CHAPTER 2

PRINCIPLE AND THEORY

2.1 The origins of radon

Naturally occurring radioactivity occurs throughout the Earth's crust. Some of these radioactive nuclides decay into stable elements and others decay into another radioactive nuclide. Uranium has two radioactive nuclides, ^{238}U and ^{235}U, that decay into other radioactive nuclides and thorium has one such radioactive nuclide, ^{232}Th. The immediate disposition of an atom created in a radioactive series depends on physical and chemical properties of the element and the surrounding soil or rocks. These elements vary greatly in solubility, depending on ambient physical conditions, and may go into solution or be absorbed onto organic particles or clay minerals. Uranium, radium, and radon are the most movable, lead and bismuth are only moderately movable, while thorium and polonium remain relatively immobile.

One of the most abundant sources of naturally occurring radioactivity is the series that begins with ^{238}U. Figure 2.1 shows this series. The first 14 members in this series collectively emit gamma, beta, and alpha radiation. Because of the arrangement of half-life and chemical properties, the concentration of radioactivity of the early members of the series is proportional to the concentration of ^{238}U in the Earth.

An important deviation happens roughly midway through the ^{238}U series: ^{226}Ra decays by alpha emission and creates ^{222}Rn. In contrast with other members of the series, which are solids, radon is a chemically inert noble gas and can migrate in the environment (Committee on Risk Assessment, 1999).

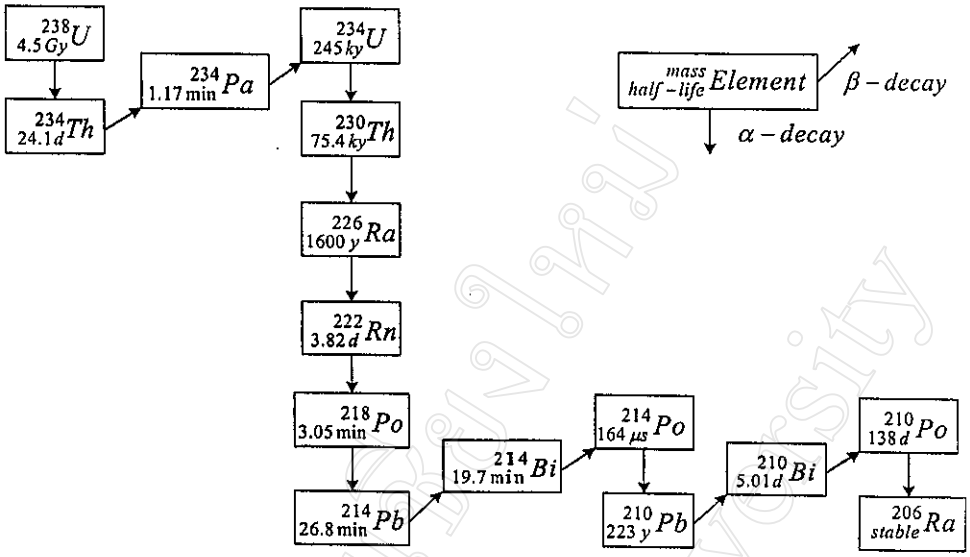

Figure 2.1 Decay scheme for naturally occurring ^{238}U chain.

The other radioactive decay series is the ^{232}Th series. In this series, ^{224}Ra decays by alpha emission and creates ^{220}Rn. ^{220}Rn is a short-life inert noble gas and all other members of the series are solids. Figure 2.2 shows the ^{232}Th decay series.

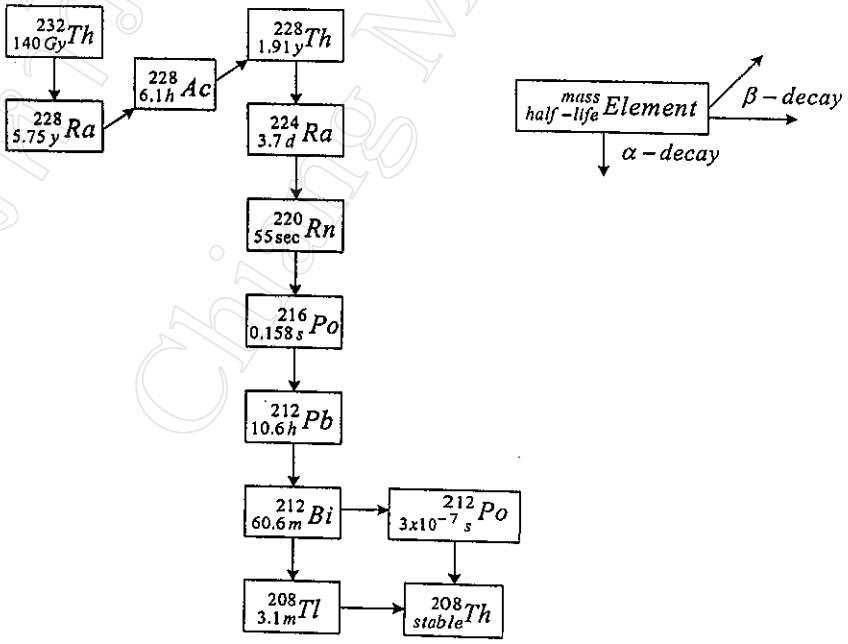

Figure 2.2 Decay scheme for naturally occurring ^{232}Th chain.

2.2 Migration of radon in overburden

Uranium in soils and rocks is the source of most radon. The decay series, beginning with ^{238}U, is a major source of natural radiation exposure. Local high levels of uranium are due mainly to the underlying rock type and its mineral composition. A significant uranium daughter is radium, ^{226}Ra, which has a half-life of 1,600 years. Radium's daughter is radon, ^{222}Rn, and it has a half-life of 3.82 days.

Because radon is a gas, it has much greater mobility than uranium and radium, which are fixed in the solid matter of rocks and soils. Radon can more easily leave rocks and soils by escaping into fractures and openings in rocks and into the pore spaces between grains of soil. Migration of radon in soil gas is controlled by two processes. These processes are molecular diffusion and fluid flow. The law of radioactive disintegration is simple and unvarying. The calculation of the amount of radon generated by a given amount of ^{238}U is easy provided the radioactive series is in equilibrium at least to the level of radon. However, analysis of the escape of gas from its source and its movement through the overburden is more complex. This depends on a large number of variables, such as the emanation coefficient of the source, the diffusion coefficient of the overburden, and the geometrical configuration of the whole system.

In the case of radioactive series in equilibrium, it can be shown that

$$\lambda_1 N_1 = \lambda_2 N_2 = \cdots = \lambda_n N_n \qquad (2.1)$$

where λ_n is the decay constant of the isotope n of the series and N_n, is the number of atoms of isotope n. This relationship shows that 1 gram of natural uranium is in equilibrium with 3.713×10^{-7} curies, or 3.713×10^{5} picocuries, of radon. However, only a fraction of the radon so generated can escape from the generating medium and enter the overburden (Kanaree, 1998).

2.2.1. Radon diffusion equations

For homogeneous half space, the two equations of Fick's law (Schroeder and others, 1996) describe radon diffusion. For the vertical z-axis, Fick's first law equation is

$$\phi = -D\frac{\partial C_z}{\partial z} \tag{2.2}$$

where, ϕ is the particle current density (flux, $Bq.m^{-2}.s^{-1}$).

D is the diffusion coefficient of the medium ($m^2.s^{-1}$).

C_z is the radon concentration in one unit volume of soil at depth z ($Bq.m^{-3}$).

Fick's second law of radon diffusion equation is

$$\frac{\partial C_z}{\partial t} = -\frac{\partial \phi}{\partial z} - \lambda C_z + P_z \tag{2.3}$$

where, λ is the decay constant of radon = 2.11 x 10^{-6} s^{-1}, and P_z is the radon production rate at depth z ($Bq.m^{-3}.s^{-1}$).

From equations (2.2) and (2.3), the radon diffusion equation can be written as

$$\frac{\partial C_z}{\partial t} = D\frac{\partial^2 C_z}{\partial z^2} - \lambda C_z + P_z \tag{2.4}$$

For steady state condition ($\frac{\partial C_z}{\partial t} = 0$) and constant radon production rate ($P_z = P_0$), the solution of equation (2.4) is:

$$C_z = \frac{P_0}{\lambda}\left[1 - \exp^{\left(-z\sqrt{\lambda/D}\right)}\right] \tag{2.5}$$

2.2.2 Radon diffusion plus fluid flow equation

For homogeneous half space having a steady state condition and a constant radon production rate (P_0), the effect of vertical movement of diffusing radioactive gas on the radon concentration at depth C_z is:

$$D\frac{d^2C_z}{dz^2} + v\frac{dC_z}{dz} - \lambda C_z + P_0 = 0 \qquad (2.6)$$

where, v is velocity of upward fluid flow in $m.s^{-1}$. The solution of equation (2.6) is:

$$C_z = \frac{P_0}{\lambda}\left[1 - \exp^{\left(-v/2D - \sqrt{v^2/4D^2 + \lambda/D}\right)z}\right] \qquad (2.7)$$

2.3 Theory of soil-gas permeability measurement

Measurements of soil-gas permeability have taken on added significance as a result of increased efforts to determine the entry rates of radon into buildings and to develop methods of mapping the radon potential of soils. Soil-gas permeability was measured by placing a perforated probe in the ground and then measuring the relationship between an applied pressure and the resulting rate of gas flow through the probe. The permeability probe was operated by pumping air into the formation under constant pressure. The data will be analyzed based on a mathematical model for the flow/pressure relationship. The geometry of the measurement probe is important in that it determines the numerical value to be assigned to the geometrical shape factor. This geometrical shape factor consists of the product of a dimensionless geometrical factor, which depends on shape of the probe, and a length that is characteristic of the size of the probe.

To develop a theory, air flow from a buried probe to the surface must be considered. The soil is assumed to be homogeneous and isotropic and a steady state is considered. Furthermore, the air is assumed to be

incompressible, meaning that pressure differences are very much smaller than atmospheric pressure. Under these assumptions the air flow is proportional to the pressure difference between the probe and the surface (Damkjaer and Korsbech, 1992). This relationship can be represented by:

$$Q = S\frac{k}{\mu}\Delta P \tag{2.8}$$

where, Q = Volumetric flow rate ($m^3 .s^{-1}$)
S = geometric shape factor (m.)
k = permeability (m^2)
μ = dynamic viscosity of the gas (Pa.s)
ΔP = applied pressure difference (Pa)

Shape factors can be determined for various geometrical probes (Moseley *et al.*, 1996). The shape factor for a sphere buried in a semi-infinite slab of soil was given by Nazaroff and Sextro (1989) and by van der Graaf and de Meijer (1992). The equation for determining shape factor of a sphere is

$$S = \frac{8\pi hr}{2h - r} \tag{2.9}$$

where, S = shape factor (m) for the spherical cavity.
h = depth (m) of the sphere below the soil surface.
r = inner radius (m) of the spherical cavity.

The equation of Hahne and Grigull (1975) to determine the shape factor for porous cylinders buried horizontally to the surface is

$$S = \frac{2\pi L}{\ln\left(\frac{L}{r}\left[\sqrt{1+\left(\frac{L}{4h}\right)^2} - \frac{L}{4h}\right]\right)} \tag{2.10}$$

where, S = shape factor (m) for the porous cylinder.
L = length (m) of the cylinder.
h = depth (m) below the surface.
r = inner radius (m) of the porous cylinder.

The Hahne and Grigull (1975) shape factor equation for a porous cylinder oriented perpendicular to the surface is

$$S=\frac{2\pi L}{\ln\left(\frac{L}{r}\sqrt{\frac{4h-L}{4h+L}}\right)} \tag{2.11}$$

where, the symbols are the same as for equation (2.11)

The shape factor equation for an ellipsoid with its major axis parallel to the surface was given by van der Graaf and de Meijer (1992) as

$$S=\frac{8\pi c}{\ln\left[\frac{(a+c)(\sqrt{c^2+4h^2}-c)}{(a-c)(\sqrt{c^2+4h^2}+c)}\right]} \tag{2.12}$$

Where, c = half the distance (m) between the foci of the ellipsoid.
a = semi-major axis (m) of the ellipsoid.
h = depth (m) below the surface.

The shape factor equation for an ellipsoid with its major axis perpendicular to the surface was given by Damkjaer and Korsbech (1992) and by van der Graaf and de Meijer (1992) as

$$S=\frac{8\pi c}{\ln\left[\frac{(a+c)(2h-c)}{(a-c)(2h+c)}\right]} \tag{2.13}$$

where, the parameters are the same as for equation (2.12).