THE ORIGIN OF INDOOR RADON

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INTRODUCTION

The major source of radon in single-family dwellings is the soil underneath (1). The principal route of entry into dwellings built on concrete slabs is through cracks and other openings. Two processes operate: the diffusion of radon through air-filled pores of soil and the pressure-driven flow of soil air. Small but persistent pressure gradients are created in the soil by the buoyancy of warm indoor air (the stack effect) and the effects of wind across open chimneys (the venturi effect) and across the fabric of the dwelling. Empirical and semi-empirical information indicates that pressure-driven flow is often the dominant process, particularly in the case of high radon levels (2,3,4). More recently, the radon transport equation describing the flow of radon from soil into dwellings through cracks in the concrete floor slabs has been solved numerically using the finite difference method (5). The solutions have been used to indicate the circumstances under which the pressure-driven flow mechanism might be expected to dominate and assist in the quantification of the parameters that determine high indoor radon levels.

MODELS OF RADON MOVEMENT

The steady state transport equation for the flow of radon in soil under concentration and pressure gradients is given by:

$$\frac{D_e}{p} \nabla^2 C_{Rn} - \frac{1}{p} \underset{\sim}{v}.\nabla C_{Rn} - \lambda (C_{Rn} - C_o) = 0 \qquad \ldots\ldots (1)$$

where D_e is the effective diffusion coefficient of radon in soil, p is the soil porosity, C_{Rn} is the soil radon concentration and λ is the radon decay constant. The model assumes a uniform volume source of radon and C_o is the concentration deep below the surface. $\underset{\sim}{v}$ is the linear flow velocity and is given by:

$$\underset{\sim}{v} = - \frac{k}{\mu} \nabla P \qquad \ldots\ldots (2)$$

where k is the air permeability of soil, μ the viscosity of soil gas and ∇P is the pressure gradient.

This model has been applied to a concrete raft 2r metres wide with a 2w cm wide crack in the centre. The length of the crack was assumed to be large in comparison with its width and height. The volume of soil beneath the raft was taken to be 5 m deep and extended 4 m beyond the walls. The concrete slab was assumed to be impermeable. This geometry can be repeated to represent periodic cracks.

From the transport equation, the concentration gradient of radon and hence radon flux at the top of the crack were determined (5). In this paper we calculate the radon concentrations that would exist in a dwelling with a ventilation rate of 0.5 air changes per hour, a volume of 250 m^3 and a floor area

of 50 m^2. The following values were also used: $\mu = 1.83 \times 10^{-5}$ kg m^{-1} s^{-1}, $D_e = 9 \times 10^{-7}$ m^2 s^{-1} and p = 0.35.

THE EFFECT OF CRACKS

Figure 1 shows the radon concentration in the dwelling plotted against air permeability of soil for different crack widths and periodicities. The radon concentration at depth was taken as 10^4 Bq m^{-3} and the pressure difference at floor level between outside and inside air was taken as 5 Pa. This would arise, for example, in a dwelling with a temperature difference between inside and outside of about 20°C. The radon concentration in a dwelling with a bare floor is also shown.

The following conclusions can be drawn from the figure:

a) The crack width and periodicity have a relatively small effect on the indoor radon concentration. This would imply that reducing high radon ingress in dwellings by caulking of cracks in a concrete floor will only be effective if all cracks are sealed. Even minor cracks may still be significant sources of radon.

b) At permeabilities below 10^{-10} m^2, the radon concentration in a dwelling with a cracked floor is not substantially lower than would arise from a bare floor. The reduction in radon concentration from a cracked floor at high permeabilities is due to fresh air being drawn from outside through the soil adjacent to the walls. The model used for the bare floor did not however take account of the effect of fresh air being drawn from soil adjacent to the walls.

THE EFFECT OF PRESSURE DIFFERENCE

Figure 2 shows the indoor radon concentration plotted against air permeability for different pressure differences at floor level between outside and inside air (+ denotes that the room is at lower pressure than atmospheric; - denotes a higher pressure). The crack width was taken as 0.5 cm with a 1 m period. C_o was again taken as 10^4 Bq m^{-3}. The concentration due to diffusion only is also shown ($\Delta P = 0$).

At permeabilities below about 10^{-12} m^2, the increasing pressure difference has relatively little effect on indoor radon concentrations. Between 10^{-12} and about 10^{-10} m^2, the concentration increases to a peak value which is about 15 times that due to diffusion alone. This peak is shifted to lower permeabilities with increasing pressure difference but the magnitude of the peak value is unaffected. Beyond the peak, the concentration decreases with increasing permeability for the reason given above. Extending the sealing of the soil immediately adjacent to the wall would reduce the depletion of the radon in the soil and hence increase the radon flux into dwellings.

For soil with a permeability in the region of 10^{-11} to 10^{-10} m^2, increasing the pressure difference from 2 to 10 Pa, causes an increase in the radon concentration by a factor of about 3. Further increase in the pressure difference would not increase the radon concentration beyond a maximum level owing to the fact that the position of the peak is progressively moving towards the lower permeabilities.

The reduction in radon concentration due to a negative pressure difference is marked. The implication is that over-pressurisation of a dwelling may well be successful in reducing high radon levels. However, over-pressurisation of the dwelling itself may well result in condensation being produced in the walls. Over-pressurisation of the soil under a fairly intact concrete slab may however be an effective means of reducing high levels and avoid this problem. Such an effect has been demonstrated (6).

CLASSIFICATION OF SOILS

Figure 3 shows the bands of radon concentration C_o and air permeability of soil which result in radon concentrations in dwellings of 100 and 400 Bq m^{-3} for a range of pressure differences. These values correspond respectively to the NRPB recommended upper bound for new dwellings and action level for existing dwellings (7). The figure therefore defines the circumstances in terms of permeability and radon in soil gas concentrations in which these levels might be exceeded. If assumptions are made regarding the radon emanating fraction of soils (here, an average value of 20% is used), this figure leads to a relatively simple classification of soils in terms of both radium-226 activity and radon in soil gas concentration. This is shown in Table 1 along with examples of possible soil types. Similar classifications based on more empirical considerations have been proposed by other workers (2,8,9) and this work provides some theoretical support.

It is noted that the model discussed here does not deal with two matters, both of which may significantly influence radon ingress into dwellings. These are tunnel flow caused by cracks and fissures in the underlying rock and the presence of a water table. In the first situation, the ingress of radon will not be dependent on permeability, and it is possible that soil gas could be transported over large distances and lead to high indoor radon levels. Some evidence for this mechanism is provided by the relatively high levels observed in limestone regions (1). The presence of a high water table will on the other hand lead to reduced soil gas flow, and this also has been observed (2).

REFERENCES

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Table 1: Combination of radiological parameters and air permeabilities of soils that might lead to radon concentrations above the Upper Bound of 100 Bq m^{-3}

^{226}Ra (Bq kg^{-1})	C_o (Bq m^{-3})	k (m^2)	Example
25	10^4	10^{-10}-10^{-9}	Gravel
100	5 10^4	10^{-11}-10^{-10}	Sand
500	2 10^5	10^{-12}-10^{-11}	Silt
2000	2 10^6	10^{-13}-10^{-12}	Till

Figure 1: Indoor radon concentration versus soil permeability for different crack widths and periodicities

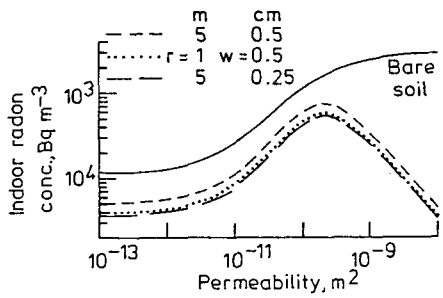

Figure 2: Indoor radon concentration versus soil permeability for different pressure differences

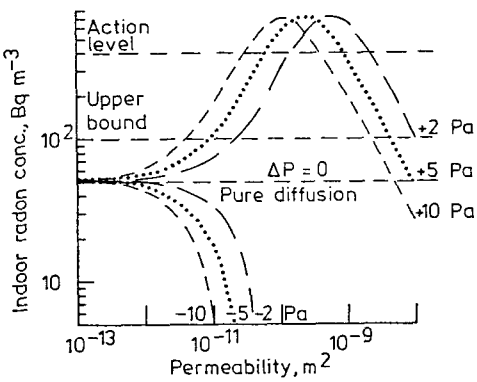
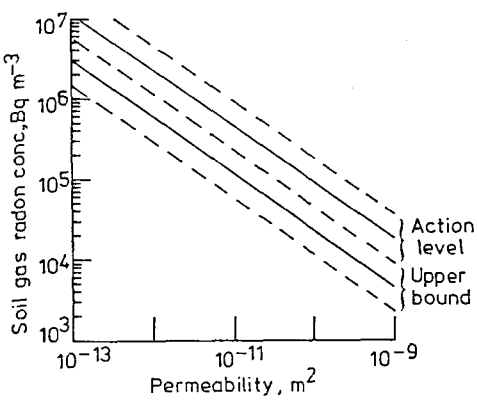
Figure 3: Soil gas radon concentration, C_o, versus soil permeability showing bands of values defining the Upper Bound and Action level