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Radon in Houses - A Building Science Approach

D.A. Figley and R.S. Dumont

ABSTRACT

Radon has emerged as one of the most elusive indoor air pollutants. Due to the large number of houses in which high radon levels have been discovered, the majority of activity in the radon area has dealt with mitigation or remedial action to reduce the levels. Often, the focus of the work has not been to develop a strong scientific basis for understanding and analyzing the problem but rather to find the first solution that would reduce the indoor concentration below a specified level. Predictions of indoor concentrations for specific sites have not been successful.

It is unlikely that there will ever be a universally accepted "upper limit" for the indoor radon concentration. At present, Health and Welfare Canada is suggesting 22 pCi/L whereas the United States and many European countries are using 4 pCi/L. It is important, therefore, to develop relationships and information on the parameters that affect indoor radon concentrations. This will provide a universally applicable knowledge base that will not be tied to achievement of a specific indoor concentration.

This paper includes an overview of some of the basic building factors that influence indoor radon concentrations and discusses some of the potential control strategies. Starting from a simple mass-balance model, the impact and significance of indoor and outdoor sources, ventilation and radon removal devices on the indoor radon concentration are discussed.

Control methods are divided into two major categories; primary control methods that focus on minimizing the radon gas entry into the building and secondary control methods which deal with isolating or removing radon from the occupied areas of the building. Primary control methods involve modifications to the building envelope to restrict radon entry. Recent IRC/PRS research on instrumentation and methods to characterize the air leakage through below grade building envelope will be discussed with a focus on developing improved construction technology.

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Overview

This paper outlines some of the basic engineering principles that affect indoor radon concentrations in buildings. The focus of the paper is to summarize some of the existing construction technology related to the control of radon in buildings and to identify some of the major research tasks necessary to place Canadian contractors, regulators and the general public in a position to be able to decide when, where and how radon control strategies should be implemented.

One basic assumption of the paper is that there will never be a universally accepted "upper limit" for the indoor radon concentration. Thus, the paper focuses on discussing relationships between and information on the parameters that affect indoor radon concentrations. With adequate engineering information about radon dynamics in buildings, competent users will be able to make informed decisions about the indoor radon levels that they wish to achieve.

Radon has emerged as one of the most elusive indoor air pollutants. Efforts to predict indoor concentrations on a site specific basis have met with only limited success. Mitigation techniques used to reduce existing levels are often ineffective. These limitations occur primarily because the underlying cause of the radon problem is not properly identified and therefore, the correct technology is not applied.

Building Science Principles

Simply stated, the process involves the entry of a pollutant (radon gas) into a conditioned space and the dispersion and decay of the pollutant within the space. The decay of the radioactive gas results in the formation of various intermediary byproducts called radon daughters or decay progeny. During the decay process, the release of alpha particles is of specific interest since, if inhaled, these particles can cause lung cancer.

Although the dynamics of the behaviour of radon gas and the subsequent decay progeny are unique, the basic industrial hygiene principles common to all indoor air pollution problems can be used to identify the basic problem components.

Considering a simple, single zone chamber with an outdoor air supply, indoor and outdoor radon sources and internal space conditioning (Figure 1), a simple mass balance model yields the equation:

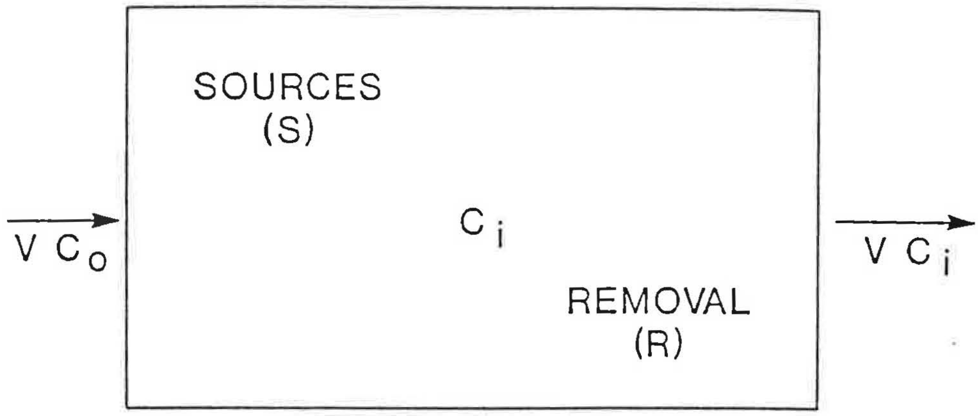

Figure 1. Single zone steady-state mass balance model

$$C_i = C_o + \frac{S - R}{K \cdot V} \qquad (1)$$

where:

- C_i = indoor radon gas concentration (pCi/m^3)
- C_o = outdoor radon gas concentration (pCi/m^3)
- S = indoor radon gas source strength (pCi/s)
- R = radon gas removal rate (pCi/s)
- K = ventilation efficiency (%)
- V = outdoor air exchange rate (m^3/s)

Equation 1 is a simplified expression that can be used to identify the major parameters that must be considered and the impact that changes in the parameters will have on the resulting indoor radon concentration. In practice, all of the parameters will be complex functions that may never be adequately defined.

Fundamental principles of industrial hygiene consider elimination or isolation of indoor pollutant sources as primary control strategies to minimize pollutant exposure. Often, primary methods are passive and simple to use but require a good understanding of the pollutant sources. Ventilation and pollutant removal systems are considered secondary control methods since the pollutant is already in the air and human exposure can occur. Design priorities should be directed towards attaining the highest possible control at the primary level, with secondary methods being used for "fine-tuning" of the conditions.

Concentration Measurements

Radon levels are commonly measured either as gas or daughter concentrations. In either case, most monitors measure alpha activity (either total or residual) and use this activity in conjunction with the radon decay constant and empirical coefficients to calculate the radon concentration. Radon gas levels may be of more use to the building scientist since they represent the true building source of the pollutant. Radon daughter levels are of more significance to the health professional as they are more directly related to lung dose and subsequent disease.

Radon gas concentrations are most often expressed in picocuries per litre (pCi/L) which is a direct measurement of the rate of alpha particle generation. The working level concentration (WL) is the integral of the number of alpha particles and the energy associated with each particle. Usually, the monitors can not measure the individual particle energies, so an assumption about the distribution of the various particles is made. Most working level monitors capture the attached daughters on a high efficiency particulate filter and measure the alpha activity on the filter. This method does not account for the loss of the unattached daughters directly, so another empirical coefficient is used to estimate the attached/unattached fraction and correct the measurement. Obviously, the simple monitors can have large errors in the working level estimates when "typical values" are used for these coefficients rather than actual values.

Radon measurements are also influenced by the measurement system's capability and the purpose of the end user of the data. If the levels vary with time, long term averages (total alpha counts divided by total time) may give a better estimate of the total exposure but lack the ability to give intermediate results. Consecutive short term measurements will give a better profile of the levels but can be costly. Typical exposure times for commercial radon monitors vary between 2 and 180 days.

Each of the terms in equation 1 will be briefly discussed:

Indoor Concentrations

Unlike most air pollutants, it is not the gas (radon) which is the problem, but rather the radon gas decay products (daughters) that are of major health concern. A complete analysis of the overall situation requires information on the primary sources of radon gas entry into the building and an evaluation of the radon gas as it subsequently decays into the various daughter products. The decay process of radon gas into its various progeny is well defined, however the true equilibrium is influenced by a host of indoor environmental factors including temperature, humidity, suspended particulate concentration and size distribution, furnishings and wall finish, ion concentration and ventilation system performance. One field study (1) conducted to establish the range of the equilibrium factor (F) between radon gas and the daughter products for typical residences, found a range of F from 0.02 to 0.6 depending upon the time and location of the sample. A second study (2) found values of F between 0.5 and 1.0 depending upon circulation fan operation.

A single instantaneous reading of the radon level inside a house is usually not a satisfactory means of characterizing the radon hazard. Figure 2 presents a plot of the radon daughter levels in a house over a six day period during the heating season.

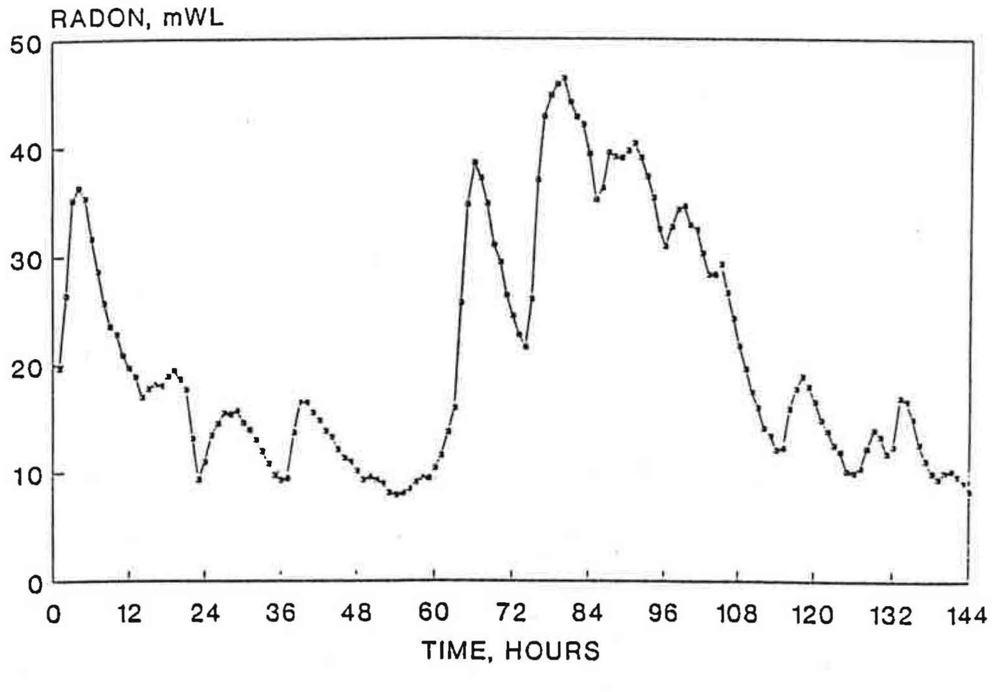

Figure 2. Temporal variation of basement radon levels in one house

As can be seen from the graph, there is a variation of about 6 to 1 in the radon daughter levels over the time period. ASHRAE (3) suggests a value of 27 milliworking levels (mWL) as the guideline value for the annual average radon level. As shown on the graph, a set of readings taken between hours 12 and 65 would yield a much different assessment of the house than the readings taken between hours 66 and 108. Even larger variations have been found in houses. These variations can not be accounted for by the variation in the overall air exchange rate of the house, suggesting that the source term can vary significantly. These data also illustrate the difficulties involved in analytically modelling such a process.

Outdoor Concentrations

In most cases, the concentration of radon gas in the outdoor air is very low (4). Equation 1 shows, however, that ventilation can be a potential problem if the source is contaminated. Certain geographical areas may have higher background levels that could result in significant indoor levels. Construction techniques such as unventilated crawlspaces can trap and concentrate radon emanating from the soil and can contaminate ventilation air sources if they are not properly located.

Indoor Sources

Indoor radon sources will fall into two basic categories:

1) Building Sources

Some building components have been found to contain radioactive materials that can release radon gas. These materials include gypsum in wallboard and concrete aggregate materials (4). While not generally considered a major source in most situations, methods must be developed for screening building materials.

Radon gas generated in the soil and migrating into a building by diffusion or convective air flow through the building envelope is, in most cases, the major indoor source of radon (Figure 3).

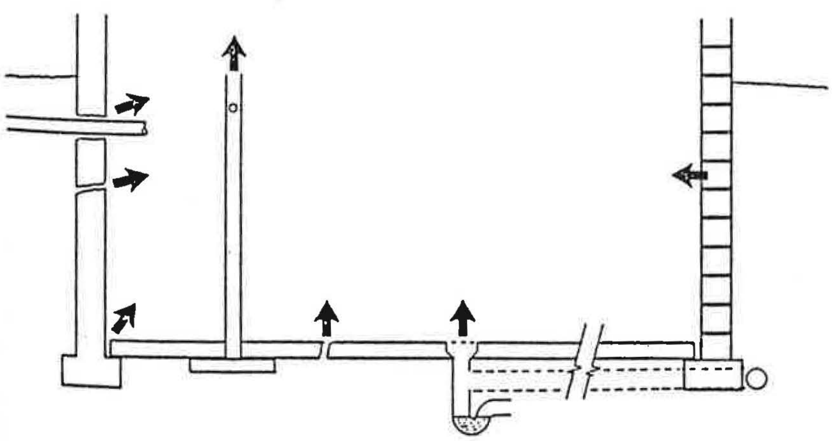

Figure 3. Potential soil gas entry sites

Characterizing this source requires methods for assessing the radon supply potential of the soil, the entry pathways through the below grade building envelope and the driving potentials for the flow.

Radon gas concentrations in the soil vary with location and may be a primary factor in understanding the wide and often unexpected variations in indoor radon concentrations. In the Florida Statewide Environmental Radiation Study (5), radon concentrations in the soil were measured adjacent to 3000 houses. The values ranged from below 100 pCi/L to in excess of 1600 pCi/L.

2) Other Sources

Radon in water has been identified (6) as a potential source of indoor contamination. High concentrations are most commonly found in water from underground sources since surface water supplies allow the radon gas to diffuse into the atmosphere. In one New England study of over 100 wells (6), radon in the well water averaged 22,000 pCi/L.

Indoor vectors of contamination may include evaporation of radon gas from standing water and direct aerosol dispersion via showers and sprays.

It is also possible to have high radon concentrations in natural gas. As radon has a half-life of 3.8 days, much of the radioactivity is usually dissipated by the time the natural gas reaches the consumer. In 19 days, the radioactivity of a sample of gas in a pipeline would be reduced to 1/32 of its original value.

Removal Mechanisms

As with other indoor air contaminants, removal of radon from the indoor air should be considered as a secondary source of control. The United States Environmental Protection Agency (7) does not recognize radon removal devices as being an effective method of radon control.

The principle behind radon removal strategies involves removing the radon gas or the radon daughters. Radon daughters in the air are either attached or free. Attached daughters can be attached to solid surfaces (plateout) or suspended aerosols and/or particles (condensation nuclei).

Research studies have identified the absorption and transport characteristics of radon gas on activated charcoal (8). Expanding on these basics, Abrams (9) has developed a residential radon control device that is self-contained and regenerates the charcoal automatically. Drawbacks of the design include the complexity and cost of the required mechanical equipment and ongoing charcoal maintenance.

Control of daughter products concentrates on increasing the plateout of the daughters so that they are not available for inhalation or removing the aerosols with the daughters attached. Plateout rates are very site specific and appear to be related to air ion concentrations, surface conditions within the space, humidity and many other factors that are not easily measured or controlled. Removal of the daughters attached to airborne particles has been accomplished using high efficiency air cleaners, either filters or electrostatic precipitators. Again, the on-site performance of the systems varies widely.

<u>Ventilation</u>

The role of ventilation in the control of radon concentrations is very complex. Equation 1 shows that the ventilation rate is inversely proportional to the indoor concentration; however, this assumes that the ventilation does not modify the radon source strength. In practice, ventilation systems can affect the radon sources in many ways.

Increasing the negative pressure in the house (unbalanced ventilation with excess exhaust change, to or return air from the lower levels of the house) may increase the rate of entry of radon gas through the below grade building envelope. Increased mixing of air between zones of the house will tend to make the levels more uniform, reducing the high levels but increasing the low levels. Management of the ventilation system may be an important factor in minimizing human exposure to radon; however, the number of possible house configurations and occupancy scenarios makes customized "tuning" of the systems somewhat impractical.

Construction Technology to Control Radon Entry

Working from the assumption that the primary source of radon in buildings is the entry of soil gas through the below grade building envelope, a number of control strategies have been developed.

The source strength of radon due to the flow of radon through the below grade portion of a building consists of two main transport mechanisms, 1) diffusion of the gas through the envelope materials, S_d and 2) pressure driven flow through openings in the envelope system, S_p.

Control strategies work from these basics. Of the two transport mechanisms, it is widely believed (4,6) that airflow through foundation openings is the major source. Initial efforts should create a building envelope that has a low permeability to radon gas and is as airtight as possible. If necessary (the criteria are difficult to establish) additional techniques can be applied to reduce the pressure gradient across the envelope, thereby minimizing the transport of radon across the barrier.

1) <u>Diffusion</u>

The flow of a gas by diffusion through a material is given by Fick's law:

$$m/A = -D_v \cdot (dC/dy) \qquad (2)$$

where:
- m/A = radon gas mass flux ($pCi/s \cdot m^2$)
- D_v = radon diffusion coefficient (m^2/s)
- $\frac{dC}{dy}$ = radon gas concentration gradient ($pCi/m^3 \cdot m$)

If the soil gas radon concentration is high, or the permeability of the envelope material to radon gas is high, diffusion may constitute a major source of radon gas. Equation 2 can be summed over all of the below grade surfaces to estimate the total radon gas source strength due to diffusion, S_d. To date, there are very little data on the radon diffusion characteristics of common building materials such as concrete, polyethylene and wood.

2) Pressure Driven Airflow

The rate of airflow through an opening is given by:

$$Q = C\ \Delta P^{n} \tag{3}$$

where:
- Q = airflow rate (m^3/s)
- C = flow coefficient ($m^3/s \cdot Pa^n$)
- ΔP = pressure difference across the opening (Pa)
- n = flow exponent (between 0.5 - 1.0)

In the case of radon gas in soil, equation 3 can be coupled with the radon concentration in the soil gas to determine the radon source strength due to airflow as:

$$S_p = Q \cdot R \tag{4}$$

where:
- S_p = radon source strength due to airflow (pCi/s)
- R = radon concentration in the soil gas (pCi/m^3)

The flow coefficient is more complex than the case of a simple crack or hole. The overall flow resistance is a combination of the flow resistance of the foundation opening, R_f, and the adjacent soil, R_s (Figure 4).

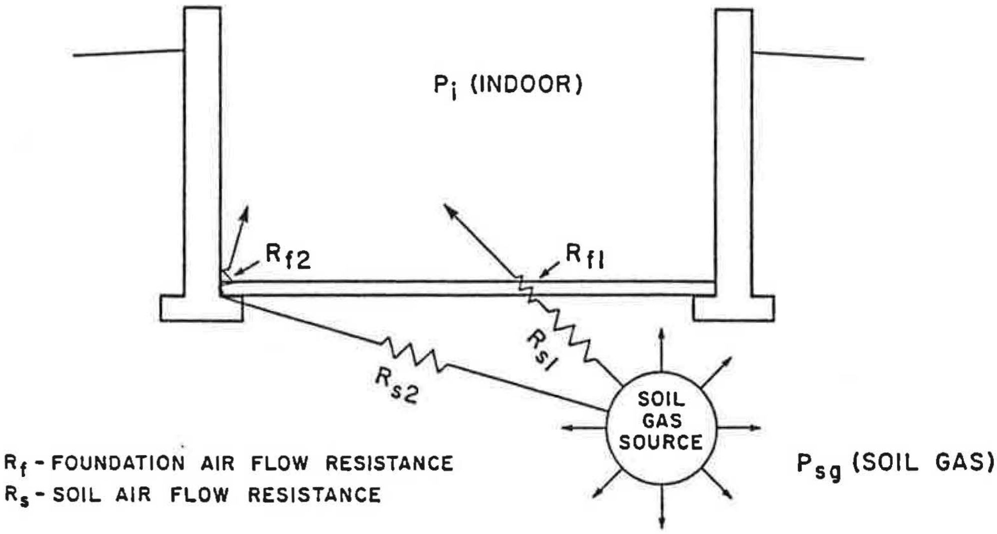

Figure 4. Radon gas entry schematic

Variations in the air flow resistance of the soil can be caused by many factors including changes in the density, moisture content, grain size and temperature.

The differential pressure across the below grade building envelope is more complex than that across the above grade portion of the building. The true differential is a combination of the indoor air pressure at the opening and the pressure of the soil gas. The soil gas pressure is coupled to the atmospheric pressure but may lead or lag the atmospheric pressure by several days, causing as much as a several kPa pressure difference when the atmospheric pressure is changing rapidly. This must be considered when evaluating control strategies that attempt to pressurize the building to exclude radon, since the practical pressurization range is in the order of pascals, not kilopascals.

Sub-slab Depressurization

The principle behind sub-slab depressurization is to reduce the pressure in the cavity between the soil and the building envelope below the pressure indoors. This will prevent airflow into the building and may also reduce the potential for diffusion. In practice, it is difficult to develop a negative pressure field around the entire below grade envelope since construction practice and soil properties vary greatly. The exhaust air volume required to achieve depressurization will vary depending on the air tightness of the below grade envelope and the soil conditions. This technique will remove air from indoors and may contribute to undesirable negative pressure conditions and heating energy consumption. A tight below grade envelope will minimize these problems. Cold outdoor air drawn in by the exhaust system may lower the soil temperature and possibly freeze/heave the foundation or plumbing services if the air is channelled down a particular location due to soil shrinkage adjacent to the foundation or a high permeability backfill soil.

Barrier Techniques

The installation of an airtight barrier or barrier system will minimize soil gas entry due to airflow. If the barrier incorporates a radon gas diffusion retarder, additional control will be achieved. The value of barrier techniques lies in their low cost and low maintenance; however, their long-term

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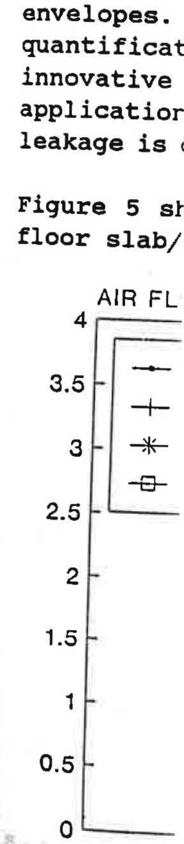

Figure 5. A
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effectiveness must be proven. A wide variety of systems will emerge over the next few years, incorporating simple sheet polyethylene and more exotic barrier materials. The last decade of experience with building "airtight" houses has shown that airtightness is more than a specification and details on a drawing, it is a complex combination of research and technology transfer to the building industry. The diffusion, chemical and structural properties of these materials must also be established to ensure reliable field performance.

The authors (10) have developed a prototype technique to characterize the air leakage sites of below grade building envelopes. This technique will allow the identification and quantification of air leakage sites and will permit evaluation of innovative tightening systems, both for new and retrofit applications. Data from the studies will identify where air leakage is occurring so that appropriate controls can be developed.

Figure 5 shows the spatial variation of air leakage through the floor slab/wall interface for one house.

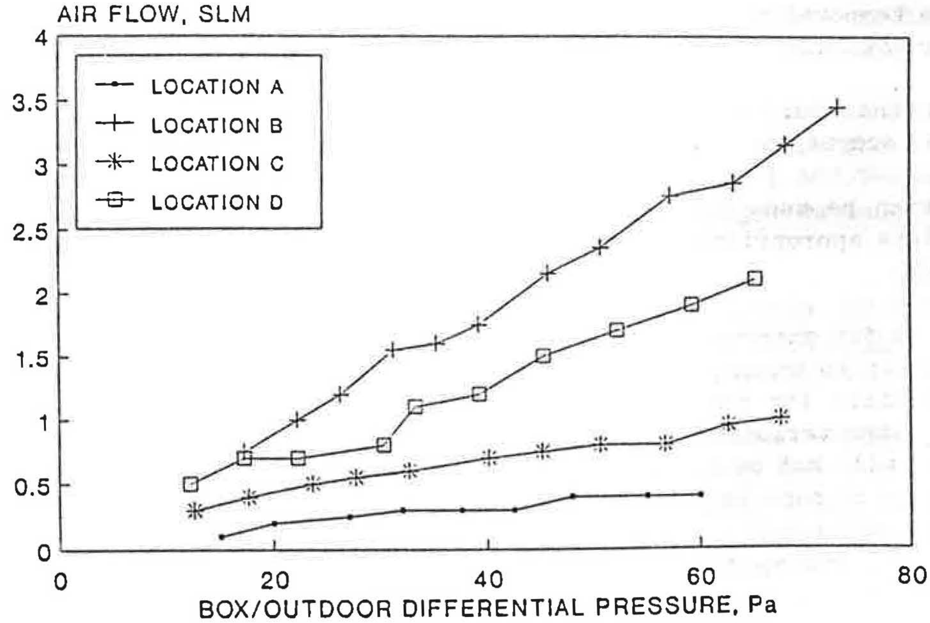

Figure 5. Air leakage characteristics for various one meter sections of floor slab/wall interface

The air flows were measured using a box (10) to isolate one meter lengths of the floor slab/wall interface. It is important to note the large variation since it highlights the errors in interpreting test data that could occur if single, isolated measurements are used to develop a control strategy.

Research Needs

Radon is an area where there is tremendous public pressure to supply information and results. To date, most studies have focused on measuring indoor levels and developing control techniques that would reduce the level in a given building. Unfortunately, many of the conclusions drawn from the work are not based on building science and therefore, are not broadly applicable to other buildings.

Since control studies are usually done sequentially on the same building, the results lack the scientific credibility of a properly conducted experiment. Difficulties in controlling or monitoring the many factors that influence the indoor radon concentration make conclusions from these studies questionable. For example, the large temporal variations of indoor concentrations (Figure 2) that occur naturally can mask the true effect of building modifications.

Given that barrier techniques represent the essential first step in a successful radon control program, accurate methods for assessing the barrier systems must be developed. These methods can then be used to support the development of various levels of barriers appropriate for the range of site conditions occurring in Canada.

Methods for characterizing the radon "potential" of building sites will help to ensure that the control methods that are selected are appropriate for the actual conditions. Given the wide range of site characteristics, a single, universally applied radon control system will not be feasible or appropriate. As with seismic design criteria or snow loads, requirements based on geographical location may be sufficient. Alternatively, site testing (similar to soil tests to assess structural capacity) may be warranted in some instances.

Valid computer based indoor air contaminant models must be developed. These models will be able to combine the range of barrier capabilities with the range of site conditions to identify what combinations will yield acceptable radon control.

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