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A PRELIMINARY COMPUTATIONAL INVESTIGATION OF RADON REDUCTION STRATEGIES IN A LARGE BUILDING

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ABSTRACT

Indoor radon levels primarily depend on radon entry from the concrete slab and dilution due to outdoor air entering a building. Inter-zonal airflow plays an important role in fresh air dilution in a large building compared to a residential dwelling. Radon transport in the soil and slab, zone radon balance, airflows and indoor pressures in a large building are simulated. The finite element method is used to simulate pressure and radon distributions in the soil and slab. The air distribution system is also simulated, using a network model and is coupled with a lumped model for the zones. Predictions agree reasonably well with experimental data obtained from a building in Florida. Sensitivity studies show the influence of outdoor airflow and soil radium content on indoor radon levels. A discussion of radon reduction strategies for large buildings is also presented.

INTRODUCTION

Indoor radon level is an important element affecting indoor air quality. Radon is a primary cause of lung cancer and a dominant source of natural radiation exposure. It mainly comes from soil, rock and ground water through the concrete slab and enters into a building. Through the floor, radon can enter a building in two ways: diffusion through the concrete slab and advection through cracks in the concrete driven by air pressure gradient. Since radon entry from radon diffusion is usually less than from advection, one indoor radon reduction strategy is to seal the cracks in the concrete slab. Indoor radon levels can also be reduced by adding more fresh air through the air distribution system or through natural ventilation. Other methods include active sub-slab depressurization and reducing diffusion from the concrete slab by choosing materials with appropriate properties.

The paper simulates radon transport in the soil and slab, zone radon balance, airflows and pressures in the air distribution system and zones in a large building. The Polk Life and Learning Center in Bartow, Florida, was chosen for simulation, because the U.S. Environmental Protection Agency (EPA) and the Southern Research Institute (SRI) were monitoring this building for airflows, indoor pressures and radon concentrations. Predictions are compared with experimental data provided by SRI. In addition, parametric studies are used to gauge the efficacy of radon reduction strategies for this large building in question. FSEC 3.0 (1992), developed at the Florida Solar Energy Center, is used to simulate the large building. Numerical scheme of FSEC 3.0 is based mainly on finite element method for radon transport in the soil and slab (Swami, et al., 1992).

MATHEMATICAL FORMULATION

A brief description of the relevant governing equations for radon transport, zone contaminant balance and airflow are given below. All the equations and algorithms were integrated in the computation platform, FSEC 3.0 (1992), to provide the following broad capabilities:

- Radon transport in the soil and slab
- Inter-zone airflow, including air distribution system
- Zone contaminant balance, including radon
- Zone thermal and moisture balance
- Heat and moisture transport in building envelope
- Several HVAC system models, including VAV box performance
- Duct heat and moisture exchange

Radon Transport and Pressure Equation

The pressure equation, derived from Darcy's equation for airflow through a porous media, is given as (Yuan & Roberts, 1981):

$$\frac{\partial P}{P_0 \partial \tau} = \nabla \cdot \left(\frac{K}{\mu} \nabla P \right) \tag{1}$$

It should be noted that Darcy's law is valid for a Reynolds number $R_{eK} < 1$ (Cheng, 1985).

Radon transport equation, including multiphase radon generation and transport in porous medium (Rogers & Nielson, 1991), may be expressed as

$$\frac{\partial C_a}{\partial \tau} = \nabla \cdot (D_c \nabla C_a) - \frac{K_c}{\mu} \nabla P \cdot \nabla C_a - \lambda C_a + R \rho \lambda E_c \tag{2}$$

HVAC System (Duct and multizone airflow and pressure)

Mathematical formulations for several elements of the air distribution system used in this simulation are listed below.

Power Law Element - Cracks

Based on the power law, the airflow through a crack is expressed as

$$\dot{m}_{ij} = C_{m,j} (\Delta P)^{n_j} = C_{m,j} (P_i - P_j)^{n_j} \tag{3}$$

where $\dot{m}$ is mass flow rate. C_{mj} is the flow coefficient at j-th crack and ΔP is the pressure difference across the crack. The "i" indicates i-th zone where air flow enters and "j" indicates the j-th zone or specific ambient condition where air flow leaves. "n_j" is exponent of flow equation at the j-th crack.

Duct System

The pressure loss in ducts due to friction is given by

$$\Delta P_f = f \frac{L}{D} \frac{\rho v^2}{2} \tag{4}$$

The dynamic losses due to the fitting is

$$\Delta P_d = C_0 \frac{\rho v^2}{2} \tag{5}$$

Total pressure loss is

$$\Delta P = \Delta P_f + \sum \Delta P_d \tag{6}$$

Zone Radon Balance Equations

The indoor radon balance equation at the i-th zone may be written as

$$V_i \frac{\partial C_{a,i}}{\partial \tau} = F_{entry,i} + Q_{ret,i} (C_{a,\infty} - C_{a,i}) + \sum_{j=1}^{noz} Q_{j-i} (C_{a,j} - C_{a,i}) \tag{7}$$

It should be noted that Q_{ret} is the return flow to the building return plenum in this simulation. The ambient radon concentration will be modified by combining all return flow from all zones with the outdoor air flow. Its weighted expression is

$$C_{a,\infty} = \frac{Q_{OA} C_{\infty} + \sum Q_{ret,i} C_{a,i}}{Q_{OA} + \sum Q_{ret,i}} \tag{8}$$

VALIDATION

The Polk Life and Learning Center in Bartow, Florida, was chosen by the U.S. EPA and the Florida Department of Community Affairs (FDCA) to study diagnostics and mitigation of radon. It is a slab-on-grade facility of approximately 18,000 ft^2 in size and consists of a conference, cafeteria, staff office space, classroom, a kitchen area, janitorial closets, audiology room, and a workshop. The Bartow area is known to have high ambient radon levels. The building design plan indicates a 21 ton (AC-1) direct expansion split system and a distribution system of supply ductwork with total 2.652 m^3/s (5620 cfm), AH-1. Each zone is supplied with one or more Variable Air Volume (VAV) boxes. Maximum outdoor airflow rate is 0.566 m^3/s (1200 cfm, F-1). However, results from a recent testing and balancing report showed maximum capacities of 3.326 m^3/s (7047 cfm) for the supply fan and 1.438 m^3/s (3047 cfm) for the outdoor fan. All experimental data are provided by SRI. The layout of the air distribution system is shown in Figure 1.

Based on the air conditioning plan of the building, the air distribution system had to be separated into a number of component elements used in the simulation. Components include ducts with different cross section and lengths, VAV boxes, and the fans. An individual VAV box or fan is considered one element, and a duct with the same shape and cross section is also considered one element. The parameters of most elements required for the simulation were obtained from the ASHRAE handbooks and U.S. EPA. However, where the parameters of some elements are not known, these parameters were adjusted to match experimental data.

In order to model radon entry correctly, a 3-D soil and slab discretization becomes necessary to obtain radon entry rate from the slab. Large elements are used in the present simulation to reduce computational time. Since cracks are not defined explicitly, weighted-average properties combining air and concrete are used for the elements containing cracks.

From the layout of the Polk Life and Learning Center, it was decided to divide building into seven (7) zones. These zones labeled Room 102 for Zone 1, Conference room for Zone 2, Cafeteria for Zone 3, Rm 105 for Zone 4, Audiology room for Zone 5, Room 109 for Zone 6, and Corner room for Zone 7, respectively, are shown in Figure 2. Measurement data are available for Zones 1, 2, 3, 5 and 6.

Airflow and Pressure Simulation

Airflows and pressures were first simulated to obtain the indoor pressures and inter-zone airflows for the detailed simulation of radon transport in the soil and slab. The predicted airflows were then compared to design and test data. Constant inlet flow is assigned to the fan and outdoor air pressures are set to zero gauge. All VAV boxes are assumed to be fully open. Compared to design data from the air conditioning plan, the maximum percent difference in airflows between prediction and design was found to be 6.04%. Compared to the test data from the testing and balancing report, the maximum percent difference in airflows between prediction and testing data was 4.62%. The details of air distribution system simulation is given in Gu, et al. (1993).

Simulation Results of Indoor Radon Level in a Typical School Day

A typical school day is chosen to validate simulation results. Tests were conducted, by US EPA and SRI, between 6:00 AM, 4/21/93 (Wednesday) to 6:00 AM, 4/22/93 (Thursday). The A/C was on during the first twelve (12) hours and off in the next twelve (12) hours.

When the A/C is on, a outdoor air is brought through the duct system to dilute indoor radon. When the A/C is off, no outdoor air enters the zone, and indoor radon concentrations increase due to radon entry from the slab.

Figures 3 through 6 compare the prediction to measured data for different zones. As expected, indoor radon concentrations decrease during the A/C on-time period and then increase linearly, based on the magnitude of radon entry rate from the slab in the individual zone, when the A/C is off.

It is evident that while the agreement at the beginning and end of the "on" cycle is good, the model predicts higher radon dilution rates in the "on" cycle than shown by experiment. However, the model and experiment compare very well during the "off" period. The disparity noted during "on" times appears consistently in all zones. This is a significant cause for concern and is possibly due to two factors. 1) The model assumes well mixed zones which may not be true in actuality. The ventilation efficiency may not be 100% leading to different radon levels within a zone and a single-point measurement may be insufficient. Secondly, due to unavailability of data on ambient radon levels, we assumed a constant of 129.5 Bq/m^3 (3.5 pCi/L) for simulation. Results of other work for the Florida Radon Research Program (see Tyson et al., 1993) show that ambient radon levels may not only be higher than established action levels, but may also vary cyclically during a 24-hour day. Clearly, the model would predict lower rates of dilution and would approach measured values if higher ambient radon levels varying with time are used in the simulation. Undoubtedly, these two factors namely, ventilation efficiency and ambient radon levels, must be investigated further before answering the question definitively.

PARAMETRIC STUDY AND RESULTS DISCUSSION

The effect of varying outdoor airflow, ambient radon level and soil radium content are analyzed below.

Varying Outdoor Airflow

Figures 7 and 8 show indoor radon levels as a function of outdoor airflow for different ambient radon levels when the A/C is on. Indoor radon levels decrease with increasing outdoor airflow through the air distribution system. When small amounts of outdoor airflow are introduced, indoor radon levels increase dramatically because of less dilution. However, when a large amount of outdoor airflow is introduced, (above 0.708 m^3/s (1500 cfm) for this building), there is little effect on indoor radon levels. As long as the ambient radon level is lower than the indoor level, adding more outdoor air can dilute indoor radon. However, when the ambient radon level is higher than indoor levels, outdoor airflow will have the opposite effect; that is, the indoor radon level will increase. This is an important consideration in determining action levels for indoor radon.

Varying Ambient Radon Level

Figures 9 and 10 show the indoor radon level varying with ambient conditions for different amounts of outdoor airflow through the air distribution system. Indoor radon levels at different zones tend to increase linearly with increased ambient radon levels. Consequently, even though a large amount of airflow is introduced, the indoor radon level may remain high when the ambient radon level is high because fresh air dilution is not effective.

Varying Soil Radium Content

Figures 11 through 14 show the effect of soil radium concentration at different outdoor airflow rates and ambient radon levels. The indoor radon level increases when radium concentration in the soil increases, and vice versa. From this investigation, the relationship between indoor radon and soil radium content seems linear for a certain amount of airflow. The audiology room has the highest indoor radon level in the building based on the simulation results. This was also shown in the measured data (Menetrez and Kulp, 1993).

Through the limited parametric study, it is clear that outdoor airflow reduces indoor radon levels by dilution for this particular building. However, ambient radon concentration is also a factor, especially in high radon level areas, such as at Bartow, Florida. Since bringing in more outdoor air produces a higher energy demand, any radon reduction strategy should be carefully evaluated to optimize indoor air quality needs and energy consumption. Figures 7 and 8, show that an outdoor airflow rate above 0.708 m^3/s (1500 cfm) has little effect on indoor radon levels. Therefore, a controlled amount of outdoor air should be used to achieve satisfactory indoor air quality and minimize energy penalty at the same time.

CONCLUSION

Multizone airflow, indoor pressure and radon concentration, and radon entry from the slab are simulated in a large building Polk Life and Learning Center in Bartow, Florida. Reasonable comparisons between simulation and measurements were obtained for one typical school day. Following the validation, parametric studies showed that the outdoor air flow reduces indoor radon concentrations for this particular building. Outdoor radon levels should be considered a factor when outdoor air is used for dilution.

The amount of outdoor airflow plays an important role in reducing indoor radon levels. However, the penalty of increased energy demand need to be considered. Optimal conditions should be determined in order to minimize energy penalty while maintaining acceptable indoor air quality.

Caveats

It is crucial to note that the nature of the work performed here is an exploratory one primarily to establish the potential of using models to analyze large buildings and to identify the essentials areas for experiment and simulation to compliment each other in providing accurate, yet cost efficient strategy to study radon in large buildings. This was substantially achieved through a preliminary simulation of airflows and pressures in a school building monitored by the US EPA and SRI. Since only a limited set of experimental data were available, several assumptions were made to successfully complete the simulations. The results presented in this paper should, therefore, be viewed in light of the assumptions stated and applied only to the specific problem analyzed. The result should in no way be construed to represent generalizations for large-buildings.

ACKNOWLEDGEMENT

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NOMENCLATURE

C_a	Radon concentration [Bq/m^3]
$C_{a,\infty}$	Ambient radon concentration [Bq/m^3]
C_o	Dynamic loss coefficient
D	Hydraulic diameter [m]
D_c	Effective radon diffusion coefficient [m^2/s]
E_c	Effective ^{222}Rn emanation coefficient [dimensionless]
f	Friction factor
i	i-th zone
j	j-th zone
K	Bulk air permeability in porous media [m^2]
K_c	Effective air permeability in porous media [m^2]
L	Duct length [m]
$\dot{m}$	Airflow rate [kg/s]
noz	Number of zones
P	Pressure [Pa]
P_o	Reference pressure [Pa]
$Q_{j\text{-}i}$	Indoor air flow from j-th zone to i-th zone [m^3/s] ($Q_{i\text{-}i}$=0)
Q_{ret}	Return flow rate from zone [m^3/s]
Q_{OA}	Outdoor airflow through the air distribution system [m^3/s]
R	Soil ^{226}Ra concentration [Bq/kg]

R_{eK} Reynolds number based on air permeability, $R_{eK} = \rho v K^{1/2} \mu^{-1}$
v Air velocity [m/s]
V Zone volume [m^3]
λ ^{222}Rn decay constant [$2.1 \times 10^{-6}\ s^{-1}$]
μ Dynamic air viscosity [1.8×10^{-5} Pa.s]
ρ Bulk dry density [kg/m^3]
τ Time [s]

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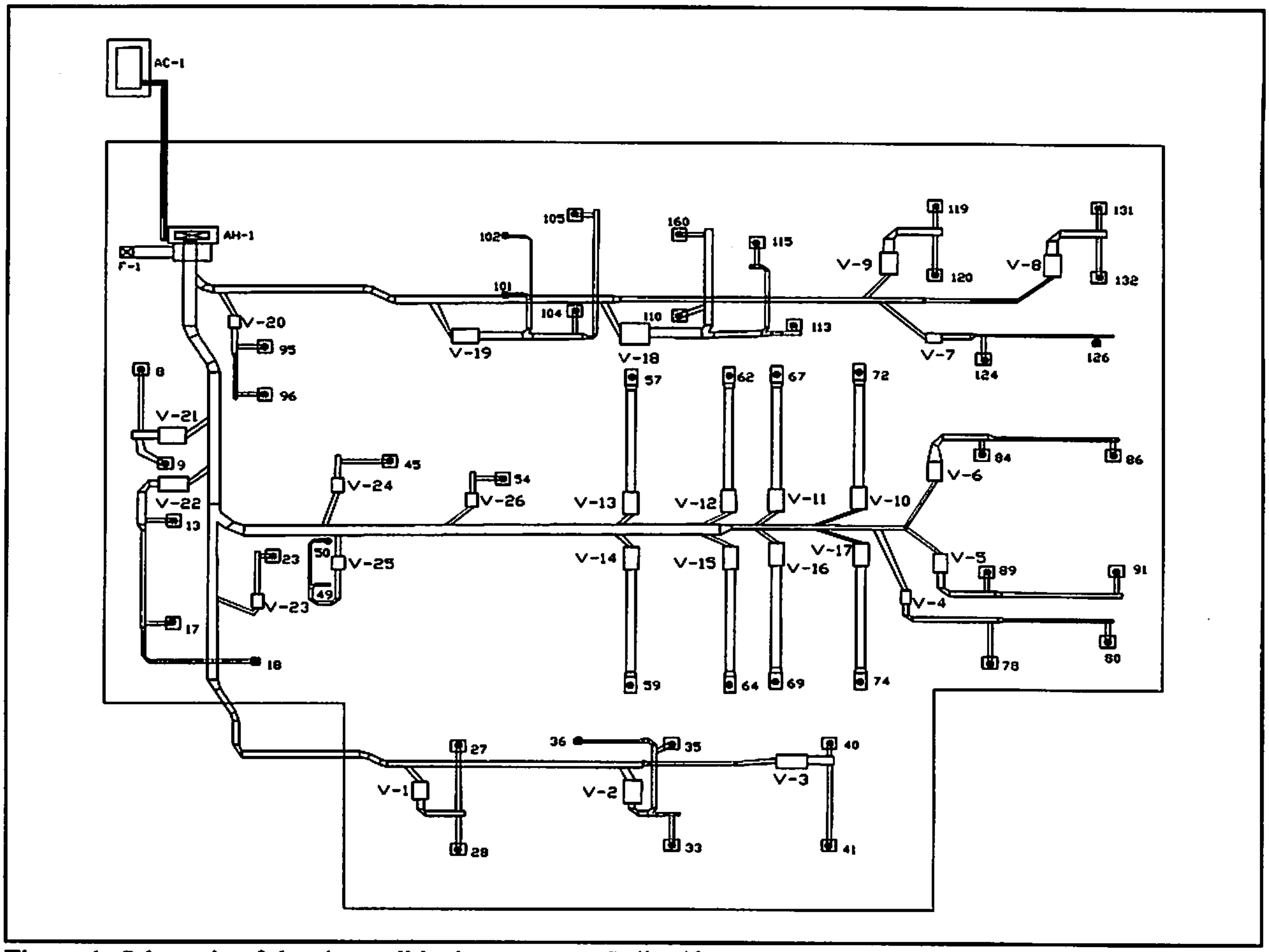

Figure 1. Schematic of the air conditioning system at Polk Life and Learning Center

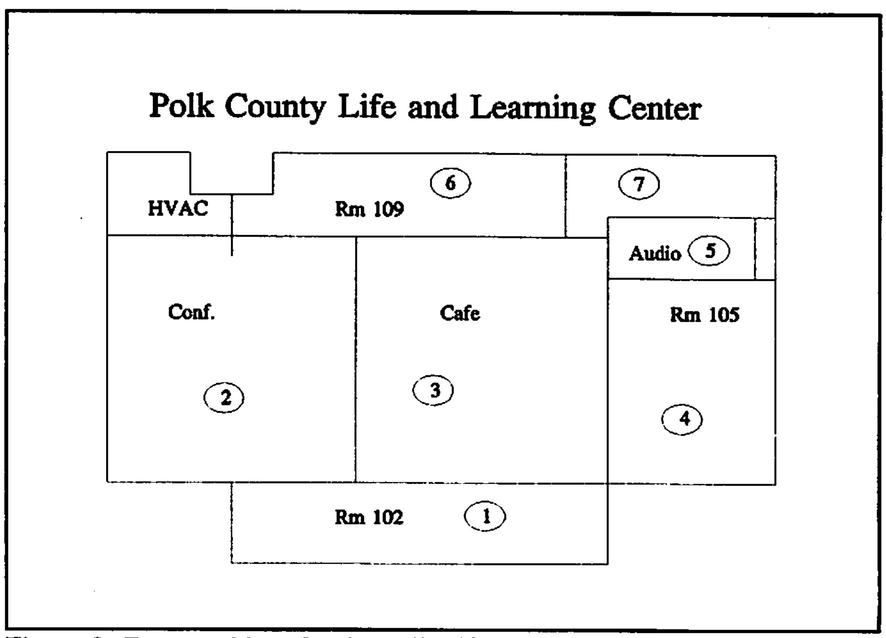

Figure 2. Zone partitions for the Polk Life and Learning Center.

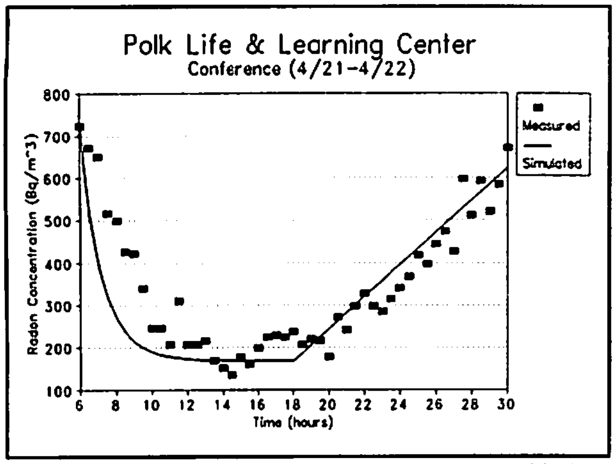

Figure 3. Comparison of predicted and measured indoor radon levels in the Conference Room on a typical school day.

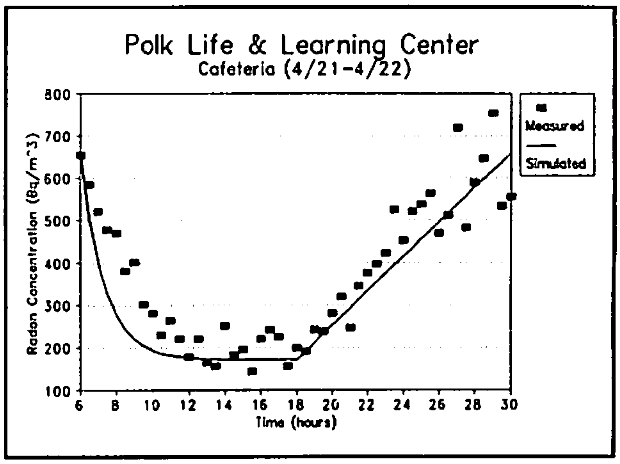

Figure 4. Comparison of predicted and measured indoor radon levels in the Cafeteria on a typical school day.

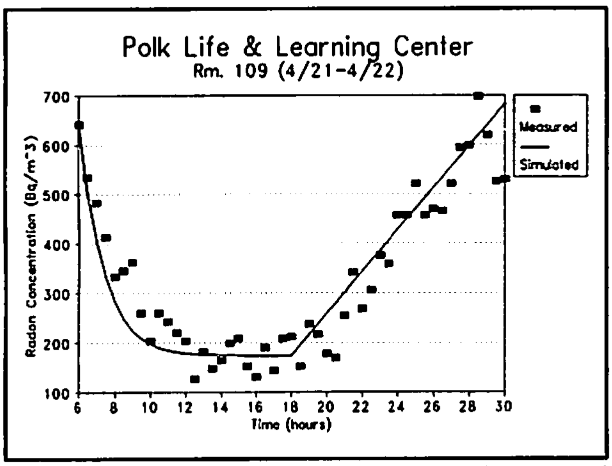

Figure 5. Comparison of predicted and measured indoor radon levels in the Room 109 on a typical school day.

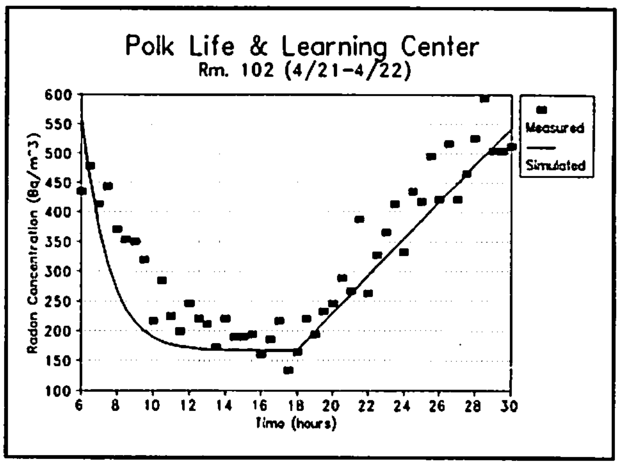

Figure 6. Comparison of predicted and measured indoor radon levels in the Room 102 on a typical school day.

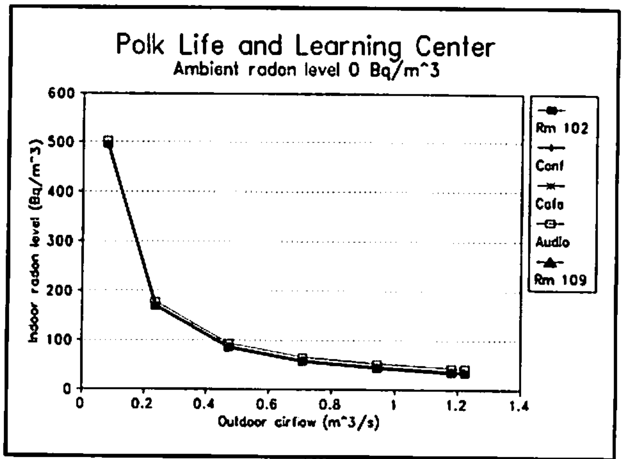

Figure 7. Effect of outdoor airflow on indoor radon levels.

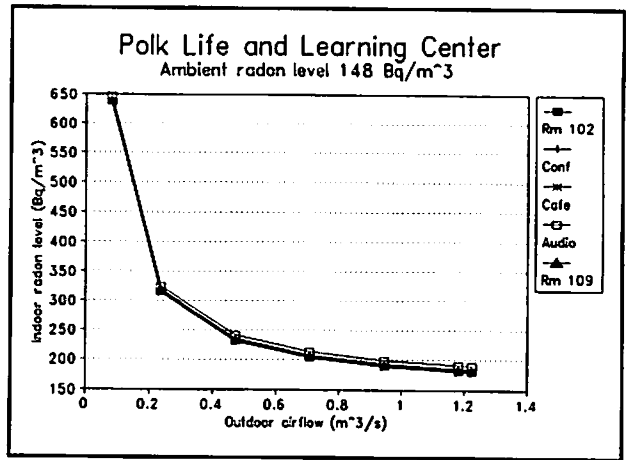

Figure 8. Effect of outdoor airflow on indoor radon levels.

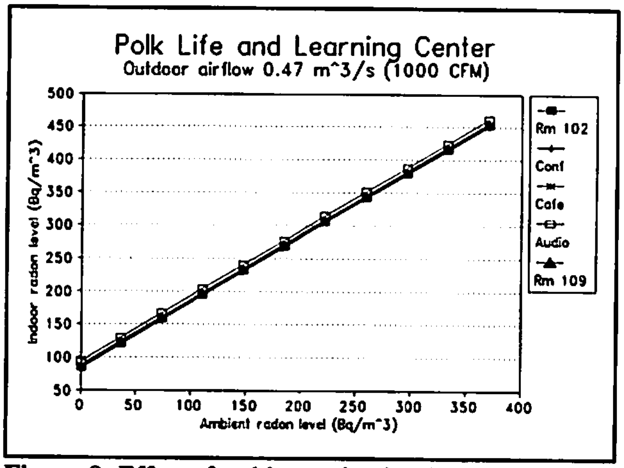

Figure 9. Effect of ambient radon level on indoor radon levels.

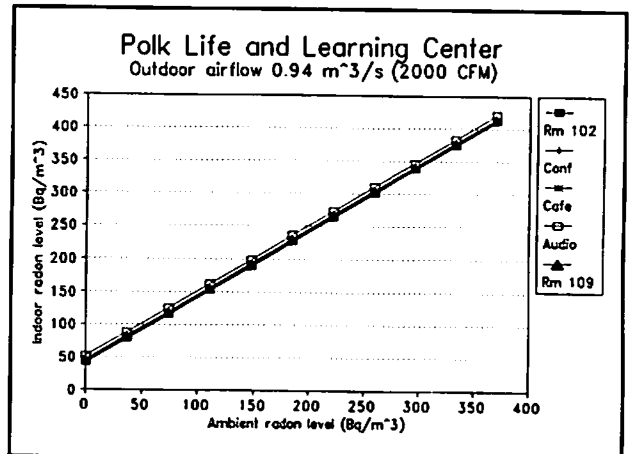

Figure 10. Effect of ambient radon level on indoor radon levels.

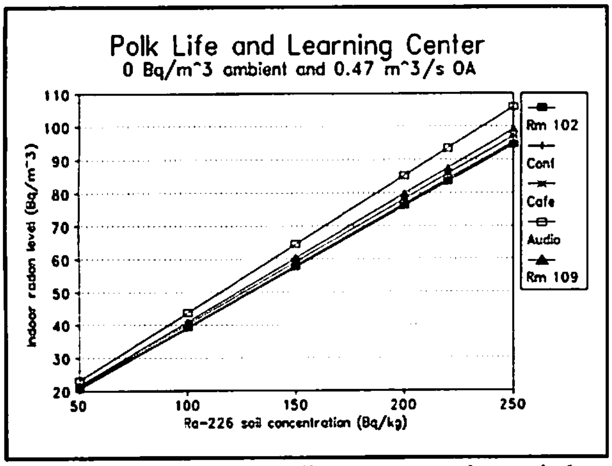

Figure 11. Effect of soil radium concentration on indoor radon levels.

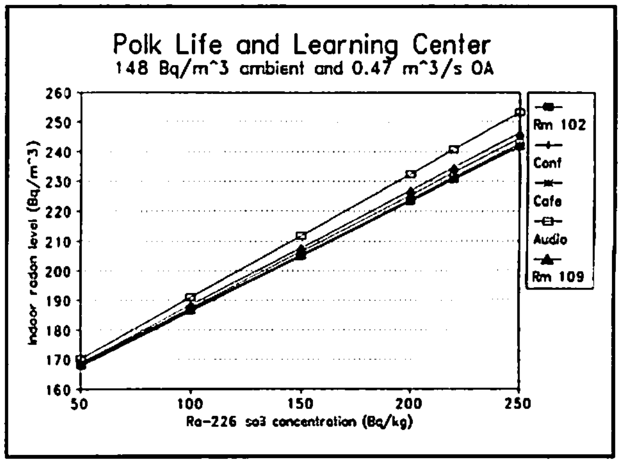

Figure 12. Effect of soil radium concentration on indoor radon levels.

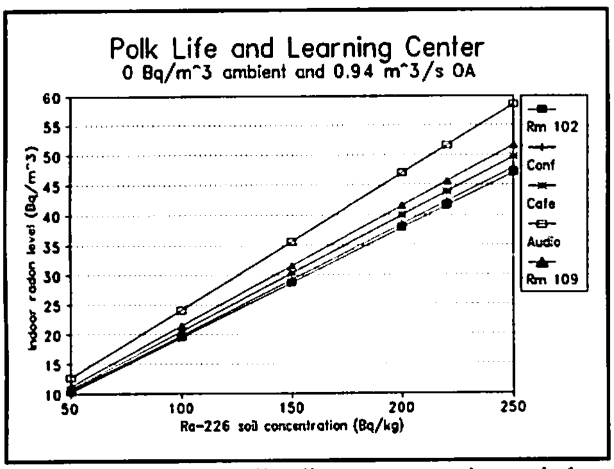

Figure 13. Effect of soil radium concentration on indoor radon levels.

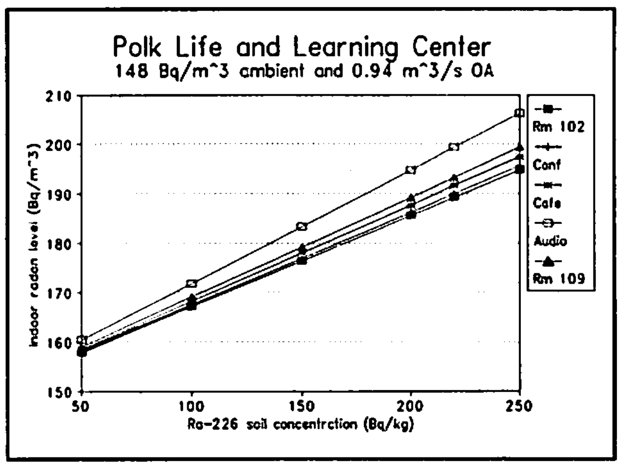

Figure 14. Effect of soil radium concentration on indoor radon levels.