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MODELING RADON SOURCES AND INGRESS

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INTRODUCTION

Twenty years ago it was believed that radon levels in houses were generally low and relatively constant, as shown by contemporary radon-in-housing surveys in the United States (Peterson 1977; Prichard et al. 1983; George 1983) and Canada (Aitken 1977; Tanaguchi 1978; McGregor 1980). The seasonal average radon concentration was low; distributed log-normally with geometric means between 10 to 30 $Bq.m^{-3}$, and geometric standard deviation (GSD) of about 2.0. Most concentrations were only slightly above the average radon concentration in outside air. Less than 1% of houses had concentrations over 150 $Bq.m^{-3}$.

Radon supply rates from water and natural gas were known to be low. The major radon source was radium present in building materials and soil. Radon from these sources was believed to diffuse down the concentration gradients in these porous media to the house.

DIFFUSION MODEL OF SOURCE AND INGRESS

Ignoring water and gas as radon sources, the equation that relates the average radon concentration and average radon supply into a building is:

$$\text{Average Radon Concentration } \overline{R} = \frac{\text{Radon supply rate}}{V} = (S_a + S_b + S_s) \cdot \frac{1}{V} \tag{1}$$

where:

S_a = Average radon supply rate from outside air ($Bq.s^{-1}$)
S_b = Average radon supply rate from radium in building materials ($Bq.s^{-1}$)
S_s = Average radon supply rate from radium in soil ($Bq.s^{-1}$)
V = Average ventilation flow ($m^3.s^{-1}$).

Much of the radon that emanates from the radium trapped in the mineral grains that make building materials escapes into the air because the material thickness is comparable to the radon diffusion length. The radon supply rate therefore depends mainly on the total radium present in the material. The radon diffusion length in soil ranges from 1 cm in moist clay soils to 1-2 m in well drained gravel soils. The radium concentration in surface soil was known (40 $Bq.kg^{-1}$) and relatively constant. Predicted diffusive radon supply rates from both building materials and surrounding soil were large enough to produce house concentrations in the 10 to 60 $Bq.m^{-3}$ range.

The observed variability of radon from house to house and region to region could be explained by variations in radon emanation fraction for soil and building materials; foundation design; and differences in soil diffusion lengths. However, as high radon levels were uncommon even in areas believed to have soil with long diffusion lengths, it appeared that elevated radon concentrations could only be caused by high radium concentrations in soil or building materials.

In the early 1970's elevated radon concentrations in housing were identified in areas of naturally elevated soil radium such as the phosphate region of central Florida (Guimond 1978), and in a few towns where houses were built on land contaminated with uranium mining or refining residues (Knight 1977; Knight 1978; Nero 1983). Remedial actions based on a diffusion entry model were successful. Residues were located by γ-surveys. The radon diffusion length in residues was ~1 m, and when they were removed for a distance of +2 m from the foundations, radon concentrations decreased to "normal". At some sites, residues were placed only on one side of the building. Radon flux measurements on foundation surfaces identified the source location. Some sites had building materials containing residues with elevated radium activity, identified by γ-surveys and radon flux measurements. These materials were removed or covered with radon-barriers.

All of this supported the diffusion model for radon sources and ingress. As high radium activity sources were needed to cause elevated radon concentrations, and there were few areas of high natural soil radium concentrations, the logical consequence of this model was that few members of the public were exposed to high radon concentrations, and radon could not be a significant public health problem. If there was a need to identify regions where the risk from radon was sufficient to justify some action, they could be detected and delineated by γ-survey. As diffusion sources have nearly constant outputs, the radon concentration in a house was expected to vary only with changes in ventilation, and a single short-term measurement would give a good estimate of the seasonal average radon concentration.

NEW INFORMATION

By the late 1970's, investigation programs carried out in Canadian uranium mining towns had found houses with average concentrations over 750 $Bq.m^{-3}$ (Scott 1983), but of these houses lacked an adjacent high activity radium source. Extensive soil measurements found that uranium mining or refining residues were present only on the soil surface (mine waste rock was used for driveways) and removal did not change the house radon concentration. There was no buried radium source, and the soil had a typical environmental radium concentration of 40 $Bq.kg^{-1}$. Measurements of radon flux rates from walls and floors showed no directional effect, and were too low by a factor of at least 10 to explain the radon concentrations in these houses. Radon concentrations in these houses varied widely from day to day, and measurements over many days were needed to give a good estimate of the seasonal average concentration. None of these observations was consistent with a diffusion model.

The observation that radon concentrations in interior ground water drainage sumps was often similar to the soil gas radon concentration suggested that small flows of radon-rich soil gas could provide the high radon supply needed for these high radon houses. Pressure/flow measurements on interior ground water drainage systems and on joints and openings in the foundation concrete showed that a pressure difference of a few Pa between the house and soil would bring in enough soil gas and radon to cause high radon concentrations (Scott 1978).

This led to a new ingress model independent of diffusion. The driving force was the pressure difference from soil to house generated by variable thermal, wind and atmospheric pressure changes. A high radium source was no longer needed to produce large concentration gradients. The important parameter was the volume of soil from which radon could be collected and transported to the house.

The implications of this paradigm shift for mitigation activities were considerable. First, as normal soils could provide high radon supply rates, a γ-survey would not reliably identify high houses. Second, radon supply and house concentrations were inherently variable. A single short-term measurement would not reliably identify high radon houses. Long-term measurements were needed to estimate seasonal averages. Third, it suggested new mitigation approaches. Soil-generated radon could be excluded from buildings by closing the foundation openings, or reversing the soil pressure gradients. This has become the radon mitigation method of choice. Applying surface radon barriers or reducing the soil gas radon concentration by removing the source is necessary only in cases of radium contamination.

FLOW MODEL OF SOURCE AND INGRESS

The value of a model lies not only in its power to explain observations, but also in suggesting new directions for investigation. If soils with common radium concentrations could produce high radon concentrations in houses, then high houses could be found *anywhere*. That they were not found *everywhere* showed that particular soil conditions were needed. If these conditions could be identified on a cost-effective basis, then "radon-prone" areas could be identified by soil measurements before houses were built. Radon-resistant features could then be added to the foundations to prevent high radon concentrations in houses.

The ingress model of Equation 1 can be modified to allow for a pressure driven soil gas and radon flow:

$$\text{Average Radon Concentration } \overline{R} = \frac{\text{Radon supply rate}}{V}$$
$$= \left(S_a + S_b + S_s + \frac{C_{soil} \cdot P_d}{(I_{soil} + I_{foundation})} \right) \cdot \frac{1}{V} \tag{2}$$

where:

S_a = Average radon supply rate from outside air ($Bq.s^{-1}$)

S_b = Average radon supply rate by diffusion from radium in building materials ($Bq.s^{-1}$)

S_s = Average radon supply rate by diffusion through building materials from radium in soil ($Bq.s^{-1}$)

C_{soil} = Average radon concentration in soil gas near foundation openings ($Bq.m^{-3}$)

P_d = Average pressure differential from soil surface to foundation openings (Pa)

I_{soil} = Airflow resistance of soil around the house foundation ($Pa.s.m^{-3}$)

$I_{foundation}$ = Airflow resistance of building foundation ($Pa.s.m^{-3}$)

V = Average ventilation flow ($m^3.s^{-1}$).

In conventionally constructed houses, the foundation resistance is much less than the soil resistance, and can be ignored. The pressure differential, P_d, across the soil depends on temperature, wind and building size and style. Ventilation also depends on temperature, wind, building size and style, and so for many houses $P_d.V^{-1}$ is almost constant $\approx$100 $Pa.s.m^{-3}$. Accordingly, Equation (2) can be simplified for high concentration houses where soil gas is the dominant radon supply to:

$$\text{Average Radon Concentration } \overline{R} = \frac{\text{Soil gas radon supply}}{V} = \frac{C_{soil} \cdot P_d}{I_{soil} \cdot V}$$
$$\text{or } \overline{R} \approx 100 \cdot \frac{C_{soil}}{I_{soil}} \text{ Bq.m}^{-3} \tag{3}$$

This is the simplest soil gas flow model. The average house radon concentration can be estimated from the soil gas concentration at depth C_{soil}, and the soil resistance I_{soil}. This requires, in turn, a source model of the soil to predict C_{soil} and an ingress model of the soil to predict I_{soil}.

Standard geological texts treat "soil" as a assemblage of fine particles. Pore size, air permeability (k m^2), and soil gas radon concentration are related to particle size and radium content. A source model based on soil as a granular material (Rogers and Neilson 1991a, 1991b) shows that C_{soil} is a complex function of radium content, grain size and moisture, but at 40 $Bq.kg^{-1}$ radium, C_{soil}≈80 $kBq.m^{-3}$.

Revzan and Fisk (1990) calculated I_{soil} as $7.2\times10^{-7}.k^{-1}$ for a basement in uniform permeable soil by numeric solution of the two-dimensional flow equation. Equation (3) shows for C_{soil}=80 $kBq.m^{-3}$, I_{soil} must be lower than about 5×10^4 $Pa.s.m^{-3}$ for average >150 $Bq.m^{-3}$. An I_{soil} of 5×10^4 $Pa.s.m^{-3}$ is equivalent to a soil permeability of about 10^{-11} m^2.

Standard texts list soil permeability as a function of soil type (grain size distribution). An ingress model can be based on soil type. Table 1 shows the nominal permeability of clean sand and gravel as 10^{-11} m^2, and of silty sand and gravel as 10^{-12} m^2. Most soils contain some clay, and have permeability <10^{-12} m^2.

When this analysis was carried out in 1982, the logical consequence was that only a small percentage of the North American public would be exposed to high radon concentrations. Regions of elevated soil radium were rare. High permeability soil types such as glacial or river valley gravel deposits covered only a small percentage of the total area. Most of the housing stock was built on low permeability soil types high in silts and clays such as coastal plains, river flood-plains, and dried sea and lake bottoms.

FAILURE OF THE SIMPLE SOIL MODEL

Since that time, large scale radon surveys have been carried out over most of the United States (White 1992). We now know that radon-prone areas are common, and occur in areas of normal soil radium. This means that low resistance soils are not limited to sand and gravel deposits. For example, more than 75% of the screening measurements in North Dakota were greater than 150 $Bq.m^{-3}$, and >10% were greater than 750 $Bq.m^{-3}$, but most of the area is covered with thick glacial clays of low radium content! Table 1 suggests that these deposits have permeability ~10^{-15} m^2, and by Equation 3 this should be an area of extremely low radon concentration.

Soil radium and permeability measurements in this region (Schumann et al. 1990) found low to average soil radium and soil gas radon concentrations, but soil permeability >10^{-12} m^2. This is similar to the nominal permeability of silty sand, and is 3 orders larger than the 10^{-15} m^2 expected from the soil description. The main reason why the permeability of this soil is much higher than the value given in Table 1 is that the near-surface materials on which houses are built have been affected by weathering. This produces fissures in the soil both by the annual shrink-swell cycles (Yokell 1988) and the chemical changes produced in the clay minerals. The permeability of the soil depends on the size and number of the fissures, not the soil grain size. Table 1 does not apply to the soils on which houses are built.

Soil resistance cannot be measured in clay soils, for most methods measure permeability on small samples. The house measures the soil resistance over >400 m^3 of soil. Small sample measurements will overestimate resistance. Even soils that do not contain enough clay to fracture are often layered, with horizontal permeability much higher than the vertical permeability. Research methods have been developed recently to measure permeability averaged over volumes of 30 m^3 (Garbesi, 1993)

Finally, I_{soil} as calculated from the viscous resistance to air movement is an overestimate of the soil resistance. This is equivalent to treating the soil as an electrical resistance network. The soil around the building contains up to 10 m^3 of air, and the electrical equivalent of this is capacitance. The correct equivalent circuit for the soil is therefore a RC network, as shown in Figure 1, and I_{soil} is the soil *impedance* - which is always smaller than resistance if the voltage (pressure) varies. Soil gas flows therefore depend on the size and the rate of change of the pressure differential.

Changes in wind speed and direction cause house-soil dP/dt values in the range 0.01 - 1 Pas^{-1}. Atmospheric pressure changes also cause house soil dP/dt values in the range 0.01 - 1 $Pa.s^{-1}$. The soil time constant (RC) is about 20 s at 10^{-12} m^2, so the AC flows can be larger than the DC flows. A more correct version of the radon supply rate equation is $Q_T = C_{soil} \sum_{f=0}^{\infty} \frac{\overline{P}(f)}{I_{soil}(f)}$ Bqs^{-1}, where C_{soil} = average radon concentration in soil gas near foundation openings ($Bq.m^{-3}$); $P(f)$ = the average positive pressure difference (Pa) from soil surface to building interior at frequency f (s^{-1}); and $I_{soil}(f)$ = soil impedance ($Pa.s.m^{-3}$) at frequency f (s^{-1}). The soil gas supply rate will always be higher than that predicted from viscous resistance alone (f=0).

This has significant implications for work investigating the factors controlling radon supply. Even complex finite difference models of the building and soil will underestimate radon supply rate if they are based on pure resistive elements and constant pressures. Measurement of soil permeability alone is not enough to estimate soil impedance. Methods are needed to measure the soil air capacity as well.

As I_{soil} depends on the amplitude and frequency of pressure fluctuations, the pressure across the soil must be treated as a variable, not a constant. Many pressure measurements average over periods of 1000 s or longer to measure the "steady-state" value, and deliberately reject the 1 to 100 s period pressure fluctuations as "noise". Measurements with short averaging times are needed to determine the joint distribution of amplitude P_w and period ω of the pressure fluctuations.

There are also areas where the soil overburden is so thin that house foundations rest on weathered rock. This can give rise to very high radon concentrations. For example, houses in Pennsylvania with 40 $kBq.m^{-3}$ are built over shear zones in weathered granite. The effective air permeability of the fractured shear zone rock was as high as 10-10 m2, equivalent to sand and gravel. Radium has concentrated in these zones up to 500 $Bq.kg^{-1}$, leading to sub-foundation soil gas concentrations as high as 2 $MBq.m^{-3}$ (Reimer and Gundersen 1989). The effective permeability of weathered rock depends entirely on the fracture pattern, and is dominated by the largest fracture that intersects the foundation. Permeability cannot be predicted from rock type alone.

This high permeability "soil" type was ignored in 1982, for the granite bedrock that covers much of Canada does not have a weathered layer. It was removed by glaciers. Excavation of this solid rock requires high-cost drilling and blasting, so builders avoid these areas, placing houses in easily excavated gravel deposits. In contrast, much of the U. S. was not glaciated, so large areas are covered with easily excavated weathered limestone bedrock. These areas have potential for high permeability and locally increased radium concentration.

CONCLUSIONS

In 1972 a diffusion-based radon source and ingress model predicted that high radon concentrations in houses would be very rare, and limited to areas of high radium concentrations in soil or building materials. Discovery of regions of normal soil radium with high radon concentrations in houses lead to a soil gas flow model of radon source and ingress. In 1982 this model predicted that high radon concentrations in houses would be uncommon, and limited to a few regions of gravel soil or high radium concentration in soil or building materials. Extensive radon surveys now show that high radon concentrations are common, and occur in many soil types.

"Soil" is a more complex entity than was assumed in 1982. The soil model used then assumed that soil gas radon depended mainly on the soil radium concentration. We now know that there is considerable variation, as shown by Figure 2. The simple flow model assumed that I_{soil} depended only on the soil particle size distribution. Much of North America is covered with clay soils and weathered bedrock soils where I_{soil} is not determined by the fracture pattern, not the soil particle size. It now seems that different soil models will be needed for different areas of the U. S. Realistic models must also deal with the effect of rapid variations in the driving force produced by wind and atmospheric pressure variations.

The approach discussed above can be described as "Bottom-up" modeling, which starts with a grain of sand, and works its way up to a house. More information is needed at every step. An alternative approach to prediction is "Top-down" modelling. This starts with radon measurements in houses, and looks for correlations between soil, geology and other parameters that can be exploited for prediction. This has only become possible because the cost of radon survey measurements has fallen greatly in the past 10 years. In the short-run, the "top-down" approach seems the most promising for predicting the location of new radon-prone areas.

Modelling and predicting radon is interesting, but it is only the first step toward the goal of minimizing radon exposure to the population. Many radon-prone areas have been identified by radon surveys, so the problem in those areas is not producing a model to explain what we already know. The problem is the practical one of "How can a jurisdiction justify adopting low radon construction requirements" and "How can low radon construction designs be produced in large numbers?". These are political/technical problems rather than scientific ones, but they must be solved before radon exposure to the population can be reduced.

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Table 1 Soil types and permeability

Soil Description	Permeability (m^2)[a]
Well-graded gravel	1×10^{-8}
Uniform coarse sand	1×10^{-9}
Uniform medium sand	1×10^{-10}
Clean, well-graded sand and gravel	1×10^{-11}
Uniform fine sand	1×10^{-12}
Well-graded silty sand and gravel	1×10^{-13}
Silty sand	1×10^{-13}
Uniform silt	1×10^{-14}
Sandy clay	1×10^{-15}

[a] after Tanner (1990)

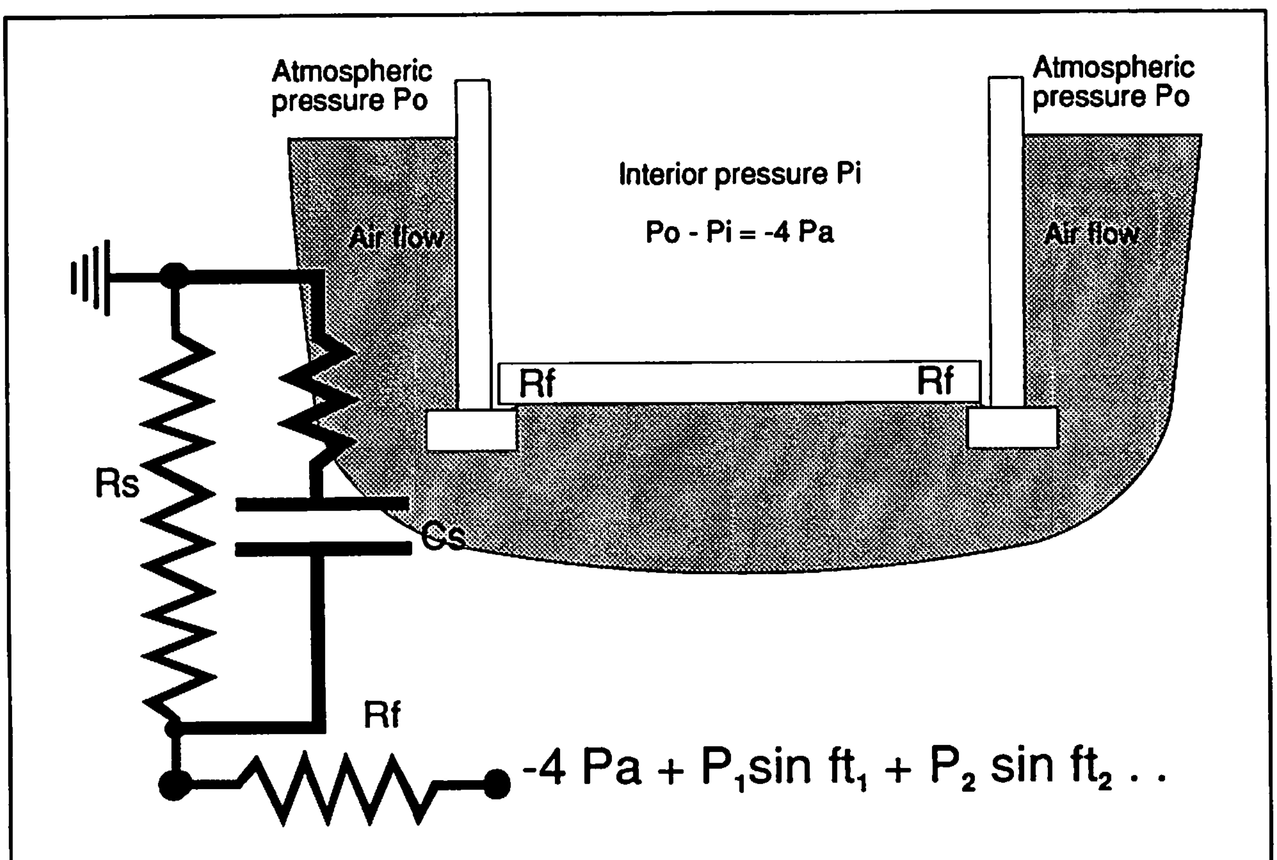

Figure 1 Soil Impedance - Equivalent Circuit

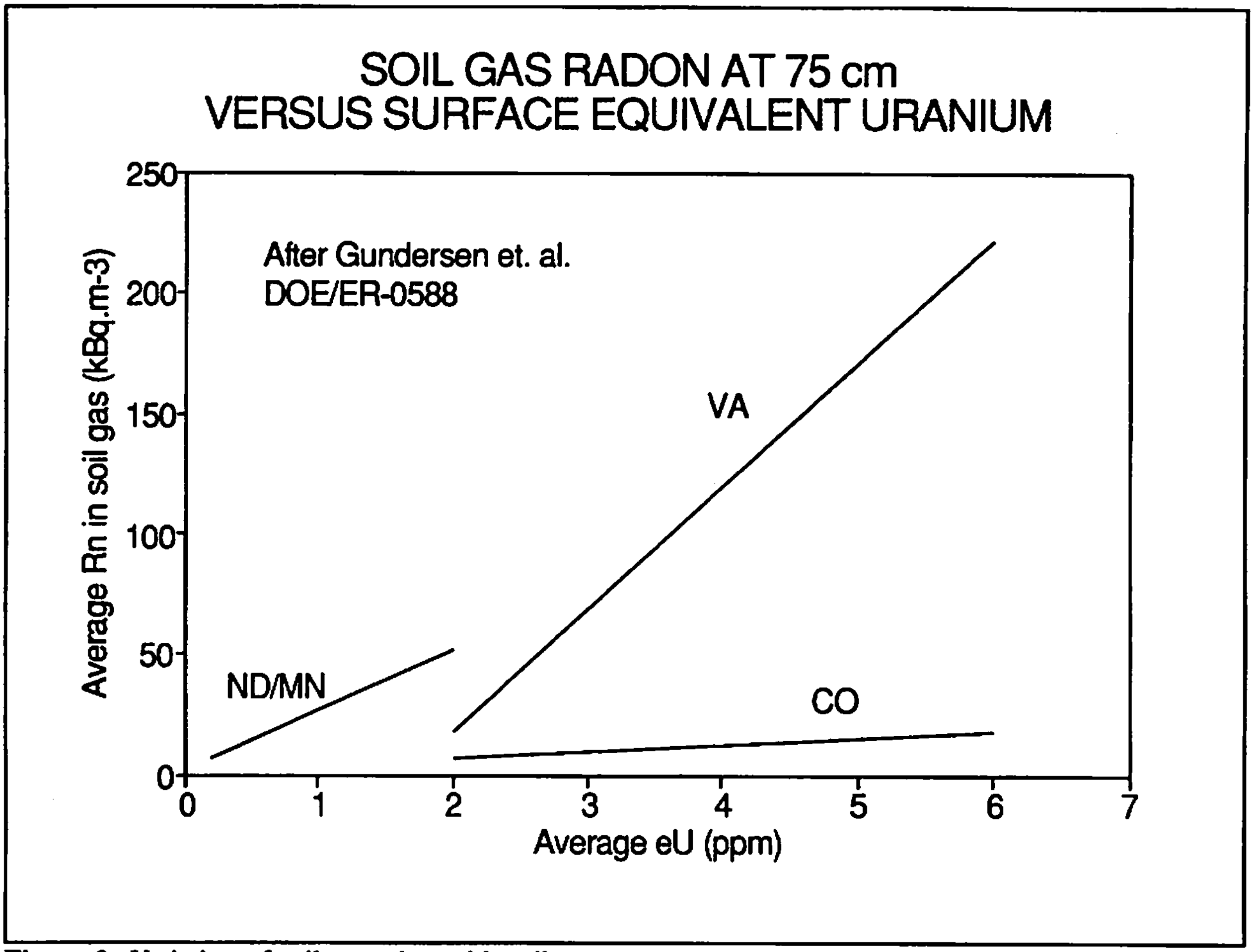

Figure 2 Variation of soilgas radon with soil type