LBL-25762 c.2
Preprint

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OCT 1 1988

Submitted to Radiation Protection Dosimetry

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November 1987

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APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

LBL-25762 c.2

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Submitted to *Radiation Protection Dosimetry* November 1987

Predicting the Rate of Radon-222 Entry from Soil into the Basement of a Dwelling due to Pressure-Driven Air Flow

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ABSTRACT

A combination of analytical and numerical methods is applied to the problem of computing ^{222}Rn transport from soil into a dwelling having a basement. Transport is assumed to occur solely by pressure-driven air flow, and the basement shell is assumed to have a single dominant leak that is uniformly distributed around the perimeter at the level of the floor. The results show that for small flow rates of air through the soil, the radon entry rate into the basement increases in proportion to ΔP_o, the outdoor-indoor pressure difference at the soil level. For large flow rates, the entry rate increases only in proportion to $\Delta P_o^{2/3}$, due to depletion of radon concentration in the soil. A sample calculation indicates that via this transport mode, soil having ordinary ^{226}Ra content and moderately high permeability can be responsible for indoor radon concentrations of order 500 Bq m^{-3}, greater than recommended guidelines for new housing.

INTRODUCTION

Radon-222 produced in the soil near a building foundation migrates by a combination of molecular diffusion and forced flow, the latter induced both by environmental factors — e.g., wind, temperature differences, and changes in barometric pressure — and by building operational factors — e.g. the use of exhaust ventilation. Forced air flow through the soil and into buildings via their substructures is believed to be responsible in most of the cases in which high indoor ^{222}Rn concentrations have been observed. However, our present understanding of the transport processes and entry mechanisms is incomplete. The general equation describing radon transport in soil cannot be solved analytically for common building geometries and numerical analyses have been carried out for only a few cases.

In the present paper, radon entry from soil into a residential basement by pressure-driven flow is examined by a combination of analytical and numerical techniques. To make the analysis tractable, the building is represented by an idealized physical system. The analysis yields the

relationship between the radon entry rate and several controlling variables: ^{226}Ra content of soil, emanation coefficient, soil permeability, porosity, outdoor-indoor pressure difference, and building geometry. A sample calculation is presented to demonstrate that ^{222}Rn entry from a soil with moderately high permeability can yield high indoor concentrations even if the ^{226}Ra content of the soil is ordinary.

BUILDING REPRESENTATION

Two prominent openings for soil-gas entry in a house with a basement are (1) a floor-wall joint that often occurs in cases where the floor and walls are formed from poured concrete; and (2) a perimeter drain-tile system that is connected through an untrapped line to a basement sump. These two cases are illustrated in Figure 1, cases a and b. The analysis in this paper is intended to apply directly to these cases.

The objective is to compute the rate of radon entry into the basement from the soil as a function of the controlling variables. The path for radon migration from soil into a basement is idealized as a buried cylinder having a horizontal axis, as shown in Figure 1c. The length of the cylinder, L, is taken to be equal to the building perimeter; as L is typically much greater than the other length scales in the problem, H and r, the problem may be solved in two dimensions, neglecting end effects. Because of the presence of the basement walls, it is expected that the actual rate of ^{222}Rn entry into a building would be in the range 50-100% of that predicted for the idealized geometry.

ANALYSIS OF RADON ENTRY RATE

Several further assumptions and approximations are introduced in setting up the mathematical problem. The soil is assumed to extend infinitely in both horizontal directions and downward from the soil surface. The soil is assumed to be homogeneous with respect to all of its relevant characteristics: permeability, porosity, ^{226}Ra concentration, temperature, and emanation coefficient. The soil is also assumed to be isotropic with respect to permeability. The potential influence of soil moisture on transport is neglected. The pressure at the soil surface is assumed to be uniform and constant; the cylindrical cavity is at a lower dynamic pressure that is also uniform and constant. The dynamic pressure difference between the soil surface and the cavity is much smaller than atmospheric pressure, so that compressibility effects may be neglected. Radon entering the soil at its surface is neglected, as its concentration is much smaller than that in the soil pores at depth.

Although ^{222}Rn transport in soil occurs by a combination of molecular diffusion and forced

convective flow, in this paper, diffusion is neglected. This approximation is generally appropriate for considering buildings in which the rate of ^{222}Rn entry from soil is high. More specifically, diffusion may be neglected whenever the following condition is satisfied [1]:

$$\frac{k\,\Delta P_0}{\mu} \gg \frac{D_e}{\varepsilon} \tag{1}$$

where k is the permeability coefficient of soil, ΔP_0 is the difference in the dynamic pressure between the soil surface and the cavity, μ is the dynamic viscosity of air, ε is the soil porosity, and D_e is the effective diffusion coefficient of radon in the soil pores.

Making a final, reasonable, assumption that the air velocity in soil is proportional to the gradient of the dynamic pressure, i.e. that Darcy's law holds, we may describe the steady-state ^{222}Rn transport in the soil by a set of three equations [1]:

$$\nabla^2 P = 0 \tag{2}$$

$$\mathbf{v} = -\frac{k}{\mu}\nabla P, \tag{3}$$

$$G - \lambda I - \frac{\mathbf{v}}{\varepsilon}\cdot\nabla I = 0 \tag{4}$$

where P is the dynamic pressure, ∇ is the gradient operator, $\mathbf{v}$ is the superficial or Darcian velocity vector, λ is the radioactive decay constant of radon, G is the radon generation rate in soil air, and I is the radon activity concentration. (The dynamic pressure at a point is given by $P = P_a - P_{a,0} + \rho g h$, where P_a is the air pressure at the point, $P_{a,0}$ is the air pressure at a reference height, h is the height of the point above the reference level, ρ is the air density and g is the acceleration of gravity.) Equations (2)-(4) express, respectively, the conservation of air mass in the soil pores, Darcy's law, and the radon activity balance in the soil pores. The terms on the left-hand side of equation (4) account, respectively, for radon generation by the decay of radium, radioactive decay, and transport. The radon generation rate is related to more fundamental parameters by

$$G = f\,\rho_s\,A_{Ra}\,\lambda\,\frac{1-\varepsilon}{\varepsilon} \tag{5}$$

where f is the emanation coefficient, ρ_s is the density of the soil grains (commonly 2.65×10^3 kg

m^{-3}), and A_{Ra} is the radium content of the soil. The boundary conditions for equations (2)-(4) are that the dynamic pressure is uniform at the soil surface and within the cavity, and that the radon activity concentration is zero at the soil surface.

The problem is solved in two independent steps. First, the dynamic pressure field in the soil pores is determined by solving equation (2). An analytical solution is possible, using a transformation to bipolar coordinates [2]. In the cartesian coordinates indicated in Figure 1c, the dynamic pressure field in the soil is given by

$$\frac{\Delta P(x,z)}{\Delta P_o} = \frac{\tanh^{-1}\left[\dfrac{2z\,(H^2-r^2)^{1/2}}{H^2-r^2+z^2+x^2}\right]}{\tanh^{-1}\left[\dfrac{(H^2-r^2)^{1/2}}{H}\right]} \tag{6}$$

where ΔP is the dynamic air pressure at the soil surface minus that at point (x,z) in the soil. The air velocity at any point in the soil is obtained by applying equation (3) to equation (6). The total rate of flow of air into the cavity is obtained by integrating the velocity over the cavity surface. The result is

$$Q = \frac{2\pi\ \Delta P_o\ k\ L}{\mu\ \sinh^{-1}\left[(H/r)^2 - 1\right]^{1/2}} \tag{7}$$

In the limit $r \ll H$, $Q \rightarrow 2\pi\ \Delta P_o\ k\ L\ [\mu\ \ln(2H/r)]^{-1}$.

The second step is to solve equation (4), given the velocity field determined from equations (3) and (6), to determine the radon concentration as a function of position at the surface of the cavity. Once this result is obtained, the radon entry rate into the cavity is determined by integrating the product of the radon concentration and the soil gas velocity over the surface of the cavity.

This approach to computing the radon concentration at the cavity surface is most easily understood by considering a fluid streamline originating at the soil surface, traversing the soil, and entering the cavity. Consider a frame of reference that follows the streamline at the rate of air flow. Because diffusion is neglected, the radon concentration at the center of this frame of reference is governed only by the rates of production and decay in the soil pores. Thus, given the assumptions of soil homogeneity and negligible radon concentration above the soil, the radon concentration at any point in the soil is simply

$$I = \frac{G}{\lambda}(1-e^{-\lambda t}) \tag{8}$$

where t is the time of travel along the appropriate streamline from the soil surface to the given point. The problem has therefore been reduced to determining t as a function of position along the perimeter of the cavity. Since v is known as a function of position from equations (3) and (6), t may be determined for any point on the cavity surface by integrating $\frac{ds}{-v}$ along the streamline from the cavity to the soil surface, where ds is a differential distance vector along a streamline. This integration was accomplished numerically, using a fourth-order Runge-Kutta method [3] applied at 360 equally spaced points around the cavity perimeter.

RESULTS

The fluid streamlines and pressure isobars are presented for a representative case in Figure 2. Transit times through the soil are noted for each streamline. Note that the transit time for a given streamline is proportional to $\varepsilon H^2/(\Delta P_0 k)$.

The dependence of radon flux into the cavity on the controlling variables is summarized in Figure 3. There are two regimes. For low rates of air flow into the cavity, the radon concentration at the cavity surface is given by the limiting value G/λ. In this situation, the minimum transit time for an air parcel from the soil surface to the cavity is longer than the radon half life. The radon entry rate into the cavity, F, is given by QG/λ, or

$$F = \frac{2\pi\ G\ L\ \Delta P_0\ k}{\mu\lambda\ \ln(2H/r)} \tag{9}$$

For high rates of air flow into the cavity, the radon concentration at the cavity surface is depleted to a value less than G/λ because of the short time of transit, relative to the radon half-life, of air from the soil surface to the cavity. In this depletion regime, the radon entry rate is given by

$$F = 4.0\ GL\ H^{2/3}\ \varepsilon^{1/3}\left[\frac{\Delta P_0\ k}{\mu\lambda\ \ln(2H/r)}\right]^{2/3} \tag{10}$$

The depletion regime occurs under the condition $\{\Delta P_0\ k\} > \{0.5\ \varepsilon\ \mu\ \lambda\ H^2\ \ln(2H/r)\}$.

APPLICATION: HIGH ENTRY RATES FROM SOIL WITH ORDINARY RADIUM CONTENT

It is a common belief that a rich deposit of uranium (and, therefore, radium) is necessary to support high indoor radon concentrations [4]. The results of the previous section may be used to

demonstrate that soil with ordinary radium content can cause high indoor radon concentrations if it is even moderately permeable.

Consider the conditions indicated in Table 1. The values for all soil parameters other than permeability are estimates of the median values for the United States. The permeability corresponds to a uniform medium sand. The building parameters correspond to a detached one-story house with a full basement and a perimeter drain tile system connected to a sump. The pressure difference is chosen to typify wintertime conditions in colder parts of the United States. More detailed data on parameters in Table 1 can be found in reference 1.

Under these conditions, the normalized air flow rate into the cavity is 4.9, so the depletion regime prevails. Applying Equation (10) yields a radon entry rate of 41.5 Bq s^{-1}. The resulting indoor radon concentration, assuming the air on the main floor is well mixed with that in the basement, is 660 Bq m^{-3}. The actual expected value is in the range of 330-660 Bq m^{-3}, for reasons indicated in the section "Building Representation," above. Assuming an equilibrium factor of 0.5 applies, this range corresponds to 1.65-3.30 times the ICRP recommendation of 100 Bq m^{-3} for maximum acceptable radon decay product concentrations in new dwellings [5].

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Table 1. Soil and building parameters used in sample calculation

Parameter	Symbol	Value
permeability	k	1.0×10^{-10} m^2
porosity	ε	0.4
radium content	A_{Ra}	40 Bq kg^{-1}
emanation coefficient	f	0.3
pressure difference	ΔP_o	5.0 Pa
depth to cavity	H	1.5 m
cavity radius	r	0.15 m
cavity length	L	40 m
building volume	V	450 m^3
air-exchange rate	λ_v	0.5 h^{-1}

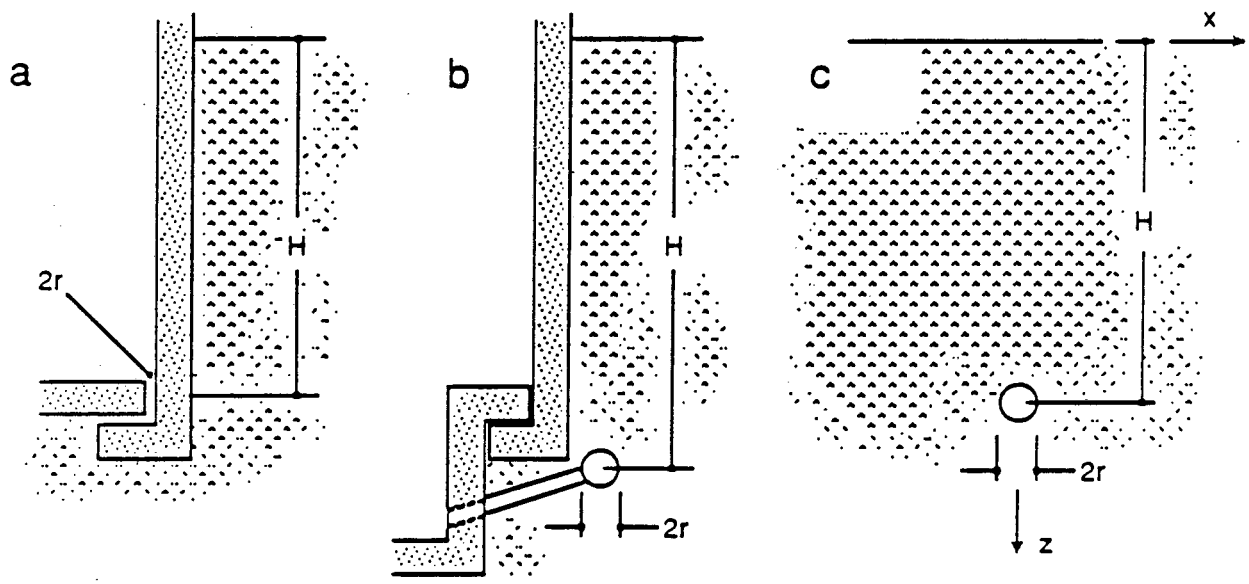

Figure 1. Idealized representation of radon entry from soil into a basement. Many basement houses have a dominant pathway to the soil sir via (a) the floor-wall joint, or (b) a perimeter drain tile system connected to a sump. Radon entry in these cases is modeled as (c) an isolated buried cylinder with a horizontal axis. The length of the cylinder is taken to be equal to the perimeter of the basement floor.

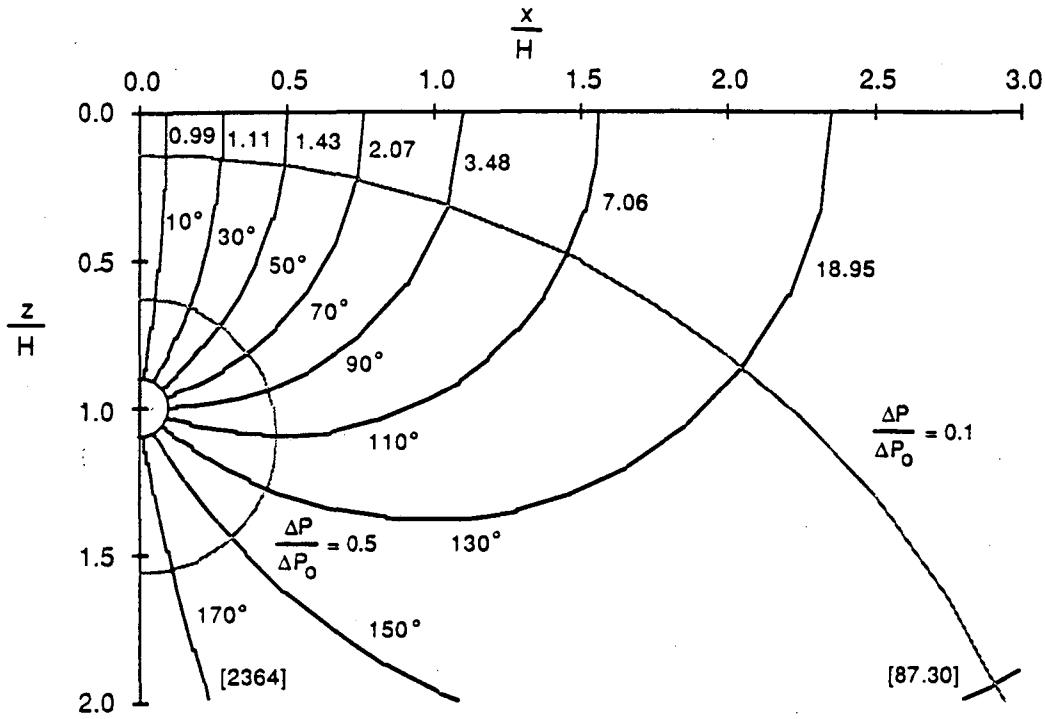

Figure 2. Airflow trajectories and pressure isobars in the soil for r/H = 0.1. Each trajectory is labeled with (a) the angle from vertical to its point of entry into the cylinder (10°-170°), and (b) the normalized travel time, τ, from the soil surface to the cylinder (0.99-2364). By definition, $\tau = (\varepsilon\mu\lambda^2 H^2 t)/(\Delta P_0 k)$, where t is the actual time; other symbols given in text.

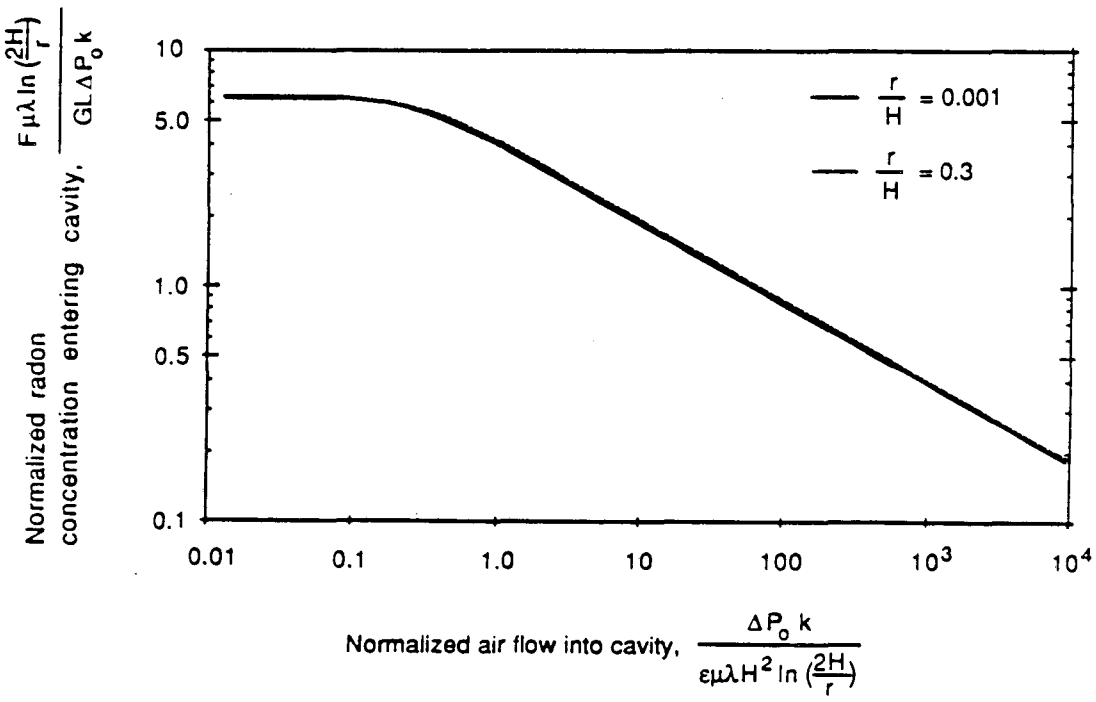

Figure 3. Radon concentration entering the cylindrical cavity vs. the air flow into the cavity, in dimensionless form.

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