United States
Environmental Protection
Agency

Air and Energy Engineering
Research Laboratory
Research Triangle Park NC 27711

April 1991

Research and Development

EPA

The 1991 International Symposium on Radon and Radon Reduction Technology:

Preprints - Additional Papers Sessions I - X

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

The 1991 International Symposium on Radon and Radon Reduction Technology

Additional Papers

Table of Contents

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

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

ABSTRACT

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

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

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

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

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

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

The activity-aerosol size distribution refers to the physical size distribution of the particles containing the alpha activity. The term "unattached fraction" has historically been applied to progeny existing as ions, molecules, or small clusters; the "attached fraction" designates progeny attached to ambient particles (6). Using newer methods for characterizing activity-aerosol size distributions, the unattached fraction has been identified as ultrafine particles in the size range of 0.5 to 3.0 nm (6). Typically, mines have higher aerosol concentrations than homes and the unattached fraction would be expected to be higher in homes than in mines. Because of differing sources of particles in the two environments, aerosol size distributions could also plausibly differ between homes and mines.

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

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

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

THE COMMITTEE'S APPROACH

To address the charge of undertaking further dosimetric modeling, the committee obtained data on the various parameters included in dosimetric lung models that contributed to uncertainty in assessing the risk of indoor radon. The committee not only reviewed the literature, but obtained recent and unpublished information from several investigators involved in relevant research. After completing this review, the committee selected values for parameters in dosimetric models that it judged to be best supported by the available evidence. The committee then utilized a dosimetric model, developed in part by the Task Group of the International Commission for Radiological Protection, to compare exposure-dose relations for exposure to radon progeny in homes and in mines. While the report provides the exposure-dose figures, the committee expressed its principal findings as a ratio, termed K in the BEIR IV report (1). K, a unitless measure, represents the quotient of the dose of alpha energy delivered per unit of exposure in a home to the dose per unit exposure for a male miner exposed in a mine. If the K factor exceeds unity, the delivered dose per unit exposure is greater indoors whereas if it is less than unity, the delivered dose per unit exposure is less indoors.

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

THE COMMITTEE'S FINDINGS

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

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

Across the wide range of exposure conditions and exposed persons considered by the committee, most values of K were below unity (Table 4). For both secretory and basal cells, K values indicated lesser doses of alpha energy per unit exposure, comparing exposures of infants, children, men and women in homes with exposures of male miners underground. While the highest values of K were calculated for children, the values for children did not exceed unity, suggesting that children exposed to radon progeny are not at greater risk for lung cancer on a dosimetric basis.

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

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

SUMMARY

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

REFERENCES

1. National Research Council (NRC). 1988. Health Risks of Radon and Other Internally Deposited Alpha-Emitters. BEIR IV. Committee on the Biological Effects of Ionizing Radiation. Washington, D.C.: National Academy Press.

2. Samet, J.M. Radon and lung cancer. J Natl Cancer Inst. 81: 745-757, 1989.

3. Lubin, J.H. Models for the analysis of radon-exposed populations. Yale J Biol Med. 61: 195-214m 1988.

4. National Council on Radiation Protection and Measurements (NCRP). 1984b. Evaluation of Occupational and Environmental Exposure to Radon and Radon Daughters in the United States. NCRP Report 78. Bethesda, MD: National Council on Radiation Protection and Measurements.

5. International Commission on Radiological Protection (ICRP). 1987. Lung Cancer Risk from Indoor Exposures to Radon Daughters. ICRP Publ. No. 50. Oxford: Pergamon Press.

6. National Research Council. Comparative dosimetry of radon in mines and homes. Panel on dosimetric assumptions affecting the application of radon risk estimates. National Academy Press, Washington, D.C., 1991.

7. George, A.C. and Breslin, A.J. Deposition of radon daughters in humans exposed to uranium mine atmospheres. Health Phys. 17: 115-124, 1969.

8. Cheng, Y.S., Swift, D.L., Su, Y.F. and Yeh, H.C. Deposition of radon progeny in human head airways. In: Inhalation Toxicology Research Institute Annual Report 1988-89. Lovelace Biomedical and Environmental Research Institute, Albuquerque, NM, 1989. LMF-126.

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

<u>Physical Factors</u>

Aerosol characteristics: Greater concentrations in mines; differing size distributions

Attached/unattached fractions: Greater unattached fraction in homes

Equilibrium of radon/decay products: Highly variable in homes and mines

<u>Activity Factors</u>

Amount of ventilation: Probably greater for working miners than for persons indoors

Pattern of ventilation: Patterns of oral/nasal breathing not characterized, but mining possibly associated with greater oral breathing

<u>Biological Factors</u>

Age: Miners have been exposed during adulthood; entire spectrum of ages exposed indoors

Gender: Miners studied have been exclusively male; both sexes exposed indoors

Exposure pattern: Miners exposed for variable intervals during adulthood; exposure is lifelong for the population

Cigarette smoking: The majority of the miners studied have been smokers; only a minority of U.S. adults are currently smokers

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

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

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

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

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

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

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

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

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

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

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

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

*Taken from Table 5-1 in reference 6.

THE NEED FOR A COORDINATED INTERNATIONAL ASSESSMENT OF THE RADON PROBLEM

F. Steinhäusler
International Atomic Energy Agency
Vienna

INTERNATIONAL SYMPOSIUM ON
RADON AND RADON REDUCTION TECHNOLOGY
"A New Decade of Progress"

April 2-5, 1991

Philadelphia, Pennsylvania, USA

7695t

The Need for a Coordinated International Assessment of the Radon Problem

F. Steinhäusler
International Atomic Energy Agency
Division of Nuclear Safety
P.O. Box 100, A-1400 Vienna, Austria

1. The radon problem - an issue of growing awareness

Radon is a natural pollutant which has been part of the human environment through all stages of evolution. However, the level of Rn-exposure has undergone various "technological enhancements" from the pre-historic days of taking up a habitat inside a cave dwelling, to the present day energy-efficient dwellings with ventilation rates below 0.3 air changes/hour.

As early as in the 1950's and 1960's individual scientists have emphasized the overriding dose contribution from radon (Rn) and its short-lived decay products (Rn-d) in comparison to those doses that the majority of their colleagues were dealing with at the time, i.e. resulting from the nuclear fuel cycle or nuclear weapon testing programmes (Hu 56, Po 65).

In the 1970's and the 1980's two series of scientific meetings stressed increasingly the importance of the radon issue, published in the form of proceedings of the US-DOE sponsored International Symposium Series "The Natural Radiation Environment", Houston (USA) and of the International Specialist Meetings held in Pocos de Caldas (Brazil), Bombay (India), Rome and Capri (Italy). During this period the first large scale national Rn surveys were conducted and regulatory guidelines issued in Scandanavia and Canada.

At the international level the Organization for Economic Cooperation and Development, Nuclear Energy Agency (OECD-NEA, Paris, France) and the Commission of the European Communities (CEC, Brussels, Belgium) reviewed all available Rn related information on metrology and dosimetry in the first half of the 1980's (OE 83, OE 85). Furthermore, CEC-NEA jointly initiated the International Intercomparison and Intercalibration Programme (IIIP), which has now been taken under the auspices of the IAEA. The CEC took a leading role in European research related to the Natural Radiation Environment (NRE) in general and in the Rn-issue in particular and supported several national programmes among its Member States (CE 80). In the second half of the 1980's the largest national Rn-research and survey programme so far has been undertaken in the USA (Co89) under the leadership of the Department of Energy (DOE) and the Environmental Protection Agency (EPA).

All internationally available information has been compiled regularly in the UNSCEAR reports. Over the past thirty years the previously seemingly invariable "constant" of 1 mSv for the average annual effective dose from all NRE sources was increased to 2.4 mSv (UN 88).

In view of the above 30+ years of evidence it is difficult to understand the statement made by the Health Physics Society in 1991, itself a most valuable source for radon-related data, ... "it was not until recently that it was realized that the largest radiation exposures received by most individuals come from the natural sources of radiation, primarily radon and its radioactive decay products " (HP91).

2. The global dimension of the radon problem

At all times everybody is exposed to radon (Rn) and its decay products (Rn-d) anywhere on earth. Therefore this topic warrants a global approach on the research and the regulatory level. In the following section some of the major international and national activities in response to the increasing significance of the Rn-problem are discussed.

2.1. IAEA-CEC coordinated research

In response to the requests from Member States of the International Atomic Energy Agency (IAEA, Vienna, Austria) and in recognition of the global concern over the Rn issue the IAEA, jointly with the CEC, initiated the Coordinated Research Programme (CRP) on "Radon in the Human Environment". The World Health Organization (WHO, Geneva, Switzerland) and the International Cancer Research Agency (IARC, Lyon, France) agreed to provide logistic support in all areas related to the assessment of potential health effects. The potential for US-EPA and US-DOE involvement in Quality Assurance Programmes and risk assessment studies of this CRP is currently being explored.

Altogether 111 projects from five continents have been recommended for a phase-wise inclusion in the CRP. In addition, 25 CEC-approved projects are part of the CRP.

The objective of the CRP is to coordinate international research efforts aimed at the quantification of the impact of environmental Rn on man. Four areas are emphasized:

a) international intercalibration and intercomparison of Rn-measurement technology;

b) standardization of large scale Rn-survey techniques;

c) institutionalised exchange of information on Rn-levels, dosimetric methods and associated risk assessment, and mitigation techniques through Research Coordination Meetings under the auspices of the IAEA;

d) establishment of an international databank on Rn. This databank would enable members of the international scientific community and national regulatory agencies to obtain structured access to the results obtained from the multiple large scale Rn-surveys, which will be performed over the next five years mainly in the USA, Canada, Africa, Europe and Asia, Provided that the input data have fulfilled certain criteria, these data sets can be used for follow-up research, ranging from optimisation of technical remedial measures to improved lung cancer risk assessment. Finally such a database facilitates the exchange of scientific and technical know-how from developed to developing countries.

The implementation of the first phase of the CRP started in 1990 by awarding 12 Research Contracts and 37 Research Agreements (Fig. 1). The second phase, concerning the acceptance of the remaining projects, is scheduled for 1992.

The CRP-Quality Assurance Programme (QAP) is an essential element of the CRP (Fig. 2). For this purpose it is intended to invite the participants in the former OECD-NEA/CEC International Intercalibration and Intercomparison Programme (IIIP), as they are: ARL (Melbourne, Australia), NRPB (Didcot, UK), EML (New York, USA) and US-BM (Denver, USA). These laboratories, well-renowned in Rn metrology, are able to act as "Reference Centres" for designated "Regional Coordinated Centres": Ministry of Public Health (Beijing, China P.R.) for the Asian-Pacific region; Institute of Radiation Protection and Dosimetry (Rio de Janerio, Brazil) for the South American region; Ghana Atomic Energy Commission (Legon, Ghana) for the African region; Institute of Atomic Physics (Sofia, Bulgaria) for the Eastern European region and Middle East; Centre of Radiation Hygiene (Prague, CSFR) for the remaining European regions.

Quality control is maintained by the interchange of Rn-detectors between Regional Coordination Centres and Reference Centres. This will involve an initial calibration and subsequent qualifying tests. The aim of the initial calibration is the establishment of calibration factors, lower limit of detection, reproducibility, accurance and linearity of the detectors used in the CRP. An exposure test regime in a Rn-chamber will include blanks, low-, medium- and high level Rn-exposure of the detectors, taking into account different climatic exposure conditions. The analysing laboratory will be informed of the actual exposure values. For the qualifying tests CRP-participants provide detectors to a Reference Centre as above, but the analysing laboratory is not informed of the exposure levels prior to the reporting of their results. This test will be repeated annually. Pre-defined criteria for passing the test will be used, e.g. the mean value for each group of exposure category would be within ± 25% of the calibration exposure (except blanks).

Surveys will be carried out in two stages. In a pilot Rn-survey all logistic and technical components for the follow-up large scale Rn-survey are tested. Secondary aims are the training of survey personnel and the establishment of the necessary national and regional programme infrastuctures. A follow-up large scale Rn-survey is aimed at determining yearly averaged indoor Rn-values using a standardized survey protocol. Since these surveys are carried out in areas with largely different climatic and socio-economic characteristics, it is necessary for the standardized format to be adopted to the local needs.

Each participant who does not already have an established integrating Rn-detection system, is provided with:

- passive open-faced track-etch detectors (material: LR 115) for short-term integrating screening measurements (exposure period: 1 week);

- passive electric-based ion chambers (material: permanently charged Teflon material) and/or passive track-etch detectors (material: CR-39) for repeated long-term integrating measurements (exposure period: 6 months).

In the pilot-type surveys, sites are selected on a pseudo-random method, based on population distributions, in one urban and one rural community each. Detectors are distributed and collected after exposure either by mail or survey teams, following the guidelines of a standardized experimental protocol. The large scale-type surveys are population-based, with statistically chosen sampling of dwellings within each

Member State. The detailed sampling method is country-specific and takes into consideration different approaches to approximate optimal randomization. The preferred method consists of a questionnaire being mailed to randomly selected individuals, together with a pre-paid, pre-addressed envelope. Upon return of the completed questionnaires, detectors are sent to those interested parties. This approach should improve the rate of active participation and maximize detector return. Optionally, the questionnaire can be completed individually by the survey team at the time of distribution of the detector in the randomly selected dwelling.

The results of the CRP are planned to be summarized in 1995 in the form of joint IAEA/CEC publications in the IAEA Safety Series and will include a summary of: a) the practical implications of the findings of the CRP, with the emphasis on international guidance on Rn control; and, b) the results of the IIIP on Quality Control organized prior to and under this CRP.

2.2. International research activities

The international research community is currently carrying out intensive Rn-ralated research. The main activities involve about 30 European research teams collaborating within the framework of the CEC Rn-programme (Si 91), approximately 50 US-institutions engaged in Federal Rn activities in the USA and worldwide additionally approximately 100 laboratories among the other IAEA-Member States. In this section some of the main Rn-related research activities outside the USA are described (the corresponding contact persons are listed in the Appendix).

a) Research in detection and analytical methods

Development of a device for continuous Rn-measurements in water, based on an integrated Rn-deemanation device and scintillation counter (A-Pi); the use of Po 210-activity on glass surfaces as an estimator for past Rn indoor exposure (A-Sa); optimisation of passive/open alpha track etch detectors for the short and long term estimation of the Potential Alpha Energy Concentration (PAEC), including thoron (Rn 220) daughters (A-An[1]); development of a low-level continuous Rn- and thoron- PAEC monitor, using α-spectroscopic analysis of Po 218, Po 214 and Po 212 (A-Ku); optimisation of a low level environmental thoron monitor, using Po 210-deposition on a surface barrier detector in a high tension field (A-Ke); thoron detection based on flow-through scintillation cells and multiple time analysis of recorded pulse events (A-Fa); simulation of rapidly changing environmental Rn/Rn-d levels with a walk-in type test facility (A-Sc); optimisation of quality assurance programmes for national indoor Rn-surveys (A-Bo); accuracy tests of integrating Rn-detectors (A-Me).

b) radon dynamics and aerosol science

behaviour of the unattached fraction in underground environments with variable aerosol concentration (A-Bu); the effect of mechanical air filtration and electrostatic precipitators on the unattached fraction and the equilibrium fraction of Rn-d indoors (A-Ko); sub-micron sized Rn-d particle size distributions in mines (A-Bol); modelling of atmospheric diffusion of Rn and thoron, describing the relationship between atmospheric concentration and the vertical diffusion coefficient (A-Cu); indoor behaviour of Rn-d in dependence of aerosol attachment, nuclide desorption from the aerosol and Rn-d plate-out on surfaces (A-Po); the effects of seasonal differences on indoor Rn (A-Pa); determination of the Rn and thoron exhalation rate and its dependence on surface cover and material temperature (A-Le, A-Al); development of rapid diagnostic techniques for determining Rn entry rates into dwellings (A-Ra); in situ-determination of Rn exhalation, combining time-dependent Rn and Rn-d measurements (A-Al); in situ-determination of gas permeability in soil with miniature probes (A-Da); temporal RaA-variability indoors, using continuous measurements (A-Ni); measurement of Rn-d equilibrium activity deposited on surfaces by analysis of the spatial distribution of alpha tracks on CR-39 (A-La); Rn diffusion characteristics through hydrocarbons for application in oil exploration (A-Ra[1]);

c) outdoor studies

airborne surveys in order to correlate outdoor-, indoor Rn levels and geology (A-Gr); ship-based atmospheric studies on the Rn- and Rn-d distribution trend over the equatorial Pacific Ocean (A-Mo); model validation describing the temporal variation and horizontal distribution of Rn in the atmosphere (A-Ik); wash-out effects on atmospheric Rn-d (A-Fu); temporal variation of the specific activity of Rn-d in rainwater (A-Yo); multi-parameter correlation of the Rn concentration with the variation of the atmospheric boundary layer (A-Ka); enhancement of outdoor Rn-levels due to uranium mining (A-Kr); optimisation of radon potential mapping, using airborne-, ground surveys and borehole radiometric procedures (A-Ba);

d) indoor studies

influence of fly-ash containing construction materials on indoor Rn levels (A-St); thoron and thoron decay products indoors due to building materials (A-Cl); survey of workplaces with elevated Rn levels (A-Di); Rn-levels in dwellings built on uranium deposits and phosphate rocks (A-Si); identification of dwellings with high Rn-levels due to wall constructions using soil (A-Do); atmospheric Rn concentration in underground subway transport systems (A-An); identification of sources in dwellings with extremely high Rn-levels situated in former uranium mining communities (A-Th); thoron decay product exposure assessment for inhabitants of volcanic tuff-made dwellings (A-Sc[1]); correlation of Rn-d levels with the unattached fraction in houses with anomalous Rn-levels (A-Ro); Rn-levels in tourist caves, show mines and historical monuments (A-Ro, A-Hu).

e) <u>dosimetry and risk assessment</u>

microdosimetry of inhaled Rn-d by simulating randomized energy deposition at different cells (A-Ho); low dose extrapolation of Rn-related dose-effect curves with a hypothetical threshold (A-Ci); lung cancer risk assessment based on case-control studies in normal and coal brick-dwellings (A-De, A-Wa).

3. <u>International regulatory approaches to radon control - a mosaic of options</u>

Over the past 25 years the International Commission on Radiological Protection (ICRP) has drastically changed its approach to Rn control. In 1966 the ICRP categorically declared that its dose limitations referred only to exposures from technical practices that added to the natural background radiation (IC 66). In 1991, however, the proposed revised recommendations acknowledge that "....radon in dwellings needs special attention" (IC 91). For existing dwellings the ICRP discriminates between the recommendation of a vague "guidance" for owner-occupied dwellings and an "action level" for rented properties, without specifying any numerical values. Also the advice provided on the choice of action level is rather philosophical, i.e. it should be such that the number of houses in need of remedial work should not be "unmanagable". From the view point of the ICRP a recommendation for a "new building" is not really warranted because the concentration of radon cannot be determined with confidence until its completion and having been occupied for about a year. By then it is an existing dwelling . Finally the ICRP admits it is proceeding "cautiously" and recommends to continue using its Recommendation no. 39, i.e. an equilibrium equivalent concentration (EEC) of 200 Bq/m^3 as a "reference level" for new dwellings. This would result in an effective dose of 12 mSv/yr with the present lung model. However, "revised recommendations in due course" are already announced.

The World Health Organization (WHO) recognizes in 1989 that "...radon and its daughter products remain a matter of concern due to widespread occurrences and the total delivered dose" (WH 89). Using a different approach, it accounts for the extent of mitigation required in the case of existing buildings (Ah 90): if the annual average EEC exceeds 100 Bq/m^3, remedial actions should only be taken, provided they are simple to implement. This caveat does not apply if an annual average of EEC > 400 Bq/m3 is prevailant and then prompt actions should be taken. WHO recognizes "new buildings" as being a different situation than already existing dwellings and recommends that an annual average EEC of 100 Bq/m3 should not be exceeded.

The Commission of the European Communities (CEC) recommends to use a dose-related "reference level". If an effective dose of 20 mSv/y is exceeded, this should be "cause for consideration" of "simple, but effective" countermeasures (CE 90). Applying presently available dosimetry this corresponds to an annual average EEC of 200 Bq/m^3 (F = 0.5). Also the CEC recognizes the difference between existing and new buildings and recommends in the latter case a "design level" of 10 mSv/yr (= EEC: 100 Bq/m^3; F = 0.5). It is emphasized by the CEC that a) all decisions should be based on annual averages of Rn or Rn-d, using integrating techniques;
b) adequate Quality Assurance Programmes should be in effect.

In the following two examples for national regulatory actions are discussed. In Austria the total radiation exposure indoors resulting from building materials is regulated, i.e. the sum resulting from external gamma radiation and exhalation of Rn (ON 88). Different equations apply for single component- or multiple-compound building materials. The materials are considered suitable if the resulting effective dose from the total indoor exposure does not exceed the average national value of 2 mSv/yr. Contributions from cosmic rays, Rn from drinking water, etc. are excluded in this recommendation on building materials.

In 1980 the Swedish government took the lead worldwide to introduce a system of comprehensive limits and recommendations for decreasing Rn concentrations in all dwellings (NB 80). At present a Rn- "action level" of 200 Bq/m^3 is used for existing dwellings, provided simple measures can be taken; otherwise 800 Bq/m3 are recommended. For new dwellings a Rn- "design level" of 140 Bq/m3 is in effect. In 1985 Rn has been recognized officially as an urgent health problem requiring action (SG 85). Therefore, the government recommended each municipality to take appropriate measures to ensure via building permit that in new buildings the average collective exposure to Rn-d and to gamma radiation is decreased as far as it is practical and economically reasonable (Fa 90).

4. Recommendations for a unified approach

Radon represents a multidisciplinary issue on an international scale. Therefore it appears advantageous to use a unified approach to its solution. Such an internationally coordinated approach should address the following areas:

4.1 Research needs

In the following areas further research is needed in order either to overcome actual lack of data or to improve existing databases.

a) Source Term Characterisation:

Radon 220 (Thoron, Tn) and its decay products (particularly ThB) may represent a non-negligible component of the indoor environment in some areas; more measurements are needed to characterize occurrence and dynamics of these nuclides; Rn-related convective/advective/diffusive/ transport phenomena need quantification for a variety of environmental boundary conditions, such as under the influence of meteorological parameters; interaction of pressure-driven flow with subsoil; multizone transport and interzone flow; quantification of Rn-entry into spaces; Rn/Tn generation and mobility in soil and rocks as a function of: soil moisture, -porosity, -type, -depth, weathering; emanation process into gas and vapour phases dependent on pore space, grain size, permeability; microdistribution of radium 226 within grains.

b) Aerosol Sciences:

Chemical and physical characteristics of Rn/Tn and their decay products, e.g.: formation of cluster ions and their reaction products; dynamics of Rn-d/Tn-d interactions with indoor aerosol (size distribution, diffusion coefficient, recoil phenomena, plateout rate); Rn-d/Tn-d interaction with other indoor pollutants: generation rate of free radicals, ions, neutral products; long-term measurements of unattached fraction in a variety of environments, including size distribution studies and humidity effects.

c) Dosimetry:

Microdosimetric calculations to obtain values for the quality factor and RBE for Rn-d; biological dosimetry for evaluating prior Rn-d/Tn-d-exposure, using samples of bone, teeth, blood, hair, etc; refined dosimetric modelling for infants, children, sick and older people using actual morphological and physiological data rather than scaling factors only; development of species-specific physical models of different regions in the respiratory tract.

d) Radiobiology

Molecular approach to mechanisms of Rn/Tn-induced injury:
Rn/Tn-in vitro exposure of human cell cultures; biophysical and biochemical modelling for the identification of cellular markers for pre-malignant or malignant cells; use of molecular probes of genes cloned as recombinant DMA molecules to study Rn/Tn-induced DNA changes; activation of oncogenes;

Cellular approach:

quantification of the changes of parameters indicative for transformation processes, such as:
anchorage-independent growth, immortalization, growth enhancement; abnormal expression of growth factors; adaption studies to ultra-low levels of Rn-d exposure (hormesis); Tn-d distribution in different organs after inhalation; interaction of Rn-d/Tn-d smoke and other irritants known to occur indoors and underground;

4.2 Logistic requirements and aspects of programme design

Over the next few years a large number of Rn-programmes will be carried out worldwide. In order to achieve optimal cost-effectiveness and comparability of results international coordination is desirable also in the implementation of these programmes, addressing logistic requirements and programme design:

a) standardisation of the data collection-methods for describing the Rn exposure indoors and outdoors in different types of exposure situations (homes, schools, offices, factories, public buildings, recreational areas, health spas, mines) and reflecting the subsequent use of the data (real estate transaction, design of mitigation procedures, epidemiological research);

b) definition of minimum criteria to be fulfilled by quality assurance programmes concerning different measurement programmes (short-term integration, long-term integration; measurements of Rn-, Rn-d, thoron daughters and unattached fraction; Rn determination methods for soil gas, water, exhalation rates);

c) establishment of an international Rn-databank

d) harmonization of the international regulatory approach to risk limitation from Rn-exposure, differentiating between the residential-use of owner occupied buildings, rented accomodations, public buildings and work places;

e) provision of information material (graphical, audio-visual) for specific target groups, such as public health services, scientific-technical community, real estate agents, Rn-testing companies and contractors, and the media. This material should be scientifically sound, presented but also sufficiently interesting to reach the target audience. It should assist in obtaining a positive response from the public, thereby adding to improved control of the exposure situation.

f) development of durable Rn-mitigation techniques for different architectural styles and geo-climatic regions, taking into account the cost-effectiveness of achievable dose-reductions;

Summarizing it appears advantageous to find an international agreement on a unified approach to view the issues of "Radon in indoor air" and related public health risks from individual and collective exposures in a consistent manner with risks from other radiation sources but also from all other contaminants occurring indoors, such as microorganisms, organics, combustion products and passive cigarette smoke.

References

(Ah 90) AHMED, J.U, Radon Overview in Natural Environment and Dwellings, Proc. Int. Conf. High Levels of Natural Radiation, Ramsar, Iran, 3-7 November 1990 (in press).

(CE 80) Proc. CEC-Seminar on the "Radiological Burden of Man from Natural Radioactivity in the Countries of the European Communities", Le Vesinet, Paris, 1979, CEC Publ., Luxembourg (1980).

(CE 90) CEC, Recommendation of the Commission, Doc. no. 90/143/Euratom (1990).

(Co 89) Committee on Indoor Air Quality (CIAQ) Radon Work Group, Federal Radon Activities Inventory, US-DOE/EPA Rep. no. DOE/ER-0409, Washington D.C., USA (1989).

(Fa 90) FALK, R., Management of the Radon Problem in Sweden, Proc. First Int. Sem. "Managing the Indoor Radon Problem", Mol, Belgium (1990).

(HP 91) Health Physics Society (HPS) Position Statement, Perspectives and Recommendations on Indoor Radon, The HPS Newsletter, Vol. XIX, No. 1, p. 3 (1991).

(Hu 56) HULTQUIST, B., Studies on Naturally Occuring Ionizing Radiations, Kungl. Svenska Vetenskapsakademiens Handligar, Fjärde Ser. Vol.6, No. 3 (1956).

(IC 66) ICRP, Recommendations no. 9 (1966).

(IC 91) ICRP, Recommendations of the Commission (1991).

(NB 80) National Board of Health and Welfare, Ordinance SOSFS (M) 71, Stockholm, Sweden (1980).

(OE 83) OECD-NEA Group of Experts, Dosimetry Aspects of Exposure to Radon and Thoron Daughters, Report ISBN 92-64-12520-5, Paris, France (1983).

(OE 85) OECD-NEA Group of Experts, Metrology and Monitoring of Radon, Thoron and their Daughter Products, Report ISBN 92-64-12767-4, Paris, France (1985).

(Po 65) POHL, E., Biophysikalische Untersuchungen über die Inkorporation der natürlichen radioaktiven Emanationen und deren Zerfallsprodukte, Sitzungsber. Oesterr. Akad. Wiss. II, Vol. 174, pp. 309 (1965).

(Si 91) SINNAEVE, J., The European Research Programme and the Commission of the European Communities, (this symposium).

(SG 85) Swedish Government, Proposition 1984/85:181, Stockholm, Sweden (1985).

(UN 88) United Nations Scientific Committee on the Effects of Atomic Radiation, Sources, Effects and Risks of Ionizing Radiation, UNSCEAR Report to the General Assembly (1988).

(Wa 90) WALKINSHAW, D.S., Proc. 5th Int. Conf. on "Indoor Air Quality and Climate", Toronto, Canada (1990).

(WH 89) WHO, Report on the Twelfth Intersecretarial Meeting on Air Pollution Problems in Europe, Geneva, Doc. no. EUR/ICP/CEH 199 (1989).

Appendix

(A-Al)	ALDENKAMP, P.J., University, Groningen, The Netherlands.
(A-An)	ANNANMAEKI, K., Centre f. Rad. and Nucl. Safety, Helsinki, Finland.
(A-Anl)	ANDRU, J., Kodak Pathe, Sevran, France.
(A-Ba)	BALL, T.K., Geological Survey, Nottingham, United Kingdom.
(A-Bo)	BOCHICCHIO, F., National Institute of Health, Rome, Italy.
(A-Bol)	BOULAUD, D., CEA/IPSN, Fontenay-aux-Roses, France.
(A-Bu)	BUTTERWECK, G., University, Göttingen, Germany.
(A-Ci)	CIGNA, A., ENEP, Saluggia, Italy.
(A-Cl)	CLIFF, K.D., NRPB, Chilton, United Kingdom.
(A-Da)	DAMKJAER, A., University, Lyngby, Denmark.
(A-De)	DERI, Zs., Inst. of Nuclear Research, Debrecen, Hungary.
(A-Di)	DIXON, D.W., NRPB, Chilton, United Kingdom.
(A-Do)	DOI, M., Nat. Inst. of Rad. Sciences, Chiba, Japan.
(A-Fa)	FALK, R., Radiation Protection Institute, Stockholm, Sweden.
(A-Fu)	FUJITAKA, K., Nat. Institute of Rad. Sciences, Chiba, Japan.
(A-Gr)	GRASTY, R.L., Geological Survey, Canada.
(A-Ho)	HOFMANN, W., University, Salzburg, Austria.
(A-Hu)	HUSSEIN, M.I., Atomic Energy Authority, Cairo, Egypt.
(A-Ik)	IKEBE, Y., University, Nagoya, Japan.
(A-Ka)	KATAOKA, T., Inst. of Public Health and Env. Sciences, Okayama, Japan.

(A-Ke) KESTEN, J., University Göttingen, Germany.

(A-Ko) KOJIMA, H., Science University of Tokyo, Japan.

(A-Kr) KRIZMAN, M., University, Ljubljana, Yugoslavia.

(A-Ku) KUROSAWA, R., Waseda University, Tokyo, Japan.

(A-Le) LETTNER, H., University, Salzburg, Austria.

(A-La) McLAUGHLIN, J.P., University College, Dublin, Ireland.

(A-Me) MELLANDER, H., Radiation Protection Institute, Stockholm, Sweden.

(A-Mo) MOCHIZUKI, S., Institute of Technology, Muroran, Japan.

(A-Ni) NISHIMURA, K., Science University, Tokyo, Japan.

(A-Pa) PAPASTEFANOU, C., University, Thessaloniki, Greece.

(A-Pi) PILLER, G., Bundesamt f. Gesundheitswesen, Fribourg, Switzerland.

(A-Po) PORSTENDOERFER, J., University, Göttingen, Germany.

(A-Ra) RANNOU, A., CEA/IPSN, Fontenay-aux-Roses, France.

(A-Ral) RAMOLA, University, Salzburg, Austria.

(A-Ro) ROX, A., Staatl. Materialprüfungsamt, Dortmund, Germany.

(A-Sa) SAMUELSSON, C., University Hospital, Lund, Sweden.

(A-Sc) SCHULER, Ch., Paul Scherrer Institute, Villigen, Switzerland.

(A-Scl) SCIOCCHETTI, G., ENEA, Cassacia, Italy.

(A-Si) SINGH, J., University, Amritsar, India.

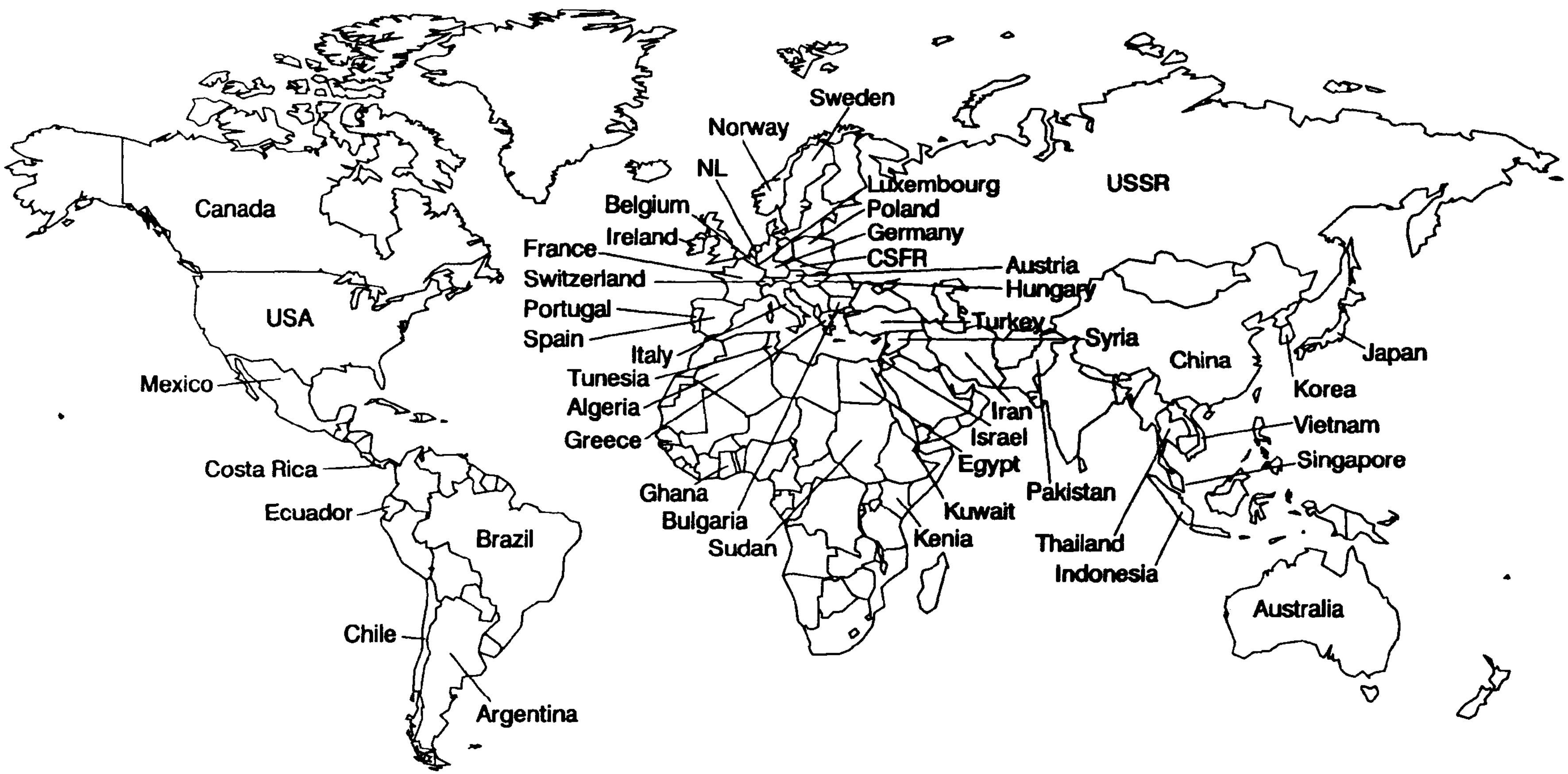
(A-St) STEGNAR, P., University, Ljubljana, Yugoslavia.

(A-Th) THOMAS, J., Inst. of Hygiene and Epidemiology, Prague, Czechoslovakia.

(A-Wa) WANG, Z., Ministry of Public Health, Beijing, China.

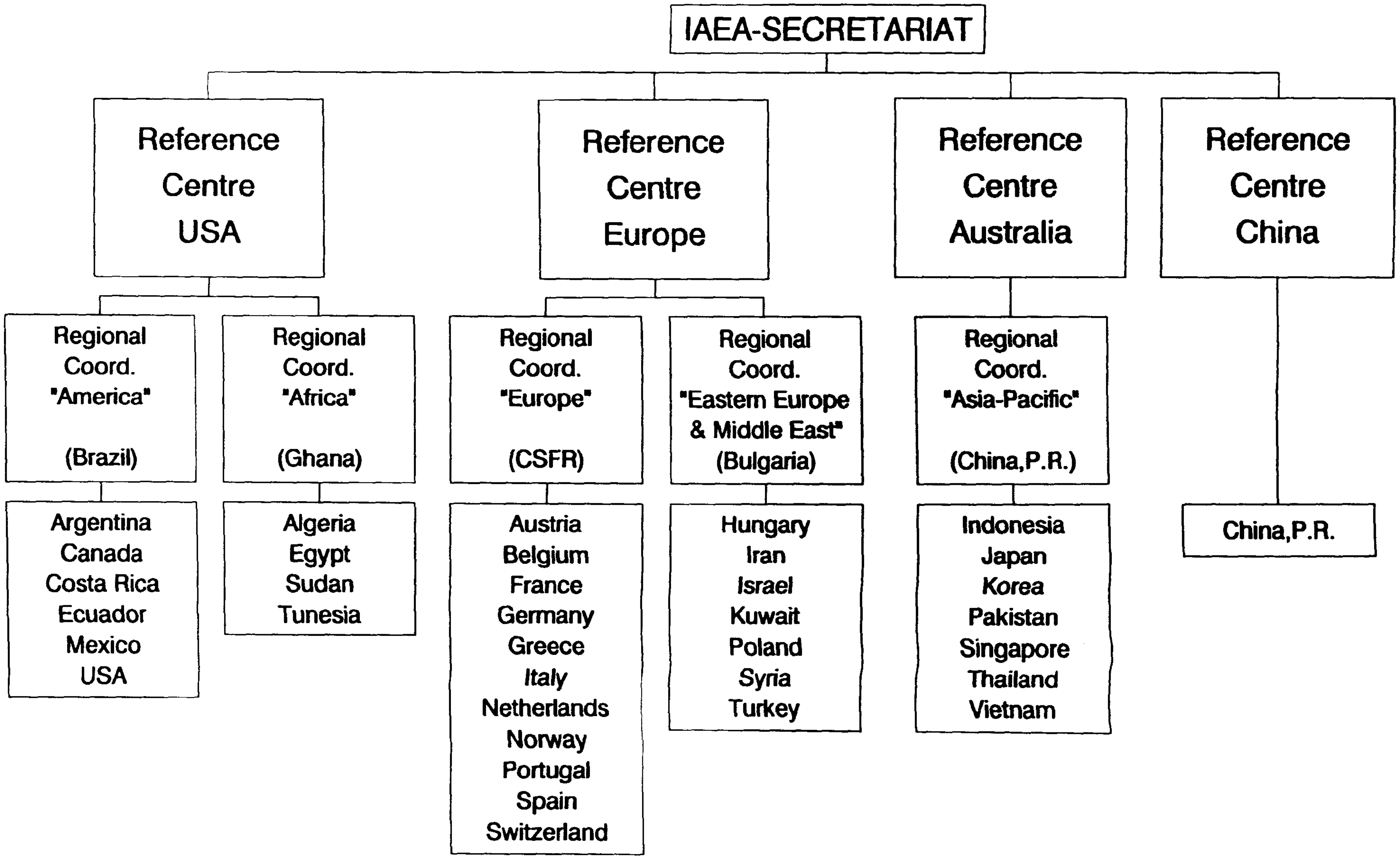
(A-Yo) YOSHIOKA, K., Inst. of Public Health and Env. Sciences, Shimane, Japan.

Fig. 1: Participants in the IAEA Co-ordinated Research Programme "Radon in the Human Environment" (Status: February 1991)



STEIN68/91-02-25,FL/LP

Fig. 2: Implementation of Quality Assurance Programme within the Framework of the IAEA-CRP "Radon in the Human Environment"



STEIN69/91-02-25,FL/LP

EPA RADON POLICY AND ITS EFFECTS ON THE RADON INDUSTRY

by: David Saum
Infiltec
Falls Church, VA 22041

Although the EPA has always stated a goal of solving the indoor radon problem through private sector testing and mitigation, EPA programs may be impeding the development of a viable private radon industry. Several possibilities for modification of the EPA programs are discussed: 1) "sunset" provisions for EPA programs that would schedule their termination so that the private sector could plan for privatization, 2) increased utilization of voluntary consensus standards organizations such as ASTM and ASHRAE to replace EPA protocols and guidelines, 3) cost/benefit analyses of impact of past and future EPA programs on the radon industry, 4) an EPA ombudsman to serve as a contact point for radon industry comments to the EPA, 5) increased radon industry participation in future development of EPA programs and guidelines to prevent surprises and allow for longer term planning, 6) a revision of the EPA authority to issue guidelines, protocols, examinations, etc. so that this de facto rulemaking would be subject to the same review as formal EPA rule making.

INTRODUCTION

What is the proper response of the federal government to the indoor radon problem? This paper will briefly consider policy approaches, outline the problems with the current EPA indoor radon programs, and offer suggestions for a change in direction current federal policy that should offer better services to the public by allowing market forces to operate more efficiently.

Under our constitutional republic, all governmental authority must be authorized by the constitution which makes no mention of indoor radon. We must assume that the current activities are authorized under the "general welfare" clause in the preamble. This phrase allows for broad interpretation which varies with the vision of the current executive, legislative and judicial branches. The EPA, as a member of the executive branch, appears to be following President Bush's vision (last stated in The State-of-The-Union address) of relying on the private sector whenever possible and returning power to the states and localities. Congress appears to have agreed by authorizing the EPA to assist the states in developing and regulating radon activities, and the most recent legislation is the Indoor Radon Abatement Act (IRAA) of 1988. All of this activity has been characterized the EPA and Congress as "non regulatory" since radon is naturally occurring and its primary exposure has been in private residences where the government does not want to intrude. The EPA has issued radon guidelines and has provided "voluntary" proficiency demonstration programs to assist the states in determining who is capable of measuring and mitigating radon problems. The EPA has also provided extensive public information, and it has often stated that it wants private industry to provide a solution to the indoor radon problem through a non regulatory program.

Unfortunately, this non regulatory approach has resulted in a highly regulated marketplace from the point of view of private industry participants. More and more states have enacted regulation to make it impossible to perform radon related work without full compliance with all the latest EPA "voluntary" programs. Mandatory state regulation through the use of voluntary EPA programs appears to be an ideal situation to state regulators since they can rely on the authority of the EPA to legitimize the state programs at little or no expense. But it presents an increasing burden to those in the industry who face increased competition from competitors trained by EPA developed courses and certified by EPA developed examinations, increased costs to private industry from fees mandated to support these programs, and an increased paperwork burden from an ever increasing "voluntary" protocols and revisions to these programs. The EPA has no attempted to justify these programs by offering proof that these programs offer the public a higher quality and more cost effective service.

These programs each appear to be well intentioned, but in their sum they are creating an industry that is focussed around the lowest common denominator. The only standard of quality is whether a firm has the required EPA "certification". These programs were created without significant industry input, they are completely controlled and managed by the EPA without continuing industry input, there is no plan for eventual privatization of these programs, an increasing bureaucracy is being created to support these programs, and Congress has directed the EPA to support these programs through the imposition of user fees on the industry but not the States who are the prime beneficiaries. Many persons who have remained in the industry despite the current severe recession are discussing whether to hold on a little while longer in the hope that the competition will succumb before they do, or whether to begin a strike against the increasing governmental regulations on the industry.

POSSIBLE EPA APPROACHES

What approaches could the federal government have used in dealing with the indoor radon problem? Within the current federal economic and political constraints at least three approaches can be imagined:

Laissez-faire Approach

Although true laissez-faire would involve no governmental programs, we can imagine approaching laissez-faire by limiting the federal government to the conduct of limited research to identify the problem, issuing recommendations, and leaving the market place to develop solutions. This approach assumes the indoor radon problem is not an immediate emergency of such complexity that emergency measures are called for, and that the complexity of society requires the variety of solutions that can best be offered by relying on individual initiative rather than a bureaucracy. The primary disadvantage of this approach is that it might have taken longer for a significant market solution to have developed, given what we now know about the public apathy and the extraordinary amount of education that it has taken to generated even today's marginal response. Possible advantages of this approach include low cost to the federal government, and the potential for the development of a "Sears or McDonalds" approach to radon where some large, well financed company would have the incentive to devote the resources necessary to develop a high quality radon service firm. In today's market where anyone can get EPA "certification" there is little advantage to offering a well established, brand-name, quality service. One disadvantage is that the states would have to develop their own programs for certifying competent firms, such as they currently do for home improvement contractors.

Bootstrap-Sunset Approach

Under a bootstrap-sunset approach, the federal government assumes that the problem is serious enough to justify the development of programs for training and proficiency demonstration to get the industry started, but the government realizes that this bureaucracy can never be able to deal with the evolving complexities of the situation and so each program would have a sunset provision so that they could be taken over by industry groups or private firms. In this way, the EPA could prevent the heavy hand of bureaucracy from becoming a permanent burden on the industry and determining every aspect of its future. One disadvantage is that the states would eventually have to develop their own programs to identify the competent members of the profession. This approach would not require continuing expenditures by the federal government and the imposition of user fees to pay for them.

Bureaucratic Approach

Under the bureaucratic approach, the federal government assumes that the problem is so complex that a permanent federal bureaucracy should be developed to control all aspects of the radon industry through "voluntary" guidelines and programs that are offered to the states as the basis for their non-voluntary regulation. One disadvantage of this plan is that it is expensive, even if it is financed by mandatory user fees, because in any case the funding will come from the public. Another hidden cost of the program is that it stifles new market solutions to the problems because the heavy hand of bureaucracy drives out the best services, reducing everything to a common denominator. The primary advantages are that the states will have a simple solution to the problems of providing lists of competent "EPA certified" firms. This appears to be the approach that the EPA has selected.

EVALUATION OF CURRENT EPA PROGRAMS

When the indoor radon problem was first identified in the mid 1980s, EPA researchers provided contractors with vital information on radon mitigation and testing, and the EPA policy office provided much needed public information material. This activity seemed to be an excellent marriage between public and private interests that served to bootstrap a market solution to the problem. However, now that the radon industry is maturing, it is time to consider the potential benefits of returning as much of the EPA radon program as possible to the private sector. Many of the services now being provided by the EPA are in areas such as training, certification, and calibration are not special types of services (such as law enforcement and court systems) that can only be provided by the government. Privately provided services are generally acknowledged to be more efficient , and this privatization of indoor radon will certainly provide a welcome reduction of government expenditures in this time of budget deficits. An orderly transition to private services should provide services that are more responsive to the marketplace, and the alternative to privatization is a permanent government bureaucracy which has never been the stated intention of the EPA or Congress.

RMP Program

Consider, for example, the EPA's Radon Measurement Proficiency (RMP) Program. Certainly everyone wants to have accurate measurements, and RMP initially provided a valuable service when no private sector services were available. Unfortunately, the current program may actually be impeding the development of private sector efforts to provide calibration and quality assurance services. Wouldn't it be preferable to have many private calibration facilities, conveniently located, offering competitive services; rather than a few of EPA laboratories in distant locations offering very limited services? The presence of the "implied EPA certification" provided by RMP makes it difficult for anyone to take the private labs seriously. The private sector can not compete with the authority of EPA pronouncements, even if the private service is demonstrably better.

A second problem with RMP is that it is a proficiency demonstration program that does not certify contractors, but everyone who uses the program (contractors, states, and local governments, etc.) treats it as a certification of calibration. Private labs find it impossible to sell real calibration services since they do not have the EPA authority, and why should anyone go to the extra expense of going through two programs (RMP and private) when all anyone asks for is the RMP seal of authority). The net result is that RMP has resulted in a low level of calibration in the industry because it has monopolized the calibration business and then offered very infrequent services (approximately every 2 years).

A simple privatization plan for the EPA RMP program would begin with an announcement by EPA of a date (e.g. June 1, 1992) after which the EPA would no longer provide laboratory services for the RMP program. The EPA would also announce conditions under which private laboratories could provide the equivalent laboratory service in lieu of the EPA labs. This would allow the private laboratories to make plans to take over this service. The EPA might initially provide an intercalibration service to certify these new labs, and it might even work with the National Institute of Standards and Technology (NIST) to develop improved radon calibration standards. Currently there does not appear to be any EPA effort to assist private labs in taking over the RMP role. In addition, EPA literature would be modified to indicate that the public should look for testing firms that can "demonstrate fulfillment of a plan to provide accurate measurements either through private calibration facilities or though the temporary EPA RMP". Ultimately the EPA could turn the remainder of the RMP program (record keeping, publishing lists, etc.) over to the highest bidder or an industry trade group.

RCP Programs

In contrast to RMP, the EPA Radon Contractor Proficiency (RCP) Program is an example of an EPA program where some consideration has been given to privatization. In order to stimulate and guide the radon mitigation industry, the EPA developed training courses and exams on radon mitigation, and these courses were originally given by the EPA. To protect its investments in this program, and guarantee geographic distribution of these services, the EPA competitively selected regional training centers where the courses and exams are given from the EPA prepared materials. In addition to these centers, private firms can apply to give the courses if they met specified criteria.

Ideally, the entire RCP program would be turned over to the private sector. This includes updates to the courses and exams, and will require a number of changes since the program was developed without significant industry input or control. Today the radon industry does not have a formal role in revising the examinations or courses, there is no formal plan to phase out EPA control, there is no appeals process for RCP examination results, no grading criteria have been published, and there is no EPA response to comments submitted after completion of the examination or course. The RCP exam also diminishes the possibility of competition among radon mitigation companies. Home owners do not want to hear about a contractor's years of high quality work and innovative solutions, they just want to know "Are you EPA certified?".

De Facto Rulemaking

All the EPA guidelines, recommendations, and proficiency demonstrations quickly become de facto rules because the states are quick to incorporate them into law or local regulations. But the EPA is not required to subject these de facto rules to the same level of public scrutiny as their other formal rule making activity. All of these activities should be open to public scrutiny, and anyone who submits written comments should have a response in writing as to the disposition of the comments. An EPA indoor radon ombudsman is recommended as a contact point for comments on current EPA programs. The industry has lost confidence that any of its comments are taken seriously unless they are made though congress.

User Fees for EPA Programs

The EPA was authorized by the IRAA to implement user fees with the goal of recovering costs in programs like RMP and RCP. Again this appears to be an excellent idea in these days of budget deficits and "pay as you go". Since RCP and RMP are voluntary and provide valuable services, why shouldn't the users pay for them.

The case for user fees would be stronger if the programs were truly voluntary and the programs had not made it impossible for the private sector to provide equivalent services. Much of the industry does not have any choice, they must participate in RCP and RMP or the State will not allow them to stay in business. For this reason, the EPA should consider privatization of these services as an alternative to user fees for cost recovery.

It is well known that the demand for free or underpriced services/items of value is very large, and I think that the EPA has proven this again at great expense, especially in the RMP program. Some sort of price (not necessarily money) must be imposed in order to avoid wasting money on applications that come from companies that are not serious about providing radon services. But this does not mean that the proposed fees must be related to cost recovery.

Let's take cost recovery to its logical extreme. There is only one ultimate "payer" in business and that is the customer. If there are increased costs to the industry, then the customer is ultimately going to have to pay for it. In todays radon mature market, the consumer has largely decided to ignore the problem, and the radon business is primarily related to a small percentage house sales. I estimate that in this market approximately 10,000 mitigation jobs and about 100,000 testing jobs are done every year, and a mitigation job costs about ten times more than a test. I also estimate that the EPA is spending about $10 million per year on indoor radon, and if this was allocated to each test and mitigation and test proportional to their present cost, then simple algebra shows that we would have to add $500 to the cost of each mitigation and $50 to each test in order to provide full cost recovery for the EPA radon program. Would the public put up with this surcharge or even a fraction of it?

Quality Assurance Programs

A Quality Assurance (QA) Program has been suggested as part of RMP for all radon test companies. This could be considered as a response to the realization that RMP has become the primary radon industry calibration program, even though it was never meant to provide that service, and it is a very poor substitute. Privatization of this aspect of RMP is somewhat confusing because the marketplace would probably not recognize the artificial distinction that is being made between "demonstrating proficiency" and running a measurement QA program. Again we see an apparently good idea that could result in all companies offering "EPA certified QA Plans", making it impossible for the consumer to determine which companies have a serious commitment to QA. A more effective approach to accurate measurements might be to encourage "double blind" evaluations of testing companies where testers would be evaluated without their knowledge, and the results would be published for all to see. Then there would be a real premium on QA - not just a paper requirement

RMP Examinations

A "voluntary" examination for radon testers is under development that would require that all test personnel attend EPA approved training courses. Again, no cost/benefit or industry impact studies have been offered by the EPA to justify this program to the industry, but it will certainly give the states an easy way to recommend test companies. Again, the radon industry has had no part in this development, and no plan for its ultimate privatization has been suggested.

RCP Mitigation Protocols

The next step in the RCP program appears to be the promulgation of EPA protocols for radon mitigation. It seems that when radon mitigators signed up for the voluntary RCP exam, they agreed to adhere to EPA mitigation guidelines. The draft protocols contain valuable material, and they would make a useful technical resource document that might replace or supplement the aging 1987 EPA Technical Guidance document on radon mitigation. Unfortunately, the new document was produced without formal industry input, without a cost/benefit analysis, and without plans for consensus approval and periodic updates. The IRAA directed the EPA to work with consensus standards groups such as ASTM, an this should be expedited by EPA. During the extensive open review necessary to arrive at a consensus document, all substantive comments must be dealt with in writing, and there is an automatic provision for periodic updates. The EPA is currently under no such restrictions for developing its current "voluntary" guidance and recommendations. Under current EPA policy, we can expect a cursory review period for the EPA mitigation protocols, after which the states will pick them up, as gospel, and create an increased level of regulation for the radon industry.

Redraft of "Citizen's Guide to Radon"

The EPA recently asked for comment on a new draft of the "Citizens Guide to Radon" which contained major shocks for the radon industry. Since this draft was prepared in response to the IRAA which directed EPA to recommend that home owners reduce their indoor radon levels as close to ambient as possible, few in the radon industry expected new EPA guidance that would effectively raise the radon action level that the radon industry is currently implementing. The technical arguments in this debate are outside the scope of this paper, but I think it is safe to say that if the industry had understood that the EPA was heading in this direction, then many in the industry would have reconsidered their commitment to the radon business. As you can understand, business people have to make long range plans, and it would be very helpful if they knew as early as possible about major policy shifts that might radically alter the economics of their business. Preliminary EPA response to industry comments suggests that the EPA did not anticipate the negative industry response to the draft Guide. This misunderstanding might have been avoided if the EPA had performed a cost/benefit analysis on the radon industry in addition to their study of the impact on the U.S. population. The radon industry could provide valuable input in these matters if there was a partnership between EPA and industry that allowed for continuing communication during the development of these guidelines, protocols, examinations, etc. Although the Citizens Guide contains only recommendations and guidance, it has an impact on the U.S. population and the radon industry that is comparable to any EPA rule making. Therefore, this guidance should be subject to the same full public review as formal EPA rule making.

RECOMMENDATIONS

It appears that Congress did not direct the EPA to work as a partner in assisting the private sector to create a high quality radon industry with a planned rapid transition to a fully private sector effort. Rather, it has effectively directed the EPA to create programs that have taken over the management of the industry with no plans for future privatization. It is no wonder that there are few signs from the industry of increasing self management, since the burden of EPA regulation increases daily.

It's ironic that these problems are taking place as Eastern Europe throws off the shackles of central planning and acknowledges that most problems are more efficiently solved by the free market. Well meaning controls that stifle innovative market solutions must be guarded against with constant vigilance. Sometimes we forget that the radon industry is a trade that is closer to home improvement contracting than it is to brain surgery, and radon industry regulation should be consistent with that fact.

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.

REVIEW OF RADON AND LUNG CANCER RISK

By: Jonathan M. Samet
University of New Mexico Medical Center
Albuquerque, NM 87131

Richard W. Hornung
National Institute for Occupational Safety and Health
Cincinnati, OH 45226

ABSTRACT

Radon, a long-established cause of lung cancer in uranium and other underground miners, has recently emerged as a potentially important cause of lung cancer in the general population. The evidence for widespread exposure of the population to radon and the well-documented excess of lung cancer among underground miners exposed to radon decay products have raised concern that exposure to radon progeny might also be a cause of lung cancer int he general population. To date, epidemiological data on the lung cancer risk associated with environmental exposure to radon have been limited. Consequently, the lung cancer hazard posed by radon exposure in indoor air has been addressed primarily through risk estimation procedures. The quantitative risks of lung cancer have been addressed primarily through risk estimation procedures. The quantitative risks of lung cancer have been estimated using exposure-response relations derived from the epidemiological investigations of uranium and other underground miners. We review five of the more informative studies of miners and recent risk projection models for excess lung cancer associated with radon. The principal models differ substantially in their underlying assumptions and consequently in the resulting risk projections. The resulting diversity illustrates the substantial uncertainty that remains concerning the most appropriate model of the temporal pattern of radon-related lung cancer. Animal experiments, further follow-up of the miner cohorts, and well-designed epidemiological studies of indoor exposure should reduce this uncertainty.

Further information regarding the paper may be found in:
J. M. Samet and R. W. Hornung, "Review of Radon and Lung Cancer Risk", Risk Analysis, Vol. 10, No. 1, 1990, pp. 65-75.

Risk Analysis, Vol. 10, No. 1, 1990

Workshop on Indoor Air Quality

Review of Radon and Lung Cancer Risk

Jonathan M. Samet[1,3] and Richard W. Hornung[2]

Received March 7, 1989; revised October 25, 1989

Radon, a long-established cause of lung cancer in uranium and other underground miners, has recently emerged as a potentially important cause of lung cancer in the general population. The evidence for widespread exposure of the population to radon and the well-documented excess of lung cancer among underground miners exposed to radon decay products have raised concern that exposure to radon progeny might also be a cause of lung cancer in the general population. To date, epidemiological data on the lung cancer risk associated with environmental exposure to radon have been limited. Consequently, the lung cancer hazard posed by radon exposure in indoor air has been addressed primarily through risk estimation procedures. The quantitative risks of lung cancer have been estimated using exposure–response relations derived from the epidemiological investigations of uranium and other underground miners. We review five of the more informative studies of miners and recent risk projection models for excess lung cancer associated with radon. The principal models differ substantially in their underlying assumptions and consequently in the resulting risk projections. The resulting diversity illustrates the substantial uncertainty that remains concerning the most appropriate model of the temporal pattern of radon-related lung cancer. Animal experiments, further follow-up of the miner cohorts, and well-designed epidemiological studies of indoor exposure should reduce this uncertainty.

KEY WORDS: Radon; radon decay products; lung cancer; indoor air pollution.

1. INTRODUCTION

As information on air quality in indoor environments accumulated during the 1970s, it became apparent that radon and its decay products were invariably present indoors, and that concentrations reach unacceptably high levels in some dwellings.[1] The evidence for widespread exposure of the population to radon and the well-documented excess of lung cancer among underground miners exposed to radon decay products [2] have raised concern that exposure to radon decay products might also cause lung cancer in the general population.

Radon is an inert gas which is a naturally occurring decay product of radium-226, the fifth daughter of uranium-238. After radon forms from decay of radium-226, some of the radon molecules leave the soil or rock and enter the surrounding air or water.[3] As a result, radon is ubiquitous in indoor and outdoor air. Radon decays with a half-life of 3.82 days into a series of solid, short-lived radioisotopes. Two of these decay products emit alpha particles, high-energy and high-mass particles, which are highly effective in damaging tissues. When these alpha emissions take place within the lung as inhaled radon progeny decay, cells lining the airways may be damaged and lung cancer may result.

The measure of occupational exposure to alpha radiation from radon decay products is the "Working Level

[1] Department of Medicine, and The New Mexico Tumor Registry, Cancer Center, University of New Mexico Medical Center, Albuquerque, New Mexico 87131.
[2] National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Mail Stop R-4, Cincinnati, Ohio 45226.
[3] To whom all correspondence shoul be addressed.

Month" (WLM). One Working Level (WL), a concentration unit, is any combination of short-lived radon decay products in 1 L of air which results in the release of 1.3×10^5 MeV of potential alpha energy. The WLM, a cumulative measure of exposure, is the product of radon decay products concentration in WL and duration in working months of 170 hr.

Concentrations in homes are most often reported as pCi/L; a curie is a measure of the rate of radioactive decay. An indoor concentration of 100 pCi/L is approximately 0.5 WL, assuming a 50% equilibrium of radon with its decay products. Thus, the Environmental Protection Agency's guideline of 4 pCi/L translates to 0.02 WL; annual occupancy of a home at this concentration for 75% of time results in exposure of 0.8 WLM.

Epidemiological methods have been used to assess directly the lung cancer risk associated with exposure to radon decay products indoors. However, the available data on environmental radon are limited and preliminary, and the findings of epidemiological investigations cannot yet be used to characterize the risks of indoor radon. Consequently, the lung cancer hazard posed by radon exposure in indoor air has been addressed primarily through risk estimation procedures. The quantitative risks have been estimated using risk projection models incorporating exposure–response relationships derived from the epidemiological investigations of underground miners.

This presentation reviews currently applied risk projection models for lung cancer resulting from radon exposure. We initially consider the investigations of underground miners, and discuss the methodology and limitations of the principal studies. We then describe and compare the most widely used risk projection models.

2. INVESTIGATIONS OF MINERS

2.1. Introduction

Occupational lung disease associated with the mining of radioactive ores was documented as early as the fifteenth century among miners in the Erz Mountains of eastern Europe. In 1879, Harting and Hesse[4] reported that miners in this area developed cancer of the lung. During the twentieth century, it was recognized that these and other underground mines were contaminated with radon, and that the decay products of radon were the agents directly associated with the production of lung cancer.

At present, the health risk associated with exposure to radon decay products can be best characterized by examining the more informative epidemiologic studies of underground miners. We describe the methods and findings of five major studies. About 15 additional populations of radon-exposed miners have been investigated. The report of the Biological Effects of Ionizing Radiation Committee (BEIR) IV provides a comprehensive review.[2]

2.2. Czechoslovakian Uranium Miners

The latest update of the Czechoslovakian study reported on four cohorts of uranium miners with follow-up ending December 31, 1980 (Table I).[5] The groups had exposures to radon decay products ranging from an average of 3.2–303 WLM, and varying follow-up, ranging from 6–30 years. To date, excess lung cancer mortality has been found principally in the cohorts with highest exposure and longest follow-up.

The most recent follow-up has detected significantly elevated risk of lung cancer from exposures as low as 50–99 WLM.[5] Risk estimates were reported as either attributable or absolute risks, and are therefore difficult to compare to studies reporting estimates as relative risks. The overall attributable risk of lung cancer was estimated to be 20.0 per WLM/10^6 person years.

The Czech study also identified several factors that modify the exposure–response relationship of lung cancer risk with cumulative exposure. The attributable risk of lung cancer was found to increase with age at initial exposure, although lung cancers were found at young ages (before 40 years). An exposure rate effect was identified; low exposures for long duration produced higher risk than high exposures for short duration when cumulative exposure was equal. The joint effect of cigarette smoking and exposure to radon decay products was approximately additive. Finally, the investigators examined mortality for other causes of death and found a

Table I. Czechoslovakian Uranium Miners Study

	Study group			
	A	B	C	D
No. of miners	2194	1849	3799	1561
Mean exposure (WLM)	303	134	6.1	3.2
Mean length of follow-up (yrs)	30	25	10	6
Attributable risk (per WLM per 10^6 PYRS[a])	23.0	19.1	20.9	NA

[a] PYRS = person-years.

statistically significant risk of basal cell carcinoma of the skin.

One of the strongest features of the Czech study is the large size of the cohorts (Table 1). The exposure data for these miners are also very extensive. The average number of measurements in each mine ranged from 101–690 per year. The follow-up period was also quite long (25–30 years) for two of the four groups. The low exposure groups may be informative in the future. Since over 5000 miners have average exposures below 10 WLM, further follow-up of this group could provide invaluable information concerning the effects at levels that are near the average lifetime exposure in the U.S. homes.

Interpretation of the Czech study has been made difficult by the analytical methods employed and the manner in which the results have been presented; as a result, comparison with other studies has been difficult. While methodology used in early analyses of the Czech data was apparently different from that used in other studies of miners, the latest analysis was based on an approach comparable to the widely used modified life table approach.

The exposure databases are also limited by the measurement, before 1960, of radon rather than decay products. Accurate estimates of concentrations of radon decay products can only be obtained if the equilibrium ratio of radon to its decay products is known. Smoking information was also incomplete on the cohorts with the highest exposures and the longest follow-up.

2.3. Ontario Uranium Miners

The study includes 15,984 uranium miners who had no known asbestos exposure.[7] Requirements for entry into the study included receiving a miner's physical exam between 1955–1977 and working at least 1 month underground. Exposure estimates were made by combining WL measurements with work history information for experience before 1968. After 1968, exposure was obtained directly from the mining companies. The exposure estimates were made in two ways: "Standard" WL values were obtained by averaging quarterly measurements in each year; "special" WL values were obtained by weighing the measurements toward the highest levels found. The "special" WL values were regarded as upper bounds of the actual exposures experienced by the miners. The mean cumulative exposure levels in this cohort were about 40 WLM for "standard" values and 90 WLM for "special" values (Table II).

Lung cancer mortality was analyzed using a modified life table approach and found to be significantly increased for exposures in the categories of 40–70 WLM (mean = 53 standard WLM) and higher. A linear dose–response model was employed; the model estimated the excess lung cancer risk to be 1.3% per WLM for the "standard" values. The latest analyses also showed a decrease in risk with time since last exposure to radon decay products.

Table II. Ontario Uranium Miners Study

No. of miners	15,984
Mean length of follow-up (yrs)	15.1
Mean exposure	
Standard WLM	40
Special WLM	90
Percent excess relative risk/ WLM	
Standard WLM	1.3
Special WLM	0.5
Attributable risk (per WLM per 10^6 PYRS)	
Standard WLM	7
Special WLM	3

This study is important because of the large number of miners with relatively low exposures, and for the consideration given to exposures received in other types of hard-rock-mining. In addition, appropriate analytical methods have been used, and the dose–response relationship has been estimated.

At the end of follow-up in 1981, the cohort was relatively young, with median age of 49 years. Since lung cancer mortality rates increase sharply in the fifth and sixth decades, this cohort has not yet been followed for sufficient time for description of the full temporal expression of excess lung cancer risk associated with exposure to radon decay products. Information on cigarette smoking is not available for cohort members; however, the investigators are addressing this potential limitation by conducting a case-control study within the cohort. The exposure database may be limited by reliance on the opinions of mining engineers for exposure estimates for some mines in the years before 1968.

2.4. New Mexico Uranium Miners

This cohort consists of approximately 3500 underground uranium miners who had worked at least 1 year underground prior to December 31, 1976 (Table III).[8] This study group includes only about 100 members of the Colorado Plateau cohort; in comparison with the earlier Colorado Plateau cohort, its members are younger and received lower cumulative exposures. At the most

Table III. New Mexico Uranium Miners Study, Colorado Plateau Uranium Miners Study, Swedish Iron Miners Study

	New Mexico uranium miners	Colorado Plateau uranium miners	Swedish iron miners
No. of miners	3500	3346	1415
Mean follow-up (yrs)	18	22	44
Mean exposure (WLM)	113	821	81
Median exposure (WLM)	36	430	—
Attributable risk (per WLM per 10^6 PYRS)	—	6.3	19.0
% excess relative risk/WLM	1.1	1.2	3.6

recent follow-up, which extended through 1985, the mean exposure was 113 WLM and the mean follow-up interval was 17.7 years. The latest analysis was a nested case-control study involving 65 lung cancer cases and 230 controls. A proportional hazards model was used to estimate relative risk. The effect of cumulative exposure was found to be curvilinear downward at the highest exposure interval. Subsequent analyses were restricted to total cumulative exposures less than 1000 WLM. A linear model fit the data well in this range, with a relative risk increase of 1.1% per WLM. A multiplicative relationship between cigarette smoking and exposure to radon decay products was also found. Relative risk was estimated to decline with increasing age at risk. In contrast to the Ontario and Colorado Plateau studies, relative risk did not vary significantly during the first 15 years after ceasing to work in the mine, but was found to increase 15 years or more after cessation of exposure.

Since average exposures in the New Mexico study were approximately 20% of the mean exposures in the Colorado Plateau study, extension of risk estimates from this study to the indoor environment requires less extrapolation than from studies with substantially higher exposures. Also, because the New Mexico miners worked more recently than the Colorado Plateau miners, the exposure levels for the New Mexico study tend to be better documented. Cigarette smoking histories are available for most of the subjects.

The case-control analysis must be interpreted with caution until results from the full cohort are available. By contrast, the Colorado Plateau analysis used the entire cohort of 3346 miners, including 256 lung cancer cases. Given the high relative risks seen in both of these groups, a case-control design with less than four controls per case might not produce risk estimates with the same degree of precision as estimates from analysis of data from the full cohort.

2.5 Swedish Iron Miners

This is a study of 1415 Swedish iron miners born between 1890 and 1919, who were alive in 1930 and worked at least 1 year underground between 1897 and 1976 (Table III).[9] Exposures ranged from 2–300 WLM with an average exposure rate of 4.8 WLM per year. The average cumulative exposure was reported to be 81.4 WLM, which was calculated with a lag of exposure by 5 years to account for cancer latency. The average total cumulative exposure without discarding any exposure was 93.7 WLM.

Of the 1415 miners, 1294 were observed between 1951 and 1976, and 50 lung cancer deaths occurred during this period. The expected number of deaths based upon Swedish national mortality rates was calculated to be 14.6 (standardized mortality ratio [SMR] = 342 for lung cancer). With control for cigarette smoking, the SMR increased to 391. Significant excess risk was shown for exposures above 80 WLM. The attributable risk was estimated as 19.0 per 10^6 person-years per WLM (Table III).

An attempt was made to consider the confounding effects of such co-carcinogens as cigarette smoking, diesel exhaust, arsenic, chromium, and nickel. On the basis of an informal statistical analysis that required many assumptions, the joint effect of cigarette smoking and exposure to radon decay products was considered to be additive. The effects of the other potential confounding exposures were discounted because of the small concentrations found to be present in the mines in this study. Indoor radon exposures were not considered to be of consequence because of low lung cancer rates in the surrounding communities.

This cohort has the most lengthy follow-up of the five studies considered here. The average time in the study was 44 years, with 99.5% ascertainment of vital status. The confirmation of cause of death was thorough, since approximately one half of all deaths in Sweden are followed by autopsy. Also, the exposures were relatively low with an average rate of 4.8 WLM per year.

This study is potentially limited by the sparse data from which cumulative exposures of individual miners were assigned. Reconstruction of past concentrations of radon was based upon measurements first taken in 1968, information on ventilation conditions in prior years, and consistency of radon measurements in groundwater between 1915 and 1975. Although the investigators consider that exposures were accurate to ±30%, the exposure estimates could not be validated and their accuracy is uncertain.

Analyses related to smoking are potentially flawed because smoking histories were not available for all subjects. A sample of the responses to a 1972–1973 survey of active miners and surface workers and from a 1977 survey of retirees were considered. Smoking histories for the lung cancer cases were obtained primarily from surrogate sources.

Differential exposure misclassification may have been introduced by the method used to assign exposure. Exposure assignment for lung cancer cases was apparently done differently from that for noncases. A detailed history of each mine area worked was obtained for lung cancer cases only, whereas noncases were assigned exposure based upon a weighted average of annual mine exposure levels. Any differential treatment of cases and noncases can potentially introduce a bias into the risk estimates.

2.6 Colorado Plateau Uranium Miners

The U.S. Public Health Service conducted a study of 4127 underground uranium miners with at least 1 month of underground exposure between 1950 and 1964. These miners worked in the four-state area of Colorado, New Mexico, Arizona, and Utah. The risk assessment conducted by the National Institute for Occupational Safety and Health (NIOSH) was confined to 3346 white male miners.[10] As shown in Table III, the average exposure was 821 WLM (median of 430 WLM), the highest of the five studies considered. Follow-up began as early as 1950 and ended December 31, 1982, with an average length of 22 years.

The NIOSH risk assessment used a generalized version of the Cox proportional hazards model to estimate relative risk and to identify factors potentially influencing the risk estimates. Over the full range of exposure (1–10,000 WLM), the dose–response function was found to be nonlinear, with a decreasing trend at the higher exposure levels. However, in the range of current interest in relation to indoor air (below 600 WLM), the risk model was essentially linear with excess risk estimated as 1.2% per WLM.

Other factors found to influence the exposure–risk relationship included age at initial exposure, time since last exposure, exposure rate, and cigarette smoking. Miners first exposed at older ages were at increased risk of lung cancer compared to those first exposed at younger ages. Relative risk was found to decrease with time since cessation of exposure. Exposures received at low exposure rates over long duration were more hazardous than high exposure levels for short duration, cumulative exposure being equal. Finally, cigarette smoking had a synergistic relationship with exposure to radon decay products. The relationship appeared to be closer to multiplicative, with the most likely estimate being slightly submultiplicative.

The Colorado Plateau and New Mexico studies are only large studies of underground miners with cigarette smoking information for most cohort members. The cohort is relatively large and has been followed closely since the study's initiation in 1950.

The primary weakness of this study in relation to current risk assessment needs is the high cumulative exposures received by most subjects. Risks estimated at lower levels therefore depend to some degree upon trends found at higher levels of exposure. Some of the exposure data may be biased on the high side due to the use of exposure measurements for years after 1960 that were made by mine inspectors who usually oversampled high exposure areas. Smoking data were obtained on all miners, but the last update of this data was in 1969. Therefore, the cumulative cigarette consumption of miners who quit smoking after this date will be overestimated by extrapolation of the smoking histories.

2.7 Discussion

Although the five studies were conducted on different cohorts of miners, using different analytical approaches and varying amounts of data, the findings demonstrate several consistent patterns. Each study showed an exposure–response relationship between the lung cancer excess and cumulative exposure to radon decay products. Table IV presents the relative risk estimates for each study in relation to cumulative exposure. The excess relative risk per WLM ranges from 3.6% per WLM for the Swedish miners to 1.1% per WLM in the New Mexico uranium miners. These estimates are not strictly comparable since they are based upon different analytical techniques, different treatment of the exposure data, and varying degrees of adjustment for cigarette smoking. However, considering the differences among the five studies, the risk estimates are remarkably homogeneous. In fact, the BEIR IV Committee analyzed data from three of these five cohorts (Sweden, Ontario, and Colorado Plateau) and found that the relative risk in the Swedish cohort was approximately 1.6% per WLM.[2] In addition, BEIR IV found no significant differences among the risk coefficients derived from the

Table IV. Comparison of Relative Risk Coefficients for Lung Cancer Among Five Studies of Underground Miners

Study	Excess relative risk/100 WLM
Czechoslovakian uranium miners	1.5
Ontario uranium miners	1.3[a]
New Mexico uranium miners	1.1
Swedish iron miners	3.6[b]
Colorado Plateau uranium miners	1.2

[a] Based upon "standard" WLM values.
[b] This estimate was calculated by discarding the first 10 years of exposure and lagging by 5 years. When the first 10 years exposure was included, RR dropped to 1.6 as estimated by BEIR IV Committee.

four cohorts for which data were analyzed. The Committee concluded that the overall relative risk coefficient from the four studies was approximately 1.5% per WLM.

Several factors other than cumulative exposure appear to influence the risk of lung cancer. The Czech and Colorado Plateau studies demonstrated an increasing risk with older age at initial exposure. A decrease in relative risk with time since last exposure was found in the Colorado Plateau and Ontario studies. The Colorado Plateau and Czech studies showed an exposure-rate effect in which lower exposure rates for longer duration were more hazardous than higher exposure rates for shorter duration when cumulative exposure was equal. A similar dose-rate effect has been found in a number of animal studies of exposure to radon decay products although at very high exposures.[11,12] Finally, all five studies found an increased risk of lung cancer among smoking miners compared to nonsmoking miners, at least to the degree that the data permitted. The joint effect of radon decay products exposure and cigarette smoking ranged from additive in the Swedish and Czech studies to approximately multiplicative in the Colorado Plateau and New Mexico studies.

3. RISK ASSESSMENT MODELS

3.1 Introduction

Protection of the health of underground miners and of the general population has provided a strong rationale for making quantitative estimates of the lung cancer risk posed by radon. A risk projection model describes the temporal expression of the radon-associated lung cancer as well as the effects of potentially important cofactors, such as cigarette smoking, age at exposure, and age at risk. The two most widely applied models are the relative risk and attributable risk models; the relative risk model assumes that the background risk is multiplied by the risk of radon, whereas the attributable risk model assumes that the excess risk is additive to the background risk. A model may also describe the risk as varying with time since exposure. The manner in which radon exposure and cigarette smoking are assumed to interact strongly influences the results of risk estimation models for radon. If a multiplicative interaction is assumed, then the risks for smokers, already much greater than for nonsmokers, are multiplied by the risk from radon exposure. If an additive interaction is assumed, then the same excess risk is added to the background rates for smokers and for nonsmokers. The interaction between the two agents might plausibly take some form other than purely additive or purely multiplicative.

Diverse risk projection models have been developed.[2,13–16] Models for environmental radon were recently published by the National Council for Radiation Protection and Measurements (NCRP),[13] the International Commission on Radiological Protection (ICRP),[14] the Environmental Protection Agency (EPA),[16] the National Institute for Occupational Safety and Health (NIOSH),[15] and the Biological Effects of Ionizing Radiation Committee (BEIR IV) of the National Research Council[2] (Table V). Each of the models estimates lung cancer risk on the basis of the epidemiological evidence from underground miners, but the assumptions underlying the models and the resulting risk projections differ. In this paper, we focus on the NCRP, ICRP, and BEIR IV models because these models are most widely used for assessing the risks of environmental radon. The EPA and NIOSH models are briefly described.

3.2 NCRP Model

NCRP Report No. 78 describes an attributable risk model adapted from an earlier report by Harley and Pasternack.[17] The annual attributable risk is calculated as:

$$A\ (t/t_0) = R\ (Pt/Pt_0)\ e^{-\lambda(t-t_0)}$$

where $A\ (t/t_0)$ is the attributable annual lung cancer rate at age t for 40 years and above due to a single annual exposure at age t_0; R is the risk coefficient; P_t/P_{t_0} is the lifetable correction and $\lambda(\lambda = \ln 2/20\ \text{yr}^{-1})$ describes the decrease in risk with time since exposure. The risk coefficient (R), 10×10^{-6} per year per working level month (WLM), represents the arithmetic average of coefficients available when the report was prepared.

Table V. Recent Risk Projection Models for Radon and Lung Cancer

Agency	Type of model	Source of risk estimate
National Council on Radiation Protection and Measurements[13]	Attributable risk, time-dependent	Average risk coefficient from principal studies of miners
International Commission on Radiological Protection[14]	Constant relative risk	Adjusted risk coefficient from 3 studies of miners
Environmental Protection Agency[16]	Constant relative risk	Range of coefficients based on studies of miners
National Institute for Occupational Safety and Health[15]	Relative risk, time-dependent	Risk based on Colorado Plateau uranium miners
National Research Council[2]	Relative risk, time-dependent	Risk based on analysis of 4 studies of miners

The absolute risk model was selected by the NCRP committee as appropriate for describing the appearance of lung cancer in uranium miners; additionally, the comparability of additive risks in smoking and nonsmoking Swedish miners employed at the Malmberget mines and studied by Radford and Renard was cited. The term $e^{-\lambda(t-t_0)}$ was included to describe loss of transformed cells by repair, cell death, or other mechanisms. Because lung cancer is infrequent before age 40 years, the model did not project cancers until age 40. In this model, correction for higher bronchial doses in children did not greatly change risk projections, and, accordingly, a single dose conversion factor was use for males and females of all ages.

For an average annual exposure of 0.2 WLM, the model estimates the increment in lifetime risk as 0.18%. If expressed uniformly over a 45-year period (ages 40 through 85 years), then the model projects 9000 radon-attributable lung cancer deaths annually in the U.S.

3.3 ICRP Model

ICRP Publication 50 details a constant relative risk model for lung cancer resulting from radon, and applies this model to a reference population with lung cancer mortality and activity patterns representative of more developed countries. The ICRP committee justified the choice of the constant relative risk approach on data from studies of miners and the atomic bomb survivors. The best estimate of the relative excess risk was derived from the studies of Colorado Plateau uranium miners, Czechoslovakian uranium miners, and Ontario uranium miners. The average from these studies, 1.0% per WLM, was adjusted to 0.64% to account for contributions from carcinogens other than radon in the mining environment and for differing dosimetry in homes and mines. For exposure received before age 20 years, a threefold increase in effect was assumed on the basis of the pattern of age-dependence in the atomic bomb survivors and of the increased bronchial dose in children.

The model was then used to estimate the lung cancer risk associated with constant lifetime exposure. The reference population for this analysis was assumed to be in a steady state with lung cancer frequency of 60 per 100,000 among males and 12 per 100,000 among females. The analysis assumed that 65% of time was spent indoors at home, 20% in other indoor locations, and 15% outdoors. For this population at exposure rates less than 3 WLM annually, the attributable relative risk was 0.5 per WLM per year. Assuming an indoor exposure of about 1 pCi/L, approximately 10% of the lung cancer in the reference population was attributable to indoor radon.

BEIR IV Model

The BEIR IV Committee obtained data from four studies of underground miners: U.S. uranium miners in the Colorado Plateau; underground uranium miners in Saskatchewan and in Ontario, Canada; and underground metal miners in Sweden. The committee first carried out separate but parallel analyses of the four data sets and then a formal analysis of the combined data. The analysis used relative risk models for the age-specific lung cancer mortality rates that incorporated terms for potential modifying factors, such as age at first exposure and age at risk, as well as for exposure to radon decay products.

The models were fit to the individual studies and then to the combined data set using Poisson regression. In analyzing the data sets, the committee used a form of relative risk model which was termed the Time-Since-Exposure model. Rather than considering cumulative exposure prior to age at observation, this model estimates the effects of exposures received in distinct time windows before the age at risk. The version of the model used by the committee estimated the effects during three windows: exposures received from the fifth through the ninth year before age at risk, from the tenth through the fourteenth year, and from the fifteenth year and beyond. The general form of this model is

$$r(a) = r_0(a)\,[1 + \beta\,\gamma\,(a)\,(d_1 + \theta_2 d_2 + \theta_3 d_3)]$$

where d_1, d_2, d_3 are the exposures received during the three windows, and 0_2 and 0_3 represent variation in the effects of exposure among the windows.

The analyses showed reasonable consistency among the cohorts; the final model was

$$r(a) = r_0(a)\,[1 + 0.025\gamma(a)\,(W_1 + 0.5W_2)]$$

where $r_0(a)$ is the age-specific baseline rate; $\gamma(a)$ is 1.2 for (a) less than 55 years, 1.0 for (a) 55–64 years, and 0.4 for (a) 65 years or more; W_1 is WLM of exposure received 5–15 years before age (a) and W_2 is WLM received 15 years or more before age (a). This model departs from the widely used constant relative risk model, in which the increase in relative risk associated with a given exposure is constant over time after exposure. The BEIR IV Time-Since-Exposure model implies that the effect of exposure wanes as the interval since exposure lengthens.

3.5 EPA Model

The EPA used a constant relative risk model to predict that radon causes 5000–20,000 lung cancer deaths annually. Based on the studies of miners, a range of relative risks from 1–4% per WLM was assumed. The model also adjusted for differences in breathing rates of miners (30 l per minute) and of average adults (15.3 l per minute), assuming that dose varies directly with minute ventilation.

3.6 NIOSH Model

NIOSH used a generalized form of the Cox proportional hazards model to account for possible departures from a constant relative risk.[15] The NIOSH modeling approach described lung cancer mortality patterns as a function of cumulative exposure to radon decay products, exposure rate, age, cigarette smoking, and time since last exposure without making assumptions about exposure effects regarding nonmining populations. The NIOSH model showed a decreasing effect of exposure above 2000 WLM, but the model was essentially linear below that level with a relative risk coefficent of 1.2% per WLM. An exponential decrease in relative risk after cessation of exposure was found with relative risk reduced by 50% 14 years after leaving the mines.

4. COMPARISON OF THE NCRP, ICRP, AND BEIR IV MODELS

Although each uses risk coefficients which are derived from the studies of miners, the three models differ substantially in describing the expression of excess risk associated with radon exposure (Tables VI and VII). The NCRP model generally projects the lowest excess risk because it is an additive model, and the radon-associated excess declines over time. The ICRP model, a constant relative risk model, projects the highest risks. Exposures received by age 20 years lead to a particularly large excess because of the threefold higher risk assumed up to age 20 years than in subsequent ages. In the BEIR IV model, the percent excess risk varies with both age and time since exposure.

When smokers and nonsmokers are considered separately, the substantial difference between assuming an additive or a multiplicative interaction between smoking and radon exposure is evident (Table VIII). The additive NCRP model projects small increments for smokers in comparison with the multiplicative ICRP and BEIR IV models. Lifetime excess lung cancer risks for smokers estimated by the models are markedly different. For example, Land [18] has calculated the excess lung cancer risk per 100,000 smokers exposed to 1 WLM at age 15 as: NCRP—7.4, ICRP—278.7, BEIR IV—114.5; for exposure to 1 WLM at age 35 years, the corresponding estimates are 15.5, 94.3. and 129.4.

5. CONCLUSIONS

For some dimensions of the radon problem, the degree of uncertainty is minimal. The causal association

Table VI. Features of Selected Risk Projection Models for Radon and Lung Cancer

	NCRP	ICRP	BEIR IV
Form of model	Attributable risk	Relative risk	Relative risk
Time-dependent	Yes; risk declines exponentially after exposure	No	Yes; risk declines as time since exposure lengthens
Lag interval	5 years	10 years	5 years
Age at exposure	No effect of age at exposure	3-fold increased risk for exposures before age 20 years	No effect of age at exposure
Age at risk	Risk commences at age 40 years	Constant relative risk with age	Lower risks for ages 55 years and older
Dosimetry adjustment	Increased risk for indoor exposure	Decreased risk for indoor exposure	No adjustment
Risk coefficient	10×10^{-6}/year/WLM	Excess relative risks: 1.9%/WLM at ages 0–20 years and 0.64%/WLM for ages 21 years and above	Excess relative risk of 2.5%/WLM but modified by time since exposure

of radon with lung cancer has been amply documented by studies of underground miners and by complementary animal studies.[2] Both the epidemiological and the animal data show that lung cancer risk increases with increasing exposure to radon or its decay products. The epidemiological evidence also indicates synergism between exposure to radon decay products and cigarette smoking, although the extent of the synergism is uncertain.[2] Epidemiological studies have not yet empirically demonstrated that radon in indoor environments causes lung cancer, but current understanding of the dosimetry of radon decay products in the respiratory tract indicates that radon should have approximately equivalent carcinogenic potency in homes and in mines.[2]

Substantial uncertainties remain, however, with regard to other facets of the radon problem. The quantitative relationship between exposure to radon and radon decay products and lung cancer risk has not been precisely described, and uncertainties about the effects of age, gender, cigarette smoking, and other factors on this relationship await resolution. Extrapolation of risk estimates based on studies of miners to the general public requires assumptions in areas of uncertainty. We also lack exposure information based on a large and representative sample of the nation's homes.

The studies of uranium and other underground miners have provided a relatively extensive database for estimating the exposure–response relationship between exposure to radon decay products and lung cancer risk. Although the populations of miners studied to date have been diverse and methodology has varied among the epidemiological studies, the risk coefficients derived from the miners are remarkably consistent (Table IV).[2] The range of the coefficients covers approximately one order of magnitude, in spite of potential bias from differential and nondifferential misclassification of exposure to radon decay products and of the diagnosis of lung cancer.

Recently published risk projection models for lung cancer associated with environmental radon have incorporated risk coefficients based on the studies of miners.

Table VII. Increments[a] in Lung Cancer Risks for One WLM Projected by NCRP, ICRP, and BEIR IV Models

Increment at age (years)	NCRP[a] (%) Male	NCRP[a] (%) Female	ICRP (%)	BEIR IV (%)
Exposure at age 15 years				
35	0	0	1.9	1.5
50	0.3	0.7	1.9	1.5
65	0.05	0.2	1.9	0.5
85	0.02	0.1	1.9	0.5
Exposure at age 35 years				
50	0.6	1.4	0.6	3.0
65	0.1	0.4	0.6	0.5
85	0.05	0.2	0.6	0.5

[a] The excess is additive for the NCRP model. The percent excess relative risk was calculated for illustration using sex-specific lung cancer mortality rates for the U.S., 1980–1984. The additive increments are 3.0×10^{-6}, 1.8×10^{-6}, and 0.9×10^{-6} for ages 50, 65, and 85 years, respectively, for exposure at age 15 years; and 6.0×10^{-6}, 3.5×10^{-6}, and 1.8×10^{-6}, respectively, for exposure at age 35 years.

Table VIII. Lung Cancer Mortality Rates per 100,000 Projected for Nonsmoking and Smoking Males at Age 65 Years by NCRP, ICRP, and BEIR IV Models[a]

	NCRP	ICRP	BEIR IV
Exposure to 10 WLM at age 15 years			
Nonsmoking	59.8	69.0	60.9
Smoking	698.3	828.8	731.3
Exposure to 10 WLM at age 35 years			
Nonsmoking	61.5	61.5	60.9
Smoking	700.0	738.3	731.3

[a] Background lung cancer mortality rates estimated as 58.0×10^{-5} for nonsmokers and 696.5×10^{-5} for smokers.[2]

The principal models differ substantially in their underlying assumptions and consequently in the resulting risk projections (Tables VI–VIII). The committees that developed these models offered rationales for the assumed pattern of temporal expression of excess risk that were based on biological mechanisms and epidemiological evidence. The resulting diversity illustrates the substantial uncertainty that remains concerning the most appropriate model of the temporal pattern of radon-related lung cancer. Animal experiments and further follow-up of the miner cohorts should reduce this uncertainty.

At present, however, risk modeling remains the principal approach for quantifying the hazard of environmental radon. Which risk model should be chosen for this task? While we cannot justify the choice of a particular model, we consider that the epidemiological data from miners are not consistent with an additive model, such as that published by the NCRP.[13] The largest data set, which is based on the Colorado Plateau uranium miners, indicates synergism between smoking and exposure to radon decay products, and the data reject an additive model for the two exposures.[10] The evidence from a recent study of New Mexico uranium miners is consistent.[8] The epidemiological data also support a declining effect as the time since exposure lengthens.[2,10] Thus, a constant relative risk model, such as that published by the ICRP,[14] may not be biologically appropriate. The BEIR IV model describes the effect of radon exposure on lung cancer risk as varying with time since exposure; the BEIR IV model also assumes a multiplicative interaction between smoking and radon exposure. Use of the BEIR IV model for environmental radon, however, requires the extrapolation of risks from four cohorts of adult male miners observed over particular age and time spans to the general population. New epidemiological and experimental data should provide more refined risk models with less uncertainty.

ACKNOWLEDGEMENT

Supported in part at the University of New Mexico by the U.S. Department of Energy, Office of Energy Research, under grant no. DE-FG04-86ER60452.

REFERENCES

1. A. V. Nero, Jr. "Radon and its decay products in indoor air: an overview, *in* W. W. Nazaroff and A. V. Nero Jr. (eds.), *Radon and Its Decay Products in Indoor Air* (New York, John Wiley & Sons, 1988), pp. 1–53.
2. National Research Council, Committee on the Biological Effects of Ionizing Radiation (BEIR IV). "Health Risks of Radon and Other Internally Deposited Alpha-Emiters" (Washington, D.C., National Academy Press, 1988).
3. W. W. Nazaroff, B. A. Moed, R. G. Sextro "Soil as a Source of Indoor Radon: Generation, Migration, and Entry," *in* W. W. Nazaroff and A. V. Nero Jr. (eds.), *Radon and Its Decay Products in Indoor Air* (New York, John Wiley & Sons, 1988), pp. 57–112.
4. F. H. Harting and W. Hesse, "Der lungenkrebs, die bergkrankheit in den schneeberger gruben," *Vjschr Gerechtl Med Offentl Gesundheitswesen* 31, 313–337 (1879).
5. J. Sevc, E. Kunz, L. Tomasek, V. Placek, and J. Horacek, "Cancer in Man After Exposure to Radon Daughters," *Health Phys* 54, 27–46 (1988).
6. J. Sevc, E. Kunz and v. Placek, "Lung Cancer Mortality in Ura-

nium Miners and Long-Term Exposure to Radon Daughter Products," *Health Phys* **30**, 433–437 (1976).
7. J. Muller, W. C. Wheeler, J. F. Gentleman, G. Suranyi, and R. Kusiak, "Study of Mortality of Ontario Miners, *in* E. Stocker (ed.), *Occupation Radiation Safety in Mining, Proceedings of the International Conference* (Toronto, Ontario, Canadian Nuclear Association, 1985), pp. 335–343.
8. J. M. Samet, D. R. Pathak, M. V. Morgan, M. C. Marbury, C. R. Key, "Radon Progeny Exposure and Lung Cancer Risk in New Mexico Uranium Miners: A Case-Control Study," *Health Phys* **56**, 415–421 (1989).
9. E. P. Radford and K. G. St. Clair Renard, "Lung Cancer in Swedish Iron Miners Exposed to Low doses of Radon Daughters, *N Engl J Med* **310**, 1485–1494 (1984).
10. R. W. Hornung and T. J. Meinhardt, "Quantitative Risk Assessment of Lung Cancer in U.S. Uranium Miners, *Health Phys* **52**, 417–430 (1987).
11. F. T. Cross, R. F. Palmer, G. E. Dagle, R. H. Busch, and R. L. Buschbom, "Influence of Radon Daughter Exposure Rate, Unattachment Fraction, and Disequilibrium on Occurrence of Lung Tumors, *Radiation Protection Dosimetry* **7**:381 (1980).
12. C. K. Hill, F. M. Buonaguro, C. P. Meyers, A. Han, and M. M. Elkind, "Fission Spectrum Neutrons at Reduced Dose Rates Enhance Neoplastic Transformation, *Nature* **298**, 67–69 (1982).
13. National Council on Radiation Protection and Measurements, "Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States, Report 78 (Bethesda, Maryland, National Council on Radiation Protection and Measurement, 1984), 204 pp.
14. International Commission on Radiological Protection, *Lung Cancer Risk from Indoor Exposures to Radon Daughters* (Oxford, Pergamon Press, 1987; ICRP Publication 50).
15. National Institute for Occupational Safety and Health, "Criteria for a Recommended Standard . . . Occupational Exposure to Radon Progeny in Underground Miners" (Washington, D.C., U.S. Government Printing Office, October 1987; DHHS Publication No. 88–101).
16. U. S. Environmental Protection Agency, *Radon Reference Manual* (Washington, D.C., United States Environmental Protection Agency, Office of Radiation Programs, September 1987; EPA Publication No. 520/1-87-20).
17. N. H. Harley and B. S. Pasternack, "A Model for Predicting Lung Cancer Risks Induced by Environmental Levels of Radon Daughters, *Health Phys* **40**, 307–316 (1981).
18. C. E. Land, "The ICRP 50 Model," *Proceedings of the Annual Meeting of the National Council on Radiation Protection and Measurements*, Bethesda, Maryland, pp. 115–126 (1989).

DEPARTMENT OF HEALTH & HUMAN SERVICES

Public Health Service

Centers for Disease Control
National Institute for
Occupational Safety & Health
Robert A. Taft Laboratories
4676 Columbia Parkway
Cincinnati OH 45226

March 14, 1991

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

Dear. Mr. Dyess:

I was contacted by Ms. Sharon Thompson, who asked me to send you a copy of the presentation to be given at the symposium in Philadelphia, Pennsylvania, April 2-5, 1991. Since the deadline for receipt is Monday, March 18, please contact Julie Krafft at (513) 841-4244 so that we can be certain that you have received the paper.

The enclosed paper is a published copy of my presentation, which has been given previously. I am not familiar with copyright laws, but I want to be assured that they will not violated. It may be acceptable to copy the original if the purpose is to provide handouts to attendees, but I am not completely certain that this is not a violation. I am certain that the presentation cannot be republished from this copy. If there is a problem, please contact Julie Krafft as soon as possible.

Thank you for your assistance.

Laurence R Catlett
for Richard W. Hornung

ESTIMATING RADON LEVELS FROM Po-210 IN GLASS

by : J. Cornelis*, H. Vanmarcke**, C. Landsheere* and A. Poffijn*
* Nuclear Physics Laboratory, State University of Gent
Proeftuinstraat 86, B-9000 Gent, Belgium
** Radiation Protection, Nuclear Research Center, S.C.K./C.E.N.
Boeretang 200, B-2400 Mol, Belgium

ABSTRACT

The α-decay of Po-210 may become a useful indicator of the radon exposure during the last decades. The uncertainties associated with this technique were studied both experimentally and theoretically.

The depth distribution of absorbed Pb-214 and Pb-210 in glass is calculated using the theory of Lindhard for low energy heavy ions. It is found that 29.8 % of the absorbed Po-214 reappears at the glass surface after α-decay. The surface layer in which the decay products are absorbed is less than 100 nm. Measurements of the α-activity of Po-214 show that cleaning the glass once removes 85% of the deposited activity.

Room model calculations indicate that the ratio of the Po-210 surface activity to the radon air activity is about equally dependent on the deposition constant of the unattached decay products and on the attachment rate. The presence of aerosol sources, for instance, lowers the surface activity by a factor of two. Experimental investigations prove this finding.

INTRODUCTION

Lively in 1987 (1) and Samuelsson in 1988 (2) put up the idea of using the α-activity of Po-210, absorbed in vitreous glass, to determine the long term radon exposure in the living environment. The technique may be used as a retrospective exposure measure, for instance, in epidemiological studies.

The parameters influencing the absorbed and deposited Po-210 activity are indicated in figure 1. A fraction of the airbone Po-218, Pb-214, Bi-214, Po-214 and Pb-210 deposits on macroscopic surfaces. Half of the deposited activity recoils into the surface, upon α-decay, forming a thin absorbed layer. Subsequent α-decay makes a fraction of the absorbed activity to reappear at the surface. Household cleaning largely wipes away the deposited activity. The values of the transfer probabilities will be assessed in the next sections.

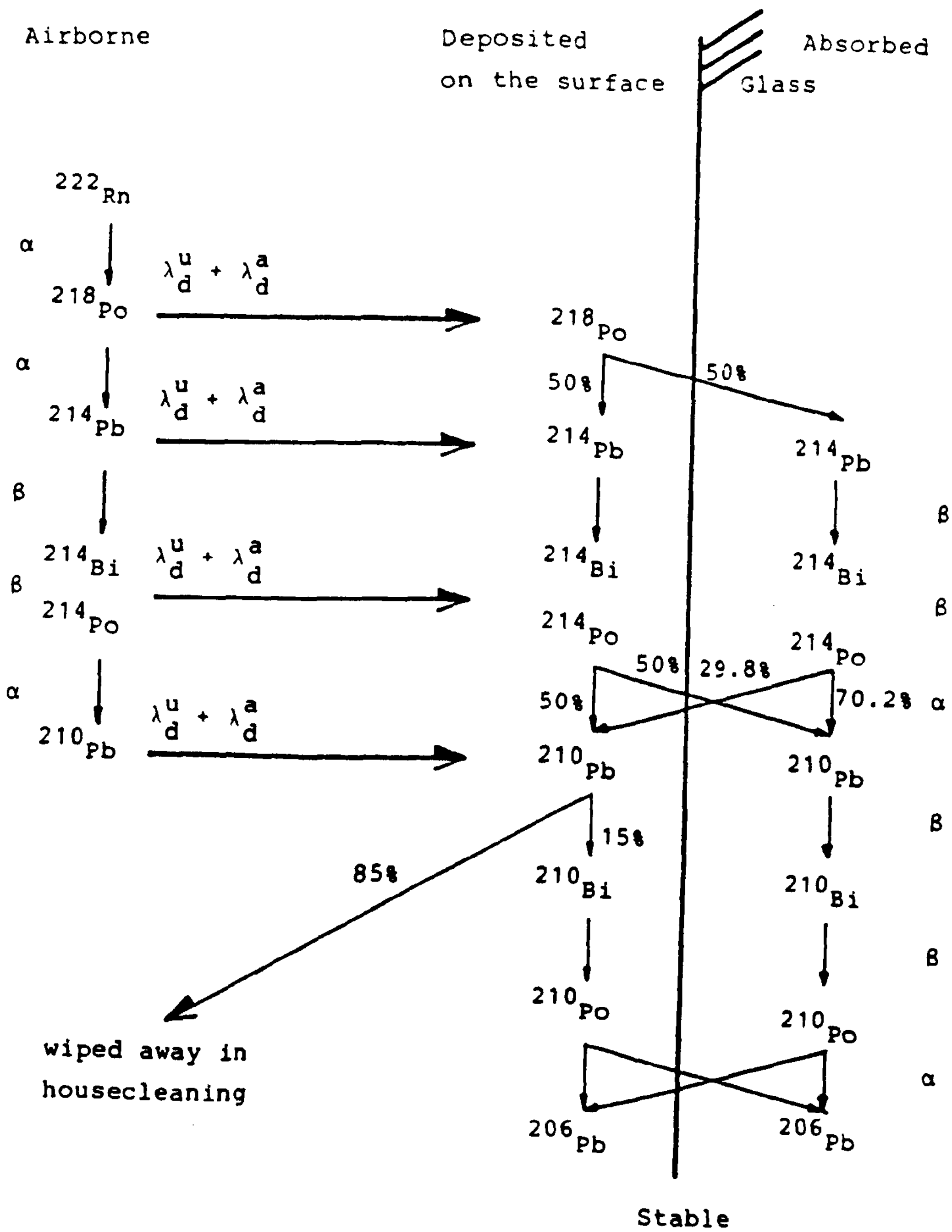


Figure 1. Decay-product deposition and absorption mechanisms and associated transfer probabilities.
λ_d^u is the deposition constant of the unattached decay products and λ_d^a is the deposition constant of the attached decay products.

DEPTH DISTRIBUTION OF Pb-214 AND Pb-210

The theory of Lindhard (3) provides a framework to determine the range of low energy heavy ions in amorphous media. Two recoil nuclei have to be considered, Pb-214 with a recoil energy of 112 keV and Pb-210 with a recoil energy of 146 keV. The details of the calculation are beyond the scope of this paper. They are published in dutch by Landsheere (4). A description in english is available on request.

The depth distributions of Pb-214 and Pb-210 are shown in figure 2. The full line and the broken line are calculated from Pb-214 and Pb-210 nuclei deposited on the surface of vitreous glass and recoiling into the glass.

The dot and dash line is the depth distribution of Pb-210 from Po-214 absorbed in the glass. The diffusion of the radon decay products in glass is negligable so that Pb-214 and Po-214 have the same distribution just as Pb-210 and Po-210. The depth distribution of Po-210 will always be a mixture of the two Pb-210 lines. The contribution of each line depends on the values of the transfer probabilities of the room model (see figure 2).

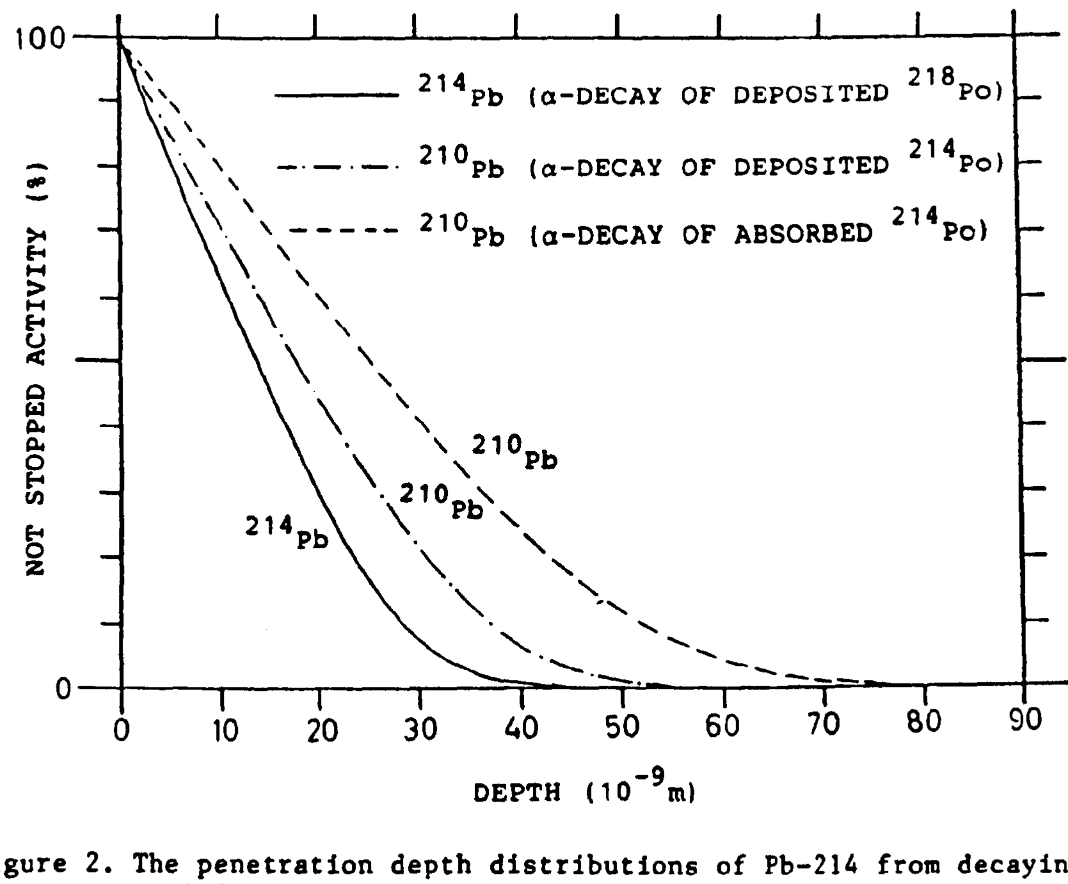


Figure 2. The penetration depth distributions of Pb-214 from decaying Po-218 deposited on the surface and of Pb-210 from deposited Po-214 and from absorbed Po-214.

The probability for recoiling Pb-210 to reappear at the surface of the glass is calculated from the depth distribution of absorbed Pb-214. The resulting probability is 29.8%.

CLEANING EFFECTS ON DEPOSITED DECAY PRODUCTS

An experimental arrangement was setup to investigate wether cleaning removes the deposited activity (see figure 3). A radon chamber of 1 m^3 was filled with radon laden air having a relative humidity of 50%. NaCl aerosol was produced with an atomiser and supplied to the chamber at least 4 hours before performing a measurement.

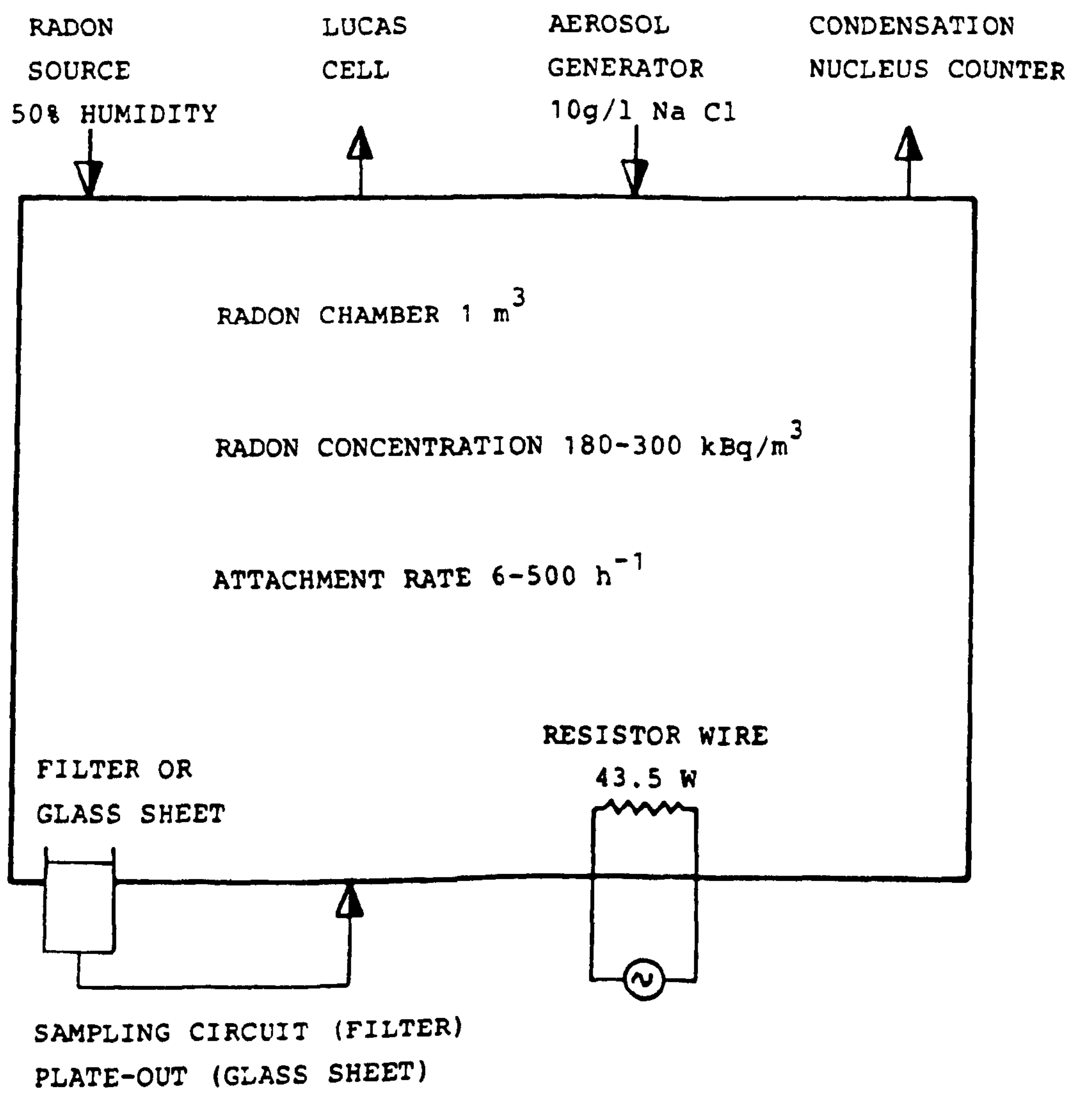


Figure 3. Experimental setup.

The aerosol concentration was measured with a condensation nucleus counter. Turbulence was standardised with a resistor wire dissipating continuously 43.5 W in the radon chamber. A glass sheet was exposed until steady state activities for the shortlived decay products were reached. The Po-218 and Po-214 α-activity of the glass sheet was measured outside the radon chamber for 20 min. Then the glass was cleaned with a cloth containing alcohol and the remaining Po-214 was registered.

Cleaning removes activity from the glass. The number of counts if no cleaning would have taken place was obtained from a filter measurement. The details of the procedure are given by Cornelis (5). The non-wiped fraction is shown in figure 4 as a function of the attachment rate. The indicated error is one standard deviation. The attachment rate was calculated from the particle concentration using the formula of Bricard (6). The diameter distribution was measured a few times with an electrostatic classifier. About 35% of the activity remains on the glass after cleaning. The scatter at high attachment rates is due to counting statistics caused by low plate-out. The lines are the calculated ratios of the absorbed activity to the total activity (absorbed + deposited). They are assessed from the room model using two sets of deposition constants for the unattached decay products. The dashed line was calculated with the same value for the three shortlived decay products (11 l/h, 11 l/h, 11 l/h). Recent experiments (7) indicate that the unattached deposition constant of Po-218 has a higher value than the one of Pb-214. Different values were taken to calculate the full line (11 l/h, 5.5 l/h, 5.5 l/h). A higher deposition constant for Po-218 gives less deviation between theory and experiment (see figure 4).

Cleaning the glass once doesn't remove all of the deposited activity. From the difference between the experimental and the theoretical values (see figure 4) it is concluded that about 15% of the deposited activity remains on the glass.

CALCULATION OF THE Po-210 SURFACE ACTIVITY

The fraction of the Po-210 activity remaining on vitreous glass depends on the values of the parameters of the room model. Most of the variability is due to the deposition constant of the unattached decay products and due to the attachment rate. The surface activity of Po-210 is given in table 1 assuming a radon air activity of 1 Bq/m^3 during 50 years. During this period the following conditions are assumed to be present on an average.

- Ventilation rate 1.0 l/h.
- Surface to volume ratio 3 l/m (a typical value for a furnished room).
- 15% of the deposited activity is not cleaned away.
- Deposition constant of the unattached decay products 10 l/h or 20 l/h or 30 l/h. The same value is taken for all of the decay products.
- Deposition constant of the attached decay products is 1/100 of the deposition constant of the unattached decay products.
- Attachment rate 20 l/h or 40 l/h or 100 l/h.

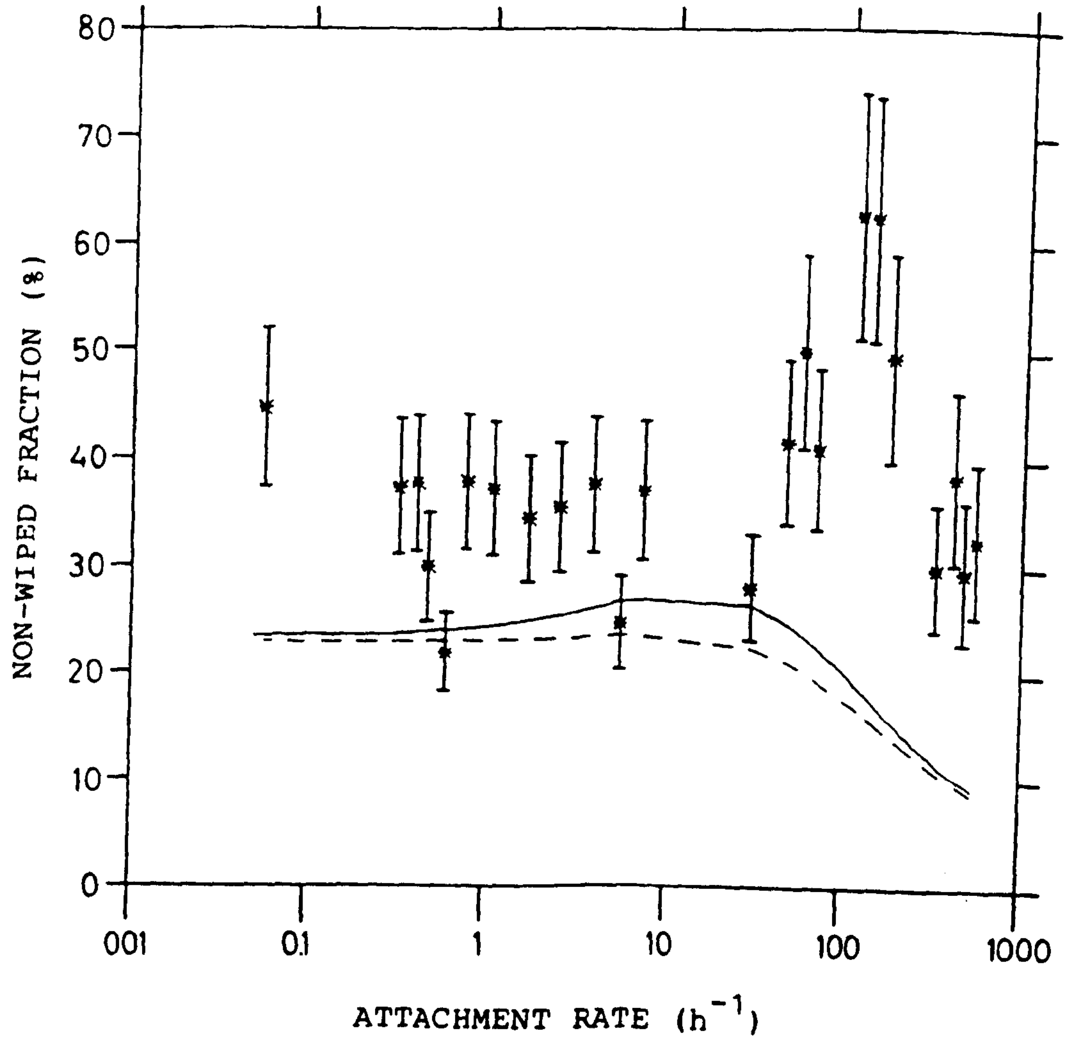


Figure 4. The remaining Po-214 activity after cleaning the glass sheet with a cloth containing alcohol versus the attachment rate. The lines are calculated from the room model using two sets of deposition constants for the unattached decay products. Only the absorbed fraction is assumed to withstand cleaning.

The surface activity of Po-210 is only 3 to 13% of the radon air activity. The attachment rate and the deposition constant are about equally important. The lower and the higher values of the attachment rate are typical for rooms without and with aerosol sources. The surface activity is about a factor of two lower if aerosol sources are present in the room. Turbulence influences the deposition constant. The presence of a convection heater near the vitreous glass, for instance, will enhance the surface deposition.

These considerations indicate that an accurate determination of the cumulated radon activity involves an estimation of the time averaged attachment rate and of the time averaged deposition constant of the unattached decay products.

TABLE 1. THE DEPOSITED AND ABSORBED SURFACE ACTIVITIES OF Po-214 AND Po-210 ASSUMING A RADON AIR CONCENTRATION OF 1 Bq/m^3 DURING 50 YEARS

				Without cleaning		With regular cleaning
X	λ_d^u	Deposited Po-214	Absorbed Po-214	Deposited Po-210	Absorbed Po-210	Absorbed + 15% deposited Po-210
1/h	1/h	Bq/m^2	Bq/m^2	Bq/m^2	Bq/m^2	Bq/m^2
20	10	0.12	0.04	0.07	0.07	0.08
20	20	0.16	0.06	0.09	0.10	0.11
20	30	0.18	0.08	0.10	0.11	0.13
40	10	0.08	0.03	0.05	0.05	0.06
40	20	0.13	0.05	0.08	0.08	0.09
40	30	0.15	0.06	0.09	0.09	0.10
100	10	0.05	0.01	0.04	0.03	0.03
100	20	0.09	0.03	0.06	0.05	0.06
100	30	0.11	0.04	0.07	0.06	0.07

DISCUSSION

The depth distributions of Pb-214 and Pb-210 in glass were calculated from recoiling surface activity and from recoiling Pb-210 already absorbed in the glass, using the theory of Lindhard (3) (see figure 2). Diffusion of the radon decay products in glass is negligable so that Pb-210 and Po-210 have the same distribution. In practice the depth distribution of Po-210 is composed of the two Pb-210 distributions. The importance of each distribution depends mainly on the aerosol and plate-out conditions in the room.
The probability for absorbed Po-214 to reappear at the surface of the glass upon α-decay is 29.8%.

The absorbed decay products are found in a thin layer of less than 100 nm, see figure 2. It should be investigated if decades of household cleaning doesn't remove this layer.
Another problem arises when the vitreous glass is not regularly cleaned. Dust will cover the glass so that a fraction of the recoil nuclei will be stopped in the dust and will be wiped away when the glass is eventually cleaned.
These considerations indicate the need for some tedious experimental work.

Experimental investigations indicate that 15% of the deposited activity remains on the surface of vitreous glass when cleaned once with a cloth containing alcohol. This may be due to radon decay products forming chemical bonds to the glass or to deposition of the decay products into microcracks present on the surface of glass.

ACKNOWLEDGMENT

This work is partly funded by the Commission of the European Communities under contract BI7*-0047-C(JR).

It is not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

REFERENCES

1. Lively, R.S. and Ney, E.P. Surface radioactivity resulting from the deposition of Rn-222 daughter products. Health Phys. 52 : 411-415, 1987.

2. Samuelsson, C. Retrospective determination of radon in houses. Nature. 334 : 338-340, 1988.

3. Lindhard, J., Nielsen, V. and Scharff, M. Approximation method in classical scattering by screened coulomb fields. Mat. Fys. Medd. Dan. Vid. Selsk. 36 : 10, 1968.

4. Landsheere, C. Experimentele en theoretische studie van de fraktie van de Po-210 aktiviteit geabsorbeerd in glas. Student thesis, State Univ. Gent, Nucl. Phys. Lab., 1989.

5. Cornelis, J. Experimentele studie van de invloed van aerosolen op de in glas geabsorbeerde fractie van de Po-210 activiteit. Student thesis, State Univ. Gent, Nucl. Phys. Lab., 1990.

6. Bricard, J. Physique des aérosols II, nucléation, condensation, ions, électrisation, propriétés optiques. Report Commisariat à l'Energie Atomique, R-4831, 1977.

7. Vanmarcke, H., Landsheere, C., Van Dingenen, R. and Poffijn, A. Influence of turbulence on the deposition rate constant of the unattached radon decay products. Accepted for publication in Aer. Science and Techn. 14, 1991.

GUIDELINES FOR
RADON/RADON DECAY PRODUCT TESTING
IN REAL ESTATE TRANSACTIONS
OF RESIDENTIAL DWELLINGS

PREPARED BY

AMERICAN ASSOCIATION OF RADON SCIENTISTS AND TECHNOLOGISTS

REAL ESTATE TESTING COMMITTEE

This document has come about from the hard work over the past two years of many talented individuals who are professionally involved in radon. The document started in a real estate testing committee of the Eastern Pennsylvania Chapter of AARST. The committees year and a half work was completed and turned over to a special sub-committee of the National AARST Technical Committee in October of 1990. This national committee is presently composed of the following individuals: Co-Chairs - Bill Brodhead & Richard Roth, Rich Tucker, Jack Dempsey, Dan Cutler, John Sykes, Ian Thompson, Bill Belanger.

This draft document is the most recent version and although close to a final version is still open to revision and comments. The intent of the committee is to have a final version approved for presentation to the National AARST membership for a vote at the EPA Symposium during the first week of April.

Todate there have been many inquires for the most recent version of this document from state agencies in order to help guide them in setting state policies. It is anticipated that this will be the first such document to address real estate testing directly and thus be influential in the direction that testing regulations take in this critical area.

Please call or fax comments to:

Bill Brodhead Co-Chair of AARST Testing Committee
2844 Slifer Valley Rd.
Riegelsville, Pa. 18077
(215) 346-8004 Fax (215) 346-8575

DRAFT
Version 14B
March 1991

GUIDELINES FOR RADON/RADON DECAY PRODUCT TESTING
IN REAL ESTATE TRANSACTIONS OF RESIDENTIAL DWELLINGS

TABLE OF CONTENTS

This is a living document that is not intended to limit innovative techniques or research, inhibit or prevent consumer choices or prevent positive changes in the industry and, as such, will be reviewed for content, applicability and new developments in the field on a periodic basis.

DEFINITIONS

Terms used in this document are defined as follows:

Action Guidelines - The level of radon or radon decay products in a home above which the EPA recommends taking corrective action and below which the EPA recommends that the occupant should decide if they should take corrective action to further reduce their exposure.

Active Detector - A radon or radon decay product detector that includes electronics or an active pump.

ARE - The absolute value of the relative error as defined by the EPA.

$$ARE = \left| (MV - AV) / AV \right|$$

where MV = Measured Value, and AV = Actual Value.

Attic Ventilator - An exhaust fan installed in the roof or gable of a dwelling that is used to ventilate the attic space.

Average - The number obtained by dividing the sum of a set of quantities by the number of quantities in the set.

Citizen's Guide - EPA Document OPA-86-004 "A Citizen's Guide To Radon", or any revision, amendment or substitution to this document. The Citizen's Guide is an explanation for homeowners of what radon is, how to test their own house for it, and what action would be appropriate based on the test results.

Client - Person, persons or businesses who have contracted with a radon testing company to perform a radon survey in a dwelling involved in a real estate transfer.

Closed-House Conditions - Those conditions defined in the EPA Measurement Protocols and this document for the limiting of building ventilation.

Coefficient of Variation (COV) - The percentage of variation of one measurement to another measurement.

The formula is:
First measurement = M1
Second measurement = M2

$$\frac{\sqrt{(M_1 - M_2)^2 / 2}}{(M_1 + M_2)/2}$$

Combustion Appliance - A unit designed for heating that burns a fuel inside a dwelling that should have the exhaust gases vented to the outside. Examples of this are wood/coal stoves, fireplaces, oil and gas furnaces, boilers and water heaters. A heat pump or a freestanding kerosene stove is not included in this definition.

INTRODUCTION

The American Association of Radon Scientists and Technologists (AARST) is a national, non-profit professional and trade association devoted to benefiting the public health and to formulating measurement and remediation guidelines that assist its members in maintaining a high level of integrity, among other objectives.

Scientific studies since the 1950's have shown a direct relationship between elevated radon and radon decay product concentrations and an increased probability of the incidence of lung cancer. In view of the potential increased risk from lung cancer associated with elevated radon and radon decay products, we, as a professional association, recommend that every occupied dwelling be tested for radon or radon decay products as outlined in the EPA pamphlet, "A Citizen's Guide To Radon" or this guideline.

We further recommend in situations where a dwelling is involved in a real estate transfer, with its many complicating and demanding factors, that it be tested by a professional radon testing technician who is EPA proficient and/or state certified and that the test, as a minimum be conducted according to the guidelines given in this document.

We also recommend that after the installation of a radon mitigation system, a short term test or tests be performed by a testing technician. If the results of this test are below EPA action guidelines, a long term test or several short term tests in different seasons should be done to better define the average concentration of the locations tested and insure that the levels have been adequately reduced.

PURPOSE

This document provides voluntary guidelines for AARST members and other radon testing professionals to follow when conducting radon and radon progeny measurements in residential dwellings involved in the process of a real estate transaction. The purpose of this document is to prescribe procedures and actions which will ensure that accurate measurements are made with a high level of quality assurance and in a manner that is ethical and professional.

Compliance with these guidelines requires that all applicable provisions be completely followed. Exceeding these guidelines is encouraged when doing so is compatible with the purpose of this document.

The Appendices that follow this guideline are listed strictly as examples and are not a part of the this guideline. The use of the information or examples in the Appendices is not required to comply with this guideline.

SCOPE

This guideline applies to measurements of indoor radon and radon decay products made in conjunction with real estate transactions of residential dwellings as defined within this document.

Detector - Any radon or radon decay product measuring device that is used by a testing company and with which the company has successfully passed the most recent EPA RMPP round for that type of detector and/or has met any government or government recognized certification requirements of the state in which the detector is used.

Diagnostic Measurements - Measurements used to help diagnose radon entry routes, radon flux and building conditions. They may or may not follow this guideline or the EPA Measurement Protocols.

Dwelling - A permanent residential structure that is or could be occupied at least 10 hours per week. Excluded are dwellings that are situated above livable spaces over which the occupant of the dwelling has no control. It does not include commercial, industrial, or institutional buildings.

EPA - The United States Environmental Protection Agency.

EPA Measurement Protocols - The following EPA documents: "Interim Indoor Radon and Radon Decay Product Measurement Protocols" (EPA 520/1-86-04, April 1986); "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, February 1987); and "Indoor Radon and Radon Decay Product Measurement Protocols" (February 1989) or any revision, amendments, or replacements to these documents that describe how a radon measurement is to be made. Any reference to EPA Protocols refers to those in effect at the time of testing.

Equilibrium Ratio - The ratio of the potential alpha energy concentration in the air to that which would exist if all short lived radon decay products were in equilibrium with the radon present. A formula for determining the equilibrium ratio is: ER = (WL X 100) / pCi/L.

Follow-up Measurements - Radon measurements that are made to confirm whether the average yearly radon levels, indicated from previous measurements, are above the EPA recommended action level.

Fresh Air Supply - An air duct or air intake that routes outside air to a heating or cooling air handling system to add fresh air to the dwelling.

Lived-In Area - A habitable space within a dwelling that is used for cooking, dining, eating, sleeping or living in. It does not include areas used for closets, storage, hallways, utility rooms, laundry rooms or bathrooms.

Long Term Testing - Any radon or radon decay product measurement that is acknowledged as appropriate and acceptable in the EPA measurement protocols and has a duration of more than three months.

Lowest Livable Area - The lowest level of the house that is a lived-in area or could be converted into a lived-in area without major structural changes such as lowering the floor to create necessary head room.

Make-up Air - Fresh air that is routed directly from the outside to a combustion appliance to supply combustion air that would otherwise be drawn from indoor air.

MARE - The mean absolute value of the relative errors as defined by the EPA, MARE = the average of the ARE's.

Mitigation System - The permanent installation of materials, equipment or an apparatus that is specifically designed to reduce radon or radon decay product levels in a dwelling.

Non-Interference Agreement - A written agreement that is signed by both a representative of the testing company and by the party or parties responsible for maintaining the required conditions of the radon survey at the dwelling being tested, wherein the parties state that they understand and will maintain the necessary conditions for a proper test to be conducted.

Normal Occupied Temperature - Typically this is between 65 and 75 degrees in the lived in portions of the dwelling. It can however be different in rooms that are occupied irregularly, such as an unfinished basement or an attached green house.

Occupant - A person living in a dwelling who may or may not be the owner of the dwelling, and is responsible for the dwelling.

Parties - Owner(s) of the dwelling, buyer(s) of the dwelling, anyone acting as an authorized agent for the buyer(s) or owner(s), any person who is responsible for maintaining the dwelling to be tested on behalf of the owner.

Passive Detector - A radon or radon decay product measuring device that contains no energized electronic parts or pumps. Examples of passive detectors are charcoal canisters and vials, electret ion chambers, or alpha track detectors.

pCi/L - A unit of measurement of the concentration of radioactivity in a fluid, usually a gas. One pCi/L corresponds to 0.037 radioactive disintegrations per second in a liter of air. One pCi/L is the equivalent of 37 Bq/m3.

Primary Measurements - Radon or radon decay product measurements that provide an averaged concentration over the exposure period. The detector shall be located as specified in the EPA Measurement Protocols. The detector shall be exposed in accordance with the recommendations of the detector manufacturer or supplier. The detector exposure time shall not be less than the recommended time as specified in the EPA Measurement Protocols, the Citizen's Guide or any future EPA Real Estate Testing Protocols. The detector shall not be exposed for fewer than 48 continuous hours.

Radon - When used in this guideline without modification, the terms "radon" or "radon measurement" refer to the radioactive elements radon (222Rn) and/or its short-lived decay products. If this document states "radon gas", the term refers only to 222Rn, a naturally occurring radioactive element which is a gas and is measured in units of picocuries per liter (pCi/L) or in units of Becquerels per cubic meter (Bq/m3).

Radon Decay Products - Refers to the first four decay products of radon gas, Polonium 218, Lead 214, Bismuth 214, and Polonium 214. Radon Decay Products are also referred to as radon progeny or radon daughters. The concentration of these products is a combined measurement that is reported in units of working level (WL).

Radon Survey - The process of a testing company following these guidelines in the placing of detectors to sample and analyze the air of a dwelling, either passively or actively, to measure the radon or radon decay product concentration during the test period.

Real Estate Transactions - This refers to the refinancing of a dwelling or the transfer of the title of a dwelling to a new owner and preparing for such actions.

Responsible Individual - This refers to the person or persons who is/are responsible for assuring that closed house conditions are being maintained at a dwelling during a radon survey. This responsible individual does not necessarily have to be the owner of the dwelling.

RMPP - Radon Measurement Proficiency Program sponsored by the EPA to determine the proficiency of testers testing for radon gas and radon decay products

Severe Storm - A period of at least two hours during a test period when the outside winds average at least 25 miles per hour greater than the normal wind speed or there has been over 3/10" of rainfall greater than a typical rainfall for that area in 24 hours.

Shall - indicates a requirement that is necessary to fully adhere to the provisions of this document.

Short Term Testing - Any radon or radon decay product measurement that is a primary measurement and has a duration of from two days to three months.

Should - indicates an advisory recommendation that is to be applied whenever practical.

Structural Area - Each area of a dwelling located directly above a distinct foundation type. Examples of distinct foundation types are a basement, crawl space or slab on grade.

Structural Openings - These are openings from the livable and lived-in portions of the dwelling to the outside that allow a significant exchange of air between the inside and the outside. Examples of these openings would be large air spaces around pipes that penetrate above grade, windows that are broken or will not fully close, large gaps around cellar doors, and crawl space foundation vents.

Test Period - This includes the continuous sampling time of the radon or radon decay product detector. If the detector sampling period is four days or fewer in duration, then the test period must be immediately preceded by 12 hours of closed house conditions. The detector exposure period shall be in increments of 24 hours, plus or minus 2 hours for each day of exposure length. This means that a three day test can be exposed from 66 to 78 hours. The exceptions to this are: An exposure period cannot be fewer than 48 hours; an exposure period cannot be less than the minimum exposure time recommended in the EPA Measurement Protocols, future EPA Real Estate Testing Protocols, the Citizen's Guide or regulations of the state in which the test is being carried out; an exposure period shall be in accordance with the manufacturer or supplier recommendations.

Testing Company - A company or an individual who provides a radon survey for a dwelling involved in a real estate transfer.

Testing Technician - The person responsible for placing and retrieving the radon or radon decay product detector. This person may be the owner, an employee or a sub-contractor of the testing company. This technician shall abide by all the requirements of the state in which the test is being conducted. The technician shall be under the supervision of the testing company. The technician shall have, as a minimum, attended a state or federally approved radon testing course that fulfills any necessary educational requirements for state certification in the state in which the test is being performed, or shall have been continually employed for one year as a testing technician under the supervision of a state certified company.

Whole House Fan - A large exhaust fan used to ventilate the whole house. Typically the fan is installed in the ceiling or attic of the dwelling and draws air from the ceiling of the highest floor of the dwelling.

Working Level (WL) - A measurement unit of the energy that is released by the successive disintegrations of the four short term decay products that follow radon gas in a measured volume of air over a specified amount of time.

1.0 TESTING GUIDELINES

1.1 The guidelines of this document shall be followed unless superseded by the EPA Measurement Protocols or any regulations or certification requirements of the state in which the radon survey is being performed. The testing requirements of any state shall be followed for measurements performed in that state. The existing laws, ordinances and regulations of all governing bodies shall be complied with in any location in which business is being conducted. If any state or Federal regulations has minimum requirements and these guidelines exceed the state or federal regulations, then, these guidelines should be followed.

1.2 Real estate transfer radon tests in a state which has a certification program shall only be conducted by a state certified testing technician or certified testing company. In all cases the placement and retrieval of the detector for the primary measurement of a radon survey shall only be performed by a testing technician.

1.3 A radon survey shall have a minimum of one primary measurement in each lowest livable structural area of the residential dwelling. The same type or a combination of different types of detectors exposed concurrently can be implemented. The testing technician may make any number of additional or diagnostic measurements to obtain additional information. The measurement placement shall conform to the current EPA measurement protocols for screening and follow-up measurements.

1.4 The testing device shall not be moved, covered or have its performance altered during the radon survey by anyone.

1.5 Dwellings that are being tested with short term measurements shall have emphasis placed on maintaining closed-house conditions during the measurement period.

1.5.1 The testing company shall determine who is the responsible individual for the dwelling during the test period. The testing company shall inform the responsible individual of the requirements of and the need for closed-house conditions as well as all other conditions of the test before the detector is exposed.

1.5.2 When the radon survey is four days or fewer in duration, the testing technician shall inquire to determine if closed house conditions have been maintained for the twelve hours prior to the start of the test. If the testing technician discovers that closed house conditions were not maintained or discovers strutural openings that are due to disrepair or structural defects and these openings allow a significant amount of ventilation, the radon survey shall not be initiated until such structural openings have been corrected and twelve hours of prior closed house conditions have been maintained including the repair of the openings mentioned. Closed house conditions prior to the start of the radon survey do not need to be maintained if the exposure period extends to at least four days with an appropriate detector.

1.5.3 Closed house conditions require that all the windows shall be kept closed and external doors shall be closed except for normal momentary entering and exiting during the test period. All windows and exterior doors shall be inspected by the testing technician at the placement and retrieval of the detector.

Heating, air conditioning, and heat recovery ventilators can be operated normally. Operation of dryers, range hoods, and bathroom fans should be kept to a minimum. The responsible individual, however, should be warned that over-use of an exhaust appliance may effect the final readings. Whole house fans shall not be operated. Portable window fans shall be removed from the window or sealed in place. Window air conditioning units shall only be operated in a recirculating mode. Fireplaces or combustion appliances that are not primary heat sources shall not be operated. No ceiling fans, portable dehumidifiers, portable humidifiers, portable air filters portable room air conditioners, to operate in the same room as the detector. If the dwelling contains an air handling system, the air handling system shall not be set for continuous operation.

1.5.4 For short term testing, a notification that a radon survey is in progress, with the conditions of the test stated on the notification, shall be posted in a conspicuous location at the dwelling so that all occupants shall have access to information about the test and the conditions of the test. Appendix D is an example of a testing notification form.

1.5.5 The responsible individual shall be requested to sign a non-interference agreement that indicates a knowledge of the testing conditions of this guideline and a willingness to co-operate in maintaining the required test conditions. If such an agreement cannot or will not be signed by the responsible individual, the testing company shall indicate why the signature was not obtained. Appendix A and B are examples of Non-Interference Agreements.

This signed agreement, along with an inspection of the dwelling at the placement and retrieval of the detector, the informing of the responsible individual, and the posting of a testing notification, shall fulfill a test company's minimum requirements for verifying closed house conditions. This guide does not require the testing technician to be responsible for inspecting for closed house conditions 12 hours before the start of the test or between placement and retrieval.

1.6 Test periods that are four days or less and are made immediately following the installation of a radon mitigation system shall not begin the exposure period for a minimum of 24 hours after the system is completed and operating. Closed house conditions shall be maintained for the 24 hours preceding the start of this test. Test periods that are greater than four days can, however, be started immediately after completing the radon installation.

1.7 If the radon survey is to be a long term measurement, closed house conditions do not have to be maintained. The testing individual or testing company shall, however, recommend to the owner or occupant of the dwelling that at least half the test period should be during the season that the home will most likely be operated with closed house conditions and that reasonable closed house conditions should be maintained during the test period so that the results of the test are more accurate indicators of the yearly average.

1.8 New construction shall not be tested unless the test complies with EPA testing protocols and the following items, if such items are part of the completed dwelling, are installed and completed before the radon survey is initiated: all insulation, all exterior doors, all windows, all fireplaces and fireplace dampers, all ceiling coverings, all interior coverings and interior trim for the exterior walls, all exterior siding, weatherproofing and caulking. If the testing technician or testing company knows work is to be done inside the dwelling during the test period which will interfere with the performance of the test, the testing company shall re-schedule the test.

2.0 QUALITY ASSURANCE

2.1 The testing individual or testing company shall have and abide by a written Quality Assurance Plan (QAP) and a written Standard Operating Procedures (SOP). The QAP and SOP shall be prepared in accordance with the EPA Measurement Protocols and ANSI N323-1978 as well as any relevant EPA, ANSI and detector manufacturers documents.

2.2 All detectors shall only be used according to manufacturers specifications for all primary measurements.

2.3 At least one or a minimum of 20% of all active detectors shall be calibrated at least once a year in a radon chamber that is inter-compared with an EPA or DOE radon chamber or shall calibrate with a source that is traceable to the National Institute of Standards and Technology (NIST). Calibrations shall be according to the manufacturers protocols and shall include all necessary checking of equipment functions.

If the calibration test "ARE" for any active detector or the "MARE" of a group of similar passive detectors is greater than 25%, then the testing company shall make any necessary corrections and repeat the comparison test as specified above, or discontinue testing service with the detector or detectors until its accuracy is confirmed by the test specified above.

2.4 All other active detectors used by the testing company will be inter-compared at least 5% of their usage with a detector calibrated according to the procedures listed in 2.3. If any of these testing company inter-comparisons produce an "ARE" greater than 10% from the calibrated detector, then the deviant detector or detectors shall be recalibrated to match the chamber calibrated detector and recompared to the chamber calibrated detector to verify accuracy before being used again.

2.5 To assure proper operation of active instruments between calibrations, the instrument should be tested with a check source prior to each measurement survey. Ambient background radiation readings and/or blank samplers or detectors shall be obtained at the sampling frequency specified by the manufacturer.

2.6 Each active detector shall have its identification code and its latest calibration date written on the outside of the detector.

2.7 All calibration and check source data shall be recorded and maintained by the testing company.

2.8 QAP's for testing companies that utilize passive detectors shall include a minimum of approximately 5% of each type of passive detector deployed or 25 each month, whichever is smaller, set aside as blanks. These blanks will be treated identically as similar field detectors except they will be kept sealed in a low radon environment, less than 0.5 pCi/l, during the exposure period of the field detectors and returned for analysis along with the field detectors. If one or more of the field blanks produces a measurement result that is significantly greater than the LLD or other standard specified by the manufacturer for that detector then additional blanks will be returned for analysis. If any of these blanks also have measurement results greater than the LLD commercial use of this detector type will be discontinued until correction can be made and verified by the processing laboratory.

2.10 QAP's for testing companies shall include a minimum of approximately 10% of each type of detector deployed or 50 each month, whichever is smaller, exposed as a duplicate with another detector, side by side exposure. Each duplicate shall be treated identically. If possible the duplicates shall not be identified as such to the processing laboratory. These duplicates shall be distributed throughout the radon surveys conducted during the month. If any of these duplicate measurements have greater COV than 25% from each other at radon concentrations greater then 4 pCi/l than duplicate measurements will be made with the next radon exposure of the same detector. If this duplicate measurement also produces a COV more than 25% from the duplicate detectors, then commercial use of this detector will be discontinued until the precision of the detector is verified to be within the above standard.

3.0 REPORTING TEST RESULTS

3.1 The test report shall be in writing and either mailed, faxed or handed to the client within five business days after the results are available to the testing company. All reporting statements required by this document shall be included in the test report. The client should be informed of any reporting of results to persons other than the client.

3.2 The test report shall contain all individual primary measurement results and their locations. The test report shall contain a description of the type of detector used, its manufacturer, model or type and the detector identification numbers. No average of any measurements made throughout the dwelling shall be reported. Any diagnostic measurements shall be reported as such.

3.3 If there is a visible active radon mitigation system installed in the dwelling, the testing company shall include a statement in the test report indicating the presence and operation of a mitigation system at the time of placement and retrieval of the detector. The testing company should include a statement that the testing company makes no claims as to the proper operation of the system.

3.4 Any readily visible structural openings shall be noted on the test report as to their presence and condition.

3.5 Any Known variation from the required test conditions during the test period that the testing company or testing technician discovers shall be included in the test report. If the testing technician or testing company discovers that the test area is not maintained at normal occupied temperatures during any portions of the test period at the time of placement or retrieval of the detector, the test report shall report this condition.

3.6 The test report should describe the general limitations of the test such as the following statements: the testing company cannot be assured that the necessary conditions of the test were interfered with or that any interference would influence the radon or radon decay product measurement; there is an uncertainty with any measurement result due to statistical variation and other factors; there are daily and seasonal variations in radon concentrations due to changes in the weather and operation of the dwelling; if a severe storm occurred during a short term test period, it may raise or lower the radon levels of the building, and it may be necessary to repeat the test.

3.7 The measurements shall be reported in units that are appropriate to the measurement method. Any test results that convert the measurements to the unit of another product shall include a statement similar to the following:

> Any conversions from WL to pCi/L or pCi/L to WL are only approximate conversions and are not likely to be the true concentration of the converted value.

3.8 All test results shall include a statement which recommends that the dwelling be retested for each of the following situations whether the dwelling has or has not been mitigated:

a) Occupancy by a new owner
b) A period of six months since a short term test
c) A period of three years since a long term test
d) A new addition to the dwelling
e) An alteration is made to the dwelling which could change the ventilation pattern of the dwelling
f) Major cracks occur in the foundation walls or slab
g) An unsealed penetration is made in a foundation wall or slab
h) Significant construction blasting or earthquakes
i) Changes are made or happen to an installed mitigation system*

APPENDIX A

EXAMPLE OF A NON-INTERFERENCE RADON TEST AGREEMENT FOR RESIDENTIAL DWELLINGS

REQUIRED CONDITIONS OF THE RADON SURVEY

Radon and radon decay product concentrations in a dwelling fluctuate. The following test recommendations were developed by the USEPA to provide standardized conditions under which a short term radon test is to be performed in order to reduce the variation in radon levels in a dwelling. These conditions will tend to maximize the radon measurement in order to determine if a dwelling has the "potential" to have an elevated radon level. If the result is elevated, the EPA recommends further testing to better determine the yearly average concentration.

The radon technician has my permission to install and retrieve radon testing devices at the property listed below. AGREE ____ DISAGREE ____

I/WE will not move, cover or try to alter or effect the performance of the test devices. AGREE ___ DISAGREE ___

I/WE will not touch, and/or remove any non-interference controls which may be used. AGREE ___ DISAGREE ___

I/WE will not operate equipment, other than a HRV, which brings fresh air directly into the building. AGREE ___ DISAGREE ___

I/WE will not use any whole house ventilating fans, wood stoves or fireplaces unless they are primary heaters. AGREE ___ DISAGREE ___

I/WE will keep all windows closed and external doors closed except for normal momentary entering and exiting. AGREE ___ DISAGREE ___

I/WE agree that the normal occupied operating temperature be maintained at the test location. AGREE ___ DISAGREE ___

I/WE will notify the testing co. during or at the test conclusion if any conditions of the agreement are violated. AGREE ___ DISAGREE ___

I/WE agree that the above conditions have been or will be maintained by all persons at the test location during the testing period. If the measurement period is four days or less I/WE verify and agree that these conditions have been or will be maintained for the 12 hours before the detector is exposed. AGREE ___ DISAGREE ___

Property Location: ______________________________

Detector Type & Locations   Testing Technician ______________________

1st______________________   Owner ______________________

2nd ______________________   Agent ______________________

3rd ______________________   Signing Date ____________

Installed Date/Time ____________   Retrieval Date/Time ____________

Comments:

APPENDIX B

EXAMPLE OF A NON-INTERFERENCE RADON SURVEY AGREEMENT FOR RESIDENTIAL DWELLINGS

REQUIRED CONDITIONS OF THE RADON SURVEY

Radon and radon decay product concentrations in a dwelling fluctuate from hour to hour, from day to day and from season to season. The following test recommendations were developed by the EPA to provide standardized conditions under which a short term radon test is to be performed in order to reduce the variation in radon levels in a dwelling. These conditions will tend to maximize the radon measurement in order to determine if a dwelling has the "potential" to have an elevated radon level. If the result is elevated, the EPA recommends further testing to better determine the yearly average concentration.

If the test conditions below are not adhered to, the test results may be deemed invalid. The following conditions must be read, understood and followed:

All windows must be kept closed. All doors must be kept closed except for normal, momentary entering and exiting.

The radon detector cannot be moved, covered or altered in any way.

Heating, air conditioning, dryers, range hoods, bathroom fans and attic ventilators can be operated normally. If any heating, air conditioning or ventilating equipment has a built in fresh air supply, it shall be turned off or the inlet closed. Fireplaces or wood stoves shall not be operated, unless they are a primary heat source. Whole house fans shall not be operated. Window fans shall be removed or sealed shut. The dwelling shall be maintained at its normal operating temperature.

These test conditions shall be maintained for 12 hours prior to the start of the radon detector being exposed, unless the test is longer than four days in duration.

If there are any questions, or the test conditions are not met, please contact the testing company at (Co. Phone Number)

I/We the occupant or building custodian understand and will inform all parties in this dwelling of the above conditions of the test. I/we agree to maintain these conditions during the test period.

Property Location: ______________________________

Technician ____________________ Owner ____________________

Installed Date/Time ______________ Retrieval Date/Time ______________

Detector Locations ______________________________

Date __________ Comments:

APPENDIX C

NON-INTERFERENCE CONTROLS

INTRODUCTION

The following are examples of non-interference controls which may or may not be used to help deter or determine that interference has occurred during a radon survey. These examples do not provide complete assurance that a radon survey has or has not been interfered with.

This appendix is provided for reference purposes only and are not required by the guidelines to verify closed house conditions unless these examples are directly specified in the guidelines.

EDUCATION

Before the radon survey is begun, educate all parties responsible for the dwelling to be tested about the conditions of the radon survey, and the necessity to adhere to these conditions or the test results may be deemed invalid. This includes the owner and occupants of the dwelling as well as the real estate brokers or any individuals responsible for the dwelling during the test.

Inform all individuals who may or will enter the dwelling about the conditions of the test by prominently displaying a notification of a radon survey in progress and the conditions of the test, on or near all exterior doors that are normally used for entrance into or out of the dwelling or in another prominent location.

AGREEMENTS

Have the owner or the person responsible for the dwelling read and sign a non-interference agreement.

WINDOWS & DOOR SEALS

Windows, especially those in the same room as the detector, can be marked with seals placed between the window sash and the jambs to identify any movement. Some seals should be visible to help deter anyone from attempting to open the window during the test period. The window could also have invisible seals installed to reduce the chance of someone removing all the seals and later replacing the removed seals when the window is closed. Some of the possible seal materials include clear double stick tape, white paper seals, and removable non-staining adhesive caulk. The seals can be further altered to avoid tampering by using color coded tape or coloring it at the test site, initialing or coding white paper seals or slicing the seal to make it difficult to remove or open the window without tearing the seal.

Exterior doors that are not the primary entrance into the dwelling could be sealed in a similar manner as the windows or with seals on the door hinges.

DETECTORS

A continuous radon or radon decay product detector can be used that gives interval measurements. An unusual variation in concentrations might indicate that the dwelling was ventilated or the performance of the equipment was altered or that severe weather conditions took place during the exposure period.

To determine if a detector is moved during a test period the detectors can be installed in a noted position or on top of a paper with a coded grid or light sensitive paper. The paper would first be installed with double stick tape to secure it in place. The detector would then be placed in a noted location on the grid so that any movement of the detector could be determined at the time of retrieval. The movement of the detector can then be documented by drawing a circle around the detector in its changed position.

The radon entry location into the detector could have a loop of double stick tape installed in such a manner that it does not obstruct the entry of radon into the detector but reduces the possibility of the entry location being covered.

The detector could be placed in or on a motion detector that does not interfere with the performance of the detector but detects any movement.

The detector could be placed to overhang the edge of its stand so that any attempt to cover it up would be difficult.

If the detector stand is portable, the stand could be taped to the floor in a manner that would indicate any attempt to move the stand.

VENTILATION EQUIPMENT

Switches which control ventilation equipment could be held in place with a double stick tape or white initialed tape. This may include the fresh air supply control for a window air conditioner. In an unoccupied home, a seal could also be placed on the electrical control panel to indicate changes in the power supply to the heating equipment.

GRAB SAMPLES

Grab samples taken of radon and/or radon decay products at the beginning and/or end of the test period can be compared to the average test results from the whole exposure period. If there is a significant difference in the readings, it might indicate the building had been ventilated either before or during the exposure period. Grab samples can be used to locate the measurement device in the highest radon location that still falls within the protocols placement location.

MEASUREMENTS of RADON and RADON DECAY PRODUCTS

If both radon and radon decay product measurements are made at the same time at the beginning and/or end of a measurement period, the equilibrium ratio between the readings can be obtained. If there is significant variation in the readings or the reading is significantly low it may indicate that excessive ventilation has taken place.

TEMPERATURE MEASUREMENTS

Temperature readings of the outdoor and the indoor testing area taken at the beginning and end or throughout the measurement period might indicate excessive ventilation if the indoor temperature is significantly closer to the outdoor temperature as compared to the normal occupied temperature of the dwelling.

APPENDIX D

EXAMPLE OF RADON SURVEY IN PROGRESS NOTIFICATION FORM

RADON SURVEY IN PROGRESS

DO NOT REMOVE THIS NOTIFICATION

The following conditions must be maintained:

1) Do not open any windows. Do not open any doors except for normal momentary entering and exiting.
2) Do not touch, cover, move or alter the performance of any radon detectors or non-interference controls.
3) Do not operate any whole house fan(s). Do not use any fireplace(s) or wood stove(s) unless they are the primary heat source.
4) Operate heating and air conditioning normally. Turn off any equipment which supplies fresh air to the house unless it is vented supply air to a combustion appliance.
5) **The testing locations must be maintained at their normal occupied temperature.**

NOTE:

Exhaust fans such as the dryer, range hood, bathroom fan or attic ventilating fan can be operated. This equipment should only be operated normally because any exhaust fan or any combustion appliance may increase the negative pressure in the dwelling, which can raise or lower the radon concentration. Windows must be kept closed because they can create negative pressure in the lower portions of the house due to the warm air escaping or the direction of the wind, which can raise or lower the radon levels

From: ____________________

Responsible Party: ____________________ To: ____________________

UNIT VENTILATOR OPERATION AND RADON CONCENTRATIONS IN A PENNSYLVANIA SCHOOL

By: Norm Grant
Quoin Partnership, Architects & Engineers
Trappe, Pa.

Bill Brodhead
WPB Enterprises, Inc.
Riegelsville, Pa.

ABSTRACT

An elementary school in Pennsylvania was tested in the spring of 1990 and discovered to have elevations ranging from 5.5 to 76 pCi/l in 25 different rooms. The school is divided between an older wing that is a slab on grade with an access tunnel around the perimeter and a newer wing that has half the classrooms over a slab and the other half over a walk out multipurpose room, kitchen and maintence room. Although typically the operation of a univent heater will reduce radon concentrations in a room because of the introduction of outside air, it was discovered however that in the older wing of the school, the heaters were responsible for a significant portion of the radon entering the classrooms. This paper is a review of the operation of the univent heaters and alterations to the units and the operation of the building in order to determine the radon pathways and how they might be controlled.

EXECUTIVE SUMMARY:

Diagnostic testing was conducted over several days from December 22, 1990 through January 14, 1991. It included radon detection utilizing sampling techniques at specified intervals, as well as, averaging monitors. Additional types of measurements were made to determine building and radon behavior under various operating and potential remediation conditions.

Radon exists in varying concentrations (from near 0 to approximately 1700 pCi/l) beneath the floors in contact with the ground in virtually all areas of the school. This radon is migrating into the building and then diffuses through the building, following normal air currents in the structure. The diffusing process tends to dilute the radon to levels from about 2 to 90 pCi/l within the occupied areas of the building.

The mechanical systems of the building, both wings, are presently not operating as designed. For example, in the old wing' there is far less outside air being introduced than necessary for Pennsylvania Department of Education requirements. This contributes to higher interior radon concentrations (and may also contribute to a higher transmission of communicable diseases). The apparent lack of operation of a portion of the mechanical system to relieve pressure in the new wing may be forcing radon to migrate to the old wing.

Radon can be remediated by using the following techniques and/or combinations thereof:

1. *Subslab depressurization* - Creating a slightly lower pressure under the floor(slab) of a structure to intercept or "vacuum off" the radon before it has an opportunity to penetrate any openings on the foundations and/or floor.
2. *Sealing* - Effective blocking of entry routes for any subslab gas.
3. *Building pressurization* - Creating a slightly greater interior pressure than exists below the building slab so that the building effectively resists the entry of any gas from below.
4. *Dilution* - Introducing sufficient outside air to reduce interior radon concentrations to acceptable levels.
5. *Conducive condition avoidance* - Removing operational conditions which enhance radon entry into a structure.

The greatest success with radon remediation has historically been achieved with a combination of the first two approaches. Each method has its advantages and disadvantages, none is effective "forever," without some attention/maintenance. It should be clearly understood that because of environmental conditions (expansion, contraction, settling, mechanical wear, deterioration, weathering, etc.), once a building is remediated, it should be regularly retested to insure that the system is functioning as intended. The US Environmental Protection Agency suggests annual retesting. There are maintenance procedures that may be involved in the system implemented.

OLD WING:

Remediation can be most cost-effectively achieved by subslab depressurization in the old wing by utilizing the existing subslab utility tunnel as part of that depressurization system. This has been effectively demonstrated by the temporary system in operation. That temporary system should be made permanent and be supplemented by additional appropriate sealing techniques to reduce radon concentrations to within acceptable levels. The asbestos-containing materials in the tunnel should be removed and new insulation applied to the piping in the tunnel to minimize energy loss.

Since evidence indicates inadequate and improper operation of various functions of the mechanical system, that entire system should be "tuned-up" to insure proper functioning of all components and outside air introduction. Unit ventilators should be installed in normally-occupied rooms which do not have them.

There was a "conducive condition" which clearly increased the potential for radon entry from the tunnel to the classrooms: When the unit ventilator fans operated, they virtually "inhaled" any radon that existed in the tunnel below. The unit then distributed that radon-laden air to the classroom. The solution to that problem has been identified and implemented, namely, reducing the tunnel pressure beyond the capability of the unit ventilator to draw on it, reducing the capability of the unit to "inhale" from the tunnel, and sealing penetrations between the unit and the tunnel, all without affecting unit ventilator performance.

Since the utility tunnel was an integral part of the old wing mechanical system, and is now excluded from that use by its functioning as the plenum for a subslab depressurization system, new provisions for proper operation of the mechanical system must be implemented. This will involve providing grilles in each of the classroom doors.

NEW WING:

The mechanical system on the Main Level should be returned to its intended mode of operation. A unit ventilator should be provided in the special education classroom.

On the Main Level, a subslab depressurization system, which could be integrated with the Lower Level system, should be designed and implemented.

On the Lower Level, a subslab depressurization system should be designed and partially implemented to address those areas of highest subslab concentrations. That system should include provision for addressing the lack of porosity of the subslab material so that adequate, relatively-consistent, depressurization can be achieved. The design should also incorporate sealing apparent cracks and construction joints in the floor, as well as, the cores of the block walls, at or near, the floor of the Storage Corridor and the Faculty Dining Room.

The design should commence so that implementation of the Lower Level remediation could occur over a few weekends or during Spring vacation.

RELOCATABLES:

Since radon detected in this area is significantly lower that most other parts of the school and it is speculated that radon may be migrating from the old wing, it would be appropriate to wait until the remainder of the building is remediated before undertaking a campaign to relieve a problem that may not exist.

TIMING:

Since levels well in excess of 20 pCi/l have been confirmed by multiple tests, the US EPA recommends that action be taken within several weeks to implement remediation.

PROCEDURE:

1. Design and specify the radon remediation system incorporating all appropriate techniques outlined herein, the necessary mechanical system redesign elements, the mechanical system "tune-up," the terms and conditions of all contracts, and the bid package(s)/documents.
2. Advertise for bids when appropriate.
3. Evaluate bids.
4. Select contractor.
5. Implement remediation.

DISCUSSION - OBSERVATIONS ("Old" Wing):

Heating/Ventilating System:

Classrooms:

The heating system consists of steam-supplied unit ventilators manufactured by Herman Nelson (no longer in business) in each classroom. The unit ventilators include provision for outside air and return air mixing to respond individually to room conditions. Return air is delivered to each unit by means of a plenum chamber built behind integral bookcases/storage shelving. There is no direct opening for return air through the front of the enclosure from the room to the return air chamber (lowest portion) of the unit ventilator.

An "on-off", and three-position fan speed control is readily accessible at the unit. There is a centralized pneumatic temperature control system which controls outside air introduction, steam delivery and day-night temperature selection and fan operation (entirely dependent on the position of the local fan controls) via day thermostats in each classroom and night setback thermostats in two classrooms (Rooms 2 and 6).

During school-day operation, each unit ventilator responds to the thermostat and fan controls manually-set in its respective classroom. During the night mode, the unit ventilator fans are disengaged and the unit ventilators respond to the night thermostats by adjusting steam application to all units.

As part of the original heating and ventilating design, the school is provided with a utility tunnel containing steam supply piping, steam condensate return piping, hot and cold water piping, sink drain piping, and electrical conduits. Some of these pipes are insulated with seriously-deteriorating asbestos-containing insulation. This tunnel also served as relief for fresh air introduced by the unit ventilators. Each classroom contains grilles (18 in X 16 in) open to the tunnel. Originally, a normally-running fan was provided at the accumulated end of the tunnels in the boiler room to continually withdraw air from each classroom via the utility tunnel, discharging that air into the boiler room where it would become combustion air for the boiler and/or would be forced to the outside through a large louver above the exterior double door. According to maintenance personnel, the relief fan has not operated "in years." However, because of the tunnel configuration, heating of tunnel air, and the higher temperature level in the boiler room, there is air movement occurring in the tunnel caused by convection, from the tunnel extremities to the boiler room.

It is important to note that the positions of the indoor and outdoor dampers in the unit ventilators is a function of mechanical adjustments, and these adjustments varied significantly from classroom to classroom. Because of this, the percentage of damper opening and closing could not be ascertained by the damper mechanism indicator. It was demonstrated that the dampers in half of the classrooms did respond to thermostat settings by automatically adjusting the dampers accordingly, but the exact ratio of outside to return air could not be visually determined. In one case (Room #3), the return air damper was "caught" on pneumatic control tubing and could not move. [We extricated it.]

In classrooms 2, 4, 6, and 8 the outside air dampers remained closed regardless of the operating mode. In three classrooms the Honeywell air stream control device is disconnected. In classroom 4, there is a steam leak and also, the steam to the unit ventilator does not shut off, even though the thermostat is satisfied. In classroom 5, the damper modulated inconsistently.

Day thermostats were set between 60 and 75 degrees Fahrenheit. Night thermostats were set at 64 and 70 degrees Fahrenheit.

DISCUSSION - OBSERVATIONS ("Old" Wing):

Other Spaces:

The office areas, health room, lobby, corridor, boys and girls rooms are heated by means of thermostatically-controlled steam-supplied cabinet unit heaters and convectors. In these cases, there are no automatic provisions for outside air supply. Whereas the office, health, and lobby have operable windows, the interior office, corridor, faculty (snack), and boiler rooms have non-operable windows. The girls and boys rooms have no windows.

It was observed behind some exterior wall convectors that there are direct openings into the exterior wall wythes and block cavities.

The flooring above steam pipe routing in the lobby area was hot (as opposed to warm) to the touch. Actual temperature measurements revealed that this floor was maintained at 112 degrees Fahrenheit, when the building was in the heating mode. (note: Water above 110 degrees F is generally considered to be scalding.)

DISCUSSION - EXISTING DRAWING ANALYSIS ("Old" wing):

Structure:

Interior and exterior wall footings are constructed of porous concrete masonry units (blocks) which, on the interior continue as walls up through the floor slabs.

There is indication that there should be 4 in. of stone directly below the floor slabs.

The tunnel volume is approximately 6800 cubic feet.

The energy-saving retrofits were designed to reduce both heat loss by the reduction in glass window surfaces and exfiltration by providing "tighter" construction details.

Heating and Ventilating:

The boiler(steam generator) is specified as 60 bHp.

The unit ventilators are specified as 1000 cfm, 450 cfm outside air, 43.0 MBH total, with a 1/12 Hp motor.

The boiler room tunnel exhaust fan is specified as 4210 cfm at 1/4 in. static pressure, with a 1/2 Hp motor.

The unit heater in the lobby and the convector in the faculty room are supplied by steam piped in terra cotta sleeves under the floor from the tunnel to the units.

The boys and girls rooms have a common exhaust fan. The private lavatory in the office area has an exhaust fan.

DISCUSSION - POTENTIAL RADON ENTRY ROUTES ("Old" wing):

The initial building audit revealed several conditions that could contribute to radon infiltration into the occupied spaces. The extent, size, configuration, and construction materials(porous block footings and walls and dirt/shale floor) of the utility tunnel present a natural path for any subslab radon to accumulate and/or move. There are several direct openings from the tunnel to each room for air relief, heating pipe sleeves, and electrical conduits. In addition, five rooms (Rooms 1, 3, 4, 7 and the Health Room) have loosely-fitting tunnel access doors with holes at the handles, built into the floor.

The hollow cores of interior wall blocks, because of temperature variations within the cavity, cause an air flow from below the floor to the interior of the building and to above the ceiling. This could be radon-laden air, which depending on a number of conditions could be infiltrating the building.

There is a significant crack in the terrazzo floor of the corridor in the vicinity of the office area. This breach will allow passage of subfloor gases.

It was indicated that classroom doors are normally kept open during the school day unless noise control is necessary. This tends to equalize radon levels.

It is possible, because the pressure relief dampers are closed in the new wing, that radon may be migrating between the "old" and "new" wings, as well as, between the old wing and the relocatables.

DISCUSSION - TESTING METHODOLOGY

Appendix A contains previous test data made available by the School District and the Pennsylvania Department of Environmental Resources to Quoin Partnership.

In the process of building analysis, consideration was given to potential radon remediation techniques, the most successful of which has proven to be subslab depressurization (the interception of radon gas below the slab by creating a slight vacuum in the space below the slab and safely exhausting the gas to the exterior).

The initial effort concentrated on a detailed audit of the building, its systems, and the existing operation of those systems under various conditions. Secondly, it was intended to prepare the building to operate as it would during school conditions during the winter, since this would result in the probable worst case scenario, under which minimum introduction of outside air occurs therefore radon concentrations would be expected to be the highest.

In the worst case operating mode the building would then be tested, based on previous screening and confirmatory radon measurements. Testing included determining whether or not the building was pressurized (working against radon entry) or depressurized (enhancing radon entry) relative to the exterior and the ground beneath the structure. To make these pressure measurements it was necessary to drill through the structural slabs (floors) in selected rooms which are in contact with the ground.

Under those same conditions, pressure measurements were made between various locations within the structure and components of the building to ascertain potential radon infiltration routes and radon behavior within the building, and to identify any building systems operations which might be contributing to radon infiltration.

Visual chemical smoke tests were conducted to determine the behavior of the air (and other gases, including radon) at selected locations within the structure. These tests could indicate radon entry points, radon transmission (communication) within the building and its structural elements, and potential success of remediation techniques.

At most floor slab penetrations, radon sampling was done to obtain a profile of apparent subslab radon concentrations.

In the original (1956) wing of the school, a sub-floor utility tunnel which extends virtually around the entire perimeter offered a high probability of subslab radon distribution to various parts of the building. Radon measurements were taken at various locations in this "tunnel."

Very short term(less than one minute) radon sampling measurements were taken by "Pylon" radon monitors for relative comparison between tested points. Longer-term (hours and days) radon measurements were taken utilizing electret devices and "Pylon" monitors, the latter set to record levels in desired increments of time (hourly and in some cases every 15 minutes), so that radon levels under different operating conditions of the building could be compared.

Additional environmental parameters (temperature and air flow) were measured under various conditions as needed.

RESULTS/CONCLUSIONS - OLD WING

Conclusions

The subslab Pylon sampling indicates that radon exists and/or migrates to varying degrees throughout the area below the building.

Radon concentrations in the tunnel were as high as 436 pCi/l. Entry to that space should only be done by personnel with the proper radon protective equipment.

There are multiple intentional (pipe sleeves, relief grilles, etc.) and unintentional openings (normal construction situations) between the tunnel and occupied spaces and the subslab areas and occupied spaces which allow radon entry.

All walls with hollow cores represent potential radon infiltration routes, because they are supported by hollow core foundation walls which extend several feet below the floor slabs.

The spaces without unit ventilators or exhaust fans, and consequently, with no fresh air introduction have no means of diluting or exhausting any radon that enters the space.

Operation of the unit ventilator fans, at any speed, results in a negative pressure at the base of each unit. That negative pressure is sufficient to cause any gas, including radon, which exists in the tunnel to be drawn into the unit ventilator return air chamber, and from there, to be distributed to the classroom.

The automatic response and mechanical linkage adjustment of the unit ventilator outside air introduction is inconsistent. Air flow data indicates that some units provide no outside air introduction while others provided far less than the original design criteria and consequently, far less than the current Pennsylvania Department of Education requirements. Therefore, there is, in some cases, no dilution for radon entering a classroom, and in others, less than adequate outside air introduction.

Depressurizing the tunnel by means of a HEPA negative air unit, without sealing slab penetrations providing significant leakage points, would have resulted in unsatisfactory depressurization of the areas below the slab. Once obvious/major openings from the rooms to the tunnel had been sealed, depressurization was achieved, therefore this demonstrates adequate subslab communication, and a satisfactory long-term subslab pressure reduction method.

Attempting a potential interim method of flushing the building with outside air and then operating under normal interior conditions without subslab depressurization resulted in unacceptable radon build-ups in a matter of a few hours. Therefore, flushing only, is not an acceptable interim measure to reduce radon.

Subslab depressurization by exhausting tunnel air to reduce tunnel pressure to -0.020 relative to the rooms, is, in itself, insufficient to reduce radon concentrations in all areas to 4 pCi/l or less.

Tunnel depressurization does not reduce subslab pressures in the interconnecting corridor between the wings.

RESULTS/CONCLUSIONS - OLD WING

Recommendations:

1. All asbestos-containing materials in the tunnels should be removed. This will allow subslab depressurization utilizing the existing tunnel for the exhaust plenum without addressing the hazards of asbestos: There will be no maintenance and disposal of any asbestos filters. Radon remediation workers requiring access to the tunnel will only require radon protective breathing apparatus rather than full protective clothing (and the associated disposal costs), as well. Removal of the deteriorating pipe insulation will allow complete and proper insulation of the steam and hot water pipes with the resultant energy savings. Lastly, maintenance personnel can have access to the tunnels for maintenance and repair with only breathing precautions (for radon) rather than complete body and breathing protection for asbestos.

   NOTE: Radon remediation can be undertaken without removing asbestos-containing materials in the utility tunnel. Such remediation will significantly increase radon remediation costs because of the expense associated with reduction in remediation worker efficiency associated with the necessary asbestos protective required for workers and the building; as well as, the costs associated with disposal of contaminated clothing.

2. All openings between the tunnel and the exterior, and the tunnel and the occupied spaces, should be sealed against radon infiltration. Any existing openings in the interior tunnel walls should remain to aid in subslab depressurization. Exterior tunnel wall penetrations, if any, should be similarly sealed. All existing classroom pressure relief grilles should be permanently sealed. Mechanical system design-compatible pressure relief louvers should be provided in all classroom doors such that during outside air introduction the room remains slightly pressurized relative to the subslab area.

3. A code-compliant tunnel depressurization system should be provided to create a minimum negative pressure of -0.020 at all subslab locations. The system should include a roof-mounted fan, (with appropriate air-flow annunciation) above the boiler room, interconnected to the existing tunnel duct in the boiler room. All existing and new duct work should be designed to prevent and/or sealed against, any radon leakage into the boiler room. The system shall be provided with all code-required smoke detection and interlocked, if necessary, with the exhaust fan.

4. The lower front panel enclosure for each classroom unit ventilator should be perforated to reduce the negative pressure in the lower portion of the unit, immediately above the floor and tunnel below it. (This recommendation has been implemented by SGASD staff.)

5. The mechanical heating and ventilating system should be "tuned-up" to insure proper control and mechanical operation, including appropriate outside air introduction per the Pennsylvania Department of Education Plancon requirements. Unit ventilators should be provided in occupied spaces presently without outside air introduction.

6. Potential additional measures which could be implemented to help alleviate radon infiltration include:
   A. Drilling and sealing the hollow cores of the masonry units of the uppermost row of the exterior wall of the tunnel.
   B. Removal (and subsequent replacement) of bookshelves and storage shelves adjacent to the unit ventilators to seal any potential infiltration routes not observable without their removal.
   C. Install an independent subslab system for the interconnecting corridor between the wings.

SPRING GROVE AREA SCHOOL DISTRICT

RADON DIAGNOSTIC TESTING DATA

December 26, 1990, 6:00 PM

Pressure Differentials - Room #1 Unit Ventilator[inches H_2O] (Main Level-Old Wing)

[Both top control access doors closed during measurements]

Room to exterior: +0.010
Room to tunnel: -0.020

		Lower Left Side	Lower Center	Lower Right Side
Front of enclosure in place:				
Fan Speed	Off	+0.001	Not Accessible	Not measured
	Low	-0.034	Not Accessible	-0.038
	Medium	-0.040	Not Accessible	-0.043
	High	-0.044	Not Accessible	-0.048
Front of enclosure removed:				
Fan Speed	Off	Not measured	Not measured	Not measured
	Low	-0.002	-0.005	-0,002
	Medium	-0.002	-0.006	-0.003
	High	-0.002	-0.007	-0.004

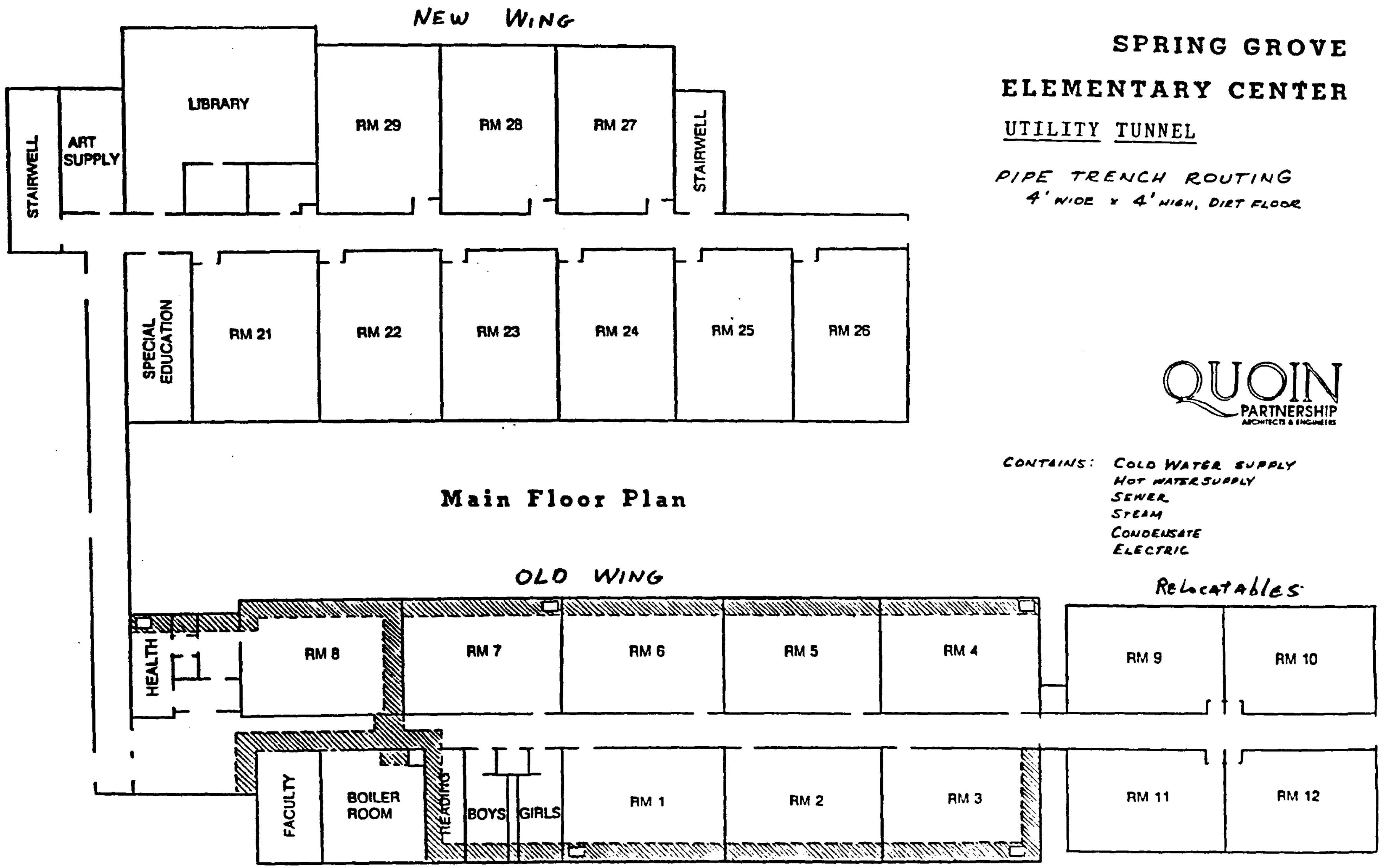
SPRING GROVE ELEMENTARY CENTER

UTILITY TUNNEL

PIPE TRENCH ROUTING
4' WIDE x 4' HIGH, DIRT FLOOR

QUOIN PARTNERSHIP
ARCHITECTS & ENGINEERS

CONTAINS: COLD WATER SUPPLY
HOT WATER SUPPLY
SEWER
STEAM
CONDENSATE
ELECTRIC



REV NO.

SGASD

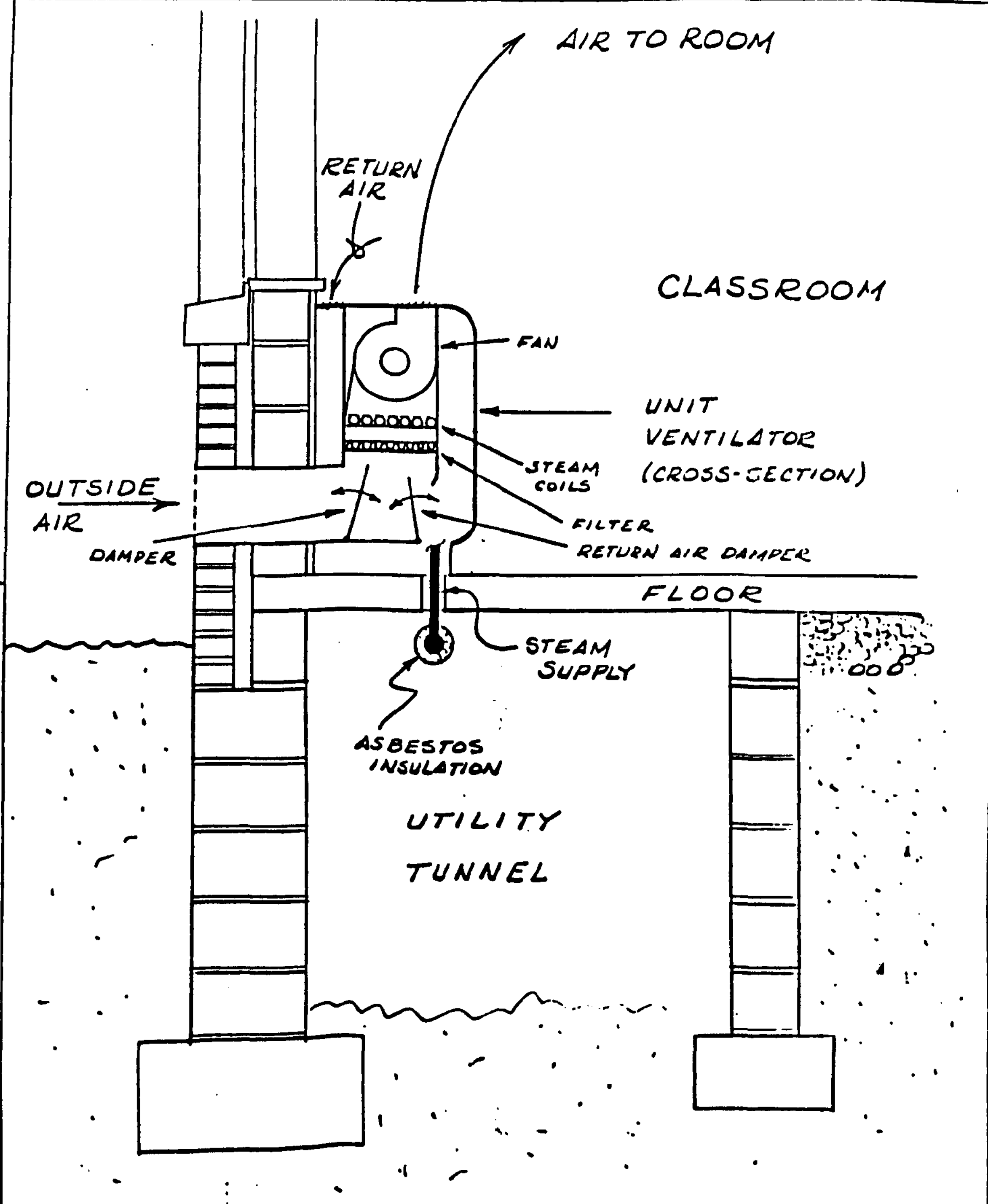
PROJ NO. 90495.01

TITLE

CLASSROOM WALL SECTION WITH UNIT VENTILATOR

QUOIN PARTNERSHIP
ARCHITECTS & ENGINEERS
646 MAIN STREET
[illegible], PA 19426-2518

REVISIONS



MADE BY	APPROVALS	
ISSUED 1-23-91		SKNCG012391

PRESSURE FIELD EXTENSION
USING A
PRESSURE WASHER

NEW JERSEY DEP SPONSORED PROJECT
INNOVATIVE MITIGATION RESEARCH AWARDS

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

ABSTRACT

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

Radon remediation is typically done with sub-slab ventilation systems. Sub-slab ventilation installation failures are often due to an incomplete pressure field extension that allows radon to continue to enter the building. Over half the homes we mitigate do not have a good gravel base under the slab. This project investigated a technique for extending the pressure field in tight soils from a single suction point by the creation of sub-floor tunnels using commonly available high pressure washers. Two buildings with the appropriate tight non-rocky soil were tested for pressure field extension before and after tunneling with the high pressure washer.

The tunneling under the slab was an effective method for extending the pressure field. This technique holds good promise for mitigators dealing with tight soils and limited choices for suction hole locations.

PRESSURE FIELD EXTENSION USING A HIGH PRESSURE WATER JET

PROBLEM STATEMENT:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

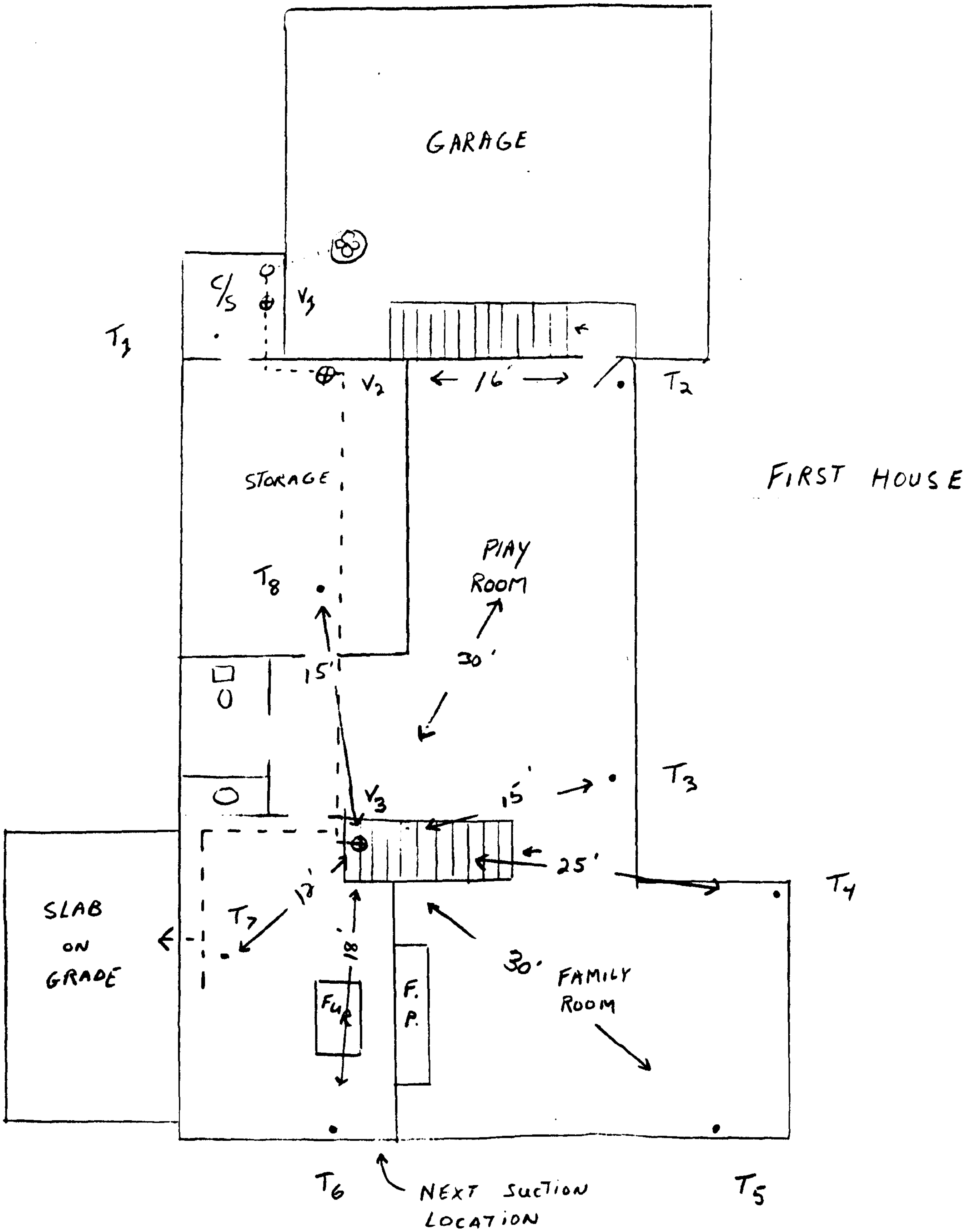
Three days later I repeated the floor pressure measurements and was surprized that they had not changed. Upon opening the pipe into the floor to inspect the suction hole I discovered that most of the pipe inlet had become blocked by loose plastic that was used as a backer rod around the pipe in the enlarged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

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

FIRST HOUSE PRESSURE FIELD EXTENSION MEASUREMENTS

ALL MEASUREMENTS DONE WITH BASEMENT TO OUTSIDE DOOR OPEN

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



GARAGE
C/S
V_1
T_1
V_2
16'
T_2
FIRST HOUSE
STORAGE
PLAY
ROOM
T_8
30'
15'
V_3
15'
T_3
25'
T_4
SLAB
ON
GRADE
T_7
12'
18'
30'
FAMILY
ROOM
FUR
F.
P.
T_6
NEXT SUCTION
LOCATION
T_5

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

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

ABSTRACT

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

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

INTRODUCTION

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

TYPE OF CAPS TESTED

OPEN PIPE

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

CAP A

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

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

DRYER VENT CAP

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

DRAFT INDUCER

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

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

TURBINE VENT

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

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

Figure 1 illustrates each type cap tested.

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

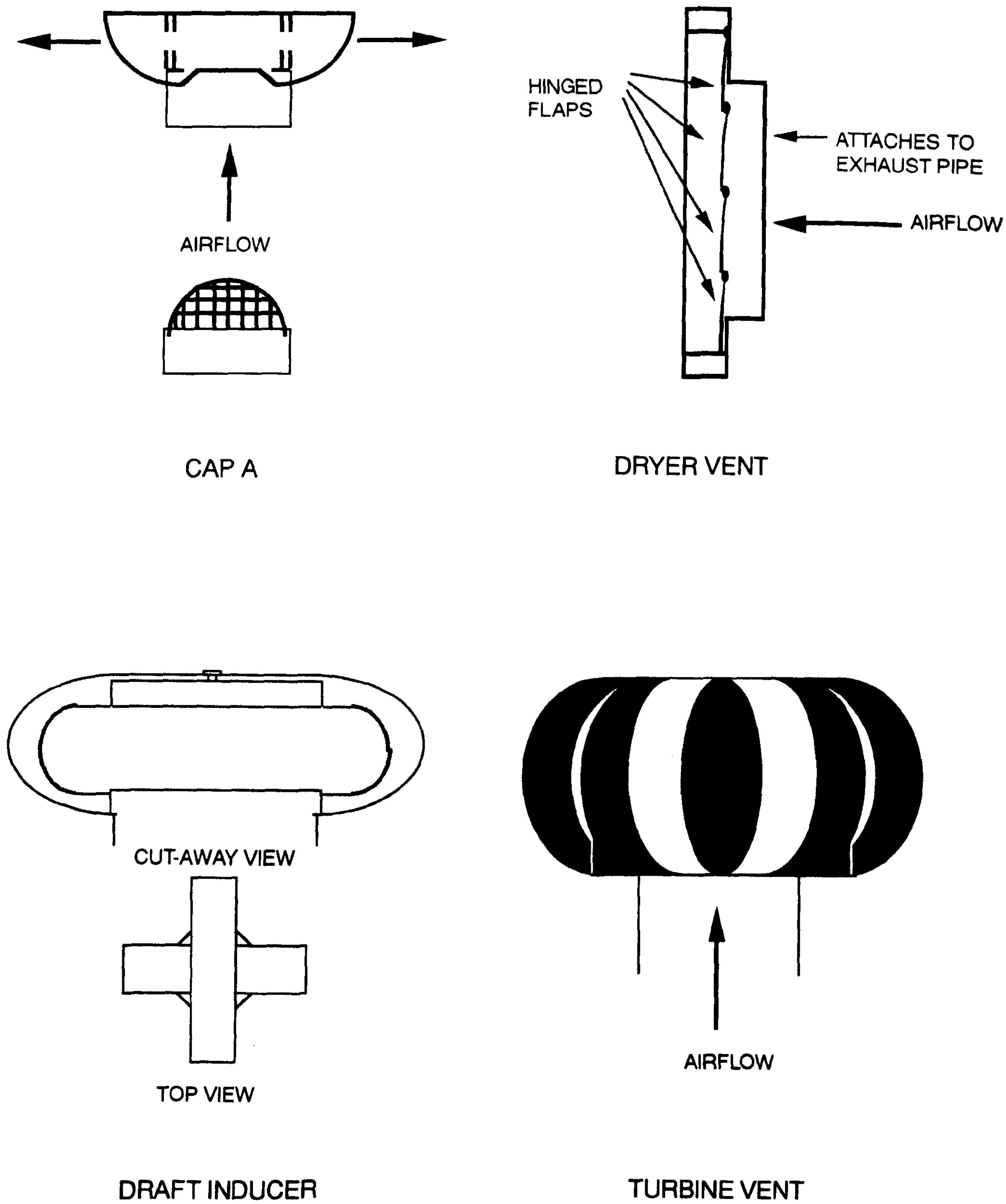


Figure 1. Types of caps tested.

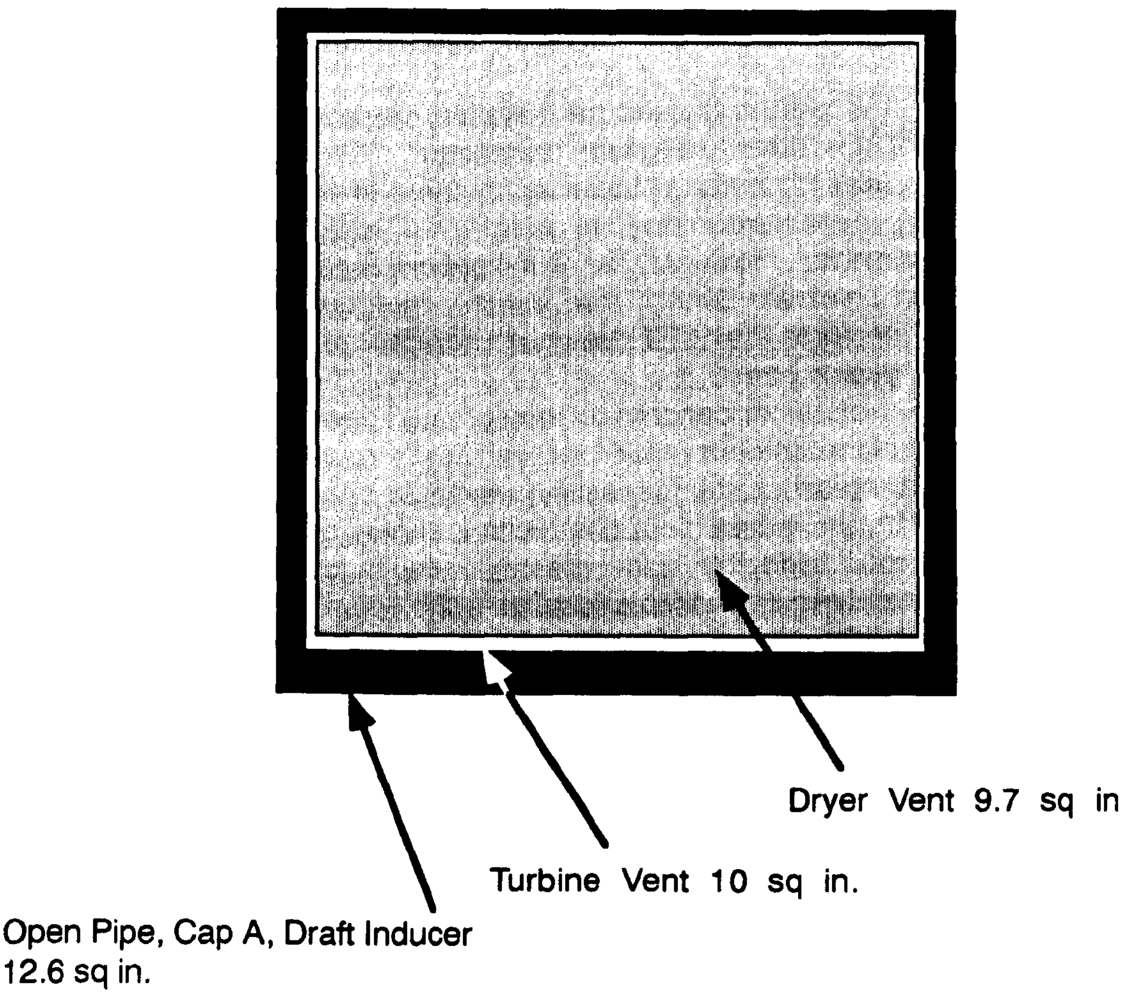


Figure 2. Relative exhaust areas. Drawings are approximately to scale.

TEST PROCEDURES

BACKPRESSURES CAPS PLACE ON THE PIPE

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

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

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

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

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

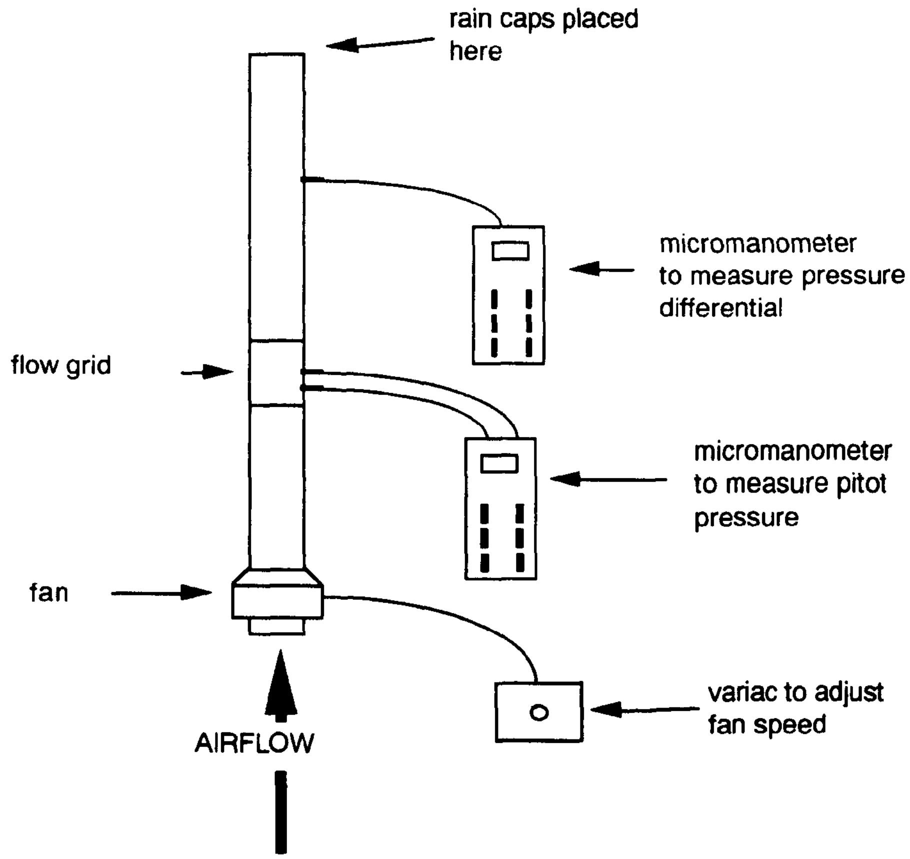


Figure 3. Equipment layout for system backpressure tests.

INDUCED DRAFT TESTS

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

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

Figure 4 illustrates the equipment configuration.

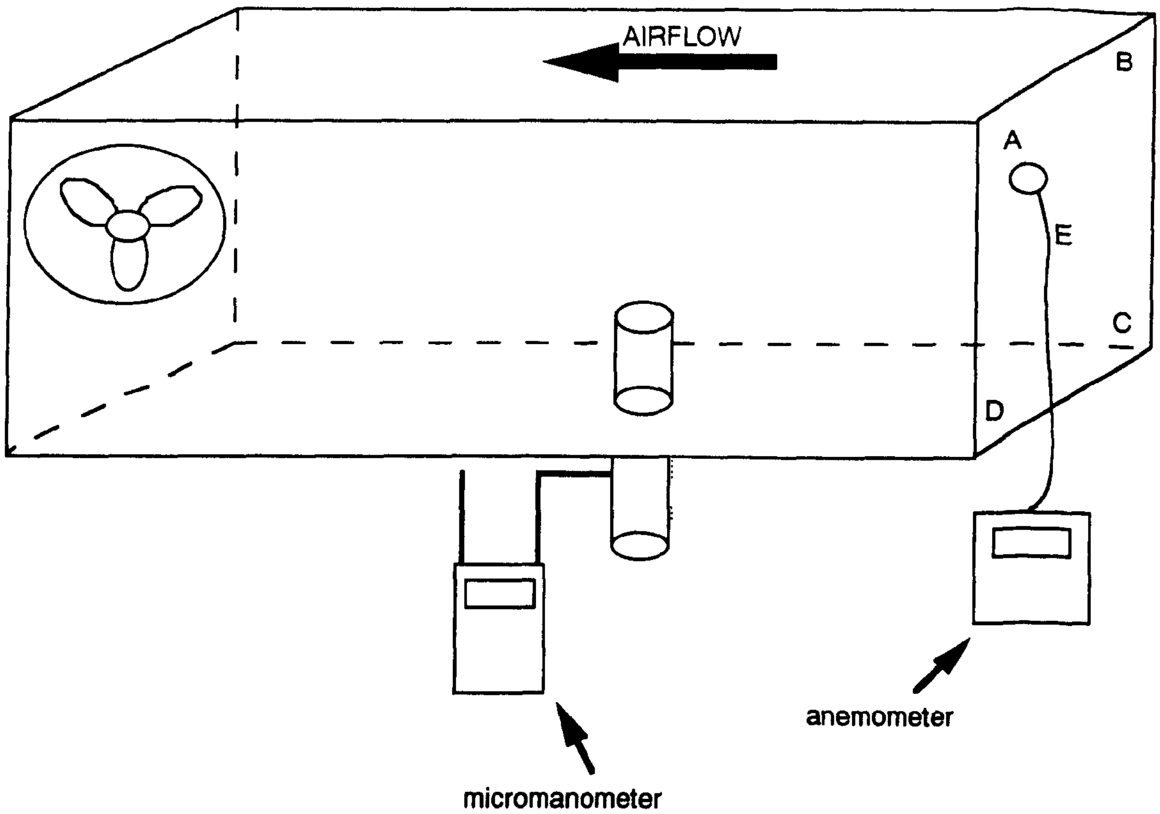


Figure 4. Equipment layout for induced draft tests.

RESULTS

BACKPRESSURE TESTS

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

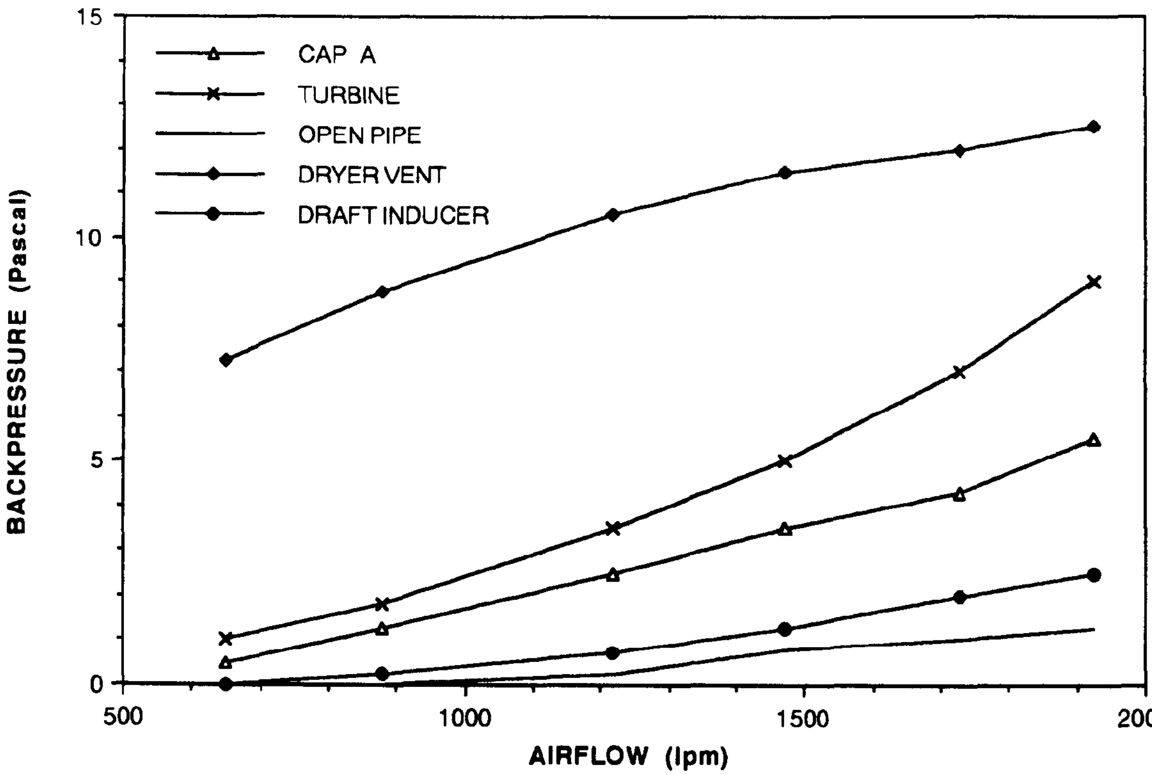


Figure 5. Backpressure in pipe due to caps.

INDUCED DRAFT TESTS

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

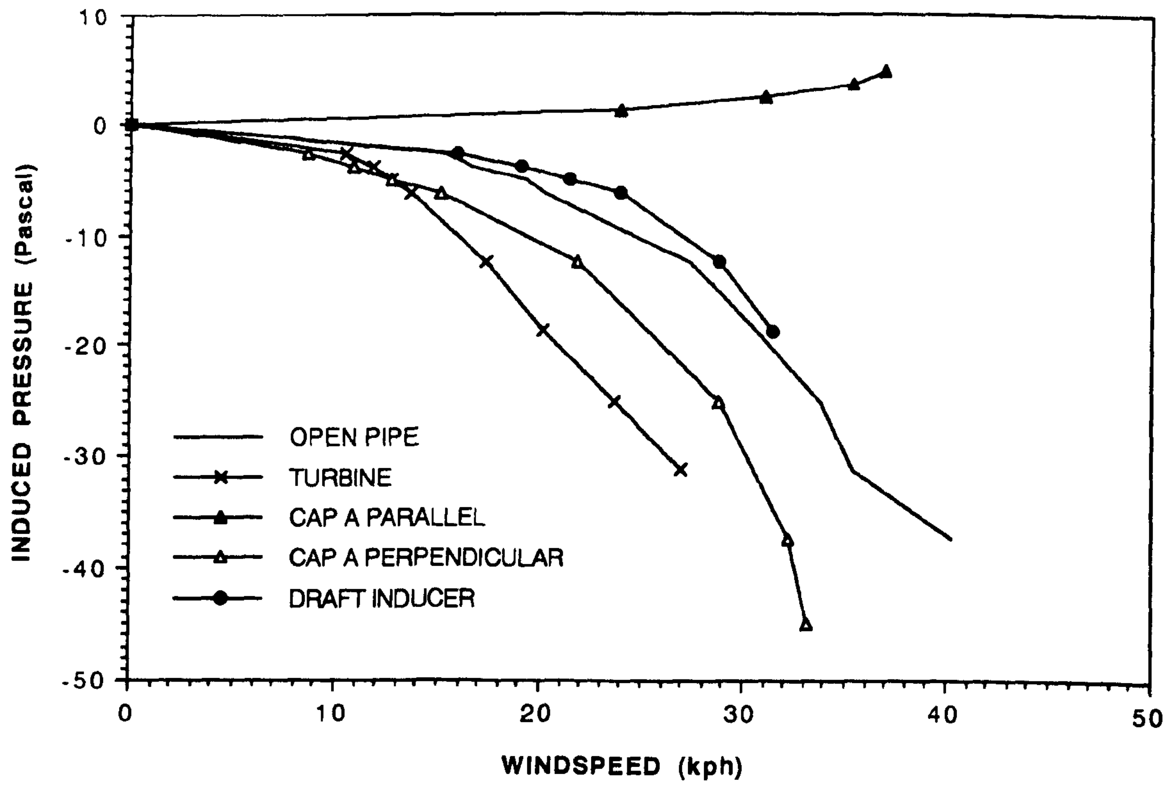


Figure 6. Induced pressure results.

CONCLUSIONS

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

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

A MODELING EXAMINATION OF PARAMETERS AFFECTING RADON AND SOIL GAS ENTRY INTO FLORIDA-STYLE SLAB-ON-GRADE HOUSES

R.G. Sextro, K.L. Revzan and W.J. Fisk

Indoor Environment Program
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

ABSTRACT

This paper discusses the use of a finite-difference numerical model to examine the influence of soil, fill, and construction characteristics on convective entry of radon and soil gas into slab-on-grade houses. Such houses, built with a perimeter, hollow-core concrete block stem wall and an above-grade floor slab resting on fill, are typical of a portion of the Florida housing stock. When the building is depressurized with respect to the ambient pressure, radon-bearing soil air will flow through various combinations of soil, fill, and blockwall components, entering the house through perimeter slab-stem wall gaps or interior cracks or other openings in the floor slab. At a constant building depressurization, the model predicts the steady-state pressure, flow, and radon concentration fields for a soil block 10 m deep and extending 10 m beyond the 7-m-radius slab. From the concentration and pressure fields, radon and soil gas entry rates are then estimated for each entry location. Under base case conditions, approximately 93 percent of the soil gas entry is through the exterior section of the stem wall, 5 percent is through the interior section of the stem wall, 2 percent through an interior slab opening, and less than 1 percent through gaps assumed to exist between the stem wall and footing or the stem wall and floor slab. In contrast, 57 percent of the radon entry rate occurs through the interior section of the stem wall, 22 percent through the interior slab opening, 20 percent through the exterior section of the stem wall, and less than 0.5 percent through the gaps. Changes in fill permeability have significant effects on radon entry, while changes in blockwall permeability are largely offset by increased flow and entry through structural gaps. These results, along with those from other model configurations, will be discussed.

This work has been supported, in part, by the U.S. Environmental Protection Agency. This paper has been reviewed in accordance with the U.S. EPA peer and administrative review policies and has been approved for presentation and publication.

INTRODUCTION

The role of convective flow of soil gas in transporting radon into buildings is widely acknowledged; however, the factors that affect radon entry can be complex. These flows will depend upon the driving pressure, the type and location of the openings connecting the building interior with the surrounding soil environment, and upon the characteristics of the soil medium (1,2). The nature of these openings is strongly influenced both by the type of building substructure and by the specific construction details. The driving pressure, which is the pressure difference between the surface of the soil surrounding the building and the building interior, is caused by the stack effect (due to temperature differences between the inside of the building and the outdoors), wind loading on the building shell, and the operation of heating and/or air conditioning systems.

In response to the discovery of elevated radon concentrations in a fraction of the Florida housing stock (3), the State of Florida and the U.S. Environmental Protection Agency have established the Florida Radon Research Program, with the broad goals of conducting research on radon entry into housing typical of that built in Florida and to investigate and develop techniques that limit radon entry into existing buildings or new construction (4). One objective of the research is to understand how indoor radon concentrations are influenced by details of the building substructure and the adjacent soils and fill materials.

We have developed and refined several detailed numerical models of radon transport through soil and entry into buildings (5,6,7) in order to investigate factors influencing soil gas and radon migration, including characteristics of the building and the surrounding soil. In the present study, a two-dimensional, steady-state finite-difference numerical model, utilizing cylindrical symmetry, has been assembled, with boundary conditions appropriate for one form of the slab-on-grade construction used in Florida housing. The model has been used to explore the influence of soil and building parameters on soil gas and radon entry. This paper summarizes the results of these simulations and discusses their implications for possible methods of limiting soil gas and radon entry. Greater detail is presented in reference (8).

MODEL DESCRIPTION AND APPROACH

MODEL OVERVIEW

The model used in this study is based upon a finite-difference numerical code in which the soil is assumed to be isothermal and the relationship between gas flow and driving pressure is assumed to be linear (Darcy's law) (5,6). We have used a form of the model in which the Cartesian coordinates are transformed into a cylindrical coordinate system. This, in effect, reduces the model to two dimensions for computing purposes. Since many of the structural elements of interest to our analysis are at the perimeter of the house or can be chosen to have cylindrical symmetry, there is little loss of generality in using cylindrical coordinates. This approach permits increased resolution and/or more rapid convergence with only modest loss in realism in moving from a fully three-dimensional treatment (6). Because we are interested in a parametric analysis, the benefit of greater speed outweighed the slight loss in accuracy compared with a fully three-dimensional configuration.

Details of the model, including the appropriate governing equations, are presented in references (6,8). We discuss here some of the major features and assumptions of the model. Boundaries for the soil block have been chosen to be 10 m from the footing in both the radial (r) and vertical (z) directions, as indicated in Figure 1. The bottom surface of the slab and the outer surfaces of the footing are assumed to be no-flow boundaries. Thus the model does not explicitly account for radon entry by diffusion through the concrete slab; rather, this entry rate is calculated separately (9). The model does, however, include migration of radon in the soil and fill by diffusion.

A static pressure difference is applied between the surface of the soil exterior to the building and the floor slab (top) surface, the mouth of the interior slab gap and the opening between the slab edge and the outer element of the stem wall (subsequently referred to as the slab edge opening). These geometries are illustrated in Figures 1 and 2, and are discussed in greater detail in the next section. In the general case we have assumed that the slab edge opening is sufficiently large so there is no pressure drop associated with flow through this opening. Thus, the static pressure difference is effectively between the inner surfaces of the stem wall, the mouth of any of the gaps, and the exterior soil surface. We have also modeled two cases where this general picture is altered. In the first case, the stem wall is assumed to be filled with impermeable concrete, so that the only gap is between the top of the interior element of the stem wall and the bottom of the floor slab. In the second case, we reduce the size of the slab edge opening so that pressure drop does occur across it, reducing the pressure difference between the exterior soil surface and the stem wall interior.

We assume that all air and radon entering the stem wall interior also passes through the slab edge opening into the house. Soil gas and radon can also enter the house through the interior floor slab gap. In order to compute the static pressure at the soil or fill surface located at the bottom of the various gaps, we use an algorithm (10) to compute the pressure drop across a gap, ΔP_g:

$$|\Delta P_g| = \frac{12\mu t}{w^2}|\bar{v}| + \frac{\rho(1.5+n)}{2}v^2. \tag{1}$$

where t is the length of the gap in the flow direction, w is the gap width perpendicular to the flow, n is the number of bends in the gap, and v is the average air velocity in the gap (*i.e.*, the flow rate through the gap divided by the gap area). The constants μ and ρ are the dynamic viscosity and density of air, respectively.

The model computes the pressure field throughout the soil and fill region by solving the Laplace equation. Soil gas transport is then calculated, from Darcy's law, which assumes a linear relation between applied pressure and fluid velocity. The mass balance equation describing radon migration, including radon generation, radioactive decay, and both convective and diffusive radon transport, is solved to determine the radon concentration field. The model then yields soil gas and radon entry rates at each entry point. This paper presents only the soil gas and radon entry rates at selected entry locations and, for the base case, the radon concentration in the fill adjacent to the entry locations.

BUILDING SUBSTRUCTURE AND SOIL GEOMETRY

A large fraction of houses built in Florida are constructed with a slab-on-grade substructure, of which there several variants (11,12). For this work, we have modeled an above-grade concrete slab floor which rests on a perimeter hollow-core concrete block stem wall. The slab edge rests on a chair block, which is the top course of blocks in the stem wall. There is an opening between the edge of the floor slab and the outer section of the stem wall, as noted earlier. The floor is also supported by fill material placed within the boundaries of the stem wall and elevated above the natural grade. A vertical section of the substructure is shown in Figure 1. As indicated in Figure 2, where the floor and stem wall are shown in greater detail, gaps are assumed to exist between both the inner and outer elements of the stem wall and the footing, and between the inner portion of the stem wall and the bottom of the floor slab. The gap dimensions are chosen as an input parameter. We also examined the effect on soil gas and radon entry of eliminating the gaps at the bottom of the stem wall.

The inner and outer elements of the concrete blocks that comprise the stem wall are assumed to be permeable to air flow; this permeability is another input parameter for the model. These wall elements are modeled as vertically homogeneous; that is, no provision is made for differences due to mortar joints between the blocks. In order to simplify the model, we have not included the block webs -- sections of the block that connect the inner and outer wall elements. In the general case, the interior of the block is open and flow through the webs themselves should be not significantly affect our results. In the cases where the stem wall is filled with concrete, we also assume that these webs are not present and thus no flow path is provided. The concrete footing and floor slab are assumed to be impermeable to gas flow. An interior gap in the slab floor is included in the model, with radial location and gap width as model inputs. The length of this gap is defined by the radial location.

As can be seen in Figure 2, the fill below the slab and on top of the footing is defined as a separate region to enable us to specify fill properties that may differ from those of the natural soil. The two parameters of greatest interest here are both the air permeability and the radium content of the soil or fill.

BASE CONFIGURATION

We have chosen a set of parameters that constitute a base case for our modeling. These have been selected based on reviews of the available data on Florida housing (11,12) and on soil and fill properties (13,14). Because we were interested in evaluating the effects of varying several of the soil and/or building substructure features on soil gas and radon entry, we also established a range over which each parameter was varied. The base case values and ranges are summarized in Table 1. As noted earlier, the fixed dimensions for the slab, soil block, and the stem wall details are indicated in Figure 2.

In the base case, we have used an effective radon diffusion coefficient of 2×10^{-6} m^2 s^{-1} for the soil and fill and an 'infinite depth' radon concentration, C_∞, of 37 kBq m^{-3} which is equivalent to soil or fill with a radium concentration of 46.5 Bq kg^{-1} and an emanation coefficient and porosity of 0.2 and 0.4, respectively. The pressure difference between the top of the slab and the top of the soil outside the building was chosen to be -2.4 Pa.

The parametric investigation was carried out using two approaches. First, each parameter was varied individually, with the remaining parameters held fixed at their respective base case values. Second, in some cases we varied more than one parameter at the same time in order to explore more fully the effects of the parameters of interest. In these cases we varied:

1) the soil permeability for high (10^{-9} m^2) and low (10^{-15} m^2) fill permeabilities;

2) independently the soil and fill permeabilities when the slab gap is the only soil gas entry path;

3) the soil, fill, and stem wall permeabilities independently when the core of the concrete blocks making up the stem wall is filled with impermeable concrete;

4) the stem wall permeability when both gaps between the bottom of the stem wall and the concrete wall footing are completely closed; and

5) the size of the slab edge opening.

RESULTS AND DISCUSSION

In the base case, the predicted soil gas and radon entry rates due to convective flow are 5.1×10^{-4} m^3 s^{-1} and 1.6 Bq s^{-1}, respectively. The distribution of soil gas and radon flows through the various entry points shown in Figure 2 are summarized in Table 2. The model simulations predict that 93 percent of the total soil gas entry occurs through the exterior side of the stem wall, while about 6 percent proceeds through the interior surface of the stem wall. Most of the gas flow is through the sides of the stem wall, rather than through the 3 mm wide gaps at the top and bottom of the stem wall. Only 1.6 percent of the total soil gas entry is predicted to occur at the interior slab gap, which in the base case is located at 3 m radius. This corresponds to a crack length of 18.8 m. These relative entry rates are consistent with the path length of the flow lines -- and therefore the resistance to flow -- connecting the exterior soil surface and the specific entry point.

The distribution of the radon entry rates associated with this air flow is different, with almost 59 percent predicted to occur through the interior side of the stem wall, 21 percent through the exterior side of the stem wall, and 20 percent through the interior slab crack. The predicted radon concentrations at each of the entry points, shown in Table 2, indicate that, although the largest fraction of gas flow occurs through the exterior side of the stem wall, the radon concentration in the adjacent soil is low due to diffusion to the atmosphere and to dilution by the atmospheric air entering the soil through a short flow path. In contrast, the radon concentrations are much higher in the fill materials located adjacent to the interior side of the stem wall and below the interior of the slab.

In comparison with the convective radon entry rate, the diffusive entry rate, based on a radon diffusion coefficient for concrete of 5×10^{-8} m^2 s^{-1} and a concrete porosity of 0.2, is 0.5 Bq s^{-1} (9). Thus, for a single-story house with a volume of 500 m^3 and an average air exchange rate of 0.5 h^{-1}, the total indoor radon concentration would be 31 Bq m^{-3} for this base case soil and substructure.

Results of selected model runs in which the effects of different parameters are evaluated are shown in Table 3 and in Figure 3. We extensively investigated the effects of changes in permeability of the soil, both alone and in conjunction with variations in other parameters or assumptions. Changes in soil permeability alone had a somewhat modest effect on radon entry in the base case, since flows at the higher soil permeabilities are then limited by the fill permeability. The role of the fill in determining flows is demonstrated by comparing the predicted radon entry rates when the fill permeability is chosen to be either high (10^{-9} m^2) or low (10^{-15} m^2). For high fill permeability, radon entry is limited by the permeability of the underlying soil. When both are high, the increased radon entry rate is significant, almost 30 times the base case. On the other hand, if the fill has a low permeability, total radon entry is quite low and is essentially unaffected by changes in soil permeability.

Another effect that arises when soil permeability is varied is the change in the importance of the various radon entry locations. As soil permeabilities are reduced below that of the base case, radon entry through the exterior of the stem wall changes only slightly as soil permeabilities range from 10^{-12} to 10^{-9} m^2. However, entry through the interior side of the stem wall is reduced as the soil permeability is reduced below the base case, and increases as the soil permeability increases. Radon entry at the interior slab gap behaves in a similar fashion, though it does not increase as much with increasing soil permeability. Thus at the low end of the range of soil permeabilities modeled here, radon entry through the exterior side of the stem wall is the largest single component; as soil permeability increases, the relative importance of this entry pathway decreases. At the high end of the soil permeability range, approximately 88 percent of the radon entry occurs through the interior side of the stem wall, almost 10 percent is through the interior slab gap, and about 2 percent occurs through the exterior side of the stem wall.

If the soil is layered, the effects on radon entry of variations in the permeability of the layer depend upon the location of the layer. We modeled two different layered soil cases in which the permeability of the soil layer was varied while those of the fill and the remaining soil were held fixed at the base case values. In the first configuration, the soil layer began at grade level (*i.e.*, in direct contact with the fill material) and extended 1 m deep. In the second case, the soil layer began at 0.5 m below grade (which is the depth of the bottom of the footing) and extended to 1.5 m below grade. As shown by the results in Table 3, when the layer is in contact with the fill (assuming the fill has the base case permeability), the layer has a larger effect on radon entry than when the soil layer is deeper.

Interestingly, filling the stem wall interior with impermeable concrete has only a modest effect on total radon entry. In this case, we assume that there is still a gap between the top of the concrete-filled stem wall and the bottom of the floor slab. As shown in Table 3 and Figure 3, total radon entry still increases with increasing soil permeability, though for a given permeability the radon entry rate is lower than in the base case. One can also see that the effects on radon entry of changing the fill permeability when the stem wall is filled with concrete are also modest. These results can, in general, be explained by the fact that the pressure field distribution in the adjacent fill is altered when the stem wall interior is impermeable. The larger pressure gradient at the remaining entry point, which compensates somewhat for the reduced number of entry points, results in a higher soil gas and radon entry rate.

Similarly, changing the permeability of the stem wall itself has very little effect on total radon entry, as can be seen from Figure 3. Again, this is due to compensating effects. As long as the wall permeability is greater than that of the adjacent fill, flow through the wall is the most important. As the wall permeability decreases below that of the fill, the gaps between the wall and the footing and between the wall and the floor slab become increasingly important flow pathways as the pressure field is altered due to the changing wall permeability.

We also parametrically examined the effect of the size of the slab edge opening on the radon entry rate. In our initial problem definition, we assumed that this opening was sufficiently large so that no pressure drop occurred at this point -- effectively applying the full -2.4 Pa static pressure difference between the exterior soil surface and the inner surfaces of the stem wall. In actual construction practice this opening may in fact be much smaller, in effect reducing the driving force for convective flow into the stem wall interior. Holding all the soil and wall parameters at their base case values, the effect of closing this opening to 1 mm reduced the total radon entry by about 40 percent. Radon entry via this opening drops by about a factor of 4 in this case, but the predicted entry via the interior slab gap increases by almost a factor of 2, compensating somewhat for the reduction at the stem wall. This increased entry rate at the interior slab gap arises because the pressure gradient in the fill region near the stem wall is reduced, thus more of the air flow through the soil is directed toward this interior opening.

In addition to the flow of soil gas into the stem wall, via the wall material itself or through the gaps indicated in Figure 2, there is air flow through that portion of the exterior wall that is above grade. In fact, in the base case, this flow is 6.3×10^{-3} m^3 s^{-1}, which is about 12 times the total predicted soil gas flow from the soil into the house (we have not included this entering outdoor air as a source of radon, just as we have not included infiltration through the house superstructure as a radon source). In order to investigate the effects of changing the flow balance between the inner and outer stem wall elements we increased the permeability of the above-grade portion of the exterior stem wall element to 10^{-9} m^2 and fixed the permeability of the remainder of the wall at 10^{-12} m^2 (as might be achieved with a wall coating or sealant). With the slab edge opening reduced to 1 mm, the the radon entry rate through the stem wall is reduced dramatically to 0.01 Bq s^{-1} from 0.9 Bq s^{-1} in the base case. Total radon entry predicted for the entire substructure is not reduced as much, to about 37 percent of the base case rate, because radon entry through the interior slab gap increases in response to the changes in the pressure field distribution, as described earlier.

The effect of water table depth on the predicted radon entry rate was found to be small. For a water table (modeled as a change in the position of the no-flow boundary at the bottom of the soil block) depth between 2.5 and 10.5 m below grade, the radon entry rate was essentially unchanged. At depths less than 2.5 m, the entry rate reduction was small; at 0.5 m deep, the radon entry rate was predicted to be 0.88 Bq s^{-1}.

Finally, we investigated the effect on predicted radon entry of changes in the radium content of the soil and fill. First, it should be noted that, if the radium content (and thereby the soil gas radon concentration) was increased uniformly in both the soil and fill, the radon entry rate would increase proportionately (except for minor reductions due to the slight increase in diffusive losses from the soil surface). If the fill radium content is changed from the base case, the radon entry rate does not change proportionately, as can be seen from Table 3. Larger changes in radon entry can occur if the radium content of the soil below 1.5 m were to increase, as might be the case where a high radium soil layer was close to the surface. The effects of similar changes in radium content of soil below 5.5 m are diminished, reflecting the fact that any additional radon from the enhanced radium content is transported through the soil by means of diffusion into the soil and fill region where convective transport into the structure becomes important.

CONCLUSIONS

Application of our finite-difference models, incorporating key features of the soil, fill, and substructure, has provided additional insight into transport of soil gas and radon through the soil and into a building. The model results have also shown that changes in the characteristics of various entry locations or pathways can impact radon migration and entry at other locations, leading to compensating effects. As one example of this, a reduction in the permeability of the stem wall elements reduces flow through the wall materials, but soil gas and radon entry increases through the gaps at the top and bottom of the stem wall in response to the changes in the pressure field in the adjacent fill. Thus the total radon entry rate is not significantly affected. Similarly, a reduction in the size of the opening at the slab edge to 1 mm or less is necessary to effect any significant reduction in the total radon entry rate. If the interior opening in the floor slab is eliminated (but the stem wall entry is unchanged), the total radon entry rate is reduced by only 10 percent over the base case rate. If, on the other hand, all entry points at the stem wall are eliminated (as might be accomplished by use of a solid, one-piece wall and floor slab) the total radon entry rate is reduced by 66 percent (assuming that the floor-slab gap is present).

Changes in the air permeability of the soil and fill can have the most significant effect on radon entry. Increased soil permeability (above the 10^{-11} m^2 value assumed in the base case) will increase total radon entry; if accompanied by an increase in fill permeability, the increase in radon entry rate is more dramatic. On the other hand, if the fill permeability alone is reduced below the base case value (4×10^{-11} m^2), radon entry is reduced substantially. At very low fill permeabilities, convective flow of radon from the soil is essentially negligible, and is largely invariant with regard to changes in other parameters. Even at a more modest fill permeability of 10^{-12} m^2, total radon entry is reduced by 80 percent from the base case rate. It should be noted that these results assume that the fill material maintains its integrity; that is, no cracks or gaps develop in the fill or in those regions of the fill penetrated by utility pipes or conduit.

Changes in radium content of the fill have some effect on total radon entry, though the more significant effects occur for fill radium contents more than 3 times the base case. Changes in the soil radium concentration can have a more important effect, depending upon the depth of the radium-bearing layer. In the case where the radium content of the soil below 1.5 m is a factor of 5 times that of the base case, radon entry increases by more than 3 times the base case value, while a 10-fold increase in radium provides a radon entry rate that is 6 times greater than in the base case. For a radium-rich soil layer below 5.5 m, the changes are less pronounced, with only a 25 percent increase in radon entry arising from a 10-fold increase in the radium content.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Environmental Protection Agency through Interagency Agreement DW89934620-0 with the U.S. Department of Energy. The work was also supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division, and by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Ecological Research Division of DOE, under contract DE-AC03-76SF00098.

REFERENCES

1. Nazaroff, W.W., Moed, B.A., and Sextro, R.G. (1988). Soil as a Source of Indoor Radon: Generation, Migration, and Entry. In *Radon and Its Decay Products Indoors*, Nazaroff, W.W. and Nero, A.V., eds., pp 57-112. Wiley, New York.
2. Nero, A.V. and Nazaroff, W.W. (1984). Characterizing the Source of Radon Indoors. *Radiation Protection Dosimetry* 7, 23-29.
3. Geomet Technologies Inc. (1988). Florida Statewide Radiation Survey. Geomet Report IE-1808. Germantown, MD.

4. Sanchez, D.C., Dixon, R., and Williamson, A.D. (1990). The Florida Radon Research Program: Systematic Development of a Basis for Statewide Standards. Presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA., Paper A-1-3, U. S. EPA.

5. Loureiro, C. O., Abriola, L. M., Martin, J. E., and Sextro, R. G. (1990). Three Dimensional Simulation of Radon Transport into Houses Under Constant Negative Pressure. *Environ. Sci. Technol.* 24, 1338-1348.

6. Revzan, K. L., Fisk, W. J., and Gadgil, A. J. (1990). Modeling Radon Entry into Houses with Basements: Model Description and Validation. Lawrence Berkeley Laboratory Report LBL-27742. Berkeley, CA.

7. Narasimhan, T. N., Tsang, Y. W., and Holman, H. Y. (1990). On the Potential Importance of Transient Air Flow in Advective Radon Entry Into Buildings. *Geophysical Research Letters* 17, 821-824.

8. Revzan, K. L., Fisk, W. J., and Sextro, R. G. (1990). Modeling Radon Entry into Florida Houses with Concrete Slabs and Concrete-block Stem Walls. Lawrence Berkeley Laboratory Report LBL-30005, Berkeley, CA.

9. Zapalac, G. H. (1983). A Time-Dependent Method for Characterizing the Diffusion of Radon-222 in Concrete, *Health Phys.*, 45(2), 377-283.

10. Baker, P. H., Sharples, S., and Ward, I. C. (1989). Air Flow Through Cracks. *Building and Environment,* 22(4), 293-304.

11. Scott, A. G., and Findlay, W. O. (1983). Demonstration of Remedial Techniques Against Radon in Houses on Florida Phosphate Lands. Report EPA-520/5-83-009 (NTIS PB84-156157), U. S. EPA, Montgomery, AL.

12. Acres International Corporation (1990). Radon Entry Through Cracks in Slabs-on-Grade, Vol. 2, Sealants for Cracks and Openings in Concrete Slabs-on-Grade. Acres Report P09314. Amherst, NY.

13. Nielson, K. K., and Rogers, V. C. (1990). Correlation of Florida Soil-Gas Permeabilities with Grain Size, Moisture, and Porosity. Rogers and Associates Report RAE-8945-1. Salt Lake City, UT.

14. Roessler, C. E., Smith, D. L., Bolch, W. E., Hintenlang, D. E., and Furman, R. A. (1990). Gas Permeabilities and Radon Content of Florida Fill Materials and Soils. University of Florida Report, Gainesville, FL.

TABLE 1. BASE CASE VALUE AND RANGE FOR MODEL PARAMETERS

Parameter	Base Case Value	Range
Soil air permeability:		
a. total soil block b. soil layer 0-1 m deep* c. soil layer 0.5-1.5 m deep*	10^{-11} m^2	10^{-12} - 10^{-9} m^2
Fill air permeability:		
a. all fill b. exterior to stem wall	4×10^{-11} m^2	10^{-15} - 10^{-9} m^2
Stem wall air permeability:		
a. both vertical wall elements b. inner wall element c. outer wall element	10^{-10} m^2	10^{-15} - 10^{-9} m^2
Slab opening:		
a. width	3 mm	1 mm - 10 cm
b. radial distance	3 m	0 - 7 m
Radium content (relative to base case):		
a. fill b. soil below 0.6 m depth* c. soil below 4.6 m depth*	1	0.1 - 10
Water table:		
a. depth below surface	10 m	0.5 - 10 m

*Depth with respect to grade level

TABLE 2. BASE CASE SOIL GAS AND RADON ENTRY AT VARIOUS ENTRY POINTS

Entry Location	Fraction of Soil Gas Entry* (percent)	Radon Concentration (percent of C_∞)	Fraction of Radon Entry† (percent)
Interior side of the stem wall:			
a. top gap	0.06	88	0.65
b. bottom gap	0.06	87	0.65
c. side of wall	5.0	88	53.
d. bottom of wall	0.23	87	2.5
e. top of wall	0.24	88	2.6
Exterior side of the stem wall:			
a. bottom gap	0.98	5	0.67
b. side of wall	88.	3	18.
c. bottom of wall	4.	5	2.7
Slab opening	1.6	98	20.

* Total base case soil gas entry = 5.1×10^{-4} m^3 s^{-1}

† Total base case radon entry = 1.6 Bq s^{-1}

TABLE 3. EFFECTS OF SELECTED PARAMETERS ON RADON ENTRY

Parameter	Radon Entry (Bq s^{-1})			
Soil air permeability (m^2):	10^{-12}	10^{-11}	10^{-10}	10^{-9}
a. all other parameters = base case	0.4	1.6	6.6	13
b. fill permeability = 10^{-9} m^2	0.63	2.1	13	47
c. fill permeability = 10^{-15} m^2	$5. \times 10^{-4}$	$5. \times 10^{-4}$	$5. \times 10^{-4}$	$5. \times 10^{-4}$
d. filled stem wall	0.16	1.2	3.8	5.1
e. soil layer 0 to 1 m deep*	0.64	1.6	4.2	7.9
f. soil layer 0.5 to 1.5 m deep*	0.74	1.6	2.5	3.3
g. slab opening only	0.14	0.55	1.1	1.2
Fill air permeability (m^2):	10^{-15}	10^{-13}	10^{-11}	10^{-9}
a. all other parameters = base case	5.3×10^{-4}	$5. \times 10^{-2}$	1.1	2.1
b. filled stem wall	$6. \times 10^{-4}$	4.8×10^{-2}	0.8	1.6
c. slab opening only	$3. \times 10^{-5}$	$3. \times 10^{-3}$	0.2	1.6
Radium content (relative to base case):	0.1	1	5	10
a. fill	1.3	1.6	2.6	4
b. soil below 0.6 m*	0.75	1.6	5.1	9.3
c. soil below 4.6 m*	1.5	1.6	1.7	2.0
Width of slab edge opening (cm):	0.1	0.2	1	5
a. all other parameters = base case:	0.88	1.5	1.6	1.6

* Depth with respect to grade level

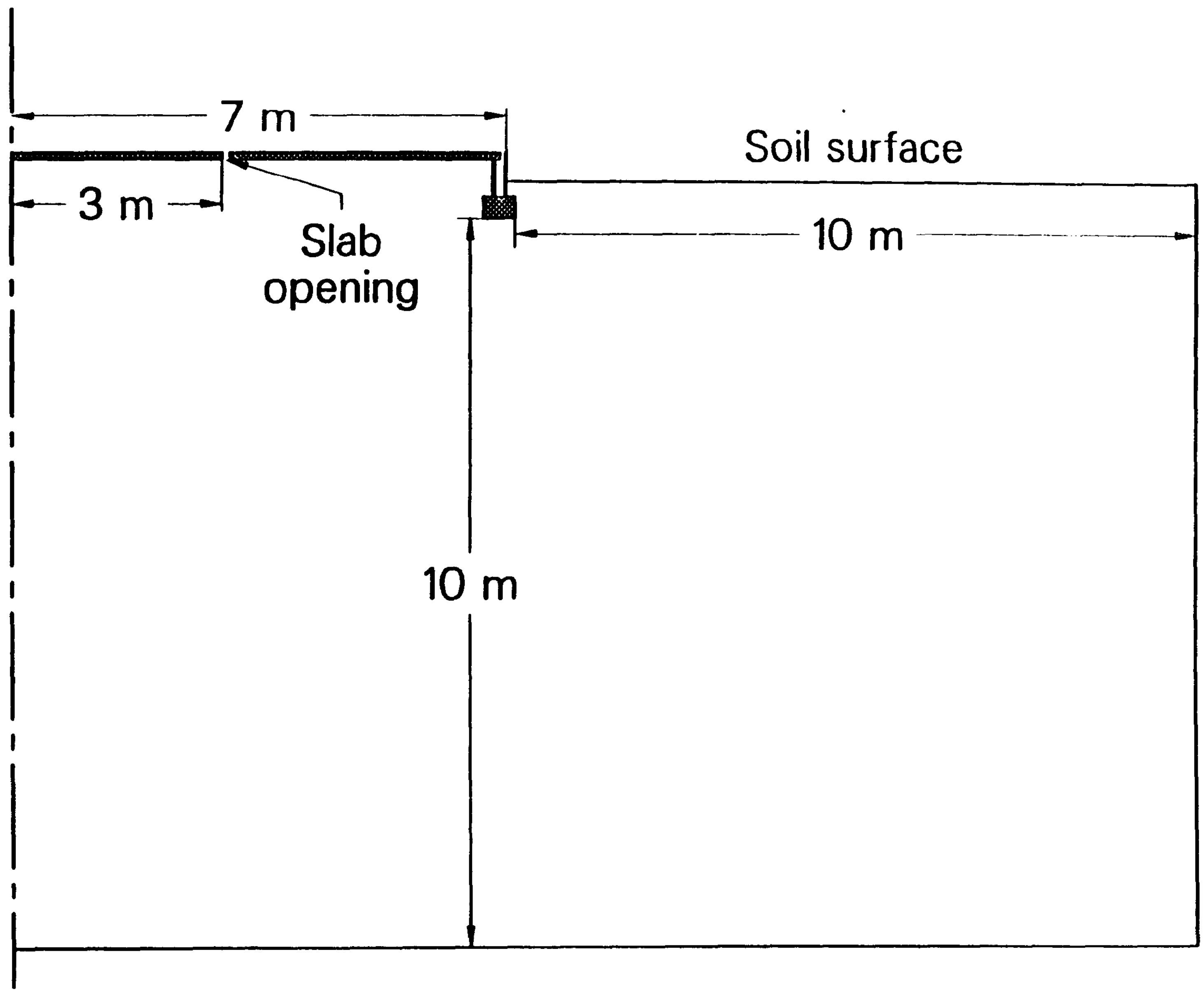


Figure 1: Vertical cross-section of the region modeled showing the dimensions of the soil block and the location of the slab gap for the base case. Greater detail for the stem wall is presented in Figure 2.

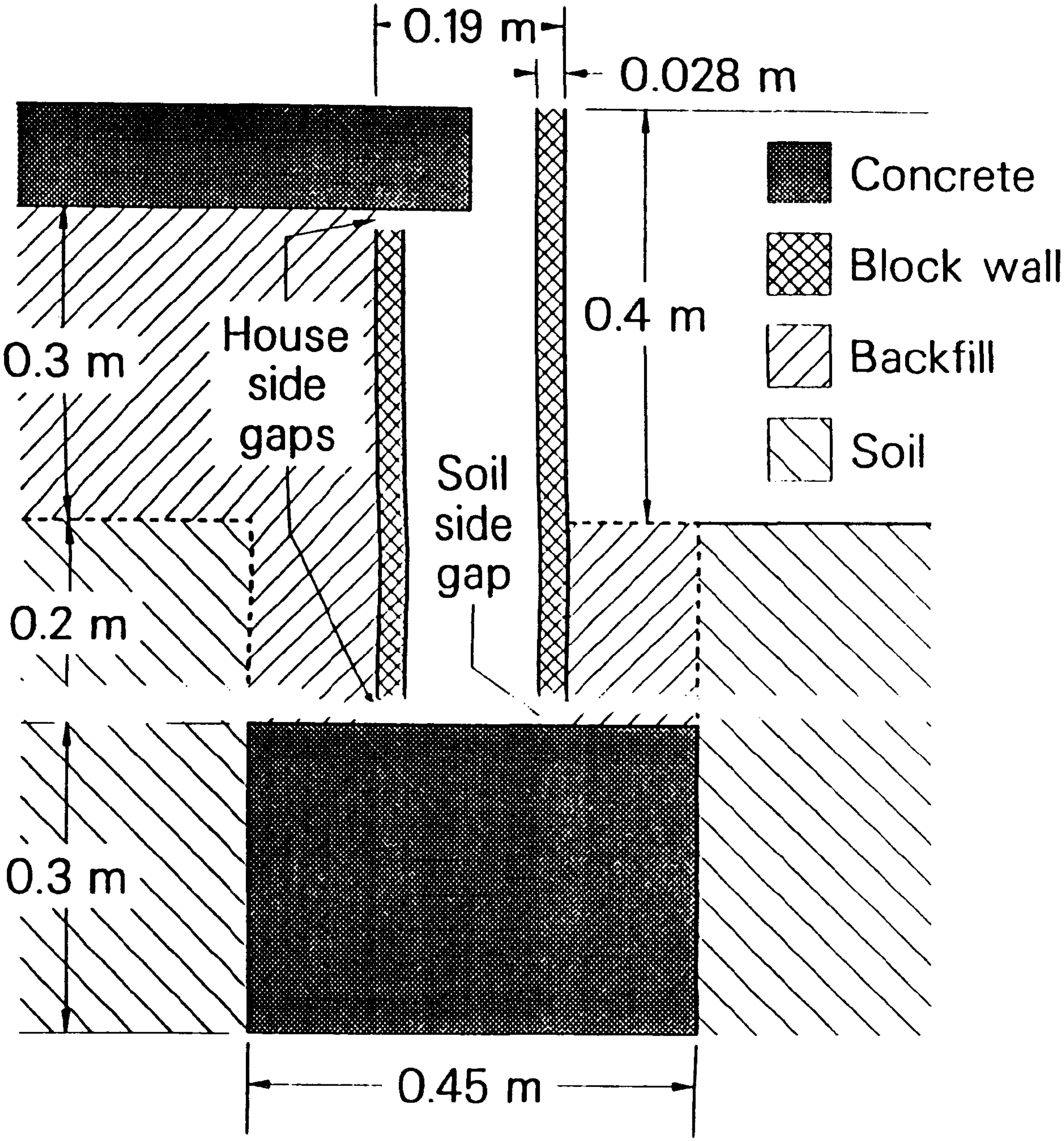


Figure 2: **Detail of the stem wall, showing the fixed dimensions for the wall height, dimensions of the footing, and fill depth and location with respect to the footing. The size of the *gaps at the top and bottom of the stem wall is exaggerated in this diagram.* In the base case, their widths are 3 mm. The floor slab thickness if 10 cm.**

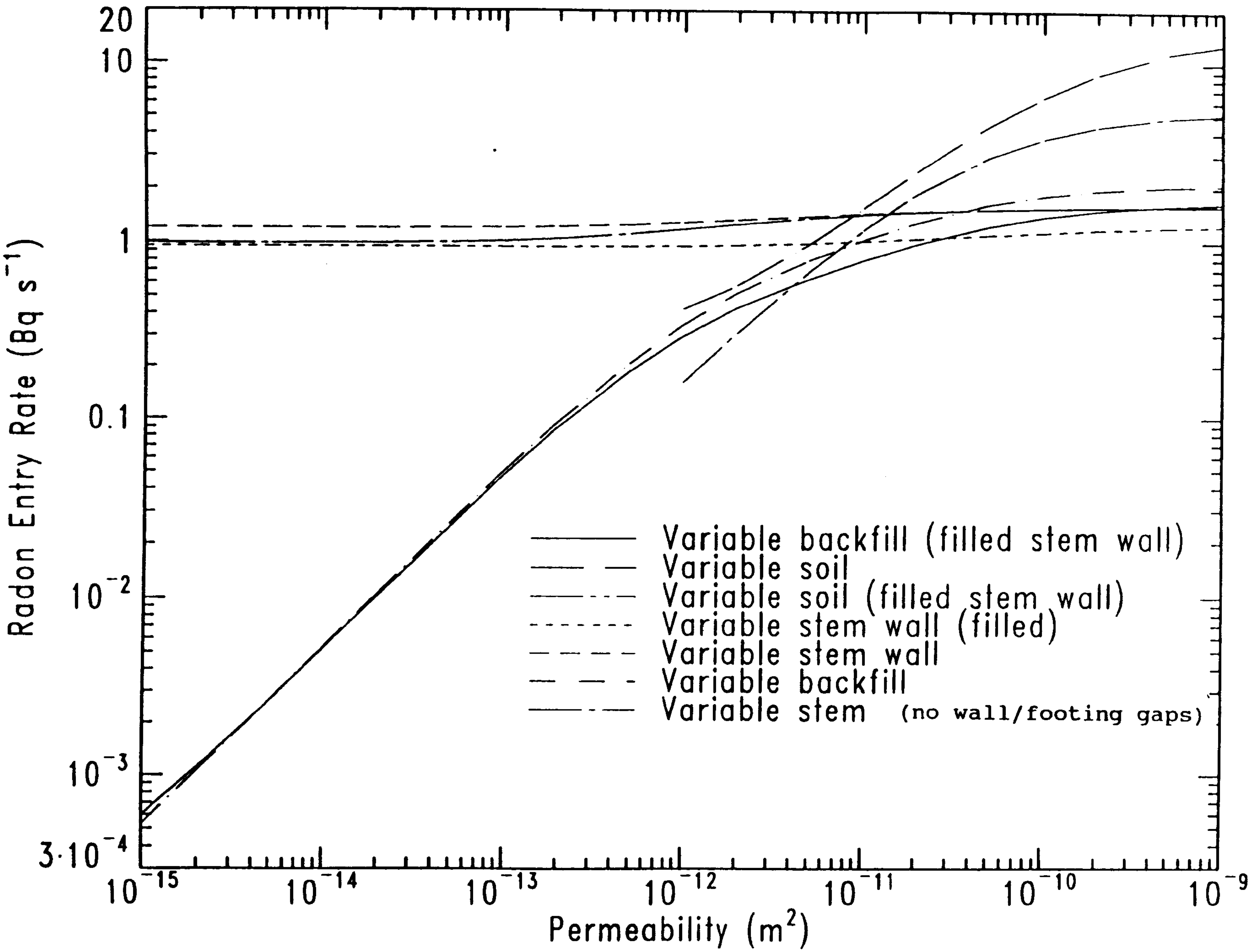


Figure 3: **Range of radon entry rates produced by variations in the soil, backfill, and stem wall permeabilities for open and concrete-filled stem walls. Also shown are entry rates when the stem wall/footing gap is eliminated. In each case, all other parameters have the base case value.**

RADON DYNAMICS IN SWEDISH DWELLINGS: A STATUS REPORT

Lynn M. Hubbard, Nils Hagberg, Anita Enflo, Gun Astri Swedjemark

Swedish Radiation Protection Institute
Box 60204
S-10401 Stockholm, Sweden

ABSTRACT

A status report of a long term study on radon entry into Swedish dwellings is given. Both physical modelling and continuous measurements of radon and other relevant parameters in real home environments are being used in the investigation. Building characteristics typical of Swedish dwellings and geological factors typical of Swedish ground are discussed with regard to their relevance to radon entry. The research homes used in this study are described and factors affecting radon entry are compared to similar factors in the New Jersey Piedmont research houses. Current results of the measurements in the research homes are presented and the dynamic modelling being developed to study the temporal behavior of radon indoors is introduced.

INTRODUCTION

Several researchers in recent years have begun to focus on understanding the various mechanisms driving radon entry into dwellings, and to what extent these mechanisms cause indoor radon concentrations to vary with time. Driving forces such as temperature differences between the indoors and outdoors, the wind, and the effects of indoor ventilation systems have been observed in relationship to temporal variations in indoor radon concentrations (1). Understanding these mechanisms driving radon entry will ultimately be useful in designing more effective ways to mitigate homes with high indoor radon concenrations, and in constructing better protocols for measuring radon indoors.

Our own research focuses on understanding the behavior of some basic parameters associated with radon entry and movement indoors. The quantity of main interest is the amount of air infiltrating a dwelling from the radon-containing soil gas versus the relatively radon-free outdoor air. We hope to understand how the amount of air infiltrating a dwelling from these two different sources changes with relation to each other, with time, and with environmental driving forces such as temperatures inside and outside the dwelling and the wind. We are using both theoretical modelling and measurements in real houses to obtain a better understanding of these processes.

This report is organized as follows. We begin with a brief description of building characteristics which are typical in Sweden, which is intended to provide a background for understanding the types of radon problems which exist in Sweden. This discussion is followed by a description of our current data collection procedures in two research houses, and the houses are described and compared to the houses in the Piedmont Project (1). We conclude with a report on our ongoing efforts at modelling indoor radon concentrations.

BUILDING CHARACTERISTICS OF SWEDISH HOUSES

THE SOIL

The radon concentration in the soil gas in Swedish soil has always been found to be at least 5000 Bq/m^3 at a depth of 1 meter. It is usually between 20,000-40,000 Bq/m^3 in moraine and 30,000 - 150,000 Bq/m^3 in gravel. When the soil contains some alum-shale the radon concentration can be as high as $1\text{-}2x10^6$ Bq/m^3. Moraine is very common in Sweden and other glaciated terrains such as in Canada and the northern United States. In addition, eskers are very common in Sweden, which are long ridges or mounds of sand, gravel, and boulders deposited from flows under or around stagnated glaciers from the last ice age, and the soil is very permeable. The combination of the rather high radon concentration in the soil air and the permeability of the soil give most of Sweden a rather high potential for radon ingress into houses.

BUILDING MATERIALS AND BUILDING FOUNDATION

Most Swedish one-family houses are built of wood, with the exception of the Skåne landscape in the south of Sweden, where most houses are built of stone materials. During the last decade brick and concrete have been more common in the whole country. In about 10% of the 1976 building stock, (which includes both one-family houses and apartments in multi-family houses), alum-shale based concrete had been used. Alum-shale based concrete contains enhanced levels of ^{226}Ra of between 600 - 4300 Bq/kg, and was produced between 1929 and 1974. The alum-shale materials give radon levels in many houses in the range of 400-800 Bq/m^3. Most multi-family houses are built of concrete or brick.

Houses built with basements (or cellers) are the most common in Sweden. Before 1940, houses built with crawlspaces were about equally common as those built with basements. During the 1970s, houses built with a slab-on-grade became increasingly more popular. The proportion of the housing stock, as a function of year when built, with either slab-on-grade, crawlspace, or basement (celler) can be seen in figure 1.

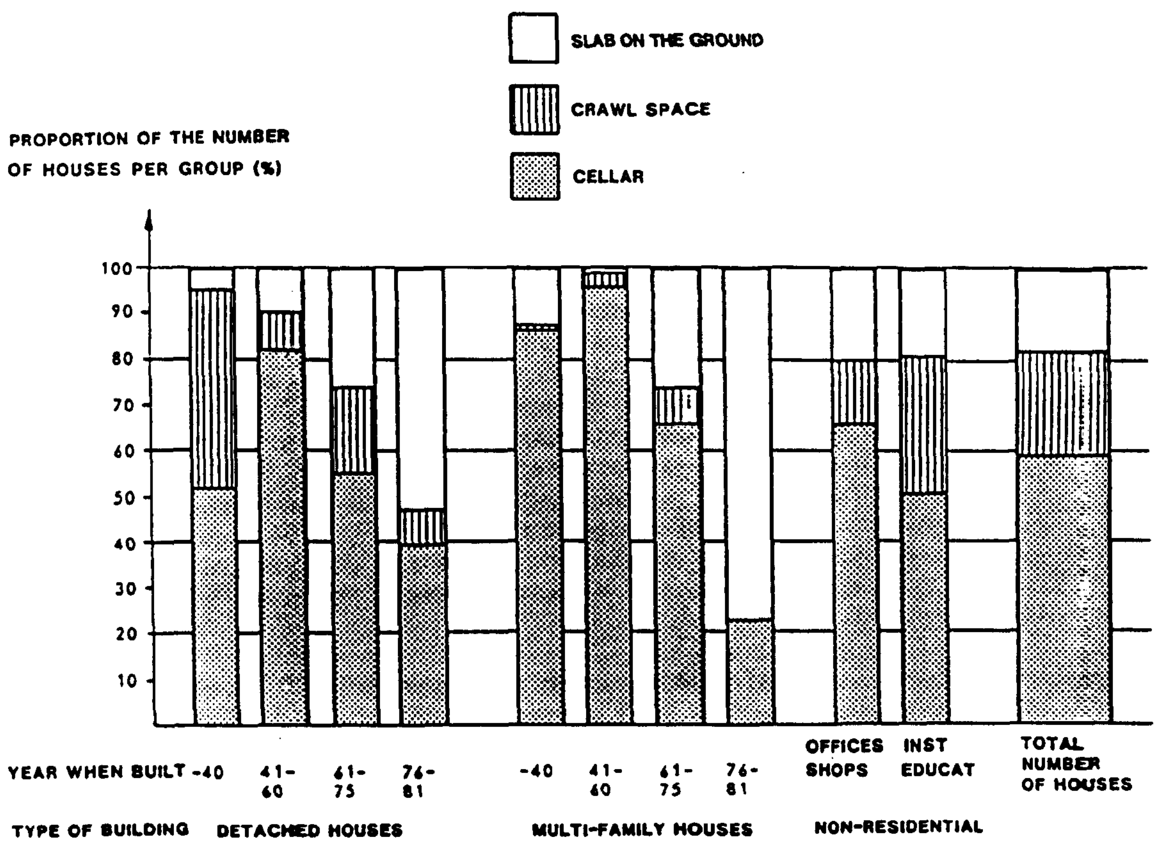


Figure 1. Type of building foundation in Swedish buildings.

VENTILATION

The most common ventilation system in Swedish detached houses is natural draught ventilation combined with a kitchen fan. An increasing number of houses built during the 1970's used mechanical exhaust ventilation, which began to be changed to mechanical inlet and outlet ventilation with some kind of heat recovery during the 1980's.

The older multi-family houses have natural draught ventilation and an increasing ratio of those built since 1945 have mechanical exhaust ventilation. Since 1980 mechanical ventilation has been required in multi-family houses.

Our current research program on radon dynamics in Swedish homes concentrates on understanding radon entry in two houses which are somewhat typical in design. We describe them next, and discuss how they differ from houses one of us has studied in a previous research project called the Piedmont Project, which was funded by the USEPA (1).

MEASUREMENTS IN RESEARCH HOUSES

We currently have two houses for study which are of somewhat typical Swedish design. During the past year we have instrumented the two houses for collecting continuous data, which includes environmental temperatures in a variety of locations indoors and outdoors, pressure differences across the building shell in a variety of locations, and radon gas concentrations in differenct indoor or subfloor zones. The data are recorded electronically and hourly averaged data are stored in a computer located at the house. The two houses both have indoor radon concentrations which average between 100-200 Bq/m3 in the living level and the source of the radon is the soil gas.

The first house, (labeled 901), was instrumented in March, 1990, and data collection began at that time. This house was built in 1960, and the substructure consists of a basement with two attached crawlspaces, and a single living level floor above the substructure. The basement is a finished working space with a poured concrete slab. Both crawlspaces, which can be accessed from the basement through small doors with vents, have dirt floors. The house is of wood construction with a concrete block substructure. It is heated by hot water radiators with the water heated by an oil burner located in an attached room adjacent to the house. The house contains a natural draught ventilation system. This house will be the more difficult to model of the two research homes, because of its more complicated substructure.

The second house, (labeled 902), was instrumented in October, 1990, and data collection began Nov. 1. This house was built in 1907, and is entirely of wood construction. It is located on an esker and thus the soil is rather sandy and permeable. The structure of 902 is simple, consisting of a rectangular two-storied house on top of a small crawlspace on top of the ground. The house is heated with electrical radiators and contains a natural draught ventilation system. We hope the simplicity of the structure, shown in figure 2, will be useful in our modelling efforts.

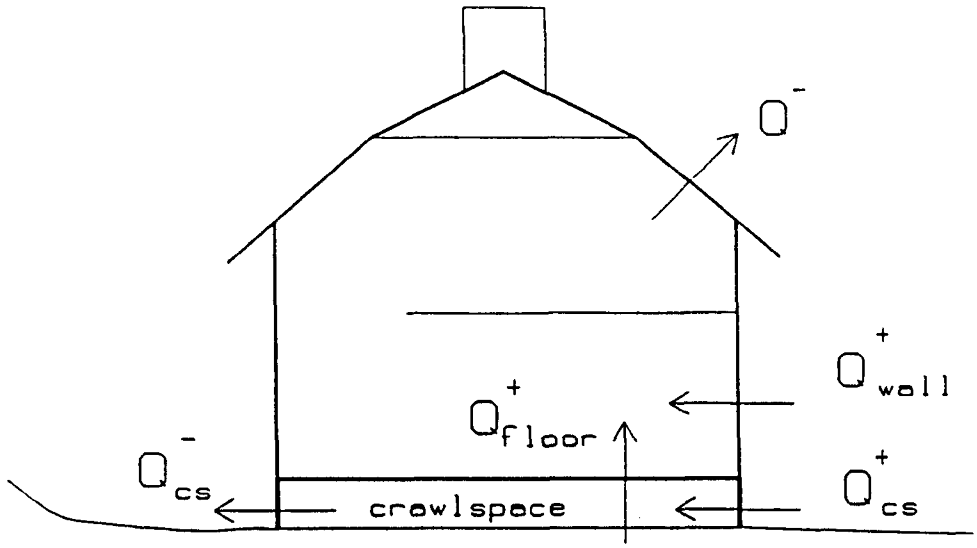


Figure 2. Research house 902, which is located on an esker. The Q's label air inflows and outflows needed for modelling.

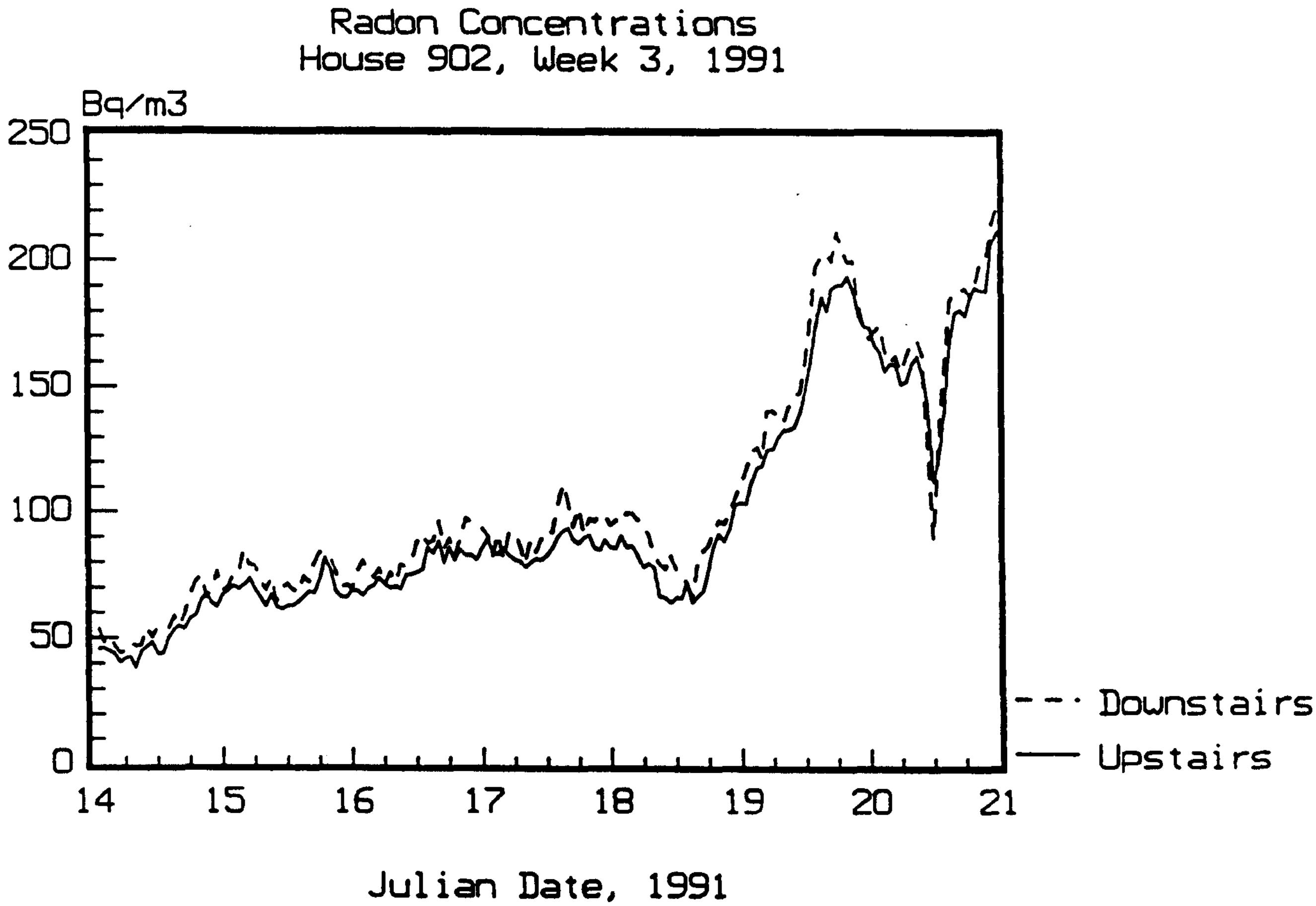


Figure 3. Hourly averaged radon concentrations.

Despite the fact that House 902 is a two-story house, the two levels are connected by considerable open space, and it acts very much like a single indoor zone. Figure 3 shows the radon concentrations upstairs and downstairs during one week in January, 1991, and the close agreement between the two indicates good mixing of the indoor air. The pressure difference between the downstairs and upstairs has also been continuously measured and is never larger than a few tenths of a Pascal. We thus treat House 902 as a single indoor zone in our radon flow model.

Both homes have natural draught ventilation, which is the most common type of ventilation system in Swedish detached houses. Natural draught ventilation does not work very well in the summer season when the outdoor temperature is about the same as the indoor temperature and the house has a low air exchange rate, as do most houses in Sweden. However, in the fall, winter, and spring natural draught is a rather efficient means of ventilating. Also, natural draught ventilation does not add any perturbing pressure differences across the building shell, as have been observed before in the New Jersey Piedmont homes due to unbalanced air handlers, which greatly complicates the modelling of the airflows and infiltration. Figure 4 shows the daily radon concentration varying nicely with the outdoor-indoor pressure difference and temperature difference in research house 901, showing that during non-windy days infiltration should be well described in a model using stack pressures alone.

The most significant factor affecting the daily dynamics of radon entry which differs in the current research from the Piedmont Project is the type of ventilation in the homes. All seven of the Princeton/ORNL research homes had forced air ventilation. The difference between the daily variations in the radon concentrations when the forced air ventilation system was in use versus when electric heaters were brought in to heat the home was quite large in the one home where this experiment was performed (2). In most cases the pressure differences across the building shell created by the air handler use were dominant over the effect of the indoor-outdoor temperature differences in their effect on the hourly variations of the radon.

Other differences between these research houses and the Piedmont research houses are the following. The Piedmont homes generally had unfinished basements with hollow block walls, a poured concrete slab with either a perimeter drain or a perimeter crack, and a sump. The hollow block walls played a role in radon entry because of their extremely porous nature, as did the perimeter drains and sumps with their direct connection to soil gas. These obvious entry routes usually make mitigation straightforward, by enough sealing of the entry routes to make depressurizing the area beyond the barrier created by the slab and walls possible. As is generally known now, this can usually be accomplished by sealing of perimeter drains and sumps and applying suction with a fan to the subslab. These methods are not suitable in the current Swedish research homes because of the exposed dirt floors in the crawlspaces. Either basement or crawlspace ventilation or soil ventilation using a radon well, especially in house 902 which has such permeable soil, will be applied here, if mitigation is desired by the homeowners.

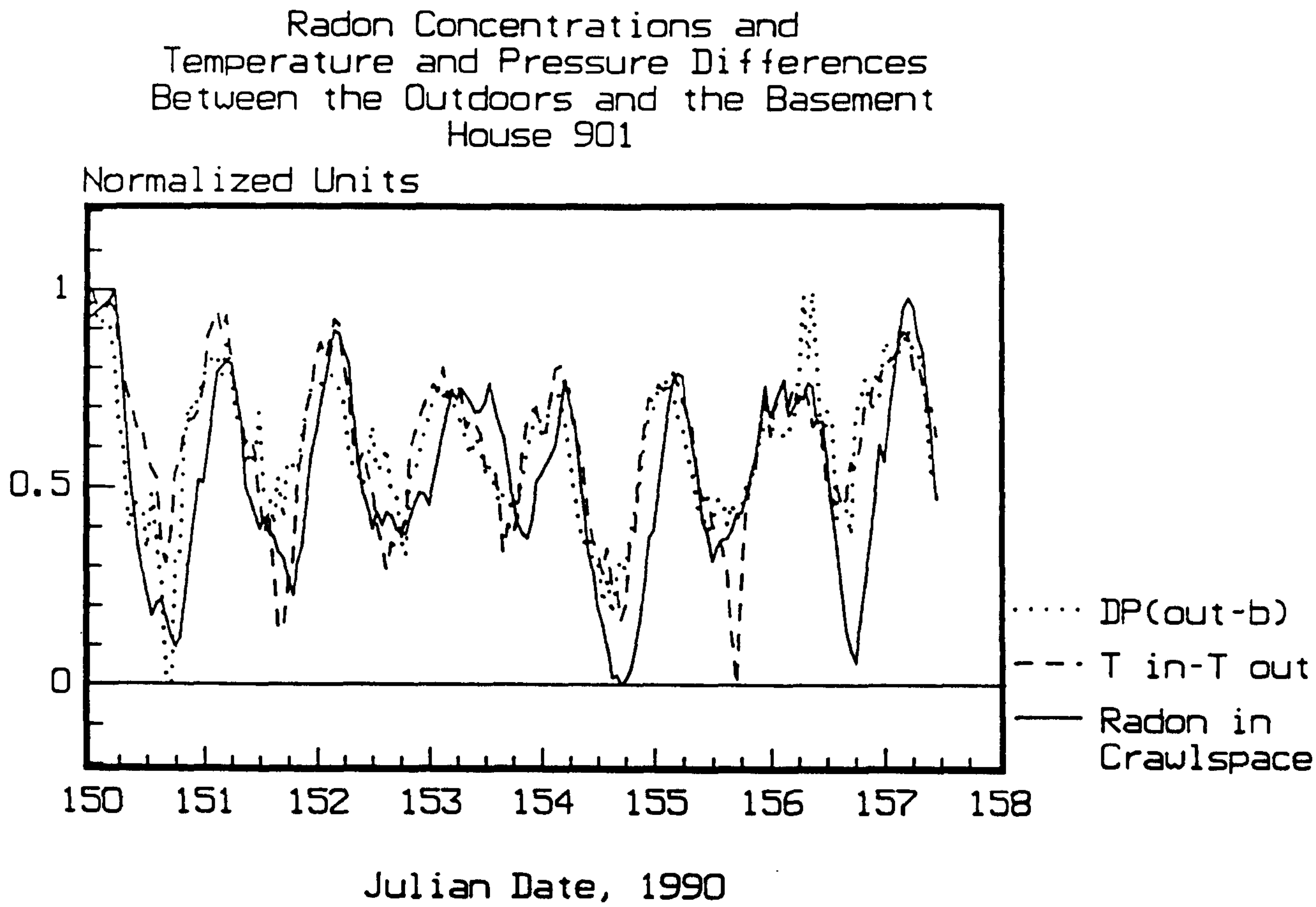


Figure 4. The curves were normalized to facilitate comparison. Maximum and minimum values for each curve are: 1) radon concentrations, 670 and 326 Bq/m^3, 2) temperature differences, 16 and -12 °C, and 3) pressure differences, 1.7 and -1.1 Pa.

MODELLING RADON ENTRY

We have previously described a model for calculating the time dependent radon concentration in different indoor zones, called the radon flow model (1). It takes as its input the airflows between indoor zones and between the indoors and the outdoors, at each time period Δt, and the initial radon concentration in each zone. It gives as its output the modelled (or predicted) radon concentration in each zone as a function of time. The equations for predicted radon in zone i, neglecting the radon decay term because for our research houses it is insignificant compared to the flow terms, are the following.

$$[Rn(t)]_i(\text{predicted})=[Rn(t-1)]_i+[Rn(t)]_i(\text{inflow})-[Rn(t)]_i(\text{outflow}) \quad (1)$$

where

$$[Rn(t)]_i(\text{inflow}) = \frac{\Delta t}{vol_i} \times [\Sigma_j Q(t-1)_{j\rightarrow i} \times [Rn(t-1)]_j + Rn'_i] \quad (2)$$

$$[Rn(t)]_i(\text{outflow}) = [Rn(t-1)]_i \times \frac{\Delta t}{vol_i} \; \Sigma_j Q(t-1)_{i\rightarrow j} \quad (3)$$

and where

- i,j — index the different indoor zones and the outdoors;
- $Q(t)_{i\rightarrow j}$ — is the flow from zone i to zone j during the time period from t-1 to t;
- $[Rn(t-1)]_i$ — is the predicted radon concentration in zone i at t-1;
- vol_i — is the volume of zone i;
- Δt — is the short time period during which radon concentrations in each zone are held constant; and
- Rn'_i — is a radon entry rate from outdoors, which is 0 except in the zone or zones which have flow directly from the soil gas.

The tricky part in implementing this model is obtaining the airflows between indoor zones and between indoor zones and the outside. In our previous application of this model we used as input airflows in a research home which were measured using a multi-tracer gas system. That system measured time-varying airflows at the same time we were measuring time varying radon concentrations, which gave us the ability to check the modeled radon concentrations. The agreement between the modelled and the measured radon in the two indoor zones was quite good, indicating how well the measured airflows represented the true situation (1). It is not always possible to have a multi-tracer gas system available in research houses, however. In fact only a few such systems exist in the world.

The next best alternative to measuring the airflows is to model them. In fact, modelled airflows are more desirable than measured ones from a pedagogical viewpoint because, once the airflows are properly modelled, we can use the model to learn more about radon entry by altering the input parameters.

Our current modelling efforts have been concentrated on developing a simple formulism for modelling the airflows, treating the air infiltrating from the soil gas separately from the air infiltrating from the outdoor air. There exists several indoor airflow and infilration models which could be adapted for use in indoor pollution transport models, such as the radon flow model. However, they require detailed house specific knowledge on leakage characteristics, such as the location and type of flow paths beween zones and around the building shell, and they are often cumbersome and difficult to use.

Our initial goal is to see how simple we can make an infiltration model and retain enough of the physics to learn something from the model. Consider the simplest case for modelling and for predicting the airflows and the radon concentration. That would consist of simply one indoor zone connected to both the outdoors and to a source of radon in the soil gas. We have been fortunate enough to obtain just this type of house for one of our research homes; as mentioned earlier in connection with figure 3, House 902 can be treated as a single indoor zone. This has made it rather easy to begin our effort at modelling airflows and predicting radon and check the predictions on a simple, but real, home environment. The flows labeled in figure 2 are the relevent airflows to model for a single indoor zone. Q^{+}_{floor} is the airflow which will carry the radon into the house from the crawlspace. For modelling radon entry during the winter months we assume the flow from the indoors to the crawlspace is negligible.

We have begun by considering only the temperature difference between the indoors and the outdoors as the driving force for air infiltration. Because of the large number of days in Sweden during the fall, winter, and spring months which have significant temperature differences between the indoors and the outdoors, stack effect pressure differences caused by differences in the indoor and outdoor temperatures are an important driving force for air infiltration in Swedish houses.

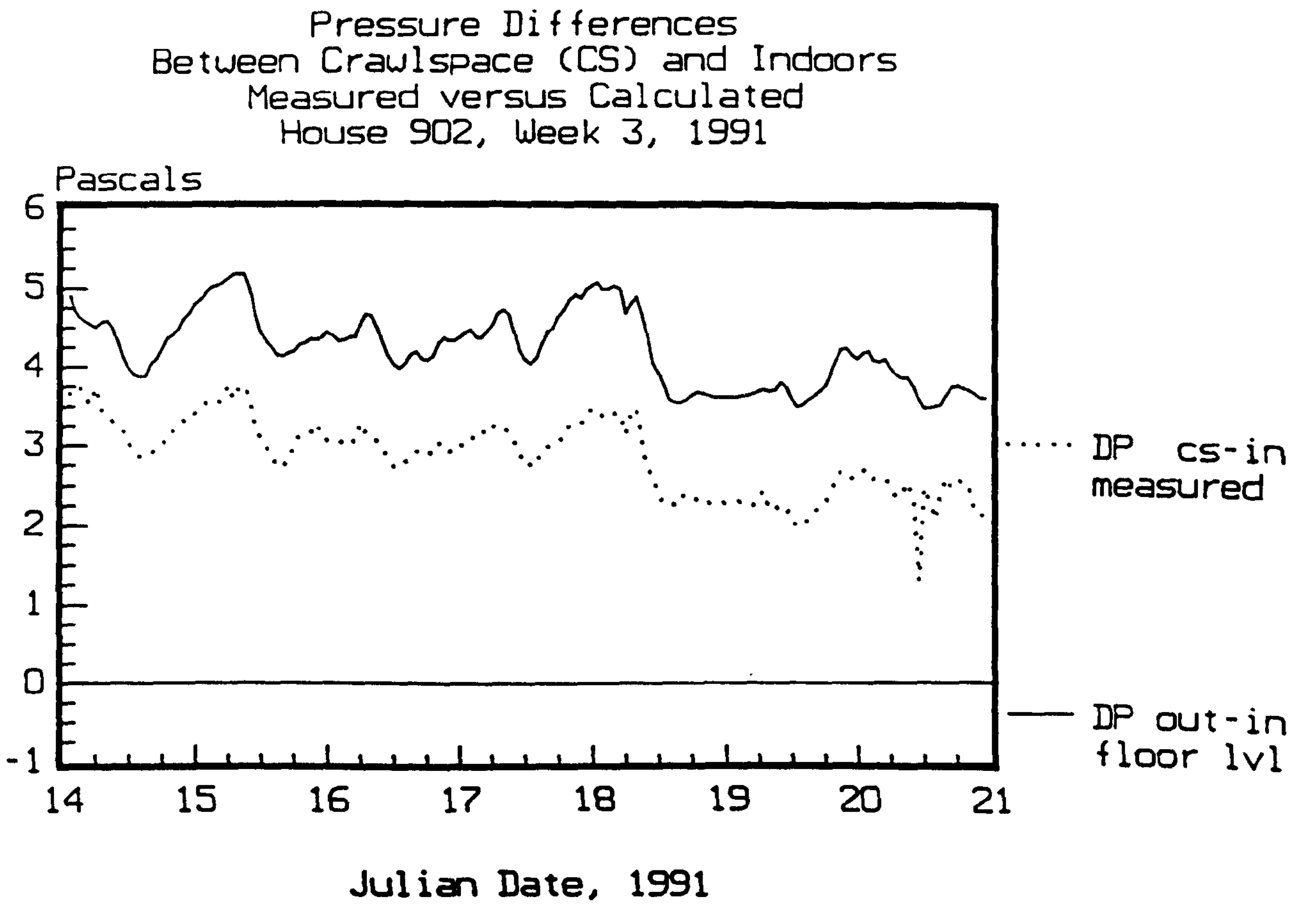
The stack pressure is the difference in pressure difference between the indoors and the outdoors at one level, or height, on the building versus another level on the building. But the pressure difference must be known at one of the heights to know it at any other, which is why the stack pressure is often referenced to a neutral pressure plane, labeled β_o, where the pressure difference is zero. We also use the neutral pressure plane as a point of reference, and find that often one can solve the continuity equations exactly for β_o.

The stack pressure difference between the outdoors and a single indoor zone is given (in Pascals) by:

$$\Delta P_s(\beta) = -\rho_{out} g H_s (\beta - \beta_o)\left(\frac{T_{in} - T_{out}}{T_{in}} \right) \qquad (4)$$

where ρ_{out} is the density of the outdoor air, g is the acceleration due to gravity, (m/sec^2), T_{in} and T_{out} are indoor and outdoor temperatures, (K), β is a dimensionless height, $z = H_s\beta$, (and β_o refers to the height z_o where the indoor pressure equals the outdoor pressure), and H_s is the height dimension of the building over which the stack pressure is being calculated, (m). The sign convention for equation (4) and all pressure differences reported in this paper is the pressure outdoors minus (-) the pressure indoors.

We have chosen a week in January, 1991, during which there was little wind, to compare the measured pressure difference between the indoors and the crawlspace, recorded hourly from a transducer measuring in the center of the floor area, with the calculated stack pressure difference at the floor level, (β=0), using equation (4). The hourly measured indoor and outdoor temperatures and the stack height of house 902 are the input to equation (4). This comparison is shown in figure 5, and it is encouraging how well the stack pressure reproduces the measured pressure difference during this non-windy week. The bimp on day 20 in the measured pressure difference and also in the radon concentrations shown if figure 3 correspond to a time when the homeowner aired the house.



CONCLUSION

We are currently modelling airflows using the stack pressures alone to determine infiltration. The stack pressures are modelled using temperatures measured at the research house. We will check the modelled radon concentrations using data measured at the research house during non-windy days or weeks. Pressure differences modelled from the effect of wind are intended to be added separately to the model. Our ultimate goal is to determine to what approximation we can model indoor radon concentrations using a simple formalism based on temperature differences and the wind. Once we have determined that, we can use the model to learn more about the radon dynamics as a function of parameters, such as the leakiness to the soil gas versus the leakiness to the outdoor air. A future report will present details of the model formalism and results.

Acknowledgments. The authors thank Leif Nyblom and Hans Möre for crucial help with the instrumentation and data loggers.

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. The work described in this paper was, however, partially funded by the the CEC/NRPB Association Agreement contract No. B.16.347 UK (H), which we gratefully acknowledge.

REFERENCES

1. Dudney, C.S., Hubbard, L.M., Matthews, T.G., Socolow, Gadsby, K.J., Bohac, D.L., Hawthorne, A.R., Harrje, D.T., Wilson, D.L., Investigation of Radon Entry and Effectiveness of Mitigation Measures in Seven Houses in New Jersey, Final Report ORNL-6487, NTIS TN 37831, August, 1989.

2. Hubbard, L.H., B. Bolker, R.H. Socolow, D. Dickerhoff, and R.B. Mosley, "Radon Dynamics in a House Heated Alternately by Forced Air and by Electric Resistance," in Proceedings of The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1, EPA-600/9-89-006a (NTIS PB89-167480), P. 6-1, March, 1989.

3. Tolstoy, N. and Svennerstedt, B., Repair requirements in the Swedish building stock. Report M84:10, National Institute for Building Research, Gävle, 1984 (in Swedish).

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.

RADON REDUCTION IN NEW CONSTRUCTION: DOUBLE-BARRIER APPROACH

by: 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

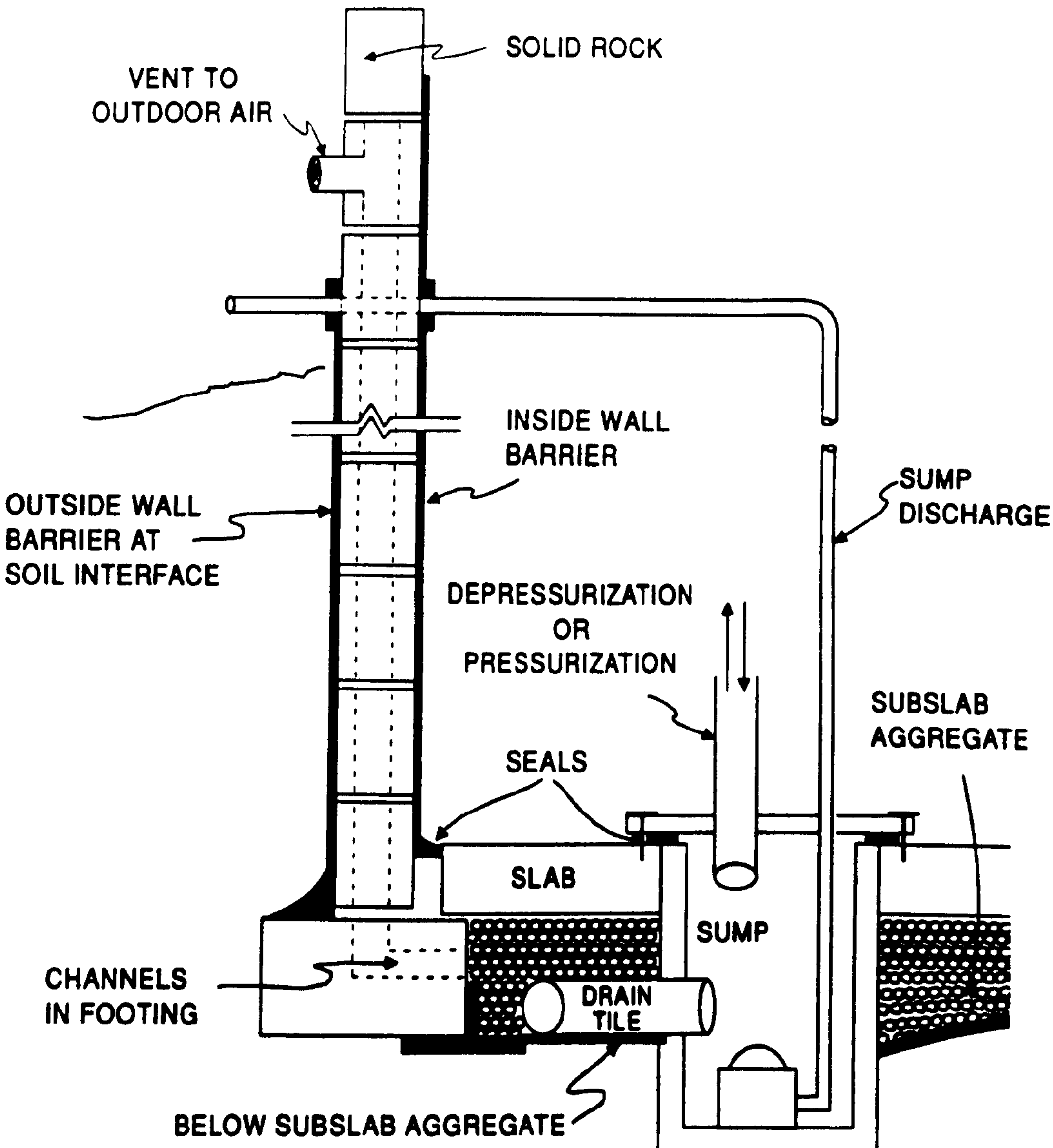


Figure 1. Double-barrier construction for a basement with sump.

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.

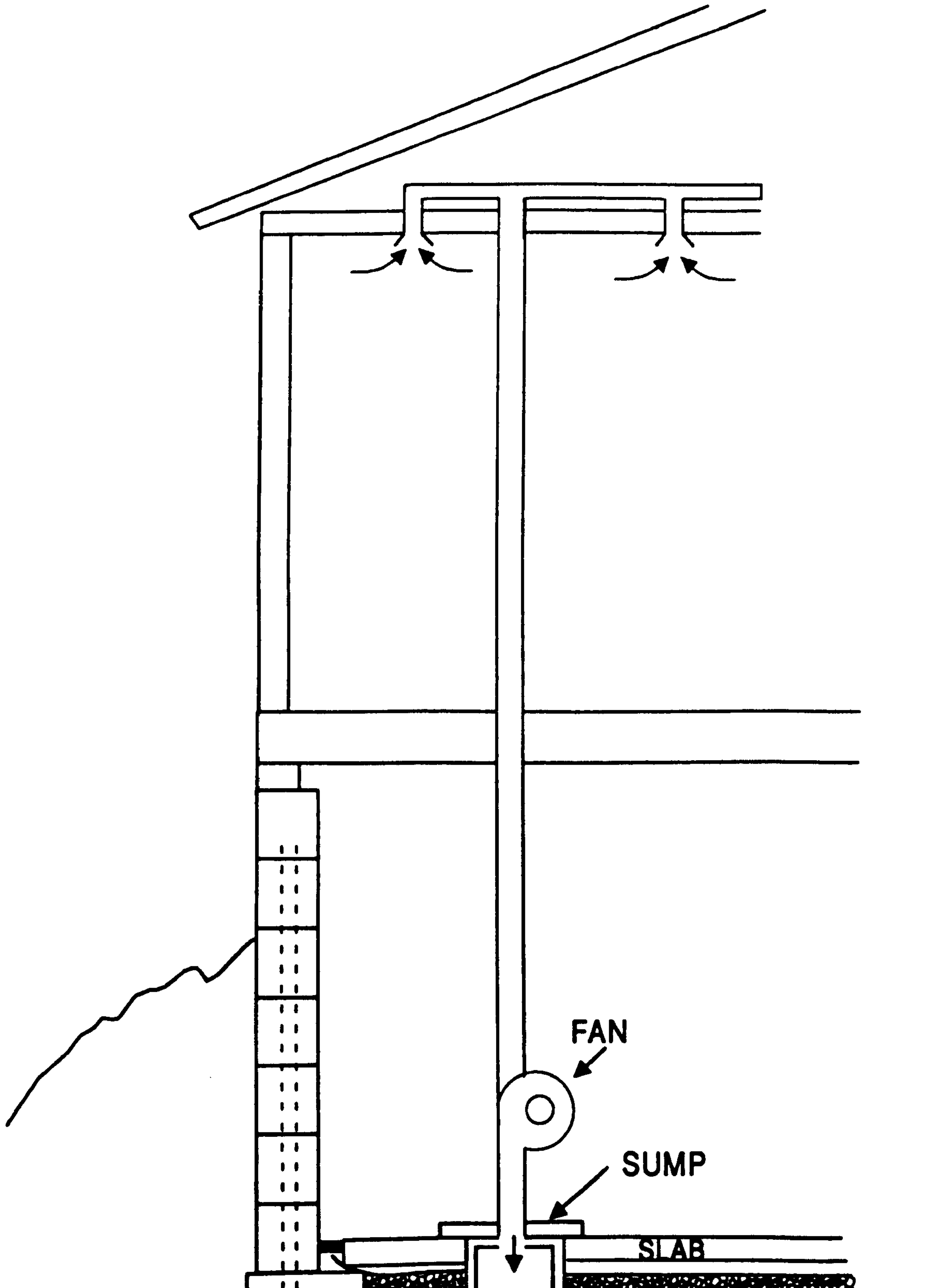
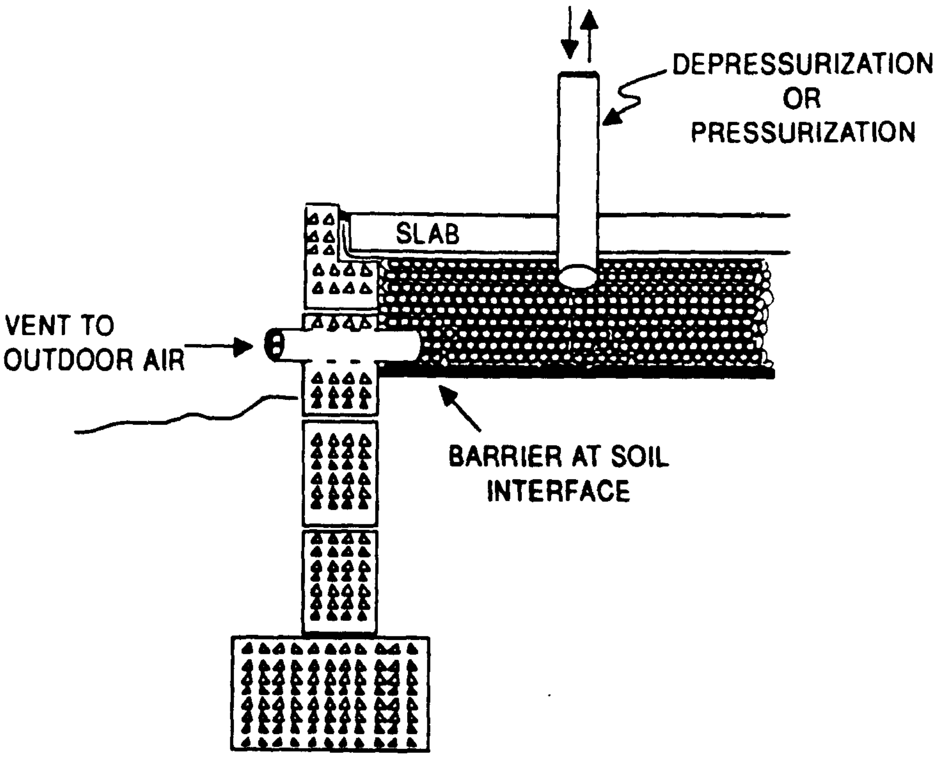
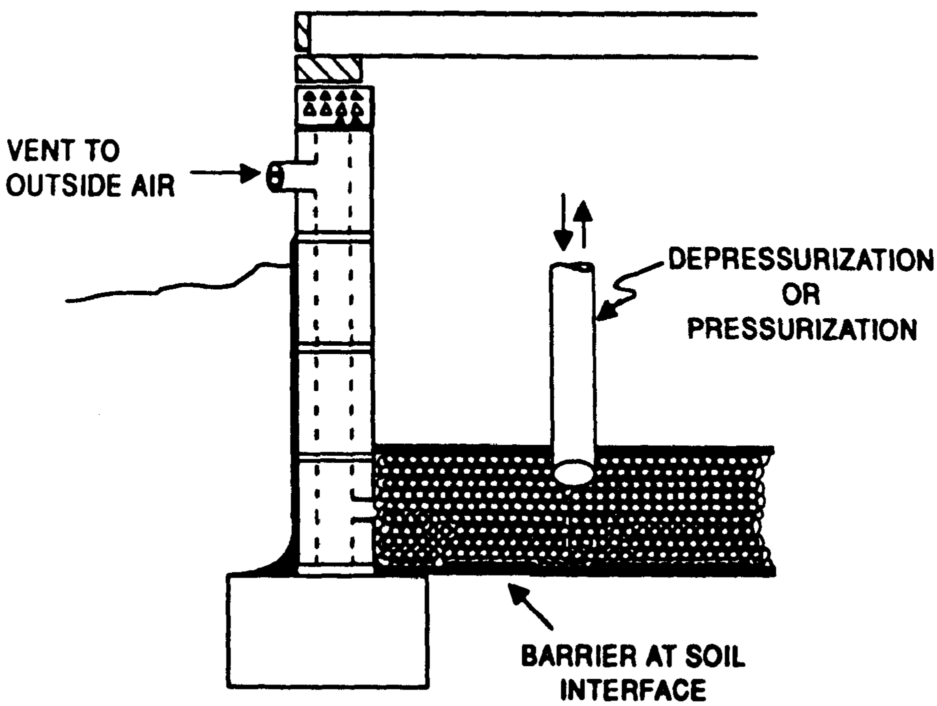


Figure 2. Double-barrier pressurization using interior air.



SLAB-ON-GRADE



CRAWL SPACE

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.

REFERENCES

1. Osborne, M.C., Radon-Resistant Residential New Construction, United States Environmental Protection Agency, EPA/600/8-88/087, July 1988.

2. Task 3 Final Report, Sampling Design, Data Collection and Analysis, Statewide Scientific Study of Radon, Prepared for the New Jersey Department of Environmental Protection, Prepared by Camp Dresser and McKee Inc., April 1989.

3. Demonstration of Mitigative Techniques in Existing Houses and New House Construction Techniques to Reduce Indoor Radon, Prepared for New York State Energy Research and Development Authority and the U.S. Environmental Protection Agency, Prepared by W.S. Fleming and Associates, Inc. (NYSERDA report in publication).

4. Brennan, T. and Osborne, M.C., Overview of Radon-Resistant New Construction, In Proceedings of the EPA 1988 Symposium on Radon and Radon Reduction Technology, Denver, CO, Oct. 1988.

5. Walkinshaw, D.S., The Enclosure Conditioned Housing (ECHO) System: A New Approach to Basement Design, In Proceedings of The Fifth International Conference on Indoor Air Quality and Climate, Toronto, Canada, Aug. 1990, Vol 3, p. 257.

TECHNOLOGICAL ENHANCEMENT OF RADON DAUGHTER EXPOSURES DUE TO NON-NUCLEAR ENERGY ACTIVITIES

by: 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.

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 μBq/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 x 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	0.134×10^5
Pb-214	-	26.8 m	8,580	7.68	0.659×10^5
Bi-214	-	19.7 m	6,310	7.68	0.485×10^5
Po-214	7.69	0.0027 m	0.0008	7.68	0.000×10^5
					1.278×10^5 or 1.3×10^5

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 equlibrium 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:

$$WL = \frac{R}{5550 \times V \times E} \quad (1)$$

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:

$$WL = \frac{(13.68 MeV/atom_A)(N_A) + (7.68 MeV/atom_{B+C})(N_B+N_C)}{1.3 \times 10^5 \ MeV/WL} \qquad (2)$$

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: $pCi_B/l. = 0.65\ C_a$ (5)

and $pCi_C/l. = 0.35\ C_a$ (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 = 1×10^{-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 nonnuclear 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.

REFERENCES

1. Gesell, T.F. and Pritchard, H.M. The technologically enhanced natural radiation environment. Health Physics. 28: 361, 1976.
2. Fry, R.M. Radiation hazards in uranium mining and milling. Atomic Energy in Australia. 18(4): 1, 1975.
3. Costa-Ribeiro, C., Thomas, J., Drew, R.T., Wrenn, M.E. and Eisenbud, M. A radon detector suitable for personnel or aera monitoring. Paper presented at the Uranium Mining Health Physics Workshop, Denver, Colorado. June 21-22, 1970.
4. Lasseur, C. Apparatus for selective continuous measurements of each solid short-lived daughter products of radon. Paper presented at the Journess d`Electronique de Toulouse, France. March 4-8, 1968.
5. Evaluation of occupational and environmental exposures to radon and radon daughters in the united states. NCRP Report No. 78. National Council on Radiation Protection and Measurements, Bethesda, Md, 1985. 83 pp.
6. Manual on radiological safety in uranium and thorium mines and mills. IAEA. Safety series No. 43. International Atomic Energy Agency, Vienna, Austria, 1976. 16 pp.
7. Scott, A.G. A field method for measurement of radon daughters in air.Health Physics. 41: 403, 1981.
8. Holmgreen, R.M. Working levels of radon daughters in air determined from measurements of RaB + RaC. Health Physics. 27: 141, 1974.
9. Bauman, A., Horvat, Đ., Kovač, J. and Lokobauer, N. Technologically enhanced natural radioactivity in a coal-fired power plant. In: K.G. Vohra, K.C. Pillai, U.C. Mishra and S. Sadasivan (ed.), Natural Radiation Environment. Wiley Eastern Limited, Bombay , 1982. p. 401.
10. Beck, H.L., Gogolak, C.V., Miller, K.M. and Lowder, W.M. Perturbations on the natural radiation environment due to the utilization of the coal as an energy source. Paper presented at the DOE/UT Symposium on the Natural Radiation Environment III, Houston, Tx. 1978.
11. Kovač, J., Cesar, D. and Bauman, A. Natural radioactivity in a phosphate fertilizer plant. In: Proceedings of the XIV Regional Congress of IRPA. Current Problems and Concerns in the Field of Radiation Protection. Yugoslav-Austrian-Hungarian Radiation Protection Meeting, Kupari, Yugoslavia, 1987. p. 69.

EXTENDED HEATING, VENTILATING AND AIR CONDITIONING DIAGNOSTICS IN SCHOOLS IN MAINE

BY - 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.

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 CO2 and other indoor air contaminants for which CO2 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.

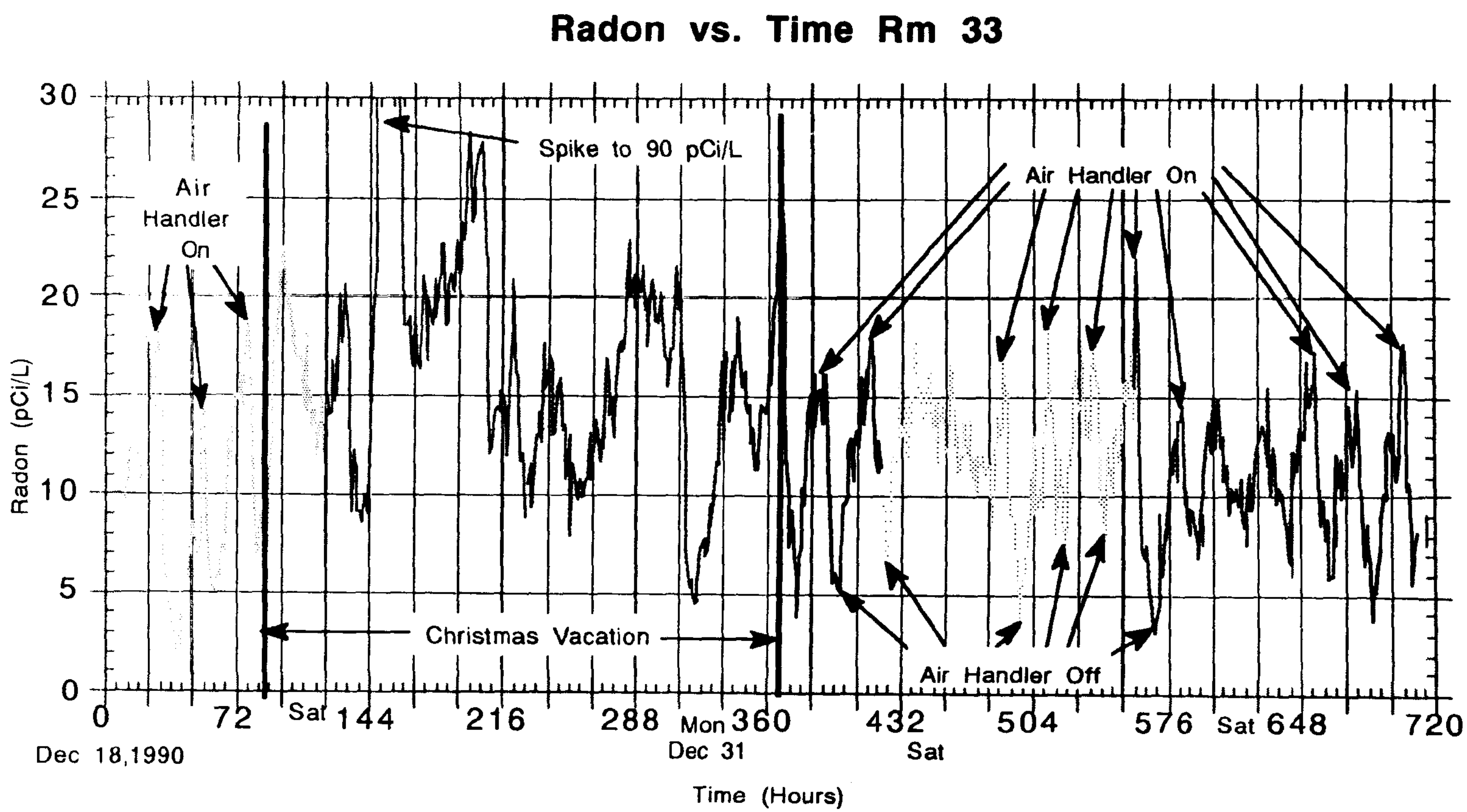
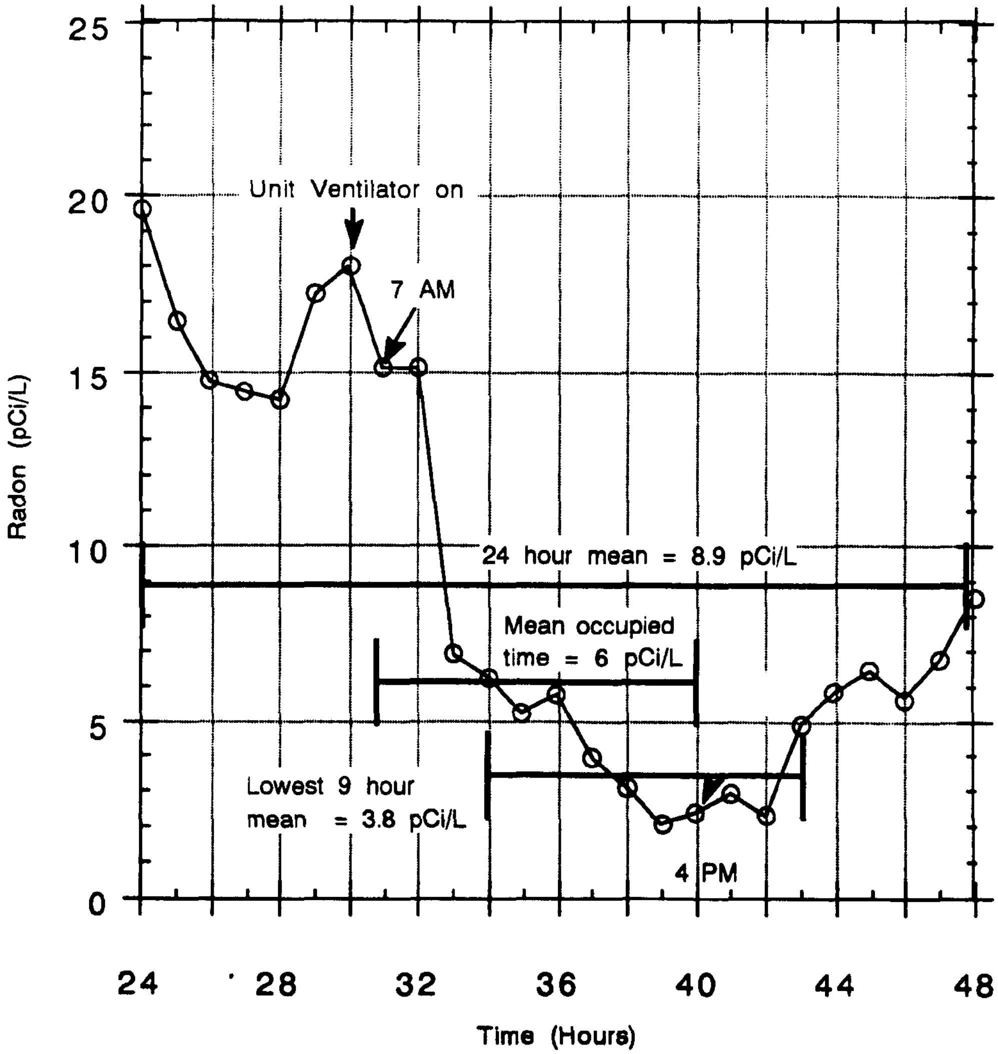


Figure 1 - Radon Levels in Room 33

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.

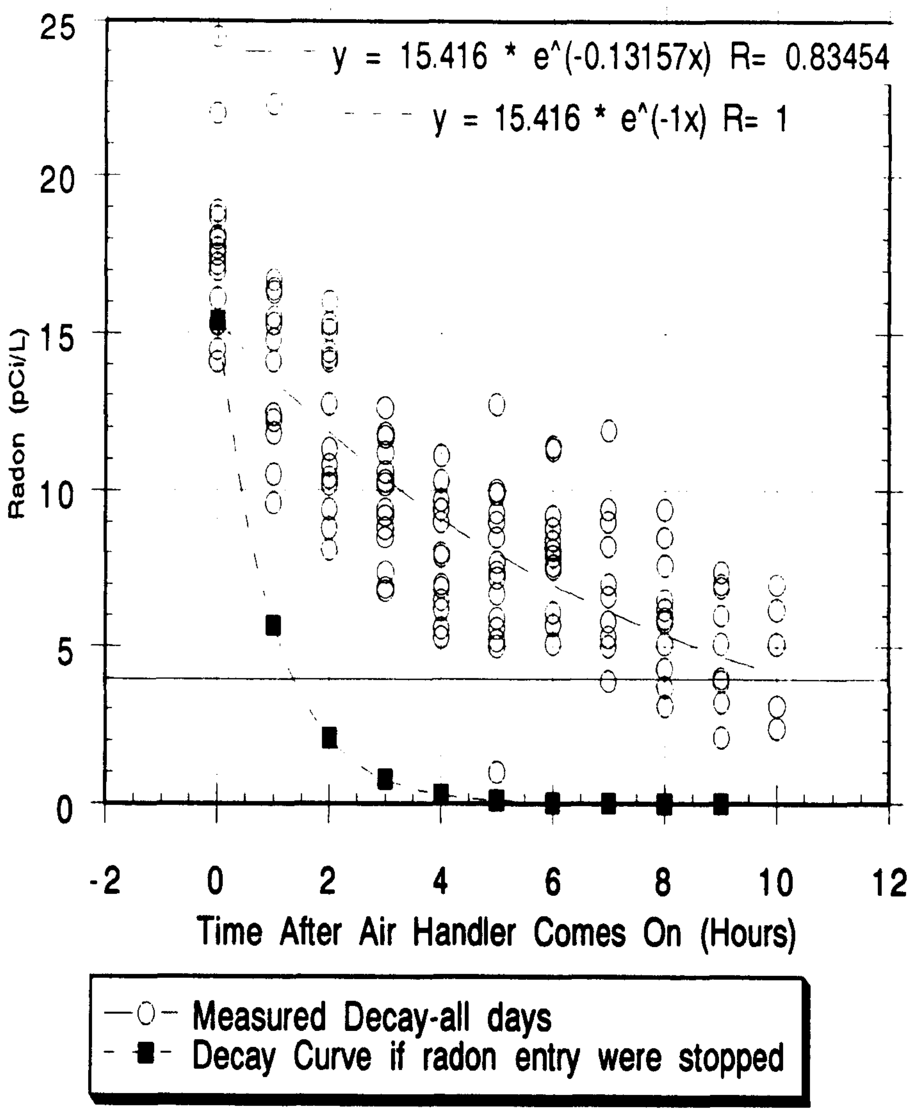
If a given amount of contaminant is released into a room and then allowed to be removed by dilution with ventilation air, it is expected that the concentration of the contaminant will decay exponentially with time[3]. The rate at which it decays is described by the solution to the continuity equation. This is given as the following :

$$C(t) = C(0) \times e^{Nt} \quad (1)$$

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

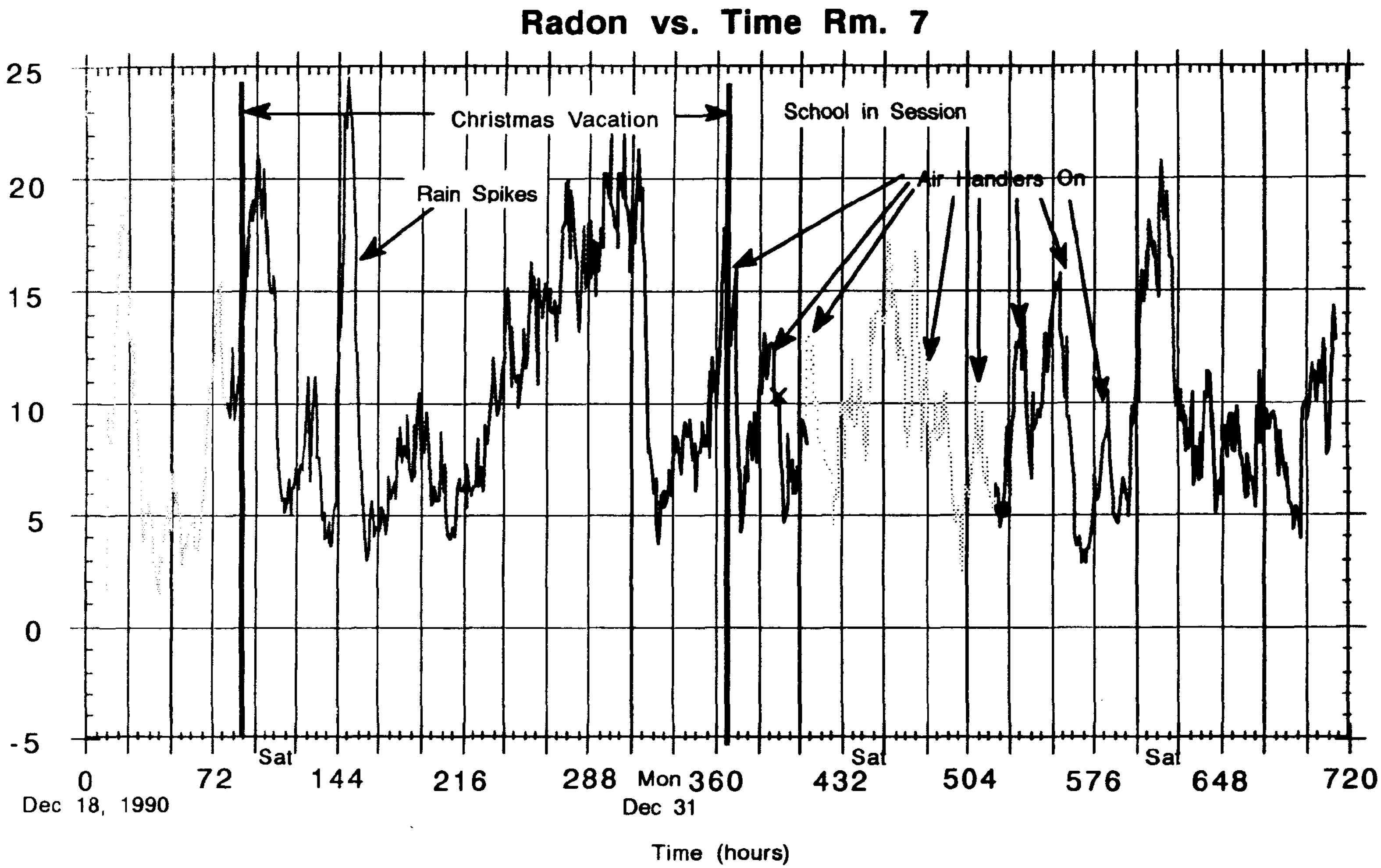


Figure 4 - Radon Levels in Room 7

Figure 5 -Reduction Rate of Radon in Room 7
Exhaust Fan On - All Days

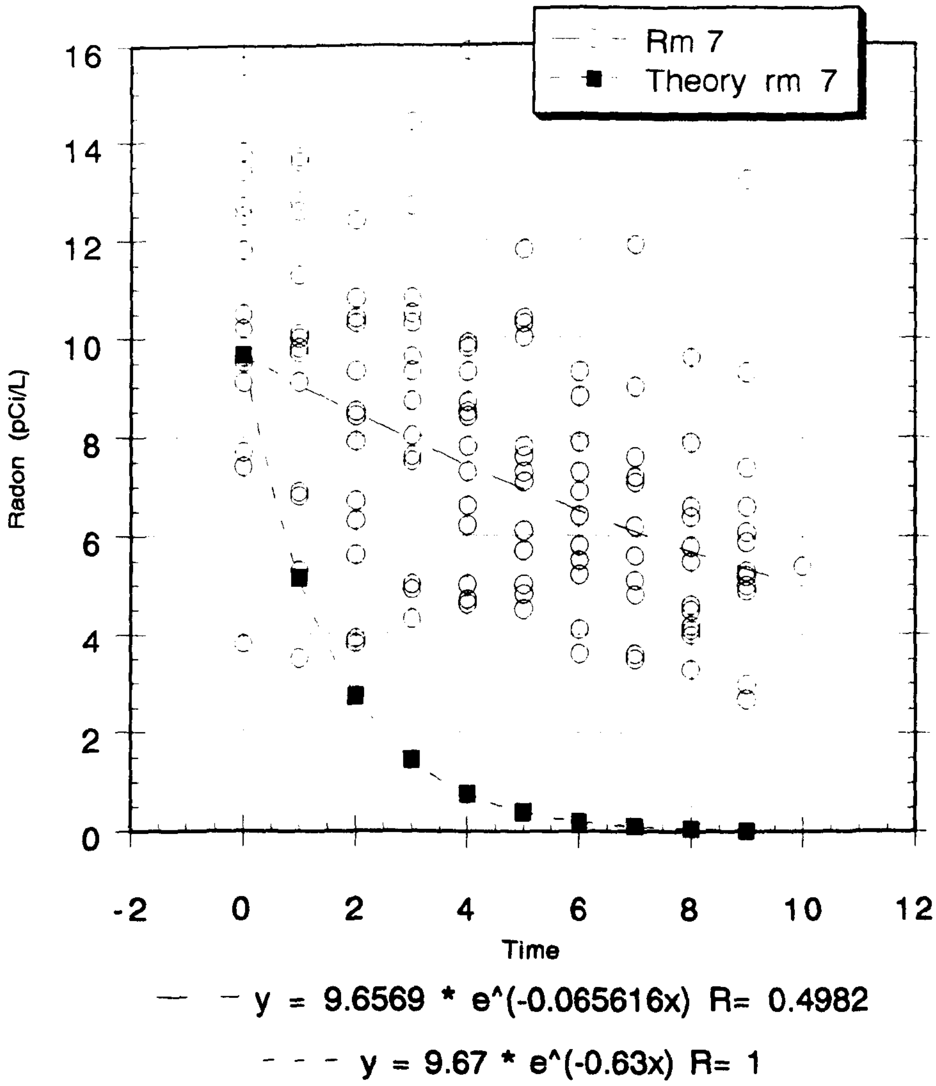
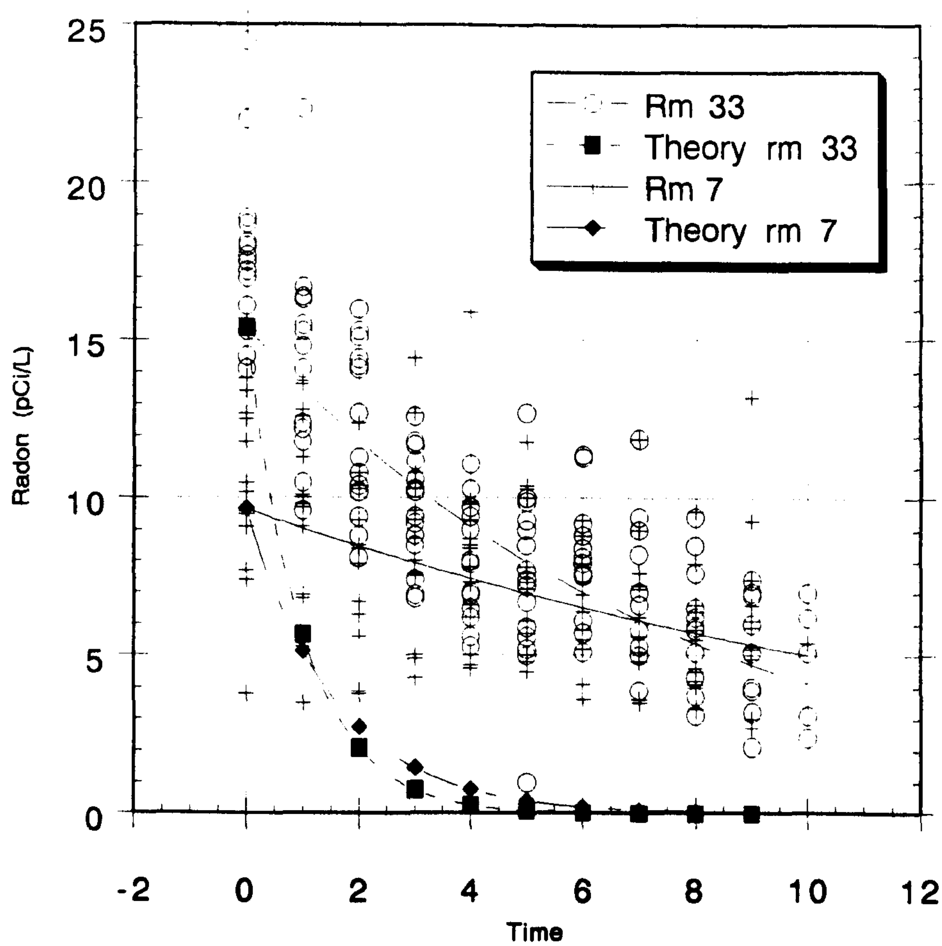


Figure 6 - Reduction Rate of Radon
Air Handlers On - Rms. 7 & 33



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

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.

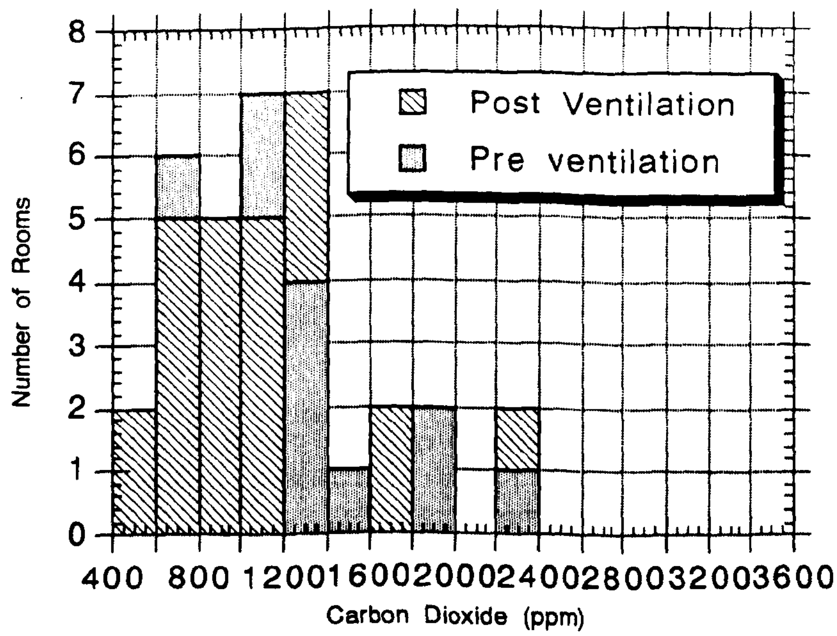
Carbon Dioxide Measurements--

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 ± 450 ppm and the post level mean was 1042 ± 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

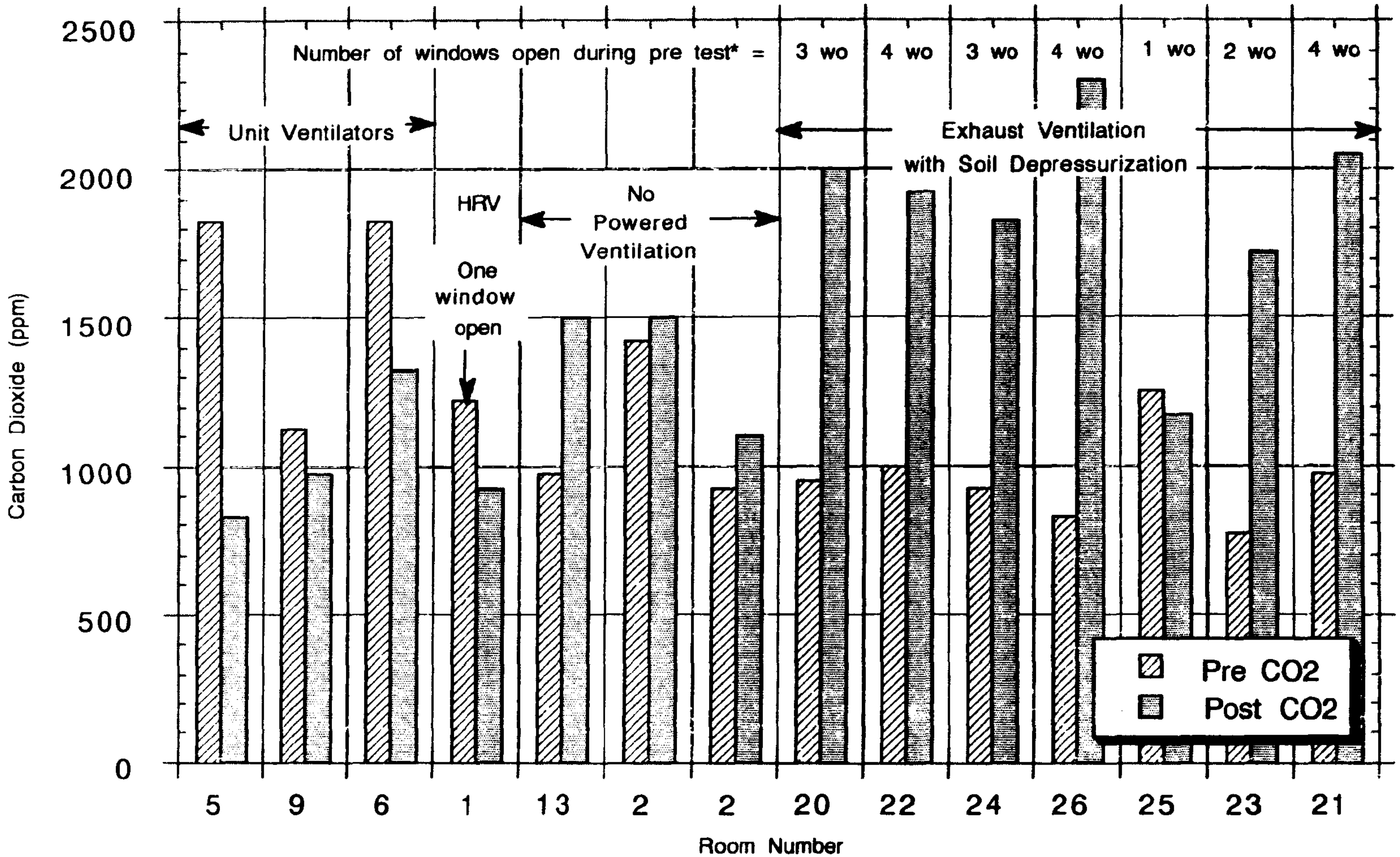


Carbon Dioxide Measurements in the Russell School--

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.