CHAPTER 1

INTRODUCTION
Chapter-I

1. General

**Radiation is the signature of nucleus.** Radiation is energy traveling through space. Sunshine is one of the most familiar forms of radiation. It delivers light, heat and suntans. We control our exposure to it with sunglasses, shade, hats, clothes and sunscreen. There would be no life on earth without lot of sunlight but we have increasingly recognized that too much of it on our persons is not a good thing. Sunshine consists of radiation in a range of wavelengths from long-wave infra-red to short-wavelength ultraviolet. Beyond ultraviolet are higher energy radiations which are used in medicine and which we all get in low doses from space, from the air and from the earth. Collectively we can refer to these kinds of radiation as ionizing radiation. It can cause damage to matter, particularly living tissues. At high levels it is, therefore, dangerous so it is necessary to control our exposure to radiation. Radiations are of two types:

1. Natural Radiation
2. Man-made Radiation

Natural radiations that are exposing the inhabitants can be further divided in two types:

(i) Terrestrial radiation
(ii) Extraterrestrial radiation

Terrestrial radiation is emitted by natural radioactive materials present in earth’s crust. These include uranium, thorium and their daughter products radon and thoron. Radiations coming from outer space in the form of cosmic rays are called extraterrestrial radiations. These radiations irradiate human beings internally as well as externally. Exposures from sources outside the body constitute the external exposure and from radionuclides taken inside the body through inhalation or ingestion constitute the internal exposure. Table-1 presents the annual effective doses to adults from natural sources (UNSCEAR, 1993).
It can be observed that radioactive elements form a major source of natural radiation and the natural radioactivity has become a major concern for mankind. Natural radioactivity is widespread in the earth’s environment and it exists in various geological formations in solids, plants, water and air. Uranium is a naturally occurring radioactive element present in trace amounts throughout the earth’s crust. Radon is a progeny of uranium decay series formed from radioactive decay of radium in the environment, soil, groundwater, oil and gas deposits and is the primary source of naturally occurring α-radiation present everywhere in the environment in varying concentration. Radon is the heaviest known gas, nine times heavier than air and is the only gas in the long decay chain of heavy metal elements (Ibrahiem et al., 1993; Malance et al., 1996; Aly Abdo et al., 1999).

Public interest and concern with the radioactivity in the environment is increasing in recent times although the phenomenon of radioactivity was discovered in the starting of 20th century by Henry Becquerel when he was carrying out experiments connected with X-rays, using uranium salts. Later, investigation on radioactivity was carried out by the Curies using minerals, particularly pitchblende which was many times more radioactive than pure uranium salts. Following this, radioactivity was discovered in

<table>
<thead>
<tr>
<th>Source</th>
<th>Annual effective dose (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extraterrestrial radiation</strong></td>
<td></td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>0.38 (16.1%)</td>
</tr>
<tr>
<td>Cosmogenic radio nuclide</td>
<td>0.01 (0.42%)</td>
</tr>
<tr>
<td><strong>Terrestrial radiation</strong></td>
<td></td>
</tr>
<tr>
<td>External exposure</td>
<td>0.46 (19.5%)</td>
</tr>
<tr>
<td>Internal exposure</td>
<td>0.23 (9.77%)</td>
</tr>
<tr>
<td><strong>Radon and its progeny</strong></td>
<td></td>
</tr>
<tr>
<td>Inhalation</td>
<td>1.2 (51.0%)</td>
</tr>
<tr>
<td>Ingestion</td>
<td>0.005 (0.21%)</td>
</tr>
<tr>
<td><strong>Thoron and its progeny</strong></td>
<td></td>
</tr>
<tr>
<td>Inhalation</td>
<td>0.07 (3.0%)</td>
</tr>
</tbody>
</table>
several materials, including Potassium, Samarium etc. The fundamental laws concerning radioactivity were also formulated in due course.

1.1 Radon

Radon is a gaseous radioactive element having the symbol Rn, the atomic number 86, an atomic weight of 222, a melting point of -71°C, a boiling point of -62°C and depending on the source, there are between 20 and 25 isotopes of radon (20 cited in the chemical summary, 25 listed in the table of isotopes). It is an extremely toxic, colorless and odorless gas. It can be condensed to a transparent liquid and to an opaque, glowing solid. It is derived from the radioactive decay of radium, used in cancer treatment, as a tracer in leak detection and in radiography. It has been identified as a leading cause of lung cancer.

Natural Radon, however, consists of three isotopes, one from each of the three natural radioactive disintegration series of uranium, thorium, and actinium (Figures 1-3).

The longest lived isotope, $^{222}\text{Rn}$ (alpha emitter of 3.82 days half-life), discovered in 1900 by the German chemist Friedrich E. Dorn, arises in the uranium series. The name radon is sometimes reserved for this isotope in order to distinguish it from the other two natural isotopes, called 'thoron' and 'actinon' because they originate from the thorium and actinium decay series, respectively. The gas thoron, $^{220}\text{Rn}$ (alpha emitter of 55.6 second half-life), was first observed in 1899 by the English scientists R. B. Owens & Ernest Rutherford who noticed that some of the radioactivity of thorium compounds could be blown away. The gas actinon, $^{219}\text{Rn}$ (alpha and gamma emitter of 3.92 second half-life), was found in 1904 independently by Friedrich O. Giesel & Andre-Louis Debierne, to be associated with actinium. Tables -2 and 3 show the decay chain of $^{222}\text{Rn}$ and $^{220}\text{Rn}$.
Figure 1: U-238 Decay Series (Adopted from Radiation Safety Division, Bhabha Atomic Research Centre, Mumbai, India)
**Figure 2**

Th decay series (Adopted from Radiation Safety division Bhabha Atomic Research Centre, Mumbai India)

**232 Th DECAY SERIES (4n)**

With product half life, gamma energy (in keV), alpha and beta energy (in MeV) and yields (in %)

- **232 Th** → **228 Ra**
  - α (87.1 y, 111.1 y)
  - β (57.7 keV, 53.0 keV, 13.5 keV, 5.0 keV)

- **228 Ra** → **224 Ra**
  - α (16.5 y, 2.1 y, 0.24 y)
  - β (84.4 keV, 71.6 keV, 62.0 keV)

- **224 Ra** → **220 Rn**
  - α (1.1 y, 2.1 y, 0.45 y)
  - β (52.7 keV, 39.3 keV, 22.0 keV)

- **220 Rn** → **216 Po**
  - α (9.9 y, 2.9 y, 0.64 y)
  - β (13.5 keV, 9.1 keV, 5.9 keV)

- **216 Po** → **212 Bi**
  - β (1.05 keV, 0.69 keV)
  - γ (73.3 keV, 55.6 keV)

- **212 Bi** → **208 Pb**
  - β (1.1 y, 0.10 y, 0.05 y)
  - γ (73.3 keV, 55.6 keV)

- **208 Pb** → **Stable**
  - β (0.10 y, 0.05 y)
  - γ (73.3 keV, 55.6 keV)

**Significant gamma energies are given in boxes**

- 74.8 keV, 77.1 keV, 115.2 keV, 136.6 keV, 260.5 keV, 415.2 keV
- 51.7 keV, 55.6 keV, 73.3 keV, 92.2 keV, 115.2 keV, 136.6 keV, 260.5 keV, 415.2 keV
- 2.04 MeV, 3.01 MeV, 1.23 MeV
- 80.5 MeV, 90.6 MeV, 100.9 MeV, 157.6 MeV, 165.1 MeV, 200.5 MeV, 226.4 MeV, 305.5 MeV

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*Note: The diagram illustrates the decay series of Th-232 with specific radionuclides and their properties.*
Figure-3

$^{235}$U decay series (Adopted from Radiation Safety division Bhabha Atomic Research Centre, Mumbai India)
### Table-2

The decay products of $^{222}\text{Rn}$, a gaseous member of the naturally occurring radioactive series $^{238}\text{U} \rightarrow ^{206}\text{Pb}$

<table>
<thead>
<tr>
<th>Traditional Name</th>
<th>Isotope</th>
<th>Half-Life</th>
<th>Radiations</th>
<th>$\alpha$-particle decay energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radon</td>
<td>$^{222}\text{Rn}$</td>
<td>3.82 days</td>
<td>$\alpha$</td>
<td>5.45</td>
</tr>
<tr>
<td>Radium A</td>
<td>$^{218}\text{Po}$</td>
<td>3.05 minutes</td>
<td>$\alpha$</td>
<td>6.00</td>
</tr>
<tr>
<td>Radium B</td>
<td>$^{214}\text{Pb}$</td>
<td>26.8 min</td>
<td>$\beta, \gamma$</td>
<td>-</td>
</tr>
<tr>
<td>Radium C</td>
<td>$^{214}\text{Bi}$</td>
<td>19.8 min</td>
<td>$\beta, \gamma$</td>
<td>-</td>
</tr>
<tr>
<td>Radium C'</td>
<td>$^{214}\text{Po}$</td>
<td>164 $\mu$s</td>
<td>$\alpha$</td>
<td>7.69</td>
</tr>
<tr>
<td>Radium D</td>
<td>$^{210}\text{Pb}$</td>
<td>22.3 years</td>
<td>$\beta, \gamma$</td>
<td>-</td>
</tr>
<tr>
<td>Radium E</td>
<td>$^{210}\text{Bi}$</td>
<td>5.01 days</td>
<td>$\beta$</td>
<td>-</td>
</tr>
<tr>
<td>Radium F</td>
<td>$^{210}\text{Po}$</td>
<td>138.4 days</td>
<td>$\alpha$</td>
<td>5.30</td>
</tr>
<tr>
<td>Radium G</td>
<td>$^{206}\text{Pb}$</td>
<td>stable</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

### Table-3

The decay products of $^{220}\text{Rn}$, a gaseous member of the naturally occurring radioactive series $^{232}\text{Th} \rightarrow ^{208}\text{Pb}$

<table>
<thead>
<tr>
<th>Traditional Name</th>
<th>Isotope</th>
<th>Half-Life</th>
<th>Radiations</th>
<th>$\alpha$-particle decay energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thoron</td>
<td>$^{220}\text{Rn}$</td>
<td>55.6 s</td>
<td>$\alpha$</td>
<td>6.29</td>
</tr>
<tr>
<td>Thorium A</td>
<td>$^{216}\text{Po}$</td>
<td>0.15 s</td>
<td>$\alpha$</td>
<td>6.78</td>
</tr>
<tr>
<td>Thorium B</td>
<td>$^{212}\text{Pb}$</td>
<td>10.64 h</td>
<td>$\beta$</td>
<td>-</td>
</tr>
<tr>
<td>Thorium C</td>
<td>$^{212}\text{Bi}$</td>
<td>60.55 min</td>
<td>{$\beta$ (66.3%) (to $^{212}\text{Po}$), $\alpha$ (33.7%) to ($^{208}\text{Ti}$)}</td>
<td>6.1</td>
</tr>
<tr>
<td>Thorium C'</td>
<td>$^{212}\text{Po}$</td>
<td>0.3 $\mu$s</td>
<td>$\alpha$ (to $^{208}\text{Pb}$)</td>
<td>8.78</td>
</tr>
<tr>
<td>Thorium D</td>
<td>$^{208}\text{Ti}$</td>
<td>3.05 min</td>
<td>$\beta$ (to $^{208}\text{Pb}$)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$^{208}\text{Pb}$</td>
<td>Stable</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

$\alpha = \text{alpha emission, } \beta = \text{beta emission, } \gamma = \text{gamma emission}$
In each decay chain the radon isotope results from an alpha emission by radium. Hence one may rigorously infer that radon production is in proportion to the radium present in the earth. Usually, $^{222}$Rn and $^{219}$Rn are produced in uranium rich areas whereas $^{220}$Rn in thorium rich areas. The relative importance of the three radon isotopes increases with their mean lives and relative abundance. $^{219}$Rn is the shortest lived and is virtually always produced in much smaller amounts than $^{222}$Rn, since the natural $^{235}$U/$^{238}$U ratio of these ultimate progenitors is 0.00719. Hence $^{219}$Rn is largely ignored. $^{220}$Rn too is short lived relative to $^{222}$Rn and consequently moves a much smaller distance from its source than $^{222}$Rn. In air, for diffusion constant of 0.1 cm$^2$/s$^{-1}$, the mean distances of diffusive motion are 2.2 m for $^{222}$Rn and 0.029 m for $^{220}$Rn. Hence in circumstances where signals from relatively distant resources or processes in the earth are sought, $^{222}$Rn is by far the dominant nuclide and $^{220}$Rn provides only uninteresting local background that one wants to exclude during detection.

Health hazards of radon and thoron are not primarily due to these isotopes directly but due to their short lived daughters that can be inhaled. Because radon is a noble gas with a life time that is long relative to breathing times, most of it that is inhaled is exhaled again rather than decaying or becoming lodged in the lungs and later decaying. In contrast, the immediate, promptly decaying daughters of $^{222}$Rn ($^{218}$Po, $^{214}$Pb, $^{214}$Bi and $^{214}$Po), which are the part of a condensed phase, attach themselves to aerosols and can be inhaled. These daughter products then get deposited on epithelial surfaces within the lung and decay out shortly. When radon decays to form its progeny ($^{218}$Po and $^{214}$Po), they are electrically charged and can attach themselves to tiny dust particles, water vapours, oxygen, trace gases in indoor air and other solid surfaces. These daughter products remain air borne for a long time. The dust particles (aerosols) present in the atmosphere can easily be inhaled into the lung and can adhere to the epithelial lining of the lung, thereby irradiating the tissue by $\alpha$-particles. Bronchial stem cells and secretion cells in airways are considered to be the main target cells for the induction of lung cancer resulting from radon exposure. The radon contributors to the human exposure are shown in Figure - 4. Since the longest lived of the four daughter products, $^{214}$Pb has a half life of less than 27 minutes, the whole sequence of decay can be completed before.
the normal clearance processes of the lung. As a result the sensitive surfaces of the bronchi are irradiated by the decay products. The most energetic and destructive of these are the heavily ionizing short range alpha particles from the polonium isotopes $^{214}\text{Po}$ and $^{218}\text{Po}$. 

![Figure - 4 Radon contributors to human exposure](image)
1.2 Thoron and its progeny

Because of its short half life (55 sec) thoron concentrations in a room generally fall off exponentially with distance from its source which is usually internal room surfaces. Due to this, for comparability of thoron measurements it may be necessary for the measurement protocol to include a precise statement on measuring the thoron concentration at some specific distance (x-cm) from the source or as close as practicable to walls and other room surfaces. This latter recommendation has particular relevance to human exposure assessment as during sleep people generally breathe air close to walls. In this situation the lung dose due to the thoron gas itself may even be greater than that from the inhalation of thoron progeny. These may typically be present in the room air at much lower concentrations and will be much more uniformly distributed in the air than the thoron gas itself. Since the correlation between thoron gas and its progeny $^{212}$Pb cannot always be ensured, a correct estimate of the dose may even require measurement of both the gas itself and its progeny. In many investigations, however, the particular scope in mind may only require one type of measurement to be made. Nevertheless, further studies on the spatial and temporal distributions of thoron and its progeny are needed in order to establish reliable protocols for measurements in the interests of comparability of measurement data. For thoron measurements in water, as in the case of radon in water measurements, it is recommended that procedures should be adapted to reduce thoron losses during sampling.

1.3 Sources of indoor radon

Main sources of radon in the environment are due to the ambient levels produced by the widespread distribution of uranium and its decay products in the soil. Every square mile of source soil, to the depth of six inches, contains approximately one gram radium which releases radon in small amounts to atmosphere (Weast, 1980). The main contributors to the indoor radon levels are as follows:
1.3.1 Soil

Soil is the primary source of radon in indoor atmosphere where it is produced by the radioactive decay of radium, found in trace quantities. Soil and rock have concentrations of elements in the uranium and thorium series which vary widely. Estimated average concentrations of uranium and thorium are 25 Bq kg$^{-1}$ each in soil (UNSCEAR, 1986). Radon gas which is chemically inert, then transport through soil and into dwellings through cracks and other openings in the building materials directly. This may be the possible mechanism for the radon transport into the buildings. There are two mechanisms by which radon enters from soil: the first is the movement of radon by molecular diffusion through the air pore system in soil, where the soil is assumed to be relatively stationary and the second significant mechanism of entry is the pressure driven flow which is created by forces that drive air infiltration into buildings viz. the thermal stack effect and wind loading on the building shell. Fractures and holes in building foundations as small as 0.5 mm are enough to allow convective migration and gas transport.

1.3.2 Building materials

Building materials may be an important source of indoor radon when the radium content of materials is elevated above normal values and emanation rates are very high. Building materials are more easily characterized as indoor radon source than the soil or rocks which constitute building materials. Measurement of emanation rates or ratios for soil and rock performed both in connection with interests in uranium exploration and for the use of radon as an atmospheric tracer, have been reviewed in detail by Tanner (1987). Ingersoll (1983) has measured the radon emanation rates in a number of building materials. The results of that study indicate that strongest radon emanator is concrete and weakest, the wood. Measurements of the emanation in concrete components revealed that sand is the strongest emanator and cement, the weakest. Within a given type of building material the radon emanation rate varied substantially from one sample to another sample. Even though uranium content of materials might be approximately the same, the radon emanation rates might differ widely, for example granite and rocks used for heat
storage have a higher uranium concentration than concrete and yet they exhale radon at lower rates. It was concluded that the physical properties of the various classes of materials account for the wide dispersion of escape to production ratios and thus radon exhalation rate measurements for various materials are very important.

1.3.3 Water

Radon can be transferred to the indoor air through the use of water during typical house holds activities like showering, laundering, dishwashing etc. The amount of radon in water at the point of use depends primarily on two factors, i.e., the local geologic character; and type of water supply. The occurrence of radon in water is controlled by the chemical concentration of radium in the host soil or rock and by emissivity of radon into the water. The physical condition of the rock matrix appears to play an important role in radon release into water. Experimental and theoretical considerations indicate that diffusion along micro crystalline imperfections dominates the release of radon into the surrounding water (Hess et al., 1985). Highest levels were observed in drilled wells; especially in granite area and lower concentrations were found in water from dug wells and surface water sources.

It is likely that, in normal circumstances, radon escaping from groundwater in the soil does not give rise to higher concentration in buildings. The reason is partly that concentrations in the soil air are normally as high as in groundwater, partly that the water content in the soil horizon immediately above the water table is so great that diffusion through the soil is prevented. Only if the radon concentration in the groundwater is much higher than that in the soil gas, and if the groundwater is in motion or flows out at the surfaces, it is likely that sufficient radon will be released to affect its concentration in the building.

1.3.4 Meterological Parameters

Varying environmental conditions have been found to affect the rate of radon emanation. Jonassen and McLaughlin (1977) found pressure dependence for long term emanation rates from concrete walls. However, Ingersoll (1981) did not observe any detectable increase in emanation rate with a pressure drop down to 20 inches of mercury
for 2 to 3 days. Similarly the effect of temperature is uncertain. Stranden et al., (1984) measured increased radon exhalation from concrete samples with increase in temperature. However, Auxier et al., (1973) found that within the normal range of home temperature, the temperature of the concrete is not a sensitive parameter and has negligible effects on the emanation rate.

Moisture has been found to have significant effect on the radon emanation rate. Auxier et al, (1973) reported that if moisture increases from the normal 2-4% by weight to 6-8 % by weight, the emanation rate may increase by 10-20%. Ingersoll (1981) found an even greater effect. By increasing the moisture of the concrete sample by 4% (weight) there was an increase in radon emanation of about 100%.

1.4 Radon induced health effects

The exposure to radon and its progeny can give rise to many health related malignancies. While the association of radon to lung cancer is well known, several studies have related radon to risk of leukemia, melanoma, cancer of kidney and prostate. A brief introduction of various health effects of radon is being given here.

1.4.1 Lung cancer

Radon is the second leading cause of lung cancer (Sevc et al., 1976). The main epidemiological evidence for role of radon in causing lung cancer comes from the various studies on miners in different countries. Some of the results of these studies are summarized in Table 4&5. Most of these studies consistently show an increased risk of lung cancer of miners. Though it is believed that in some of these studies, elements other than radon and thoron, such as arsenic and silica dust present in mine atmosphere might have influenced the results. But in other cases where radon and progeny exposure has been low, little or no excess of lung cancer has been observed. Therefore, taking these studies together, the role of radon as a cause of lung cancer in miners is well supported by epidemiological observations. As regards the indoor radon exposure and lung cancer risk for general population, several studies have been carried out since 1979. Most of these studies have been of case-control type. Results of these studies are given in Table-6 and
most of these suggest the effect of radon regarding the lung cancer. Svensson et al., (1987) clearly established the association of oat-cell cancers in women with indoor radon. Another study (Damber and Larsson 1987) also established predominance of squamous and small cell carcinomas in people living in non-wooden houses than those living in wooden houses. A recent nation wide-control study has been reported from Sweden (Pershagen et al., 1984).

Radon and its progeny were regarded as radiation health hazards encountered only in the mining and processing of uranium ores. This notion has changed markedly as a result of increasing efforts made in many States to measure radon in dwellings, mines other than uranium mines and workplaces suspected of having high atmospheric radon levels. In temperate and cold regions, energy conservation measures have been taken in buildings that have resulted in reduced ventilation rates and increased radon concentrations, particularly in winter months. This rise in the indoor air concentration of radon was recognized as a radiation health hazard, potentially causing an increase in the incidence of lung cancer. Radon thus became a concern not only in underground mines but also in buildings in areas with elevated levels of radon in soil gas or in buildings constructed with materials containing significant levels of radium. According to an assessment by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000) environmental radon accounts for half the human exposure to radiation from natural sources.
<table>
<thead>
<tr>
<th>Type of Mining, Country</th>
<th>Exposure or concentration mean values</th>
<th>Person-years</th>
<th>Lung Cancer deaths Observed</th>
<th>Expected SMR</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal, U.S.A.</td>
<td>0.05-0.40 WL</td>
<td>23862</td>
<td>47</td>
<td>16.1</td>
<td>Wagoner et al., 1963; Waxweiler et al., 1981</td>
</tr>
<tr>
<td>Uranium, U.S.A</td>
<td>821 WLM</td>
<td>62556</td>
<td>185</td>
<td>38.4</td>
<td>Lundin et al., 1971; Placek et al., 1983</td>
</tr>
<tr>
<td>Uranium, Czechoslovakia Tin, U.K.</td>
<td>289 WLM</td>
<td>56955</td>
<td>211</td>
<td>42.7</td>
<td>Kunz et al., 1978</td>
</tr>
<tr>
<td>Tin, U.K.</td>
<td>1.2-3.4 WL</td>
<td>27631</td>
<td>28</td>
<td>13.27</td>
<td>Fox et al., 1981</td>
</tr>
<tr>
<td>Iron, Sweden</td>
<td>0.5 WL</td>
<td>10230</td>
<td>28</td>
<td>6.79</td>
<td>Jorgesen, 1984</td>
</tr>
<tr>
<td>Iron, Sweden</td>
<td>81.4 WL</td>
<td>24083</td>
<td>50</td>
<td>12.8</td>
<td>Radford &amp; Renard, 1984</td>
</tr>
<tr>
<td>Fluorspar, Canada</td>
<td>Up to 2040 WLM</td>
<td>37730</td>
<td>104</td>
<td>24.38</td>
<td>Morrison et al., 1988</td>
</tr>
<tr>
<td>Uranium Canada</td>
<td>40-90 WLM</td>
<td>202795</td>
<td>82</td>
<td>56.9</td>
<td>Muller et al., 1985</td>
</tr>
<tr>
<td>Uranium Canada</td>
<td>17 WLM</td>
<td>118341</td>
<td>65</td>
<td>34.24</td>
<td>Howe et al., 1986</td>
</tr>
<tr>
<td>Iron, U.K.</td>
<td>0.02-3.2 WL</td>
<td>17156</td>
<td>39</td>
<td>25.50</td>
<td>Kinlen &amp; Willows, 1988</td>
</tr>
<tr>
<td>Pyrite, Italy</td>
<td>0.12-0.36 WL</td>
<td>29577</td>
<td>47</td>
<td>1.1</td>
<td>Battista et al., 1988</td>
</tr>
<tr>
<td>Uranium-Non smokers, U.S.A.</td>
<td>720 WLM</td>
<td>7861</td>
<td>14</td>
<td>1.1</td>
<td>Roscoe et al., 1989</td>
</tr>
<tr>
<td>Tin, U.K.</td>
<td>10 WLM/year for 30 years</td>
<td>-</td>
<td>15</td>
<td>3.4</td>
<td>Hodgson &amp; Jones, 1990</td>
</tr>
<tr>
<td>Tin, China</td>
<td>2.3-0.9 WL by time</td>
<td>175143</td>
<td>981</td>
<td>-</td>
<td>Xiang-Zhen et al., 1993</td>
</tr>
</tbody>
</table>
Table-5
Main results of some case–control studies of lung cancer in miners exposed to radon and progeny (adopted from Axelson, 1995)

<table>
<thead>
<tr>
<th>Type of mining</th>
<th>Exposure or concentration mean values</th>
<th>Number of cases to control</th>
<th>Number of exposed cases Ratio</th>
<th>Rate ratio, max</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron, Sweden</td>
<td>0.1-0.2 WL</td>
<td>604/(467 × 2 + 137)</td>
<td>20</td>
<td>7.3</td>
<td>Damber &amp; Larsson, 1982</td>
</tr>
<tr>
<td>Iron, Sweden</td>
<td>0.3-1.0 WL</td>
<td>38/403</td>
<td>33</td>
<td>11.5</td>
<td>Edling &amp; Axelson, 1983</td>
</tr>
<tr>
<td>Uranium U.S.A.</td>
<td>30-2, 698 WLM</td>
<td>32/64</td>
<td>23</td>
<td>Infinite</td>
<td>Samet et al., 1984</td>
</tr>
<tr>
<td>Uranium U.S.A.</td>
<td>472 WLM in cases</td>
<td>65/230 (Nested)</td>
<td>All</td>
<td>1.5% WLM</td>
<td>Samet et al., 1989</td>
</tr>
<tr>
<td>Tin, China</td>
<td>515 WLM in cases</td>
<td>107/101</td>
<td>7</td>
<td>20.0</td>
<td>Qia et al., 1989</td>
</tr>
<tr>
<td>Tin, China</td>
<td>373 WLM</td>
<td>74/74</td>
<td>5</td>
<td>(13.2) 1.7 % per WLM</td>
<td>Lubin et al., 1990</td>
</tr>
</tbody>
</table>
## Table-6
Main results of some case–control studies of lung cancer in miners exposed to radon and progeny (adopted from Axelson, 1995)

<table>
<thead>
<tr>
<th>References</th>
<th>Number of cases to control</th>
<th>Rate ratio</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axelson, et al., 1979</td>
<td>37/178</td>
<td>1.8</td>
<td>Significant trend; crude exposure assessment</td>
</tr>
<tr>
<td>Lanes et al., 1982</td>
<td>50/50</td>
<td>2.1</td>
<td>Published abstract only</td>
</tr>
<tr>
<td>Edling et al., 1984</td>
<td>23/303</td>
<td>Up to 4.3</td>
<td>Special account for geology and radon emanation</td>
</tr>
<tr>
<td>Pershagen et al., 1984</td>
<td>Two sets of 30/30</td>
<td>-</td>
<td>Significantly high exposure for smoking cases</td>
</tr>
<tr>
<td>Damber &amp; Larsson, 1987</td>
<td>604/(467 × 2 + 137)</td>
<td>Up to 2.0</td>
<td>For more than 20 years non-wooden houses</td>
</tr>
<tr>
<td>Svensson et al., 1987</td>
<td>292/584</td>
<td>2.2</td>
<td>Women with Oat cell cancer</td>
</tr>
<tr>
<td>Lees et al., 1987</td>
<td>27/49</td>
<td>Up to 11.9</td>
<td>Risk of 11.9 for 10 WLM</td>
</tr>
<tr>
<td>Axelson, et al., 1988</td>
<td>177/673</td>
<td>Upto 2.0</td>
<td>Clear effect for rural residents only</td>
</tr>
<tr>
<td>Svensson et al., 1989</td>
<td>210/209 +191 (Hospital)</td>
<td>Up to 1.8 (in middle exp. Category)</td>
<td>Females; rare ratio 3.1 for small cell cancers</td>
</tr>
<tr>
<td>Schoenberg et al., 1989</td>
<td>433/402</td>
<td>Up to 1.7 (small cell)</td>
<td>Females in high risk area (China), slight effect for small-cell cancers only</td>
</tr>
<tr>
<td>Blot et al., 1990</td>
<td>308/356</td>
<td>Up to 7.2</td>
<td>Females; little effect but in higher exposure category</td>
</tr>
<tr>
<td>Ruosteenoja, 1991</td>
<td>238/434</td>
<td>Up o 1.9</td>
<td>Lower effect at the highesty exposure</td>
</tr>
<tr>
<td>Pershagen et al., 1992</td>
<td>210/209 + 191 (Hospital)</td>
<td>1.7 as average</td>
<td>Rate ratio up to 21.7 for smokers and high exposure</td>
</tr>
</tbody>
</table>
1.5 How Does Radon Get Into Homes?

Radon is a radioactive gas. It comes from the natural decay of uranium that is found in nearly all soils. It typically moves up through the ground to the air above and into the home through cracks and other holes in the foundation. Home traps radon inside where it can build up. Any home may have a radon problem. This means new and old homes, well-sealed and drafty homes and homes with or without basements. Radon from soil gas is the main cause of radon problems. Sometimes radon enters the home through well water. In a small number of homes, the building materials can give off radon too. However, building materials rarely cause radon problems by themselves. Radon gets in through:

1. Cracks in solid floors
2. Construction joints
3. Cracks in walls
4. Gaps in suspended floors
5. Gaps around service pipes
6. Cavities inside walls
7. The water supply
1.6. Risks of radon exposure at workplaces

Since radon is a gas, it may escape into the air from the material in which it is formed and since uranium and radium occur widely in soil, rocks and water, radon gas is ubiquitous outdoors as well as indoors, the air that we inhale contains radon. Radon decays to a number of short lived decay products ("progeny") that are themselves radioactive. These may attach to available aerosol particles in the atmosphere, thereby forming what are termed 'attached' radon progeny whose size will reflect the size distribution of the ambient aerosol. Those radon progeny that do not attach to aerosols remain in what is termed the 'unattached' state, and these unattached particles are usually found to be in the approximate size range of 0.5–5 nm. If inhaled, both unattached and attached radon progeny may deposit in the lungs and irradiate lung tissue as they decay.

In lung dosimetry models in which deposition sites of radioactive material and locations of target cells are taken into account, the risk per unit of inhaled radioactive material is considered to be much greater for radioactive material in the unattached state than for radioactive material in the attached state (NRC, 1988). While it is the radon progeny rather than radon gas itself that presents the greater risk, the word 'radon' is also used generally as a convenient shorthand for both the gas and its progeny. Radon has been recognized as a radiation hazard causing excess lung cancer among underground miners (ICRP, 1981). Consequently radon has been classified as a human carcinogen. Since the 1970s evidence has been increasing that radon can also represent a health hazard in non-mining environments (ICRP, 1993). Since environmental radon on average accounts for about half of all human exposure to radiation from natural sources (UNSCEAR, 2000), increasing attention has been paid to exposure to radon and its associated health risks in both industrialized and developing countries. One particularly important factor is the radioactive equilibrium between radon and its progeny. This is expressed as the ratio of the total alpha particle energy that the particular mixture of radon and its progeny will emit to the total energy emitted by the same concentration of radon gas in perfect equilibrium with its progeny. For most indoor environments of interest, the state of equilibrium between radon and its progeny is fairly constant, and this ratio is usually taken to be 40–50%. However, depending on conditions (especially
ventilation conditions), some workplaces may exhibit values of this ratio down to 20% or up to 80%. For these more extreme cases it may be desirable to modify some of the information in this report relating to radon concentrations. Much of the discussion in the scientific literature on indoor radon is expressed in terms of radon concentrations rather than concentrations of radon decay products, for two principal reasons. Firstly it is much easier to measure concentrations of radon gas than concentrations of its progeny, especially for long term measurements. The second reason is that, owing to the higher dose conversion factor of the unattached fraction of radon progeny in lung dosimetry models and the inverse relationship between the unattached fraction and the equilibrium factor in indoor air, the effective dose relates.

1.7 Natural Radioactivity

Radioactive decay is spontaneous phenomenon of emission of particles or electromagnetic radiation from an atomic nucleus. Thermodynamic instability of a nucleus is responsible for the spontaneous decay so as to obtain more stable nucleus. Nuclear decay is accompanied by emission of alpha, beta, gamma, neutron, proton and even heavier elements (isotopes).

Radioactivity is a part of our earth and it has existed all along. Naturally Occurring Radioactive Materials (NORM) are present in its crust, the floors and walls of our homes, schools or offices and in the food. There are radioactive gases in the air we breathe. Our own body muscles, bones, and tissues contain naturally occurring radioactive elements. Radioactivity is the term used to describe disintegration of atoms. The atom can be characterized by the number of protons in the nucleus. Some natural elements are unstable. Therefore, their nuclei disintegrate or decay, thus releasing energy in the form of radiation. This physical phenomenon is called radioactivity and the radioactive atoms are called nuclei. The radioactive decay is expressed in units called Becquerel. One Becquerel equals one disintegration per second. The radionuclides decay at a characteristic rate that remains constant regardless of external influence, such as temperature or pressure. Half life differs for each radionuclide, ranging from fractions of a second to billions of years. For example, the half life of Iodine-131 is eight days, but for Uranium 238, which is present in
varying amounts all over the world, it is 4.5 billion years. Potassium 40, the main source of radioactivity in our bodies has a half life of 1.42 billion years.

Natural radioactivity is widespread in the earth's environment coming from Uranium (\(^{238}\text{U}\)) and Thorium (\(^{232}\text{Th}\)) series and Potassium (\(^{40}\text{K}\)), existing in various geological formations like soils, rocks, plants, water and air (Beretka and Mathew, 1985; EC, 1999; Singh et al., 1999; Kumar et al., 2003; Anjos et al., 2005; Ahmed et al., 2006). Radiological implication of these radionuclides is due to the gamma ray exposure of the body and \(\alpha\)-irradiation of lung tissues from inhalation of radon and its daughters. The assessment of gamma radiation dose and radon exhalation rate from natural sources is of particular interest as natural radiation is the largest contributor to external dose of the world population (UNSCEAR, 1993; El-Arabi, 2007). As uranium can get dissolved in aqueous solutions in hexavalent (\(U^{6+}\)) form and can be precipitated as a discrete mineral in tetravalent (\(U^{4+}\)) form. Uranium may form deposits in the earth's crust where the geological conditions become favorable. Under specific conditions such as those prevailing in the uranium mining environment lung dose due to radon progenies may be sufficiently high. Growing world wide interest in natural radiation has lead to extensive surveys in many countries. External gamma dose estimation due to terrestrial sources is essential not only due to its considerable contribution (0.46 mSv y\(^{-1}\)) to collective dose but also because of the variations of individual doses related to its path ways. These doses vary depending upon the concentrations of the natural radionuclides \(^{238}\text{U}\) and \(^{232}\text{Th}\) and their daughter products and \(^{40}\text{K}\), present in the soils and rocks which in turn depend upon the local geology and region in the world (Radhakrishna et al., 1993; Rudnic Gao, 2003).

1.7.1 Radiation Dose

Ionizing radiation can impair the normal functioning of the cells or even kill them. The amount of energy necessary to cause significant biological effects through ionization is so small that our bodies can not feel this energy as in the case of infra-red rays which produce heat. The biological effects of ionizing radiation vary with the type and energy. A measure of the risk of biological harm is the dose of radiation that the tissues receive. The unit of absorbed radiation dose is Sievert (Sv). Since one sievert is a large quantity, radiation doses normally encountered are expressed in milli Sievert (mSv) or micro Sievert.
(\(\mu\text{Sv}\)) which is one-thousand or one millionth of a Sievert. For example, one chest X-ray will give about 0.2 mSv of radiation dose.

On the average, our radiation exposure due to all natural sources amounts to about 2.4 \(\mu\text{Sv}\) a year, though this figure can vary, depending on the geographical location by several hundred percent. In homes and buildings there are radioactive elements in the air. These radioactive elements are \(^{222}\text{Rn}\) (radon) and \(^{220}\text{Rn}\) (thoron) and by products formed by the decay of radium and thorium present in many sorts of rocks, other building construction materials and in soil. By far the largest source of natural radiation exposure comes from varying amounts of uranium and thorium in the soil around the world. The radiation exposure due to cosmic rays is very dependent on altitude and slightly on latitude: people, who travel by air thereby, increase their exposure to radiation. Additionally, we are exposed to varying amounts of radiation from sources such as dental and other medical X-rays, industrial uses of nuclear techniques and other consumer products such as luminized wrist watches, ionization smoke detectors etc. We are also exposed to radiation from radioactive elements contained in fallout from nuclear explosives testing and routine normal discharges from nuclear and coal power stations.

1.7.2 Radiation Protection

It has long been recognized that large doses of ionizing radiation can damage human tissues. Over the years, as more was learned, scientists became increasingly concerned about the potentially damaging effects of exposure to large doses of radiation. The need to regulate exposure to radiation prompted the formation of number of expert bodies to consider what is needed to be done. In 1928, an independent non-governmental body of experts in the field, the International X-ray and Radium Protection Committee was established. It later was renamed as the International Commission on Radiological Protection (ICRP). Its purpose is to establish basic principles and issue recommendations on radiation protection.

These principles and recommendations form the basis for national regulations governing the exposure of radiation workers and members of the public. They also have been incorporated by the International Atomic Energy Agency (IAEA) into its Basic Safety Standards for Radiation Protection published jointly with the World Health Organization.
WHO), International Labour Organization (ILO), OECD and Nuclear Energy Agency (NEA). These standards are used worldwide to ensure safety and radiation protection of radiation workers and the general public. An intergovernmental body was formed in 1955 by the General Assembly of the United Nations as the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). UNSCEAR is directed to assemble study and disseminate information on observed levels of ionizing radiations and radioactivity (natural and man-made) in the environment and on the effects of such radiation on man and environment.

Basic approaches to radiation protection are consistent all over the world. ICRP recommends that any exposure above the natural background radiation should be kept as low as reasonably achievable, but below the individual dose limits. The individual dose limit for radiation workers averaged over 5 years is 100 mSv and for the members of the general public is 1 mSv per year. These dose limits have been established based on a prudent approach by assuming that there is no threshold dose below which there would be no effect. It means that any additional dose will cause a proportional increase in the chance of a health effect. This relationship has yet been established in the few low dose range where the dose limits have been set.

There are many high natural background radiation areas around the world where the annual radiation dose received by members of the general public is several times higher than the ICRP dose limit for radiation workers. The numbers of people exposed are too small to expect to detect any increase in health effects epidemiologically. Still the fact that there is no evidence so far any increase does not mean the risk is being totally disregarded. The ICRP and the IAEA recommend that consideration must be given to the presence of other sources which may cause simultaneous radiation exposure to the same group of the public. Also, allowance for future sources or practices must be kept in mind so that the total dose received by an individual member of the public does not exceed the dose limit. In general, the average annual dose received by radiation workers is found to be considerably lower than the individual dose limits. Good radiation protection practice can thus result in low radiation exposure to workers.
1.7.3 Health effects due to radioactivity

Generally assumed that any resulting health detriment (e.g. cancer, cellular damage etc.) is brought about by exposure to a radioactive substance and is primarily a function of the amount of energy (as ionizing radiation) absorbed per unit mass of tissue through which it passes. Ionizing radiation emitted by different radionuclides differ in their ability to penetrate matter depending both on the type of radiation emitted and its energy. Alpha particles are hardly able to penetrate the outer layer of skin and do not constitute a hazard when emitted outside the body. Beta particles are able to penetrate the outer layers of skin and can give rise to localized dose to the skin when in contact. Gamma radiations is potentially more penetrating and can deposit energy to internal organs when outside the body, the magnitude of which depends on the energy of gamma radiation emitted. Thus exposures from radionuclides may be both external and internal to the body and the relative importance of these exposures pathways depends upon the type of radiation and the radionuclides involved. Two types of health effect have been shown to result from exposure to ionizing radiation, deterministic and stochastic effects. Deterministic effects are those that occur at high doses and dose rates. These effects occur at dose levels far higher than those encountered from the use of exposure to radioactive materials under normal environmental conditions and exposures to general public. Erythema or reddening of the skin is a form of deterministic effect that may result from skin exposure (at instantaneous absorbed dose of 5Gy or more). Above the dose threshold the likely severity of such effects is affected by the dose received. The primary stochastic effect associated with radiation exposure is cancer induction. Most of the information relating radiation doses to an increased risk of cancer is derived from situation in which people have been exposed at higher doses and dose rates than normally encountered (e.g. Nagasaki and Hiroshima bomb survivors). At lower levels of dose and dose rate, it is difficult to demonstrate an increased cancer incidence from radiation exposure because of the high natural incidence of cancer, which is a major confounding factor in the epidemiological studies, particularly at low doses and dose rates. Information about the way in which radiation interacts with cells, however, supports what has become known as the linear no-threshold hypothesis. Uranium nuclides emit alpha rays of high ionization power and therefore, it may be hazardous if inhaled or ingested in higher quantity or dose. Uranium a
primordial radionuclide occurs in dispersed state in the earth,\text{'}s crust. Uranium prospection through the analysis of soil, rocks, plants and water has been reported by many workers (Dyck, 1979; Dunn, 1981). Uranium present in the earth is transferred to water, plants, food supplements and then to human beings. Uranium accumulated in humans may have dual effect due to its chemical and radioactive properties. High intake of uranium ad its decay products may lead to harmful effects in human beings. According to an estimate (Cothen and Lappenbush, 1983) food contributes about 15\% of ingested uranium while drinking water contributes about 85\%. An exposure of about 0.1 mg/kg of body weight of soluble natural uranium results in transient chemical damage to the kidneys (Lussenhop et al., 1958).

### 1.8 Radiation levels and their effects

The following points give an indication of the likely effects of a range of whole body radiation doses and dose rates to individuals:

- **10,000 mSv** (10 sieverts) as a short-term and whole-body dose would cause immediate illness, such as nausea and decreased white blood cell count, and subsequent death within a few weeks. Between 2 and 10 sieverts in a short-term dose would cause severe radiation sickness with increasing likelihood that this would be fatal.

- **1000 mSv** (1 sievert) in a short term dose is about the threshold for causing immediate radiation sickness in a person of average physical attributes, but would be unlikely to cause death. Above 1000 mSv, severity of illness increases with dose. If doses greater than 1000 mSv occur over a long period they are less likely to have early health effects but they create a definite risk that cancer will develop many years later.

- Above about **100 mSv**, the probability of cancer (rather than the severity of illness) increases with dose. The estimated risk of fatal cancer is 5 of every 100 persons exposed to a dose of 1000 mSv (ie. if the normal incidence of fatal cancer were 25\%, this dose would increase it to 30\%).

25
• 50 mSv is, conservatively, the lowest dose at which there is any evidence of cancer being caused in adults. It is also the highest dose which is allowed by regulation in any one year of occupational exposure. Dose rates greater than 50 mSv yr\(^{-1}\) arise from natural background levels in several parts of the world but do not cause any discernible harm to local populations.

• 20 mSv yr\(^{-1}\) averaged over 5 years is the limit for radiological personnel such as employees in the nuclear industry, uranium or mineral sands miners and hospital workers (who are all closely monitored).

• 10 mSv yr\(^{-1}\) is the maximum actual dose rate received by any Australian uranium miner.

• 3-5 mSv yr\(^{-1}\) is the typical dose rate (above background) received by uranium miners in Australia and Canada.

• 3 mSv yr\(^{-1}\) (approx) is the typical background radiation from natural sources in North America, including an average of almost 2 mSv yr\(^{-1}\) from radon in air.

• 2 mSv yr\(^{-1}\) (approx) is the typical background radiation from natural sources, including an average of 0.7 mSv/yr from radon in air. This is close to the minimum dose received by all humans anywhere on Earth.

• 0.3-0.6 mSv yr\(^{-1}\) is a typical range of dose rates from artificial sources of radiation, mostly medical.

• 0.05 mSv yr\(^{-1}\), a very small fraction of natural background radiation, is the design target for maximum radiation at the perimeter fence of a nuclear electricity generating station. In practice the actual dose is less.
## TABLE -7
Conversion Factors

<table>
<thead>
<tr>
<th>SI Unit</th>
<th>Traditional Unit Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity (Bq)</td>
<td>1 Ci = 3.7x10^{10} Bq (1 pCi = 0.037 Bq)</td>
</tr>
<tr>
<td>Concentration (Bq/m³)</td>
<td>1 pCi/liter = 37 Bq /m³</td>
</tr>
<tr>
<td>Potential alpha energy conc.(PAEC))</td>
<td>1 WL* = 1.3x10^5 MeV/liter = 2.08x10^{-5} J/m³</td>
</tr>
<tr>
<td>Exposure (J/m³ s)</td>
<td>1 WLM = 12.97 J/m³ s</td>
</tr>
<tr>
<td>Exposure (Bq/m³ y)</td>
<td>1 WLM = 74.0 Bq/m³ year (for ^{222}Rn series)</td>
</tr>
<tr>
<td>Exposure rate</td>
<td>1 WLM/year = 4.11 x 10^{-7} J/m³</td>
</tr>
<tr>
<td>Exposure rate</td>
<td>1 WLM/year = 74.0 Bq/m³ (for ^{222}Rn series)</td>
</tr>
</tbody>
</table>

1 WL = 200 pCi/ liter (50% Equil.)
ABBREVIATIONS

ICRP (International Commission on Radiological Protection)

IAEA (International Atomic Energy Agency)

IARP (Indian Association for Radiation Protection)

BEIR (Biological effects of Ionizing Radiation)

UNSCAER (United Nations Scientific Committee on the Effects of Atomic Radiation)

DEFINITIONS

Action level

The level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations (for example, chronic exposure to radon in the workplace).

Dose limit

The value of the effective dose or the equivalent dose to individuals from controlled practices that shall not be exceeded.

Effective dose

To estimate annual effective doses, account must be taken of (a) the conversion coefficient from absorbed dose in air to effective dose and (b) the indoor occupancy factor. The average numerical values of those parameters vary with the age of the population and the climate at the location considered. In the UNSCEAR 1993 Report, the Committee used 0.7 Sv Gy$^{-1}$ for the conversion coefficient from absorbed dose in air to effective dose received by adults and 0.8 for the indoor occupancy factor, i.e. the fraction of time spent indoors and outdoors is 0.8 and 0.2, respectively. These values are retained in the present analysis. The components of the annual effective dose are determined as follows:

- Indoors: $84 \text{ nGy h}^{-1} \times 8,760 \text{ h} \times 0.8 \times 0.7 \text{ Sv Gy}^{-1} = 0.41 \text{ mSv}$
- Outdoors: $59 \text{ nGy h}^{-1} \times 8,760 \text{ h} \times 0.2 \times 0.7 \text{ Sv Gy}^{-1} = 0.07 \text{ mSv}$
The unit of **effective dose** is J·kg$^{-1}$, termed the sievert (Sv). **Effective dose** is a measure of dose designed to reflect the amount of radiation detriment likely to result from the dose.

**Equilibrium Equivalent Concentration of radon (EEC radon):**

The potential alpha energy concentration (PAEC) of any mixture of radon progeny in air can be expressed in terms of the so-called equilibrium equivalent concentration of their parent nuclide, $^{222}$Rn (radon). The equilibrium equivalent concentration, corresponding to a non-equilibrium mixture of radon progeny in air, is the activity concentration of radon in radioactive equilibrium with its short lived progeny that has the same potential alpha energy concentration as the actual non-equilibrium mixture. The SI unit of the equilibrium equivalent concentration is Bq m$^{-3}$:

$$EEC_{\text{radon}} = 0.104 \, C\left(^{218}\text{Po}\right) + 0.514 \, C\left(^{214}\text{Pb}\right) + 0.382 \, C\left(^{214}\text{Bi}\right)$$

with $C\left(\right)$ the concentration of the nuclide in air. 1 Bq m$^{-3}$ EEC radon corresponds to $5.56 \times 10^{-6}$ mJ m$^{-3}$. Also 1 Bqm$^{-3}$ EEC radon is equivalent to 2.5 Bq m$^{-3}$ radon gas, assuming an equilibrium factor of 0.4.

**Equilibrium Equivalent Concentration of thoron (EEC thoron)**

The equilibrium equivalent concentration, corresponding to a non-equilibrium mixture of thoron progeny in air, is the activity concentration of thoron in radioactive equilibrium with its short lived progeny that has the same potential alpha energy concentration as the actual non-equilibrium mixture. The SI unit of the equilibrium equivalent concentration is Bq m$^{-3}$:

$$EEC_{\text{thoron}} = 0.913 \, C\left(^{212}\text{Pb}\right) + 0.087 \, C\left(^{212}\text{Bi}\right)$$

where $C\left(\right)$ is the concentration of the nuclide in air. 1 Bqm$^{-3}$ EEC thoron corresponds to $7.5 \times 10^{-5}$ mJ m$^{-3}$.

**Potential Alpha Energy Concentrations (PAEC)**

PAEC is the total $\alpha$- energy emitted by an atom as it decays through its entire radioactive series. The Potential alpha concentration is the sum of all PAE in a given volume of air divided by the volume of air. Conventional unit used is MeV L$^{-1}$. The other unit is J m$^{-3}$. Widely used unit for describing PAEC is Working Level (WL).
**Working Level (WL)**

The WL unit was developed for use in radon occupational exposure assessment since often there was incomplete information on the degree of equilibrium with daughter products. WL is the combination of radon progeny such that total potential alpha energy released on ultimate decay to $^{210}\text{Pb}$ is $1.28 \times 10^5 \text{ MeV L}^{-1}$ (rounded to $1.3 \times 10^5$). For conversion purposes, $1 \text{ WL} = 1.3 \times 10^5 \text{ MeV L}^{-1} = 2.08 \times 10^5 \text{ J m}^{-3}$.

1 WL corresponds to an activity concentration of $3700 \text{ Bq m}^{-3}$ of $^{222}\text{Rn}$. It is the dose delivered in one liter of air that results in the emission of $1.3 \times 10^5 \text{ MeV}$ of potential alpha energy.

**Working Level Month (WLM):**

Although WL was originally defined only for progeny of radon, it can also be calculated for $^{226}\text{Rn}$ and $^{219}\text{Rn}$ by letting $1 \text{ WL}$ equal to $1.3 \times 10^5 \text{ MeVL}^{-1}$ for air regardless of source. $1 \text{ WL}$ corresponds to $275 \text{ Bq m}^{-3}$ for $^{220}\text{Rn}$ and $5960 \text{ Bq m}^{-3}$ for $^{219}\text{Rn}$.

The working level is the measure of exposure rate. The exposure of an individual to radon progeny is time integral of PAEC and expressed as **Working Level Month (WLM)**. $1 \text{ WLM}$ corresponds to exposure at $1 \text{ WL}$ concentration for a period of one month (170 hrs). It is a measure of exposure rather than dose. Since the equilibrium between the parent radon isotope and progeny is rarely achieved due to plate out and ventilation.

**Indoor internal exposure due to radon inhalation**

The risk of lung cancer from domestic exposure of $^{222}\text{Rn}$ and its daughters can be estimated directly from the indoor inhalation exposure (radon)-effective dose. The contribution of indoor radon concentration from the samples can be calculated from the expression (Nazaroff and Nero, 1988):

$$ C_{\text{Rn}} = \frac{E_s \times S}{V \times \lambda_e} $$

Where $C_{\text{Rn}}$, $E_s$, $S$, $V$ and $\lambda_e$ are radon concentration (Bq m$^{-3}$), radon exhalation rate (Bq m$^{-2}$ h$^{-1}$), radon exhalation area (m$^2$), room volume (m$^3$) and air exchange rate (h$^{-1}$) respectively.
Radium equivalent activity (Ra\textsubscript{eq})

Exposure to radiation is defined in terms of radium equivalent activity (Ra\textsubscript{eq}) in Bq kg\textsuperscript{-1} to compare the specific activity of materials containing different amounts of \(^{238}\text{U}\) (\(^{226}\text{Ra}\)), \(^{232}\text{Th}\) and \(^{40}\text{K}\). It is calculated through the following expression:

\[
\text{Ra}_{\text{eq}} = C_{\text{U}} + 1.43 C_{\text{Th}} + 0.07 C_{\text{K}}
\]

Where \(C_{\text{U}}, C_{\text{Th}}\) and \(C_{\text{K}}\) are the activity concentrations of \(^{238}\text{U}\), \(^{232}\text{Th}\) and \(^{40}\text{K}\) in Bq kg\textsuperscript{-1} respectively.

Absorbed gamma dose rate (D)

The absorbed gamma dose rates (D) in air at 1m above the ground surface for the uniform distribution of radio nuclides (\(^{232}\text{Th}\), \(^{238}\text{U}\) & \(^{40}\text{K}\)) are calculated on the basis of guidelines given by UNSCEAR, (2000). The dose conversion factors for converting the activity concentrations of \(^{238}\text{U}\), \(^{232}\text{Th}\) and \(^{40}\text{K}\) into doses (nGy h\textsuperscript{-1} per Bq kg\textsuperscript{-1}) are 0.462, 0.604 and 0.0417 respectively. Thus,

\[
D = (0.462 C_{\text{U}} + 0.604 C_{\text{Th}} + 0.0417 C_{\text{K}}) \text{nGy h}^{-1}
\]

External (H\textsubscript{ex}) and Internal (H\textsubscript{in}) Hazard Index

The external hazard index is obtained from Ra\textsubscript{eq} expression through the supposition that its allowed maximum value (equal to unity) corresponds to the upper limit of Ra\textsubscript{eq} (370 Bq kg\textsuperscript{-1}). For limiting the radiation dose from building materials in Germany to 1.5 mGy y\textsuperscript{-1}, Krieger (1981) proposed the following relation for H\textsubscript{ex}:

\[
H_{\text{ex}} = \frac{C_{\text{U}}}{370} + \frac{C_{\text{Th}}}{259} + \frac{C_{\text{K}}}{4810} \leq 1
\]

This criterion considers only the external exposure risk due to \(\gamma\)-rays and corresponds to maximum Ra\textsubscript{eq} of 370 Bq kg\textsuperscript{-1} for the material. These very conservative assumptions were later corrected and the maximum permission concentrations were increased by a factor of 2 (Keller and Muth, 1990) which gives

\[
H_{\text{ex}} = \frac{C_{\text{U}}}{740 \text{Bq kg}^{-1}} + \frac{C_{\text{Th}}}{520 \text{Bq kg}^{-1}} + \frac{C_{\text{K}}}{9620 \text{Bq kg}^{-1}} \leq 1
\]

Internal exposure to \(^{222}\text{Rn}\) and its radioactive progeny is controlled by the internal hazard index (H\textsubscript{in}) as given below (Cotten, 1990):

\[
H_{\text{in}} = \frac{C_{\text{U}}}{185} + \frac{C_{\text{Th}}}{259} + \frac{C_{\text{K}}}{4810} \leq 1
\]
References


32


