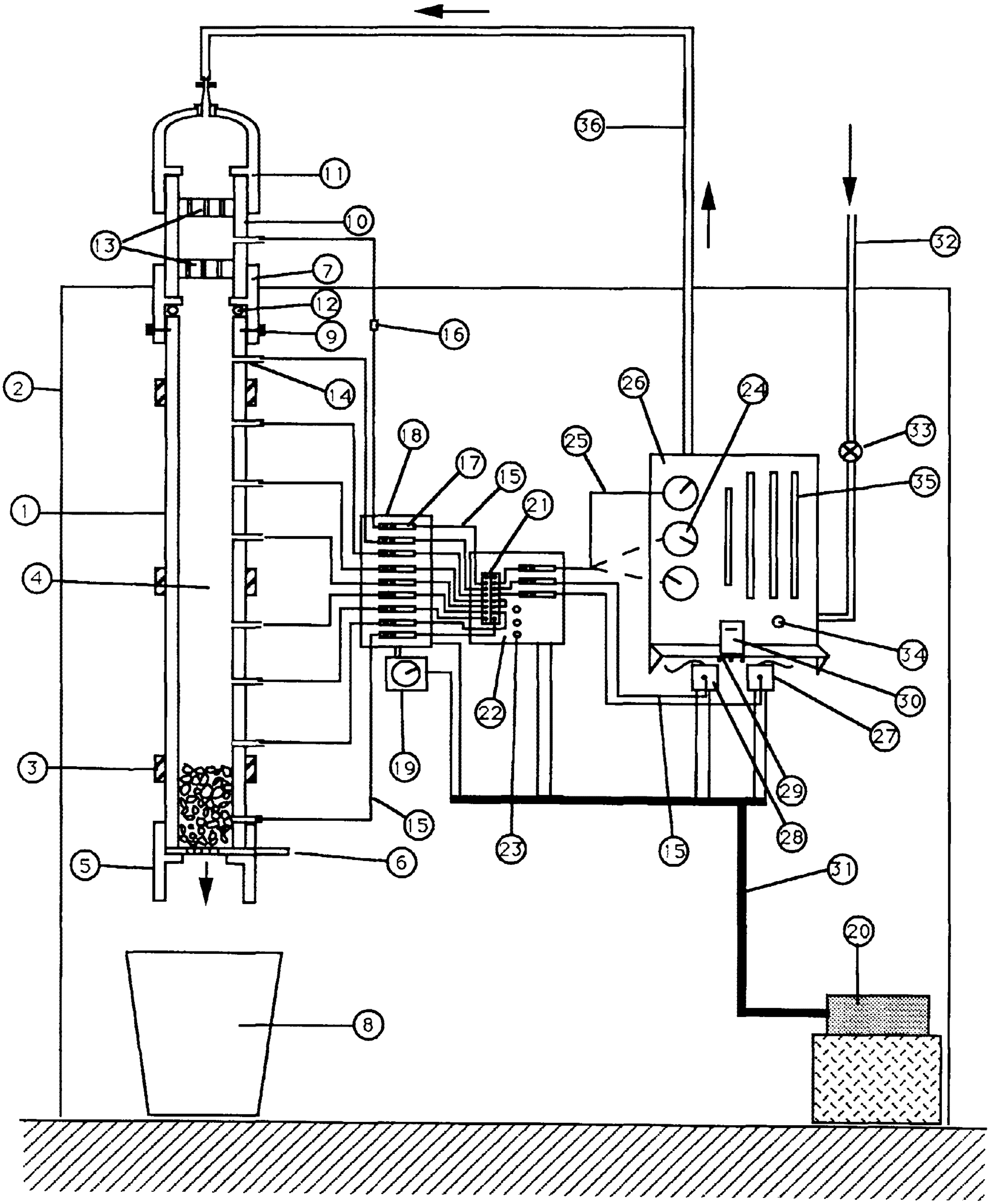



Figure 1. Sketch of the flow apparatus. List of components is attached.

<u>Key for Figure 1</u>

(1) Main Column - Schedule 40, PVC, 8 in. Pipe
(2) Test Rig Panel
(3) Support Blocks
(4) Test Material Cavity
(5) Lower Sleeve
(6) Movable 1/4 in. Aluminum Screen
(7) Upper Sleeve
(8) Collection Bin
(9) Assembly Bolts
(10) Short Pipe Section
(11) End Cap
(12) "O" Ring
(13) Flow Straighteners
(14) Pressure Taps
(15) Urethan Tubing
(16) Tubing Union
(17) Miniature Solenoid Valves
(18) Solenoid Panel
(19) Valve Selector Switch
(20) 12 Volt DC Power Supply
(21) Manifold
(22) Manifold Panel
(23) Transducer Selector Switches
(24) Pressure Gauges
(25) Interchangeable Connector Tubing
(26) Gauge and Flowmeter Panel
(27) High Pressure Transducer
(28) Low Pressure Transducer
(29) DVM Connector
(30) Digital Voltmeter (DVM)
(31) Wiring Harness
(32) Air Supply
(33) Shutoff Valve
(34) Flow Control Valve
(35) Flowmeters
(36) Tubing from Flowmeter to Column

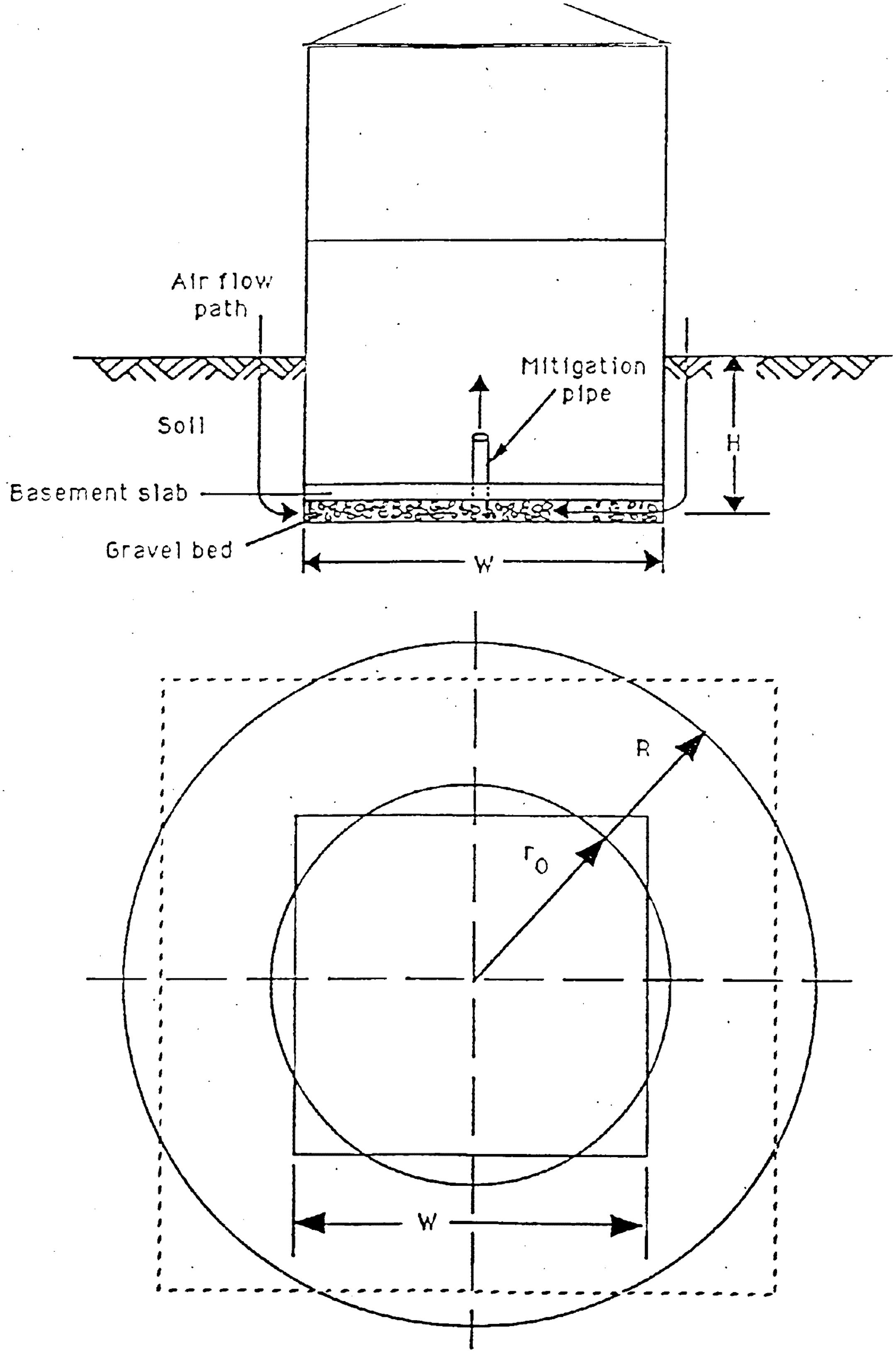



Figure 2. Disc model of a SSD mitigation system in a basement house.

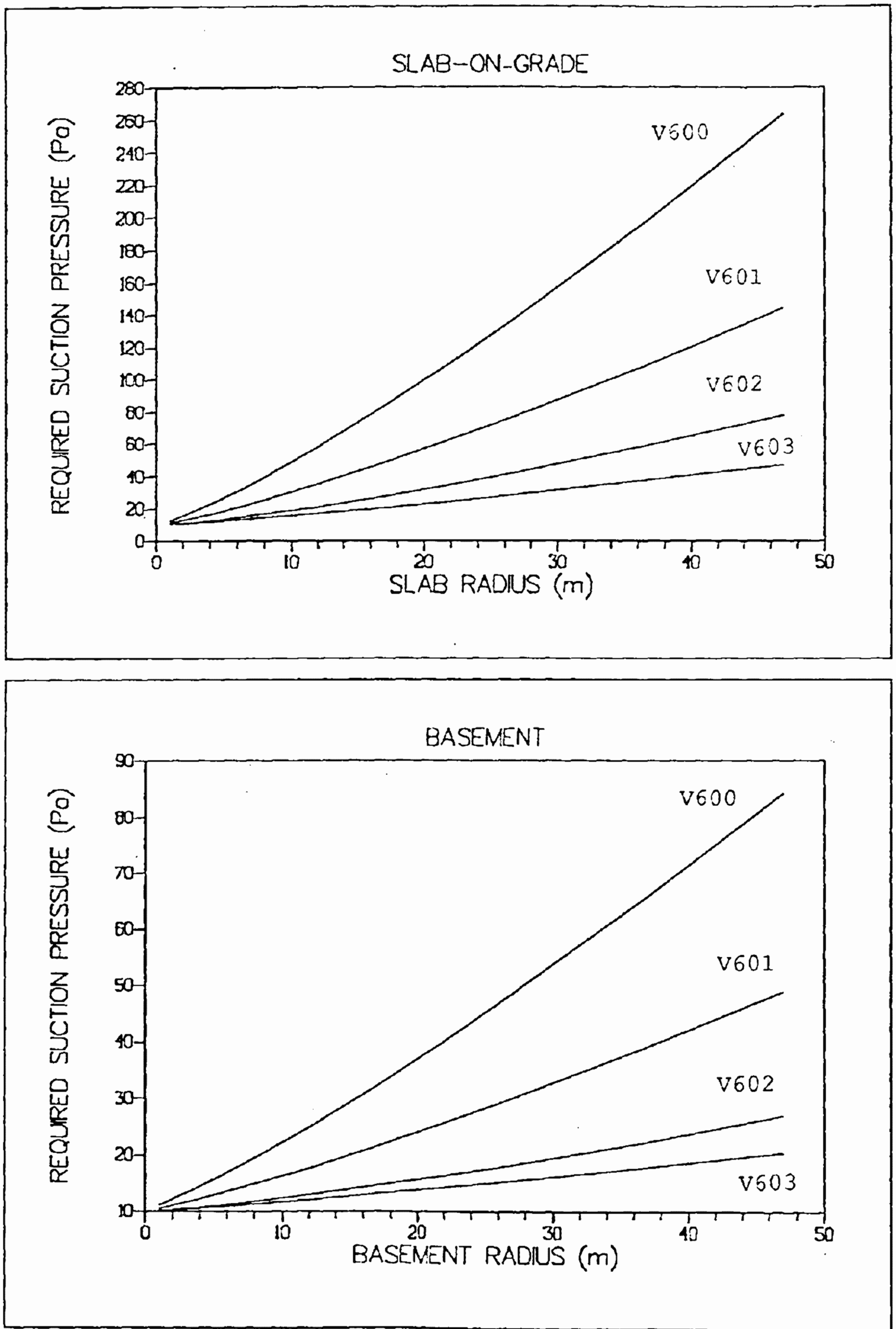
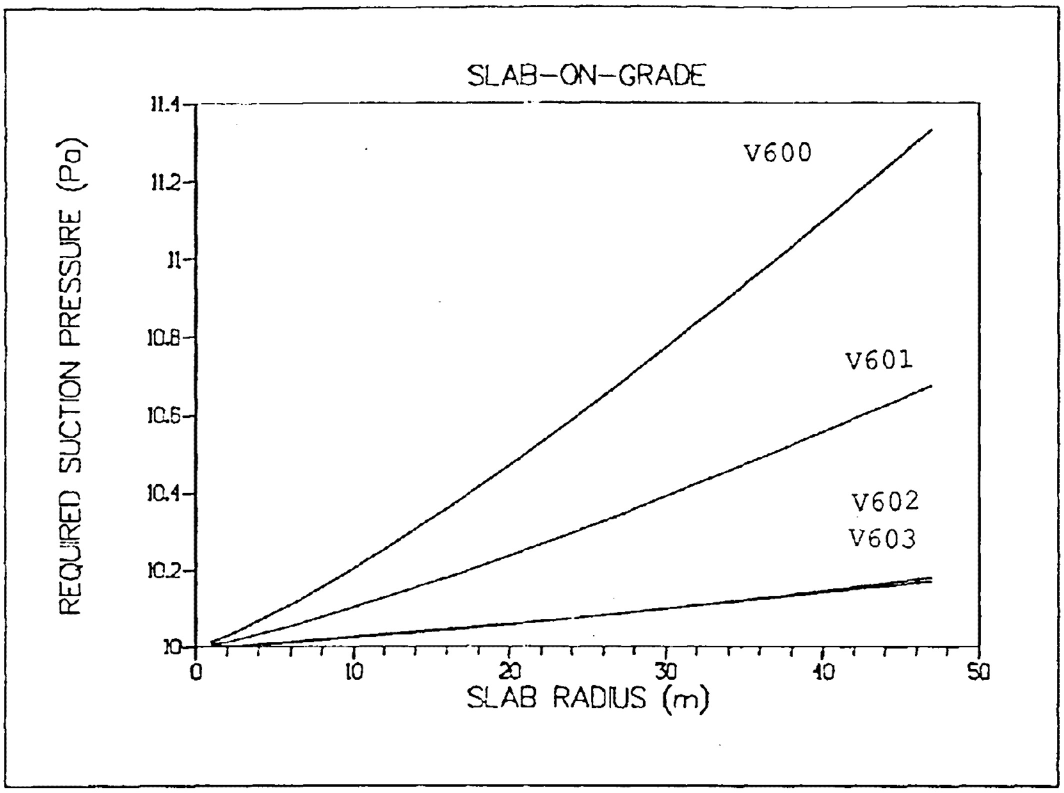



Figure 3. Pressure field extension for case (i): $k_s = 10^{-8}\ m^2$ for the four gravel mixes tested. Soil flow path length is 1 m for slab-on-grade and 3 m for basement houses.



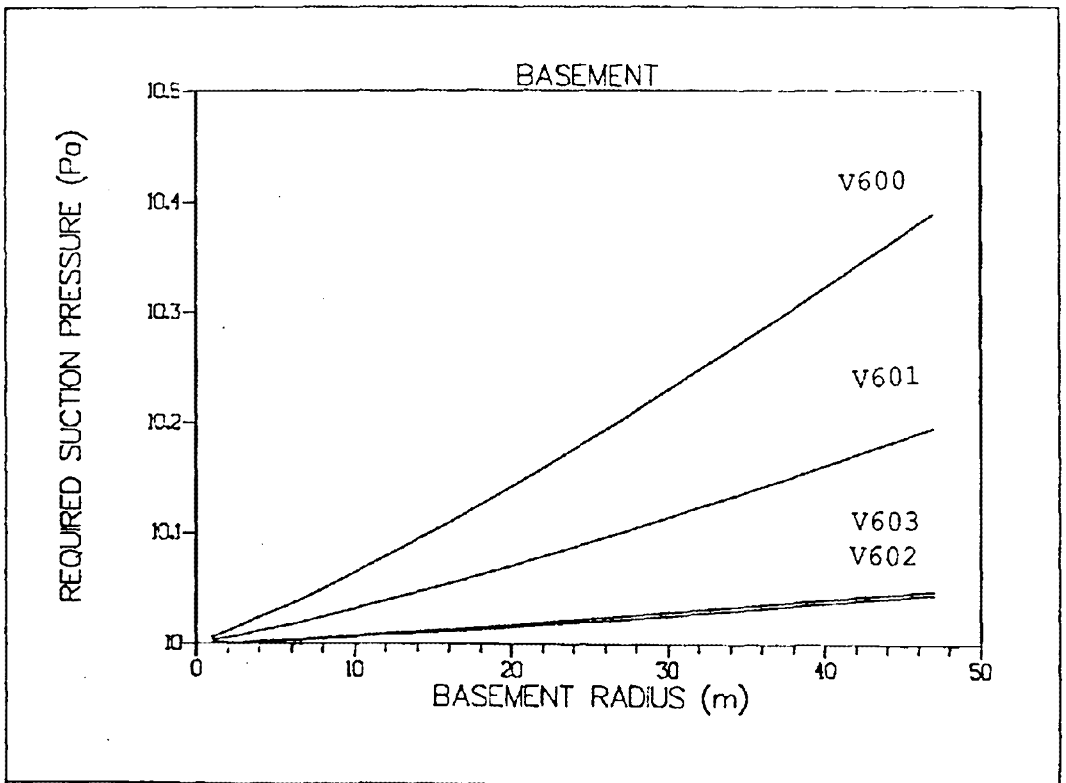




Figure 4. Pressure field extension for case (ii): $k_s = 10^{-10}\,m^2$ for the four gravel mixes tested. Soil flow path length is 1 m for slab-on-grade and 3 m for basement houses.

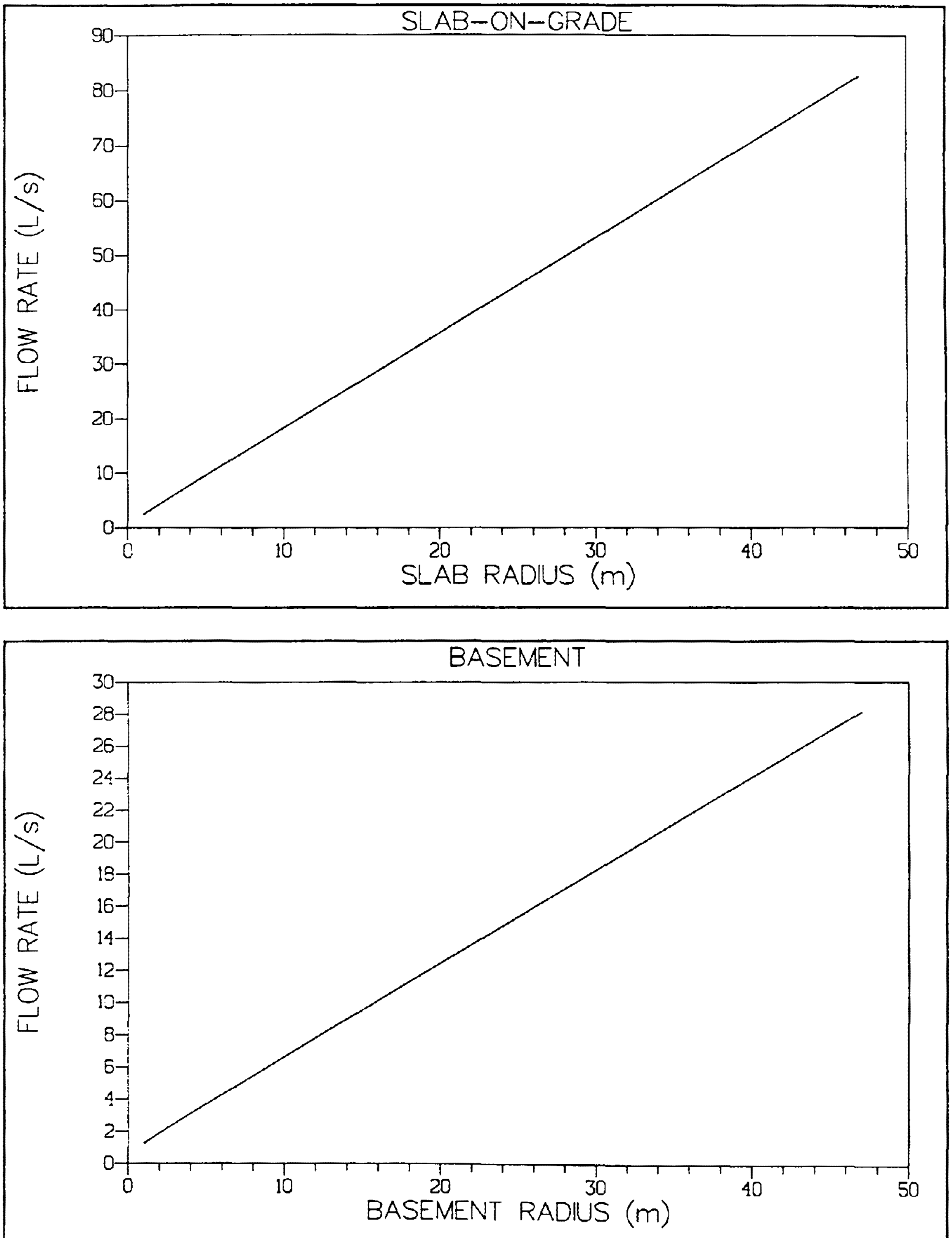



Figure 5. Total air flow rates for case (i): $k_s = 10^{-8}$ m$^2$, computed from Eq. (2).

# Session IX

## Oral Presentations

## Radon Occurrence in the Natural Environment

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

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.

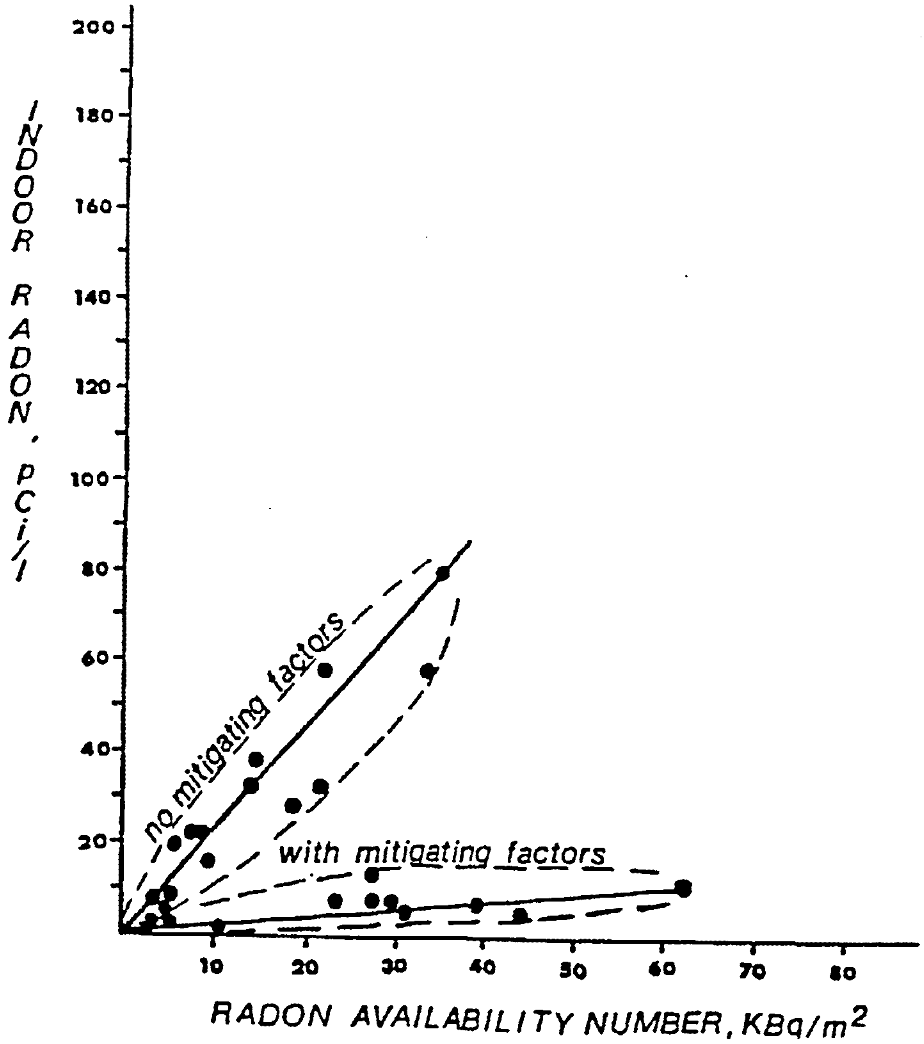



Figure 1. Correlation between soil test results (radon availability number) and indoor radon concentration.

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.

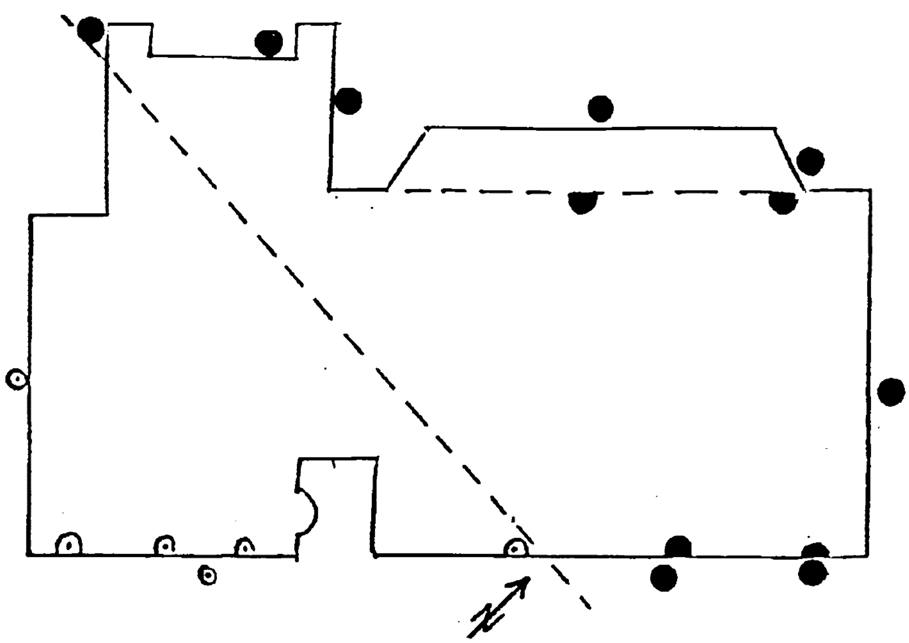


Figure 2. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N60°W fracture trends.

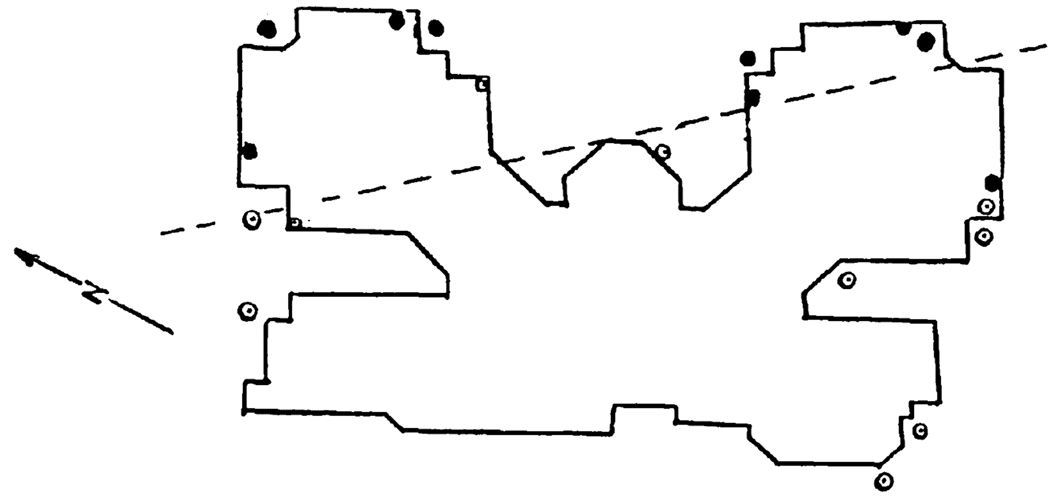



Figure 3. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N45°W fracture trends.

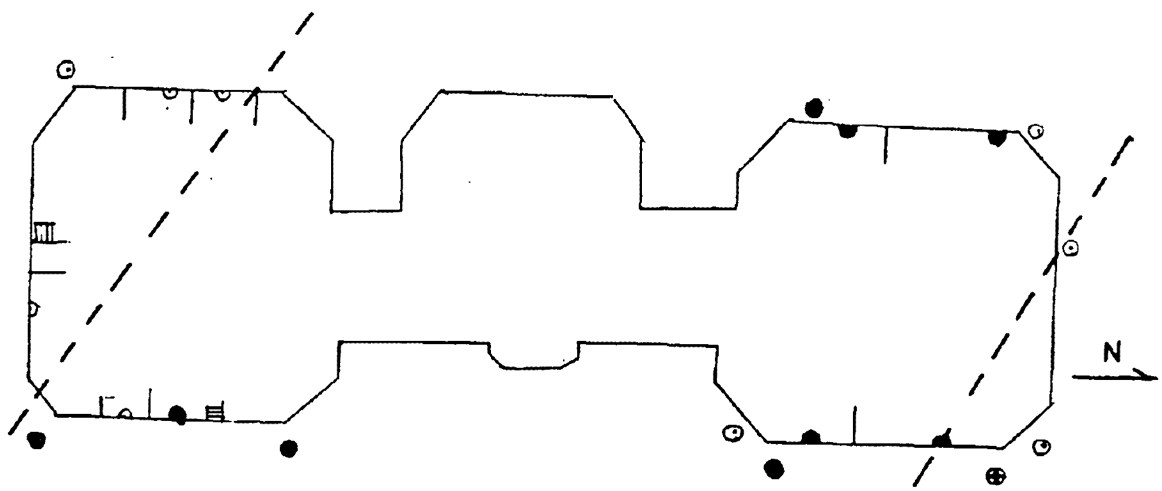



Figure 4. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N45°W fracture trends.

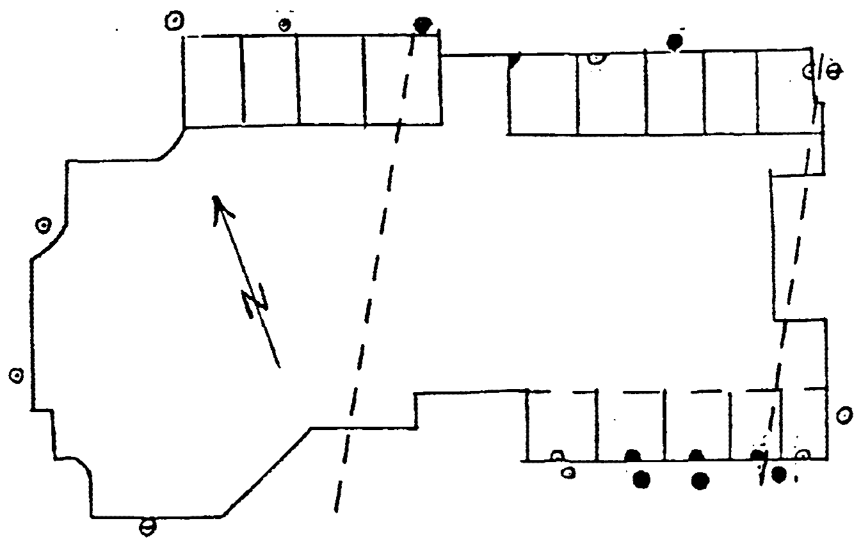


Figure 5. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N30°E trending rock layers.

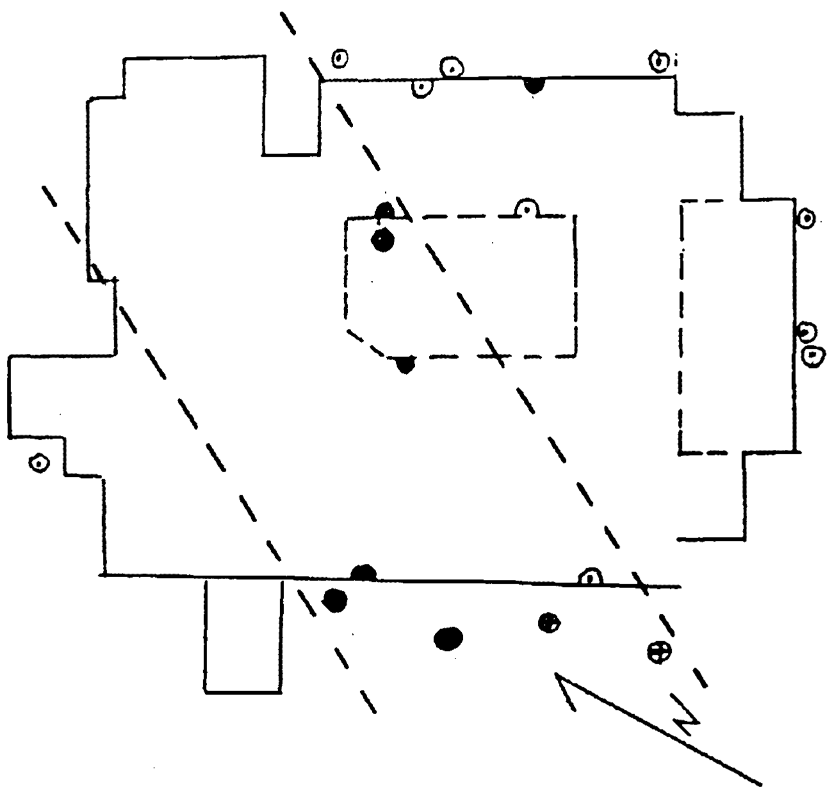


Figure 6. Footprint plan of a school showing highest soil radon potentials (RAN) and indoor slab/wall joint radon concentrations darkened. Highest soil radon potentials follow N30°E trending rock layers.

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.

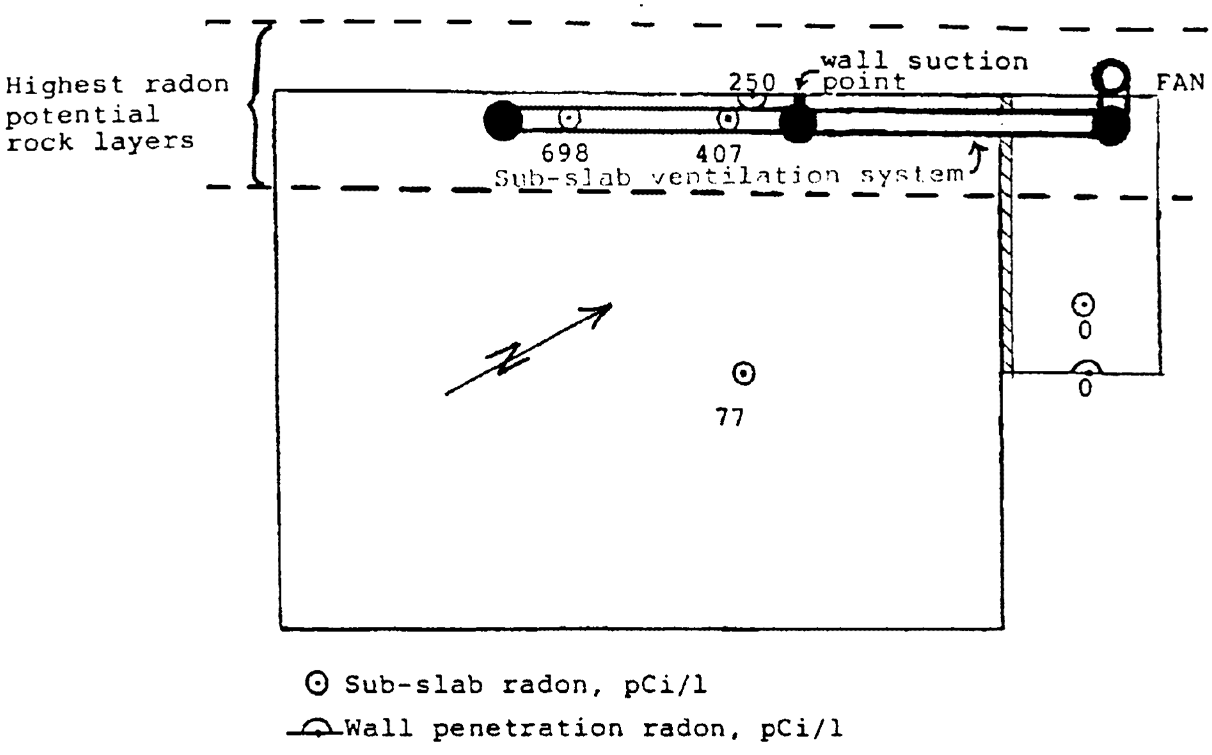



Figure 7. Footprint plan of a home showing numerical values of sub-slab and blockwall radon concentrations that indicate that the radon source is following N30°E rock layers, delineated by dash lines. Sub-slab ventilation systems penetrations are shown as darkened circles.

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.

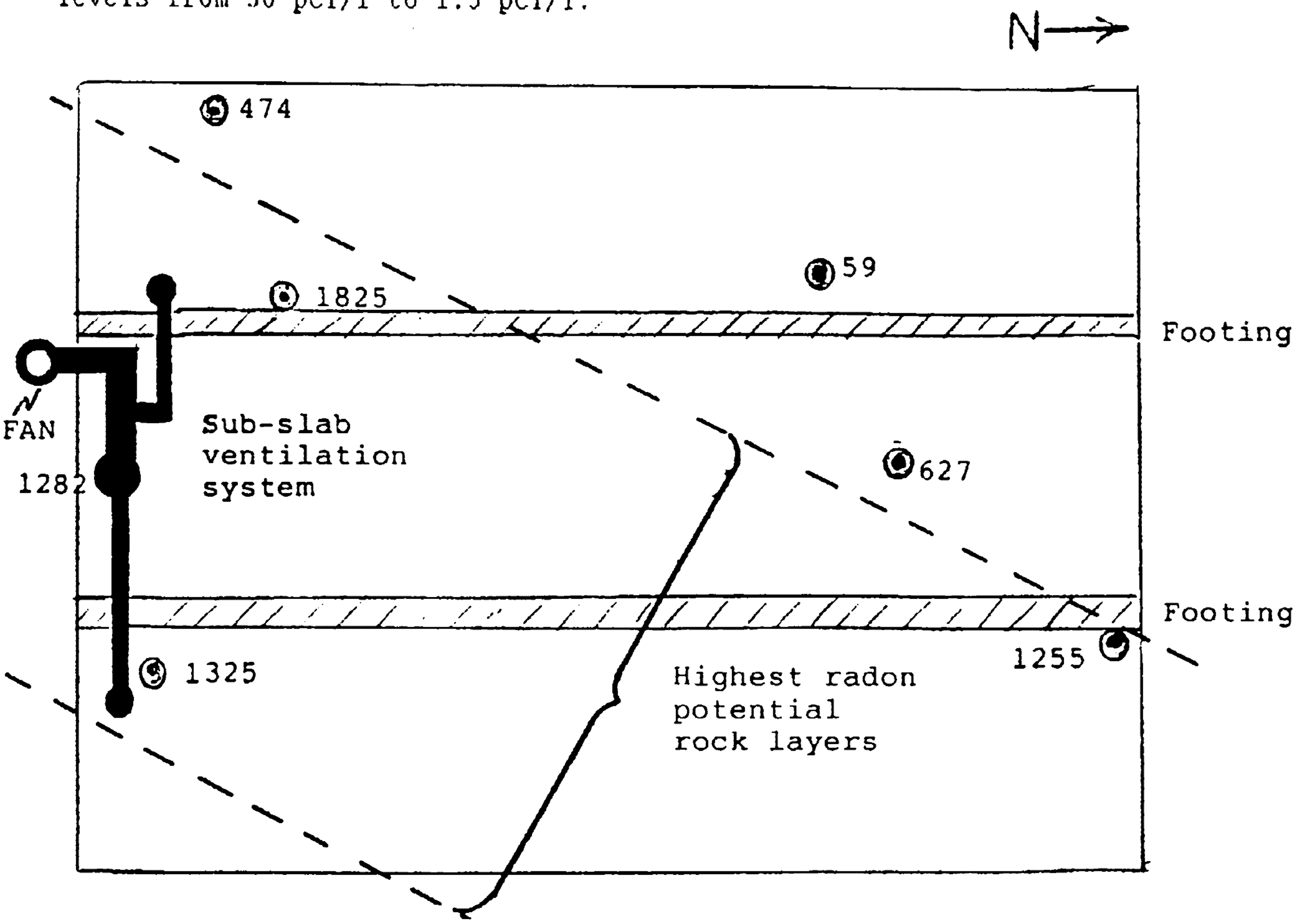



Figure 8. Footprint plan of a home showing numerical values of sub-slab and blockwall radon concentrations that indicate that the radon source is following N30°E rock layers, delineated by dash lines. Sub-slab ventilation systems penetrations are shown as darkened circles.

Figure 9 shows a workplace building with a footprint area less than 2000 ft² 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.

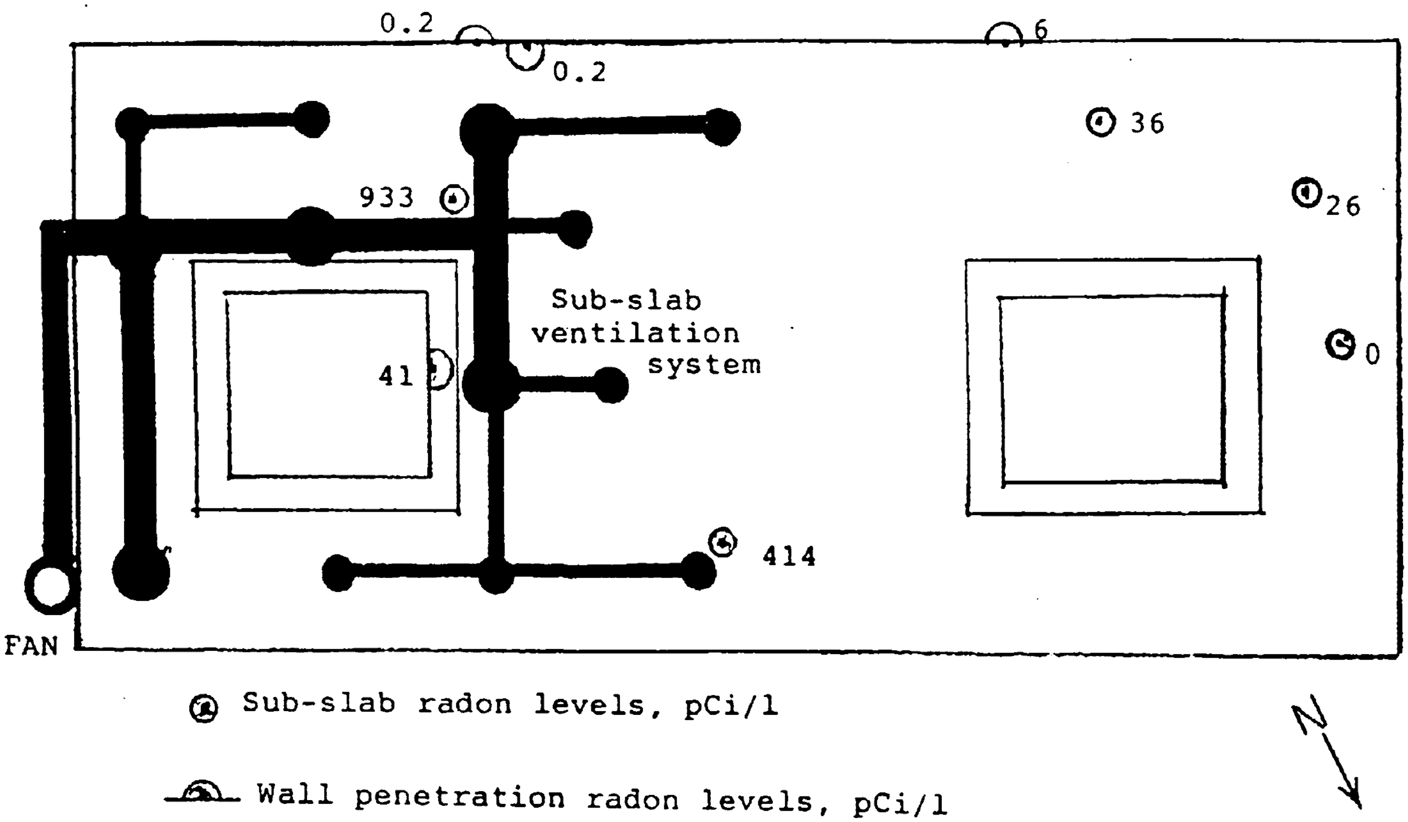



Figure 9. Footprint plan of a home showing numerical values of sub-slab and blockwall radon concentrations that indicate that the radon source is following N30°E rock layers. Sub-slab ventilation systems penetrations are shown as darkened circles.

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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# PRELIMINARY RADON POTENTIAL MAP OF THE UNITED STATES

Linda C.S. Gundersen, R. Randall Schumann, James K. Otton,
Russell F. Dubiel, Douglass E. Owen, Kendell A. Dickinson
U.S. Geological Survey, MS 939 Federal Center
Denver, Colorado 80225-0046

R. Thomas Peake and Sharon J. Wirth
U.S. Environmental Protection Agency
Washington D.C. 24060

## ABSTRACT

The geologic radon potential of the United States has been the subject of a one-year project by the U.S. Geological Survey and the Environmental Protection Agency, in cooperation with the Association of American State Geologists. 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. A numeric radon index and confidence index have been developed as part of this project to quantify and standardize geologic radon potential assessment on a regional scale. Publications from this study will be released in the fall of 1991 and will include an annotated 1:7.5 million-scale map of the United States that delineates the radon potential of 55 geologic provinces. Detailed radon potential books containing numerous indoor radon maps, geologic maps, and extensive radon bibliographies for each state will also be available.

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

Congress directed the U.S. Environmental Protection Agency (EPA) to identify areas of the United States with the potential to produce potentially harmful levels of indoor radon (Indoor Radon Abatement Act of 1988, Public Law 100-551). These characterizations were to be based on geological data and data on indoor radon levels in homes and other structures. The information is to be used to define high radon potential areas for schools, workplaces, and residences. The EPA was also directed to develop model standards and techniques for new building construction that would provide adequate prevention or mitigation of radon entry. They also acknowledge that some areas may not require any radon resistant features (1).

As part of an Interagency Agreement between the EPA and the U.S. Geological Survey (USGS), the USGS is preparing radon potential estimates for the United States in order to help identify and prioritize areas toward which states could target their resources and in which the different building code options would be most appropriate. The U.S. Geological Survey is developing several products that will provide geologically-based characterizations of radon potential at both regional and national scales. Booklets are being developed for each state that will present a general overview of the geology and known or predicted correlations between geologic features and radon in soils. The booklets will serve as a more detailed guideline for states than the national scale products, with data presented at the county scale. In the booklets, some generalizations have been made in order to estimate the radon potential of each county unit as a whole. Variations in geology, soil characteristics, climatic factors, and homeowner lifestyles can be quite large within any particular county, therefore these reports cannot be used to estimate or predict the indoor radon concentrations of individual homes or housing tracts. Indoor radon surveys used for the evaluations are also not consistently statistical at the county scale.

A geologic radon potential map of the United States is also being produced, a preliminary version of which is presented in this paper (Figure 1). The final published version of the map will be presented at a 1:7.5 million scale and will include extensive text and annotation. This map illustrates the radon potential of the country by the

Geologic Radon Potential of the United States of America

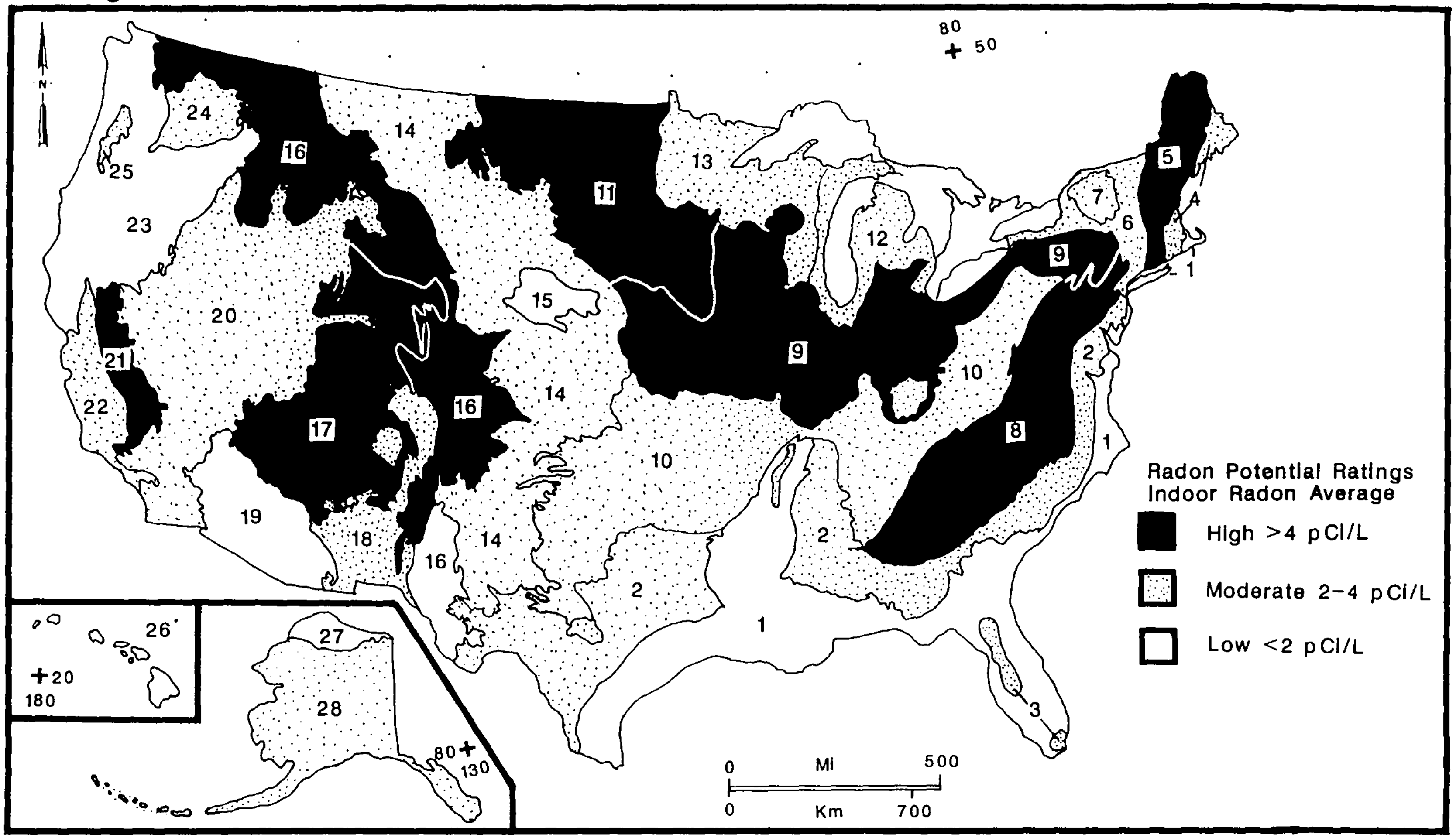


Figure 1.

major geologic provinces of relevance to the radon problem. It incorporates geologic evaluations of radioactivity, soils, surficial materials, and bedrock lithology in the context of screening indoor radon measurements for the country. The following sections describe the geologic environment of radon, the data and methodology used to evaluate radon potential, and a brief summary of radon potential of the United States by region.

## RADON FORMATION AND MIGRATION

Radon-222 ($^{222}Rn$) is produced from the radioactive decay of radium-226 ($^{226}Ra$), which is, in turn, a product of the decay of uranium-238. Other isotopes of radon occur naturally, but are of less importance in terms of indoor radon risk because of their short half-lives and less common occurrence. The exception to this is thoron (radon-220), which occurs in high enough concentrations to be of concern in a few local areas. In general, the concentration and mobility of radon in a soil are dependent on several factors, the most important of which are the soil's radium content and distribution, porosity, permeability to gas movement, and moisture content. These characteristics are, in turn, determined by the character of the bedrock, glacial deposits, or transported sediments from which the soil was derived, as well as the climate and the soil's age or maturity.

Radon transport in soils occurs by two processes, convective or advective flow and diffusion (2). Diffusion is the dominant radon transport process in soils of low permeability (generally less than $10^{-7}$ $cm^2$), whereas convective transport processes tend to dominate in highly permeable soils (generally greater than $10^{-7}$ $cm^2$) (3). Radon transport distance is limited in low-permeability soils because of the short distance radon may travel during its half life.

When radium decays in the soil, not all radon produced will be mobile. The portion of radium that can potentially release radon into the pores and fractures of rocks and soils is called the emanating fraction. When a radium atom decays to radon, the energy generated is strong enough to send the radon atom a distance of about 40 nanometers (nm, equal to $10^{-9}$ meters), or about $2 \times 10^{-6}$ inches—this is known as alpha recoil (4). Depending on where radium is distributed in the soil, much of the radon produced could end up imbedded in adjacent soil grains rather than becoming mobile in the pore space between grains. Moisture greatly affects the recoil distance a radon atom will travel. Because water is more dense than air, a radon atom will travel a shorter distance in a water-filled pore than in an air-filled pore, therefore moisture lessens the chance of a recoiling radon atom becoming imbedded in an adjacent grain. However, too much moisture can block soil pores and impede radon movement out of the soil.

Soil-gas radon concentrations can vary in response to climatic and weather variations on hourly, diurnal, or seasonal time scales. Schumann and others (5) and Rose and others (6) recorded as much as order-of magnitude variations in soil-gas radon concentrations between seasons in Colorado and Pennsylvania. The most important factors appear to be precipitation (as it affects soil moisture conditions), barometric pressure, and temperature.

## RADON ENTRY INTO BUILDINGS

A driving force (reduced atmospheric pressure in the house relative to the soil) and entry points must exist for radon to enter a building from the soil. The negative pressure caused by furnace combustion, ventilation devices, and the stack effect during cold winter months are common driving forces. Cracks and other penetrations through building foundations, sump holes, and slab-to-foundation wall joints are common entry points.

Basement homes generally have higher average indoor radon levels than nonbasement homes because basement homes provide more entry points for radon, commonly have a more pronounced stack effect, and typically have lower air pressure relative to the surrounding soil than nonbasement homes. Elevated levels of indoor radon occur in both basement and nonbasement homes, however. The term "nonbasement" applies to slab-on-grade or crawl space construction. In many homes with basements, the main floors have radon levels similar to those on the main floors of nonbasement homes, implying that occupants of basement homes are at greater risk from radon exposure only if they spend a significant amount of time in their basements.

## METHODS AND SOURCES OF DATA

The assessment of geologic radon potential for the United States was made using five main types of data: (1) geologic (lithologic), (2) radiometric, (3) soil characteristics, including soil moisture and permeability, (4) indoor radon data, and (5) building architecture (specifically, whether homes in each area are built slab-on-grade or have a crawl space versus homes with basements). These elements were integrated to produce estimates of radon potential.

### GEOLOGIC DATA

Information on the type and distribution of lithologic units and other geologic features in an assessment area is of primary importance. Rock types with naturally high uranium concentrations, usually greater than 2 parts per million (ppm), that are most likely to cause indoor radon problems include carbonaceous black shales, glauconite-bearing sandstones, some fluvial sandstones, phosphorites and phosphatic sediments, chalk, some carbonates, some glacial deposits, bauxite, lignite, some coals, uranium-bearing granites and pegmatites, metamorphic rocks of granitic composition, felsic and alkalic volcanoclastic and pyroclastic volcanic rocks, syenites and carbonatites, and many sheared or faulted rocks. Rock types least likely to cause radon problems include marine quartz sands, non-carbonaceous shales and siltstones, some clays and fluvial sediments, metamorphic and igneous rocks of mafic composition, and mafic volcanic rocks. Exceptions exist within these general lithologic groups because of the occurrence of localized uranium deposits. The most common sources of uranium and radium are the heavy minerals such as zircon, titanite, and monazite, iron-oxide coatings on rock and soil grains, and organic materials in soils and sediments. Less common are phosphate and carbonate complexes, and uranium minerals.

Although many cases of extreme indoor radon levels can be traced to high radium and (or) uranium concentrations in bedrock and sediments, some structural features, most notably faults and shear zones, have been identified as sites of localized uranium concentrations and have been associated with some of the highest known indoor radon levels. Two of the highest known indoor radon occurrences in the United States are associated with sheared fault zones in Boyertown, Pennsylvania (7), and in Clinton, New Jersey (8, 9).

### NURE AERIAL RADIOMETRIC DATA

Aerial radiometric data are used to describe the radioactivity of rocks and soils. Equivalent uranium (eU) data provide an estimate of the surficial concentrations of radon parent materials (uranium, radium) in rocks and soils. Equivalent uranium is calculated from the counts received by a gamma-ray detector in the wavelength corresponding to bismuth-214 ($^{214}Bi$), with the assumption that uranium and its daughter products are in secular equilibrium. It is expressed in units of parts per million (ppm) of uranium. Gamma radioactivity may also be expressed in terms of a radium concentration; 3 ppm eU corresponds to approximately 1 picocurie per gram (pCi/g) of radium-226.

The aerial radiometric data used for assessing radon potential in this study were collected as part of the National Uranium Resource Evaluation (NURE) program of the 1970s and early 1980s. The purpose of the NURE program was to identify and describe areas in the United States having potential uranium resources (10). The NURE aerial radiometric data were collected by aircraft in which a gamma-ray spectrometer was mounted, flying approximately 122 m (400 ft) above the ground surface. Smoothing, filtering, recalibrating, and matching of adjacent quadrangle data sets were performed to compensate for background, altitude, calibration, and other types of errors and inconsistencies in the original data set (11).

Although radon is highly mobile in soil, and its concentration is affected by meteorologic conditions (4, 12-14), relatively good correlations between average soil-gas radon concentrations and average eU values for some soils have been noted (7, 15, 16). The shallow (20-25 cm) depth of investigation of gamma-ray spectrometers, either ground-based or airborne (17, 18), suggests that gamma-ray data may sometimes provide an underestimate of radon source strength in soils in which some of the radionuclides in the near-surface soil layers have been transported downward through the soil profile or depleted by other processes. The redistribution of radionuclides in soil profiles is dependent on a combination of climatic, geologic, and geochemical factors. Given sufficient understanding of the factors involved, these regional differences may be predictable.

## SOIL SURVEY DATA

Soil surveys prepared by the U.S. Soil Conservation Service (SCS) provide data on soil characteristics. The reports are commonly available in county formats, and occasionally in State summaries, and usually contain both generalized and relatively detailed maps of soils in the area. Because of time and map-scale constraints, it was impractical to examine county soil reports for each county in the United States, so more generalized summaries at appropriate scales were used where available. For State or regional-scale radon characterizations, soil maps are compared to geologic maps of the area, and the soil descriptions, shrink-swell potential, depth to seasonal high water table, permeability, and other relevant characteristics of each soil group noted. One of the best summaries of soil engineering terms and the national distribution of technical soil types is the Soils Map of the National Atlas (U.S. Geological Survey, National Atlas of the United States, sheet 38077-BE-NA-07M-00).

Uranium and radium in soils are most often located on the surfaces of clays, with metal-oxides, especially iron oxides, with calcium carbonate, and with organic matter. As soils form, they develop distinct layers, or horizons, that are cumulatively called the soil profile. The A horizon is a surface horizon containing a relative abundance of organic matter but dominated by mineral matter. The B horizon underlies the A horizon. Important characteristics of B horizons include accumulation of clays, iron oxides, calcium carbonate or soluble salts, and organic matter complexes. In drier climates, a horizon may exist within or below the B horizon that is dominated by calcium carbonate, often called caliche or calcrete. This carbonate-cemented horizon is designated the K horizon. The C horizon underlies the B and is a zone of weathered parent material, it is generally not a zone of leaching or accumulation.

Soil permeability is typically expressed in SCS soil surveys in terms of the speed, in inches per hour (in/hr), at which water soaks into the soil, as measured in a soil percolation test. Although in/hr are not truly units of permeability, these units are in widespread use and are referred to as "permeability" in SCS soil surveys. The permeabilities listed in the SCS surveys are for water, but they are generally related to gas permeability. Permeabilities greater than 6.0 in/hr may be considered high, and permeabilities less than 0.6 in/hr may be considered low in terms of soil-gas transport.

Many well-developed soils contain a clay-rich B horizon that may impede vertical soil gas transport. Radon generated below this horizon cannot readily escape to the surface, so it would instead tend to move laterally, especially under the influence of a negative pressure exerted by a building. Depth to seasonal high water table can also be an important parameter to consider in some areas. Because water in soil pores inhibits gas transport, the amount of radon available to a home is effectively reduced by a high water table. Areas likely to have high water tables are river valleys, coastal areas, and some areas overlain by deposits of glacial origin (for example, loess).

Shrink-swell potential is an indicator of the abundance of smectitic (swelling) clays in a soil. Soils with a high shrink-swell potential may cause building foundations to crack, and thus create pathways for radon entry into the structure. In addition, swelling soils often crack as they dry; as a result, they provide additional pathways for soil-gas transport and effectively increase the gas permeability of the soil (4).

## INDOOR RADON DATA

Data from the EPA/State Indoor Radon Survey were used for the 34 States that have participated in this program between 1986 and 1990 (19, 20); for the remaining 16 States, data from the University of Pittsburgh's Radon Project (21, 22) and radon data from individual State indoor radon surveys were used where available.

### The State/EPA Radon Survey

The State/EPA Radon Survey has provided statewide characteristics of indoor radon distributions since 1987. To date, 34 States have participated in the program, with 7 additional States slated to complete the survey in 1991. This survey has compiled short-term data results in approximately 47,000 homes, representing a total population of over 21 million homes in more than 2000 counties in those participating States. Elevated screening levels have been found in every State, with 1 in 5 homes surveyed falling above the Environmental Protection Agency's Action Guideline of 4 pCi/L. The term "Action Guideline" is used as a recommendation to homeowners that remedial action should be considered at or above this level.

Each home surveyed in this program represents a much larger population of homes. The ability to achieve such statistical validity is a result of the survey's design. To obtain the goal of creating a representative measure of the distribution of radon levels in houses for major geographic areas within a State and for each State as a whole, two levels of representativeness were established: first, that a representative sample of the houses in each State be selected and, second, that the measurements within each house be representative of actual concentrations. The measurements involved short-term charcoal canister screening devices as listed in current EPA protocols (EPA-520/1-89-009). This measurement strategy could be used to: a) quickly determine if an individual house has a potential radon problem and, b) efficiently identify houses in a multiple-house survey that have elevated screening concentrations. This survey design creates a database that can reflect large geographic areas of radon distribution, characterizing States or regions within a State on a statistically valid level.

Table 1 is a summary of the EPA/State Survey data. The arithmetic means for the states range from a high of 8.8 pCi/L in Iowa to a low of 0.1 pCi/L in Hawaii. In 15 States, 20 percent or more of those homes measured were above 4 pCi/L, whereas 10 States had 10 percent or less of those homes measured above the action guideline. Although a State survey may reflect a low percentage of homes with elevated levels of radon, this does not always suggest that an insignificant number of homes could be affected by elevated levels. In California, for example, only 2.4 percent of the homes measured were above 4 pCi/L. This small percentage is misleading, however, because it represents an overall total of more than 247,000 homes that may be effected by elevated levels.

**Table 1. Indoor radon data from the State/EPA Indoor Radon Survey**

| STATE | Average | % > 4 pCi/L | RANK |
|---|---|---|---|
| Alaska | 1.7 | 7.7 | 25 |
| Alabama | 1.8 | 6.4 | 29 |
| Arizona | 1.6 | 6.5 | 28 |
| California | 0.9 | 2.4 | 32 |
| Colorado | 5.2 | 41.5 | 5 |
| Connecticut | 2.9 | 18.5 | 17 |
| Georgia | 1.8 | 7.5 | 26 |
| Hawaii | 0.1 | 0.4 | 34 |
| Iowa | 8.8 | 71.1 | 1 |
| Idaho | 3.5 | 19.3 | 16 |
| Indiana | 3.7 | 28.5 | 9 |
| Kansas | 3.1 | 22.5 | 13 |
| Kentucky | 2.7 | 17.1 | 18 |
| Louisiana | 0.5 | 0.8 | 33 |
| Maine | 4.1 | 29.9 | 7 |
| Massachusetts | 3.4 | 22.7 | 12 |
| Michigan | 2.1 | 11.7 | 23 |
| Minnesota | 4.8 | 45.4 | 4 |
| Missouri | 2.6 | 17.0 | 19 |
| North Carolina | 1.4 | 6.7 | 27 |
| North Dakota | 7.0 | 60.7 | 2 |
| Nebraska | 5.5 | 53.5 | 3 |
| New Mexico | 3.1 | 21.8 | 14 |
| Nevada | 2.0 | 10.2 | 24 |
| Ohio | 4.3 | 29.0 | 8 |
| Oklahoma | 1.1 | 3.3 | 31 |
| Pennsylvania | 7.7 | 40.5 | 6 |
| Rhode Island | 3.2 | 20.6 | 15 |
| South Carolina | 1.1 | 3.7 | 30 |
| Tennessee | 2.7 | 15.8 | 21 |
| Vermont | 2.5 | 15.9 | 20 |
| Wisconsin | 3.4 | 26.6 | 10 |
| West Virginia | 2.6 | 15.7 | 22 |
| Wyoming | 3.6 | 26.2 | 11 |

Vendor data from The Radon Project

Dr. Bernard Cohen of the University of Pittsburgh developed The Radon Project that has produced over 170,000 data points since 1986. The data collected from this radon project are not considered statistically valid due to the utilization of volunteer data and other non-random selection methods, and therefore cannot be used to accurately predict radon levels, although bias reduction was applied to the data set used in this report by eliminating certain values based on responses to questionnaires (22). The data are useful because they provide information about areas both covered and not covered by the State/EPA Radon Survey. The Radon Project collected data using charcoal canister measurement devices, similar to that used in the State/EPA Survey.

Individual State Surveys

A number of states, including Delaware, Florida, Maryland, New Jersey, New York, New Hampshire, Virginia, and Utah, have conducted their own indoor radon surveys and have collected extensive volunteer data. These data are compiled at several different scales and include zip-code, township, and county groupings. Some of these surveys were designed to be statistically valid while others may be biased toward high levels because of the volunteered nature of the data.

## RADON INDEX AND CONFIDENCE INDEX

Many of the geologic methods used to evaluate an area for radon potential require subjective opinions based on the professional judgement and experience of the individual geologist. However, these evaluations are based on established scientific principles that are universal to any geographic area or geologic setting. This section describes the methods and conceptual framework used by the U.S. Geological Survey to evaluate areas for radon potential based on the geologic factors discussed in the previous sections. The scheme is divided into two basic parts, a Radon Index (RI), used to rank the general radon potential of the area, and the Confidence Index (CI), used to express the level of confidence in the prediction based on the quantity and quality of the data used to make the determination. This scheme works best if the areas to be evaluated are delineated by geologically-based boundaries (geologic provinces) rather than political ones (State/county boundaries) in which the geology may be inconsistent across the area.

Radon Index

Table 2 presents the Radon Index (RI) matrix. Five main categories are evaluated and a point value of 1, 2, or 3 is assigned to each category. These categories were selected because the factors they represent are considered to be of primary importance in controlling radon potential and because at least some data for these factors are consistently available for every geologic province. Because each of these main factors encompass a wide variety of complex and variable components, the subjective professional judgement and experience of the geologists performing the evaluation are heavily relied upon in assigning point values to each category.

Indoor radon is evaluated using unweighted arithmetic means of the combined (basement and first-floor) indoor radon data for each county or for each geologic area to be evaluated. Other expressions of indoor radon levels in an area could also be used, such as weighted averages or annual averages.

Aerial radioactivity data used in this report are from the equivalent uranium map of the conterminous United States compiled from NURE aerial gamma-ray surveys (11).

The geology factor is complex and actually incorporates many geologic characteristics. In the matrix, "positive" and "negative" refer to the presence or absence and distribution of rock types known to have high uranium contents and to generate elevated radon in soils or indoors. Examples of "positive" rock types include granites, black shales, and phosphatic rocks. Examples of "negative" rock types include quartz sands and some clays. The term "variable" indicates that the geology within the region is variable or that the rock types in the area are known or suspected to generate elevated radon in some areas but not in others due to compositional differences, climatic effects, localized distribution of uranium, or other factors. Geologic information indicates not only how much uranium is present in the rocks and soils but also gives clues for predicting general radon emanation and mobility characteristics through additional factors such as structure (notably the presence of faults or shears) and geochemical characteristics.

"Soil permeability" refers to several soil characteristics that influence radon concentration and mobility, including soil type, grain size, structure, soil moisture, drainage, and permeability. In the matrix, "low" refers to permeabilities less than about 0.6 in/hr; "high" corresponds to greater than about 6.0 in/hr, in SCS standard soil percolation tests.

Architecture type refers to whether homes in the area have mostly basements, mostly slab-on-grade construction, or a mixture of the two. Split-level and crawl space homes fall into the "mixed" category.

To add additional weight to the geologic factor in cases where additional reinforcing or contradictory geologic evidence is available, Geologic Field Evidence (GFE) points are added or subtracted from an area's score. Relevant geologic field studies are important in enhancing our understanding of how geologic processes affect radon distribution. In some cases, geologic models and supporting field data reinforce an already strong (high or low) score; in others, they can provide important contradictory data. For example, areas of the Dakotas, Minnesota, and Iowa that are covered with Wisconsin-age glacial deposits exhibit a low aerial radiometric signature and would score only one point in that category. However, data from geologic field studies in North Dakota and Minnesota (23) suggest that eU is a poor predictor of geologic radon potential in this area because radionuclides have been leached from the upper soil layers but are present and possibly even concentrated in deeper soil horizons, generating significant soil-gas radon. This positive supporting field evidence adds two GFE points to the score which help to counteract the invalid conclusion suggested by the radiometric data. No GFE points are awarded if there are no documented field studies for the area.

<u>Confidence Index</u>

Except for architecture type, the same factors are used to establish a Confidence Index (CI) for the radon potential prediction for each area (Table 3). Architecture type is not included in the confidence index because house construction data are readily and reliably available through surveys taken by agencies and industry groups including the Bureau of the Census, National Association of Home Builders, and the Federal Housing Administration. The remaining factors are scored on the basis of the quality and quantity of data used in the RI matrix.

Indoor radon data are evaluated on the distribution and number of data points and on whether the data is consistent, randomly-sampled data (State/EPA Indoor Radon Survey or other State survey data) or volunteered vendor data (likely to be nonrandom and biased toward population centers and/or high indoor radon levels). The categories listed in the CI matrix for indoor radon data ("sparse or no data", "vendor data", and "State/EPA data") are intended as representative examples of levels of sampling density and statistical robustness of an indoor radon data set.

Aerial radioactivity data are available for all but a few areas of the continental United States and for part of Alaska. In general, the greatest problems with correlations among eU, geology, and soil-gas or indoor radon levels appear to be associated with glacial deposits. Correlations among eU, geology, and radon are generally sound in unglaciated areas and are usually assigned 3 CI points. Radioactivity data in some unglaciated areas may be assigned fewer than 3 points, and in glaciated areas assigned only one point, if the data are considered questionable or coverage is poor.

For the geologic data factor, a high confidence score is given to an area where a proven geologic model for radon generation and mobility can be applied. Rocks for which the processes are less well known or for which data are contradictory are regarded as "variable", and those about which little is known or for which no apparent correlations have been found are deemed "questionable".

The soil permeability factor is also scored on quality and amount of data. Soil permeability can be approximated from grain size and drainage class if data from standard, accepted soil percolation tests are unavailable. Percolation test data and other measured permeability data are more accurate and score a higher confidence level.

Examples of radon potential ratings applied to different geologic terrains in the United States is given in Table 4. Space does not permit including the rating tables for all of the United States.

**Table 2. Radon Index Matrix**

INCREASING RADON POTENTIAL →

| FACTOR | POINT VALUE 1 | 2 | 3 |
|---|---|---|---|
| INDOOR RADON (average) | < 2 pCi/L | 2 - 4 pCi/L | > 4 pCi/L |
| AERIAL RADIOACTIVITY | < 1.5 ppm eU | 1.5 - 2.5 ppm | > 2.5 ppm |
| GEOLOGY* | negative | variable | positive |
| SOIL PERMEABILITY | low | moderate | high |
| ARCHITECTURE TYPE | mostly slab | mixed | mostly basement |

*GEOLOGIC FIELD EVIDENCE (GFE) POINTS: GFE points are assigned in addition to points for the "Geology" factor for specific, relevant geologic field studies. See text for details.

| | | |
|---|---|---|
| Geologic evidence supporting: | HIGH radon | +2 points |
| | MODERATE | +1 point |
| | LOW | -2 points |
| No relevant geologic field studies | | 0 points |

**SCORING:**

| Rn potential category | point range | probable indoor Rn average |
|---|---|---|
| LOW | 3-7 points | < 2 pCi/L |
| MODERATE | 8-11 points | 2 - 4 pCi/L |
| HIGH | > 11 points | > 4 pCi/L |

POSSIBLE RANGE OF POINTS = 3 to 17

**Table 3. Confidence Index Matrix**

INCREASING CONFIDENCE →

| FACTOR | POINT VALUE 1 | 2 | 3 |
|---|---|---|---|
| INDOOR RADON DATA | Sparse/no data | Vendor data | State/EPA data |
| AERIAL RADIOACTIVITY | questionable/no data | north of glacial limit | south of glacial limit |
| GEOLOGIC DATA | questionable | variable | proven geol. model |
| SOIL PERMEABILITY | questionable/no data | variable | reliable, abundant |

**SCORING:**

| | |
|---|---|
| LOW CONFIDENCE | 4 - 6 points |
| MODERATE CONFIDENCE | 7 - 9 points |
| HIGH CONFIDENCE | 10 - 12 points |

POSSIBLE RANGE OF POINTS = 4 to 12

**Table 4. Radon Index and Confidence Index Examples**

| FACTOR | Des Moines Lobe region RI | Des Moines Lobe region CI | Superior Upland RI | Superior Upland CI | Michigan Basin RI | Michigan Basin CI |
|---|---|---|---|---|---|---|
| INDOOR RADON | 3 | 3 | 2 | 3 | 2 | 3 |
| RADIOACTIVITY | 1 | 2 | 1 | 2 | 1 | 2 |
| GEOLOGY | 3 | 3 | 2 | 2 | 2 | 3 |
| SOIL PERM. | 1 | 2 | 2 | 2 | 2 | 2 |
| ARCHITECTURE | 3 | – | 3 | – | 3 | – |
| GFE POINTS | +2 | – | 0 | – | 0 | – |
| TOTAL | 13 | 10 | 10 | 9 | 10 | 10 |
| | HIGH | HIGH | MOD | MOD | MOD | HIGH |

| FACTOR | Great Plains RI | Great Plains CI | Northern Coast Ranges and Cascade Mtns. RI | Northern Coast Ranges and Cascade Mtns. CI | Puget Lowlands RI | Puget Lowlands CI |
|---|---|---|---|---|---|---|
| INDOOR RADON | 2 | 3 | 1 | 2 | 1 | 2 |
| RADIOACTIVITY | 2 | 3 | 1 | 2 | 1 | 3 |
| GEOLOGY | 2 | 2 | 1 | 2 | 1 | 2 |
| SOIL PERM. | 2 | 2 | 2 | 2 | 2 | 3 |
| ARCHITECTURE | 3 | – | 1 | – | 1 | – |
| GFE POINTS | 0 | – | 0 | – | 0 | – |
| TOTAL | 11 | 10 | 6 | 8 | 6 | 10 |
| | MOD | HIGH | LOW | MOD | LOW | HIGH |

| FACTOR | Inner Coastal Plain RI | Inner Coastal Plain CI | Appalachian Carbonates RI | Appalachian Carbonates CI | Basin and Range RI | Basin and Range CI |
|---|---|---|---|---|---|---|
| INDOOR RADON | 2 | 3 | 3 | 3 | 2 | 2 |
| RADIOACTIVITY | 2 | 3 | 2 | 2 | 2 | 3 |
| GEOLOGY | 2 | 3 | 3 | 3 | 2 | 2 |
| SOIL PERM. | 2 | 3 | 2 | 2 | 2 | 2 |
| ARCHITECTURE | 1 | – | 3 | – | 2 | – |
| GFE POINTS | 1 | – | 3 | – | 0 | – |
| TOTAL | 10 | 12 | 16 | 10 | 10 | 9 |
| | MOD | HIGH | HIGH | HIGH | MOD | MOD |

## RADON POTENTIAL IN THE UNITED STATES

Areas of the United States that are geologically similar can be grouped and delineated on a map. Each region is characterized by a basic geology and climate that determines its radon potential. By examining and correlating available geologic, aerial radiometric, soil radon, and indoor radon data, generalized estimates of the radon potential of each region can be made. The following is a discussion of major geologic features and rock types and their known or expected radon potential for each geologic/physiographic region. In each case, large-scale, well-known, or highly anomalous features are discussed; this list is by no means exhaustive. Rather, it is intended to give the reader a general feeling for the geologic features in each area that are likely to produce elevated indoor radon values, point out important rock units or other geologic features where they are known, and act as a general guide for using geology to predict radon potential on a regional scale. The numbered Regions designated in the text correspond with those in Figure 1.

### REGION 1, 2, AND 3: THE OUTER AND INNER COASTAL PLAIN AND PHOSPHATIC AND LIMESTONE DEPOSITS OF FLORIDA

The Coastal Plain of the eastern and southern United States consists of a systematic progression of predominantly marine and fluvial sediments deposited during the evolution of the Atlantic and Gulf Coasts. The oldest rocks exposed in the Coastal Plain are Cretaceous in age and consist predominantly of glauconitic sandstones, chalks, and clays as well as some non-glauconitic quartz sandstones and fossiliferous limestone. These are overlain by lower Tertiary (Paleocene, Eocene and Oligocene) sands and clays, which are often glauconitic, and upper Tertiary (Miocene) fossiliferous chalks, clays, and thin sands. The youngest Tertiary sediments (Pliocene) are dominated by gravelly sands, clayey sands, and thin clay beds. Because of the consistency in the general stratigraphy of the Coastal Plain, many of the lithologic sequences are similar from state to state. Soil radon, surface radioactivity, uranium and radium concentrations, permeability, and soil grain size distributions have been measured along more than 1600 km of transects in five states underlain by Coastal Plain sediments (24, 25). In general, the data suggest that the Inner Coastal Plain, (Region 2), which is comprised of Cretaceous and Lower Tertiary sediments, has higher radon potential than the Outer Coastal Plain (Region 1), which is comprised of Middle to Upper Tertiary and Quaternary sediments. Grab samples of radon in soil gas collected at a depth of one meter averaged 700-1000 pCi/L for the Coastal Plain as a whole. The two highest soil radon measurements were taken in Inner Coastal Plain sediments; 16,226 pCi/L was measured in the glauconitic sands of the Nevasink Formation in New Jersey and 6333 pCi/l was measured in the carbonaceous shales of the Eagle Ford Group in Texas. Radon in soil gas greater than 1000 pCi/L associated with phosphatic fossil layers and glauconitic sands and clays in the Aquia, Brightseat, and Yorktown Formations from Maryland to Virginia have also been reported (26). Localized concentrations of uranium, found in roll-front uranium deposits in Texas and in marine sands and and heavy mineral deposits from Virginia to Georgia, have produced some locally high indoor radon occurrences. Heavy mineral deposits found throughout the Coastal Plain also have the potential for creating scattered local anomalies and are a potential source of thoron as well.

Comparisons with indoor radon data from the State/EPA Indoor Radon Survey (winter screening measurements from 1986-89) and other data sources show good correlations among soil radon, radionuclide data, and indoor radon data. The average for indoor radon concentrations is 1 pCi/L or less over different parts of the outer Coastal Plain. Areas underlain by Cretaceous chalks, carbonaceous shales, phosphatic sediments, and glauconitic sandstones of the Inner Coastal Plain average 2.3 pCi/L and have the highest radon potential.

Region 3 in Florida outlines the general extent of the uraniferous phosphatic deposits which cause abundant, moderate radon problems and locally high radon problems. The geologic units thought responsible for these problems include the Hawthorn Formation (27) and the Alachua and Bone Valley Formations. The southern part of Region 3 in Dade County, Florida, may be moderate in radon potential due to the Key Largo Limestone.

### REGIONS 4, 5, 6, AND 7: THE NORTHERN APPALACHIAN MOUNTAINS INCLUDING NEW ENGLAND, THE TACONIC ADIRONDACK AND GREEN MOUNTAINS, AND NORTHERN APPALACHIAN PLATEAU

Region 4 is made up of Proterozoic and Paleozoic metamorphic and igneous rocks of moderate radon potential, the main source of radon being uraniferous minerals and faults. Volcanic units in this region are low in radon potential while the schists, gneisses and granites are dominantly felsic in composition and produce moderate radon concentrations. Glacial tills and gravels have compositions derived from both local and northern rock sources and create locally high radon due to permeability and a moderate uranium source.

Region 5 is also an area of crystalline bedrock with locally derived glacial tills and gravels. The granites of this area, particularly the Conway Granite, have very high uranium concentrations. Not only do the granites and associated Proterozoic metamorphic rocks cause high indoor radon but the highest radon in ground water, with domestic well water concentrations in the 1 million pCi/L range (28) occur in the fractured granite aquifers.

Region 6 is a highly variable terrain that includes the metamorphic and igneous rocks of the Green Mountains and the Paleozoic rocks of the northern Appalachian Mountains, Appalachian Plateau, and Taconic Mountains. The Paleozoic rocks of the Appalachians includes highly deformed shales, sandstones, and carbonates. Some of the carbonates and shales cause locally moderate to high indoor radon. Gravels and tills in the Albany area also cause some local high radon.

Region 7, the Adirondacks, is a region of metamorphic and igneous rocks of contrasting radon potential. The Marcy Anorthosite complex, which forms the core of the Adirondack Mountains, is low in radon potential, whereas the metamorphic schists and gneisses that blanket the rim of the Adirondacks are locally high in radon potential due to uraniferous minerals, uranium deposits associated with several of the magnetite deposits, and shear zones. Gravels and tills cause locally high radon.

REGION 8: CENTRAL AND SOUTHERN APPALACHIAN MOUNTAINS, INCLUDING THE PIEDMONT, BLUE RIDGE, AND VALLEY AND RIDGE.

The eastern part of the Appalachian mountains, known as the Piedmont and Blue Ridge, is underlain by Proterozoic and Paleozoic-age metamorphic and igneous rocks. These rocks have moderate radon potential, with localized areas of high potential. Studies thus far have yielded an average of 1000 pCi/L for rocks of granitic composition and an average of 600 pCi/L for rocks of mafic composition. Over a thousand indoor and soil-gas radon data have been averaged for geologic units in the Appalachian region of PA, NJ, MD, and VA,and indicate that on the average, the indoor radon concentration is approximately one percent of the soil radon concentration (29). Permeability and emanating power are the main factors affecting this relationship.

Paleozoic-age sediments cover an extensive area of the western Appalachians, known as the Valley and Ridge, and consist of sandstones, siltstones, shales, and carbonates. The carbonate soils, black shale soils, and black shale bedrock can generate moderate to high levels of indoor radon. Carbonate soils derived from Cambrian-Ordovician rock units of the Valley and Ridge Province cause known indoor radon problems in eastern Tennessee, western New Jersey, western Virginia, eastern West Virginia (30) and central and eastern Pennsylvania. The carbonate rocks themselves are low in uranium and radium; however, the soils developed on these rocks are derived from the dissolution of the $CaCO_3$ that makes up the majority of the rock. When the $CaCO_3$ has been dissolved away, the soils are enriched in the remaining impurities, predominantly base metals, including uranium. Rinds containing high concentrations of uranium and uranium minerals can be formed on the surfaces of rocks involved with $CaCO_3$ dissolution. Ground water derived from these areas, however, often contains radon concentrations of 1000 pCi/L or less (31, 32). Carbonates also form karst topography, characterized by solution cavities, sinkholes, and caves, which increase the overall permeability of the rocks in these areas and may induce convective flow of radon.

In the Appalachians, the highest indoor, soil, and water radon values are most often associated with faults and fractures in the rock (28, 33, 34, 35).

REGION 10: THE NON-GLACIATED PORTION OF THE APPALACHIAN PLATEAU

The Appalachian Plateau Region contains areas of moderate, and some locally high radon potential. The carbonate soils and shales found in the Paleozoic-age domes and basins characteristic of this part of the United States have moderate to high radon potential. Of specific interest are the uranium-bearing Chattanooga shale in Kentucky (Region 9) and Tennessee (36), the Devonian-Mississippian black shales in Ohio, Pennsylvania, New York, and Indiana, and the Ordovician, Mississippian, Permian, and Pennsylvanian-age carbonates and black shales in Alabama, Indiana, Tennessee, Kentucky, Michigan, Illinois, Missouri, Iowa, Arkansas, and Oklahoma.(37). Although exposed in a limited area, Precambrian granites of the St. Francis Mountains in southeastern Missouri are among the most highly uraniferous igneous rocks in the United States (38). Granites, rhyolites and related dike rocks in the

Wichita Mountains of Oklahoma have also been evaluated as having moderate to high radon potential (39). A large area of low radon potential is underlain by the Pennsylvanian Pottsville Sandstone, which extends from eastern Ohio through West Virginia, eastern Kentucky, east-central Tennessee, and northern Alabama. Moderate indoor radon is also associated with uraniferous coal deposits in Pennsylvania and West Virginia.

REGION 9, 11, 12, 13: NORTHERN GREAT PLAINS AND GREAT LAKES

The Northern Great Plains-Great Lakes region is underlain by Wisconsin and pre-Wisconsin-age glacial deposits and loess. Much of North and South Dakota, western and southern Minnesota, and northern Iowa (Region 11) are underlain by deposits of the Des Moines lobe. Des Moines lobe tills are silty clays and clays derived from the Pierre Shale and from Tertiary sandstones and shales which have relatively high concentrations of uranium and high radon emanating power. Included within this region are clay and silt deposits of glacial lakes Agassiz, Dakota, and Devil's Lake, which generate some of the highest radon levels in the area. Southwestern North Dakota is underlain by unglaciated Tertiary sandstones, siltstones, and shales, some of which include uraniferous coals and carbonaceous shales (Region 14).

In Region 9, glacial deposits in southern Wisconsin, northern Illinois, and western Indiana are primarily from the Green Bay and Michigan lobes. These tills range from sandy to clayey and are derived mostly from sandstones and carbonate rocks of southern Wisconsin and the Illinois Basin. Eastern Indiana and western Ohio are underlain by tills derived from the Ohio and New Albany black shales. Black shales extend south of the glacial limit, forming an arcuate pattern in northern Kentucky. They also underlie and provide source material for glacial deposits in a roughly north-south pattern through central Ohio, including the Columbus area, and extend eastward into southern New York. The overall radon potential of this area is high.

In Region 12, the Michigan Basin area includes silty and clayey tills in northern Michigan and surrounding Lake Michigan. Source rocks for these tills are sandstones, shales, and carbonate rocks of the Michigan Basin which are generally poor radon sources. Exposed crystalline rocks in the central part of the Upper Peninsula of Michigan cause locally high indoor radon levels. This area has a moderate overall radon potential.

The Superior Upland of Region 13 includes glacial deposits of the Lake Superior lobe in northern Minnesota and northern Wisconsin. The underlying source rocks for these tills are volcanic rocks and mafic metamorphic and granitic rocks of the Canadian Shield that have relatively low uranium contents. The sandy tills derived from these rocks have relatively high permeability, but because of their lower uranium content and lower emanating power, they have a moderate radon potential. In central Wisconsin, uraniferous granites of the Wolf River and Wausau plutons are exposed at the surface or covered by a thin layer of glacial deposits and cause some of the highest indoor radon concentrations in the State.

Glaciated areas present special problems for assessment because bedrock material is often transported hundreds of km from its source. Glaciers are quite effective in redistributing uranium-rich rocks; for example, in Ohio, uranium-bearing black shales have been disseminated over much of the western part of the state, now covering a much larger area than their original outcrop pattern, and display a prominent radiometric high on the radioactivity map of the United States. The physical, chemical, and drainage characteristics of soils formed from glacial deposits vary according to source bedrock type and the glacial features on which they are formed. For example, soils formed from outwash or ground moraine deposits tend to be more poorly drained and contain more fine-grained material than soils formed on moraines or eskers, which are generally coarser and well-drained. In general, soils developed from glacial deposits are poorly structured, poorly sorted, and poorly developed, but are generally moderately to highly permeable and are rapidly weathered, because the action of physical crushing and grinding of the rocks to form tills may enhance and speed up soil weathering processes (40). Clayey tills, such as those underlying most of North Dakota and a large part of Minnesota, have high emanation coefficients (41) and usually have low to moderate permeability because they are mixed with coarser sediments. Tills consisting of mostly coarse material tend to emanate less radon because larger grains have lower surface area-to-volume ratios, but because these soils have generally high permeabilities, radon transport distances are generally longer, and structures built in these materials are able to draw soil air from a larger source volume, so moderately elevated indoor radon concentrations may be achieved from comparatively lower-radioactivity soils (42, 43).

REGION 14 AND 15: THE UNGLACIATED GREAT PLAINS

The Great Plains extends from eastern Montana to central Texas. The area is mostly underlain by the Cretaceous Pierre Shale and by Tertiary continental sandstones, siltstones, and shales including the White River, Ogallala, and Arikaree Formations. The lower part of the Pierre Shale has an overall higher uranium content than the upper part, and locally contains black shales. Members of the White River Formation are significant radon producers in the northern and central Great Plains, whereas the Ogallala and Arikaree Formations are principal sources for indoor radon in the central and southern part of the region from Colorado to west Texas. Carbonaceous shales and uranium-bearing coals in the White River Formation of unglaciated southwestern North Dakota generate locally very high radon levels. Other Tertiary sedimentary units, including the Green River, Wasatch, and Fort Union Formations and their equivalents, are also exposed in the area from Colorado to eastern Montana, but are of less importance in terms of radon potential. Also included in this area are the Black Hills of southwestern South Dakota, which are underlain by Precambrian granitic and metamorphic rocks and Paleozoic sedimentary rocks of moderate radon potential. Overall, the Great Plains has a moderate radon potential.

The Sand Hills (Region 15), an area of windblown quartz sands in northern Nebraska, have a low radon potential.

REGION 16: ROCKY MOUNTAINS AND PARTS OF THE WESTERN GREAT PLAINS

The Rocky Mountains have a similar high radon potential to the Appalachian region for many of the same reasons. The metamorphic and igneous rocks in the Rocky Mountains are generally similar in composition, degree of deformation, and intrusion by granites to those of the Appalachians. However, the Rocky Mountains have undergone several periods of intense and widespread hydrothermal activity creating vein deposits of uranium which cause local, high concentrations of indoor radon and radon in water in Colorado and Idaho (44-46). Colluvium and alluvium derived from crystalline rocks of the Rocky Mountains covers much of the plains along the Front Range from New Mexico to Canada and causes known moderate to high indoor radon problems in Colorado and Idaho (46, 47).The Northern Rocky Mountains comprise the northeast and north-central part of Washington and northern and central Idaho. This area is underlain by Precambrian sedimentary rocks, Paleozoic sedimentary rocks, and Mesozoic metamorphic rocks, all intruded by Mesozoic and Tertiary granitic rocks. The largest intrusive body, the Idaho Batholith, is a complex of granitic rock units ranging from diorite to granite. Uraniferous late Cretaceous to early Tertiary granites occur throughout the Northern Rocky Mountains. An extensive, though dissected, veneer of Tertiary volcanic rocks underlies much of the central Idaho portion of the Northern Rocky Mountains. Included in Region 16 are the Permian marine limestones and other marine sediments of eastern New Mexico and the west Texas Panhandle. These units, in particular the Cutler Formation, Sangre de Cristo Formation, and San Andreas Limestone, have the potential to create moderate and locally high indoor radon problems (48). Also included in Region 16 is an apron of Tertiary and Cretaceous sediments with high radon potential that contain local uranium deposits and are overlain partly by colluvium from the Proterozoic rocks of the Rocky Mountains.

REGION 17: COLORADO PLATEAU, WYOMING BASIN

The Colorado Plateau and Wyoming Basin are underlain by sedimentary rocks ranging in age from Pennsylvanian to Tertiary. The majority of the sedimentary uranium deposits of the United States are located in this region and high indoor radon in Utah, Colorado, Wyoming and New Mexico appear to correspond to the uranium deposits. Dominant rock types include arkosic conglomerates, marine limestones and shales, marginal marine sandstones and shales, and fluvial and lacustrine sandstones, shales, and limestones. Uranium occurs to some extent in most of these rock types. The most significant uranium deposits occur in Mesozoic sediments, with the Jurassic sandstones being the most common host for uranium ore. Localized sandstone-type uranium deposits are hosted in particular by the Triassic Chinle, the Jurassic Morrison and the Cretaceous Dakota Formations in this region. Mine tailings from these sedimentary deposits caused some of the earliest detected indoor radon problems (49). A small part of the Colorado Plateau is included in Region 18 and is underlain by sediments with moderate rather than high radon potential.

In the Wyoming Basin, the Permian Phosphoria Formation has moderate to high radon potential. It covers an area of 350,000 $km^2$ in southeastern Idaho, northeastern Utah, western Wyoming, and southwestern Montana and has a uranium content that varies from 0.001 to 0.65 percent. Other rocks with high radon potential in the

Wyoming Basin are the Cretaceous Mancos Shale, which is uraniferous in places, and Tertiary sandstones, siltstones, and shale, which host uranium deposits and uranium bearing coals.

REGION 17, 18, 19 20: BASIN AND RANGE

The Basin and Range (regions 18, 19, 20) is comprised of Precambrian metamorphic rocks, late Precambrian and Paleozoic metamorphosed and unmetamorphosed sedimentary rocks, Mesozoic and Tertiary intrusive rocks, and Tertiary sedimentary and volcanic rocks. The region is structurally complex, with the aforementioned rocks forming the mountain ranges and alluvium derived from the ranges filling the basins. The sedimentary rocks include marine carbonates and shales, cherts, quartzites, and sandstones, as well as fluvial and continental sandstones, siltstones, and shales. As with the Colorado Plateau, local uranium deposits occur throughout the sedimentary rocks. Areas with moderate and locally high radon potential include the Tertiary volcanic rocks, particularly the Miocene and Pliocene age rocks that are found throughout the Basin and Range Province, Precambrian gneiss in southern Nevada, and the Carson Valley alluvium, which is derived from the Sierra Nevada uraniferous granites. In Utah, Sprinkel (50) has indicated that the Wasatch fault zone and some geothermal areas have the potential to produce elevated radon. The southern part of the Basin and Range (Region 19) has fewer Tertiary volcanic rocks and is notably lower in radon potential.

The Snake River Plain in the northern part of Region 20 forms an arcuate depression in southern Idaho underlain by basaltic volcanic rocks. Alluvium from adjacent mountains and tuffaceous sedimentary rocks underlies much of the upper Snake River Valley and the western end of the Snake River Plain. Those areas underlain by basalt have low to locally moderate radon potential, however, those areas underlain by tuffaceous sedimentary rocks and alluvium along the Snake River Valley have high overall radon potential. Overall, the area has a moderate radon potential.

REGIONS 21, AND 22: SIERRA NEVADA, GREAT VALLEY, AND SOUTHERN COAST RANGES

The Sierra Nevada (Region 21) is underlain by Paleozoic and Mesozoic metamorphic rocks with the metamorphic rocks dominant in the northern part of the range and the granites dominant in the southern part of the range. Tertiary volcanic rocks are also found in the northern part of the range. The granites of the Sierra Nevada Mountains are very high in uranium and have high radon potential as does the colluvium formed on the eastern and western flanks of the mountains. The granite and colluvium are associated with high indoor radon in Nevada as well as California.

The Southern Coast Ranges include the Franciscan Formation, a complex assemblage of metamorphosed marine sedimentary rocks and ultramafic rocks, Cretaceous and Tertiary sedimentary rocks, and Mesozoic metamorphic and igneous rocks. The Tertiary marine sediments and Mesozoic igneous and metamorphic rocks are uraniferous and have moderate indoor radon associated with them. In particular the Rincon shale in Santa Barbara County may be the source for 75% of the homes having indoor radon greater than 4 pCi/L (51).

The Great Valley is made up of alluvium and colluvium derived from both the Coastal Ranges and the Sierra Nevada. Its radon potential is moderate overall but is controlled locally by source rock and permeability.

REGIONS 23, 24, 25: COLUMBIA PLATEAU,PUGET LOWLAND, CASCADE MOUNTAINS NORTHERN COASTAL RANGES, KLAMATH MOUNTAINS, AND WILLAMETTE VALLEY

A comprehensive radon potential assessment of the Pacific Northwest has been done by Duval and others (52). The Columbia Plateau (Region 23) is underlain principally by Miocene basaltic and andesitic volcanic rocks, tuffaceous sedimentary rocks and tuff. The soils formed from these rocks are low in uranium concentration and indoor radon is generally low, giving the region an overall low radon potential An extensive veneer of Pleistocene glaciofluvial outwash, eolian, and lacustrine deposits in the northern part of the Columbia Plateau (Region 24) contains locally highly permeable soils and relatively high soil uranium levels and has moderate radon potential. The subprovinces of the Blue Mountains and Joseph Upland in the central Columbia Plateau also include significant outcrop areas of Jurassic and Triassic sedimentary and volcanic rocks, weakly metamorphosed in many areas, and younger intrusive rocks which have a low to moderate radon potential.

The Puget Lowland in the northern part of Region 23 is underlain almost entirely by glacial deposits and Holocene alluvium. Most of the glacial and alluvial material of the Puget lowland is derived from the Cascades to the east and the mountains of the Olympic peninsula to the west. The Puget Lowland overall has low radon potential because of high soil moisture and low uranium content of soils. Most townships from Tacoma northward average less than 1 pCi/L radon.

The Cascade Mountains (Region 23) extends from southwestern Oregon to northwestern California and can be divided into two geologic terranes: a northerly terrane composed principally of Mesozoic metamorphic rocks intruded by Mesozoic and Tertiary granitic rocks and a southerly terrane composed of Tertiary and Holocene volcanic rocks that form locally thick volcanic ash deposits east of the Cascade Mountains. Overall, the sparsely populated Cascade Mountain Province has low radon potential because of the low uranium and high moisture contents of the soils.

The Coastal Range Province (Region 23) extends from the Olympic Peninsula of Washington south to the coastal parts of the Klamath Mountains in southwestern Oregon. In Washington, they are underlain principally by Cretaceous and Tertiary continental and marine sedimentary rocks and pre-Miocene volcanic rocks. In Oregon, the northern part of the Coastal Ranges are underlain principally by marine sedimentary rocks and mafic volcanic rocks of Tertiary age. The southern part of the Coast Range is underlain by Tertiary estuarine and marine sedimentary rocks much of them feldspathic and micaceous. The Klamath Mountains are dominated by Triassic to Jurassic metamorphic, volcanic, and sedimentary rocks with some Cretaceous intrusive rocks. These metamorphic and volcanic rocks are largely of mafic composition. Large masses of ultramafic rocks occur throughout the Klamath area. The radon potential of the Coastal Range Province is low overall. Most of the area has high rainfall and, as a consequence, high soil moisture. Uranium in the soils is typically low. Highly permeable, excessively well drained soils may cause locally elevated indoor radon levels.

River alluvium and river terraces underlie most of the Willamette River Valley (Region 25); however, many of the hills that rise above the plains are underlain by Tertiary basalts and marine sediments. The Willamette River Valley has moderate radon potential overall. Much of the area has somewhat elevated uranium present in soils and many areas have excessively drained soils and soils with high emanating power. Many townships in the valley have indoor radon averages between 2 and 4 pCi/L.

REGION 26: HAWAII

The volcanic island chain of Hawaii consists of Recent volcanic rock, predominantly basaltic lavas, ashes and tuffs, with minor carbonate and clastic marine sediments, alluvium, colluvium, dune sands, and mudflow deposits. Overall Hawaii has low radon potential. Although some soil radon is greater than 500 pCi/L (53), the lifestyles of the inhabitants and local architecture contribute to the overall low radon potential of the islands.

REGION 27 AND 28: ALASKA

Alaska is divided from north to south into two main provinces: the Arctic Coastal Plain and the Northern Foothills comprise one province (Region 27), and the the Arctic Mountains, the Central Province, and the Border Ranges comprise the other (Region 28). The Arctic coastal plain province (North Slope) consists primarily of Quaternary sedimentary rocks, mostly alluvium, glacial debris, and eolian sand and silt. A belt of Tertiary sedimentary rocks along the eastern 1/3 of the area separates the coastal plains from the foothills to the south. The Foothills province is largely composed of marine and nonmarine Cretaceous sandstone and shale, much of which is folded into westerly trending anticlines and synclines. This area has low radon potential.

The Arctic Mountains province is composed largely of faulted upper Precambrian and Paleozoic marine sedimentary rocks. The Central Province consists mostly of Precambrian and Paleozoic metamorphic rocks, Precambrian through Cretaceous mostly marine sedimentary rocks, Mesozoic intrusive and volcanic rocks, Tertiary and Quaternary mafic volcanic rocks, flat-lying Tertiary basin-fill (nonmarine clastic rocks), and Quaternary surficial deposits. The central province has several areas of uraniferous granites together with felsic intrusive and volcanic rocks. The schist that produces high indoor radon near Fairbanks is in this area.

The Border Ranges area includes the Alaska-Aleutian subprovince, the Coastal Trough province, and the Pacific Border Ranges Province. The area is composed of several mountain belts separated by a series of depositional

Cenozoic basins in a manner somewhat similar to that of the Basin and Range Province of the southwestern United States. Rocks exposed in the area include Paleozoic mafic volcanic rocks; Mesozoic mafic volcanic flows and tuffs, together with various units of shale, conglomerate, graywacke, and slate; and Tertiary and Quaternary intermediate volcanic rocks, Tertiary felsic intrusives, and Quaternary glacial deposits, eolian sand, and silt. The Coastal Trough province contains thick sequences of Tertiary continental clastic and volcanic rocks penetrated by Tertiary intrusive rocks. Mesozoic sedimentary rocks and Pleistocene glacial deposits are abundant in some areas. Cretaceous and Jurassic sedimentary and metamorphic rocks with interbedded mafic volcanic and intrusive rocks comprise most of the Border Ranges rocks. A fairly large area of lower Tertiary sedimentary and volcanic rocks is found in the Prince William Sound area. In much of this part of Alaska, annual rainfall is high (up to 170 inches), and water saturation likely retards gas flow in soils on all but the steepest of slopes. The Arctic Mountains, Central Alaska, and Border Ranges area have an overall moderate radon potential.

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# TECHNOLOGICAL ENHANCEMENT OF RADON DAUGHTER EXPOSURES DUE TO NON-NUCLEAR ENERGY ACTIVITIES

J. Kovač, D. Cesar and A. Bauman
Institute for Medical Research and
Occupational Health
University of Zagreb
Ksaver 158, P.O.Box 291
41000 Zagreb, Yugoslavia

## ABSTRACT

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 Rn-222 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 discused 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 mean values of working levels are presented, and measurement techniques are reviewed.

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

## INTRODUCTION

The exposure from man-made natural sources is called "technologicaly enhanced natural radiation" (TENR)(1). One of the first sourcesof uranium and thorium which was detected not being connected with the nuclear industry, was found during energy production using fossil fuels.

Uranium is widely distributed in nature and is a minor contaminant in all rocks, sand, and soil. Typical values for uranium are in the domain of 12 - 50 Bq/kg. Hence in ordinary back-yard soil there is of the order of 30 tons of uranium and 10 g of radium per square mile to a depth of 5 ft. Each cubic yard of ordinary soil or rock contains the order of 74 kBq of radium. This radium transforms at a constant rate into its daughter product, radon ($^{222}Rn$), and maintains a constant activity of about 74 kBq of radon per cumic yard of rock. Because all rock and soil is slightly porous some radon diffuses out of any exposed rock or soil surface. A typical value for the flow of radon from ordinary surface soils into the atmosphere is 3.7 $\mu$Bq/sec.cm$^2$, or about 3.7 kBq/day per square yard (2). This radon is diluted in the atmosphere so that typical values for the radon concentration in outdoor air are in the domain of 3.7 - 37 Bq per cubic meter of air. Radon levels will build up near the surface under still, inversion conditions when mixing is minimal. The actual volume of radon in an uranium orebody is extremely small. 37 GBq of radon occupies only 0.66 mm$^3$ at normal conditions of pressure and temperature. Thus in the 1000 tonnes of ore, with 11 GBq of Ra-226, and therefore also 11 GBq of Rn-222, there is only about 0.2 mm$^3$ of radon.

## EXPERIMENTAL PROCEDURES

### MEASUREMENTS TECHNIQUES

The radon or radon daughter measurement techniques vary considerably from modified film badge type detectors (3) to highly elaborate alpha or beta counting equipment and even solid state alpha spectrometry (4). It is desirable, for the long-term monitoring of an atmosphere, that the measurement techniques be simple, accurate and require a minimum of equipment. The techniques in this paper allow direct evaluation of the working level value which is ultimately the quantity correlated with biological hazard.

The working level (WL) is defined as any combination of short-lived radon daughters in one liter of air that will result in the emission of $1.3 \times 10^5$ MeV of potential alpha energy. Under conditions of secular equilibrium 3.7 kBq/m$^3$ (100 pCi/l) of Rn-222 produces 1 WL (5). The definition is given in Table 1.

TABLE 1. DEFINITION OF THE "WORKING LEVEL" UNIT (WL)

| Radionuclide | Alpha energy (MeV) | Half-life | Number of atoms per 100 pCi | Ultimate alpha energy per atom (MeV) | Total ultimate alpha energy (MeV/100 pCi) |
|---|---|---|---|---|---|
| Ra-222 | 5.49 | 3.8 d | 1,770,000 | excluded | - |
| Po-218 | 6.00 | 3.05 m | 977 | 6.00 + 7.68 | $0.134 \times 10^5$ |
| Pb-214 | - | 26.8 m | 8,580 | 7.68 | $0.659 \times 10^5$ |
| Bi-214 | - | 19.7 m | 6,310 | 7.68 | $0.485 \times 10^5$ |
| Po-214 | 7.69 | 0.0027 m | 0.0008 | 7.68 | $0.000 \times 10^5$ |
| | | | | | $1.278 \times 10^5$ or $1.3 \times 10^5$ |

Measurements of radon daughters can be converted to working levels by an exact calculation if the state of daughter equilibrium is known. Several authors (6) have developed methods to determine the state of radon daughter equilibrium relative to Po-218, by alpha counting a filtered air sample. The most widely applied measurement technique in the uranium mines is that of Tsivoglou, than Kusnetz.

The Thomas-Tsivoglou method for calculation of radon daughter concentrations is inconvenient for field use. The irregular counting times require manual control of the scaler with consequent probabilities of error, and an error renders the complete data set useless. The 30-min counting period limits the processing rate to two samples an hour, so at least two scalers are required if rapid changes in daughter concentrations are to be measured. With the method developed by Scott (7) and our equipment it is possible to transfer a filter from air pump to portable scaler within 40 sec, and next 15 sec is ample time to note down the scaler reading and restart. Our procedure is therefore to take an air sample from 0 to 5 min, and then count the filter from 6 to 11 minutes (the M count), and from 11.25 to 16.25 min (the R count). These are the only fixed counting times. The third 5-min count (K count) is made on the filter at a time between 45 and 90 min. The rapid estimation of WL is:

$$WL = \frac{R}{5550 \times V \times E} \qquad (1)$$

where "R" is the total number of alpha counts, "V" is the sample flow rate (liters/min), and "E" is the counting efficiency. The value for the average daughter ratio is 5539 counts, which is rounded to 5550 for convenience.

The radon monitor consists of an alpha scintillator (ZnS/Ag), photomultiplier tube, a light-tight outer housing for the detector with passive air entry and an electronic package to convert the measured pulses to a digitally recorded signal, all battery operated for field use.

For estimating WLs, paralel with alpha counting we used for a long time a single beta-counting of air sampler filters, using the method developed by Holmgreen (8), based on the Eberline Air Particulate Monitor and total low-level beta counting sistem, battery operated for field use. Since the method is unjustly forgotten, here is a reminder of the basis for WL calculation.

The method for calculation of WLs from total beta activity concentrations is based upon Table 1, using two simplifying assumptions:

1. Since at equilibrium Pb-214 and Bi-214 account for 90% of the total ultimate alpha energy, a WL estimation based on Pb-214 and Bi-214 concentrations would approximate 90% of the actual value, so a factor "F" may be introduced to compensate for the exclusion of the Po-218 contribution as a result of counting only beta activity.

2. The radon daughter concentration ratios 1:0.65:0.35 (Po-218:Pb-214:Bi-214) are employed in the model.

The ultimate energy assigned to an atom of Po-218 is 13.68 MeV, the energy of its own alpha plus the alpha energy of Po-214, its great-granddaughter. Also, Pb-214 and Bi-214, although only beta emitters, are assigned the alpha energy of Po-214, as Po-214 will ultimately be produced from either of these atoms. The energy contribution of Po-214 present in the 1 litre volume is nearly zero, because of the small population of the extremely short-lived Po-214 atoms. Equation |2| defines the WL unit:

$$WL = \frac{(13.68\text{MeV/atom}_A)(N_A) + (7.68\text{MeV/atom}_{B+C})(N_B+N_C)}{1.3 \times 10^5 \text{ MeV/WL}} \qquad (2)$$

where "$N_A$" is number of atoms of Po-218, "$N_B$" number of atoms of Pb-214, and "$N_C$" is number of atoms of Bi-214. The numbers of atoms of each daughter can be determined from Table 1. Substitution of numbers of atoms of each daughter into equation |2| yields:

$$WL = 0.001028(pCi_A/l.) + 0.005069(pCi_B/l.) + 0.003728(pCi_C/l.) \qquad (3)$$

Based upon two assumptions given above, equation |3| may be modified to become:

$$WL = F|0.005069(pCi_B/l.) + 0.003728(pCi_C/l.)| \qquad (4)$$

Also: $$pCi_B/l. = 0.65\ C_a \qquad (5)$$

and $$pCi_C/l. = 0.35\ C_a \qquad (6)$$

where $C_a$ is the total measured beta activity concentration (pCi/l.). Substitution into equation |4| of equations |4| and |5| and factoring, and taking into account that parameter "F" has an empirically determined value of 1.25, substitution into equation |4| gives:

$$WL = C_a(0.00575) \qquad (7)$$

In all our measurements we used glass fiber filters (General Electric), even we tried with molecular filters, but they were not convinient in very dusty atmosphere.

## WL IN COAL-FIRED POWER PLANT

As the combustion of coal increases, so will the magnitude of environmental and human health hazards associated with trace elements and radionuclides mobilized by the coal fuel cycle. The large fraction of coal ash that does not find a commercial application is usually dumped in the vicinity of the coal-fired power plant (CFPP). When the dumping is finished, most dry ash dumps are covered by topsoil and converted into areas for agricultural or recreational use, but not yet in Yugoslavia (9).

The coal ash may contain enhanced levels of the natural radionuclides in the uranium and series, especially fly ash. Among the decay products are the radon isotopes, Rn-222, Rn-220 and Rn-219, which are noble gases and thereby pose special problems in assessing the radiological hazard of fly ash. The fractional amount of radon lost from the parent-containing material is called the emanation coefficient or emanating power. It is important to stress the difference between radon which escapes the physical confines of the parent-containing material (emanation) and that which occurs in a gas atmosphere which may be sampled (emanation + diffusion). Beck measured the emenation coefficients of coal ash obtained from three different power plants (10). For all samples he studied, the emenation coefficients were less than 0.1. Gamma radiation from a tailings dump is in general not a serious problem. Radiation levels 1 m from the pile surface tend to be less than 0.01 mGy/h and average around 0.005 mGy/h though "hot spots" with much higher dose rates have been reported (9). As with radon emenation, higher surface dose rates are to be expected over the tailings from higher grade coal, such as in the investigated case.

For all that reasons, investigations of the hazards were undertaken in the CFPP in Croatia, because the anthracite coal used for combustion has an average 10% sulphur and a variation of uranium. In the seventies the uranium content in coal was between 500 - 1200 Bq/kg. After 1980 it declined to an average 250 Bq/kg due to opening of an different vein in the coal mine. This requested a thorough monitoring programme which included measurements of activity concentration of radionuclides in coal and ash samples, and measurements of WL. First measurements of WL were carried out at 1977. In the CFPP seven locations have been chosen, because of long-time occupational exposure, and five on-site in places with natural air flow. Measurements have been repeated in 1983, when CFPP used coal with lower uranium content. In 1977 we used only Holmgreen`s method, and in 1983 we used both, Holmgreen`s and Scott`s method. Tables 2 and 3 summarize the estimated WL values, together with occupancy time limit.

TABLE 2. WL OF OCCUPATIONALLY EXPOSED PERSONS INSIDE THE CFPP

| Work place | mWL * (1977) | Occupancy time limit | mWL (1983) | Occupancy time limit |
|---|---|---|---|---|
| 1. Conveyour belt (coal) | 8.0 | 42 h/week** unlimited | 7.0 | 42 h/week unlimited |
| 2. Conveyour belt (coal) | 15.0 | 24-42 h/week | 6.0 | 42 h/week unlimited |
| 3. Below the automatic control (ash hooper) | 80.0 | 21 h/week | 12.0 | 24-42 h/week |
| 4. Below the automatic control (ash hooper) | 60.0 | 42 h/week | 12.0 | 24-42 h/week |
| 5. Waste pile fresh | 80.0 | 21 h/week | - | - |
| 6. Waste pile old | - | - | 60.0 | 42 h/week |
| 7. Bottom ash | 80.0 | 21 h/week | 20.0 | 24-42 h/week |

TABLE 3. WL ON-SITE IN PLACES WITH NATURAL AIR FLOW

| Work place | mWL* (1977) | Occupancy time limit | mWL (1983) | Occupancy time limit |
|---|---|---|---|---|
| 1. Area around the steam generator building | 6.0 | unlimited | 6.0 | unlimited |
| 2. Under the stack | 5.0 | unlimited | 6.0 | unlimited |
| 3. Near the furnice | 5.0 | unlimited | 6.0 | unlimited |
| 4. Office building (500 m from the CFPP) | 3.0 | unlimited | - | - |
| 5. 10 km from the CFPP | 3.0 | unlimited | 6.0 | unlimited |

*mWL = $1 \times 10^{-3}$ WL. All WL values are an arithmetic mean of 3 measurements.

**42 h/week was taken as the occupancy time limit to comply with the US general population standards, since the workers in the CFPP were never considered as people occupationally exposed to radiation.

The WLs have shown great variations between two measurements depending on the radioactivity of the coal and combustion products present at the time of the measurements in the CFPP. Places on-site with good ventilation had 3 - 6 mWL. The highest WL was besides the bottom ash and fresh waste pile where even an occupancy time limit should be considered. The values for the WL are changing, so that the new data are lower than these presented in Table 2 and 3. Table 4 summarizes the estimated WL values measured in 1990, when we used only Scott`s method.

TABLE 4. WL MEASURED ON-SITE AND OFF-SITE CFPP IN 1990.

| Location | mWL |
|---|---|
| 1. Coal storehouse | 6.0 |
| 2. Below the automatic control (ash hooper) | 11.0 |
| 3. Area around the steam generator building | 6.0 |
| 4. Slag and ash pile | 6.0 |
| 5. Štrmac | 6.0 |
| 6. Vozilići | 5.0 |
| 7. Stepčići | 5.0 |
| 8. Luka Plomin | 4.0 |
| 9. Rabac | 3.0 |

There were no differences in WLs between measurements done by one or the other method. As we expected, the highest values were obtained on-site of the CFPP. Locations 5 - 9 were at different directions and distances from the CFPP, chosen in dependency on the wind-rose (Table 5).

TABLE 5. ALTITUDES, DISTANCES AND DIRECTIONS FROM THE CFPP

| Location | Altitude (m) | Distance (km) | Direction |
|---|---|---|---|
| Štrmac | 120 | 3 | SW |
| Vozilići | 100 | 5 | NW |
| Stepčići | 80 | 2 | W |
| Luka Plomin | 10 | 1 | SE |
| Rabac | 0 | 20 | S |

The most interesting case is the location Štrmac, where a hamlet was built on a ninety years old tailing site, where already the second and even the third generation of same families are dweling in the same houses.

At the location Rabac, which is at the sea shore the WL is slightly lower, since the radon levels over the sea and the ocean are much lower than over the land, due to the lower Ra-226 content of the sea. For this reason, radon levels in the atmosphere at coastal sites are very dependent on whether the wind is blowing from the land or the sea.

## WL IN FERTILIZER INDUSTRY

Three years after the beguining of the WL measurements at the CFPP, the same type of investigations has started in a fertilizer plant.

The activity mass concentrations of natural radionuclides in phosphate ore for a given radionuclide and type of fertilizer vary markedly from one country to another, depending on the origin of the components. General features are that the activity mass concentrations of K-40 and Th-232 and its decay products are always low and that the activity mass concentrations of the radionuclides of the U-238 decay series are 5 - 50 times higher than in normal soil. The degree of radioactive equilibrium between U-238 and its decay products in a given type of fertilizer depends essentially on the relative contribution of phosphoric acid, since phosphoric acid usually has a very low Ra-226 concentration. For the purpose of this, it is assumed that Th-230 and U-234 are in radioactive equilibrium with U-238 and that Pb-210 and Po-210 are in radioactive equilibrium with Ra-226.

A typical concentrations of U-238 and Ra-226 in sedimentary phosphate deposits are 1500 Bq/kg, which are generally found to be in radioactive equilibrium. When these rocks are processed into fertilizer most of the uranium and some of the radium accompanies the fertilizer, and than in the fields through crops enters the food chain.

In the production of fertilizers, phosphate rocks are used in two different ways. The first method, the acidulation of phosphate rocks was ensured by sulphuric acid, where phosphoric acid and gypsum result as normal superphosphate. The second method, where the phosphate rock is treated by nitric acid, the final product is phosphoric acid and gypsum as residue, which contains most of the radium (11).

Almost all of Ra-226 originally in the phosphate ore is discharged in the piles. The concentration of Ra-226 in piles is about 700 Bq/kg. Since the rate of radon production equals the rate of radium decay, the rate of radon production can be readily calculated. The answer is, 1 g of Ra-226 (this is also 1 Ci or 37 GBq of Ra-226) produces 74 kBq/sec of Rn-222. Thus the radon production rate in piles containing 700 Bq/kg od Ra-226 is 1.4 mBq/kg/sec. The density of dry piles is about 0.7 $g/cm^3$, which means that the production rate of radon per unit volume is about 1 $mBq/m^3/sec$.

The highest occupational radiation exposure during the process are to be expected in the fertilizer production or in the fertilizer storehouse. To check the level of radiation dose, a monitoring programme was introduced, including the determination of specific activities of natural radionuclides in ambient air, phosphate ore, phosphate fertilizers, waste products, trickling and well waters. Measurements of WLs were carried out at ten locations, twice a year for the last ten years. Five of them were inside the phosphate fertilizer plant, one on the gypsum`s pile. The off-site locations were at four different directions and distances, chosen on the basis of the wind-rose. Results are presented in Table 6.

TABLE 6. WL MEASURED ON-SITE AND OFF-SITE THE FERTILIZER PLANT

| Location | mWL |
|---|---|
| 1. Phosphate ore storehouse | 12.0 |
| 2. KCl storehouse | 4.6 |
| 3. Fertilizer package store (NPK) | 21.0 |
| 4. Inside the fertilizer production | 9.4 |
| 5. Phosphoric acid production | 4.4 |
| 6. Gypsum`s pile | 3.0 |
| 7. Off-site locations | 1.2 |

All values are an arithmetic mean of ten years measurements performed in summer and winter, always three times on each location. During the first year only beta measurements (Holmgreen) were done, and later only alpha measurements (Scott)(7,8). There were no significant differences observed during the years. For the comparison in Table 7 one year data are presented measured once by alpha and once by beta measurement.

TABLE 7. WL MESURED BY DIFFERENT METHODS

| Location | Holmgreen | Scott |
|---|---|---|
| | mWL | |
| 1. Phosphate ore storehouse | 3.1 | 3.2 |
| 2. KCl storehouse | 2.5 | 1.1 |
| 3. Fertilizer package store (NPK) | 3.5 | 4.2 |
| 4. Off-site locations | 1.4 | 1.2 |

The WL rate differs slightly not because of different measuring methods, but also due to different phosphate ore origin.

## CONCLUSION

This paper introduces WL measurements in industries where TENR is present. The CFPP is a specific case with the appearance of natural radioactivity which was very similar to open pit uranium mining, where WL measurements are routinelly done. For that reaso WL measurements were applied also in this case. When some places of occupational exposure in the CFPP were detected, the authors have tried to find out if the same problem also exists in the fertilizer industry. The appearence of places with an increase of natural radioactivity in non-nuclear industries have left the legislator, at present without a ready solution in Yugoslavia, how to systematize occupationally exposed workers, especially after the Chernobyl accident, when the public become sensitive to radiation of any origin.

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

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# A SITE STUDY OF SOIL CHARACTERISTICS AND SOIL GAS RADON

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.-<br>Depth (m) | Date<br>mo/yr | Active<br>(kBq/m$^3$) | Date<br>mo/yr | Passive<br>(kBq/m$^3$) | Date<br>mo/yr | Passive<br>(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.-<br>Depth (m) | Date<br>mo/yr | Active<br>(kBq/m$^3$) | Date<br>mo/yr | Passive<br>(kBq/m$^3$) | Date<br>mo/yr | Passive<br>(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) | $^{210}Pb/^{226}Ra$ $\pm \approx 10\%$ |
|---|---|---|---|---|
| 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) | $^{210}Pb/^{226}Ra$ $\pm \approx 10\%$ |
|---|---|---|---|---|
| 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.

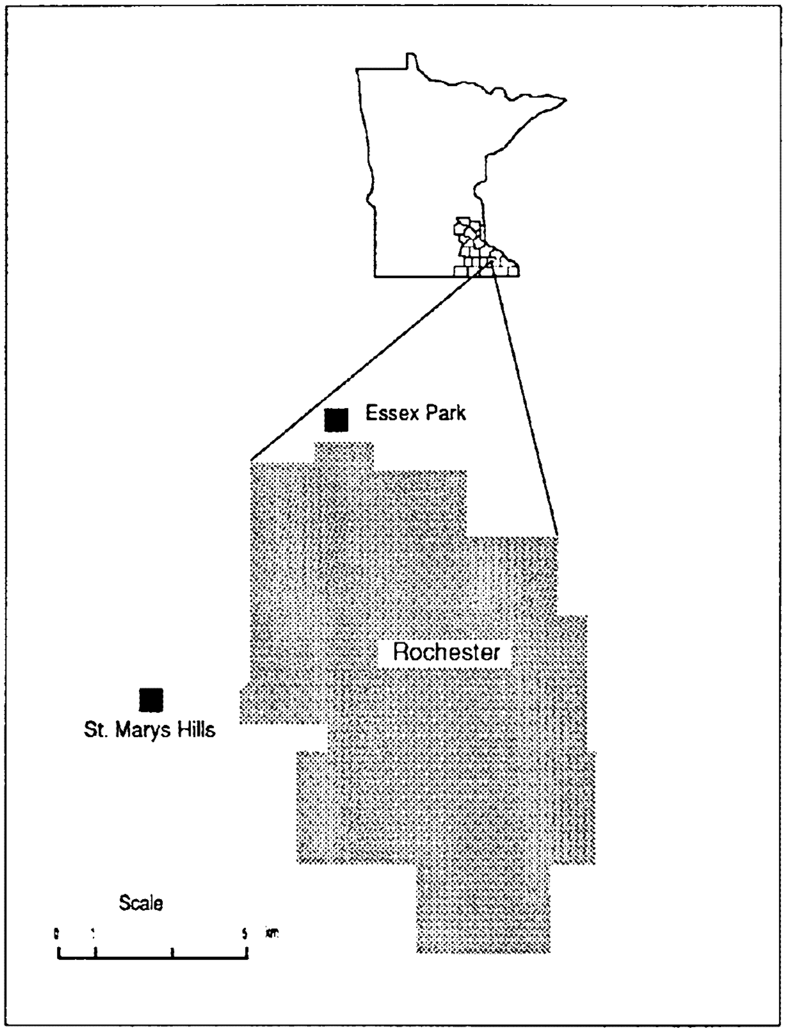


Figure 1. Map showing study areas near Rochester, Olmsted County, Minnesota

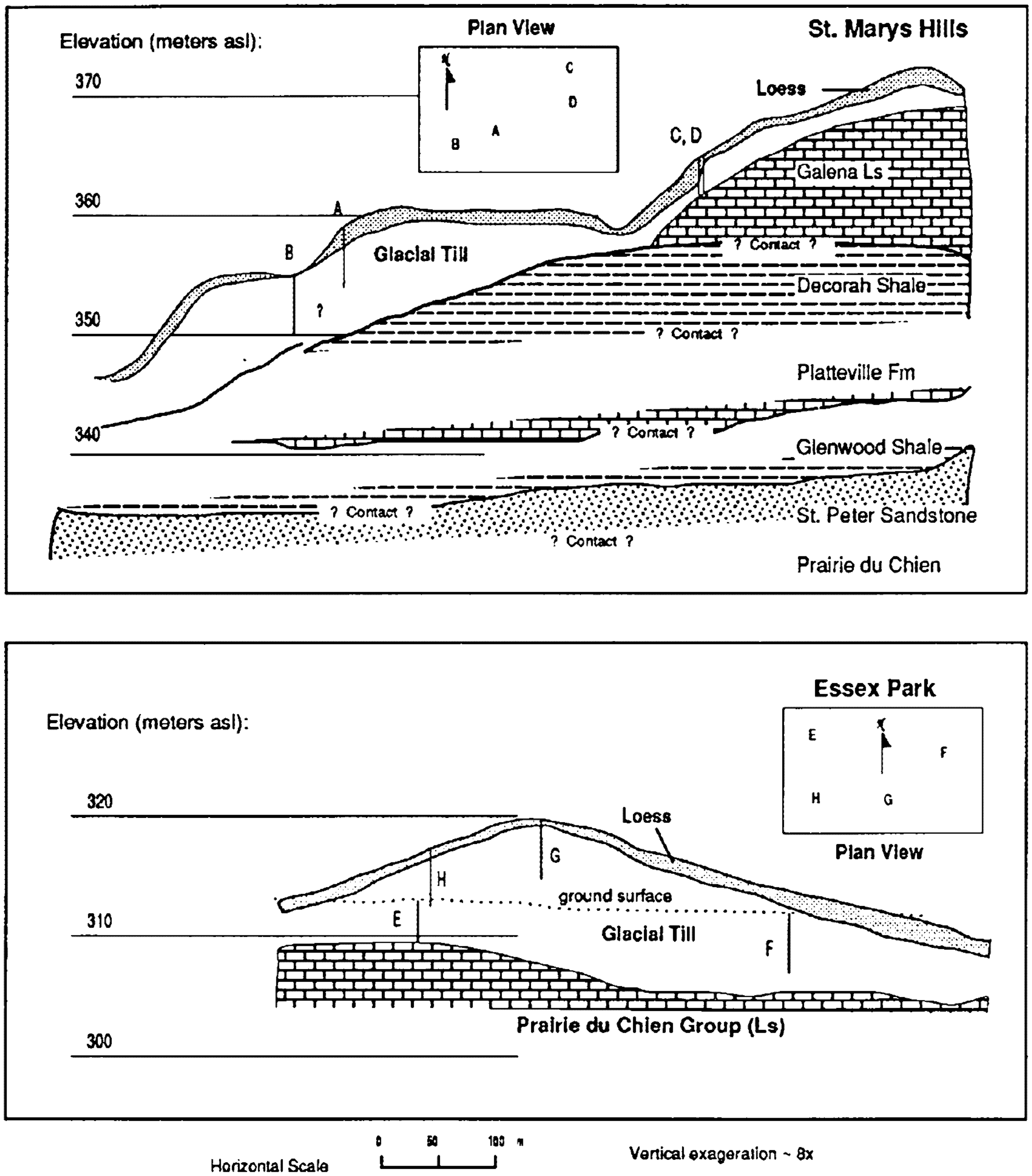


Figure 2. Profiles and location of sample holes. Modified from Plates 2 and 3, Olmsted County Atlas (4,5).

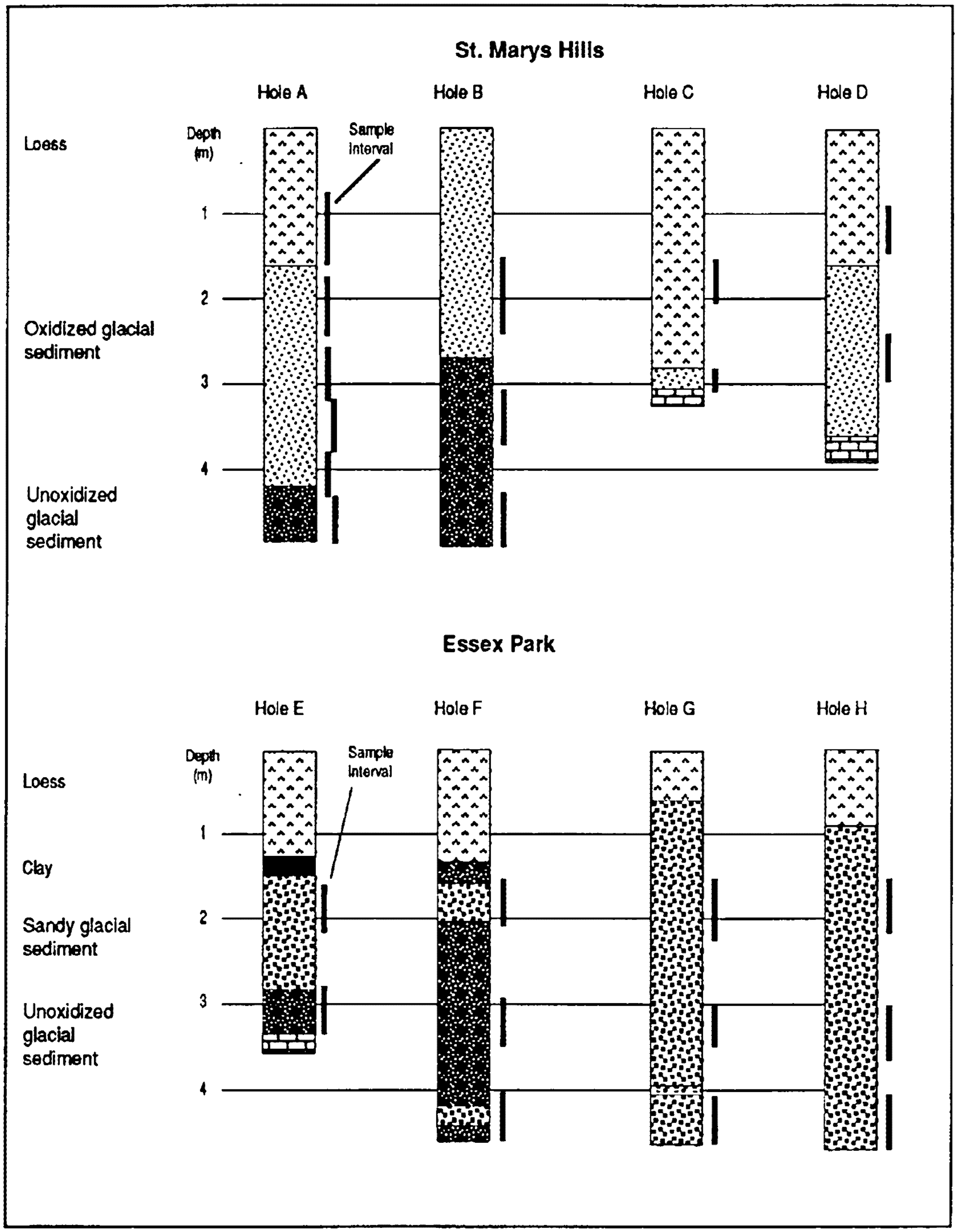


Figure 3. Borehole lithology and sample locations based on field identifications.

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

Donald Carlisle and Haydar Azzouz *
Department of Earth and Space Sciences
University of California Los Angeles
Los Angeles, California 90024

## 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 houses on the Rincon Shale exceed 4 pCi/l and 26% exceed 20 pCi/l. Measurements under "normal" living conditions show 50% exceeding 4 pCi/l. An estimated 4,000 plus houses 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 indoor radon risk identification than simple random sampling or non-random testing of houses and by the same token geological parameters can facilitate radon risk assessment on undeveloped lands. Attention is drawn to multiple populations within radon test samples and the consequent problems in estimating regional parameters.

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* Present address of Haydar Azzouz: GeoSyntec Consultants, Huntington Beach, California

## 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 houses 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 houses in the area of interest. Simple random sampling aims ideally to avoid bias by making every house 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 very brief summary on the next two pages 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 a 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 10 ppm or more in common igneous rocks, and to as much as 200 ppm, rarely 500 ppm in black shales. Contents in excess of 5 ppm are considered anomalous by some investigators. 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 accordingly 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: roughly $5 \times 10^{-10}$ $cm^2$ for silt - clay mixtures to $5 \times 10^{-6}$ cm$^2$ for coarse sand. Variations in the emanating fraction are too costly to evaluate since they depend heavily on local soil moisture content among other factors and in any event they are 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 significant than soil permeability since it tends both to reduce the radon content of otherwise impervious soil and to facilitate transfer of soil gas into a building. 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, but only 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:

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

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, extrapolated within reason, as a reconnaissance tool followed by geology, soil-gas measurement, application of the Kunz, *et al.* formulation and, where appropriate, by detailed site studies all 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 metropolitan 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 for 79 of the test houses after our radiometric compilations and our field measurements were complete and these became the basis for evaluation of our methodology (6). In the following discussion we refer to this 82-home area as the Primary or Baseline Subarea.

## 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 "equivalent" isotope 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 making 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 predominantly 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 had identified the Rincon Shale as eU and eRn-anomalous in the areas which were covered by the flight lines.

Aeroradiometric data for the Los Angeles Sheet were plotted by geological unit and informally subdivided by us 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 (7) to obtain soil gas samples: A stainless steel probe, 0.80 cm O.D., 0.16 cm I.D., 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 approach 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 were 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 Rn-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 was calibrated as configured during analysis 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 judged to be insufficiently consistent for the research stage of our work reported here and were omitted from the calculations.

The formula used to calculate radon concentration is:

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

where: $C$ = Soil-gas Rn-222 concentration in pCi/l

$N_{30}$ = Counts in 30 minutes
$N_5$ = Counts in 5 minutes
CB = Cell background (counts) prior to sample injection
T = Counting period: 25 minutes
SV = Sample volume: 0.01 liters
DF = Radioactive 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.

Even at moderate concentrations of radon this 30-minute 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. In exploration subsequent to the research reported here we have tested and adopted a counting protocol of 5 and 10 minutes with appropriate adjustment of the formula.

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 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 which the gas is drawn from 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, hemispherical or some other shape, for example. Many soils are not only layered but are randomly penetrated by fractures, root cavities or animal burrows or contain irregular zones 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.

Therefore bearing in mind cost and practicality, we have adopted the technique of permeability estimation based upon grain size distribution determined by sieving 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 measured pressure-volume pumping 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 Celsius and sieved by mechanical shaker. Soil types were categorized and permeabilities were assigned on the basis of published tables, e.g. Sextro, *et al.* (8). Because of the large number of samples involved we did not perform wet separation of clay and silt grain sizes. Nor did we measure moisture content, the degree of compaction or the 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 reproducible basis for comparison of soils at reasonable cost. Moreover it should be noted that permeability appears in the RIN formulation, above, only as its square root.

## RESULTS FROM THE PRIMARY (BASELINE) SUBAREA IN NORTHWESTERN LOS ANGELES - SOUTHEASTERN VENTURA COUNTIES

### HOUSE CHARACTERISTICS IN THE PRIMARY SUBAREA

Mention was made above of the 82 test 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 79 houses (out of 82) for which indoor radon results became available 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 houses have a basement and only 4 % have crawl space construction: the remaining 96 % are slab-on-grade. Ventilation patterns were approximately similar during the test period which was characterized by mild dry 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.

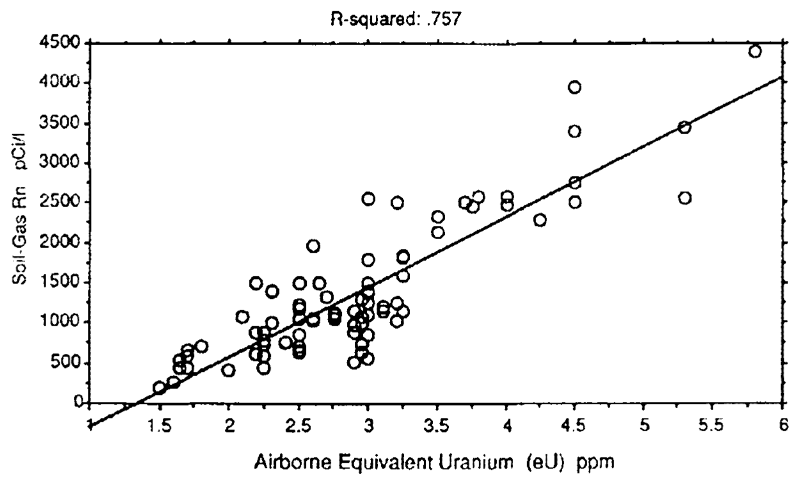


Figure 1. Airborne equivalent uranium vs soil-gas radon in the Primary Subarea

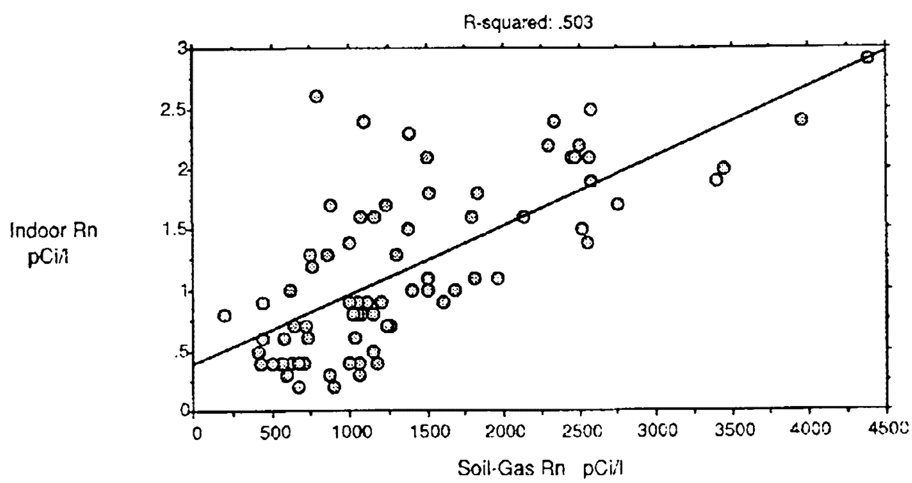


Figure 2. Indoor radon vs soil-gas radon in the Primary Subarea

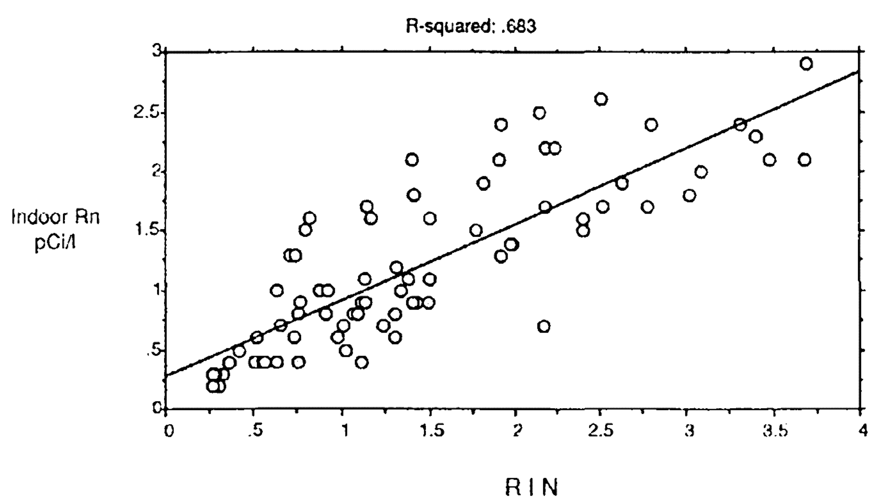


Figure 3. Indoor radon vs RIN value in the Primary Subarea

AERORADIOMETRIC DATA, SOIL-GAS RADON, RIN VALUES 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 79 houses with indoor radon measurements in the Primary Subarea. Again the correlation is very encouraging in spite of some scatter. We believe that it probably reflects in part the relative uniformity of house and weather parameters noted above. However it may also reflect the relatively well-ventilated character 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.

Sample statistics are as follows. 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. Soil-gas radon concentrations have a range from 206 to 4,390 pCi/l, and 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. Soil-gas radon concentrations most closely approach log-normality as discussed later in the paper (Figure 4).

## DISCOVERY OF THE RADON-PRONE RINCON SHALE BELT

### AERORADIOMETRIC INDICATIONS

In the entire northwestern Los Angeles - southeastern Ventura region, which includes the Primary Subarea, there are only four elongate patches in which the geological units have aeroradiometric signatures in category 5.0 to 5.9 ppm eU, the second highest of our categories, and these patches are predominantly in undeveloped terrain. None of the 82 test houses happen to be on 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.

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 averaging 6.0 to 6.9 ppm (up to 14 ppm in one place) 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 in general to associate with organic matter and with phosphate. Probe soil-gas sampling and analysis, followed by indoor 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. There is no Rincon Shale in the Primary Subarea.

## SOIL-GAS RADON IN THE RINCON SHALE

To date we have made soil-gas radon measurements at 66 locations, each with from 1 to 4 probe sites, on the Rincon Shale and soils derived predominantly from 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 soil-gas radon concentrations is from 1,100 to 20,350 pCi/l, with an AM of 6,400 pCi/l, GM of 5,045 pCi/l, and an ASD of 4,486 pCi/l. The AM is more than four and one-half times higher than the mean of soil-gas radon concentrations in the Primary Subarea or in non-Rincon units in Santa Barbara County and elsewhere in Southern California that we have tested to date.

The frequency distributions of soil-gas radon values in the Rincon Shale and in non-Rincon formations each approach lognormality but the two distributions are distinctly different and represent two separate populations. Figure 4 shows two near-Gausian curves, one derived from the logarithms of soil-gas values from the Rincon formation, the other similarly derived from non-Rincon soil-gas values. If the two different populations are lumped together on a single histogram one also sees a crudely lognormal distribution but the statistics of the lumped data are not truly representative of either population.

It may be geologically significant that the highest Rincon soil-gas radon concentrations appear to be near Santa Barbara itself, though much more data need to be obtained both to the east and the west to confirm this pattern.

## INDOOR RADON MEASUREMENTS IN HOUSES ON THE RINCON SHALE

We have now tested 85 houses in Santa Barbara County, the great majority in easterly Santa Barbara city, Montecito and Summerland. Three 3 to 7-day ACs for the screening test and one AT for the longer

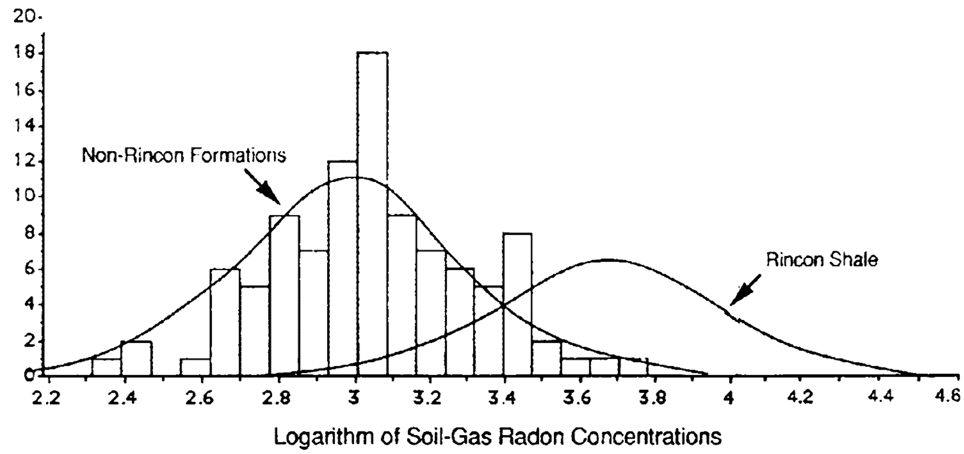


Figure 4. Frequency distributions of log soil-gas radon concentration in the Rincon Shale and in non-Rincon formations

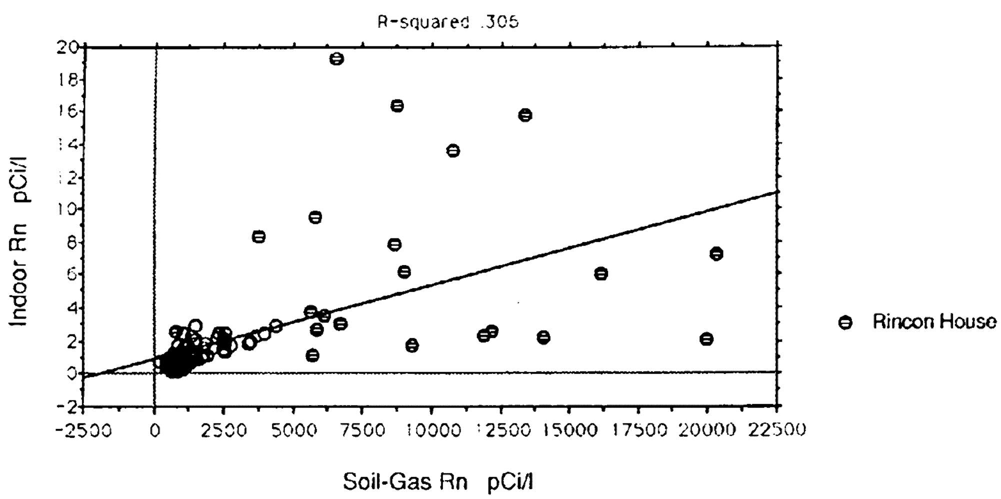


Figure 5. Indoor radon in relation to soil-gas radon in the Primary Subarea and in houses on the Rincon Shale regardless of their age.

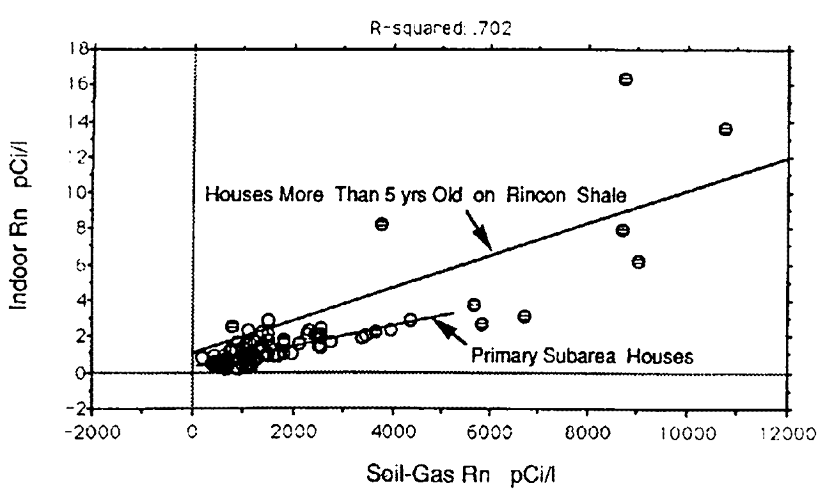


Figure 6. Indoor radon in relation to soil-gas radon in the Primary Subarea and in Rincon Shale houses more than 5 years old.

term measurement were placed in each house and retrieved by us following EPA standards. Thirty eight of these houses are on the Rincon Shale or on soils derived predominantly from Rincon Shale. Slightly over 76 % of the houses on the Rincon Shale have screening test results in excess of 4 pCi/l: twenty six percent exceed 20 pCi/l (Range 1.6 to 58 pCi/l; AM = 16 pCi/l; ASD = 14 pCi/l; GM = 11 pCi/l). Follow-on alpha track measurements of from one to six months duration, under normal living conditions show 50 % 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 (Range 1 to 19 pCi/l; AM = 6 pCi/l; ASD = 5 pCi/l; GM = 4 pCi/l). An estimated 4,000 plus houses are at the indicated level of risk: extensive new construction on the Rincon Shale is limited only by domestic water supply.

Only one house not on Rincon Shale has a follow-on measurement exceeding 20 pCi/l and that house is on a slide area with a badly cracked slab-on-grade at the time of measurement and, almost certainly, deeply cracked soil underneath.

Two subsequent independent surveys support our conclusions: one by Keller of the University of California Santa Barbara who providing single activated charcoal detectors to roughly 100 homeowners on and off the Rincon Shale (9) and a second by the California Department of Health Services also based on single ACs placed by the homeowner (10). In both cases homeowners were instructed to ensure screening test conditions

## IRREGULARITIES IN THE RELATIONSHIP BETWEEN SOIL-GAS RADON AND INDOOR RADON ON THE RINCON SHALE: SOIL FAILURE AND AGE OF HOUSE

If one combines the data on indoor radon and soil-gas radon from the total study area - i.e. the Primary Subarea and Santa Barbara Rincon Shale areas - on a single plot (Figure 5) the general correlation of soil-gas radon and indoor radon observed previously is clear enough but the scatter within the Rincon Shale portion of the data is very large. A plot of the Rincon Shale portion alone is likewise strongly scattered and shows only a weak positive relationship between indoor radon and soil-gas radon.

The failure of indoor radon to reflect soil-gas radon concentrations arises in a group of houses which have a range of high soil-gas radon concentrations around the house, often greatly exceeding 6,400 pCi/l - the mean value for Rincon Shale - but have indoor results around only 4 pCi/l. All of these houses were less than five years old at the time of testing. Though there are unfortunate exceptions, newer houses are generally built to a higher standard than those of many years ago; concrete slabs and footings are of better design even though not specifically "radon resistant," and such older practices as leaving a 1 to 2 square foot opening in slabs for plumbing access, for example, are happily discontinued. Many newer crawlspace-design houses have oversized and well ventilated crawlspaces often with subfloor insulation and vapor barriers. Moreover newer houses have not yet had time to develop concrete cracks or other openings which might allow soil gas to enter more easily.

Rincon-derived soils are montmorillonite-rich and prone to soil heaving and, on occasion, to soil flow and fracture associated with slope failure all of which disrupt the structural integrity of a house. In general the older the house, the greater the likelihood of cracks and openings for soil-gas entry and the more closely does the indoor radon value reflect soil-gas radon content. The tendency mentioned earlier for Rincon-derived soils to develop abundant large dehydration soil cracks may account for unexpected high indoor values in at least two houses in our sample but it does not account for unexpectedly low indoor values.

To test the "age-of-house" hypothesis we subtracted the data on all of those houses less than 5 years old: the result (Figure 6) is a striking improvement in the correlation between indoor radon and soil-gas radon. The improvement is equally obvious on a Rincon-only plot.

Statistics for our screening tests of houses on the Rincon Shale are: Range 1.6 to 58.4 pCi/l; AM = 16 pCi/l; GM = 11 pCi/l; and ASD = 14 pCi/l. Measurements under normal living conditions have a range of from 1 to 19 pCi/l; AM = 6 pCi/l; GM = 4.3 pCi/l; and ASD = 5.2 pCi/l.

## DISCUSSION

Figure 6 also serves once again to illustrate the existence of the two separate populations, one for houses on the Rincon Shale and the other for houses on non-Rincon formations. The existence of sub-populations, in any large region, 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. It is quite possible for simple random samples of houses to miss Rincon Shale environments especially when the random samples are small.

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 some 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 to not 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 houses and 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 X

# Oral Presentations

# Radon in Schools and Large Buildings

# SEASONAL VARIATION IN SHORT-TERM AND LONG-TERM RADON MEASUREMENTS IN SCHOOLS

Anita Schmidt[1], John T. MacWaters[2], and Harry Chmelynski[2]

[1]U.S. Environmental Protection Agency
Washington, D.C. 20460

[2]S. Cohen and Associates, Inc.
McLean, VA 22102

## ABSTRACT

During the summer of 1989, the Environmental Protection Agency initiated Phase II of the School Protocol Development Study, a year-long, in-depth radon measurement study conducted in school buildings. The purpose of the study has been to gather additional data to support and to refine the Agency's guidance and procedures for measuring radon in schools, entitled "Radon Measurements in Schools - An Interim Report".

Radon measurements were made in 21 public schools (in 7 States) selected from 130 schools previously tested in the winter of l989 (Phase I). In each school, radon levels were measured in all frequently occupied rooms in contact with the ground. Both short- and long-term seasonal measurements were made using a variety of radon measurement devices.

Results and analyses of the seasonal variation in short- and long-term tests conducted in this study are presented and discussed.

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

In April 1989, the Environmental Protection Agency (EPA) released interim guidance on radon measurement approaches for schools (1). The guidance and procedures outlined in the report were based primarily on data from an intensive study of radon conducted in 1988 in 5 schools in Fairfax County, Virginia (2). Prior to development of this document, there was little information available to school officials on procedures for radon measurement in schools.

In early 1989, EPA also initiated the School Protocol Development Study in order to refine this interim report into a final guidance document. This study has consisted of two phases. Phase I, conducted in February 1989, was a screening study of 130 schools in 16 States (3). This was not a statistically representative survey of radon levels in schools. The schools were not randomly selected, but rather were selected based on factors such as geographic location, proximity to areas with elevated radon levels, and school interest in participation. All frequently occupied rooms in contact with the ground were screened for radon.

Based on the screening results, as well as other criteria, 21 schools in 7 States were selected for Phase II. This paper describes a portion of the various results and findings from this study. The results of other measurements will be presented in a subsequent paper.

## STUDY OBJECTIVES

Phase II of the School Protocol Development Study evaluated various short- and long-term, seasonal radon measurements and various factors that may influence these measurements (4). Of particular interest is the extent of seasonal variation in measurements and the implications for testing recommendations. The Agency's current guidance recommends that schools test "in the colder months (October through March) when windows and doors as well as interior room doors are more likely to be closed and the heating system is operating"(1). When the interim guidance was published, this recommendation was based primarily on what was known about testing houses under "closed conditions", with limited information available on schools.

This study specifically gathered data in order to evaluate: the seasonal variation in shorter term measurements from 2-day open-faced charcoal canisters (OF-CC); the seasonal variation in a longer term measurement from 3-month alpha track detectors (ATD); and the seasonal variation in the relationship of these two measurements. These evaluations are presented in this paper.

The 21 schools were located in:

| | |
|---|---|
| New Jersey - 3 schools | Georgia - 3 schools |
| Minnesota - 4 schools | New Mexico - 3 schools (7 small buildings) |
| Kansas City - 4 schools KS/MO | Washington - 4 schools |

In June 1989, 3-month ATD measurements were begun according to the following schedule. ATDs were placed in all frequently occupied rooms in contact with the ground.

| | |
|---|---|
| Summer 1989 | June-August (schools unoccupied) |
| Fall 1989 | September-November |
| Winter 1989-90 | December-February |
| Spring 1990 | March-May |

Short-term measurements with 2-day OF-CC were made during the same four seasons in the same rooms with ATDs. Three (3) rounds of "2-day" tests were made over a 9-day period: on two weekends and during the intervening week. Each round covered approximately 64 hours, extending from 4 pm of the first day to 8 am on the fourth day. This was done to minimize interference with classroom hours and to accommodate normal weekend hours for school personnel conducting the measurements. The 9-day periods for each season were conducted beginning:

| | Summer 1989 | Fall 1989 | Winter 1989-90 | Spring 1990 |
|---|---|---|---|---|
| NJ | 7/21 | 10/27 | 1/5 | 3/30 |
| GA | 7/14 | missing | 1/9 | 5/11 |
| MN | 7/28 | 11/12 | 2/2 | 5/4 |
| NM | 7/21 | 10/20 | 1/19 | 4/20 |
| KS/MO | 7/21 | 10/13 | 2/2 | 4/20 |
| WA | 8/4 | 10/20 | 1/19 | 4/20 |

The purpose of the 3 rounds was to study the influence of school ventilation systems on short-term radon measurements by operating these systems differently during each round:

Round 1 Weekend

To measure the effect of minimum ventilation on radon concentrations, all ventilation systems are turned off, or set to minimum operation, during the day with a normal night-time set-back of the system

[Note: Most of the schools had provision (manual or clock-operated switches) for "night-time set-back" which keeps the building above some minimum temperature (e.g., 55 degrees) to prevent freezing and to allow quick morning warm-up. This set-back usually includes exhaust fans. Night-time set-back is usually used on weekends as well.]

Round 2 Weekdays

To measure a weekday period with normal school activity, the ventilation systems are operated on a normal, day-time setting, including normal night-time set-back of the system.

Round 3 Weekend

To measure the effect of maximum ventilation on radon concentrations, the ventilation systems are operated on a normal daytime setting, without the normal night-time set-back.

* Round 3 is equivalent to the recommended 2-day weekend approach outlined in the EPA's interim guidance document on radon measurements in schools.

## MEASUREMENT RESULTS AND ANALYSIS OF SEASONAL VARIATION

Measurement results used in this evaluation of seasonal variation are summarized and presented in Tables 1 and 2 for ATDs and Tables 3 and 4 for OF-CC. For OF-CC, note that the number of rooms varies from season to season because of occasional problems with operation of ventilation systems in a few schools. For OF-CC and for ATDs there were also small amounts of missing data in all States in all seasons due to a variety of reasons.

### ATD Results

A summary of the seasonal ATD data for each State is presented in Table 1 and a summary by school in each State is in Table 2. Two types of seasonal comparisons were done. First an analysis was done to determine if measurements within a State varied significantly from season to season, and, secondly, to determine to what extent measurements within a State for a given season deviated from a 4-season annual average measurement and from a 3-season average representing the school year (i.e., no summer measurements included).

For the first analysis, the results of a non-parametric one-way Analysis of Variance (ANOVA) test for significant differences by season are shown in the final column of Tables 1 and 2. This was done school-by-school and State-by-State. The one-way ANOVA test compares variation of room measurements for a State within each season to the observed variations across 4 seasons (or for 3 seasons) for that State. If the within-season variation is approximately equal to or greater than the across-season variation, the test reports that the seasonal means are not significantly different. Alternatively, if the within-season variation is small compared to the across-season variation, the test reports that the observed difference in season means is significant. (A 0.05 probability level is used for all ANOVA tests.)

Tables 1 and 2 show that there was significant seasonal variation in radon measurements using ATDs for most of the schools and States.

For the second analysis, a 4-season (and 3-season) average of school measurements (weighted by the number of rooms tested in each season), was computed for each State. The percent deviation of each seasonal average (e.g., winter) for a State from the 4-season (and 3-season) ATD average for that State is shown in Figures 1 and 2. (Note: data from schools in Georgia were not included in the analyses for Figures 1 and 2 because data from the fall season were not available to compute an across season average.)

An additional line has been added to Figures 1 and 2 to represent the average percent deviation for each season from the 4-season (and 3-season) average across 6 States. The seasonal average was computed by averaging the percent deviation for each State in that season.

In Figure 1, there is no single, distinct pattern of seasonal variation present. The measurements in New Jersey school rooms were lower in the summer (-8%) and fall (-8%) than the annual average from four seasons of measurements for the schools in that State, but were higher in the winter (12%) and spring (+4%). For Kansas City schools in Kansas and Missouri, the summer and winter measurements were 12% and 8% higher, respectively, than the annual average. In the winter and spring, the measurements were 10% and 9% below the average. In Washington, measurements were lower in summer (-20%) than the 4-season average, but higher in fall (+18%) and winter (+4%), and lower once again in spring (-2%). A similar pattern is present for the New Mexico schools. For Minnesota, measurements alternated from lower to higher than the 4-season average in summer and fall, respectively, but were only 1% below the annual average in winter and spring.

In Figure 2, where seasonal averages are compared to a 3-season, school year average, there is no single seasonal pattern. However, as in Figure 1, there appears to be an overall trend (for 6 States combined) of higher fall and lower spring measurements, with winter measurements not consistently above or below the long-term averages. Overall summer measurements in Figure 1 were lower than the annual average.

Another general observation can be made from Figures 1 and 2, for all States in the study, the variations in seasonal radon averages are within a range of approximately $\pm$ 20 % of the 4-season and the 3-season averages.

Open-Faced Charcoal Canister Results

A summary of the seasonal OF-CC data is presented in Table 3 by State and in

Table 4 by school. These data were analyzed in the same manner as the ATD data. The results of a non-parametric one-way ANOVA test for significant difference by season are shown in the final column of both tables. These results also show that, for the most part, there is significant seasonal variation in "2-day" measurements by school and by State.

The measurement data were next analyzed for the percent deviation of measurements from each State by season from a 3-season average (school year) for that State. For the purpose of investigating seasonal variation, only results from Round 3 are presented (Figure 3). This is the round that approximates the current recommendation in EPA's school guidance (weekend, with weekday HVAC settings, no night set-back). As was observed for the seasonal data from ATDs, there is no specific pattern of seasonal variation for OF-CC that applies to all schools or to all States measured in this study. Data for Washington and Missouri show deviations from the 3-season average for Round 3 going in opposite directions in fall and spring. For these two States, the range of variation in seasonal averages from a 3-season average is larger than for ATDs, approximately $\pm$ 50% for Washington in fall and spring and -23% for fall and +40% in spring for the two Kansas City schools in Missouri. (Note: insufficient data were available from Round 3 for the Kansas City schools in Kansas and schools in Georgia.) For New Jersey, Minnesota, and New Mexico the range of variation for all 3 seasons is somewhat smaller, +10% and -16%. Overall, the smallest variation for schools in these 5 States was in winter, with a range of +9% to -16%. As in Figure 2, there is an overall trend of higher measurements in the fall relative to a 3-season average, and lower in the spring.

Figure 4 examines the seasonal variation of Round 3 data from the 3-season average using ATD measurements. For each school room with a complete data set, the percent deviation of the OF-CC measurement in each season from the 3-season average was calculated. These room-by-room deviations were then averaged for each season for each State. (Note: complete data were not available for Kansas, Missouri, or Georgia.) These results are very similar to those in Figure 3. Again there is no single pattern for all States. Based on the combined data from the 4 States, Round 3 OF-CC results were similar to the long-term average for fall and winter. The spring measurements with OF-CC for all 4 States are lower than the 3-season ATD average.

Seasonal Variation in the Ratio of Open-faced Canister and ATD Results

The deployment of collocated "2-day" canisters and 3-month ATDs in a large number of rooms provided the data needed to compare a set of short-term and long-term radon measurements from schools. This comparison is of interest because it is useful to know to what extent a 2-day measurement may under or over estimate a longer term measurement. In addition these are two of the most commonly used devices in schools which makes the comparison of further interest.

The measurements were directly compared for each season by calculating the ratio of the "2-day" to the 3-month ATD results for each room, for each round, for each season. In general, for the resulting ratios for each round for each season, there was a wide spread in the "2-day"/3-month ratios in rooms with low radon levels, while at higher radon levels the spread was much smaller. The mean ratio of all measurements by season was then calculated. If the average ratio exceeds 1.0, this indicates that the short-term measurements for that season were higher, on average, than the 3-month measurements for that season. Ratios less than 1.0 indicate that the "2-day" measurements were lower than the 3-month measurements on average. Average ratios for each of the 3 rounds, for each season, are presented in Figure 5. In Table 5, the average ratios are presented along with additional information on the number of room measurements and the standard deviations for the ratios.

In Figure 5, the average ratios of short to long-term measurements were generally much greater than 1.0 in summer (20% to 93% above). In the winter, the mean ratios for Rounds 2 and 3 are very close to 1.0 (1% below, 7% above). In the spring, Rounds 2 and 3 OF-CC measurements are 23% and 17%, respectively, lower than the ATD results for that season. In the fall, Rounds 2 and 3 are 16% below and 7% above the ATD results. This suggests that these "2-day" results, conducted under normal weekday, occupied conditions (Round 2) or under maximum ventilation during unoccupied conditions (Round 3) are very similar on average, especially in winter, to the longer term measurements in each season or across all 4 season as indicated by the weighted yearly averages. Averaged over all seasons, Round 1 canisters were 50 % higher than the 3-month ATDs. In Round 2 and 3 the canisters are only 1 to 5 % higher than the ATDs across all seasons.

Quality Assurance

The precision and accuracy of the OF-CC and ATDs was measured by the use of a number of quality control detectors. For charcoal canisters each school had 10 percent duplicates samples and 5 percent blanks. For ATDs each school had 20 percent duplicates and 5 percent blanks. The devices were placed side by side over identical measurement intervals in each season. Charcoal canisters and ATDs were also exposed in chambers with known concentrations of radon and submitted to the analysis laboratory without being identified as spiked samples.

The overall quality control results for the study are good. The precision of duplicate canisters is considered very good, with an average coefficient of variation (COV) of 6%. This compares favorably with the suggested 10% in EPA's measurement protocols (5). The COV for duplicate ATDs was 6% for fall and winter and 19% for spring. These results are particularly good for fall and winter and considered acceptable for the spring. EPA's measurement protocols for ATDs recommend that the COV for precision should not exceed 20%.

The overall accuracy of these devices in this study were very good as measured by field blank detectors and spiked detectors. For OF-CC field blanks, the average radon level was below 0.1 pCi/L. For ATD field blanks, the average radon level was below 0.8 pCi/L. Based on results from spiked devices, the accuracy of the OF-CC is considered very good (average bias of +5%). For ATDs, the bias ranged from good (-5%) to acceptable (-19%).

## CONCLUSIONS

This assessment of seasonal variation using "2-day" and 3-month measurements indicates the following:

1. Seasonal variation was observed in school radon measurements from season to season for both "2-day" and 3-month results. This variation was significant for most of the schools and States in the study (Tables 1-4). This seasonal variation was present even though the radon levels were generally under 4 pCi/L in most of the schools.

2. There is no clear, single, pattern to this seasonal variation in the data across all the schools or States for either OF-CC or ATD results. In Figures 1-4, the average percent deviation of measurements for a given season from a long-term average vary from State to State, season to season. Patterns for any two States may go in opposite directions. Tables 2 and 4 also indicate that an apparent seasonal pattern for a State may not be consistently observed at the school level for that State. Given the wide geographical range and climatic variation, the lack of a well-defined seasonal pattern may not be unexpected.

3. In Figures 1-4, there is a general seasonal trend observed when all data for a season are combined across States. On average, summer and spring measurements for both OF-CC and ATDs tend to be lower than the annual or school year averages, higher in the fall, and close to the long-term averages in the winter. However, New Jersey and Missouri measurements did not follow this pattern for fall and spring.

4. Figure 5 suggests that a "2-day" radon measurement taken in the winter months, on average, may approximate a 3-month measurement. An exception is measurements made under conditions of minimum ventilation (Round 1). The "2-day" measurements in the fall also were close to the 3-month average radon levels. In the summer, the OF-CC measurements may over predict what a 3-month ATD measurement would indicate.

Figures 1-5 suggest that measurements taken in the winter months of the year may provide, on average, the best measurement of school year (or annual) average radon levels. These results may be due to the more uniform and stable conditions in winter compared to fall and spring. These latter two seasons usually span both cold and warm weather. Therefore, during some weeks of warm weather, windows and doors may be open (heating systems not operating). During other weeks of much colder weather, schools may be more closed up (heating systems are operating). In the winter months, the heating systems in these schools were operated routinely and doors were likely to be closed more consistently over this 3 month period than in fall and spring. The reason for the overall higher measurements in the fall compared to the lower results for the spring relative to the longer term averages is not readily apparent.

These evaluations are generally supportive of EPA's current recommendation to test schools during the colder months of the year. Perhaps a more definitive recommendation would be to test schools during the coldest months of the year for that geographic area when the heating system of the school is routinely operated. These results also suggest that winter measurements, whether taken over a few days or 3 months, may on average be a good indicator of the school year average radon levels in a school.


## ACKNOWLEDGEMENTS

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TABLE 1. ANALYSIS OF SEASONAL VARIATION IN ROOM RADON LEVELS BY STATE USING ATD MEASUREMENTS

| STATE | SEASONAL MEAN (pCi/l) AND NUMBER OF ROOMS (N) | | | | | | | | ARE DIFFERENCES ACROSS SEASONS SIGNIFICANT AT THE 0.05 LEVEL? |
|---|---|---|---|---|---|---|---|---|---|
| | SUMMER | | FALL | | WINTER | | SPRING | | |
| | N | MEAN | N | MEAN | N | MEAN | N | MEAN | |
| NJ | 100 | 1.39 | 105 | 1.39 | 105 | 1.70 | 90 | 1.60 | NO |
| GA | 129 | 3.77 | 113 | 3.02 | . | . | 121 | 2.37 | YES |
| MN | 79 | 1.32 | 68 | 1.85 | 100 | 1.42 | 107 | 1.66 | YES |
| NM | 101 | 1.06 | 96 | 1.46 | 87 | 1.44 | 91 | 1.08 | YES |
| KS | 53 | 2.51 | 48 | 2.23 | 50 | 1.73 | 53 | 1.93 | YES |
| MO | 38 | 1.28 | 38 | 1.39 | 37 | 1.21 | 39 | 1.02 | NO |
| KS & MO | 91 | 1.99 | 86 | 1.85 | 87 | 1.51 | 92 | 1.54 | YES |
| WA | 85 | 1.91 | 86 | 2.74 | 90 | 2.40 | 85 | 2.23 | YES |

(.) Missing Data

TABLE 2. ANALYSIS OF SEASONAL VARIATION IN ROOM RADON LEVELS BY STATE AND BY SCHOOL USING ATD MEASUREMENTS

| STATE | SCHOOL | SEASONAL MEAN (pCi/l) AND NUMBER OF ROOMS (N) | | | | | | | | ARE DIFFERENCES ACROSS SEASONS SIGNIFICANT AT THE 0.05 LEVEL? |
|---|---|---|---|---|---|---|---|---|---|---|
| | | SUMMER | | FALL | | WINTER | | SPRING | | |
| | | N | MEAN | N | MEAN | N | MEAN | N | MEAN | |
| NJ | 1 | 35 | 1.53 | 40 | 1.41 | 39 | 1.59 | 39 | 1.52 | NO |
| | 2 | 31 | 1.85 | 31 | 2.03 | 31 | 2.76 | 18 | 3.22 | YES |
| | 3 | 34 | 0.82 | 34 | 0.78 | 35 | 0.88 | 33 | 0.80 | NO |
| GA | 1 | 50 | 2.84 | 50 | 1.73 | . | . | 47 | 1.70 | YES |
| | 2 | 40 | 1.96 | 40 | 1.92 | . | . | 38 | 1.64 | NO |
| | 3 | 39 | 6.84 | 23 | 7.76 | . | . | 36 | 4.03 | YES |
| MN | 0 | 11 | 0.63 | 16 | 1.09 | 17 | 0.82 | 17 | 1.22 | YES |
| | 2 | 21 | 1.17 | 30 | 1.79 | 31 | 1.13 | 31 | 1.31 | YES |
| | 4 | 20 | 1.97 | 22 | 2.49 | 22 | 2.46 | 22 | 2.10 | NO |
| | 6 | 27 | 1.23 | . | . | 30 | 1.31 | 37 | 1.90 | YES |
| NM | 1 | 36 | 0.83 | 30 | 1.30 | 35 | 1.33 | 32 | 0.99 | YES |
| | 2 | 21 | 1.16 | 20 | 2.25 | 20 | 2.02 | 19 | 1.44 | YES |
| | 3 | 6 | 0.87 | 9 | 1.39 | 9 | 1.24 | 9 | 1.07 | YES |
| | 4 | 20 | 1.24 | 19 | 1.27 | 15 | 1.42 | 11 | 1.15 | NO |
| | 5 | 6 | 1.23 | 7 | 0.94 | 8 | 0.73 | 8 | 0.55 | YES |
| | 6 | 6 | 1.42 | 5 | 1.80 | . | . | 6 | 1.50 | NO |
| | 7 | 6 | 1.10 | 6 | 0.62 | . | . | 6 | 0.67 | NO |
| KS | 2 | 17 | 1.30 | 17 | 1.48 | 16 | 1.24 | 16 | 1.25 | NO |
| | 5 | 36 | 3.08 | 31 | 2.64 | 34 | 1.95 | 37 | 2.22 | YES |
| MO | 0 | 20 | 1.10 | 21 | 1.28 | 20 | 1.06 | 21 | 0.90 | NO |
| | 2 | 18 | 1.48 | 17 | 1.52 | 17 | 1.39 | 18 | 1.16 | NO |
| WA | 0 | 20 | 2.41 | 20 | 3.18 | 20 | 3.18 | 17 | 2.82 | NO |
| | 5 | 18 | 2.96 | 19 | 3.00 | 21 | 1.55 | 20 | 0.72 | YES |
| | 6 | 23 | 1.95 | 22 | 2.90 | 23 | 3.13 | 22 | 3.55 | NO |
| | 7 | 24 | 0.69 | 25 | 2.04 | 26 | 1.83 | 26 | 1.88 | YES |

(.) Missing data.

TABLE 3. ANALYSIS OF SEASONAL VARIATION IN ROOM RADON LEVELS BY STATE AND BY ROUND USING OF-CC MEASUREMENTS

| STATE | ROUND | SUMMER N | SUMMER MEAN | FALL N | FALL MEAN | WINTER N | WINTER MEAN | SPRING N | SPRING MEAN | ARE DIFFERENCES ACROSS SEASONS SIGNIFICANT AT THE 0.05 LEVEL? |
|---|---|---|---|---|---|---|---|---|---|---|
| | | SEASONAL MEAN (pCi/l) AND NUMBER OF ROOMS (N) | | | | | | | | |
| NJ | 1 | 103 | 2.24 | 105 | 1.60 | 40 | 1.95 | 71 | 3.10 | YES |
| | 2 | 103 | 1.37 | 102 | 1.32 | 70 | 2.33 | 70 | 2.17 | YES |
| | 3 | 104 | 1.42 | 101 | 1.52 | 105 | 1.78 | 106 | 1.63 | NO |
| GA | 1 | 125 | 6.20 | . | . | 121 | 4.19 | 122 | 3.45 | YES |
| | 2 | 125 | 5.67 | . | . | 116 | 3.31 | 110 | 1.72 | YES |
| | 3 | 127 | 3.07 | . | . | 119 | 3.17 | 87 | 0.88 | YES |
| MN | 1 | 104 | 2.47 | 106 | 1.69 | 103 | 1.86 | 106 | 1.98 | YES |
| | 2 | 105 | 1.73 | 106 | 1.40 | 106 | 1.48 | 106 | 0.88 | YES |
| | 3 | 105 | 1.28 | 105 | 1.97 | 105 | 1.82 | 78 | 1.54 | YES |
| NM | 1 | 100 | 1.83 | 106 | 1.52 | 106 | 1.12 | 108 | 1.50 | YES |
| | 2 | 105 | 1.05 | 105 | 1.58 | 104 | 1.14 | 108 | 0.99 | YES |
| | 3 | 107 | 1.12 | 102 | 1.38 | 97 | 1.26 | 108 | 1.17 | NO |
| KS | 1 | 52 | 2.95 | 50 | 2.24 | 52 | 2.91 | 36 | 3.15 | NO |
| | 2 | 52 | 2.74 | 52 | 2.02 | 51 | 2.07 | 37 | 1.67 | YES |
| | 3 | 52 | 3.71 | 52 | 3.47 | 52 | 2.87 | . | . | YES |
| MO | 1 | 39 | 1.60 | 39 | 1.07 | 18 | 1.66 | 18 | 1.49 | NO |
| | 2 | 39 | 1.05 | 38 | 1.23 | 17 | 1.16 | 18 | 0.31 | YES |
| | 3 | 39 | 1.07 | 39 | 1.75 | 37 | 1.71 | 18 | 3.47 | YES |
| KS & MO | 1 | 91 | 2.37 | 89 | 1.73 | 70 | 2.59 | 54 | 2.60 | YES |
| | 2 | 91 | 2.01 | 90 | 1.68 | 68 | 1.85 | 55 | 1.23 | YES |
| | 3 | 91 | 2.58 | 91 | 2.73 | 89 | 2.39 | 18 | 3.47 | NO |
| MA | 1 | 88 | 4.42 | 87 | 3.52 | 83 | 5.91 | 87 | 4.54 | YES |
| | 2 | 86 | 2.34 | 87 | 1.92 | 85 | 2.55 | 86 | 1.28 | YES |
| | 3 | 86 | 1.60 | 87 | 2.89 | 85 | 1.83 | 87 | 0.90 | YES |
| ALL | 1 | 611 | 3.35 | 493 | 1.96 | 523 | 3.00 | 548 | 2.83 | YES |
| | 2 | 615 | 2.48 | 490 | 1.57 | 549 | 2.12 | 535 | 1.35 | YES |
| | 3 | 620 | 1.88 | 486 | 2.06 | 600 | 2.08 | 484 | 1.32 | YES |

(.) Missing Data

TABLE 4. ANALYSIS OF SEASONAL VARIATIONS IN ROOM RADON LEVELS BY STATE, BY SCHOOL, AND BY ROUND USING OF-CC MEASUREMENTS

| STATE | SCHOOL | ROUND | SUMMER N | SUMMER MEAN | FALL N | FALL MEAN | WINTER N | WINTER MEAN | SPRING N | SPRING MEAN | ARE DIFFERENCES ACROSS SEASONS SIGNIFICANT ? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SEASONAL MEAN (pCi/l) AND NUMBER OF ROOMS (N) | | | | | | | | |
| NJ | 1 | 1 | 38 | 2.61 | 39 | 1.94 | 40 | 1.95 | 40 | 1.85 | NO |
| | | 2 | 40 | 1.69 | 39 | 1.12 | 40 | 1.66 | 40 | 1.50 | NO |
| | | 3 | 40 | 1.30 | 37 | 0.99 | 40 | 1.24 | 40 | 1.09 | NO |
| NJ | 2 | 1 | 31 | 2.94 | 31 | 2.15 | . | . | 31 | 4.72 | YES |
| | | 2 | 29 | 1.84 | 29 | 2.47 | 30 | 3.23 | 30 | 3.07 | NO |
| | | 3 | 31 | 2.29 | 31 | 3.14 | 31 | 3.65 | 31 | 3.21 | NO |
| NJ | 3 | 1 | 34 | 1.18 | 35 | 0.75 | . | . | . | . | YES |
| | | 2 | 34 | 0.60 | 34 | 0.57 | . | . | . | . | NO |
| | | 3 | 33 | 0.74 | 33 | 0.59 | 34 | 0.72 | 35 | 0.86 | YES |
| GA | 1 | 1 | 49 | 4.77 | . | . | 49 | 2.51 | 49 | 2.40 | YES |
| | | 2 | 47 | 6.19 | . | . | 45 | 1.92 | 35 | 1.22 | YES |
| | | 3 | 49 | 2.40 | . | . | 48 | 2.33 | 47 | 0.59 | YES |
| GA | 2 | 1 | 39 | 2.92 | . | . | 38 | 2.47 | 36 | 2.19 | NO |
| | | 2 | 40 | 3.18 | . | . | 37 | 2.43 | 39 | 0.97 | YES |
| | | 3 | 40 | 1.77 | . | . | 34 | 1.53 | . | . | NO |
| GA | 3 | 1 | 37 | 11.54 | . | . | 34 | 8.51 | 37 | 6.06 | YES |
| | | 2 | 38 | 7.66 | . | . | 34 | 6.11 | 36 | 3.03 | YES |
| | | 3 | 38 | 5.31 | . | . | 37 | 5.77 | 40 | 1.22 | YES |
| MN | 0 | 1 | 17 | 2.41 | 17 | 0.65 | 15 | 1.61 | 17 | 2.16 | YES |
| | | 2 | 17 | 1.90 | 17 | 0.68 | 18 | 0.68 | 17 | 0.48 | YES |
| | | 3 | 16 | 0.41 | 16 | 0.64 | 16 | 0.91 | 17 | 0.98 | YES |
| MN | 2 | 1 | 29 | 2.26 | 30 | 1.55 | 30 | 1.37 | 30 | 1.64 | NO |
| | | 2 | 30 | 1.12 | 30 | 1.27 | 30 | 1.12 | 30 | 0.67 | YES |
| | | 3 | 30 | 1.73 | 30 | 2.01 | 30 | 1.74 | 2 | 3.00 | NO |

(continued)

(.) Missing Data

TABLE 4 CONTINUED

| STATE | SCHOOL | ROUND | SUMMER N | SUMMER MEAN | FALL N | FALL MEAN | WINTER N | WINTER MEAN | SPRING N | SPRING MEAN | ARE DIFFERENCES ACROSS SEASONS SIGNIFICANT ? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SEASONAL MEAN (pCi/l) AND NUMBER OF ROOMS (N) | | | | | | | | |
| MN | 4 | 1 | 21 | 3.30 | 22 | 2.74 | 22 | 2.98 | 22 | 2.25 | YES |
| | | 2 | 22 | 2.11 | 22 | 1.97 | 21 | 2.82 | 22 | 1.30 | YES |
| | | 3 | 22 | 0.63 | 22 | 3.10 | 22 | 3.38 | 22 | 1.05 | YES |
| MN | 6 | 1 | 37 | 2.20 | 37 | 1.64 | 36 | 1.69 | 37 | 2.18 | NO |
| | | 2 | 36 | 1.93 | 37 | 1.49 | 37 | 1.39 | 37 | 0.99 | YES |
| | | 3 | 37 | 1.68 | 37 | 1.85 | 37 | 1.36 | 37 | 2.01 | NO |
| NM | 1 | 1 | 31 | 1.24 | 37 | 0.74 | 37 | 1.07 | 37 | 1.19 | YES |
| | | 2 | 36 | 0.91 | 37 | 1.20 | 37 | 0.95 | 37 | 0.76 | YES |
| | | 3 | 36 | 1.87 | 34 | 0.93 | 36 | 1.13 | 37 | 0.72 | YES |
| NM | 2 | 1 | 22 | 3.07 | 22 | 3.38 | 22 | 1.76 | 22 | 1.39 | YES |
| | | 2 | 20 | 1.62 | 22 | 2.89 | 20 | 1.70 | 22 | 1.21 | YES |
| | | 3 | 22 | 0.58 | 21 | 3.35 | 22 | 2.04 | 22 | 2.53 | YES |
| NM | 3 | 1 | 7 | 1.70 | 7 | 1.67 | 8 | 1.11 | 9 | 0.87 | YES |
| | | 2 | 9 | 1.19 | 7 | 1.21 | 8 | 0.86 | 9 | 1.01 | YES |
| | | 3 | 9 | 0.84 | 7 | 1.51 | . | . | 9 | 1.21 | YES |
| NM | 4 | 1 | 20 | 1.60 | 20 | 1.14 | 19 | 0.92 | 20 | 2.75 | YES |
| | | 2 | 20 | 0.82 | 19 | 1.57 | 19 | 1.40 | 20 | 0.97 | YES |
| | | 3 | 20 | 0.52 | 20 | 0.72 | 20 | 1.09 | 20 | 0.92 | YES |
| NM | 5 | 1 | 8 | 1.35 | 8 | 1.14 | 8 | 0.41 | 8 | 0.44 | YES |
| | | 2 | 8 | 0.69 | 8 | 0.65 | 8 | 0.58 | 8 | 0.85 | YES |
| | | 3 | 8 | 0.54 | 8 | 0.40 | 8 | 0.60 | 8 | 0.26 | YES |
| NM | 6 | 1 | 6 | 2.22 | 6 | 2.17 | 6 | 1.27 | 6 | 2.50 | YES |
| | | 2 | 6 | 1.33 | 6 | 1.80 | 6 | 1.58 | 6 | 2.12 | YES |
| | | 3 | 6 | 1.85 | 6 | 1.38 | 6 | 1.45 | 6 | 1.38 | NO |

(continued)

TABLE 4 CONTINUED

| STATE | SCHOOL | ROUND | SUMMER N | SUMMER MEAN | FALL N | FALL MEAN | WINTER N | WINTER MEAN | SPRING N | SPRING MEAN | ARE DIFFERENCES ACROSS SEASONS SIGNIFICANT ? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SEASONAL MEAN (pCi/l) AND NUMBER OF ROOMS (N) | | | | | | | | |
| MN | 7 | 1 | 6 | 1.47 | 6 | 0.47 | 6 | 0.40 | 6 | 0.98 | YES |
| | | 2 | 6 | 0.72 | 6 | 0.60 | 6 | 0.38 | 6 | 0.78 | YES |
| | | 3 | 6 | 1.02 | 6 | 0.45 | 5 | 0.38 | 6 | 0.62 | YES |
| KS | 2 | 1 | 15 | 1.38 | 14 | 1.06 | 15 | 1.53 | . | . | YES |
| | | 2 | 15 | 0.75 | 15 | 1.20 | 14 | 1.09 | . | . | YES |
| | | 3 | 15 | 1.50 | 15 | 2.75 | 15 | 1.88 | . | . | YES |
| KS | 5 | 1 | 37 | 3.59 | 36 | 2.70 | 37 | 3.47 | 36 | 3.15 | NO |
| | | 2 | 37 | 3.55 | 37 | 2.35 | 37 | 2.45 | 37 | 1.67 | YES |
| | | 3 | 37 | 4.61 | 37 | 3.76 | 37 | 3.27 | | | YES |
| NC | 0 | 1 | 21 | 1.37 | 21 | 0.54 | . | . | . | . | YES |
| | | 2 | 21 | 0.90 | 20 | 1.35 | . | . | . | . | NO |
| | | 3 | 21 | 1.01 | 21 | 1.60 | 20 | 1.29 | . | . | NO |
| NC | 2 | 1 | 18 | 1.88 | 18 | 1.68 | 18 | 1.66 | 18 | 1.49 | NO |
| | | 2 | 18 | 1.22 | 18 | 1.09 | 17 | 1.16 | 18 | 0.31 | YES |
| | | 3 | 18 | 1.14 | 18 | 1.93 | 17 | 2.21 | 18 | 3.47 | NO |
| WA | 0 | 1 | 20 | 4.48 | 20 | 4.94 | 18 | 6.07 | 19 | 5.68 | NO |
| | | 2 | 19 | 0.69 | 20 | 2.79 | 19 | 2.57 | 19 | 2.06 | YES |
| | | 3 | 19 | 2.78 | 20 | 1.56 | 18 | 0.81 | 19 | 0.59 | YES |
| WA | 5 | 1 | 20 | 7.48 | 20 | 3.11 | 19 | 3.29 | 20 | 0.62 | YES |
| | | 2 | 20 | 4.26 | 20 | 1.54 | 20 | 1.66 | 20 | 0.93 | YES |
| | | 3 | 19 | 2.70 | 19 | 1.69 | 20 | 4.81 | 20 | 0.59 | YES |
| WA | 6 | 1 | 23 | 3.80 | 22 | 3.61 | 23 | 8.99 | 23 | 8.13 | YES |
| | | 2 | 23 | 2.57 | 23 | 2.19 | 22 | 4.67 | 23 | 1.30 | YES |
| | | 3 | 23 | 0.61 | 23 | 4.87 | 22 | 2.15 | 23 | 2.02 | YES |
| WA | 7 | 1 | 25 | 2.49 | 25 | 2.62 | 23 | 4.88 | 25 | 3.52 | YES |
| | | 2 | 24 | 1.84 | 24 | 1.26 | 24 | 1.33 | 24 | 0.94 | YES |
| | | 3 | 25 | 0.77 | 25 | 3.04 | 25 | 0.55 | 25 | 0.34 | YES |

(.) Missing Data

TABLE 5. SEASONAL RATIOS OF OF-C

| SEASON | ROUND | RATIO MEAN | RATIO STD | #PAIRS |
|---|---|---|---|---|
| SUMMER | 1 | 1.93 | 1.47 | 571 |
| | 2 | 1.35 | 1.05 | 574 |
| | 3 | 1.20 | 1.16 | 577 |
| FALL | 1 | 1.04 | .44 | 433 |
| | 2 | .84 | .40 | 431 |
| | 3 | 1.07 | .59 | 428 |
| WINTER | 1 | 1.44 | .77 | 368 |
| | 2 | .99 | .39 | 398 |
| | 3 | 1.07 | .69 | 448 |
| SPRING | 1 | 1.45 | .81 | 507 |
| | 2 | .77 | .45 | 495 |
| | 3 | .83 | .84 | 441 |

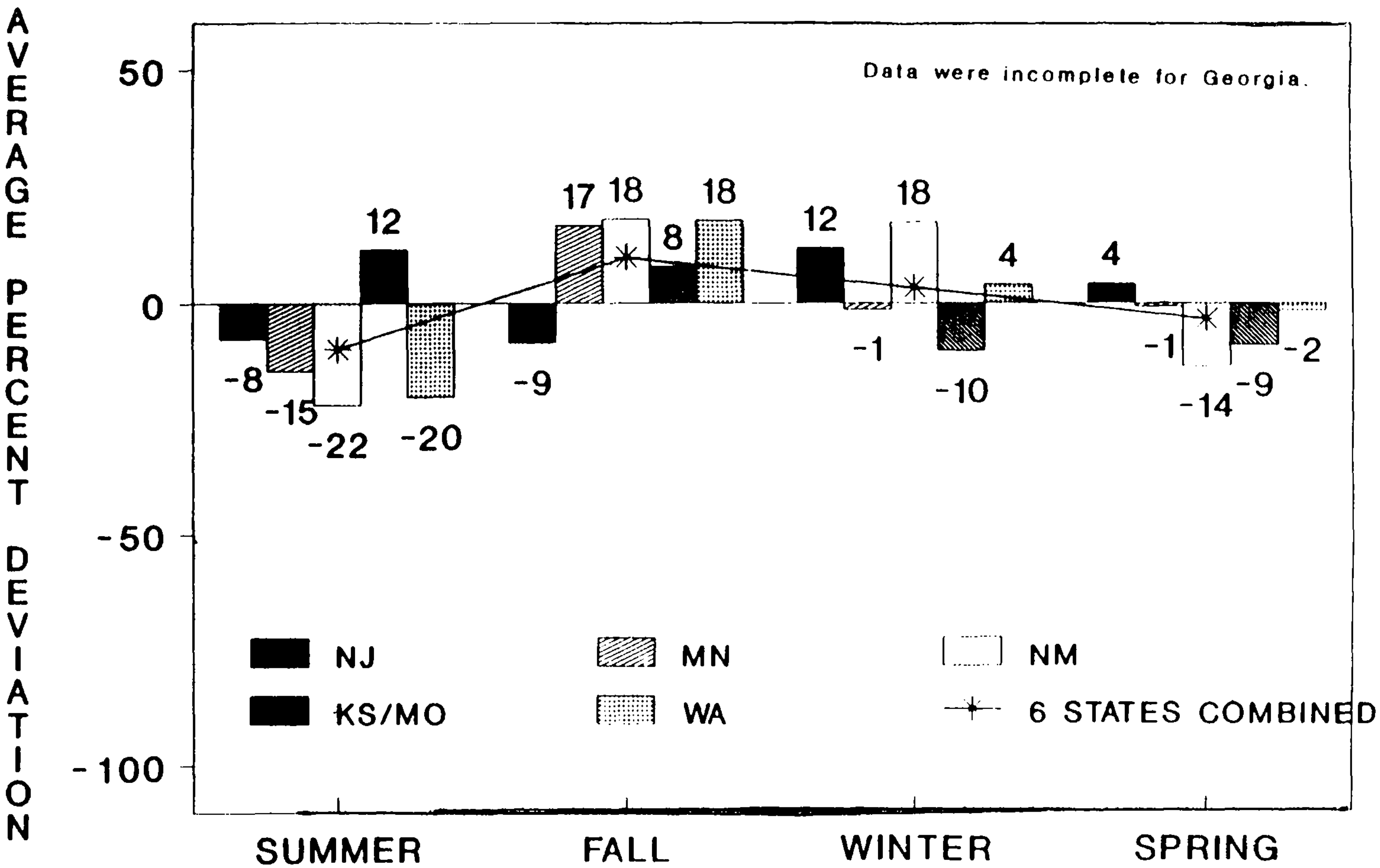


**FIGURE 1.** Seasonal Variation of ATD Schoolroom Measurements from 4-Season ATD Average

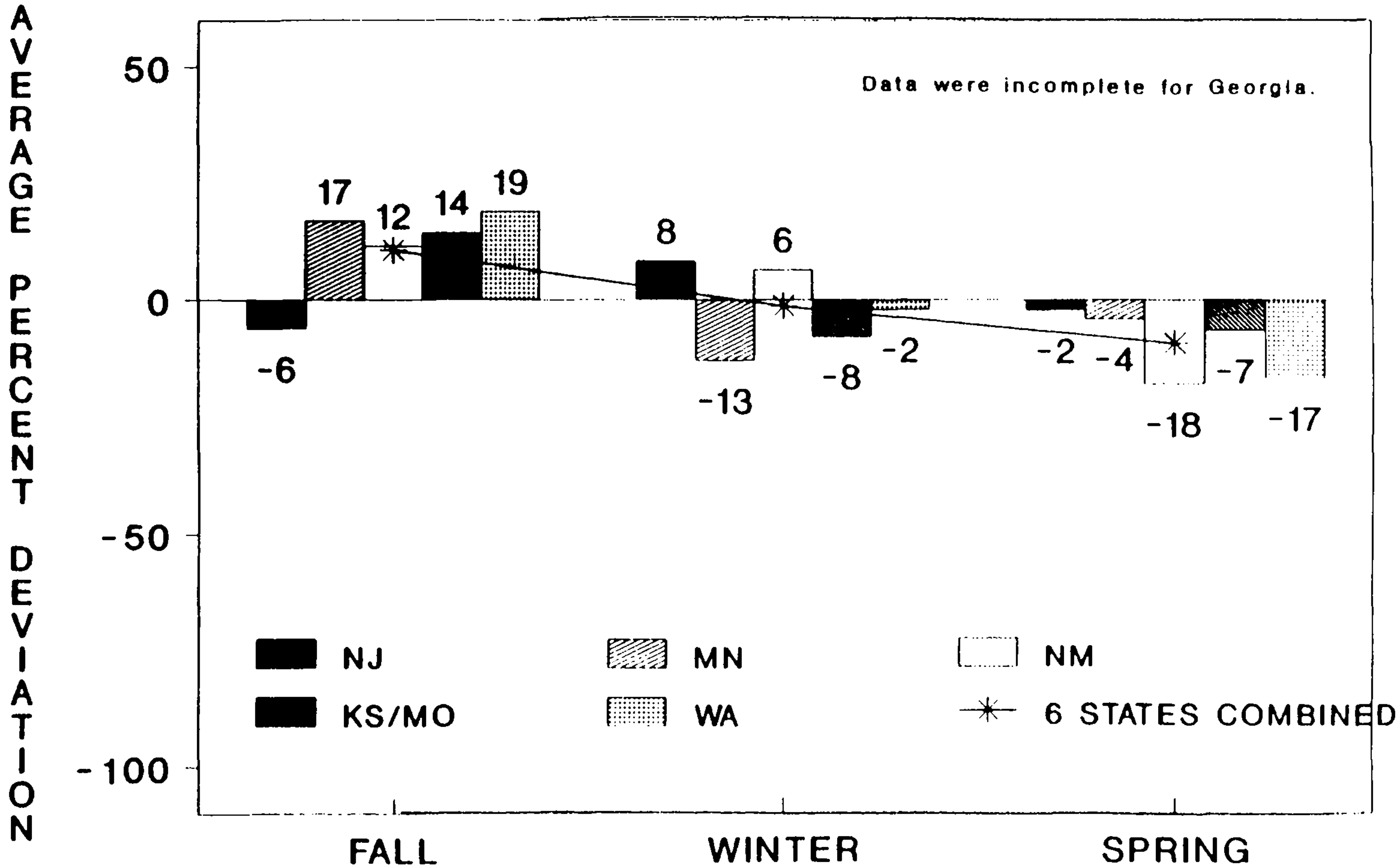


**FIGURE 2.** Seasonal Variation of ATD Schoolroom Measurements from 3-Season ATD Average

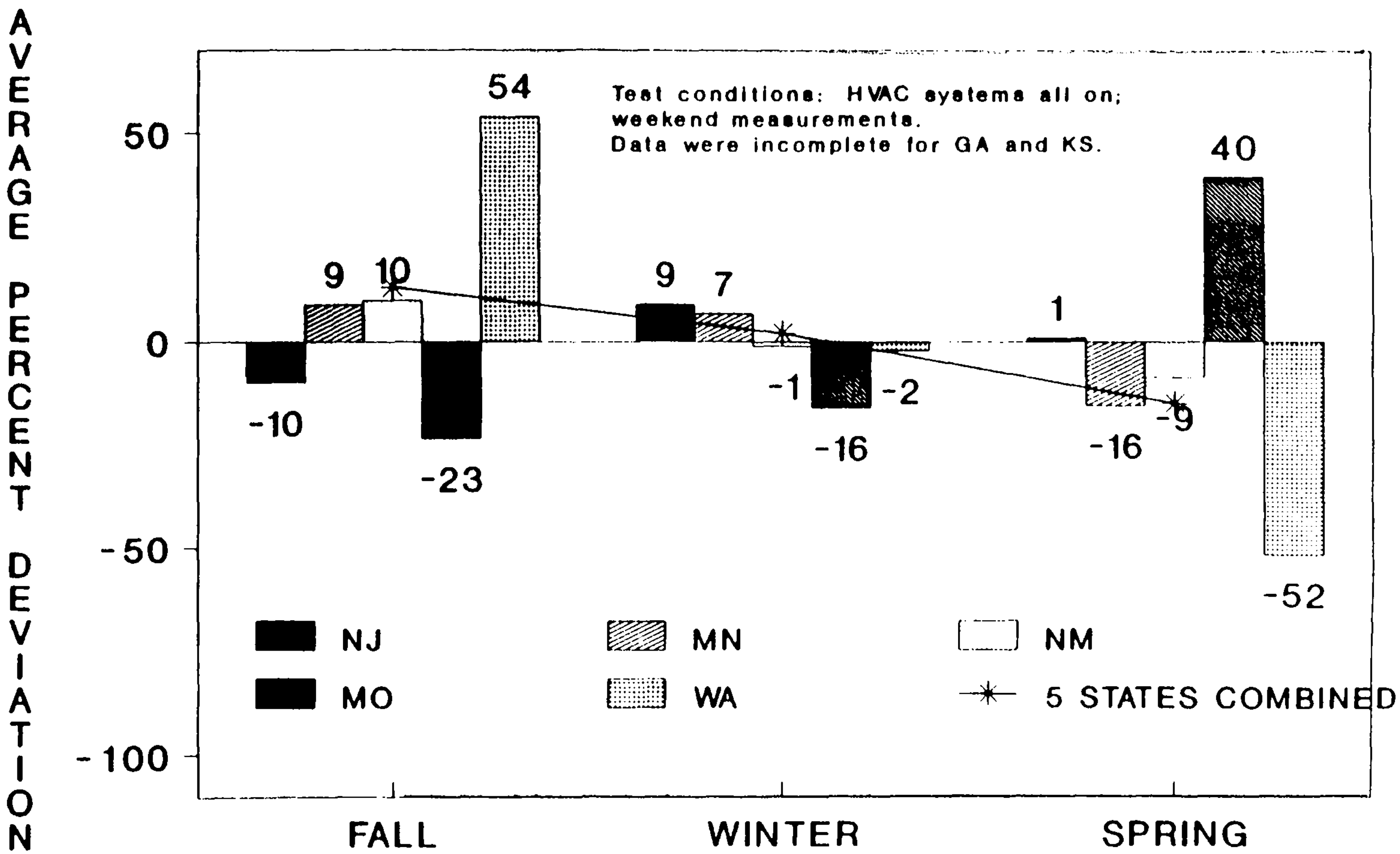




**FIGURE 3.** Seasonal Variation of Round 3 OF-CC Schoolroom Measurements from 3-Season OF-CC Average

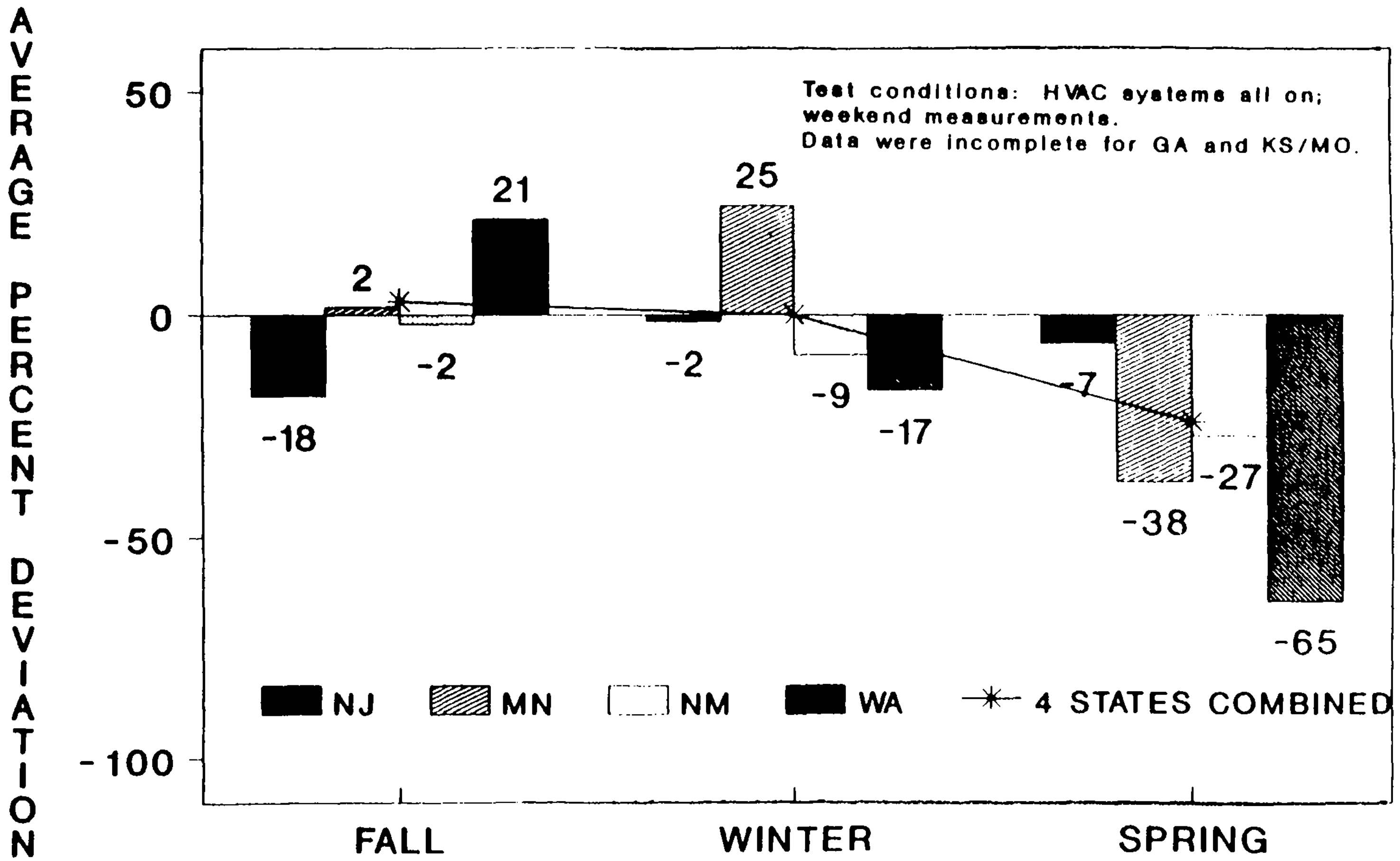


**FIGURE 4.** Seasonal Variation of Round 3 OF-CC Schoolroom Measurements from 3-Season ATD Average

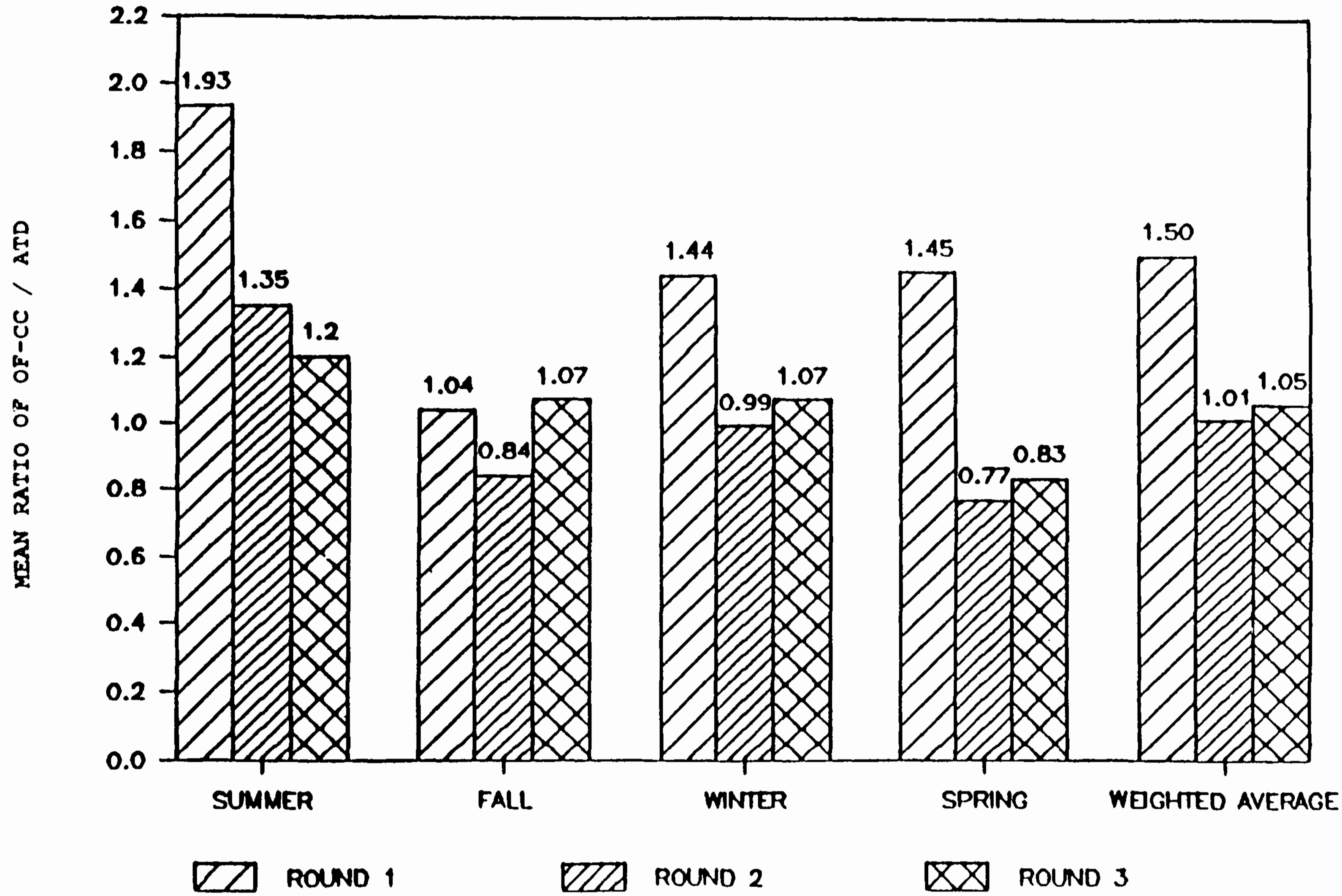


**FIGURE 5.** MEAN SHORT-TERM / LONG-TERM RATIO OF OF-CC MEASUREMENTS TO ATD MEASUREMENTS BY ROUND, BY SEASON

# Diagnostic Evaluations of Twenty Six US Schools - EPA's School Evaluation Program

Gene Fisher
Bob Thompson
EPA
Office of Radiation Programs
Washington, D.C.

Terry Brennan
Camroden Associates
Oriskany, New York 13424

William Turner
H.L. Turner Group
Harrison, Maine 04055

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.

## ABSTRACT

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. This represents the largest data bank of schools that have been diagnosed with consideration for interactions of the building with both sub-slab and heating, ventilating and air conditioning (HVAC) characteristics. Occupied classroom carbon dioxide concentrations and building shell tightness are reported. These measurements help to judge the existing outside air ventilation rates and the potential for building pressurization. Besides these technical issues, physical and institutional problems that affect the selection and implementation of radon control systems in schools are identified. Both soil depressurization and use of existing HVAC equipment were evaluated as mitigation approaches for each school. Results of this two year study suggest that the EPA should consider a new direction in large building radon abatement -- a holistic approach that considers the broader issues of indoor air quality, comfort, cost and energy issues.

**KEY WORDS:** Radon, Holistic, Schools, Large Buildings, Airtightness, Ventilation, Outside Air, EPA, Carbon Dioxide, IAQ, Indoor Air Quality, Diagnostics, Measurements.

## INTRODUCTION

The School Evaluation Program (SEP) was originally conceived in the summer of 1989 as a technical assistance program in response to an emerging need for information on diagnostic techniques and mitigation strategies applicable in schools with elevated levels of radon. The program was designed to incorporate all appropriate state of the art radon diagnostic procedures that were successfully being used in residential investigations. Occupant density is approximately 7 times greater for schools than for residential settings. Therefore, recommended or mandated ventilation rates for school rooms are several times that for residences. Accordingly, industry accepted evaluation methods for non-residential air handling systems were incorporated into the program.

The original goal of the SEP was to develop school diagnostic procedures that would consistently provide sufficient information to enable school officials and private sector contractors to choose the most effective mitigation strategy for their school. When completed, the diagnostic procedures will become part of EPA's Technology Transfer Program, and will be made available for training purposes through EPA funded Radon Regional Training Centers. Information collected also would be used to update the EPA school mitigation guidance publication.

The selection of SEP schools was based on four criteria:

1. Schools with radon screening measurements greater than 4 pCi/L.

2. Geographic location/climatic conditions.

3. Structure Type

4. A willingness by the school to mitigate based on the results of the evaluation and the recommended remediation strategy.

As a result of the selection process three schools in Washington state and three schools in New Mexico were evaluated, and results were reported at the 1990 International Radon Symposium [1]. In fiscal 1990, twenty additional schools were evaluated: three each in the states of Georgia, Iowa, North Dakota, Illinois, and New Jersey, and five in Maine.

The SEP Team in 1990 consisted of the authors of this paper -- a team that represents expertise in the areas of residential radon investigation and large building HVAC design, installation, and operation.

The evaluations performed on all twenty six (26) schools have strengthened the investigators opinion and judgement that:

- Schools are more complicated than residential homes in every respect.
- All aspects of the building dynamics and purpose must be taken into account when selecting and planning a radon control strategy.
- Low ventilation rates appear to be a serious problem in many of the nations classrooms.

An optimum control strategy would depend on each schools' specific needs and would incorporate active sub slab depressurization and HVAC mitigation techniques, independently or collectively, as required. Through extensive field experience gained by the SEP, a holistic approach to radon control and general indoor air quality in schools became apparent.

## METHODOLOGY

The conceptual model for radon entry into buildings has directed field investigations of indoor radon problems toward two areas. The first area is the ways in which the foundation and underlying materials affect radon entry and could be used to control entry by soil depressurization. The second area is an investigation of the ways in which the operation of the mechanical equipment in the building affects radon entry and could potentially be used to control radon.

Both approaches, HVAC and soil depressurization, prevent soil air entry by managing the air pressure differential relationships between the air in the soil and the air in the building. In addition, dilution by increased ventilation can have a significant role in the HVAC approach and sometimes plays a minor role in a soil depressurization approach.

## RADON ENTRY INVESTIGATION

The radon entry investigation is divided into three parts, review of radon measurements, identification of radon entry points, and soil depressurization tests. Each of these are summarized in the following paragraphs.

### Radon Measurement Data

Radon measurement data for the schools was obtained through the screening results taken as part of EPA's Phase I and Phase II school survey [2 & 3]. Several schools had initiated their own testing program and offered their measurement results for acceptance into the SEP. Most of the schools had tested many of their classrooms using the current EPA radon measurement protocol. A number of schools had performed confirmation measurements using alpha track detectors.

Radon measurements in schools have been found to vary considerably both spatially and temporally [1]. Figure 1 shows the mean classroom radon levels in the schools evaluated. Error bars of one standard deviation are given to illustrate room to room variation for simultaneous measurements. Temporal variation can be seen by using continuous radon monitors or by the sequential use of passive integrating monitors. These topics will be discussed later in the paper. Both temporal and spatial variation are the result of varying radium concentrations, locations, and transport pathways under the building. Also, variations are caused by air pressure differences resulting from the dynamic interaction of occupants, building, mechanical equipment and outside weather conditions [4].

The maintenance personnel and school safety officers proved to be invaluable assets in the investigation of every school. They provided a wealth of information about the operation and maintenance of the school building and the mechanical equipment within the a school. Often they could provide blueprints for the school and in all cases were able to supply fire exit plans.

The radon screening measurements for a school were plotted room by room on a floorplan of the school, such as the fire exit floorplans available for most public buildings. By plotting radon screening measurements on the fire exit plans, the pattern of radon concentrations could be studied. Often this was not particularly enlightening. For example, in many schools, screening measurements ranged between 2 and 8 pCi/L. Given the temporal variation of school room radon levels, it is difficult to make a meaningful distinction between a 3 pCi/L screening measurement and a 6 pCi/L screening measurement. This amount of difference might easily occur in the same room at different times.

In some schools, the pattern of radon levels was more helpful. For example, a wing in a school that has relatively uniform, elevated concentrations in all the rooms might well have a widely dispersed entry mechanism that the other wings do not. Anecdotal observations included: 1) the air handler that supplied conditioned air to the classrooms in one zone was drawing in soil gases and delivering it with the conditioned air, 2) all wings are built on a permeable sand but two of them have stone pebbles beneath the slab, creating a dilution break at that layer, while one wing has a slab poured directly on the site material providing a radon source at each hole in the slab. Clues like these formed the basis for the radon source and entry diagnostics, to be covered in the next section.

**Radon Entry Points**

The predominant school foundation type was slab on grade, with several of these having perimeter and internal utility tunnels under the slab. A few schools had crawlspaces and basements. The major entry points of the SEP schools were:

- joints at the edge of slabs
- water pipe penetrations and drains
- trenches containing heating pipe penetrations
- trenches used as conditioned air supply and returns
- crawlspaces with all of the above

The radon concentrations beneath the slabs of the schools were measured. The results are shown in Figure 2, with a summary of the HVAC equipment in the schools. As can be seen, levels varied from a low of 200 pCi/L to a high of 8000 pC/L with a mean of 1500 pCi/L. These are relatively low sub slab concentrations when compared to sub slab measurements in some residential buildings with elevated radon.

### Soil Depressurization Tests

In order to assess the potential for radon control by soil depressurization, a vacuum suction test was made in most schools. This test allowed visual identification of the sub slab material and measurement of how easily air could be drawn from beneath the slab. Figure 2 has a column that lists the type of sub-slab material and another that lists the amount of air that could be pulled from under the slab using the vacuum. Generally speaking, the lower the amount of air that can be drawn from under the slab, the more difficult it is to extend a low pressure field beneath the slab [5]. Low airflows generally indicate more suction points are needed for a successful soil depressurization system. In a few schools the vacuum could not compete with the suction exerted on the building by the exhaust fans.

## HVAC CHARACTERIZATION

### System Operation

Review of mechanical system plans is the first step in evaluating the expected effect of the HVAC system's effect on radon. Equipment observations must be performed in order to determine what equipment is actually being operated, its operation schedule, the control sequence, and whether the air flows are near the design quantities. Air flow observations may be as simple as visually observing the position of an outside air damper blade or the operation of an exhaust fan and the direction of air flow with a chemical smoke pencil, or may be more involved. Measurement of actual exhaust flow rates with an air balancing hood has proven valuable for determining the operational status of exhaust systems and for conducting a building shell tightness test. Observations of closed outside air intakes or inoperative make-up air supply fans were typical indicators of a HVAC system not being operated or maintained as designed [5].

The HVAC systems in the SEP schools were characterized in terms of heating and cooling, ventilation, and control strategy, and the resulting potential impact of these parameters on indoor radon levels. A wide variety of ventilation systems were found in the school buildings. The HVAC features are summarized in Figure 2.

A summary of the HVAC system types is as follows:

- 96% had a mechanical ventilation system
- 38% had a single ventilation system
- 27% had three or more ventilation systems
- 12% had no mechanical outdoor air supply

As indicated above, most of the schools had some form of mechanical ventilation system, but the majority of the system were not operating properly. One of the prominent features of the HVAC systems was the number of problems found. These problems covered a range that included inoperative equipment (broken belts, fans, controls), equipment that had never been wired, poorly maintained equipment (disabled damper linkage, dampers painted shut), poorly designed equipment (ventilators too small or not used because they are too noisy), and unwitting modification of the ventilation system (replacing the rolled steel sash window walls with insulated wall). The extent to which these types of problems were present was remarkable. Every school visited suffered from at least one of these problems.

## Ventilation Air Delivery Rate

A continuous carbon dioxide monitor was used as an indicator of ventilation rates. In an occupied classroom the C02 level is a function of the number of students and the ventilation rate. These measurements are invaluable when deciding whether a radon control approach that increases the ventilation rate is appropriate or not. Carbon dioxide measurements were made in the classrooms in the mid afternoon before students were let out. Levels over 1000 ppm indicate that the current ASHRAE guideline [6] of 15 cfm (7 L/s) of outdoor air per student is not being met. Figure 3 shows C02 levels measured in occupied classrooms of nine schools. Most rooms in these schools were above the ASHRAE guideline. The mean C02 level was 1780 ppm. Figure 4 shows radon screening measurements plotted versus the C02 levels for a number of rooms. It can be seen from this data that a room that has elevated C02 levels may not have elevated radon levels and vice versa. This chart should be viewed with caution as the radon measurements were made at a different time and in different mode than the carbon dioxide measurements. This data forms the basis for the SEP Team feeling that broader indoor air quality issues need to be considered when investigating radon in schools.

## Building Shell Pressure Relationship

A measurement of the pressure relationship between the inside of the building and outside is one of the key parameters which needs to be investigated. This can be accomplished on a not too windy day by simply making measurements through a crack in a closed doorway or window utilizing a sensitive electronic micromanometer (pressure transducer). Readings of slight positive pressure indoors (+.001 to +.010 inches water (0.25 Pa to 2.5 Pa)) will help to keep radon out during operation of the HVAC system, while negative readings will increase radon entry. By monitoring the pressure differentials while modifying HVAC operation, the potential of using existing equipment for mitigation can be evaluated.

## Building Shell Tightness Test

To determine how much make-up air would be needed to slightly pressurize a building, a fan door pressure test, or equivalent, can be performed. The results of this test will reveal the practicality of "building pressurization" to mitigate an observed radon problem. All the schools tested were within the normal leakage range for buildings of this size.

## RECOMMENDATIONS

In each of the school buildings both a soil depressurization and an HVAC approach to controlling indoor radon levels was addressed. An HVAC system approach was considered the first choice in 23 of 26 schools. This high fraction reflects the number of schools whose ventilation rates did not meet current guidelines and whose radon levels were low enough that meeting ventilation guidelines would likely control the radon through both dilution and building pressurization. Soil depressurization was often listed as a second option in the event that increasing the ventilation rate to meet guidelines did not lower the radon sufficiently, or if the school needed to respond to the radon levels more quickly than modifying the HVAC system would allow.

Any radon control strategy that is used in school buildings must comply with state and local codes or requirements for the design and installation of mechanical systems. This work typically involves a professional engineer.

## CONCLUSIONS

Conclusions from this work are:

- radon in school rooms must be seen in light of other health concerns - a holistic approach should be taken.

- there appears to be a serious problem with under ventilated schoolrooms in US schools.

- in order to use HVAC systems to control radon in schools a team approach must be used that incorporates school maintenance personnel, professional engineers, and a radon professional.

- when HVAC systems are used to control indoor radon, increased emphasis must be placed on scheduled maintenance and periodic inspection by knowledgeable staff.

- interpreting radon measurements made in classrooms is difficult because of the wide variety of activities that occur in schools.

It is the opinion of the authors that the current under ventilated status of many school rooms is the result of ignorance on the part of the general public and school officials. If the public knew that our children were trying to learn in situations where the air they breathe is contributing to drowsiness, absenteeism, poor focus of attention, and headaches, we believe this would be remedied. Once these groups understand the importance of good indoor air quality, then and only then will the funding for school design, construction, operation, and maintenance reach a level that will ensure adequate ventilation for children.

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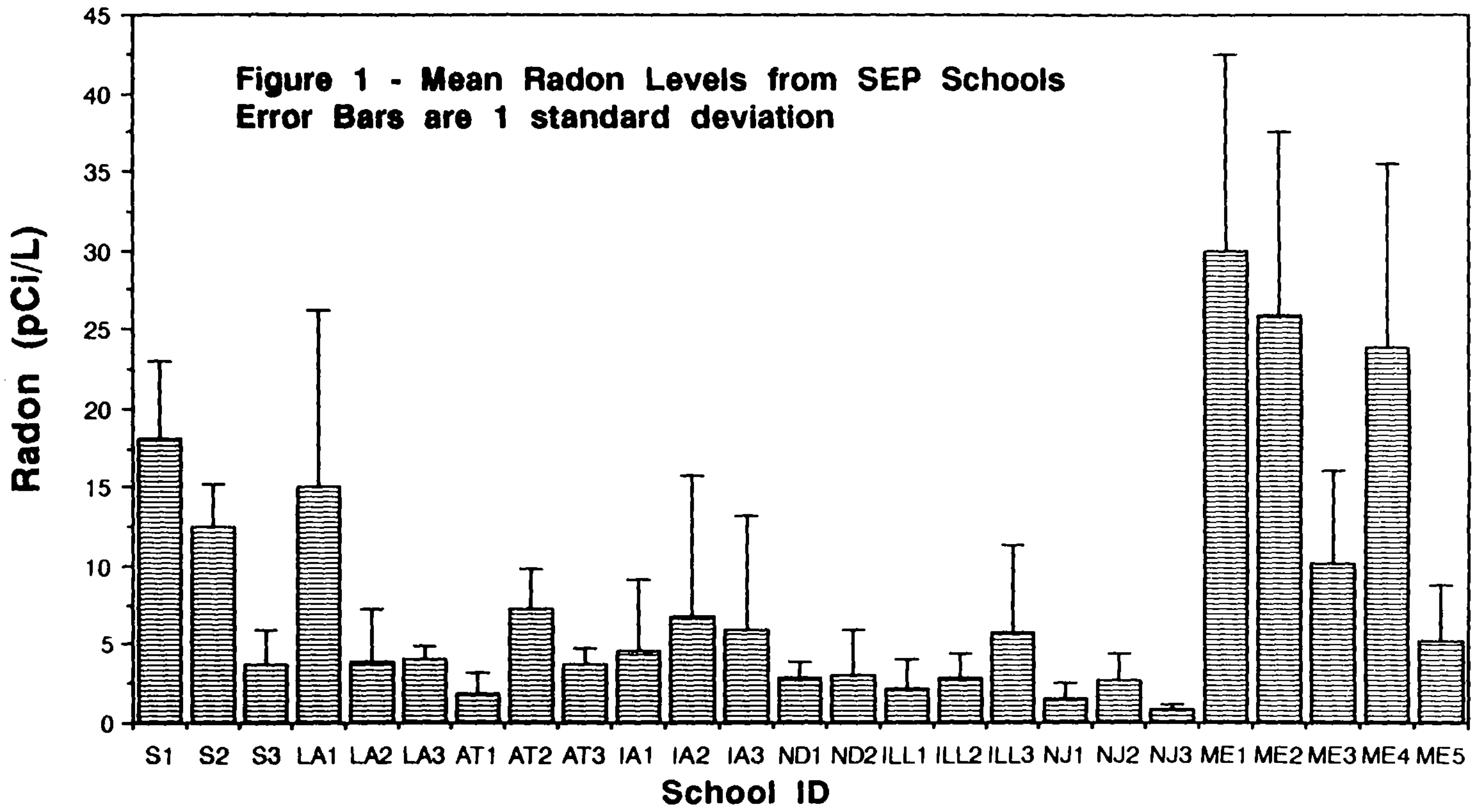



Figure 1 - Mean Radon Levels from SEP Schools
Error Bars are 1 standard deviation

## Figure 2 - Summary of School HVAC and Sub Slab Characteristics

| | | | Ventilation (cfm) (measured) | | | | Sub Slab | | Vac. | Window | Floor | Num. | Num. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sch. ID | Heating | Cooling | Exhaust | Make up | cfm/per. | Control | Material'' | Rn pCi/L | cfm | Retrofit? | Area | Student | Staff |
| S1 | Warm air | AC | 1000* | 170/OA | 10 | Tstat | FS | 600±200 | 6 | | | | |
| S2 | Hydronic | None | 5800* | OA/off | 11 | Tstat | CS | 1100±200 | 27 | | | | |
| S3 | Warm Air | AC | NT | VAV | NA | CPU man. | NT | NT | | | | | |
| LA1 | Hydronic | None | 10000 | 400/UV | 14 | Tstat | S&G | 500±50 | 20 | | | | |
| LA2 | Hydronic | None | NT* | None | NA | Tstat** | SP | 900±100 | 38 | | | | |
| LA3 | Warm Air | AC | NT* | NT/UV | NA | Tstat' | NT | NT | | | | | |
| GA1 | HP WA | HP | 3600* | OAF/off | 5 | Tstat/Clock | SP(1/4") | 800 | 43 | unk. | 49390 | 680 | 40 |
| GA2 | HP WA | HP | NT/inop. | OAF/off | NA | Tstat/Clock | SP/Clay | 1220-8000 | 25 | unk. | 44251 | unk. | unk. |
| GA3 | Warm Air | AC | NT/inop. | OA/off | NA | Tstat/Clock | SP | 4000±1000 | 40 | unk. | 60816 | 729 | 61 |
| IA1 | Hydronic | None | 2000 | Wind. | 5 | Man. | FS/Clay | 700±200 | 2~16 | blocked | 26000 | 215 | 25 |
| IA2 | Hydronic | Wall AC | 400* | Wind. | 3 | Man. | FS | 500±200 | 18 | unk. | 14000 | 110 | 10 |
| IA3 | Hydronic | Wall AC | 5000 | Wind. | 34 | Man. | S&G | 1300±200 | 17~40 | retrofit | 67564 | 115 | 30 |
| ND1 | Warm Air | None | 2300 | OA/off | 6 | Tstat/Man. | CS | 800±500 | 20 | blocked | 47500 | 350 | 36 |
| ND2 | Steam | None | 8800 | UV/Wind | 18 | Tstat/Man. | SP | 600±100 | 17~46 | retrofit | 60800 | 400 | 27 |
| ND3 | Many | None | NT | OA/HRV | NA | Tstat/Clock | gap | 700±150 | 46 | unk. | largest | unk. | unk. |
| ILL1 | Warm Air | None | 6357 | OA/UVoff | 14 | Tstat/Clock | gap | 200±100 | 60 | blocked | 41570 | 430 | 20 |
| ILL2 | Steam | None | 5100* | OA/UVoff | 10 | Tstat/Clock | FS | 700±150 | 7 | no | 36000 | 507 | 19 |
| ILL3 | Hydronic | None | NT* | OA/UVoff | NA | Tstat/Clock | Crawl | 20 | NA | limited | 28000 | 328 | 13 |
| NJ1 | Hydronic | AC | NT | OA/UVoff | NA | Tstat/Clock | S&G/SP | 2000/360 | 46 | no | 58900 | 457 | 68 |
| NJ2 | Hydronic | AC | NT | OA/UVoff | NA | Tstat/Clock | CS,SP | 1500/300 | 20 | no | 27752 | 400 | 30 |
| NJ3 | Hydronic | AC | NT | OA/UVoff | NA | Tstat/Clock | SP | 150±20 | NA | no | 32500 | 480 | 50 |
| ME1 | Hydronic | None | 5800 | UVoff | 13 | Tstat/Clock | S&G | 4500±1500 | 2&42 | no | 34000 | 374 | 44 |
| ME2 | Hydronic | None | Bill | OA/UVoff | NA | Tstat/Clock | S&G | 3500±1000 | 46 | no | 106500 | 540 | 46 |
| ME3 | Electric | None | 11300 | OA/UVoff | 9 | Tstat/Clock | S&G,SP | 3500±2000 | 10~45 | no | 167000 | 1200 | 60 |
| ME4 | Hydronic | None | NT | UVoff | NA | Tstat/Clock | SP | 2500±1000 | 32 | no | 10500 | 85 | |
| ME5 | Steam | None | NT | OA/UVoff | NA | Tstat/Clock | S&G | 2500±1000 | 25 | no | 120000 | unk. | unk. |

* many fans inoperative    Note : The Kitchen Exhaust is included in the total for most schools making cfm/person high

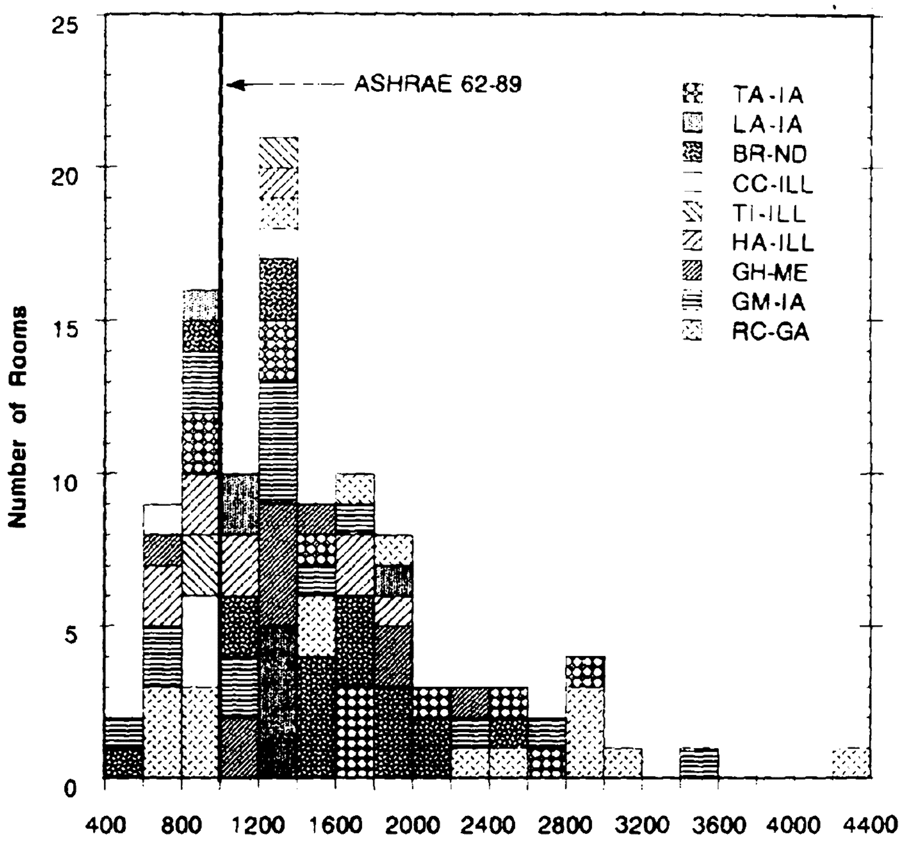
** an installed enrgy management control had been disabled

' the controls for the Unit Ventilators were in each classroom and teachers reported they didn't operate them because they were too noisy

'' FS = Fine Sand    CS = Coarse Sand    S&G = Sand and Gravel

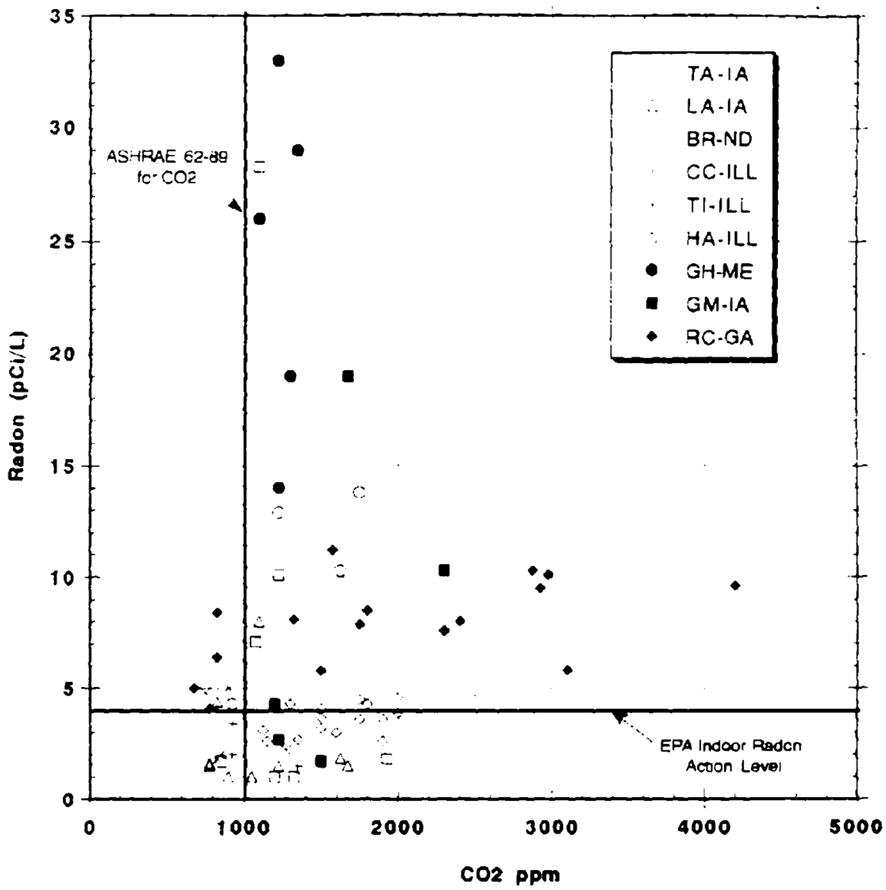
SP = Stone Pebbles    NT = Not Tested

**Figure 3 - Histogram of Carbon Dioxide Measurements Made in Occupied Classrooms SEP-1990**




Note : Measurements made in rooms with open windows or less than five people are not included in this data set.

Figure 4 - Room Carbon Dioxide vs. Radon Screening Measurements in School Rooms



# EXTENDED HEATING, VENTILATING AND AIR CONDITIONING DIAGNOSTICS IN SCHOOLS IN MAINE

Terry Brennan
Camroden Associates
RD#1 Box 222
Oriskany, New York 13424

Gene Fisher
Robert Thompson
USEPA
Office Of Radiation Programs
Washington, DC

William Turner
H.L. Turner Group
Harrison, Maine

## ABSTRACT

An extensive effort to assess the effects of HVAC system operation on the indoor radon levels was conducted. Many schools in the EPA 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. The passive vents have been blocked off.

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

In August, 1990, extended radon diagnostics were performed in two Maine Schools. The purpose was to assess the effects of returning the heating, ventilation and air conditioning (HVAC) system to the original operating specifications would have on indoor radon levels. This effort was part of the 1990 School Evaluation Program[1]. Measurements of radon, air pressure differences across the building shell and carbon dioxide levels[2] were made to help judge the system changes. While a large amount of data was collected, these measurements were open to a number of interpretations because the radon levels found in the schoolrooms during the extended diagnostics week were much lower than were found by the screening measurements made in April, 1990.

In December of 1990, followup measurements were made at the Gray High School and Russell Elementary School in Gray, Maine. The purpose of these measurements was to provide a basis upon which to judge the effect of the HVAC improvements on radon levels, air pressure relationships and carbon dioxide concentrations in occupied rooms. December was a good time to make this assessment because it represented a worst case scenario. That is, the outside air dampers in the unit ventilators and built up air handlers were closed to minimum and the competing stack effect was at the maximum. Both conditions are the result of the low outdoor temperatures found in Maine at that time of year. The measurements were carried out by a team of people. The team included : Gene Fisher and Bob Thompson USEPA Office of Radiation Programs, Washington, D.C. ; Bruce Harris, USEPA, AEERL, Radon Branch, Research Triangle Park, NC; Bill Turner, Fred McKnight, H.L. Turner Group, Harrison, Maine; Terry Brennan, Camroden Associates, Oriskany, New York; and Gene Moreau, Bob Stillwell, Maine Department of Health Engineering, Augusta, Maine.

A special note of thanks is extended to the Maine Department of Health for their active participation in this evaluation.

## PROCEDURE

The evaluation consisted of a visual inspection and measurement of key performance related variables in the Gray High School and the Russell Elementary School.

An extensive set of measurements were made in the High School. The following measurements were made :

> continuous radon (pulse ionization and semi-conductor)
> continuous air pressure differences (variable capacitance)
> carbon dioxide survey (infrared spectrometer)

Continuous radon monitors were placed in rooms 2, 7, 17, 31, 32, 33, the Guidance Office and the Conference Room. The monitors used were eight Honeywell continuous radon monitors and two femto-Tech continuous radon monitors (room 33 and room 7). The Honeywell units provide mean radon levels for 4 hour intervals and the femto-Techs for 1 hour intervals. Air pressure differences were monitored across the floor slab in rooms, 33, 7, the Conference Room and the Guidance Office. Variable capacitance chambers manufactured by Setra were connected to a data logger provided by EPA to collect pressure difference data. Calibration curves were made for each sensor using a micromanometer. Ventilation rates, outside air fractions and ventilation effectiveness were estimated by making a survey of carbon dioxide levels in the occupied classrooms. These could then be compared to carbon dioxide measurements made in the same rooms at the end of the previous school year. Data was collected from 12/18/90 until 1/16/91. This afforded the opportunity to see the classrooms operated both normally and with school in recess for the Christmas Vacation.

Additionally, measurements of sub slab radon were made in the High School and the nearby Middle School. A carbon dioxide survey was also made in the Middle School. The Middle School is very close to the High School but does not seem to have nearly the elevated radon levels that the High School does. These measurements were made to determine whether the Middle School radon levels were lower due to lower source term, construction characteristics or HVAC operation and design. The radon levels under both schools were in the range of 2000 to 4000 pCi/L. There is no evidence that the source strength is the variable causing the large difference in the radon levels in the two schools.

## RESULTS

### Overview Of Results

The results of this investigation can be briefly summarized in a few lines. The evidence supporting these conclusions are then presented.

1) average radon levels that do not distinguish between occupied and unoccupied

conditions can be misleading

2) the operation of the air handlers, both outside air and exhaust only, has a definite reducing effect on the radon concentrations in the rooms

3) the decay rate of the radon after the air handler turns on is less than would be expected given the amount of outside air that is introduced because the radon is still entering due to negative building air pressure

4) repairing the outside air functions of the air handler made dramatic improvements in the carbon dioxide levels in the rooms where outside air was introduced.

5) while effective and reliable at solving radon problems, soil depressurization in rooms with inadequate ventilation leaves children sitting in high concentrations of $CO_2$ and other indoor air contaminants for which $CO_2$ levels are an indicator.

## Effect Of Outside Air Improvements On Radon Levels And Dynamics

### Introduction--

Continuous radon levels were monitored in eight rooms of the High School. Rooms 33 and 7 are going to be used to illustrate the effects of the air handler operation on radon levels in classrooms. The resolution of the femto-Tech units in these rooms allows one hour radon levels to be used in the analysis. These rooms are representative of the two different air handling systems - exhaust fans only and unit ventilators with passive relief. Room 33 is in the new wing of the high school, contains a unit ventilator and has repeatedly shown the highest average radon levels and spikes. Room 7 is in the old wing, which has exhaust only ventilation and has shown high radon levels. The only fan powered outside air that can potentially enter Room 7 is from the gym air handlers, when they are running. Otherwise, outside air to Room 7 consists of whatever is drawn in through leakage in the building shell, window wall and corridor.

The next two major sections will examine first Room 33, the unit ventilator room and then Room 7, the exhaust only room, in detail.

### Room 33 - Unit Ventilator Ventilation--

The results of the continuous monitoring in Room 33 are shown in Figure 1. Notice that the "rain spike" in this room on Christmas eve rises from 8 to 90 pCi/L and drops again to 16 pCi/L in a 24 hour period. This is far more severe than in other monitored rooms, indicating that a substantial amount of radon is available to enter this room. As in Room 7, the radon levels in this room drop quickly when the ventilation turns on. This can be seen at the points labeled "Air Handler On" in Figure 1. Notice that on Christmas eve during a rain storm there is large spike in the radon concentration. This spike is seen in every room monitored and is interpreted as a rain spike.

The dynamics of the drop in radon that occurs when the unit ventilator comes on is illustrated by Figure 2. This graph shows the 24 hour period of December 19, 1991. Between midnight and 6 AM the radon level hovers around 17 pCi/L. At 6 AM when the unit ventilator is turned on by a timeclock control, the radon level drops in an exponential decay until it reaches a minimum of around 2 pCi/L in the late afternoon. An exponential decay of contaminant level is expected when dilution air is introduced into the room. After the unit ventilator is turned off, the radon levels begin to climb until they reach a level of 7 pCi/L again at midnight. The mean radon concentration for this 24 hour period is 8.9 pCi/L and for the occupied time it is 6 pCi/L. However, for the lowest nine hour period the mean radon level is 3.8 pCi/L. This means that the dose delivered to the occupants could be reduced 37% by starting the unit ventilator three hours earlier.

NOTE : A correction for built up radon decay products in the continuous monitor is not required for the pulse ionization device used because the decay products are collected using an electric field without being counted. However, due to diffusion lag into and outof the sensitive volume, a one hour time delay is observed in the radon dynamic.

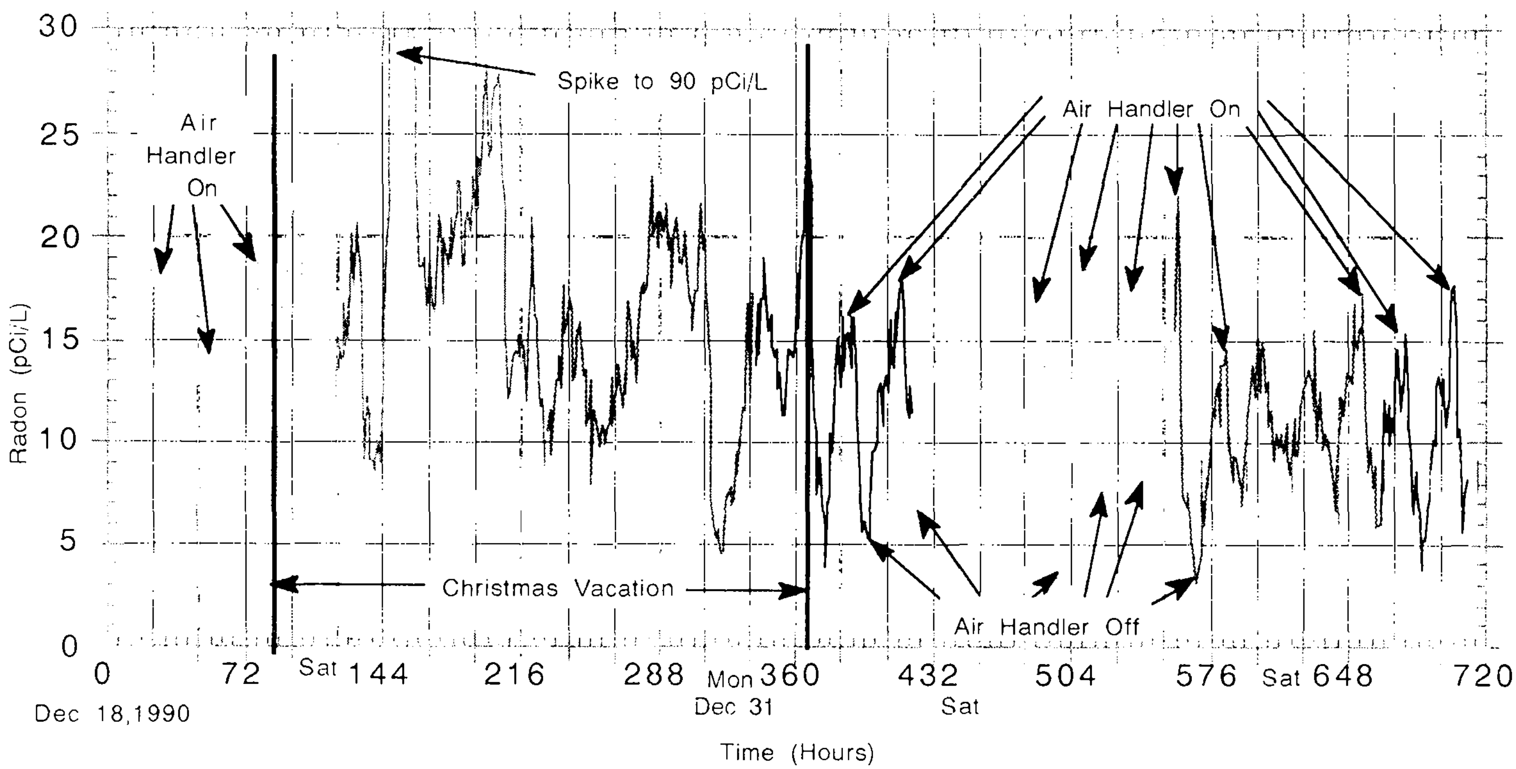



Figure 1 - Radon Levels in Room 33

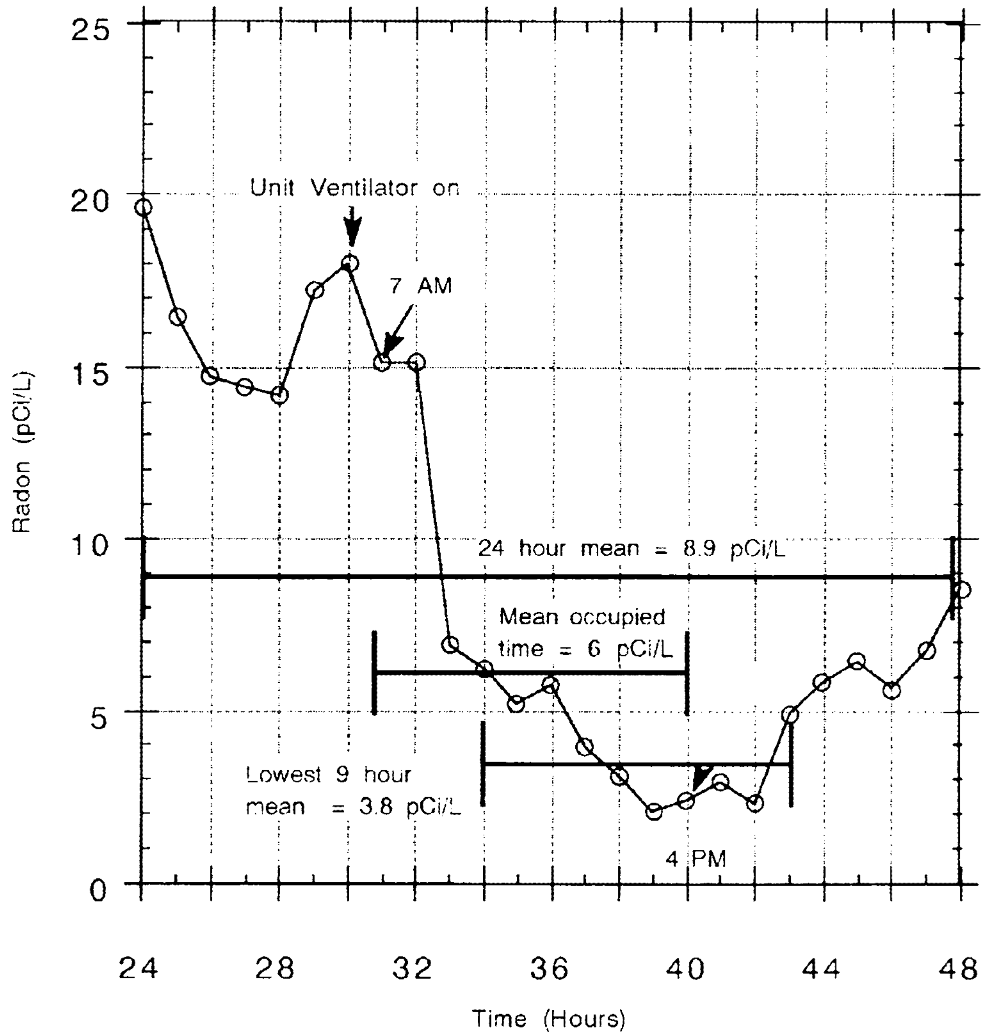



Figure 2 - Radon Dynamics in Unit Ventilator Room 33

While for this one day, the 19th of December the mean radon level for the occupied time period was 6 pCi/L, it was not so for other occupied days. In fact, the average occupied time radon level for the entire monitored period shown in Figure 1 is a higher 7.8 pCi/L. This is still 28% lower than the 10.8 pCi/L mean for the entire time period.

Another approach to understanding this dynamic is to apply tracer decay theory. This has been done in the analysis shown in Figure 3. Figure 3 was created by taking the decay curves for all the occupied days during the monitoring period and plotting them on a single graph. The time scale has been changed from consecutive hours to hours after the unit ventilator turns on. The result is a scattergram that plots all the decay data for all the occupied days on top of each other.

If a given amount of contaminant is released into a room and then allowed to be removed by dilution with ventilation air, it is expected that the concentration of the contaminant will decay exponentially with time[3]. The rate at which it decays is described by the solution to the continuity equation. This is given as the following :

$$C(t) = C(0) \times e^{Nt} \tag{1)}$$

where : $C(t)$ = concentration at time t
$C(0)$ = concentration at the start of the decay
$N$ = airchange rate in air changes per hour
$t$ = time in hours

By fitting an exponential decay curve to the data in Figure 3, the decay rate and the air exchange rate for the average day during this monitoring period can be determined. It is obvious from this curve that if the radon level at the start of the day is greater than about 8 pCi/L, the mean level during the day would not get below 4 pCi/L. The curve fit yields an air exchange rate of 0.13 air changes per hour (ACH). By direct measurement of outside air, it is known that the air exchange rate in the room is 1 ACH. This discrepancy is explained in the following way. In order for equation 1) to describe radon concentrations, the entry rate of radon after the start of the decay must be zero. The introduction of outside air has not stopped radon from entering the room. This is easily verified by a glance at the air pressure difference between the room air and the sub slab air. The room air was at a lower pressure than the sub slab air during the entire monitoring period. When the unit ventilator turned on, this difference became smaller, but the room was still negative relative to the sub slab. The radon

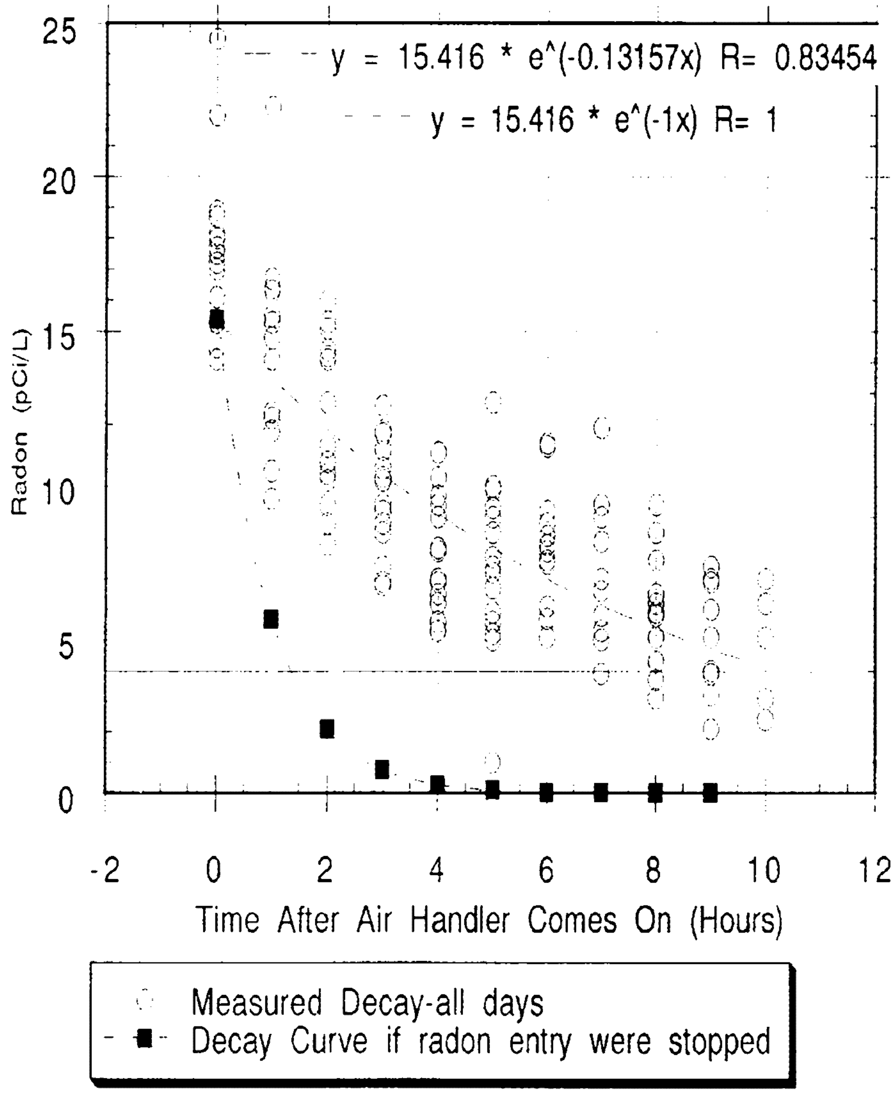



Figure 3 - Reduction Rate of Radon in Room 33
Air Handler On - All Days Combined

entry rate may have been reduced but it certainly was not stopped. If the room was pressurized by the unit ventilator then the radon concentration would have dropped according to the lower curve in Figure 3. The radon concentration would be below 4 pCi/L in a matter of an hour.

In fact, it is likely that this is the case in this room during the spring and fall when the outside temperature is warmer than in January. This is expected for two reasons. One, warmer outside air means a reduction in the air pressure differences induced by the stack effect. Two, when the outside air is warm enough gains from body heat will overheat the room and cause the outside air dampers to open more. This will increase the outside air volume and contribute to pressurizing the room.

Lastly, the room could potentially be pressurized even under the worst case condition represented by these test results. This could be accomplished by air sealing the room so that the minimum outside air flow rate would pressurize the room. Not only would this control the indoor radon but it also would result in energy savings by reducing air infiltration.

Room 7 - Exhaust Only Ventilation--

Figure 4 shows the continuous radon data in Room 7. The data begins on December 18, 1990. Christmas vacation began on December 20, 1990 and ended January 2, 1991. The radon levels in this room plummet whenever the rooftop exhaust fans turn on (see the points labeled "Air Handlers On" in Figure 1). This effect is repeatable. The radon levels drop in spite of the fact that operation of the exhaust fans drives the air pressure difference between room 7 air and the sub slab air 3 pascals lower. It is likely that the amount of radon entering the room increases when the fans turn on. Although more soil air is being drawn in by the operation of the fans, the dilution effect of the increased ventilation from above grade overwhelms the increased radon entry. Unfortunately, the increased entry is not overwhelmed enough so that the occupied radon levels are below 4 pCi/L, but are instead 7.1 pCi/L.

Figure 5 shows the agglomerated radon data for the occupied days in Room 7. This graph was generated in the same way that Figure 3 was for Room 33. The general trend of decreasing radon levels after the exhaust fan turns on is obvious. There is a great deal more scatter in this data than there was in the data from Room 33 (the unit ventilator room). The curve fit to this data shows an effective ventilation rate of only 0.065 ACH, while the measured exhaust rate informs us that there is actually 0.63 ACH (shown as the theoretical curve in Figure 5). The data from Figure 3 and Figure 5 are combined in a single graph in Figure 6. This figure highlights the similarities and differences between the dynamics of the two rooms. Notice that the theoretical curves for the two rooms almost coincide, even though the fan powered air exchange rates

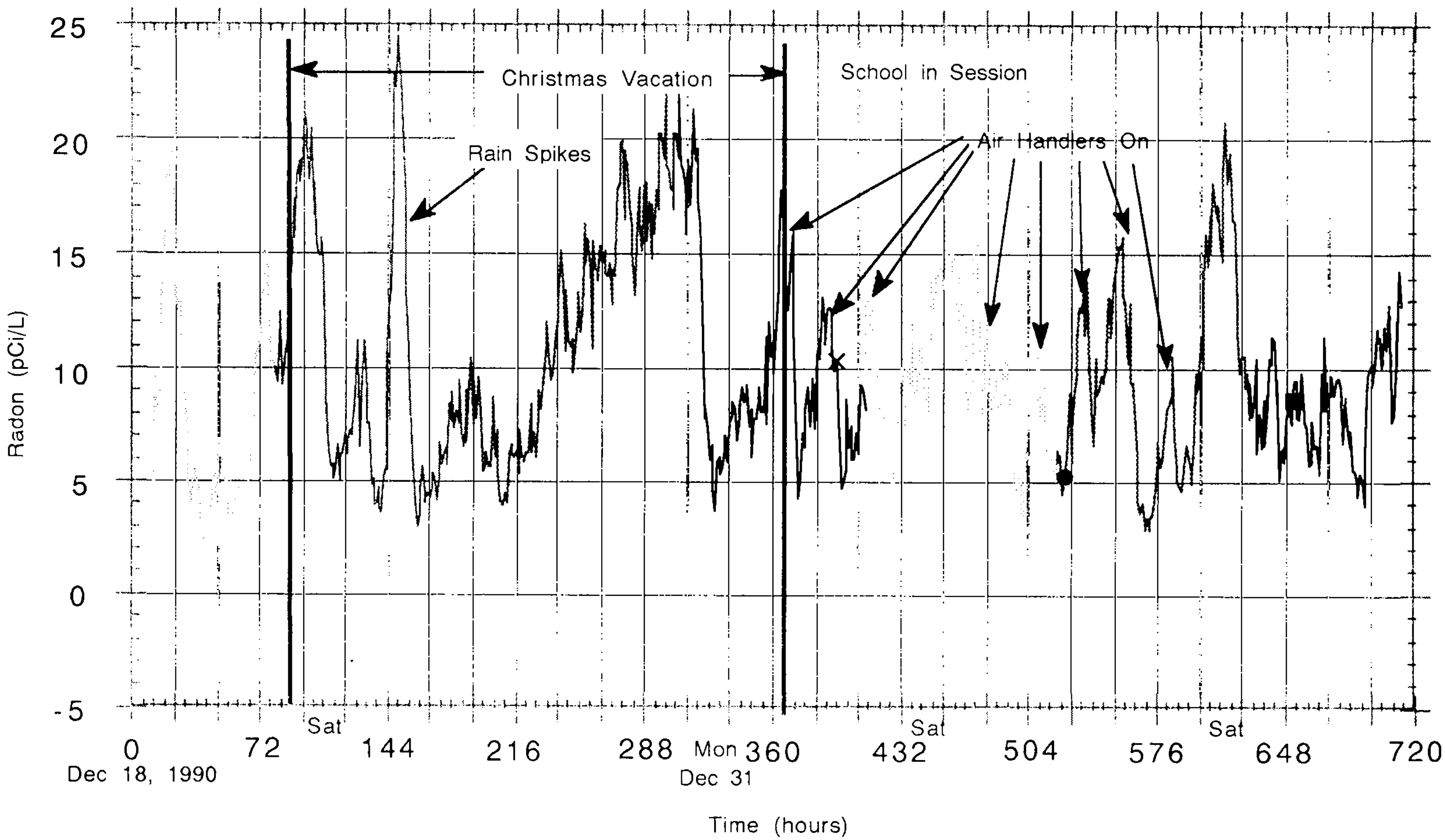



Figure 4 - Radon Levels in Room 7

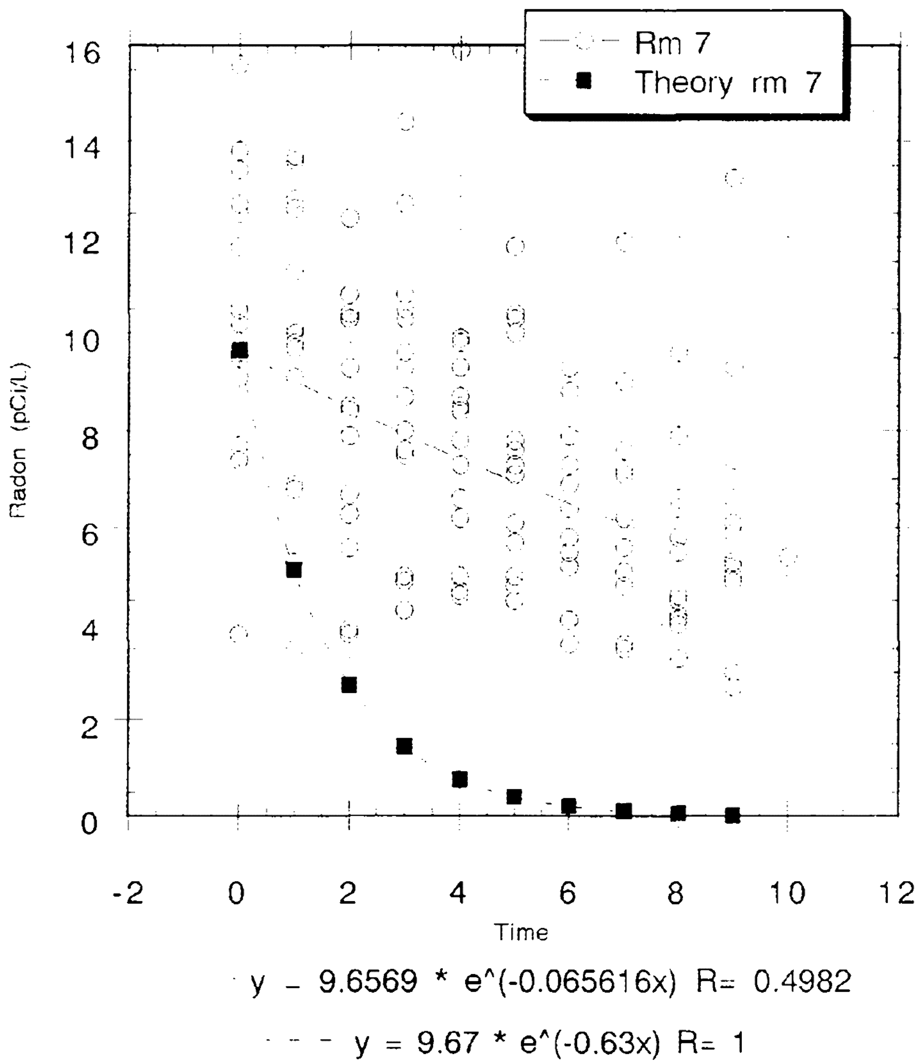
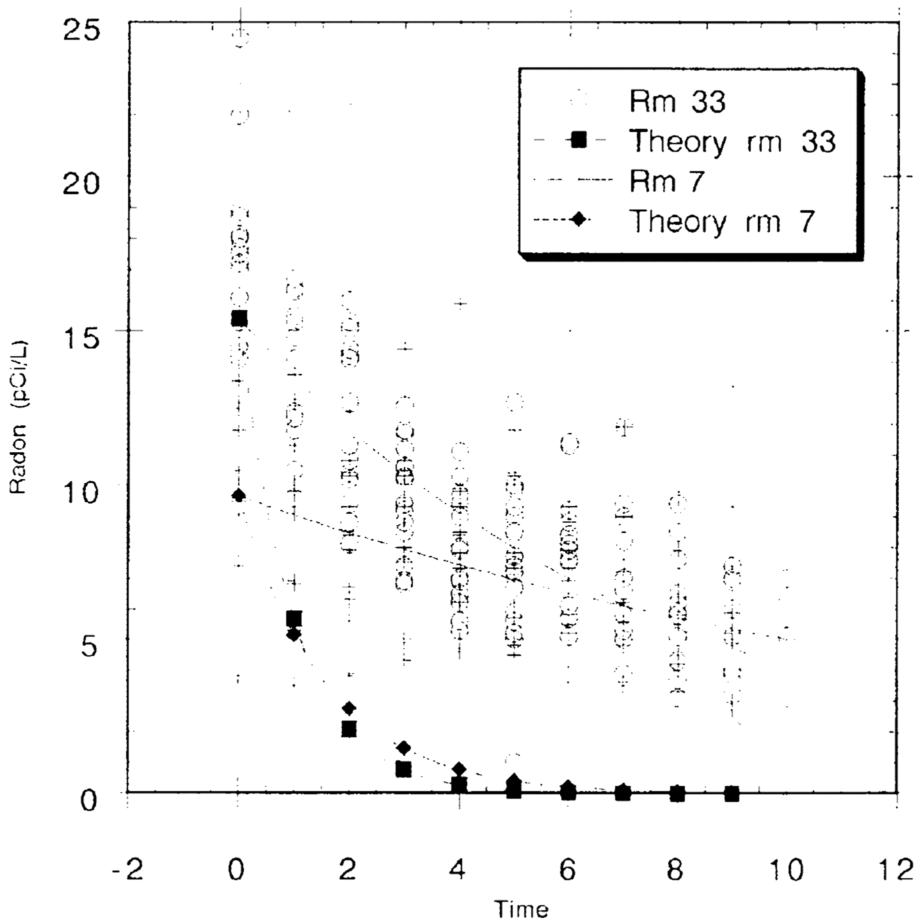



Figure 5 -Reduction Rate of Radon in Room 7
ExhaustFanOn-AllDays




y = 15.416 * e^(-0.13157x) R= 0.83454

y = 15.416 * e^(-1x) R= 1

y = 9.6569 * e^(-0.065616x) R= 0.4982

y = 9.67 * e^(-0.63x) R= 1

Figure 6 - Reduction Rate of Radon
Air Handlers On - Rms. 7 & 33

are quite different (1 and 0.63 ACH). This is largely due to the difference in source terms. Room 7 begins the average occupied day at around 10 pCi/L while Room 33 begins the average occupied day at just over 15 pCi/L.

It is tempting to attribute the differences in radon dynamics in these two rooms to the difference between exhaust only and fan powered outside air ventilation. But, two rooms, no matter the depth of study provide anecdotal, not conclusive evidence. The results of these measurements do support the current model of radon entry and control as follows :

- entry is dominated by air pressure driven mechanisms
- exhaust ventilation can lower radon concentrations, but not as effectively as powered outside air ventilation

To these two basics we can add a further hypothesis :

- unless fan powered outside air ventilation stops radon entry, the reduction rate of radon will not be as great as expected from dilution alone

and a corollary :

- exhaust only ventilation will never lower radon concentrations as quickly as would be expected from dilution alone because it does not stop the entry of radon

It is important to understand that these two suggestions apply only to dynamic radon behavior and not to steady state conditions. This only applies to the rate at which radon levels change.

Effect Of Outside Air Improvements On Carbon Dioxide Measurements

Introduction--

The reason we breathe is to get oxygen to the cells in our bodies and to remove a number of the byproducts of respiration. Carbon dioxide and water vapor are the most plentiful products of respiration. Carbon dioxide levels in outgoing breath are several thousand parts per million. Carbon dioxide measurements made in occupied rooms can be used as a surrogate for levels of indoor air contaminants that are produced by the occupants themselves and routine activities of occupants. If a simplifying assumption is made about the generation rate of $CO_2$ being constant then they also can be used to estimate the outside air ventilation rate [4]. The ventilation guidelines of

15 cfm/person in the publication ASHRAE 62-1989 Ventilation for Acceptable Indoor Air Quality should result in a steady state 1000 ppm of carbon dioxide in an occupied classroom.

Carbon Dioxide Measurements--

Carbon dioxide measurements were made in the High School and the Russell School (pre and post radon control) and in the Middle School. The pre radon control measurements were made in early June of 1990 and the post measurements were made in December of 1990.

Carbon Dioxide Measurements in the High School--

A histogram is shown in Figure 7 that differentiates between the pre and post carbon dioxide measurements. Only measurements from occupied rooms with closed windows are shown. The distribution of $CO_2$ levels has been very clearly pushed to the lower levels by the repairs made to the ventilation system. The pre radon control $CO_2$ levels had a mean of $1402 \pm 450$ ppm and the post level mean was $1042 \pm 394$ ppm. This represents a 33% decrease in the mean. From a health, comfort and alertness perspective, this is a great improvement over the situation before the ventilation equipment was repaired. Although the mean is now nearly the level recommended in the ASHRAE guidelines[4], half the rooms in the post control sample would still be considered underventilated by the current guideline. Eight percent of them (2 rooms) are above 1700 ppm, which would reflect an outside air exchange rate of 5 cfmiperson. By contrast, all the rooms in the pre mitigation set of measurements were above the current guidelines (1000 ppm) and 27% of them (3 rooms) were above 1700 ppm.

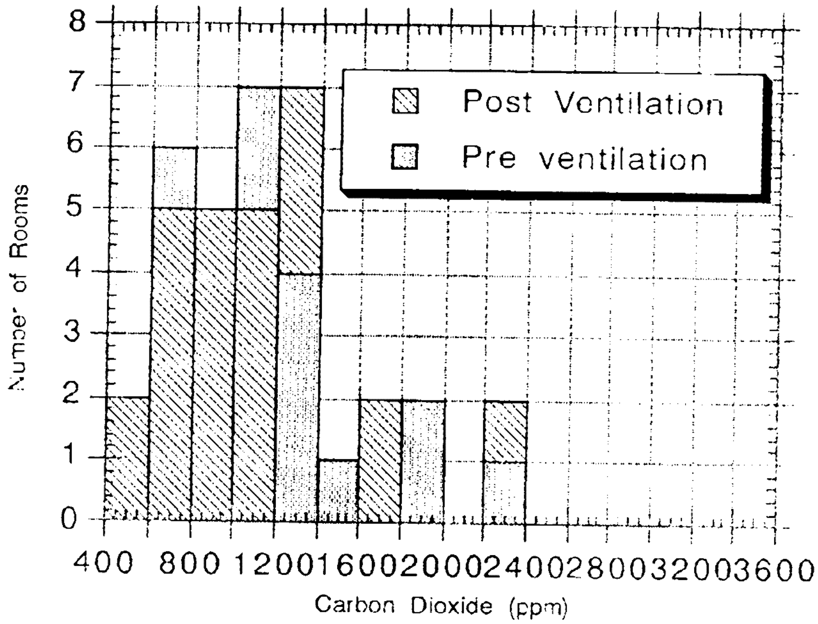


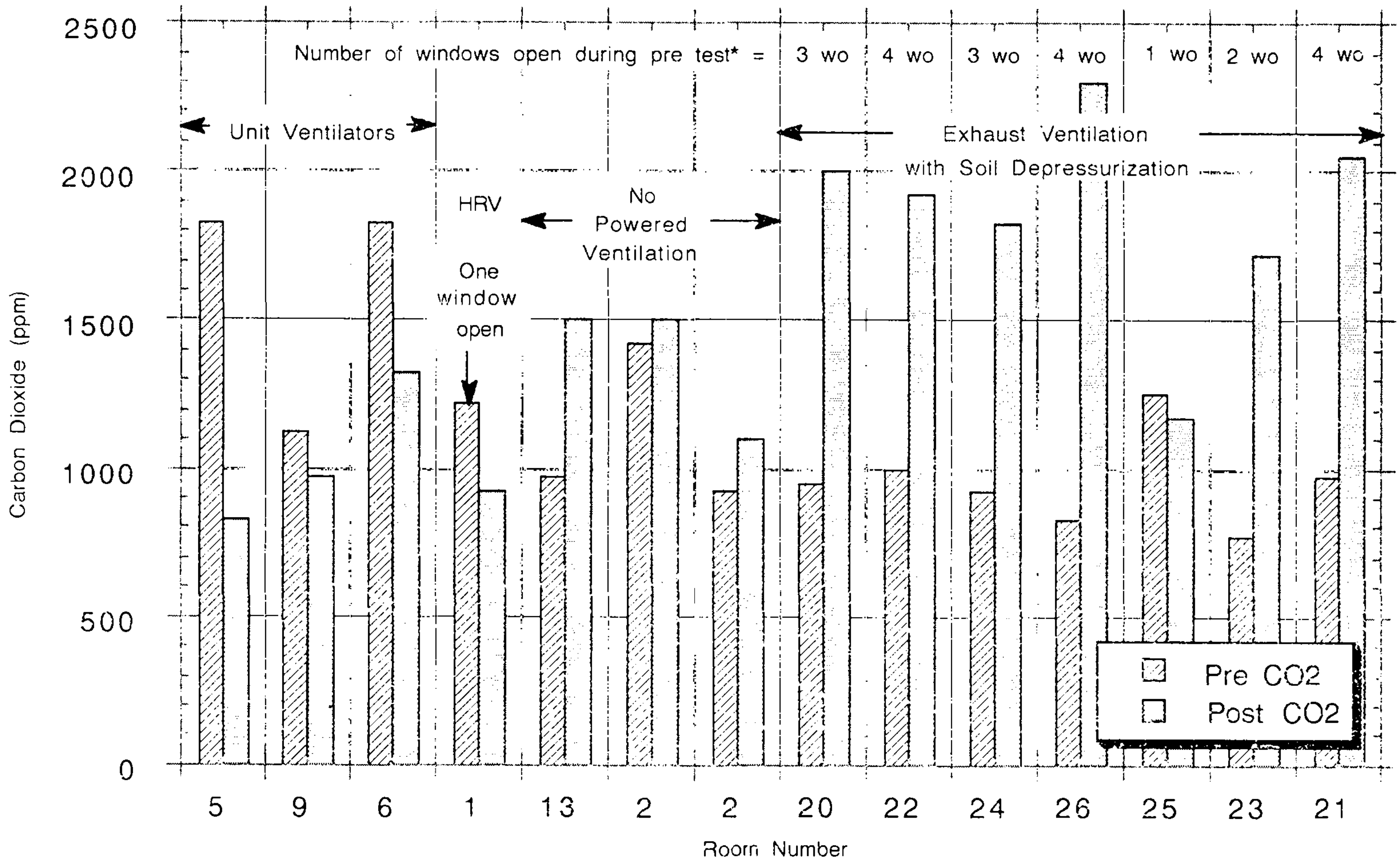

Figure 7 - Pre and Post Control CO2 Histogram for High School

Carbon Dioxide Measurements in the Russell School--

A bar graph is shown in Figure 8 that differentiates between the pre and post carbon dioxide measurements and between ventilation and radon control type. Measurements are from occupied rooms with closed windows except the pre control measurements in the exhaust only ventilation - soil depressurization rooms. These rooms had open windows during the June measurements. The number of open windows is shown on the bar graph.

The CO2 levels have been very clearly lowered by the repairs made to the unit ventilators (rooms 5, 9, and 6) and by the installation of the heat recovery ventilator (located in room 1, with no powered ventilation). Pre control CO2 levels were not available for some rooms with unit ventilators (rooms 7, 8, 10 and 11) but post control measurements were. The mean post control CO2 levels for all the rooms in which unit ventilators were repaired (5, 6, 7, 8, 9, 10, and 11) was 1350 ± 408 ppm.

Rooms 1, 2a, 2b, 3 and 4 are in the oldest wing, where there is no fan powered ventilation. Rooms 2a and 2b show slight increases in CO2 levels, averaging 1500 ppm CO2, as compared to Room 1 which has dropped from over 1250 ppm to 925




*Note No windows were open in the Unit Ventilator rooms during the CO2 tests

Figure 8 - Carbon Dioxide Levels Pre and Post Radon Control at the Russell School

ppm. This is expected considering that no changes in the ventilation of rooms 2a and 2b have taken place, but a heat recovery ventilator has been added to Room 1.

Rooms 20, 21, 22, 23, 24, 25, and 26 are in the exhaust only wing, in which soil depressurization has been used to control the radon. The radon levels in these rooms (except for the library, which is around 7 pCi/L) are averaging between 1.4 and 3.5 pCi/L. The pre control CO2 levels in these rooms must be interpreted cautiously because at least one window was open in each room when these measurements were made. The post control CO2 levels had a mean of 1857 ± 376 ppm.

None of the exhaust only rooms meet the current ASHRAE guideline for ventilation rates. In fact, none of them meets the ASHRAE ventilation guideline for the year in which they were constructed. While it is clear that soil depressurization will control indoor radon, it is also clear that it has little impact on other indoor air contaminants.

Histograms of the CO2 data from the Russell School are not presented because there is so little pre control data that did not have windows open.

## CONCLUSIONS

Conclusions for this work contribute to interpretation of radon measurements made in school rooms (and other non-residential settings) where a wide range of occupant activities and the operation of air handlers can have important effects on radon measurements. Radon measurements in the Maine Schools show that average radon levels that do not distinguish between occupied and unoccupied conditions can be misleading when the effect of air handlers is unknown.

The operation of both types of air handlers, outside air and exhaust only, has a definite reducing effect on the radon concentrations in the rooms. Unless radon is prevented from entering, the radon concentration does not drop as quickly as expected given the known amount of outside air that is being introduced. Only fan powered outside air has the chance of doing this. In the High School it is not doing so during the coldest months. It is likely that there are times during the spring and fall when the outside air dampers are open wider and the stack effect is reduced that the unit ventilator rooms are pressurized enough to prevent radon entry. Exhaust only ventilation can have reducing effects, but will always be drawing some soil air into the building. It is possible that for given source strengths and slab/building shell leakage characteristics exhaust ventilation could be good enough to control radon, but that is not so in the Gray High School.

Clearly many, if not all the classrooms investigated, were underventilated for the number of occupants. The carbon dioxide data gives plenty of evidence for this contention. Repairing the outside air functions of the air handler made dramatic improvements in the carbon dioxide levels in the rooms where outside air was introduced. However, while effective and reliable at solving radon problems, soil depressurization in rooms with inadequate ventilation leaves children sitting in high concentrations of $CO_2$ and other indoor air contaminants for which $CO_2$ levels are an indicator.

1. Fisher, G., Brennan, T.B., Turner, W. *The School Evaluation Program.* in *The 1990 International Symposium on Radon and Radon Reduction Technology : Volume V. Preprints.* 1990. Atlanta: EPA.

2. Brennan, T., Turner, W., Fisher, G. *Building HVAC/Foundation Diagnostics For Radon Mitigation in Schools and Commercial Buildings : Part 1.* in *Indoor Air '90 The Fifth International Conference on Indoor Air Quality and Climate.* 1990. Toronto, Canada

3. Charlesworth, P., *Air Exchange Rate and Airtightness Measurement Techniques - An Applications Guide.* 1988, Coventry, Great Britain: Air Infiltration and Ventilation Centre.

4. ASHRAE, *62-89 Ventilation For Acceptable Air Quality.* 1989, American Society of Heating Refrigeration and Air Conditioning Engineers.

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

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

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

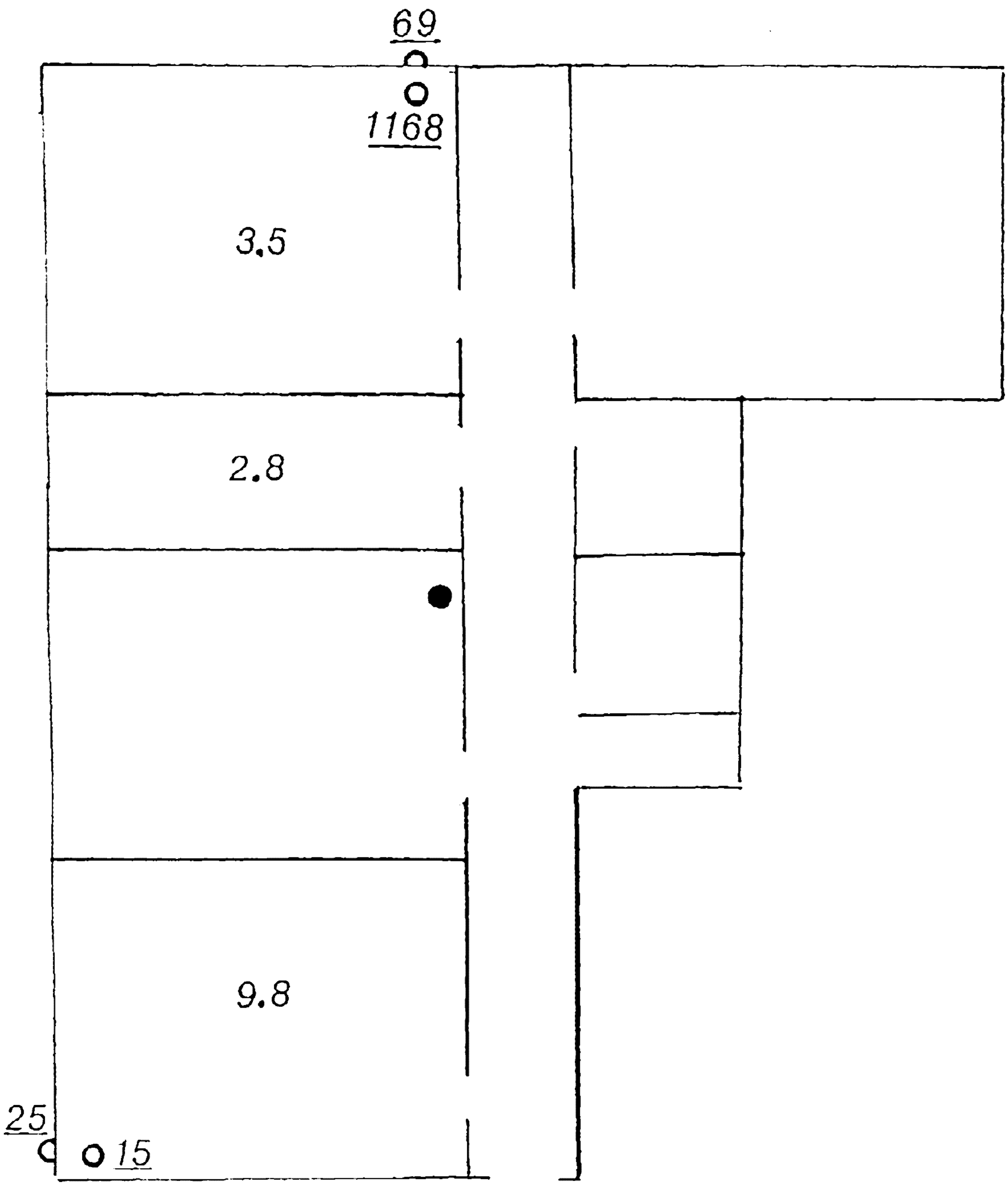



FIGURE 1. Springbrook High School - Indoor radon levels not correlated with sub-slab radon levels due to HVAC effects predominant over geologic source effects. In all Figures, indoor radon levels are in the center of each room. Both sub-slab radon levels, adjacent to circles, and blockwall radon levels,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

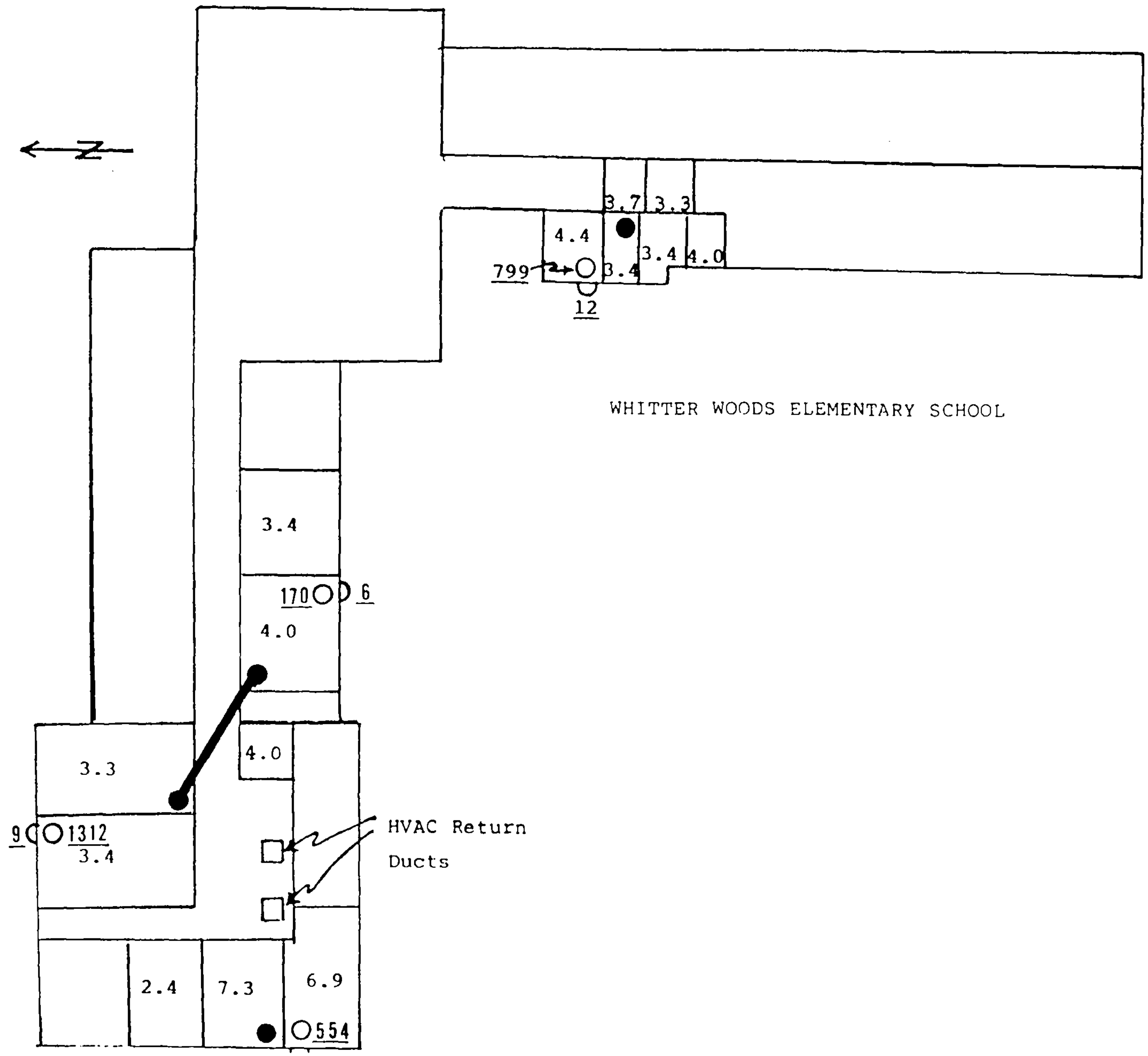



FIGURE 2. Whitter Woods Elementary School - Indoor radon levels not correlated with sub-slab radon levels due to HVAC effects predominant over geologic source effects.

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 - $\Delta$P EFFECT FROM OPEN DOORS

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

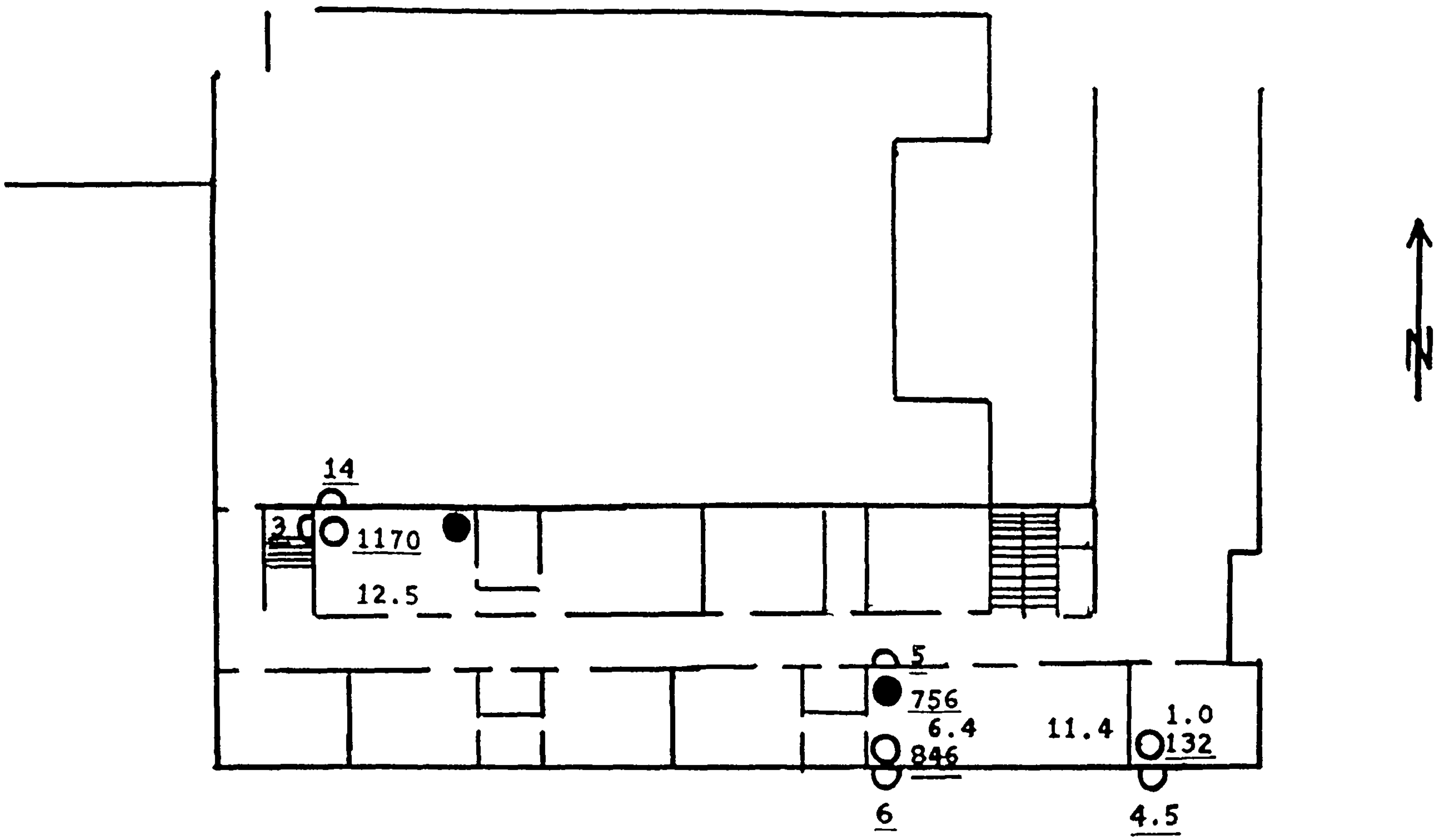



FIGURE 4. Francis Scott Key High School - Indoor radon levels proportional to sub-slab radon levels due to equivalent HVAC effects and predominant geologic control.

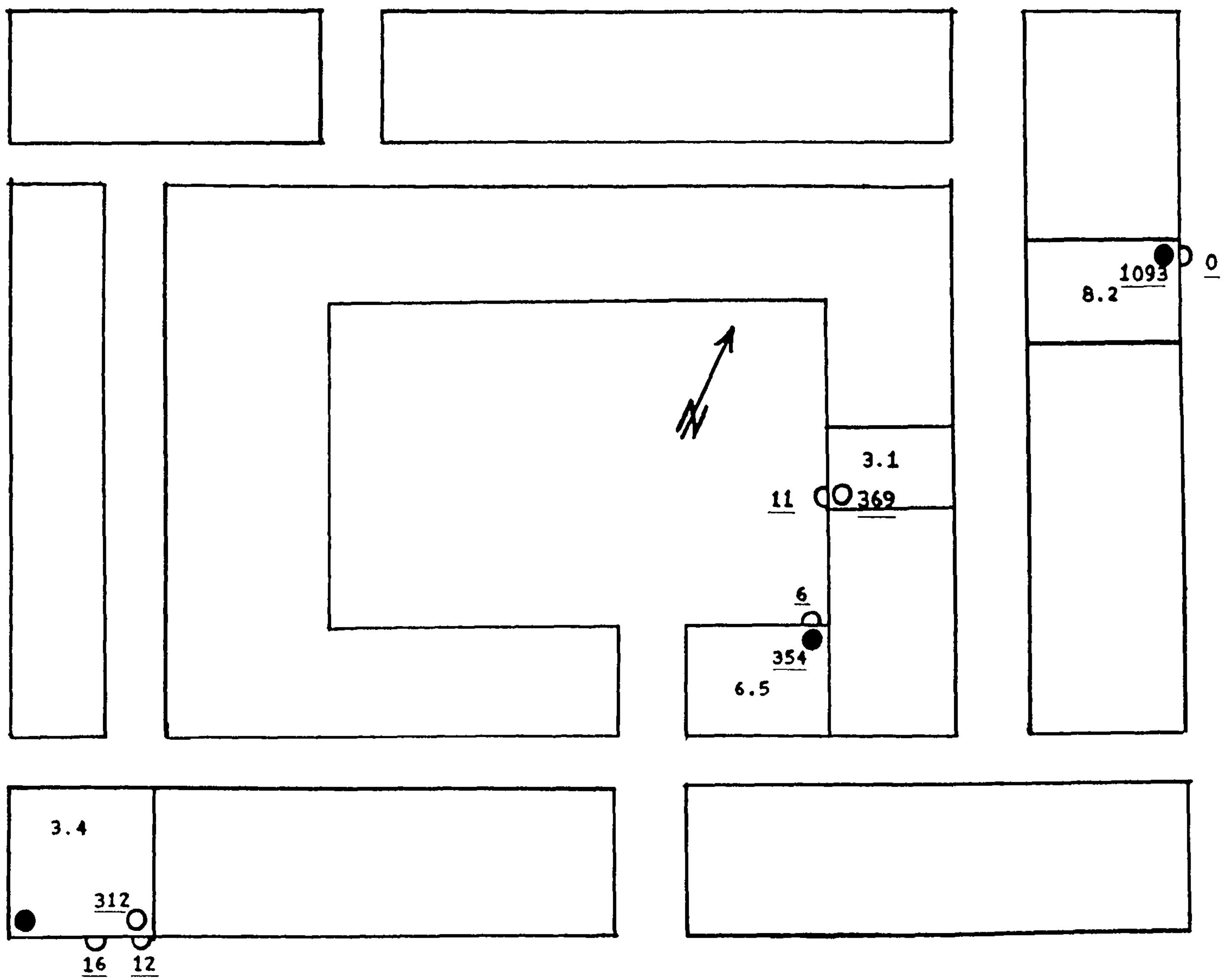



FIGURE 5. Cannon Road Elementary School - Indoor radon levels proportional to sub-slab radon levels due to equivalent HVAC effects and predominant geologic control.

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.

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.

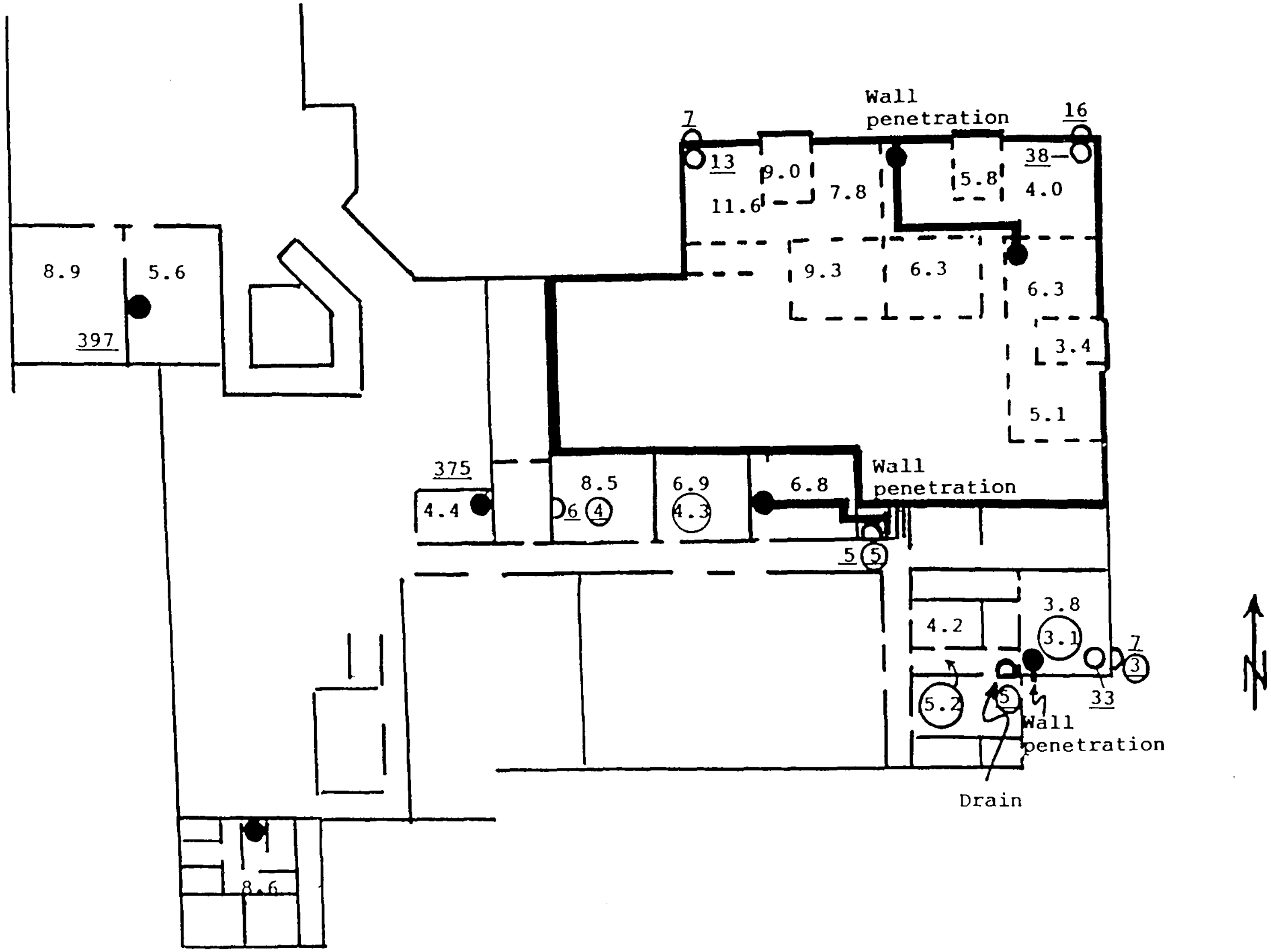



FIGURE 6. Martin Luther King Junior High School - Blockwall radon transport to second floor. Second floor slab-on-grade is outlined in bold with rooms in dashed lines. Where the second floor is above a first floor, radon levels are encircled.

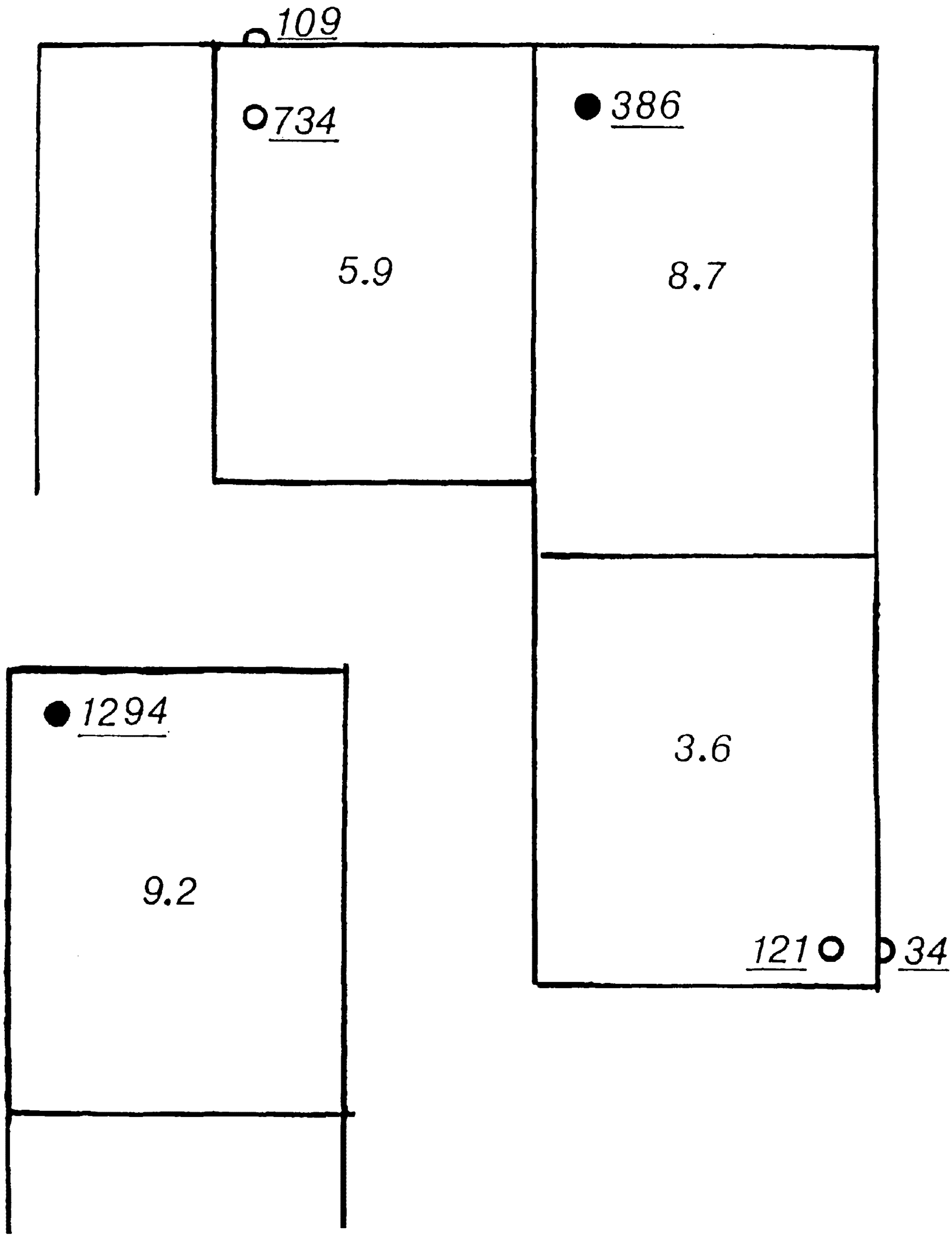



FIGURE 7. Springbrook High School - Blockwall radon concentrations correlating with adjacent sub-slab radon levels.

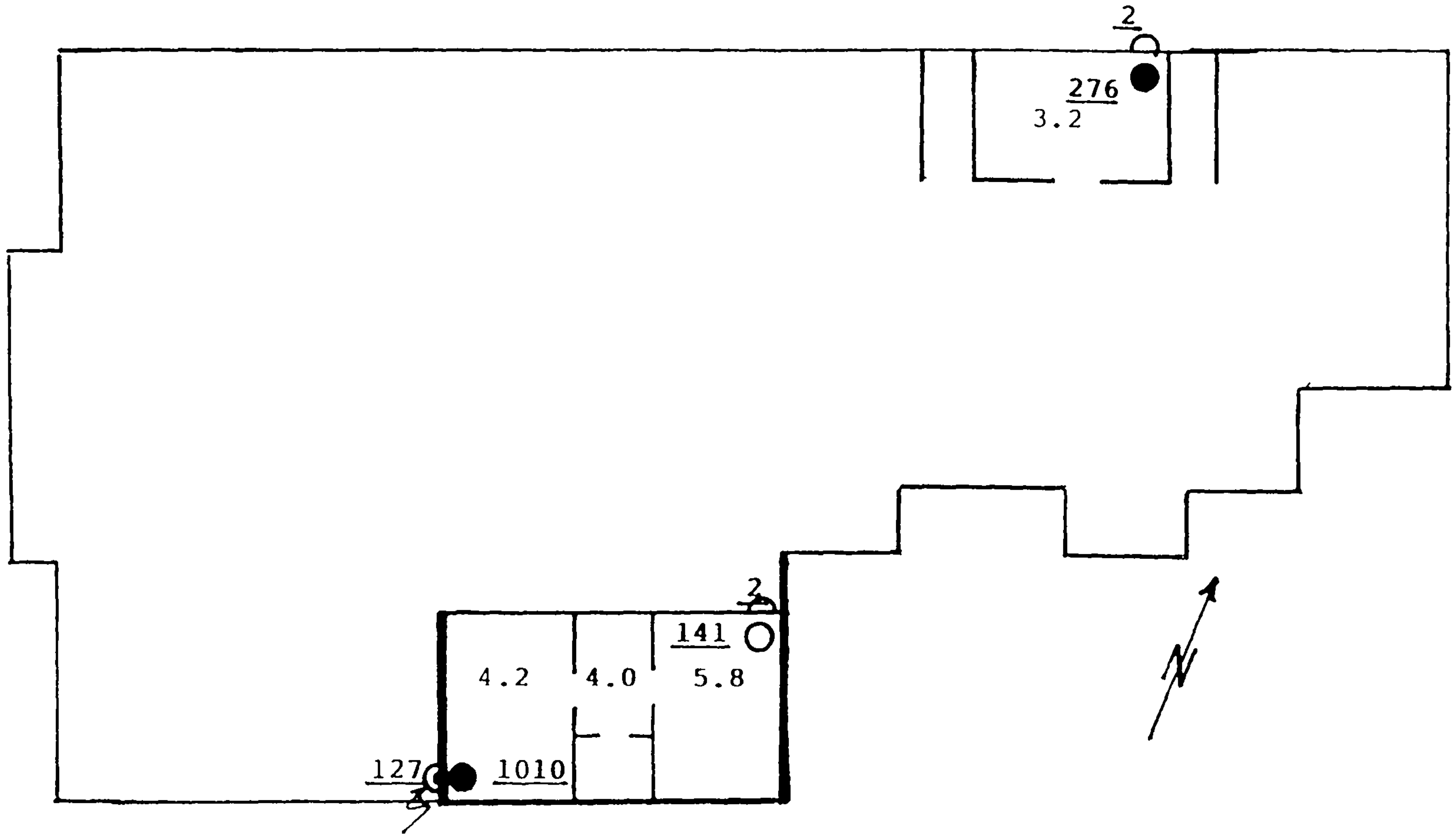



FIGURE 8. Ridgeview Junior High School - Blockwall radon concentrations correlating with adjacent sub-slab radon levels.

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 $\Delta P$ 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

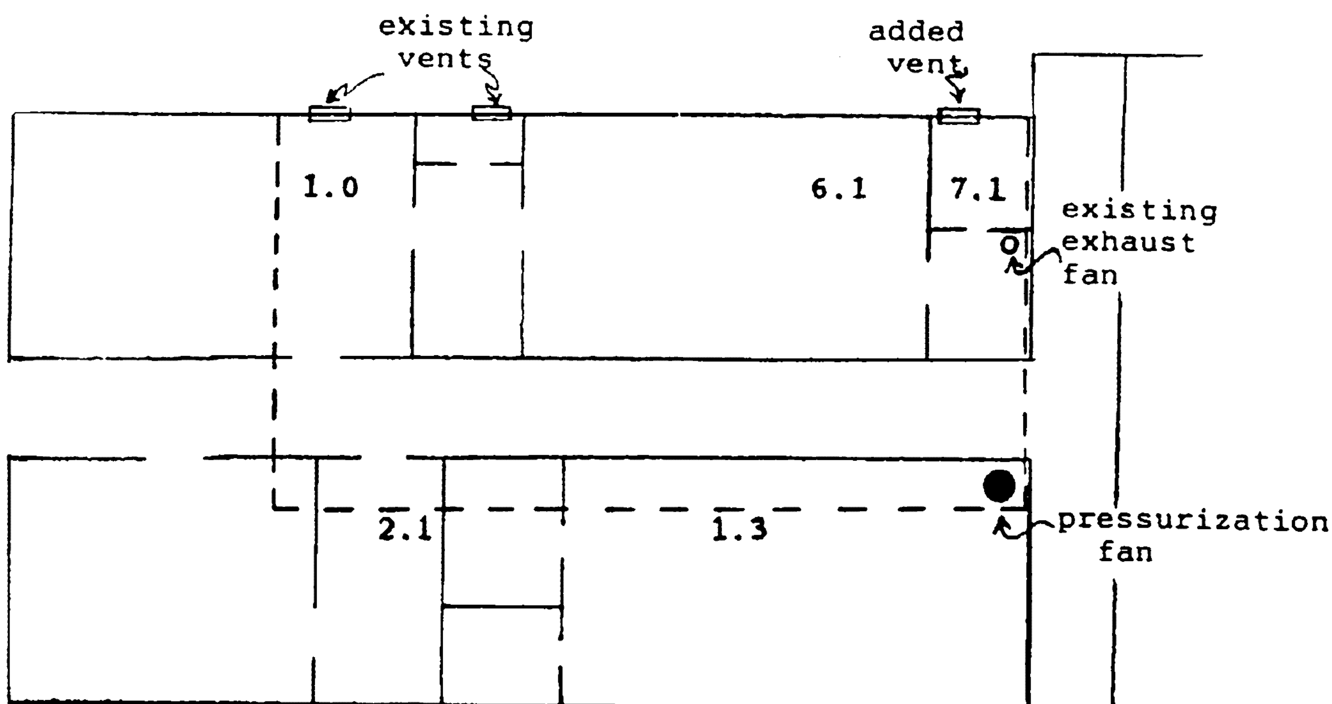



FIGURE 9. White Oak Middle School - Crawlspace area outlined with dashed line. existing exhaust fan exhausts indoor air into crawlspace.

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

| | TIME, SEC. | INDOOR/OUTDOOR, $\Delta$ 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

Bobby E. Pyle
Southern Research Institute
Birmingham, AL 35255

Kelly W. Leovic
U.S. Environmental Protection Agency
Air & Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

## 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.

<u>Crawl Space Depressurization</u>

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).

<u>Active Soil Depressurization</u>

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<br>Room 116 to Crawl space<br>Room 116 to Subpoly |
| Radon | Room 116<br>Crawl Space |
| Temperature | Room 116<br>Crawl space<br>Soil<br>Outdoors |
| Wind Speed and Direction | Outdoors |
| Relative Humidity | Outdoors |
| Rainfall | Outdoors |

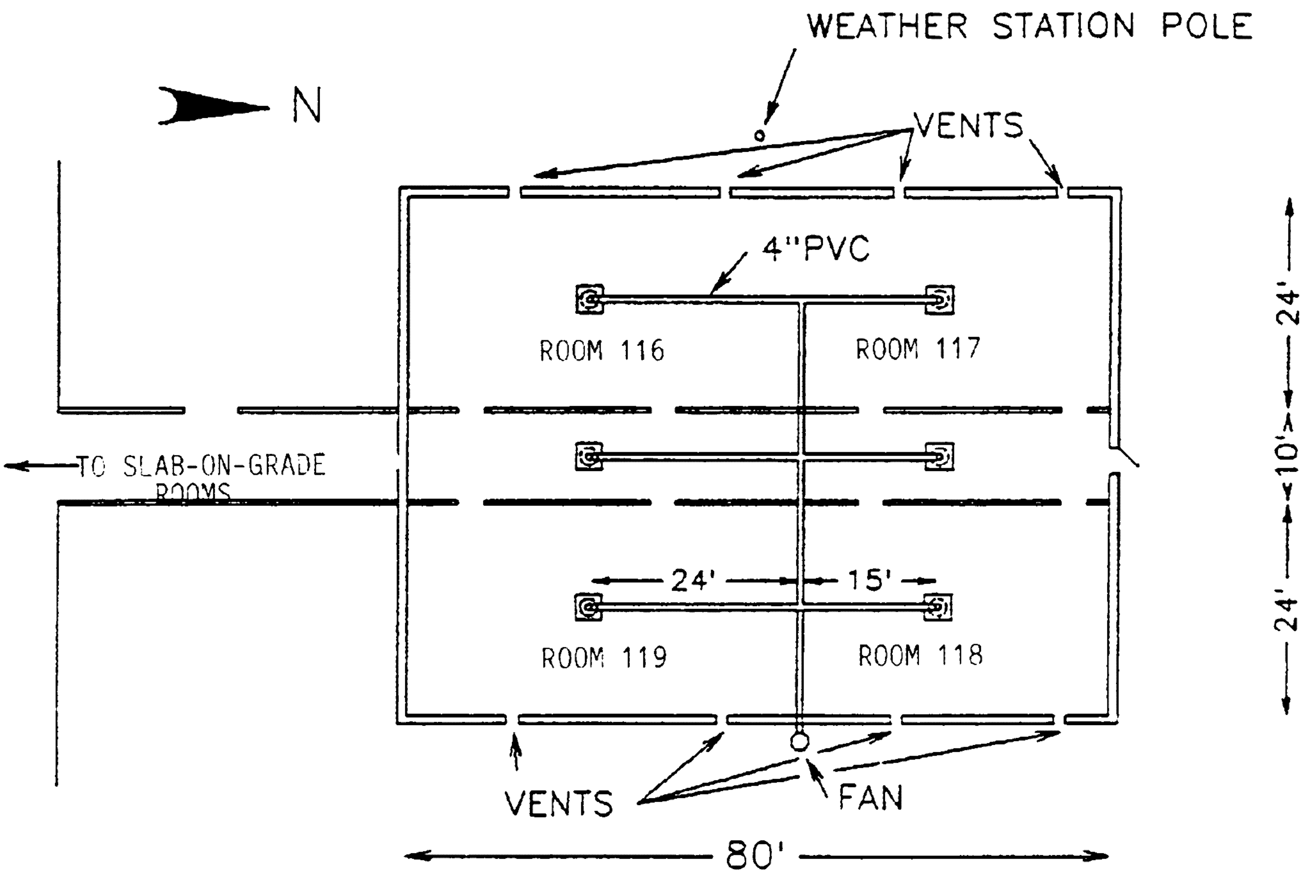


Figure 1. Plan view of the crawl space and installed ducting network.

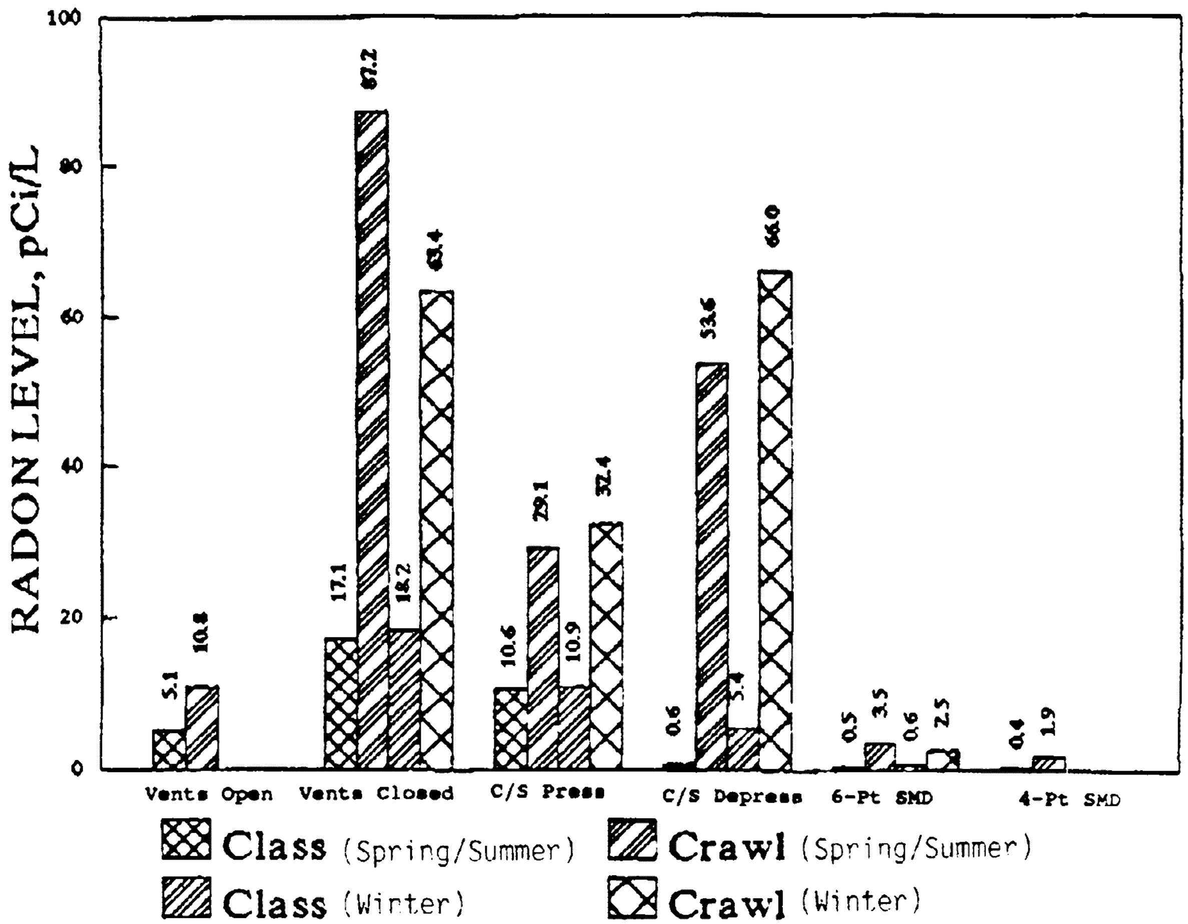


Figure 2. Average radon levels in the crawl space and in Room 116 during each of the mitigation testing periods (both spring/summer and winter).

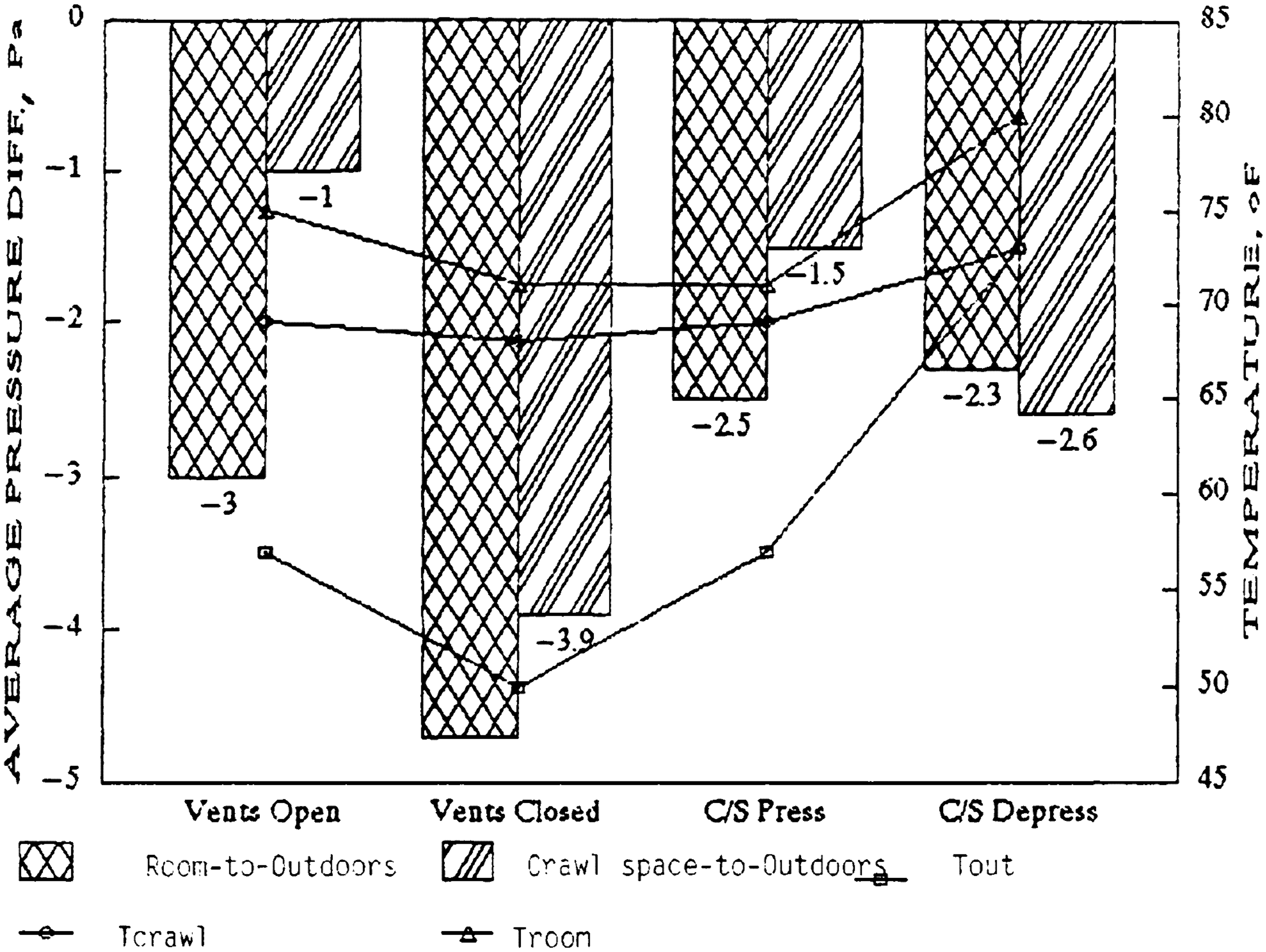


Figure 3. Average pressure differences between both the crawl space and outdoors and Room 116 and the outdoors during each of the mitigation testing periods.

# HVAC SYSTEM COMPLICATIONS AND CONTROLS FOR RADON REDUCTION IN SCHOOL BUILDINGS

Kelly W. Leovic, D. Bruce Harris, and Timothy M. Dyess
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

Bobby E. Pyle
Southern Research Institute
Birmingham, AL 35255

Tom Borak
Western Radon Regional Training Center
Ft. Collins, CO 80523

Dave W. Saum
Infiltec
Falls Church, VA 22041

## 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.

#### HVAC System Description

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.

HVAC System Description

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.

Results of Initial Measurements

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 | | | | | |
|---|---|---|---|---|---|---|---|
| | Outdoor | Classrooms | | Boiler Room | | Return Air Duct | |
| Dates | 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 | | | | |
| 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

| | Unit Ventilator Speed Setting: | | | |
|---|---|---|---|---|
| Outdoor Air Damper Position | 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 | | | | |
| 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)

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 | -0.001 | -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 | 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."

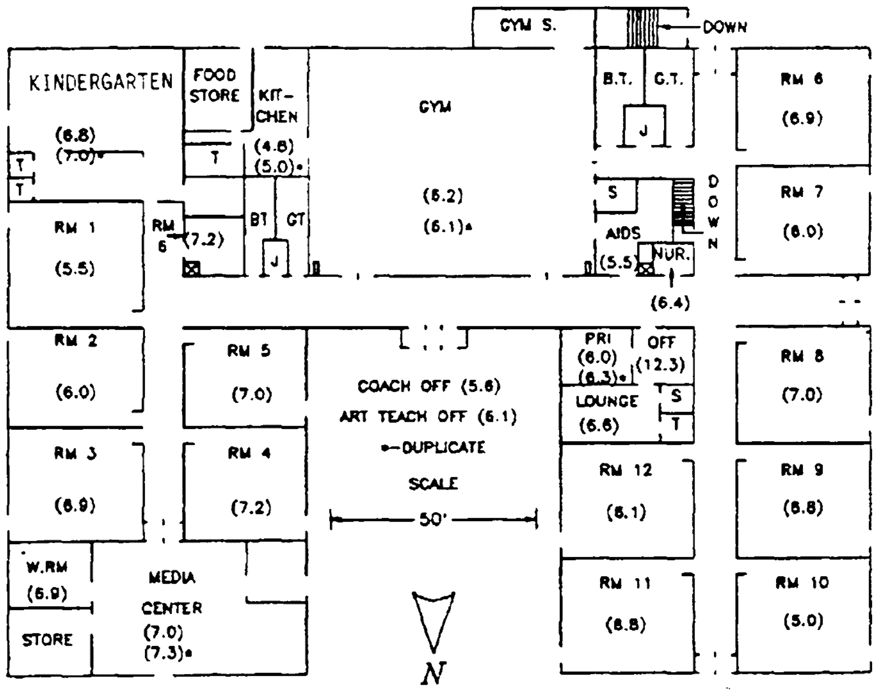


Figure 1. Results of January 1990 radon measurements in Colorado school, pCi/L.

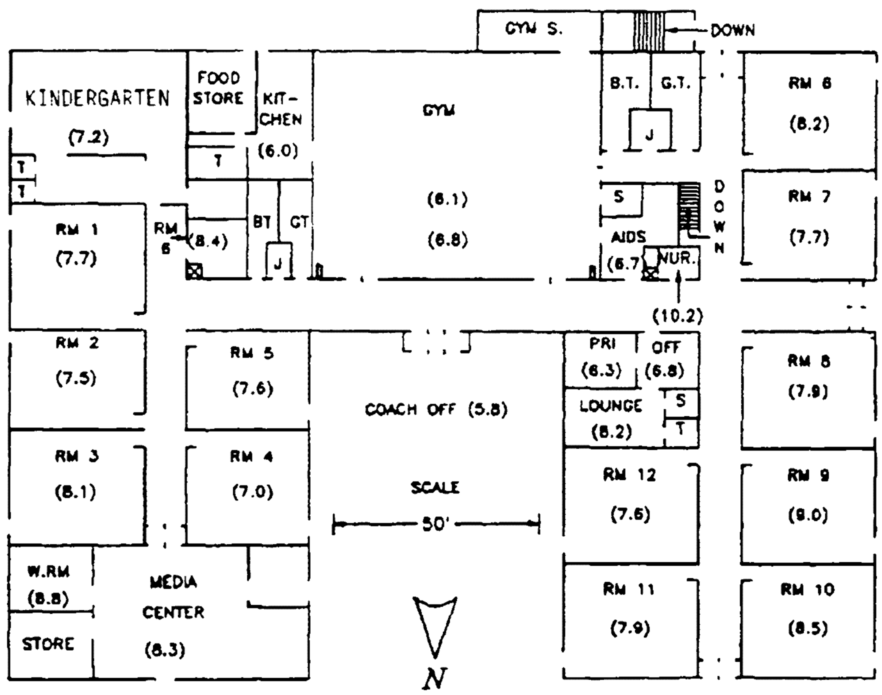


Figure 2. Results of February 1990 radon measurements in Colorado school, pCi/L

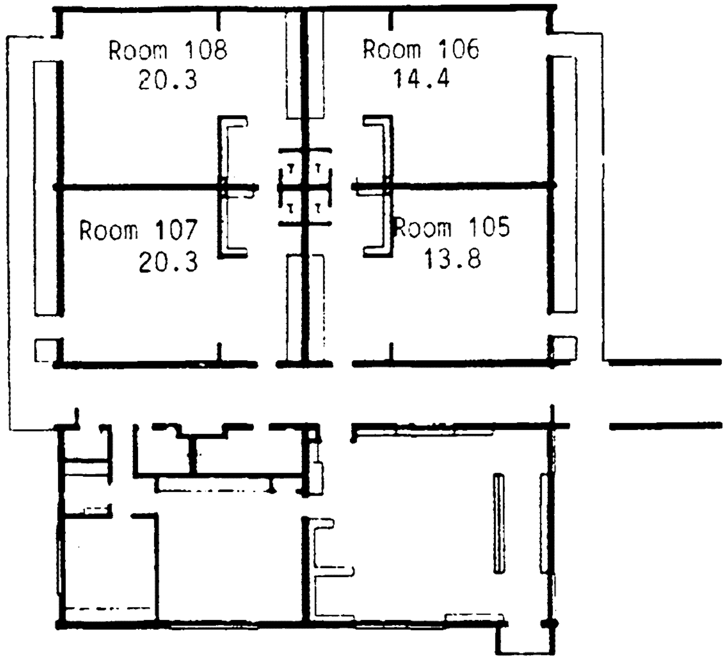


Figure 3. Results of initial radon measurements in wing of Maryland school, pCi/L.

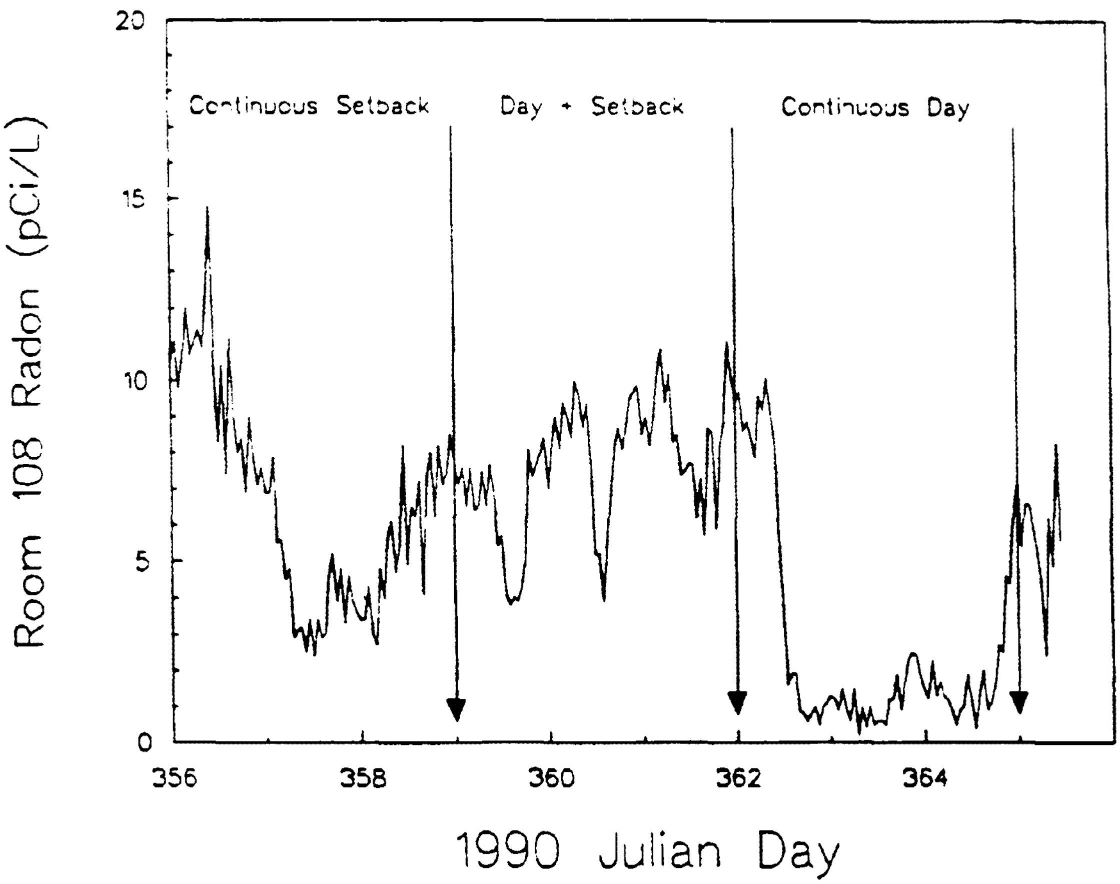


Figure 4. Continuous radon measurements in Maryland school.

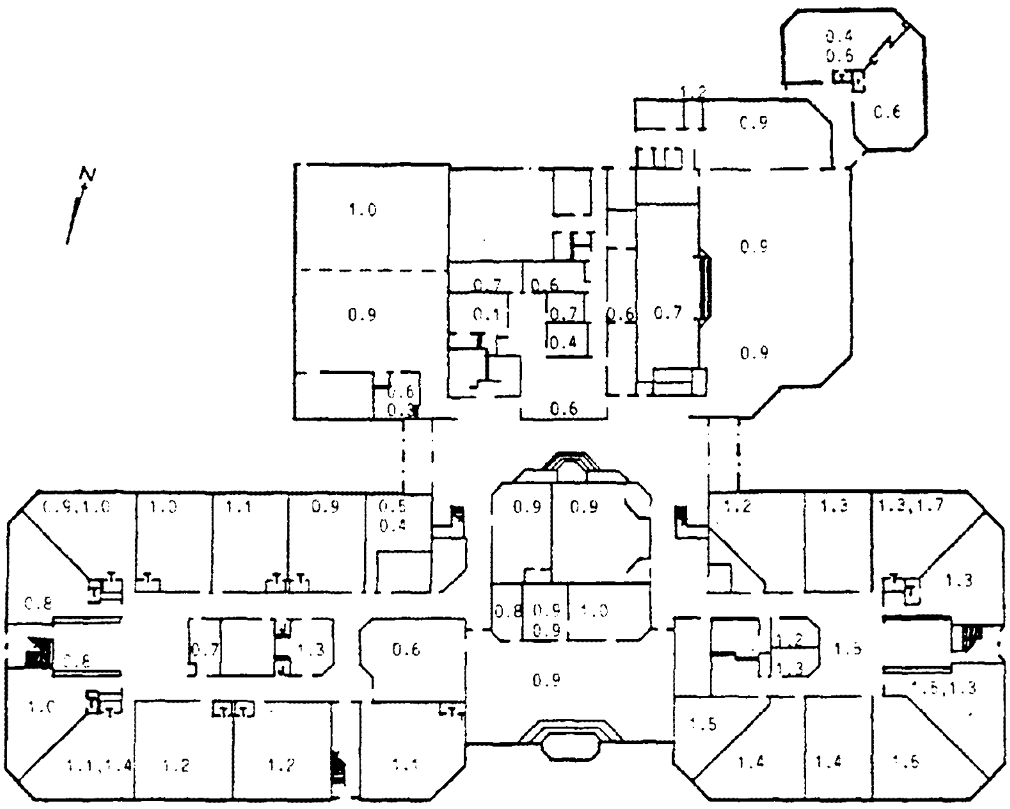

Figure 5. Results of October 1988 radon measurements in Virginia school, pCi/L

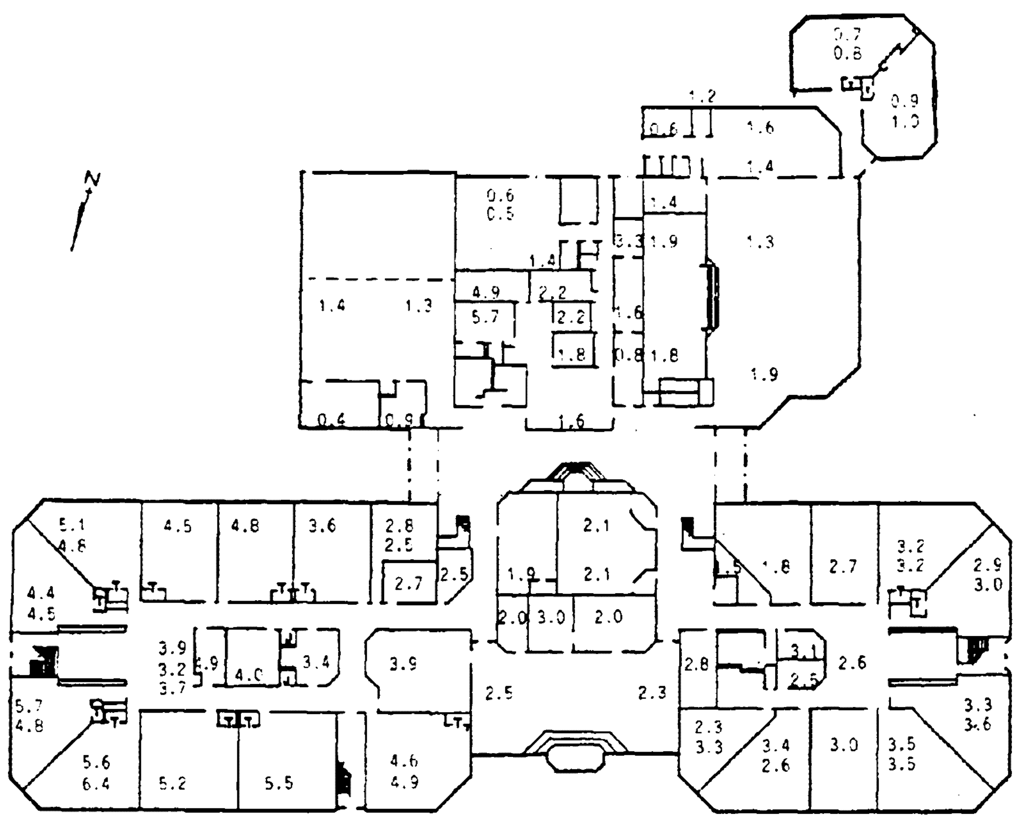

Figure 6. Results of December 1990 radon measurements in Virginia school, pCi/L.

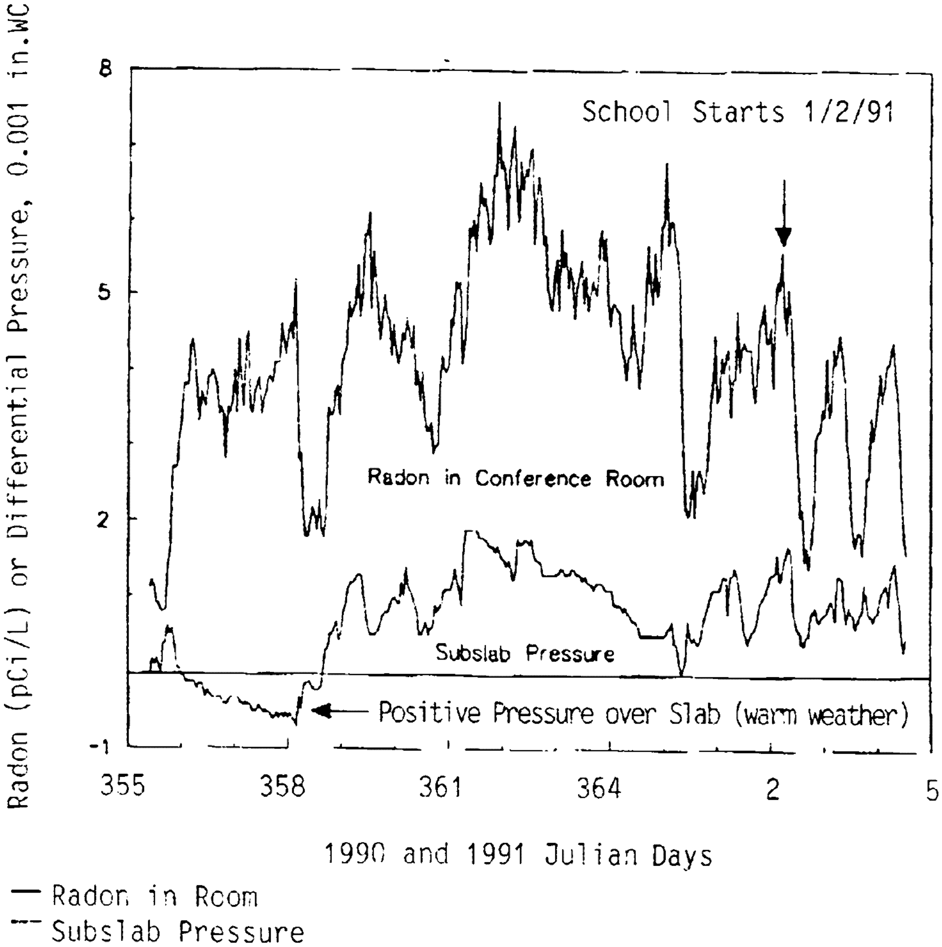


Figure 7. Continuous radon and differential pressure in Virginia school.

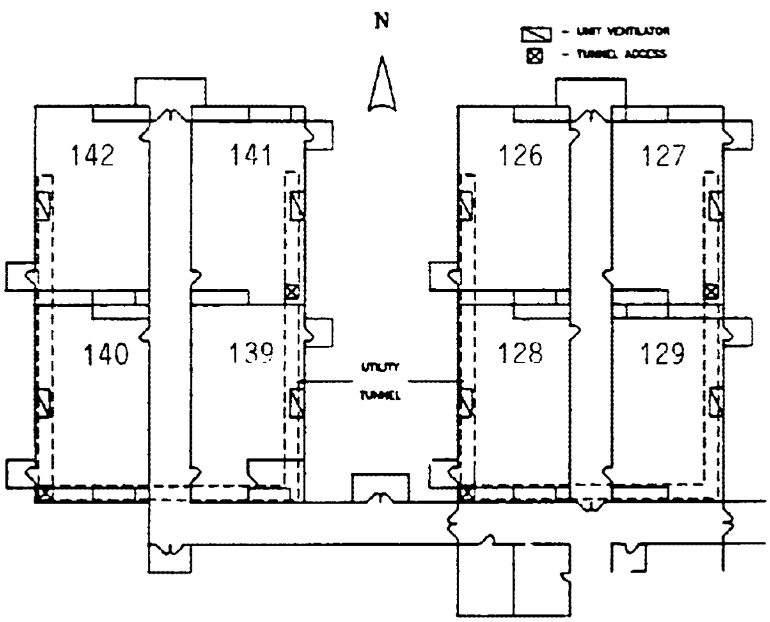


Figure 8. Partial floorplan showing utility tunnel and room locations in Washington school.

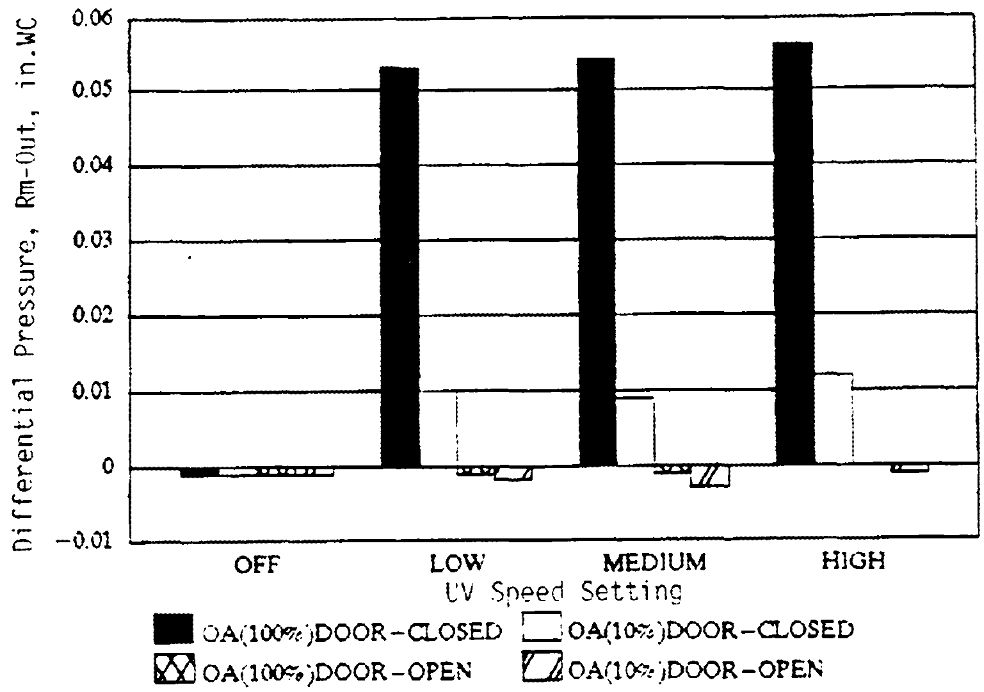


Figure 9. Differential pressure measurements in Room 139, August 1990.

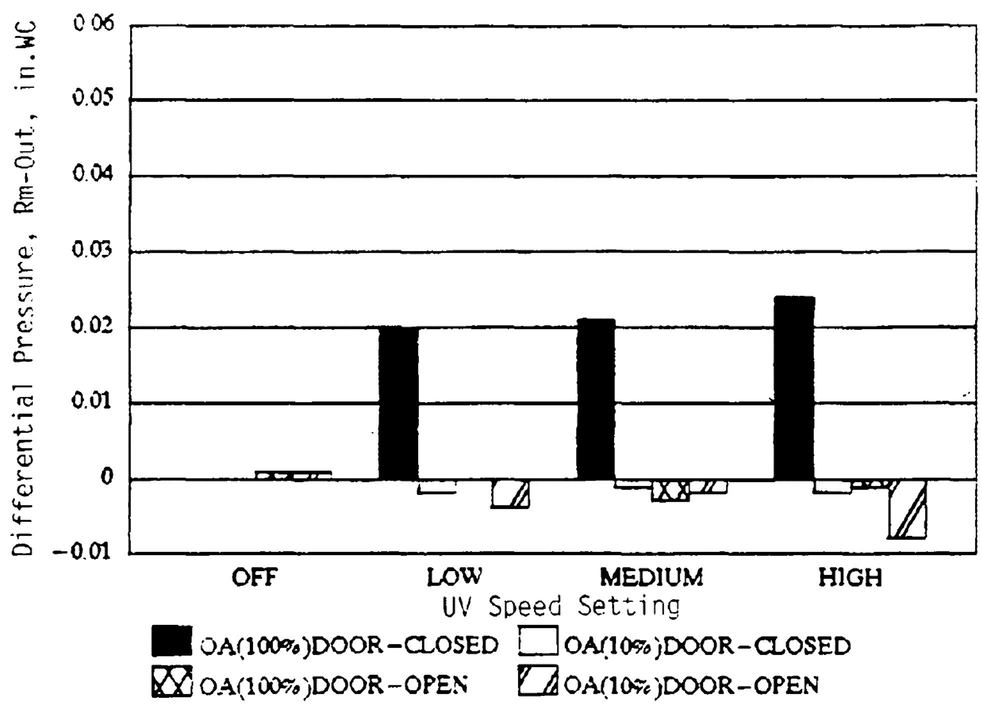


Figure 10. Differential pressure measurements in Room 140, August 1990.

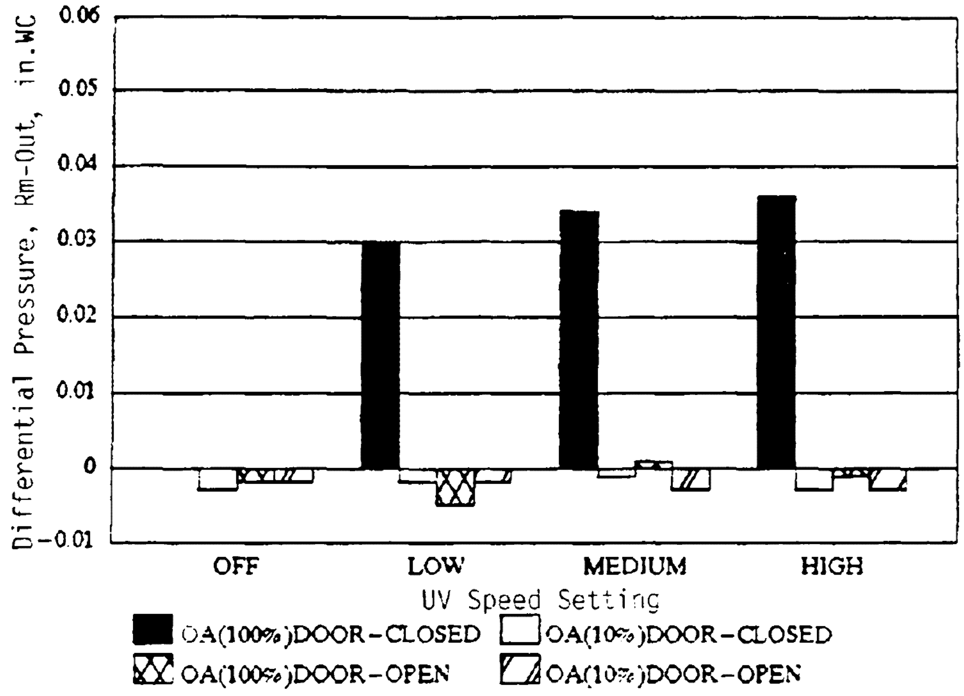


Figure 11. Differential pressure measurements in Room 141, August 1990.

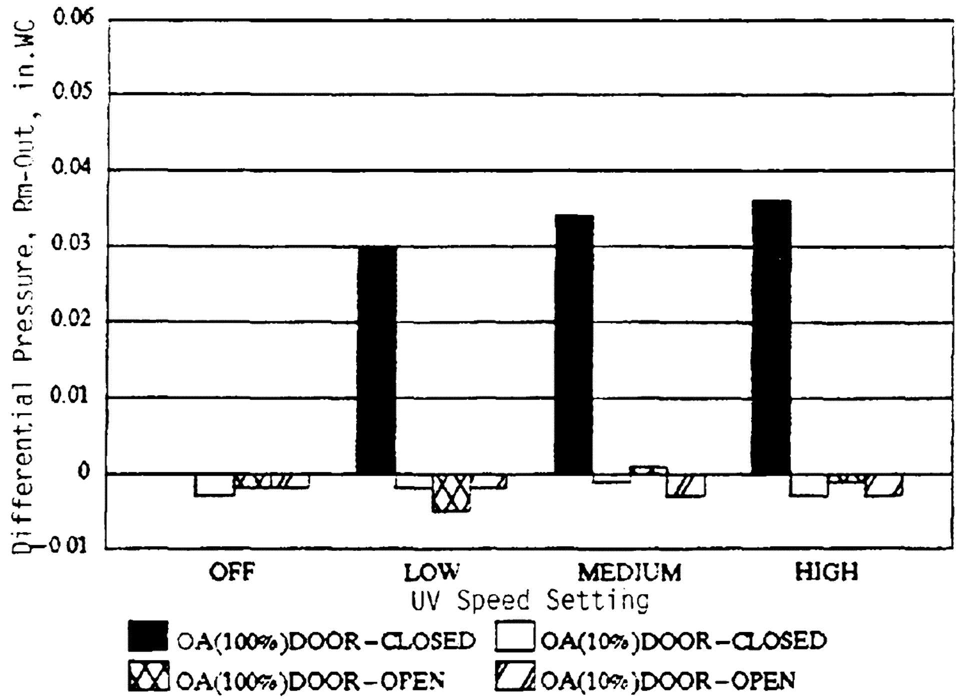


Figure 12. Differential pressure measurements in Room 142, August 1990.

# RADON DIAGNOSIS IN A LARGE COMMERCIAL OFFICE BUILDING

David Saum and Marc Messing
Infiltec
Falls Church, VA 22041

## 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 | Test Type and Date: 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) |
|---|---|---|---|---|---|---|---|
| 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

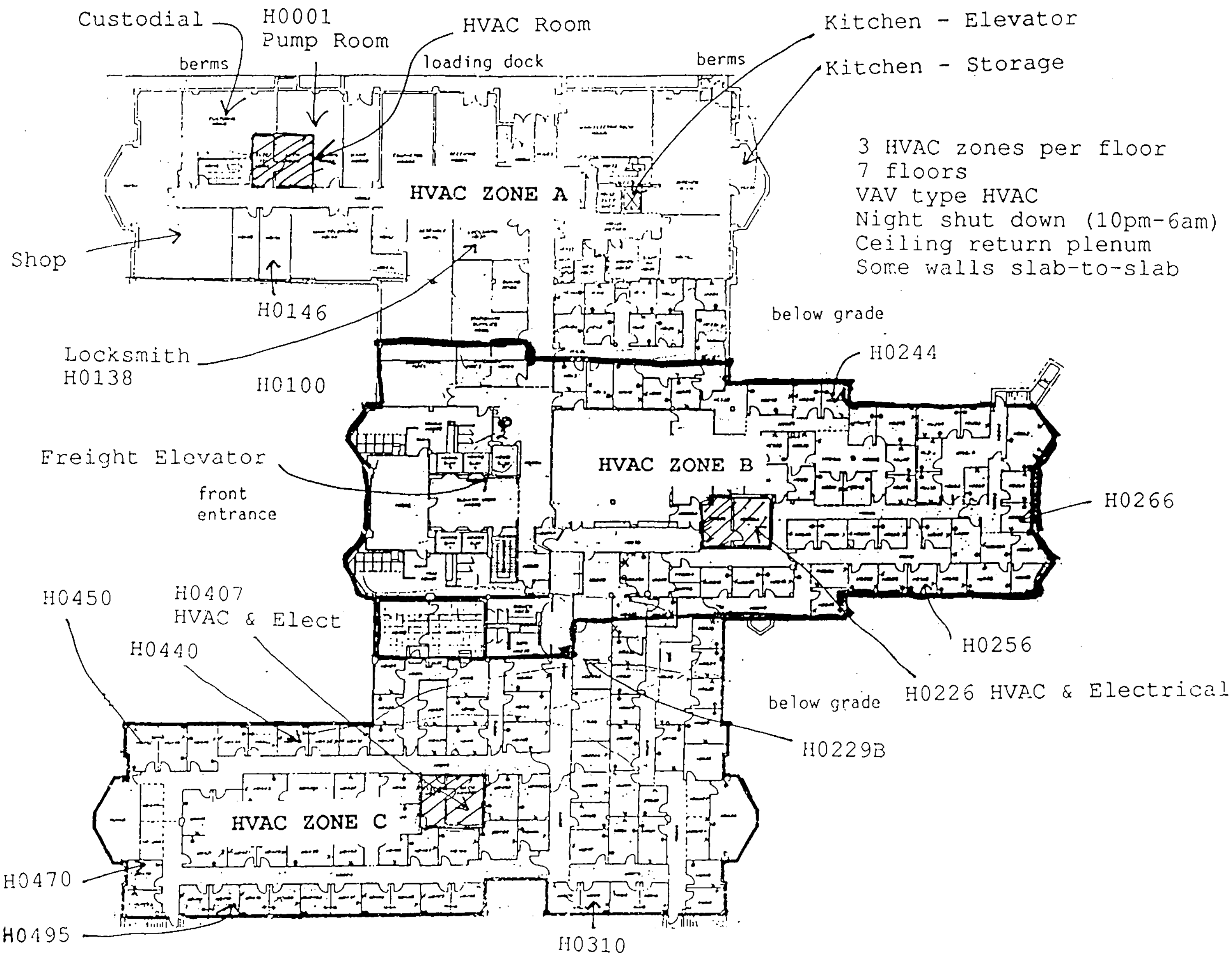


Figure 1 Basement Plan of Building

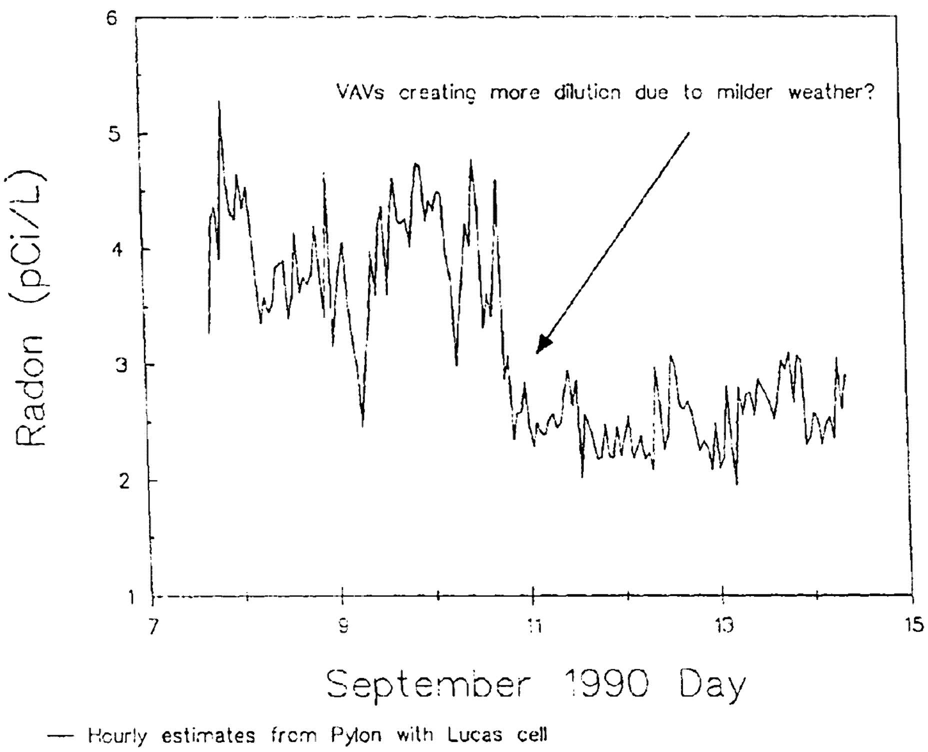


Figure 2 Continuous Radon in Zone B, Room H0226

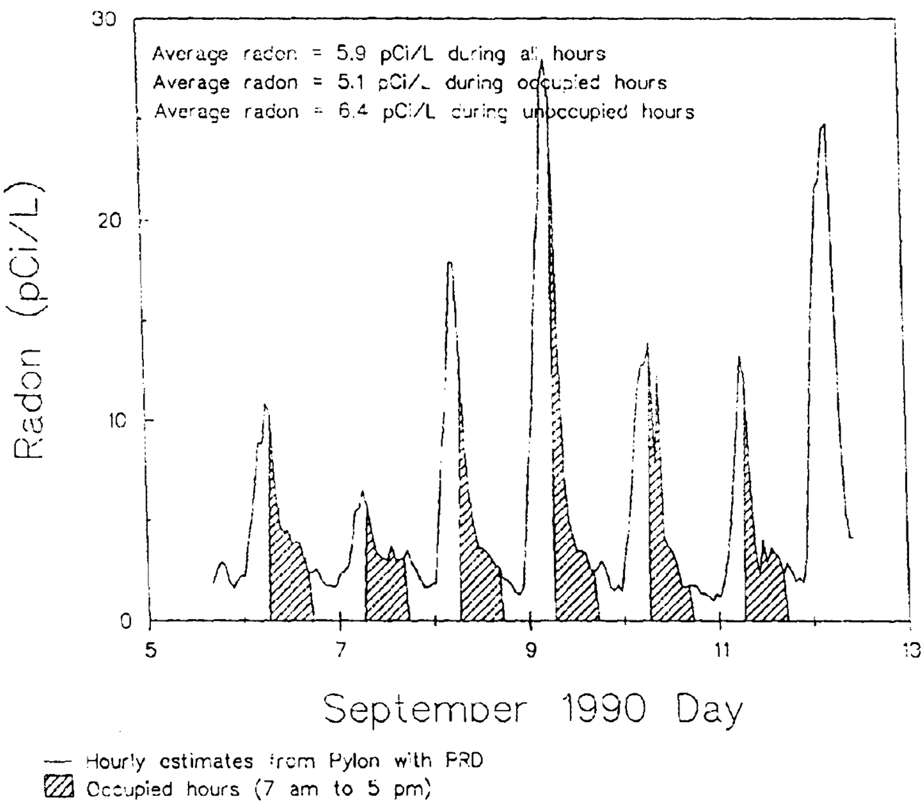


Figure 3 Continuous Radon in Zone A, Shop Room

Pressure Across Slab
(measured through drilled hole)

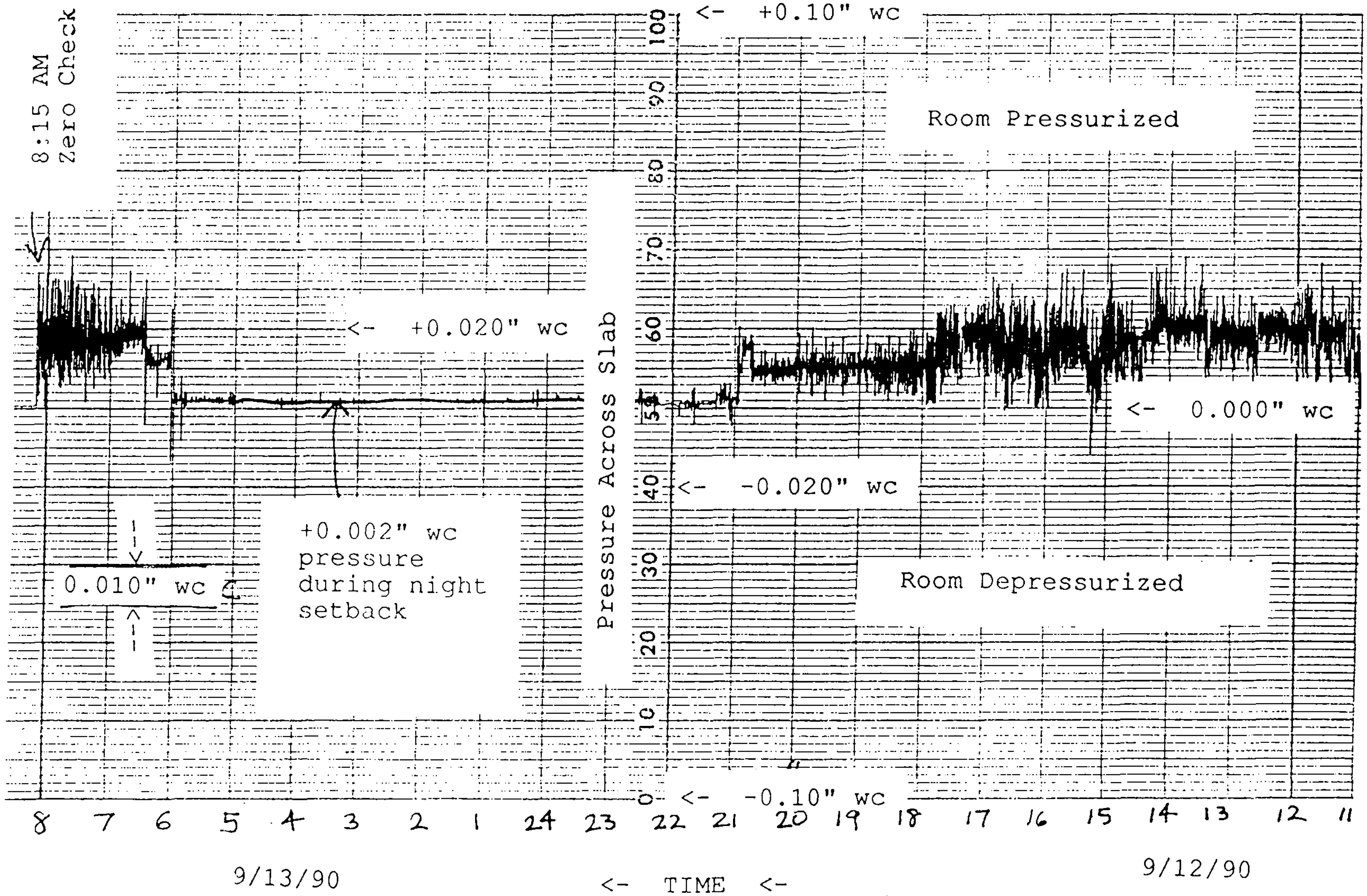


Figure 4 Continuous Pressure in Zone A, Shop Room

Pressure Across Slab
(measured through drilled hole)

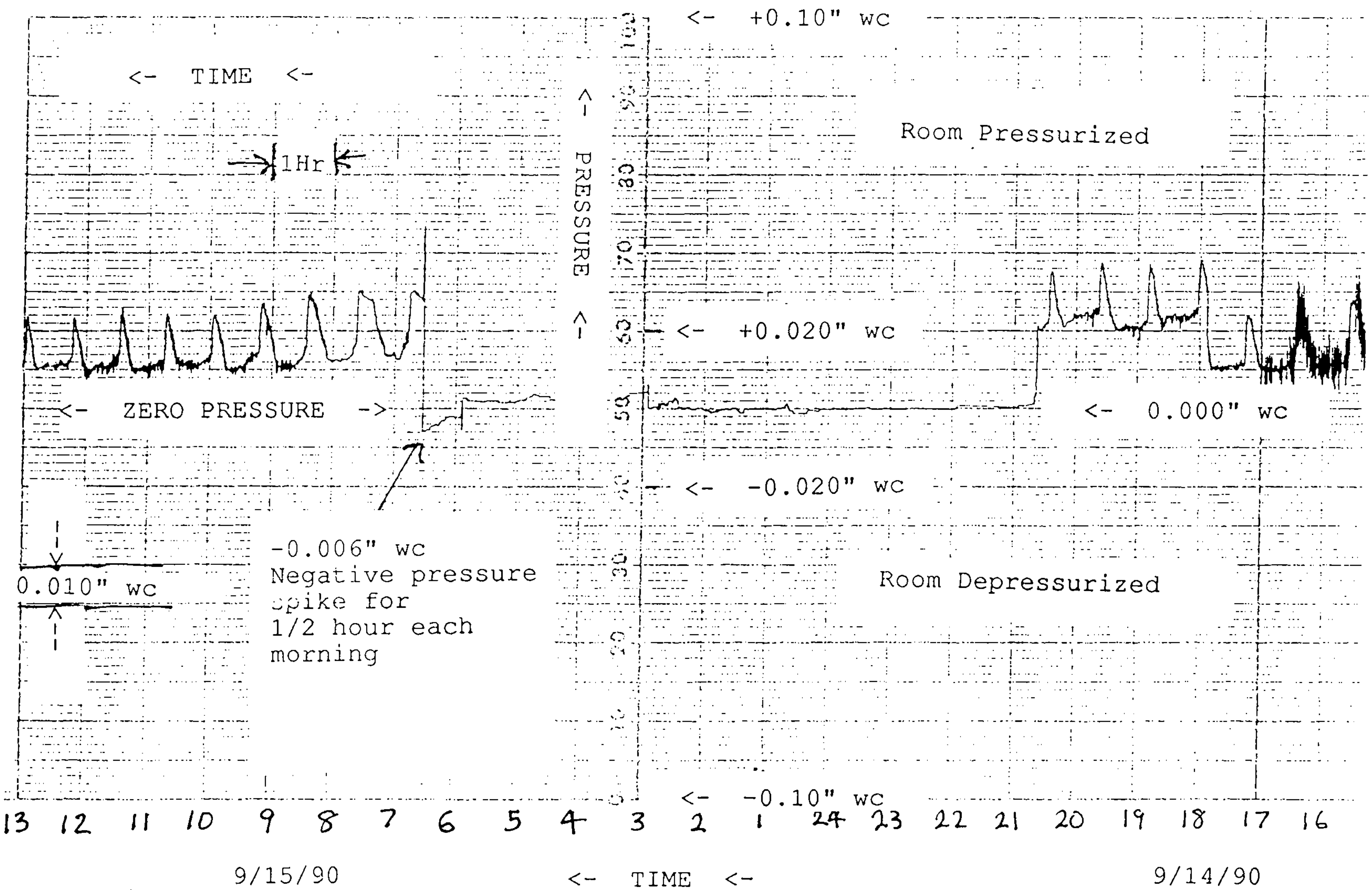


Figure 5 Continuous Pressure in Zone B, Room H0226

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

Alfred B. Craig, Kelly W. Leovic,
and D. Bruce Harris
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

## 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.

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

by: Alfred B. Craig, Kelly W. Leovic,
and D. Bruce Harris
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

## 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.

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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

(*)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.

## REFERENCES


1. Craig, A.B., K.W.Leovic, D.B. Harris, and B.E. Pyle, Radon Diagnostics and Mitigation in Two Public Schools in Nashville, Tennessee. Presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 19-23, 1990.

2. Gadsby, K.J., T.A. Reddy, D.F. Anderson, R. Gafgen, and A.B. Craig, The Effect of Subslab Aggregate Size on Pressure Field Extension. To be given at the 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, April 2-5, 1991.


## 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 | $m^3$s |
| ft | 0.30 | m |
| $ft^2$ | 0.093 | $m^2$ |
| HP | 7.46 | W |
| in. | 0.025 | m |
| in. WC | 249 | Pa |

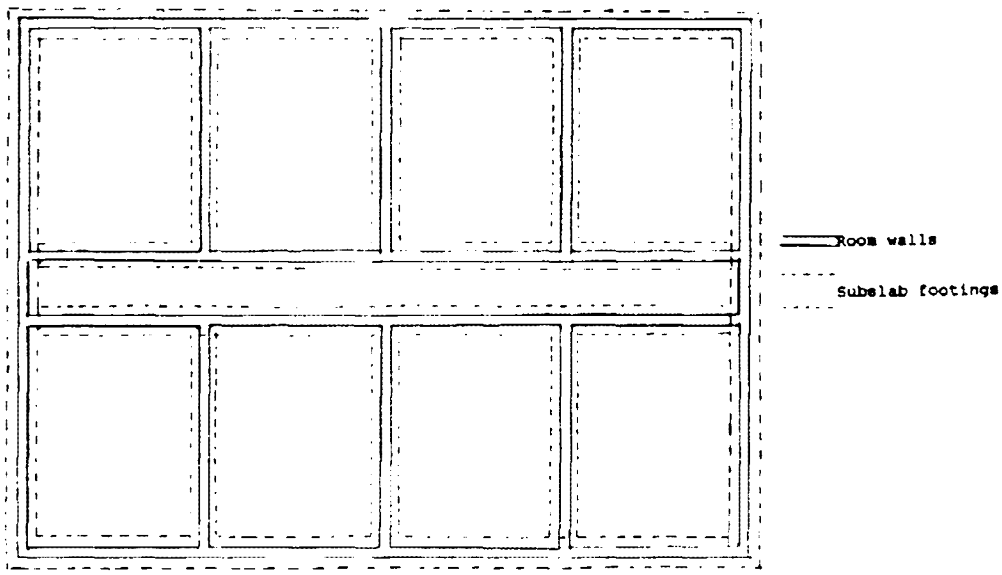


Figure 1. All walls are load-bearing.

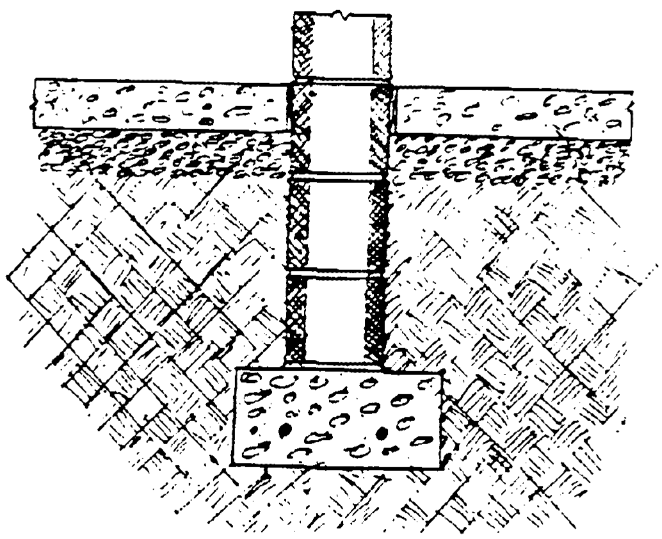

Figure 2. Section of load-bearing wall.

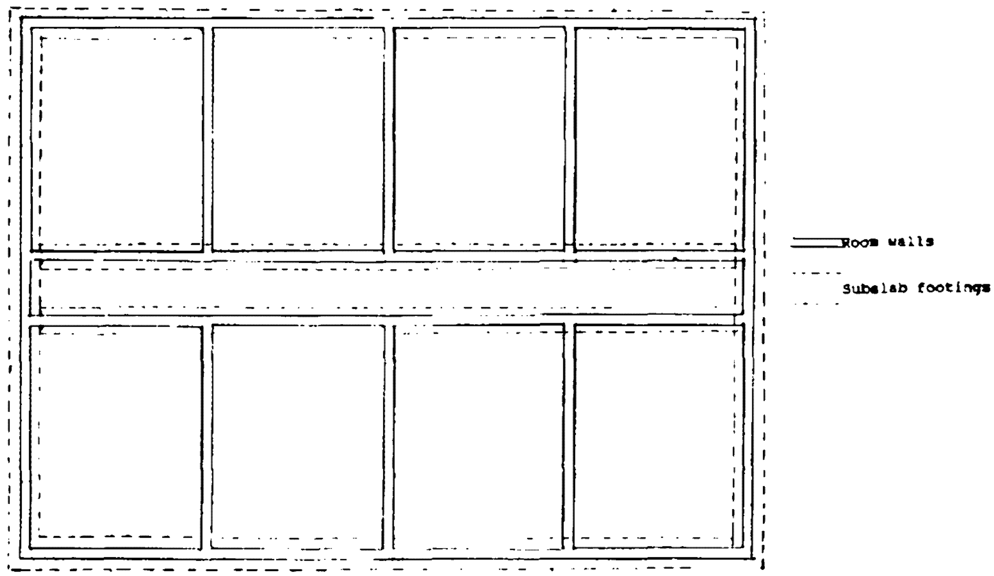


Figure 3. Hall and outside walls are load-bearing.

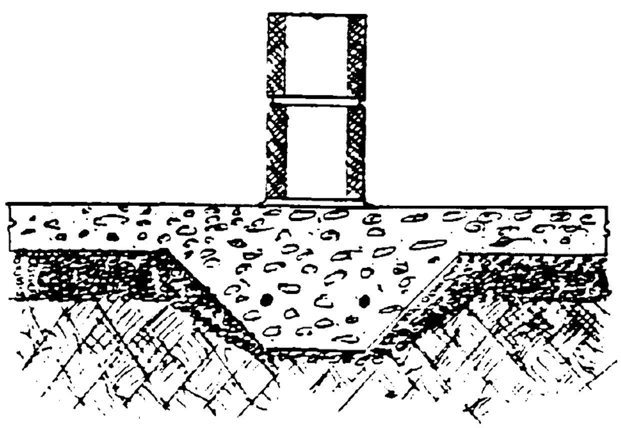

Figure 4. Section of wall resting on thickened slab footing.

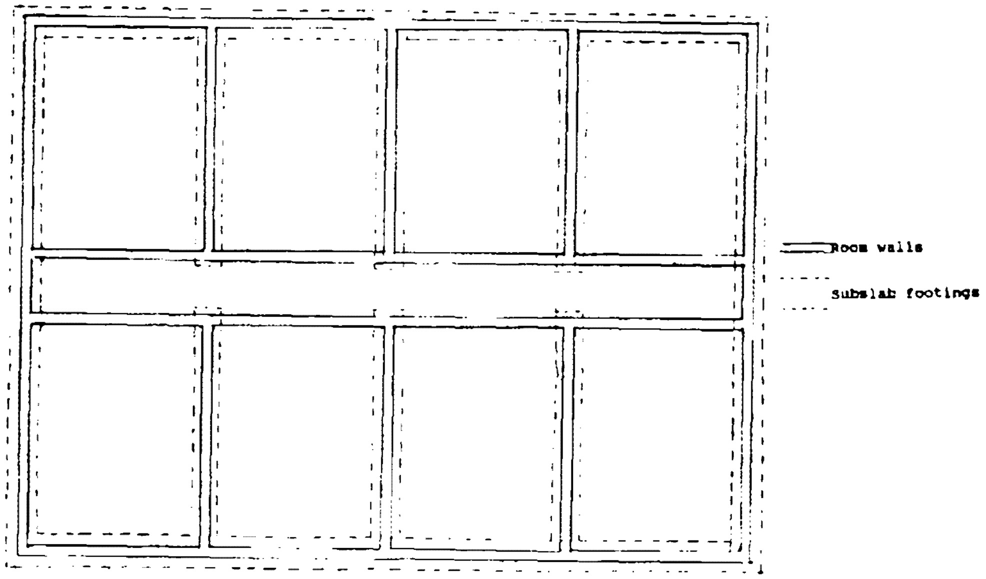


Figure 5. Walls between rooms and outside walls are load-bearing.

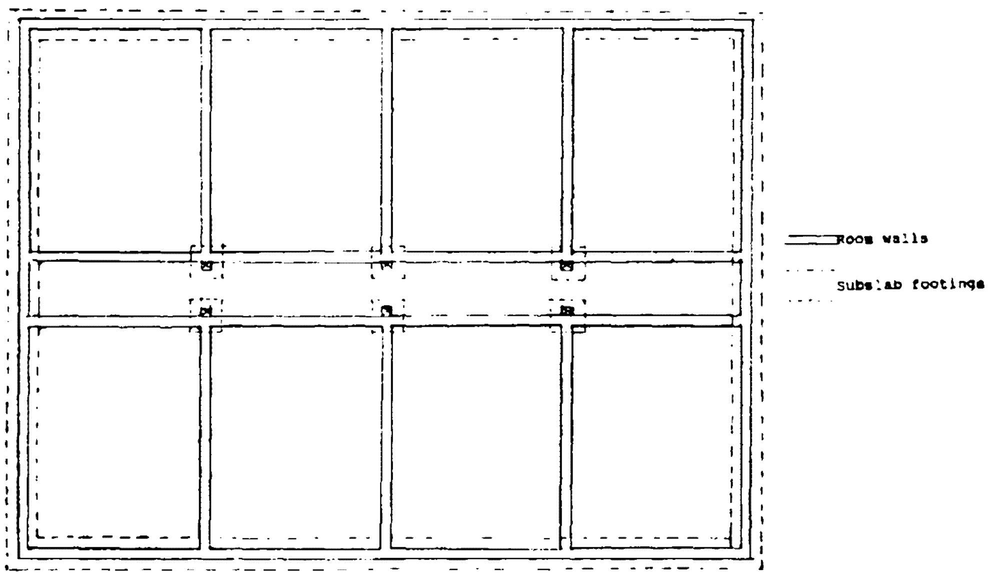


Figure 6. Outside walls and posts are load-bearing.

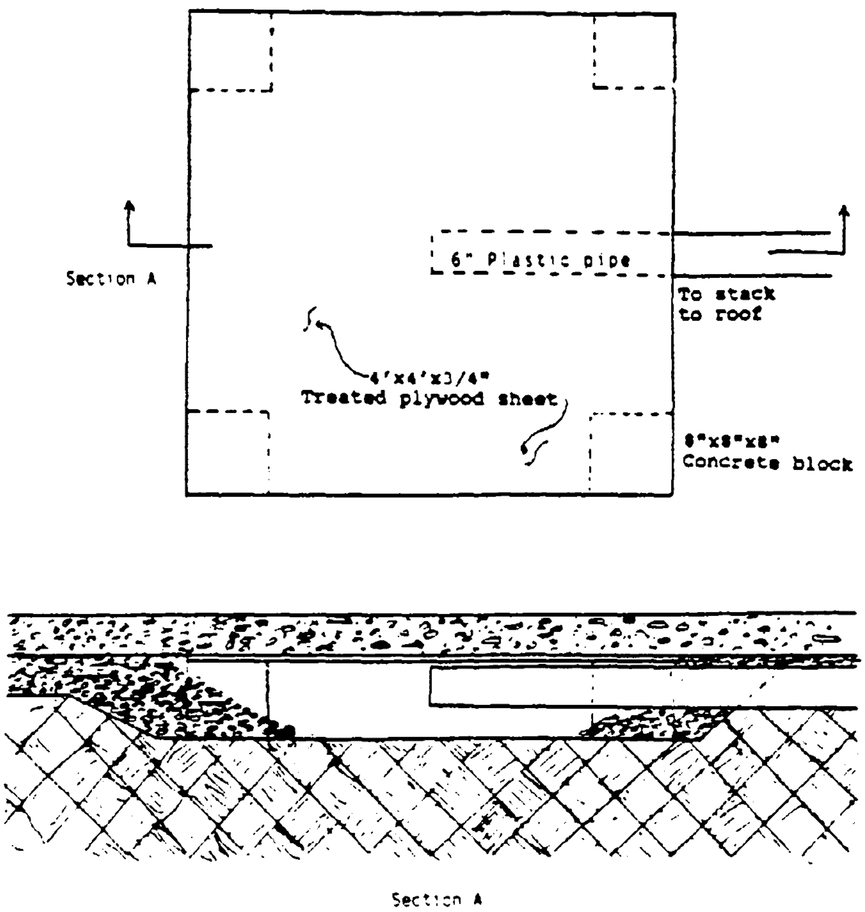


Figure 7. Design for large suction pit.

## TABLE 1. KANALFLAKT FAN PERFORMANCE

| MODEL | HP | FAN RPM | 0 | 1/8 | 1/4 | 3/8 | 1/2 | 3/4 | 1 | 1-1/2 | 2 | PIPE DIA. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | AIR FLOW (cfm) VS STATIC PRESSURE (in. WC) | | | | | | | | | |
| 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" |