CHAPTER - II

MEASUREMENT TECHNIQUES
2.1. INTRODUCTION

Several different techniques have been used to measure radon and its daughters activity inside the buildings. The methods include alpha particle counting of aerosol samples of filter paper using alpha scintillation detector (Toth 1972; Lucas, 1975; Thomas, 1972), ionization chamber (Stranden et al., 1979), surface barrier detector (Cliff, 1978; Bigu, 1986), thermoluminescent dosimeter (George and Breslin, 1978), activated C detector (Tianshan et al., 1987; Ren and Lin, 1986) and solid state nuclear track detector (Frank and Benton, 1977; Alter and Fleischer, 1981; Abu-Jarad and Fremlin, 1979). The salient features of SSNTD technique are described in Chapter III, here a brief discussion of other detectors is given.

2.1.1. Ionization Chamber

If a pair of electrodes is placed in and on opposite sides of a gas filled chamber, the ions formed by irradiation of the gas between the electrodes can be collected. As the potential across the electrodes increases, there is an increase in the number of ions that are collected before recombination occurs (Figure 2.1). These correlative increases continue until all the ions caused by the radiation
within the sensitive volume are collected (saturation voltage); then a further increase in the voltage has no effect upon the number of ions collected, and the ion current between the electrodes is constant (saturation current). The voltage region over which all the ions are collected is termed the ionization region.

At the end of the ionization region, the applied potential accelerates the ions sufficiently that they themselves start ionizing and cause secondary ions. The ions collected are both primary and secondary, and their total number at a given voltage is proportional to the number of primary ions. The constant of proportionality is called the gas amplification factor and varies from 1 to about $10^4$ across the proportionality region.

The voltage region immediately above the proportionality region shows a further increase in the total number of ions collected, but the strict proportionality to the number of primary ions no longer holds. This region is the region of limited proportionality and is ordinarily not used for measurements.

A voltage is reached where an avalanche of ions is formed and the number of ions collected is independent of the number of primary ions. This is the Geiger region and shows gas amplifications of about $10^6 - 10^9$, even at one voltage. Beyond the Geiger region lies a region of continuous discharge.
Ionization chamber operates in the ionization region and having a gas amplification factor of 2, therefore, the pulse from a $\beta$ or a $\gamma$-ray is very small indeed. These small pulses require such a very high amplification to activate a scaler for counting that an ionization counter is seldom used except only for $\alpha$, fission fragments and possibly deuterons. Ionization chamber, in simple form consists of a cylindrical conducting chamber containing a central electrode insulated from it (Figure 2.2). The gases used in it are usually air or hydrogen at atmospheric pressure, or greater pressure for $\gamma$-ray detection. For the detection of thermal neutrons, boron is introduced in the form of BF$_3$.

2.1.2. Scintillation Detector

This detector makes use of one of the several substances called scintillators which, when struck by a single particle, convert some of the energy received in the collision into a flash of visible light. The process is called the 'scintillation'. It is possible to watch a scintillator and count the flashes of light. Modern techniques, however, combine a scintillator with a photomultiplier (PM) tube, which converts the light flashes into an electric pulse. This pulse can be recorded electromechanically.

The chief advantages of a scintillation detectors are:
(i) It is very fast, i.e., it gives a pulse and comes back
Figure 2.1. Pulse-height vs applied voltage.  

Figure 2.2. Schematic diagram of an ionization chamber.
in original state to give another pulse in a very short time ($\sim 10^{-8}$ second).

(ii) In many applications it can be made to give a pulse size proportional to the energy lost by the incident particle in the scintillator.

(iii) It has higher efficiency of detection for gamma rays than gas filled detectors.

Figure 2.3 is a schematic diagram of a scintillation detector used in a counting system. The nuclear particle being detected produce a flash of light in the scintillator. By means of the pipe and reflector, a large fraction of the light is transmitted to the photocathode of the photomultiplier tube. The photoelectrons emitted at the photocathode are multiplied many times by the electron-multiplier section of the photomultiplier tube. The resulting current pulse produce a voltage pulse at the input of the preamplifier. This pulse, after passing through the discriminator and pulse shaper, is counted by the electronic counter. Alternatively, the electronic counter could be replaced by a differential pulse-height analyser, as in the scintillation type spectrometer.

A wide variety of scintillators are in use today. Some important ones are anthracene crystal, trans-stilbene crystal, some organic liquids, some gases, CsI, LiI(Sn), NaI(Tl),
Figure 2.3. Schematic diagram of a scintillation detector system.
ZnS(Ag), etc. The elements represented in brackets are called activators. They are present in a very small quantity. The presence of activator increase the efficiency of the scintillator. For γ-rays, NaI(Tl) crystals are used, for β-particles like polystyrene imprignated with anthracene are used and for α-particles, thin layer of ZnS, deposited on the photomultiplier or on a plastic surface is commonly used. For heavy particles a scintillator is 100% efficient and a resolution of about 4% is easily obtained with cesium iodide α-particles of energy 5 MeV.

2.1.3. Semiconductor Detectors

The development of semiconductor radiation detectors during the last two decade has completely revolutionized the field of nuclear radiation detectors. As an analogy, they can be considered as ionization chambers where the gaseous medium is replaced by a semiconducting solid. In a semiconductor detector, ionizing radiation produces ion pairs which are collected by the electric field applied externally, and the detector gives an electrical pulse which is proportional to the energy of ionizing radiation. Semiconductor radiation detectors offer many advantages over gass-filled or scintillation detectors, as for example (i) better resolution, (ii) better stability, (iii) windowless operation, and (iv) easier discrimination between different
Figure 2.4. Typical nuclear detection system for the detection of alpha particles by a silicon detector.
ionizing particles. A typical system of alpha particle spectrometer using silicon detector is shown in Figure 2.4. The basic features of two commonly used semiconductor detectors used in radon monitoring are discussed here.

2.1.3.1. Surface barrier detector

A silicon surface barrier detector has been very widely used for alpha particle detection. It consists of an extremely thin p-type layer produced on a high purity n-type silicon wafer, thus forming a large area p-n junction diode. A n-type silicon wafer is taken and one of its faces is etched with an acid and exposed to the air. An oxidation layer is formed on the etched surface and this layer acts like a very thin p-type layer. The detector then function like p-n junction. Good electrical contacts are provided by evaporating thin gold film (~40 µg.cm⁻²) on the back surface of n-type silicon layer as shown in Figure 2.5a. Surface barrier detectors of various types are now commercially available and they have surpassed other detectors for charged particle detection because of their long-term stability, small size, negligible window absorption and linear (pulse height versus energy) response over a wide range. The alpha particle spectra from radon and its daughters obtained by silicon barrier detection system (Bigu, 1986) is shown in Figure 2.6.
Figure 2.5 (a). Schematic diagram of a silicon surface barrier detector.

(b). Schematic diagram of a silicon p-n junction detector.
Figure 2.6. Alpha-particle spectrum from a radon sample using the SiB detection system. (Bigu, 1986).
2.1.3.2. **Diffused junction detector**

A diffused junction detector consists of a junction of p-type and n-type silicon. One starts with a slab of p-type silicon (doped with boron) and diffuses phosphorous into one face of the slab to make it n-type. Such a p-n junction, in the absence of applied electric field, will have many free holes in the left (p-type) side and many free electrons on the right (n-type) side. Under the influence of an externally applied field, electrons will be swept to the right and holes will be swept to the left. As a result, an intermediate volume around the inter-face will be cleared of carriers of both signs and this region is called the depleted region or depletion layer. The depletion layer offers ideal conditions for the detection of ionizing radiation because it has semiconductor material free of carriers. Passage of ionizing radiation (Figure 2.5b) will create hole-electron pairs which will be swept towards the electrodes by the applied field and pulse obtained to signal the passage of ionizing radiation. The alpha particle spectra from radon and its daughters obtained by diffused junction system (Bigu, 1986) is given in Figure 2.7.

2.1.4. **Thermoluminescent Detector (TLD)**

The phenomenon of thermoluminescence (TL) has been known since 1663. The essential features of the phenomenon of
Figure 2.7. Alpha-particle spectrum from a radon sample using the SiDJ detection system (Bigu, 1986).
Thermoluminescence are as follows: when radiation is incident on insulating crystals, some of the deposited energy is stored in the lattice at defect sites, colour centres, etc. Upon heating the crystals, this energy is released and fraction of it may be emitted as visible light, prior to the onset of black-body radiation. This phenomenon is known as thermoluminescence. Within certain limitations, the amount of light emitted is proportional to the radiation dose previously absorbed by the crystal.

The essential components of a TL detector are a heating system to increase the temperature of the phosphor (thermoluminescent material i.e. LiF: Mg, Ti; Li₂B₄O₇: Mn; CaSO₄: Mn; CaSO₄: Tm; CaSO₄: Dy) in a controlled manner; a device to detect the light output and convert it into an electrical signal; some means of measuring this signal; and finally a device for recording the signal.

Heating of the sample is usually achieved by ohmic heating, i.e. an electrical current is passed through a metal strip onto which the sample is placed. Alternatives include the use of streams of hot gas or of an infrared heating temperature. The temperature may be monitored by means of a thermo-couple, one junction of which is usually welded to the bottom of the heating strip. The signal from the thermo-couple can be fed back to a temperature controller which ensures that the temperature increases in the desired manner.
Heating may take place in air, but some phosphors are heated in oxygen-free \( \text{N}_2 \) or Ar in order to eliminate spurious sources of luminescence such as chemiluminescence or triboluminescence.

Light detection is usually performed with a photomultiplier (PM) tube. A lens is sometimes used to focus the emitted light onto the photocathode. In order to optimize the sensitivity of the system it is important to try to match the response of the photocathode to the wavelength of the TL emission. Even when no light is incident on the photocathode, a small current is produced owing to thermionic emission. For sensitive work it may be necessary to reduce this by cooling the PM tube.

In many systems the current from the PM tube is amplified by a dc ammeter (electrometer), and this current is used to derive the Y-axis mechanism of a chart recorder. A signal from the thermo-couple is then used to derive the X-axis mechanism of the recorder. An alternative method, often used in TL dosimetry, is to digitize the PM signal using a charge-to-pulse converter and then to count the resulting pulses. The total number of pulses counted is proportional to the integrated light output from the phosphor.

In order to check for changes in sensitivity of the TL reader, many devices, particularly commercial systems, incorporate a reference light source, and the signal produced
by this source is measured at frequent intervals. A schematic diagram of a TL readout system incorporating the above mentioned features is shown in Figure 2.8.

TLDs will readily respond to $\alpha$, $\beta$ and $\gamma$ radiations. The response to neutrons will be small unless a nuclide which yields ionizing particles upon interaction with incident neutrons can be incorporated into the phosphor. The TL output from a sample is usually directly related to the radiation dose absorbed by that sample. It can write:

$$1 = \alpha D + C \quad \ldots \quad (2.1)$$

where $\alpha$ is the TL output per unit dose and $C$ is the background level of TL, i.e. the TL obtained for zero dose. A good TL dosimetry phosphor should have a high sensitivity (i.e. a high value of $\alpha$), also the zero dose output should be low, particularly for use in personnel dosimetry where rather low doses need to be measured. It is also important that the glow curve peaks to be used for personnel dosimetry purposes should be stable against fading at normal ambient temperatures, i.e. $\sim 20$–$30^\circ$C. For environmental monitoring stability at temperatures up to $\sim 50^\circ$C may be necessary. On the other hand the glow peaks should not occur at such high temperatures that interference from black-body radiation becomes important.
Figure 2.8. Schematic diagram of a thermoluminescent detector.
2.2. **RADON MEASUREMENT USING SSNTD**

Solid state nuclear track detectors can be used both as active and passive devices for radon measurements. In active devices, airborne particulate are collected on a filter paper by sucking air through it by an air flow system and the track etch detector is placed in the immediate vicinity of the filter to record alpha particle emission from the collected daughter nuclei. Such a device was used by Abu-Jarad and Fremlin (1981) called a 'Working Level Monitor'. Several other active dosimeters are employed by many investigators (Frank and Benton, 1977) for radon measurements. These dosimeters have some disadvantages like dust clogging on the filter which causes a decrease in the air sample rate of the pump. These dosimeters can not be used for environmental monitoring on a large scale since some of them are laborious, time consuming and uneconomical.

Passive dosimeters do not rely on collecting the daughters. Their sensitivity results from contact with the ambient air and the recording of alpha particles emitted by air-borne radionuclei. Passive dosimeters have the advantage of relative simplicity of design when compared to the active dosimeters. Equipment size and costs are less and troubles with air pump and filter sampling are avoided. Track etch detectors have more favourable characteristics for use as passive dosimeters. The following configurations are generally
used by the workers for passive radon measurements with track etch detectors.

2.2.1. **Open Cup**

A plastic cup of 9.5 cm height, 6.8 cm diameter at the open mouth and 5.4 cm diameter at the bottom is fitted with a 0.8 x 2.5 x 0.2 cm plastic Track etch detector attached to the inside bottom. The open cup has been used for hundreds of thousands of soil gas measurements for mineral exploration and for earthquake prediction. This configuration measures the primary radon alpha particles originating within the cup and the RaA and RaC alpha particles coming from the plated-out nuclides on the walls of the cup. The track etch reading for an open cup is not only a function of radon and radon daughter activities but also of the plate-out characteristics of the ambient atmosphere.

2.2.2. **Membrane Cup**

The open mouth of the cup is covered with a semi-permeable plastic membrane (Ward, 1977; Fleischer et al., 1980). The membrane slows the normal diffusion of noble gases into the cup and thus discriminates against $^{220}\text{Rn}(T_{1/2}=55 \text{ Sec})$ while permitting 60-70% of $^{222}\text{Rn}(T_{1/2}=3.8 \text{ days})$ to enter the cup. This configuration is mainly used in exploration to
eliminate thoron interference and water condensation. The MEB configuration also prevents the entrance of radon daughters and is a 'radon only' device.

2.2.3. Filter Cup

The open mouth of the cup is covered with a hydrophobic microporous filter (Celanese Corp.; Celgard 4510) which permits complete infiltration of radon isotopes but discriminates against the non-gaseous radon daughters. Because of its higher sensitivity to radon, the FILT configuration is preferred to the membrane in all radon-only applications where thoron is not an important component.

2.2.4. Bare Detector

The detector is mounted flat on a card such that it views a hemisphere of air of radius at least 9.1 cm, the range of a $^{212}$Po alpha in air, or 6.9 cm, the range of the $^{214}$Po alpha (if only the $^{222}$Rn decay series is present). No surfaces should be closer than this range as daughter plate-out would then add an indeterminant alpha particle source to be registered on the detector. The bare detector measures radon plus ambient daughters and is sensitive to plate-out only with respect to daughters plating out directly on the detector. The track etch rading of a BARE detector will therefore, be a
function, not only of radon, but of the degree of equilibrium of radon with its daughters.

2.3. ALPHA PARTICLE DETECTION THEORY BY TRACK ETCH DETECTORS

The specific alpha activity can be calculated by using the relation (Kvasnicka, 1986)

$$\sigma = \frac{K \alpha m \ t}{C_{cm^2}}$$  \hspace{1cm} (2.2)

where $\sigma$ ($cm^{-2}$) is the measured track density, $\alpha m$ is the specific alpha activity ($Bq.Kg^{-1}$) and $t$ is the irradiation time. $K$ ($cm^{-2}.g$) correspond to the calibration factor.

Nuclear track etch detectors may be divided into two categories: the thin and thick nuclear track detectors.

2.3.1. Irradiation Geometry of Thick Source

A thick alpha particle source is characterised by its thickness, $h$, which is greater or equal to the range, $R_m$ ($g.cm^{-2}$), of the alpha particles of primary energies $E_0$ (MeV). The relationship describing the range, $R_m$ is

$$R_m = 0.32 \times 10^{-3} Z^{2/3} R_{air} (E_0)$$ \hspace{1cm} (2.3)

where $Z$ is the atomic number of the source material, $R_{air} (E_0)$
is the range of alpha particles of energy $E_0$ in the air.

The range of the alpha particles in the air is

$$R_{\text{air}} = 0.32 E^{1.5} \quad \ldots \quad (2.4)$$

The energetic and angle spectra of the alpha particles emitted by a surface unit of the thick source is given by (Abrosimov and Kocharov, 1962)

$$\frac{d^2 a_s}{dE \, d\cos \Theta} = \frac{a_m \, dR_m}{2 \, dE} \cos \Theta \quad \ldots \quad (2.5)$$

The energy dependence of this formula is visible if equation (2.3) is substituted for $R_m$ in equation (2.5)

$$\frac{d^2 a_s}{dE \, d\cos \Theta} = \frac{1}{2} a_m \, 0.32 \times 10^{-3} \, Z^{2/3} \, n \, A \, E^{n-1} \cos \Theta \quad \ldots \quad (2.6)$$

The detection sensitivity of any nuclear track detector depends on the alpha particle energy as well as on alpha particle incident angle $\Theta$, the detection sensitivity, $\eta(E, \Theta)$, of the detector is defined as the ratio of the through etched track density, $s(cm^{-2})$ to the fluence density of alpha particles fallen on the detector surface.

For a particular track detector response (or calibration factor) it is more convenient to simplify the experimental sensitivities, $\eta(E, \Theta)$ by the detection sensitivity function
\( \eta^* [E, \Theta(E)] \) = 
\[ \begin{align*}
\eta^* [E, \Theta(E)] &= 1 \text{ if } \Theta < \Theta_c(E) \\
\eta^* [E, \Theta(E)] &= 0 \text{ if } \Theta > \Theta_c(E)
\end{align*} \] ... (2.7)

where \( \Theta_c(E) \) is the critical angle of detection which is energy dependent.

In the case of thick alpha particle source irradiation geometry the critical angle for a certain alpha particle energy is defined by the following function normalization which uses the angle spectra of particles emitted from the thick source,

\[ \int_0^{\pi/2} \eta(E, \Theta) \sin \Theta \cos \Theta \, d\Theta = \frac{1}{2} \eta^* [E, \Theta(E)] [1 - \cos^2 \Theta_c(E)] \]

... (2.8)

2.3.2. Detector Response

Track density, \( \sigma \) (cm\(^{-2}\)), corresponding to the specific alpha activity, \( a_m \) (Bq.g\(^{-1}\)), of thick source is obtained by multiplication of equation (2.6) by the detection sensitivity function \( \eta(E, \Theta) \) and its subsequent integration

\[ \sigma = \int_{E_i}^{E_2} \int_0^{\Theta_c(E)} \eta(E, \Theta) \frac{1}{2} a_m \, 0.32 \times 10^{-3} \, Z^{2/3} \, n \, A \, E^{n-1} \cos \Theta \, dE \, d\cos \Theta \, d \theta \]

... (2.9)
where \( t(s) \) is the time of irradiation.

As for the theory of alpha activity detection by the track etch technique, its main building stone is the ratio of nuclear track density to the thick source surface alpha particle flux density. The constant ratio \( C \) can be derived as:

\[
C = \frac{\sum_{E_1}^{E_2} n E_{\gamma_1} \Theta \left(E_{\gamma_1}\right) \left[1 - \cos^2\Theta_{\gamma_1}\right] }{E_2^n - E_1^n} \Delta E
\]

(2.10)

Using equations (2.8) and (2.10) the track density in equation (2.9) becomes

\[
\sigma = \frac{a_m}{4} 0.32 \times 10^{-3} A Z_{ef}^{2/3} C (E_2^n - E_1^n) t
\]

(2.11)

if

\[
K = \frac{1}{4} 0.32 \times 10^{-3} A C (E_2^n - E_1^n)
\]

then

\[
\sigma = K Z_{ef}^{2/3} a_m t
\]

(2.12)

It is obvious from equations (2.11) and (2.12) that if the top energy detection threshold \( E_2 \) is lower than the primary alpha particle energy the response of the nuclear track detector to the specific alpha activity of the thick source does not depend on the alpha particle energy. The only factor
which has to be known or estimated is effective proton number of the source material \( Z_{ef}^{2/3} \) is computed from Bragg's relation

\[
z_{ef}^{2/3} = \sum w_i Z_i^{2/3}, \quad \ldots \quad (2.13)
\]

where \( w_i \) is the mass ratio of element \( i \) with the proton number \( Z_i \) in the sample.

2.4. **Radon Daughters Concentration**

Radon daughters concentration in terms of working level (WL) can be calculated by track etch detectors. For WL, one must know the degree of equilibrium between radon and its short-lived daughters. The equilibrium factor for radon daughters is expressed as:

\[
F_{Rn} = \frac{3700 \times C_{Rd}}{C_{Rn}} \quad \ldots \quad (2.14)
\]

where \( C_{Rd} \) is the potential alpha energy concentration in working levels (WL) of radon daughters, and \( C_{Rn} \) is the activity concentration of radon in Bq.m\(^{-3}\). A value of 0.45 has been adopted for calculating the radon concentration in the present study as reported by Subba Ramu et al. (1988) for Indian dwellings. The values of equilibrium factor for different countries reported by several investigators are presented in Table - 2.1.
<table>
<thead>
<tr>
<th>S.No.</th>
<th>Country</th>
<th>No. of Dwellings</th>
<th>Equilibrium factor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>F.R.G.</td>
<td>130</td>
<td>0.30</td>
<td>Killer and Folkerts (1984)</td>
</tr>
<tr>
<td>2.</td>
<td>Norway</td>
<td>25</td>
<td>0.50</td>
<td>Stranden et al., (1979)</td>
</tr>
<tr>
<td>4.</td>
<td>U.S.A.</td>
<td>21</td>
<td>0.60</td>
<td>George and Breslin (1978)</td>
</tr>
<tr>
<td>5.</td>
<td>Sweden</td>
<td>63</td>
<td>0.40</td>
<td>Swedjemark, (1978)</td>
</tr>
<tr>
<td>6.</td>
<td>Austria</td>
<td>250</td>
<td>0.62</td>
<td>Steinhausler (1980)</td>
</tr>
<tr>
<td>7.</td>
<td>U.K.</td>
<td>200</td>
<td>0.50</td>
<td>O'Riordan (1981)</td>
</tr>
<tr>
<td>8.</td>
<td>Finland</td>
<td>35</td>
<td>0.47</td>
<td>Makelainen (1980)</td>
</tr>
<tr>
<td>9.</td>
<td>Canada</td>
<td>-</td>
<td>0.38</td>
<td>Letourneau (1978)</td>
</tr>
</tbody>
</table>
Figure 2.9. The can geometry showing the position of the CK-39 detector.
2.5. **RADON EXHALATION RATE**

To measure the radon exhalation from building materials a 'Can Technique' was developed (Abu-Jarad et al., 1980; Abu-Jarad and Fremlin, 1983), in which a plastic track detector was placed in a small impervious vessel (Figure 2.9) which was sealed by plasticin to individual brick. In each 'Can' one plastic detector was kept at a distance 2 mm away from the surface of the wall or brick. The can dimensions were 4.5 cm in height and 7.0 cm in diameter used in present investigations. The area of the brick covered by the can was 38 cm$^2$. The detector was freely exposed to the emergent radon so that it could record the decay of radon in the whole volume of the can and that of $^{218}$Po and $^{214}$Po deposited on the inner walls of the can. This would reach an equilibrium concentration after a week or more; hence knowing the geometry of the system and time of exposure, the equilibrium activity of emergent radon could be obtained.

This technique can be used to find the radon exhalation rate from the building materials as well as the activity of radon inside the can. To measure the exhalation rate the following equation was used (Abu-Jarad et al., 1980):

$$\text{Ex} = \frac{C V \lambda/\Lambda}{\Gamma + \frac{1}{\lambda}(e^{-\lambda T} - 1)} \quad \cdots \quad (2.15)$$

where Ex is the radon exhalation per unit area and per unit
time (pCi.m\(^{-2}\).h\(^{-1}\)),

C: is the integrated radon exposure as measured by the plastic track detector (pCi.m\(^{-3}\).h),

T: is the exposure time,

V: is the volume of the can (m\(^3\)),

\(\lambda\): is the decay constant of radon (h\(^{-1}\)),

A: is the area covered by the can (m\(^2\)).

2.6. **RADON DAUGHTER EXPOSURE**

2.6.1. **Working Level (WL)**

The 'working Level' used for the radon daughter exposures now a days is a unit of radon daughter concentration. The WL unit was introduced in 1957 by the USPHS with the words 'a working level of 1.3\times10^5\) MeV of potential alpha energy per litre is suggested for radon daughter products (RaA, RaB and RaC).'

A 1968 wording for the definition of the working level unit could read: 'one WL is any combination of the short-lived daughters of radon (RaA, RaB, RaC and RaC') in one litre of air that will result in the ultimate emission by them of 1.3\times10^5\) MeV of alpha-ray energy' (Evans, 1969).

The WL unit was proposed about 1957, following recognition that the airborne radiation exposure of the human lung is
predominantly due to radon decay products RaA, RaB, RaC and RaC' filtered out of the respired air by the lung, and not to the radon gas. Accordingly, the WL unit takes no cognizance of the concentration of radon in the air. It is concerned with only the short-lived decay product of radon because a fraction (typically 20-45%) of all of these which are inhaled is retained in the lung. The WL is concerned with only the alpha radiation because the beta and gamma radiations emitted by RaB and RaC make a negligible contribution to the radiation dose in the lung, which is predominantly due to alpha particles emitted by RaA and RaC'. Every atom of the beta-particle emitters RaB and RaC will decay, most of them within minutes or hours, into RaC' and then will deliver the characteristic 7.68 MeV alpha particle of RaC'. Hence the alpha-particle energy associated with each atom of RaB and RaC is referred to in some definitions of WL as 'potential' alpha particle energy.

Each atom of RaA can deliver not only its own characteristic 6.00 MeV alpha-particle energy, but after each RaA atom has decayed through RaB and RaC into RaC' it can deliver the 7.68 MeV alpha particle of RaC' as well. Hence the 'ultimate' or 'potential' alpha particle energy associated with each atom of RaA is 13.68 MeV.

Each decaying atom of RaC' becomes an atom of the very long-lived nuclide RaB (T_{1/2} = 22 Yr.). During its long life
time a RaD atom is unlikely to remain in the lung, hence the alpha-particle energy of its subsequent decay product RaF (\(^{210}\text{Po}\)) is excluded from the WL definition, only the alpha-particle energy of the short-lived nuclides RaA and RaC' is included.

The numerical factor, \(1.3 \times 10^5\) MeV, is derived from the \(\alpha\)-decay energy ultimately delivered in the decay through RaC' of an initial mixture of 100 pCi each of RaA, RaB, RaC and RaC', that is of the short-lived decay products that are in radioactive equilibrium with 100 pCi of radon. The relevant numerical parameters are shown in Table 2.2. Note the fact that 100 pCi of RaA contributes only about 10% of the ultimate or 'potential' \(\alpha\)-particle energy in the equilibrium atmosphere visualized for the definition of WL. The largest contributor is RaB, which accounts for 52% of the ultimate \(\alpha\)-particle energy, even though RaB is a beta- and gamma-ray emitter with no alpha-particles of its own. The reason for the great importance of RaB lies in the fact that it has the longest half-period, and therefore it supplies the largest number of atoms per 100 pCi of activity. Analogously the atoms of the other beta- and gamma-ray emitter, RaC, supply 38% of the ultimate \(\alpha\)-particle energy, while 100 pCi of the actual \(\alpha\)-particle emitter RaC', contribute nearly nothing because of the short half-life and small population of atoms of RaC' in equilibrium air. From this data it can be seen that if
<table>
<thead>
<tr>
<th>Nuclide</th>
<th>4-particle energy (MeV)</th>
<th>Number of atoms per 100 pCi</th>
<th>Half-life</th>
<th>Ultimate 4-particle energy per atom (MeV)</th>
<th>Total ultimate 4-particle energy (MeV/100 pCi)</th>
<th>Fraction of total 4-energy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>222Rn</td>
<td>5.49</td>
<td>1.77 x 10^6</td>
<td>3.82 days</td>
<td>13.68</td>
<td>2.78 x 10^5</td>
<td>0.10</td>
<td>none</td>
</tr>
<tr>
<td>218Po</td>
<td>6.00</td>
<td>977</td>
<td>3.05 min</td>
<td>0.134 x 10^5</td>
<td>0.134 x 10^5</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>214Po</td>
<td>7.68</td>
<td>8580</td>
<td>26.80 min</td>
<td>0.659 x 10^5</td>
<td>0.659 x 10^5</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>214Bi</td>
<td>7.68</td>
<td>6310</td>
<td>19.70 min</td>
<td>0.485 x 10^5</td>
<td>0.485 x 10^5</td>
<td>0.38</td>
<td>0.38</td>
</tr>
<tr>
<td>214Po</td>
<td>7.68</td>
<td>10^-6 min</td>
<td></td>
<td>0.00 x 10^5</td>
<td>0.00 x 10^5</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.278 x 10^5</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>
C_2, C_3 and C_4 are the activity concentrations of RaA, RaB and RaC in pCi/1, then

\[
WL = \frac{134 \, C_2 + 659 \, C_3 + 485 \, C_4}{1.3 \times 10^5}
\]

or

\[
WL = 0.00103 \, C_2 + 0.00507 \, C_3 + 0.00373 \, C_4
\]

2.6.2. Working Level Month (WLM)

For radiation exposure, the working level unit of short-lived radon daughters concentration should be multiplied by an average breathing rate in l/min, by an average fractional retention in the lung, and by the duration of exposure. Actually the breathing rate and the fractional retention are generally omitted, and exposure is estimated as a product of WL and time. Most commonly the unit of time is an average month, that is 170 working hour. Then the exposure is expressed as 'Working Level Month', the product of WL and duration of exposure, normalized to a 1-month exposure basis.
REFERENCES


Frank A.L. and Benton E.V. (1977) Nucl. Track Detection 1, 149.


