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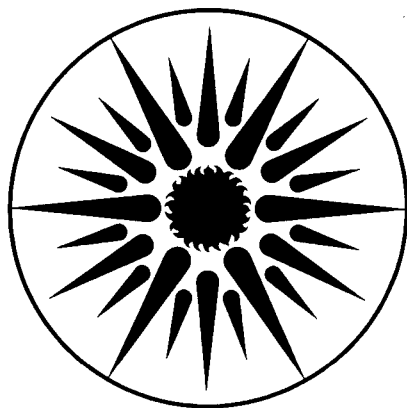
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TRANSPORT OF RADON FROM SOIL INTO RESIDENCES

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February 1984

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Abstract

To develop effective monitoring and control programs for indoor radon it is important to understand the causes of the broad range of concentrations that has been observed. Measurements of indoor radon concentration and air-exchange rate in dwellings in several countries indicate that this variability arises largely from differences among structures in the rate of radon entry. Recent evidence further suggests that the major source of indoor radon in many circumstances is the soil adjacent to the building foundation and that pressure-driven flow, rather than molecular diffusion, is the dominant transport process by which radon enters the buildings. Key factors affecting radon transport from soil are radon production in soil, flow-inducing mechanisms, soil permeability, and building substructure type.

Keywords: control techniques, indoor air quality, pollutant sources, radon, residential buildings, soil

Introduction: Accounting for the Source of Radon in Dwellings

Measurements of Radon Entry Rate

The radon concentration indoors is determined by a balance between the rate of entry from sources and the rate of removal, primarily by ventilation. The results of measurements in several countries show that the ventilation rate is more narrowly distributed than either the radon concentration or the radon entry rate, estimated as the product of the

ventilation rate and the indoor concentration (12). (See Table 1.) The broad range of indoor concentrations in the samples from Sweden, Canada and the United States is due primarily to differences in the rate of radon entry among dwellings. Thus, to understand the occurrence of high indoor concentrations, one must consider source materials and transport mechanisms by which radon enters houses.

Table 1. Measurements of radon concentration and ventilation rate in dwellings in several countries.

Country	No.	Vent. Rate (h^{-1})		Radon Conc. (Bq m^{-3})		Radon Entry Rate ($\text{Bq m}^{-3} \text{h}^{-1}$)		Refs.
		GM*	GSD*	GM	GSD	GM	GSD	
Sweden**	86	0.38	1.6	271	3.1	102	3.0	(8)
Canada	9	0.38	1.5	110	2.7	43	2.7	(20)
US (Avg.)***	73	0.64	2.0	40	3.9	25	3.7	(4,11-15)
US (GS)****	101	0.31	2.3	44	4.0	14	4.0	(12,16)
Britain	87	-	-	-	-	13	3.1	(2)
Germany	32	0.15	1.8	34	1.9	5	2.4	(23)

* GM=geometric mean; GSD=geometric standard deviation.

** Houses measured were suspected to have high radon concentrations.

*** Time-averaged for 2-day to 4-month periods; winter and spring.

**** Grab sample measurements, spring and summer.

Figure 1 portrays frequency distributions of the radon entry rate for several samples, along with estimated contributions from several sources. At the upper end of the distributions, the radon entry rate cannot be ascribed in any simple way to the sources indicated.

Sources of Indoor Radon

The sources of indoor radon, recently reviewed elsewhere (1,17), are earth-based building materials, domestic water derived from wells, and soil adjacent to the structure. Outdoor air and natural gas contri-

bute a small amount to indoor concentrations.

Building materials are a major source of elevated indoor radon concentrations only if their radium content is very high. An important example is alum-shale concrete used in Sweden from 1930 to 1975. These concretes have radium concentrations of $300\text{--}2600 \text{ Bq kg}^{-1}$, as much as two orders of magnitude larger than ordinary concretes (9,22). Ordinary building materials may be the dominant source of indoor radon in some dwellings with low to moderate concentrations. This is the case in much of continental Europe in part because a large portion of the dwellings there are in multistory buildings to which the underlying soil contributes relatively little radon per unit volume.

Domestic water derived from underground sources can in some cases contain sufficient radon to account for a high entry rate. A study in Maine found concentrations of radon in water spanning a very large range, from 7×10^2 to $6.7 \times 10^6 \text{ Bq m}^{-3}$, with the higher number implying an entry rate of about $700 \text{ Bq m}^{-3} \text{ h}^{-1}$ (7,17). However, most domestic water supplies contain radon concentrations below about 10^5 Bq m^{-3} (17), a level at which the contribution to indoor concentrations is comparable to that from ordinary building materials.

Soil has been implicated in several recent studies as an important, if not predominant, source of radon in many dwellings with average or higher-than-average concentrations (1,5,8,12,14,15,17). This conclusion is based upon two lines of reasoning: 1) no other material associated with these houses produces sufficient radon to account for the observed

levels; and 2) certain flow-inducing mechanisms, including those that drive infiltration, can cause sufficient flow of air through the building substructure to transport the radon. This latter point is essential to the conclusion because the reported range of fluxes from uncovered soil (24) cannot account for the higher entry rates observed and such fluxes, which arise from molecular diffusion, should be attenuated by factors of 25 to 50 for an intact concrete slab (3), or by a factor of four even for a severely cracked one (10).

Factors Affecting Radon Entry Via Flow Through the Substructure

Radon Production in Soil

A typical radon emanation rate for U.S. soils is in the range $(1-4) \times 10^{-5} \text{ Bq kg}^{-1} \text{ s}^{-1}$ (17). To account for a radon entry rate of $50 \text{ Bq m}^{-3} \text{ h}^{-1}$ in a 250-m^3 house requires $50\text{-}300 \text{ m}^3$ of such a soil which, assuming a single-story house with a full basement whose floor is 2 m below the soil surface, corresponds to a thickness of 0.4-3 m adjacent to the walls and floor. To account for radon entry rate of $200 \text{ Bq m}^{-3} \text{ h}^{-1}$, a 0.9-m thickness of soil having a high emanation rate ($10^{-4} \text{ Bq kg}^{-1} \text{ s}^{-1}$) would have to supply its radon to the house. For more typical emanation rates, radon from soil within up to 10 m of the basement walls must be transported into the house to account for an entry rate of $200 \text{ Bq m}^{-3} \text{ h}^{-1}$. This transport distance cannot be accounted for by molecular diffusion since the diffusion length of radon in soil is in the range 0.6-1.5 m (21).

Flow-Inducing Mechanisms

Stack effect. A pressure differential that varies with height exists across any vertical wall separating air masses of different temperatures. This "stack effect" is a consequence of the atmosphere being a compressible fluid whose density varies with temperature and which is acted upon by gravity. The stack effect is a major contributor to air infiltration, and during the heating season it gives rise to a net inward pressure on the floor and the lower part of the walls of houses. For a building height of 5 m, a temperature difference of 20°C causes a change in pressure differential from floor to ceiling of 4 Pa (19). Pressures of this scale drive infiltration rates on the order of 100 m³h⁻¹ into houses. If even a few percent of this flow passes through the soil adjacent to the building, radon entry rates at the higher end of the range observed can be produced.

Wind is the second important factor that drives air infiltration in buildings. It generates pressures of a scale comparable to those induced by temperature differences; however, the spatial distribution of pressures is quite different, as is the time scale for changes in the distribution. Wind may drive radon entry from soil, not because of a net inflow of soil gas, but rather because it causes an exchange of air between the house and the soil, with air flowing in from the soil on the windward side and out into the soil on the leeward side.

Precipitation and barometric pressure. The effects of these factors are less certain, but they may be important in some circumstances. For example, in one study of radon entry into a house with a crawl space, it

was observed that on one day of heavy rain, coincident with a moderate drop in barometric pressure, the indoor radon concentration rose to a level more than five times higher than average (14). It was postulated that either the water percolating through the soil forced soil air into the crawl space, or that the wet soil was sufficiently impermeable that the soil air was funneled into the crawl space in response to the barometric pressure change.

Soil Permeability

Soil permeabilities range over 12 orders of magnitude, from as high as 10^{-7} m^2 for gravel to as low as 10^{-19} m^2 for glacial till or marine clay (5). Permeabilities of 10^{-10} m^2 or higher are sufficient to permit enough air flow through the soil to constitute a large radon source (5). For example, for an extensively studied house near Chicago, it was estimated that an average pressure difference of 3.5 Pa could drive $3\text{--}6 \text{ m}^3 \text{ h}^{-1}$ of air through the soil if its permeability were 10^{-10} m^2 , and that this flow rate could account for a radon entry rate of $60 \text{ Bq m}^{-3} \text{ h}^{-1}$ (15). It is plausible that under certain circumstances highly permeable soils would permit sufficient flow so that radon could be drawn from soil 10 m or more away from the house.

Building Substructure

Most single-family dwellings in developed countries have one (or a combination) of three substructure types: basement, wooden floor over a crawl space, and concrete slab-on-grade. Each type has its own

characteristics pertaining to radon entry from soil.

Basement substructures appear to be the most susceptible to high rates of radon entry from soil because 1) they have relatively large area exposed to the soil and 2) given the fairly long vertical path between outdoor air and the substructure penetrations, the pressure-driven flow field through soil can extend more than a meter from the perimeter of the dwelling. If the soil is highly permeable, this latter factor permits more soil than that within a diffusion length of the structure to contribute to the radon entry rate. Typically the size of penetrations in a basement is sufficient that the flow rate of air through the soil is limited by the soil permeability.

Crawl-space. Although a well-vented crawl space effectively decoupled the house air from the soil air, much of the radon that is transported into the crawl space from the soil may still enter the house because of the stack effect (14). If the crawl space is unvented, stack-effect and wind pressure can enhance radon flux into the crawl space. This may account for the high concentrations observed in such houses in one study (18).

Slab-on-grade foundations have not been studied extensively for radon entry. In most cases this substructure type is probably less susceptible to high rates of radon entry from soil than are basements. Regardless of the permeability of the soil, any air flow through the substructure is likely to be focussed in a region near the foundation perimeter and only radon that diffuses through the soil to the concrete slab is drawn into the buildings.

Conclusion: Implications for Measurement and Control Programs

Efforts to identify houses with elevated radon concentrations should focus both on areas where soils have high radium concentrations and on areas where soils are highly permeable. Controls should be addressed to remedial measures and techniques for new construction that reduce the flow of air through the building substructure, or that provide alternative ventilation pathways for soil air.

There has been a misplaced emphasis on low ventilation rates as a major cause of high indoor radon levels. As the work presented here shows, radon entry rates are more highly variable and thus ordinarily a more important factor. At high entry rates (i.e., above $100 \text{ Bq m}^{-3} \text{ h}^{-1}$) unreasonably high ventilation rates may be needed to achieve acceptable indoor concentrations. Furthermore, the interaction between infiltration and radon entry suggests that one may be able to reduce ventilation rates without increasing indoor radon concentrations by altering the distribution of leakage in the building shell. Certain ventilation-based control strategies for maintaining good indoor air quality, such as the use of exhaust fans, may not reduce indoor radon concentrations to the degree expected -- if at all -- because of a corresponding increase in radon entry from the soil.

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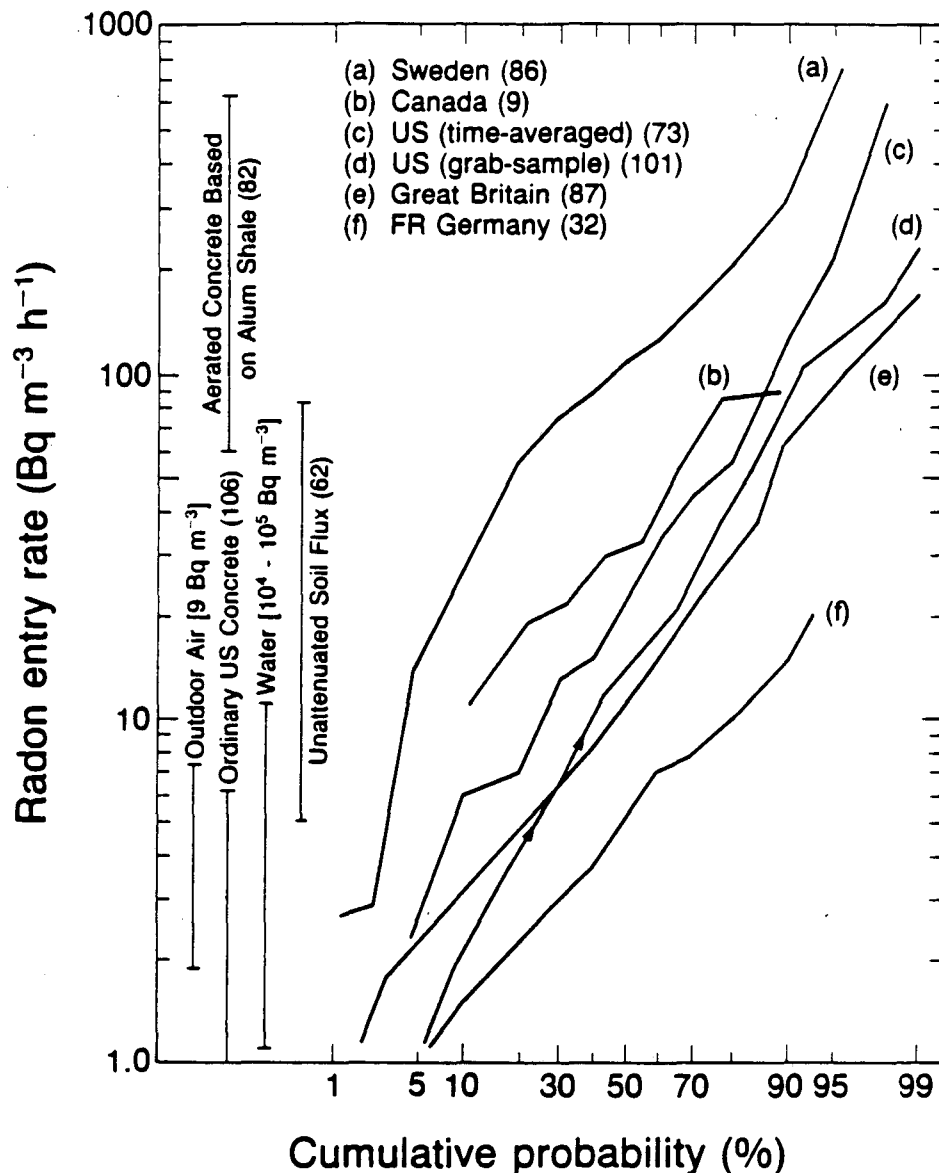
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Figure 1.

Cumulative frequency distributions of radon entry rate determined in dwellings in several countries as the product of simultaneously-measured ventilation rate and radon concentration. The number of residences in each sample is indicated in parentheses, and references for each distribution are given in Table 1. The bars at the left indicate the range of contributions expected from a variety of sources, with assumptions indicated in brackets. For each source we have assumed a house having a single-story of wood-frame construction with a 0.2-m-thick concrete-slab floor. The floor area and ceiling height are assumed to be 100 m² and 2.4 m, respectively; water usage is assumed to be 1.2 m³ per day, with a use-weighted transfer efficiency for radon to air of 0.55; the ventilation rate is assumed to be in the range 0.2-0.8 h⁻¹. [References for source contribution estimates: outdoor air (6); U.S. concrete (9); alum-shale concrete (22); water (17); soil flux (24).] (Although alum-shale based concretes can account for very high entry rates, they are not though to be the main source in all cases of high entry rate in Sweden (8).)

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