Chapter 3

**Inhalation Dosimetry**

### 3.1 Radon

Radon and its progeny were regarded as radiation health hazards encountered only in the mining and processing of uranium ore even during the latter part of the 20th century. This concept has changed markedly since 1970 when there was an increased interest among researchers to organize programs measuring the level of radon in dwellings, mines other than uranium mines, and workplaces suspected of having high atmospheric radon levels. The large scale radon surveys conducted in many countries all over the world led to the quantitative understanding of the low dose effects of radon exposures. 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 serious radiation health hazard as it brought about an increase in the incidence of lung cancer. Radon thus became a potential public health issue 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.\(^1\)

It is well known that of the total annual exposure to humans, more than 50%, is from radon and its daughter products. Radiations from the naturally occurring radioactive materials originating from earth’s crust are the major contributors of total background exposures to the human populations which includes external gamma radiations and inhalation exposures, the latter being due to radon, thoron and their progeny. The main inhalation dose is contributed by the radon progeny nuclides and this makes radon the most popular subject of studies on environmental radioactivity.\(^2\) The presence of high level of radon in indoor environment constitutes a major health hazard for man. The radon progeny is well established as causative agents of lung cancer and other types of cancers. The thoron concentration in dwellings is not considered very significant because of the short half-life of the thoron (55.6 sec) in ordinary environment. The worldwide average of thoron concentration estimated by UNSCEAR is 10 Bq/m\(^3\). As per the general assumption, the inhalation dose to the general population from thoron and its progeny is only about 10% of the inhalation dose due to radon and its progeny.\(^3\) As far as the radiological risks are concerned, the contribution of thoron and its
progeny is significantly important. This demands that the radon measurements should be accompanied by the thoron measurement for assessment of the reliable level of dose due to radio nuclides present in the environment.

As we all know uranium is ubiquitous. Radon comes from radioactive decay of radium which belongs to the uranium series. Presence of radon in the environment cannot be felt with human senses as it is a colorless, odorless, tasteless, non-flammable inert gas. The melting point of this $\alpha$- radioactive gas is -71°C and boiling point is -61.7°C. Radon has the highest gas density of about 9.73 kg/m$^3$ and is about seven times heavier than air. Being a noble gas, it has greater ability to migrate freely through soil, air, etc $^{(4)}$. There are two main isotopes of radon in nature namely $^{222}$Rn (radon) and $^{220}$Rn (thoron). Radon has its short-lived decay products namely $^{218}$Po, $^{214}$Pb, $^{214}$Bi, $^{214}$Po, $^{210}$Pb, $^{210}$Bi, and $^{210}$Po (uranium series). Thoron has $^{216}$Po, $^{212}$Pb, $^{212}$Bi, $^{212}$Po and $^{208}$Tl (thorium series) as its decay products. The half-life of $^{222}$Rn is 3.82 days and that of $^{220}$Rn is only 55.6 seconds $^{(5)}$. The radioactive decay chain of radon and thoron are shown in figure 3.1 and figure 3.2 $^{(6,7)}$. 
Figure 3.1: Decay series of radium
Figure 3.2: Decay series of thorium
Radon atoms generated in Earth’s crust enter the pore spaces and are then transported by diffusion and advection through this space. The process continues until they decay and/or released into the atmosphere. The amount of radon that escapes into the pore space depends on various factors such as the amounts of $^{226}\text{Ra}$ and $^{232}\text{Th}$ in the ground, type of the soil cover, porosity, dampness, temperature and moisture of the soil. There are several other mechanisms like alpha-recoil, emanation etc. that contribute to the escape of radon from its origin to the atmosphere. Despite the short half-life of radon, it can migrate to a fair distance from the site of generation once it is formed. Physical and chemical properties of radon enable it to be used as a geographical tracer for locating buried faults and geological structures, in exploring the uranium from mines, and for predicting the earthquakes\(^{(7)}\).

The concentration of radon in houses rises due to the exhalation from soil and walls. Entry of radon enters into the houses mainly depends on building materials and on the physical conditions of materials, radium content, porosity of the material used in the floor, walls and ceiling of the houses. The entry of gas is also influenced by the meteorological parameters such as temperature, humidity, rainfall, wind speed etc\(^{(8)}\). High radon concentration indoors is usually due to penetration from the surrounding subsoil. Underground water at times can get contaminated with radon gas, which is released during showers and other household uses. Outdoor radon concentrations are low but in houses without proper ventilation this gas may accumulate in high concentrations emitted from the soil and from building materials, resulting in large indoor activity\(^{(9)}\).

Radon moves by two basic ways: diffusion and forced flow. The specific entry rate of $^{222}\text{Rn}$ from soil ranges from 0.5 to 200 Bq/m$^3$/h resulting in an indoor concentration in the range of 0.5 – 500 Bq/m$^3$. The specific entry from the building materials can range from 1 to 50 Bq/m$^3$/h resulting in an indoor concentration of 0.7 to 10 Bq/m$^3$\(^{(10)}\). The specific entry from other sources including outdoor air, water and natural gases work out to be less than 10% of the rate from the soil and building materials\(^{(11)}\). Thus, our houses can be prominent sources of radon exposure. From the medical point of view, there is a high chance of getting lung cancer if an individual is exposed to radon gas for a long time, although low dose irradiation lowers the risk of cancer\(^{(12, 13)}\).

The radon content of outdoor air 1 meter above ground typically ranges from 4 to 15 Bq/m$^3$. The average indoor air concentration of radon varies from location to location, depending upon the uranium content and physical characteristics of the soil, moisture, winds and
building materials. In most countries the average indoor radon concentration is a few tens of Bq/m³. The International Commission on Radiological Protection (ICRP) therefore recommended action levels 200-600 Bq/m³ for homes and 500-1500 Bq/m³ for workplaces which correspond to annual doses of 3–10 mSv in either case (14-17).

### 3.2 Probable Health Effects of Radon Exposure

Radon gas decays overtime into radioactive particles that can be inhaled and trapped in the lungs as these daughter products remain airborne for a long time. When Radon decays it forms its progeny ²¹⁸Po and ²¹⁴Po, which are electrically charged and can attach them to tiny particles, water vapour, oxygen, trace gases in indoor air and other aerosols. These daughter products remain air borne for a long time and can easily be inhaled into the lung and can adhere to the epithelial lining of the lung, thereby irradiating the tissue. 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 exposure of population to high concentration of radon and its daughters for a long period lead to pathological effects like the respiratory functional changes and the occurrence of lung cancer (18).

The inhaled radon and its progenies pass from lungs into the blood and body tissues and may cause many types of soft tissue cancers such as carcinoma with lung, kidney and prostate. Some radon may be dissolved in body fats, and its daughter products transferred to the bone marrow. The accumulated dose in older people can be high, and may give rise to leukemia. Radon has also been linked with melanoma and some childhood cancers (19, 20). There is a positive association between coronary heart disease and radon exposures where an elevated risk of mortality from coronary heart disease was observed among miners with accumulative radon exposure exceeding 1000 Working Level Month (WLM) (21). Radon daughters ²¹⁸Po and ²¹⁴Po could be regarded as potential carcinogenic agents for the induction of skin cancer (22). The combination of inhalation of radon gas and smoking increases the risk of lung cancer is a significant point (18).

Just like inhaling radon, drinking water containing dissolved radon is also a health risk as it may cause stomach cancer but the risk caused by the latter is much lower than the former (23). According to Environmental Protection Agency (EPA) in the USA, thousands of preventable lung cancer deaths are attributable to indoor residential exposure to radon every year (24). After cigarette smoking, radon which causes about 15,000 lung cancer deaths per year in the
USA has been estimated to be the second leading cause of lung cancer. The World Health Organization (WHO) says radon causes up to 15% of lung cancers worldwide (25). The Committee on the Biological Effects of Ionizing Radiation (BEIR IV 1988) of National Academy of Sciences, USA has estimated lifetime risk of 350 extra lung cancer cases if one million people are exposed to 1 Working Level Month (WLM) of radon daughters (26). In a later report (BEIR VI 1999), the number of lung cancer cases due to radon exposure in homes in the United States has been estimated to range from about 3,000 to 32,000 (18).

Environmental measurements of $^{222}$Rn were mostly confined to outdoor atmospheric air earlier. Since 1970, indoor $^{222}$Rn levels were measured with keen interest, and several large scale surveys have been carried out by several agencies all over the world (15, 27).

### 3.3 Radiological Parameters Related to Radon

There is no risk factor involved even in a strong radioactive source as long as it is isolated from populated environments. It is only when people are exposed to radiation that a radiation dose is delivered (28). When any type of radiation is emitted, it produces manifold interactions that deposit energy in the medium that surrounds it. This deposition of energy is characterized as radiation dose, and if it occurs in the living tissue of individuals, it results in undesirable biological changes. Understanding these interactions leads naturally to the determination of radiation exposure and dose and the units used to define them (29).

Detecting ionizing radiations directly through our senses is not possible. There are, however, various older and newer methods by which we can detect and measure ionizing radiations. The older methods include those based on photographic films, Geiger-Muller tubes, and scintillation counters and newer techniques include those using thermo luminescent materials and silicon diodes. We can interpret the measurements we make in terms of the energy that the radiation concerned would have deposited throughout the human body or in a particular part of the body. When direct measurements are not possible as in the case of a radionuclide being deposited in an internal organ, we can calculate the dose absorbed by that organ provided that we know the activity in the organ (30). A few dosimetric quantities that have been precisely defined and that are particularly useful in radiological assessment are discussed below.
3.3.1 Absorbed Dose

The primary physical quantity used in radiation dosimetry is the absorbed dose (D). It is defined as the energy absorbed per unit mass from any kind of ionizing radiation in any target. The conventional unit for absorbed dose is the rad (radiation absorbed dose), and is equal to the absorption of 100 erg of energy in 1 g of absorbing medium, typically tissue:

1 rad = 100 erg/g

The SI unit of absorbed dose is the Gray (Gy) and is defined as the absorption of 1 J of energy per kilogram of medium:

1 Gy = 1 J/kg

From these definitions, it follows that 1 Gy = 100 rad

3.3.2 Equivalent Dose

There are differences in the way ionizing radiations interact with biological tissues. This is evident from the fact that different radiations produce different amounts of biological damage even when the deposited energy remains the same. Apart from the total energy deposited, biological effects depend also on the way in which it is distributed along the path of the radiation. Radiation damage increases with the linear energy transfer (LET) of the radiation; thus, for the same absorbed dose, the biological damage from high-LET radiation (e.g., alpha particles, neutrons, etc.) is much greater than from low-LET radiation (beta particles, gamma rays, x-rays, etc.). For instance, a tissue getting exposed to 1 Gy alpha radiation is more harmful than that getting exposed to 1 Gy beta radiation. This is because an alpha particle, being slower and more heavily charged, loses its energy much more densely along its path. That brings the necessity for another quantity which will put all ionizing radiations on an equal basis with regard to their potential for causing harm. This is the equivalent dose and it is expressed in a unit called the Sievert, symbolized by Sv.

The dose equivalent, denoted by H, is defined as the product of the absorbed dose D and radiation weighting factor $W_R$ which characterizes the damage associated with each type of radiation:

$H$ (equivalent dose) = $D$ (absorbed dose) × $W_R$ (radiation weighting factor)
Table 3.1: Values of the radiation weighting factor for different radiations \(^{(31)}\)

Source: ICRP (1991)

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Radiation weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>X rays and gamma rays (all energies)</td>
<td>01</td>
</tr>
<tr>
<td>Electrons (including beta particles)</td>
<td>01</td>
</tr>
<tr>
<td>Neutrons &lt; 10 KeV</td>
<td>05</td>
</tr>
<tr>
<td>10-100 KeV</td>
<td>10</td>
</tr>
<tr>
<td>0.1 - 2 MeV</td>
<td>20</td>
</tr>
<tr>
<td>2 – 20 MeV</td>
<td>10</td>
</tr>
<tr>
<td>&gt; 20 MeV</td>
<td>05</td>
</tr>
<tr>
<td>Protons (&gt; 1 MeV) [ICRP]</td>
<td>05</td>
</tr>
<tr>
<td>Alpha particles, fission fragments, heavy nuclei</td>
<td>20</td>
</tr>
</tbody>
</table>

3.3.3 Effective Dose

In a human, different organs have different radiological sensitivities and hence the same dose equivalent delivered to different organs produce different consequences. Moreover, a beam of radiation incident on a human body generally delivers different dose equivalents to the major body organs and tissues. Finally, ingested or inhaled sources of radiation usually produce different doses equivalents in the various body organs and tissues. Therefore, a special dose unit namely the effective dose is used to account for different organ sensitivities and the different doses received by the various organs. This helps us describe better the hazard a human body experiences when placed in a radiation field \(^{(32)}\).

Effective dose (E) = Equivalent dose (H) × Tissue weighting factor (W_T)
Table 3.2: Tissue weighting factors adopted by the ICRP (1990) for use in determining the effective dose equivalent (33)

<table>
<thead>
<tr>
<th>Tissue or organ</th>
<th>Tissue weighting factor(W_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0.20</td>
</tr>
<tr>
<td>Red bone marrow</td>
<td>0.12</td>
</tr>
<tr>
<td>Lungs</td>
<td>0.12</td>
</tr>
<tr>
<td>Colon</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.05</td>
</tr>
<tr>
<td>Breast</td>
<td>0.05</td>
</tr>
<tr>
<td>Liver</td>
<td>0.05</td>
</tr>
<tr>
<td>Thyroid gland</td>
<td>0.05</td>
</tr>
<tr>
<td>Esophagus</td>
<td>0.05</td>
</tr>
<tr>
<td>Bone surfaces</td>
<td>0.01</td>
</tr>
<tr>
<td>Skin</td>
<td>0.01</td>
</tr>
<tr>
<td>The rest</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
</tr>
</tbody>
</table>

While evaluating the dose due to radon and its progeny, many factors deserve special attention, which include aspects related to the aerosol characteristics, inherent characteristics of radon progeny and the mass of the tissue irradiated by the radon daughters deposited in the human lung. The nature of the respiratory function like the tidal volume, breathing frequency and occupancy factor also affect the dose received.

Critical issues which receive most of the short range alpha radiation from radon and its progeny is of the respiratory tract. The lower relative biological effectiveness (RBE) of gamma and beta components results in negligible dose equivalent commitment to lung tissues. The radiation dose to lung due to radon and its progeny inhalation cannot be measured directly. It is inferred from the application of a suitable dosimetric model along with measured radon activity. The most commonly used dosimetric models are the James-Birchall, the Harley-Pasternack and the Jacobi-Eisfeld models (35). Generally the dose, \(D\), can be expressed as
\[ D = L t (A' A_1^u + B' A_2^u + C' A_3^u + A A_1^a + B' A_2^a + C' A_3^a) \]  

(3.1)

where \( A_1, A_2 \) and \( A_3 \) are the total (unattached and attached) airborne activity concentrations of the radon progeny, \( L \) is the breathing rate, \( t \) is the exposure time, and \( A, B, C, A', B' \) and \( C' \) are constants characteristic of the model, group of individual and aerosol distribution. For the radon progeny (Ra- A, Ra-B and Ra-C) with their unattached fractions \( f_1, f_2 \) and \( f_3 \) the above relation can be written as

\[ D = L t (A' f_1 A_1 + B' f_2 A_2 + C' f_3 A_3 + A (1-f_1) A_1 + B (1-f_2) A_2 + C (1-f_3) A_3) \]  

(3.2)

The three models differ in the absolute values of the constants \( A, B, C, A', B' \) and \( C' \) and in the ratios between the dose values per unit of Potential alpha energy concentration (PAEC) ascribed to unattached and attached progeny. The James-Birchall and the Harley-Pasternack models ascribe much higher dose values per unit of Potential alpha energy concentration (PAEC) to the unattached than to the attached progeny, making these models very sensitive to changes in characteristics of the attached and unattached radon progeny. In the Jacobi-Eisfeld model, the ratio between the dose values of unattached and attached progeny is generally much smaller. Unless the changes in the unattached fractions are drastic, the variation in the dose predicted by the model will usually follow the changes in PAEC level.

Exposure to radon can be expressed as the amount of inhaled radon taking its potential to emit a radiation into account. In real terms it can be found as the product of radon activity concentration and the exposure time. Similarly for radon progeny, the exposure is the product of time during which the decay products were inhaled and their concentration in inhaled air.

The PAEC of radon progeny can be expressed in Joules/m\(^3\). The fact that the entire alpha energy from radon progeny is deposited in the lung tissues has given rise to a special unit being defined in radiation protection applications. The unit is known as ‘Working Level’ (WL).

One Working level is defined as a potential alpha particle energy concentration of \(1.3 \times 10^5\) MeV per liter of air for the short-lived radon daughters. This value corresponds to the presence of 100 pCi per liter or 3.7 Bq per liter of the daughters in secular equilibrium. The exposure of persons to radon daughters is often expressed in working-level months (WLM), with a working month defined as 170 h. The WLM represents the integrated exposure of an individual over a specified time period\(^{(34)}\).
When we simultaneously measure concentration of radon and its progeny, we get an idea about the equilibrium status between radon with its progeny. The equilibrium factor for radon and its progeny can be expressed as,

\[ F = \frac{WL \times 3700}{A_0} \]  

(3.3)

where WL is the decay product concentration in working level units, \( A_0 \) is the radon activity concentration, 3700 is the radon activity concentration in Bq/ m\(^3\) which, in equilibrium with its decay products, could correspond to 1 WL and F is the equilibrium factor.

Equilibrium factor is important for the assessment of dose equivalents to a part or the whole body. Equilibrium factor for indoor radon is 0.4 and that of outdoor radon is 0.6 \(^{(5)}\).

### 3.4 Inhalation Dosimetry

Since radon, thoron and their progeny concentrations contribute the most to the natural radiation dose to people, their large scale and long-term measurement has gained substantial importance \(^{(35)}\). It is well known that inhalation of the short lived decay products of radon and, to a lesser extent, the decay products of thoron and their subsequent deposition along the walls of the various airways of the bronchial tree, provides the main pathway for radiation exposure to the lungs \(^{(36)}\).

There have been various techniques to measure the radon, thoron and their daughter products in air. This includes their collection on a filter paper and subsequent alpha counting using ZnS (Ag) surface barrier detectors or alpha scintillation counters, several personnel dosimeters employing SSNTD, TLD and photographic films have also been developed. These techniques used in the time integrated mode for the measurement of radon and thoron in air, have also been used for uranium exploration, earthquake predictions and geological studies. Due to its versatility, simplicity in handling and processing, low cost and insensitivity to beta and gamma radiation, the nuclear track detector technique is the most reliable method for the integrated and long-term measurement of indoor radon activity \(^{(37)}\). Another added advantage is that the nuclear track detectors can incorporate the effects of seasonal and diurnal fluctuation of radon concentrations due to physical and geological factors as well as meteorological conditions \(^{(38)}\).
Various Types of Radon Dosimeters

A good number of instruments have been designed and developed all over the world for measuring radon, thoron and their daughter products. Summed up below are the different types of radon dosimeters.

1. Conical plastic cup (CPC) with membrane is a plastic cup similar to the dimensions of a “Terradex” cup (USA) (9.5 cm height, 6.8 cm diameter at the open mouth and 4.5 cm diameter at the bottom) with its mouth covered by a membrane. The configuration is mainly used to measure the radon concentration inside dwellings.

2. Plastic cup (PC) with membrane is a cylindrical plastic cup of 4.5 cm height, 7.0 cm diameter. The configuration is useful for the measurement of the radon exhalation rate from building materials, soil radon measurements and for radon measurements in dwellings.

3. Personal radon dosimeter (PRD) is small cylindrical plastic cup with a dimension of 2.8 cm height and 3.6 cm diameter used for personal radon monitoring.

4. Radon diffusion dosimeter (RDD) developed by Department of Atomic Energy (DAE) is a dosimeter suitable for the dusty atmospheres prevalent in mines and coal fired power plants etc. The dosimeter has a diffusion chamber made of plastic. It has an internal diameter of 5.9 cm and an internal volume of about 100 ml. The dosimeter has a perforated protective cap to prevent the entry of dust into the chamber and the discriminator membrane can be fixed inside the chamber \(^{(39)}\).

3.5 SSNTD Based Twin Cup Dosimeter

In the present work, for assessment of inhalation dose, SSNTD based twin cup dosimeter was used. It is an internationally accepted versatile dosimeter developed by Bhabha Atomic Research Centre, Mumbai for simultaneous measurement of radon, thoron and their progeny levels in the indoor atmosphere. The SSNTD based twin cup dosimeters in particular have been extensively used in various programs in HBRA, Kerala as well as countrywide radon mapping. Since the sampling is passive and integrated for long duration, the diurnal and seasonal variations in radon concentrations are being taken into account \(^{(40)}\). The figure 3.3 gives the schematic sketch of the twin cup radon-thoron dosimeter.
A plastic wall divides the dosimeter into 2 chambers each having a dimension of 4.1 cm in length and 6.2 cm in diameter comprising a volume of 125 cc. Dimensions of the dosimeter are chosen based on the ratio of the effective volume of the cup to its total volume to achieve maximum track registration for the cylindrical cup \(^{(41)}\). The dosimeter is so designed as to discriminate \(^{222}\)Rn and \(^{220}\)Rn in mixed field situations, where both the gases are present as in the monazite deposited areas.

In the twin cup dosimeter, SSNTD films can be exposed in three modes so that levels of radon, thoron and their progeny can be assessed simultaneously. The modes are called (1) Bare mode; (2) Radon cup mode and (3) Radon + Thoron cup mode as indicated in the figure 3.3. The exposure of the detector inside the cup is termed as cup mode and the one exposed open is termed as the bare mode. One of the cups has its entry covered with a glass fiber filter paper that permeates both \(^{222}\)Rn and \(^{220}\)Rn gases into the cup and is called the filter cup. The other cup is covered with a semi-permeable membrane sandwiched between two-glass fiber filter papers and is called the membrane cup. This membrane has permeability constant in the range of \(10^{-8} - 10^{-7}\) cm\(^2\)/s and it allow the buildup of about 90% of the radon gas in the compartment and suppress thoron gas concentration by more than 99%. The mean time for radon to reach the steady state concentration inside the cup is about 4.5 h\(^{(42,43)}\).

Thus, the SSNTD film (2) inside the membrane cup registers tracks contributed by \(^{222}\)Rn only, while film (3) in the filter cup records tracks due to \(^{222}\)Rn and \(^{220}\)Rn. The third SSNTD
film (1) exposed in the bare mode, which is open to the atmospheric conditions, registers alpha tracks attributable to the air borne concentrations of both the gases and their alpha emitting progeny. After loading the SSNTD detectors the dosimeter cups are covered with the rubber caps until the time of deployment in a specific house. The figure 3.4 shown is a photograph of twin cup dosimeter and its components used in the study.

![Figure 3.4: Twin Cup Dosimeter and its components](image)

A. Dismantled Twin cup dosimeter  
B. Detector fixed in one of the cups  
C. Filter, membrane, and the LR 115 detector

**Figure 3.4:** Twin Cup Dosimeter and its components
3.6 Solid State Nuclear Track Detector

It is also known as an etched track detector or a dielectric track detector. It is a sample of a solid material (photographic emulsion, crystal, glass or plastic) exposed to nuclear radiation (neutron or charged particles, occasionally also gamma rays), etched, and examined microscopically. The tracks of nuclear particles are etched faster than the bulk material, and the size and shape of these track yield information about the mass, charge, energy and direction of motion of the particles.

Solid State Nuclear Track Detectors (SSNTDs) have found remarkable application in nearly all branches of Science and Technology including studies in nuclear physics, radiography, cosmic rays, micro analysis, dosimetry, environmental science, biomedical sciences, geosciences, indoor radon measurement, earth sciences and mineral exploration (44).

The basic principle of SSNTD is that heavy ionizing particles passing through insulating media leave narrow trails of damage on an atomic scale nearly 30- 100Å. This is called 'Latent Track' as it cannot be seen with the naked eye. It is possible to view this latent track with an electron microscope. The exact nature of the physical and chemical changes occurring at the damage site depends on the charge (Z) and velocity ($\beta = v/c$, where $v$ is the particle velocity and $c$ is the velocity of light) of the particle, on the chemical structure of the detector material and also on the environmental conditions like temperature and pressure. These latent tracks can be enlarged to microscopically visible size with each alpha particle producing a distinguishable track by the method of preferential chemical etching in which the damaged region reacts at faster rate with a chemical reagent. Number of tracks per unit area in the detector is proportional to the average exposure rate and exposure time. Exposure time can range up to a year or more, if desired using improved plastic track detectors which retain alpha tracks without fading for very long time at ambient temperatures.

The meritorious advantages of SSNTD may be shortlisted as given below:

- They are extremely simple to use and inexpensive.
- They are sensitive to radiation of high linear energy transfer (LET) but are insensitive to beta rays, gamma rays and X-rays.
- One can choose from a wide variety of detectors with different sensitivities to charged particles to meet one’s specific needs.
• Simple chemicals like NaOH, KOH are used in ordinary day light to etch and make visible tracks in polymers/ mineral crystals/glasses.

• The integrating nature of the detectors allows events to be accumulated over long period of time. If the normal temperature, pressure and such environmental conditions are normal, the stored information can be preserved almost indefinitely which can be examined any time even after several years.

• They are passive detectors and do not require power supplies during its use, in contrast to electronic detectors such as ionization chambers

• Some of SSNTDs e.g. CR-39 can detect charged particles down to protons

• Their geometrical flexibility makes them suitable for angular distribution measurements in nuclear reactions

• These detectors are highly durable and pose no health effect or handling problems (45).

3.6.1 Types of Etched Track Detectors

Several detector materials using Copolymers of various carbonic acid diesters have been developed. CR-39 and LR-115 are the two most popular track detectors used in radon dosimetry. One of the greatest advantages of CR-39 and LR-115 is that the unevenness of track profiles resulting from inhomogeneity and anisotropy are found to be low in these detectors. One of the most commonly used nuclear track detector is the CR-39, which was based on polyallyl diglycol carbonate and was discovered by Cartwright. CR-39 (Columbia Resin-39) is the name of the thermo set plastic which is a polymeric form of diethylene glycol bis allyl Carbonate. Its simple formula is \((C_{12}H_{18}O_7)_n\). CR-39 can detect protons of energy up to 10 MeV and has a wide energy range for α-particles detection (0.1 MeV to 20 MeV)\(^{(46)}\). CR-39 is highly isotropic, homogenous, relatively stable to environmental conditions and there is no cross linking after radiation damage. CR-39 is being used in many fields of Science and Technology that include the personal neutron dosimeter, radon dosimeter, etc. CR-39 detects wide range of energies, however the efficiency of the CR-39 is not uniform for the whole energy range; and it is maximum for alpha particles having 3-6 MeV energy. Another most commonly used nuclear track material is the well-known cellulose nitrate which is sold under the commercial name LR 115. Other kinds of detectors are also in use, such as the Makrofol detector which is based on polycarbonate. Some natural materials that show the track effect, such as apatite, mica, olivine, etc., are used for fission or fossil track studies.
3.6.2 LR-115 Type II Pelliculable Film

In our present study, LR 115 Type II Pelliculable film is used for alpha detection. It consists of a 12-13 \( \mu \text{m} \) thick alpha-sensitive layer of red dyed cellulose nitrate plastic deposited on a 100 \( \mu \text{m} \) thick non etchable polyester base. Only the cellulose nitrate layer (6\( \mu \text{m} \) for Type I and 12\( \mu \text{m} \) for Type II films) having chemical composition of \( \text{C}_6 \text{H}_8 \text{O}_6 \text{N}_{12} \) and specific gravity 1.4 is sensitive to radiations. LR-115 films are made to convert each impact by an ionizing particle to a perforation in the colored sensitive cellulose nitrate layer. These high quality films are the result of more than 30 years’ experience of the KODAK Company in SSNTD technology. It is sensitive to alpha particles with energies in the range of 1.7- 4.2 MeV emitted by radon in the surrounding air for a distance of 1-6 cm. The films are less influenced by the moderate humidity, heat and light. LR-115 detectors do not develop tracks originating from the progeny alphas deposited on them and are therefore best suited for alpha radioactive measurements in the ambient air \( ^{(47, 48)} \).

Dosimeters using LR115 films are designed to keep the films 'Radon-proof' in order to avoid undesired exposure during storage that could result in incorrect results. The air volume between the film's surface and the protection screens is less than the minimum distance necessary for the detection of \( \alpha \)-particles. Of this reason, no background counts are observed with these dosimeters as long as their lids remain closed or the films are being kept inside the plastic envelopes that are supplied for return shipments to laboratory analysis after exposure. Although other detector materials may show higher sensitivity to \( \alpha \)-radiation, the nuclear tracks that are produced by \( \alpha \)-particles on these foils are much larger than those obtained with LR115 films. The larger size of the tracks is disadvantageous regarding the saturation level of the detectors. The higher the saturation level the longer the dosimeters can be exposed even in high radon concentration areas. The sensitivity of the LR115 films is about 1.5 - 2.4 nuclear tracks/cm², for a total radon exposure of 1 kBq/m³ \( ^{(49)} \).

The typical saturation level of LR115 film is approximately 600 tracks/mm² (diameter of tracks: 1 - 15 \( \mu \text{m} \)) compared to 50 - 400 tracks/mm² with other detector materials (diameter of tracks: 5 - 80 \( \mu \text{m} \)). The maximum exposure (saturation level) of LR115 film is in the range of 70 MBq/m³ which is significantly higher compared to other types of dosimeters. The minimum exposure, signifying the lower detection threshold, is only 2 kBq/m³. The plate out effect has an adverse influence on the precision of the Radon measurement as \( \alpha \)-particles emitted from decay products will also be detected on the film. These decay products cannot
be differentiated from radon α-particles and thus falsely inflate the final result. It is primarily the dosimeters using 'CR39' or 'Makrofol' detectors that are affected by the plate out effect, whereas it only plays a minor role in the dosimeters using LR115 film. As explained above, the reason why LR115 films are not sensitive to deposited decay products is that α-particles, generated too close to the film's surface can't be detected due to their high energies. 

3.6.3 Detector Calibration

To determine the radon concentration from nuclear track detector readings (which is the track density, or the number of tracks per unit area), one needs the knowledge of the detector sensitivity (calibration factor) which relates the track density to the total exposure of the detector to radon and its progeny. Experimental determination of this sensitivity, i.e., calibration of these detectors for radon and progeny measurements is carried out by exposing them to known concentrations of radon and/or its progeny under controlled conditions in a radon exposure chamber. It is essential to calibrate the detector under conditions which simulate those found in Indian dwellings. The calibration of the detectors has to take into consideration several features: (a) accurately known radon and thoron levels; (b) well characterized parameters with respect to daughter equilibrium factor, aerosol size, and humidity; (c) techniques used for monitoring concentrations of radon and thoron and their daughters; and (d) uniformity of radon and thoron content in the calibration chamber.

If T denotes the track densities observed on SSNTD film due to exposure in a given mode to a concentration C of given species for a time t, it is obvious that T = kCt, where, we define k as the calibration factor.

In the present work, calibration experiments were carried out at Environmental Assessment Division (EAD), Bhabha Atomic Research Centre, Mumbai, India to estimate the calibration factors separately for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in a calibration chamber.

3.7 Indoor Dosimetry Using SSNTDs

For the present investigation of inhalation dosimetry in the high background radiation area, we have used twin cup dosimeters in all the three modes of exposure. The protocol adopted for the study was formulated in consultation with the experts of Bhabha Atomic Research Centre as part of a collaborative research. The major steps of the study include deployment of the dosimeters in the selected dwellings, active measurement of ambient gamma levels in the
indoor atmosphere, retrieval of the detectors, chemical etching of the detectors, scanning of the etched track detector and estimation of inhalation dose from the track density.

3.7.1 Field Visit

This work focuses, as already stated, on the inhabitants with congenital malfunctions viz. mental retardation and cleft lip/palate from the aforementioned nine Panchayats of Kollam district. The list and details of such cases in each panchayat is provided by The Low Level Radiation Research Laboratory (LLRRL), BARC, Kollam. The list also contains number of the nearest Anganwadi of each case. For making the study comprehensive and reliable, the help of Anganwadi teachers are sought. The assistance rendered by the Anganwadi teachers in locating the residence of each case and for making further queries is invaluable. The parents and neighbours of the cases will generally be very comfortable with Anganwadi teachers as they are familiar to the inhabitants in the area. The presence of an Anganwadi teacher makes the work easier as it creates a good ground support in an entirely new environment.

Upon reaching the residence of the case, the Anganwadi teacher concerned introduces the researcher. The researcher then gives a brief but complete explanation regarding the nature and aim of the study in common man’s terms. The suitability of the case is then confirmed visually in case of cleft lip/palate, and the cases of mental retardation are confirmed by the disability certificate issued by medical board established by State Government of Kerala. This is followed by preliminary enquiries regarding the malfunction, age, domicile while birth, details of mother etc. The most important criteria for selecting a case are discussed in the section 2.8 of second chapter. If the case has been accepted as per the protocols, the parents of the case are requested to grant permission to conduct the study.

The researcher then interviews the parents of cases using the comprehensive case-control data sheet and collects information on family history, reproductive history, parental habits during pregnancy period of the mother, regularity of menstrual periods, risk factors and diseases during the pregnancy period etc. Once the data sheet is filled in, the researcher fixes a twin cup dosimeter equipped with SSNTD films preferably in the bed room for duration of three months. In the dosimeter the LR-115 (type II) films cut into 3cm x 3cm pieces are already placed in the three modes: the filter mode, the membrane mode and the bare mode. These dosimeters are also fixed with a TLD (Thermo luminescent dosimeter) for the assessment of
time averaged external gamma dose in the indoor atmosphere. Dosimeter is kept at a height of 1.5 m from the ground and care is taken to keep the bare card at least 10 cm away from any surface. This ensures that errors due to tracks from deposited activity from nearby surfaces are avoided, since the ranges of alpha particles from $^{222}\text{Rn}$ or $^{220}\text{Rn}$ progeny fall within 10 cm distance. Room dimensions, ventilation conditions, nature of construction of dwellings etc. are also noted in the data form.

The next step in the procedure of the field visit is to record the locations of the cases and controls using a satellite based Global Positioning System (Vesta HCx) having a resolution of 15m. The way points mark the houses where the study is conducted. It records all geographical parameters like altitude, latitude and longitude, which can be plotted on a graph of the experimental area. The device is very helpful in locating the houses while retrieval of the dosimeters is done.

Having taken all necessary steps for conducting the study, the possible controls for the case are also identified with the help of parents of cases and anganwadi teachers. It is estimated that on an average only three acceptable controls can be identified out of ten proposed ones which makes the whole process highly demanding.

After the exposure period of 90 days, the twin cup dosimeters were retrieved and analysed. While deploying and retrieving the dosimeters in a house, survey meter readings were taken inside and outside the house at ground level and 1 meter height from the ground. Being an active method of measurement of dose it directly gives the external gamma dose.

### 3.7.2 Chemical Etching

After the retrieval of the twin cup dosimeters, detectors were subjected to chemical etching. It is a process of analyzing the recorded tracks by treating the exposed detectors with an alkali solution. Chemical etching of the detectors was done in constant temperature etching unit. The etchant used was 2.5 N NaOH. The temperature of the alkali solution was kept at 60° C and the etching continued for duration of 60 minute under mild stirring of the etchant. After etching the exposed detectors were removed from the etchant and the detectors were washed in cold running water very carefully to ensure that no trace of the etching solution remains in the detector. After a few washing the films were kept for drying using a tissue paper and the thin etched cellulose nitrate part of the detector is peeled off from the cellulose acetate base. This is quite easily done by pinching one of the corners of the film between the thumb and
the index finger. The etched films are then counted for the tracks registered using a spark counter which has already been calibrated. The figure 3.5 shows the photograph of the specially designed etching unit used in this study.

![Figure 3.5: Constant temperature Etching unit](image)

### 3.7.3 Scanning of Etched Track Detectors Using Spark Counter

Evaluation of etched track density in SSNTDs by an optical microscope is difficult and time consuming. The attempts to automatic track counting have led to the use of image analyzer instruments and spark counting systems. Spark counting technique, which is applicable to plastic detectors, provides a convenient, economical and fast method for track counting. The
spark counting technique was invented by Cross and Tommasino (1970) developed and discussed in number of publications (52-54). Figure 3.6 shows the photograph of the spark counter used in the study.

![Photograph of the spark counter](image)

**Figure 3.6:** Photograph of the spark counter

The counting process is as follows. The thin detector is placed on the top of a thick conductive electrode, made of brass and above it is placed a Mylar foil having 0.01mg/cm² aluminum coating on one side, which acts as the second electrode. It is sometime necessary to put a relatively heavy weight on top of the aluminium foil to have an intimate contact between the thin detector and the electrodes. When the high voltage is applied, an electrical discharge on spark takes place through a track-hole. The voltage pulse produced across a load resistor can easily be counted electronically by a counter.

The spark passing through a track hole has enough energy to evaporate the thin layer of aluminium coating and produces a much larger hole in the aluminium electrode. The spark, therefore, jumps randomly from one track hole to another until all track holes are counted.
The evaporated spots on the aluminium, which have the diameter of about 100 micrometer, are equal to the number of sparks and hence to the number of track holes in the plastic track detector.

Initially a pre sparking at 900 V is applied to punch out holes, which are originally not quite etched through. After the pre sparking, the voltage is reduced to the minimum and the exposed area of the pre sparked film is counted using a fresh mylar foil. This is repeated several times and the average tracks registered is taken. Before the actual scanning of the etched films, the operating voltage of the counter was determined and the operating voltage was fixed at 500 V. The sparking head area of the spark counter is 1 cm$^2$ and this will give the track density per cm$^2$ from which the activity concentration of radon and thoron can be estimated by using calibration factors. Calibration of Spark counters were done periodically with the films exposed to a standard Am$^{241}$ source of known activity (750 dpm).

3.7.4 Estimation of Inhalation Dose

The concentrations of radon ($C_R$) and thoron ($C_T$) in Bq/m$^3$ were determined from the track densities in the three detectors using the following equations$^{(43,55,56)}$.

$$C_R (\text{Bq/m}^3) = \frac{T_m}{(d \times K_m)} \quad (3.4)$$

$$C_T (\text{Bq/m}^3) = \frac{T_f - d \times C_R \times K_{rf}}{(d \times K_{tf})} \quad (3.5)$$

Where $C_R$ is the radon concentration and $C_T$ the thoron concentration, $T_m$ and $T_f$ are the track densities (in tracks/cm$^2$) of radon and radon+thoron in membrane and filter compartments respectively. $K_m$ and $K_{rf}$ are the calibration factors for radon in membrane mode and filter mode, while $K_{tf}$ is the calibration factor for thoron in filter mode. $d$ is the exposure time (90 days). In the present study the calibration factor for radon in membrane compartment used was $K_m = 0.019 \pm 0.003 \text{ Tr cm}^{-2} \text{ d}^{-1} / \text{ Bq m}^{-3}$, that for radon in filter compartment is $K_{rf} = 0.020 \pm 0.004 \text{ Tr cm}^{-2} \text{ d}^{-1} / \text{ Bqm}^{-3}$ and calibration factor for thoron in filter compartment is $K_{tf} = 0.016 \pm 0.005 \text{ Tr cm}^{-2} \text{ d}^{-1} / \text{ Bqm}^{-3}$.

The inhalation dose due to radon and thoron in mSv/y was estimated using the formula$^{(57)}$.

$$D = \{(0.17+9F_R) \times C_R + (0.11+32 F_T) \times C_T \} \times 7000 \times 10^{-6} \quad (3.6)$$
where $F_R$ and $F_T$ are equilibrium factor for radon and thoron respectively. The values are taken as 0.4 and 0.1 for radon and thoron given by UNSCEAR 2000.

Inhalation dose measurements conducted in the selected 1432 houses of occupants which include 358 cases of congenital malfunctions and their respective controls using SSNTD based twin cup dosimeter following the prescribed protocols. The validation of the results was made through inter-comparison between our research lab and that in Environmental Assessment Division, BARC, Mumbai periodically. The inhalation dose estimates are presented and discussed in detail in the chapter 5.
References


