ENVIRONMENTAL RADIOACTIVITY: A CASE STUDY IN BANGALORE METROPOLITAN, INDIA

A THESIS

Submitted by

SUNDARESHAN .S

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EDUCATIONAL AND RESEARCH INSTITUTE
UNIVERSITY
(u/s 3 of the UGC Act 1956)
CHENNAI – 600 095

FEBRUARY 2013

DECLARATION BY THE CANDIDATE
I declare that the Thesis entitled ‘**Environmental Radioactivity: A Case study in Bangalore Metropolitan, India**’ submitted for the degree of Doctor of Philosophy is a bonafied record of work carried out by me during the period from May 2004 to June 2012 under the guidance of Dr. Sathish L.A. and has not formed the basis for the award of any degree, diploma, associate-ship, fellowship or any other similar titles.

I have also published my papers in International Journals as per list of Publication in the Annexure.

Signature of the Research Scholar

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I also certify the veracity of the candidate’s declaration related the thesis.

Signature of the Supervisor

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ABSTRACT
Conceptually this thesis is structured in to five chapters namely Introduction, Literature survey, Instrumentation, Methods of Measurements, Results and Discussions followed by Conclusions, References and list of research publications by the author. The thesis eloquent the introduction to radioactivity, sources of background radiation, manmade sources, sources of $^{222}\text{Rn}$ and $^{220}\text{Rn}$, the radioactivity in atmosphere, scope and objective of the present study. The extensive studies and surveys carried out for measuring the $^{222}\text{Rn}/^{220}\text{Rn}$ and their progeny levels, the source of $^{222}\text{Rn}/^{220}\text{Rn}(^{226}\text{Ra}/^{232}\text{Th})$, radon in water and the back ground gamma radiation levels of the different environs of the world up to date are included. Definitions, specifications and block diagrams of the instruments which are used in the study are discussed extensively. Materials and methods, Calibration facility and standardization of dosimeter, Dosimetric methodology, Inhalation dose estimates are adopted by Solid Stare Nuclear Track Detectors (SSNTD) based double chamber dosimeter cup.

The results and discussion, Variations of $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny levels in different locations, different season, different floorings, different walls, different rooms and different volume of the dwellings of Bangalore Metropolitan, India and the distribution of $^{220}\text{Rn}$ and its progeny levels in a dwelling.

ACKNOWLEDGEMENT
I bow my head to the ALMIGHTY GOD for providing me the intellectual strength to carry out this work.

It gives me an immense pleasure to express my deep sense of gratitude and indebtedness to my guide Dr. L. A. SATHISH. I have also been fortunate in receiving suggestions and assistances in my schedule of research for his guidance at every stage of the present study. I have learnt various aspects of Radon studies by his stimulating guidance and encouragements at all stages of the work. To him I remain much obliged and grateful.

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I am deeply indebted to Dean-Research, Dr.M.G.R. Educational and Research Institute University, Chennai, Tamil Nadu, India for his kind help throughout this work.

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S Sundareshan

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CONCLUSIONS

$^{222}$Rn and $^{220}$Rn concentrations
Variation on room volume
$^{220}$Rn concentration level
Annual Effective Dose rate
Correlation studies
Back ground gamma radiation levels
Essence of Radon mapping and
Future study

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<td>Analogue to Digital Convertor</td>
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<td>AM</td>
<td>arithmetic means</td>
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<td>BSK</td>
<td>Banashankari</td>
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<td>CFs</td>
<td>Calibration factors</td>
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<td>CL</td>
<td>Confidence Level</td>
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<td>CPS</td>
<td>Cycles per Second</td>
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<td>DC</td>
<td>Direct Current</td>
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<td>EEC</td>
<td>Equilibrium Equivalent Concentration</td>
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<td>EHT</td>
<td>Electrical High Tension</td>
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<td>EPA</td>
<td>Environmental Protection Agency</td>
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<td>ERR</td>
<td>Expected Risk Ratio</td>
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<td>EUC</td>
<td>Environmental Union Council</td>
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<td>GM</td>
<td>Geometric Mean</td>
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<td>GMC</td>
<td>Geiger Muller Counter</td>
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<td>GNR</td>
<td>Gandhinagar</td>
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<td>GSD</td>
<td>Geometric Standard Deviation</td>
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<td>HBRAs</td>
<td>high background areas</td>
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<td>hazard index</td>
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<td>HPGe</td>
<td>Hyper Pure Germanium Detector</td>
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<td>IAEA</td>
<td>International Atomic Energy Agency</td>
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<tr>
<td>IC</td>
<td>Integrated Circuits</td>
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<td>ICRP</td>
<td>International Commission for Radiation Protection</td>
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<td>IST</td>
<td>Indian Standard Time</td>
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<td>Jaynagar</td>
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<td>LLRDS</td>
<td>Low Level Radon Detection System</td>
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<td>LPM</td>
<td>Liter Per Minute</td>
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<td>MCA</td>
<td>Multi Channel Analyzer</td>
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<td>MDA</td>
<td>Minimum Detectable Activity</td>
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<td>MLM</td>
<td>Malleshwaram</td>
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CHAPTER 1

INTRODUCTION
Exposure to ionizing radiation originates from two major sources viz: naturally occurring and man-made sources. Naturally occurring radioactivity present on the earth’s crust can be further classified into two distinct source categories such as virgin and modified natural sources. Virgin sources of radiation are of cosmogenic or primordial (terrestrial) origin and have existed on the earth since primordial times. Modified natural sources are mainly from activities like mining, usage of fossil fuel, production of fertilizers or usage of natural materials for building constructions. The latter is known as Technologically Enhanced Natural Radiation (TENR). Natural radiation is the largest contributor to the collective radiation dose to the world population. Relatively constant exposure to the population at a location is the distinctive characteristics of this radiation. The major contribution of dose from natural radiation in normal background regions arises due to inhalation of radon and its progeny and to a certain extent, due to thoron and its progeny (Porstendorfer, 1994; UNSCEAR, 2000).

Ever since studies on uranium miners established the presence of a positive risk coefficient for the occurrence of lung cancer in miners exposed to elevated levels of radon and its progeny, there has been a great upsurge of interest in programmes concerned with the measurement of radon in the environment.

This interest was accentuated by the observations of elevated radon levels in the indoor environment in many countries that led to the realization of residential radon as being a possible public health issue in the western world. It was also hoped that in conjunction with epidemiological studies, large-scale indoor radon surveys might lead to quantitative understanding of the low dose effects of radon exposures. As a result of these, considerable amount of information is now available on the levels of radon gas and its progeny in the indoor environment across the globe (UNSCEAR, 2000).

In contrast, there exist only a few studies relating to measurements of thoron in the environment (Doi and Kobayashi, 1994; Doi et al., 1994) since it is assumed that the inhalation dose to the general population from thoron and its progeny is only about 10% of the inhalation dose due to radon (UNSCEAR, 2000). But, recent studies in many countries have revealed that this assumption may not be entirely correct (Steinhausler et al., 1994). In general, such studies are important in two ways. Firstly, any radiological impact assessment of nuclear facilities, either existing or those to be set up in the future, requires information on the exposure due to natural radiation prevalent in their vicinity. Secondly, the radiation risk coefficients are fairly well established at high doses and high dose rates, whereas little is known about the effects of radiation at low dose rates.

Several epidemiological study programmes in different countries are in progress to estimate the population exposures due to natural radiation with a view to obtain the radiation risk coefficients at low dose rate levels. In this regard, radiation surveys in high background areas (HBRAs) can provide excellent settings for epidemiological studies relating to the effects of low doses of radiation. In view of these, a comprehensive estimate of the natural inhalation dose requires both radon and thoron levels in the indoor and outdoor atmosphere.
Radio nuclides’ such as $^{222}$Rn and $^{220}$Rn, from the uranium and thorium decay chains are noble gases produced by the decay of their immediate respective parent nuclides, $^{226}$Ra and $^{224}$Ra, present in natural rocks, uranium ores and soils. The decay products of $^{222}$Rn and $^{220}$Rn are the radioactive isotopes of polonium, bismuth, lead and thallium. The $^{222}$Rn decay products are divided into two groups; the short-lived $^{222}$Rn daughters such as $^{218}$Po (RaA), $^{214}$Pb (RaB), $^{214}$Bi (RaC) and $^{214}$Po (RaC’) with half-lives below 30 min, and long-lived $^{222}$Rn decay products such as $^{210}$Pb (RaD), $^{210}$Bi (RaE) and $^{210}$Po (RaF). However, $^{220}$Rn progeny has no long-lived group. Most important radionuclide in this chain is the lead isotope $^{212}$Pb with a half-life of 10.6 h. These decay products, being the isotopes of heavy metals, get attached to the existing aerosols, suspended particulate matters, in the atmosphere.

1.1 SOURCES OF $^{222}$Rn AND $^{220}$Rn

Radio nuclides; $^{222}$Rn and $^{220}$Rn, from the $^{234}$U and $^{232}$Th decay chains are noble gases produced by the decay of their immediate respective parent nuclides, $^{226}$Ra and $^{224}$Ra, present in common rocks, uranium ores and soils. The decay products of radon and thoron are the radioactive isotopes of polonium, bismuth, lead and thallium. Radon decay products are divided into two groups; the short-lived radon daughters $^{218}$Po (RaA; 3.05 m), $^{214}$Pb (RaB; 26.8 m), $^{214}$Bi (RaC; 19.7 m), and $^{214}$Po (RaC; 164 µs) with half-lives below 30 min; and the long-lived radon decay products $^{210}$Pb (RaD; 22.3y, $^{210}$Bi (RaE; 5.01 d), and $^{210}$Po (RaF; 138.4 d). There is no long-lived group for the thoron progeny. Most important radionuclide in this chain is the lead isotope $^{212}$Pb with a half-life of 10.6 h. These daughter products, being the isotopes of heavy metals, get attached to the existing aerosol particles in the atmosphere.

Their elimination from the atmosphere occurs either by radioactive decay or by other removal processes such as plate-out or surface deposition and washout by rain. Vast difference in the half-lives of radon (3.8 d) and thoron (55 s) is a crucial parameter in governing their release from the ground and subsequent distribution in the free atmosphere. When radium decays in soil grains, the resulting atoms of radon isotopes first escape from the mineral grains to air-filled pores.

The fraction of radon escapes into the pores is known as the emanation power fraction. Although the detailed processes responsible for radon emanation from grains are not fully understood, it is believed that the main contribution to the emanation comes from the recoil processes (Nazaroff, 1988). The recoil lengths are about 0.04 - 0.06 µm in grain materials and about 60 µm in air. Also, recoil-stopping distance of radon and thoron is lower in water than in air. Hence, the moisture content has effects on the emanation power fraction (Shaskhin and Prutkina, 1970; Megumi and Mamuro, 1974; Strong and Levins, 1982; Ingersall, 1983; Stranden et al., 1984). Emanation power fraction of building materials for thoron is about 2-10 times smaller than that for radon, despite the greater recoil energy of thoron atoms.
Experimental studies on building show that it ranges from 0.2 to 30 % for radon and 0.2 to 6 % for thoron (Porstendorfer, 1994; Barretto et al., 1972).

Transport of radon through the soil takes place by diffusion and/or with gases like CO\textsubscript{2} and CH\textsubscript{4} or water moving in the soil horizons. The diffusion coefficient for radon in different soil types varies from $10^{-9}$ m\textsuperscript{2}s\textsuperscript{-1} in water medium to $10^{-5}$ m\textsuperscript{2}s\textsuperscript{-1} in air (UNSCEAR, 1982). Radon and thoron enter the atmosphere mainly by crossing the soil-air or building material-air interface.

Typical values of exhalation rate (amount of activity released per unit area of the surface per unit time) for radon in soil and building material are $0.02$ and $5 \times 10^{-4}$ Bqm\textsuperscript{-2}s\textsuperscript{-1} respectively. The same for thoron are as high as $1$ and $0.05$ Bqm\textsuperscript{-2}s\textsuperscript{-1} respectively (Porstendorfer, 1994). Radon and thoron progeny aerosols in the atmosphere are generated in two steps. After the formation from the radon isotope by decay, the freshly generated radionuclides react very fast with trace gases and air vapors, and become small particles, called clusters or unattached radionuclides with diameters varying from 0.5 to 5 nm. In addition, these radionuclides attach to the existing aerosol particles in the atmosphere within 1 - 100 s, forming the radioactive aerosols. Most of the newly formed decay product clusters are positively charged and have a high mobility (Porstendorfer and Mercer, 1979). Mobility is characterized by the diffusion coefficient that mainly controls the formation of the radioactive aerosol by attachment and their deposition on surfaces and in the human lung.

Radon and thoron in indoor environments mainly originate from emanation of the gases from the walls, floor and ceilings. Most terrestrial building materials have 1000 to 10000 times higher gas concentrations in their pore spaces than in the atmosphere, permanently maintained by the continuous decay of its parent nuclides. This high concentration leads to a large radon/thoron concentration gradient between the materials and open air. Levels of radon and thoron in the open atmosphere are governed by the balance between the exhalation rate and the atmospheric dilution processes.

### 1.2 DEFINITION, QUANTITIES AND UNITS

As is well known, the dose to the lung is primarily contributed by the radon progeny species deposited in the respiratory organs. This dose is a function of several variables such as the activity - size distribution of the species, breathing parameters etc. However, standard calculations have been made considering typical values for these parameters. Dose conversion factors estimated this way, relate the default dose to the lung per unit concentration in air. However, the radon and thoron progeny concentrations in view of their short-lived nature are expressed in terms of a special quantity known as Potential Alpha Energy Concentration (PAEC), usually expressed in the units of Jm\textsuperscript{-3}. PAEC of an atom in the decay chain is defined as the total alpha energies emitted during the decay of this atom along the decay chain starting from $^{218}$Po up to $^{210}$Pb (RaD) or $^{208}$Pb for radon or thoron respectively. PAEC of any mixture of
short-lived radon or thoron progenies in air is the sum of the potential alpha energy of all daughter product atoms present per unit volume of air.

Often, a special unit Working Level (WL) is used for quantifying the PAEC for radiation protection purposes. One WL is defined as that concentration of short-lived radon/thoron decay products in any combination, which would potentially produce 130000 MeV of alpha particle kinetic energy per liter of air.

One WL for radon concentration corresponds to the total potential alpha energy concentration of short-lived radon progeny, which are in radioactive equilibrium with a radon concentration of 3700 Bqm$^{-3}$. For thoron progeny, this corresponds to a thoron concentration of 275 Bqm$^{-3}$. The potential alpha energies per atom and unit activity of radon and thoron and short-lived daughter nuclides are given in Table 1.1 (ICRP, 1981). Radon/thoron progeny concentration exposure is often expressed in terms of Working Level Month (WLM), which corresponds to an exposure of 1 WL during a reference-working period of one month (2000 working hours per year/12 month = 170 hrs).

### Table 1.1: Potential Alpha Energy of Radon and Thoron Progeny

(ICRP, 1981; Porstendorfer, 1994)

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-life</th>
<th>Potential Alpha Energy</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>per atom</td>
<td>per Bq</td>
<td>MeV</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>3.8 d</td>
<td>19.2</td>
<td>3.07</td>
<td>9.5 × 10$^{-6}$</td>
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<tr>
<td>$^{248}$Po(RaA)</td>
<td>3.05 min</td>
<td>13.7</td>
<td>2.19</td>
<td>3620</td>
</tr>
<tr>
<td>$^{214}$Pb(RaB)</td>
<td>26.8 min</td>
<td>7.69</td>
<td>1.23</td>
<td>17800</td>
</tr>
<tr>
<td>$^{214}$Bi(RaC)</td>
<td>19.7 min</td>
<td>7.69</td>
<td>1.23</td>
<td>13100</td>
</tr>
<tr>
<td>$^{214}$Po(RaC')</td>
<td>164 μs</td>
<td>7.69</td>
<td>1.23</td>
<td>2.0 × 10$^{-3}$</td>
</tr>
<tr>
<td>$^{220}$Rn</td>
<td>55.6 s</td>
<td>20.9</td>
<td>2.34</td>
<td>1660</td>
</tr>
</tbody>
</table>
Table 1.2: Natural Radioactivity Content in Indian Building Materials

(Menon et al., 1987)

<table>
<thead>
<tr>
<th>Material</th>
<th>40K (Bqkg(^{-1}))</th>
<th>226Ra (Bqkg(^{-1}))</th>
<th>232Th (Bqkg(^{-1}))</th>
<th>Radium equivalent (Bqkg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>5-385</td>
<td>16-377</td>
<td>8-78</td>
<td>40-440</td>
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<tr>
<td>Brick</td>
<td>130-1390</td>
<td>21 - 48</td>
<td>26 - 126</td>
<td>88 - 311</td>
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<tr>
<td>Stone</td>
<td>48-1479</td>
<td>6 - 155</td>
<td>5 - 412</td>
<td>24 - 311</td>
</tr>
<tr>
<td>Sand</td>
<td>5-1074</td>
<td>1-5047</td>
<td>4 - 2971</td>
<td>22 - 7759</td>
</tr>
<tr>
<td>Granite</td>
<td>76-1380</td>
<td>4 - 98</td>
<td>103 - 240</td>
<td>25 - 525</td>
</tr>
<tr>
<td>Clay</td>
<td>6 - 477</td>
<td>7 - 1621</td>
<td>4 - 311</td>
<td>11 - 1865</td>
</tr>
<tr>
<td>Fly ash</td>
<td>6 - 522</td>
<td>7 - 670</td>
<td>30 - 159</td>
<td>56-773</td>
</tr>
<tr>
<td>Lime stone</td>
<td>6 - 518</td>
<td>1 - 26</td>
<td>1 - 33</td>
<td>5-148</td>
</tr>
<tr>
<td>Gypsum</td>
<td>70 - 807</td>
<td>7 - 807</td>
<td>1 - 152</td>
<td>59-881</td>
</tr>
</tbody>
</table>
It can be seen from these tables that $^{40}\text{K}$ is also a major source of radiation in the environment.

Table 1.3: Natural Radioactivity Content in Indian soil (Mishra et al., 1971; Sadasivan et al., 2003)

<table>
<thead>
<tr>
<th>Location</th>
<th>$^{232}\text{Th}$</th>
<th>$^{226}\text{Ra}$</th>
<th>$^{40}\text{K}$</th>
<th>Location</th>
<th>$^{232}\text{Th}$</th>
<th>$^{226}\text{Ra}$</th>
<th>$^{40}\text{K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahmedabad</td>
<td>53.0</td>
<td>24.8</td>
<td>526.6</td>
<td>Kanpur</td>
<td>23.8</td>
<td>24.0</td>
<td>850.9</td>
</tr>
<tr>
<td>Aligarh</td>
<td>82.0</td>
<td>54.4</td>
<td>530.1</td>
<td>Kharagpur</td>
<td>18.4</td>
<td>15.2</td>
<td>72.2</td>
</tr>
<tr>
<td>Bangalore</td>
<td>16.9</td>
<td>15.2</td>
<td>486.7</td>
<td>Kakrapar</td>
<td>12.4</td>
<td>12.2</td>
<td>94.4</td>
</tr>
<tr>
<td>Bhopal</td>
<td>15.7</td>
<td>11.8</td>
<td>376.8</td>
<td>Chennai</td>
<td>23.1</td>
<td>6.7</td>
<td>766.2</td>
</tr>
<tr>
<td>Bikanir</td>
<td>11.7</td>
<td>8.8</td>
<td>439.6</td>
<td>Mangalore</td>
<td>13.5</td>
<td>9.3</td>
<td>151.2</td>
</tr>
<tr>
<td>Mumbai</td>
<td>13.5</td>
<td>9.4</td>
<td>169.6</td>
<td>Meerut</td>
<td>22.0</td>
<td>22.7</td>
<td>112.3</td>
</tr>
<tr>
<td>Kolkatta</td>
<td>24.1</td>
<td>20.4</td>
<td>662.9</td>
<td>Nagpur</td>
<td>16.5</td>
<td>11.8</td>
<td>307.7</td>
</tr>
<tr>
<td>Cherrapunji</td>
<td>17.4</td>
<td>21.5</td>
<td>37.7</td>
<td>Nainatal</td>
<td>24.8</td>
<td>24.7</td>
<td>979.7</td>
</tr>
<tr>
<td>Chingalput</td>
<td>120.5</td>
<td>22.9</td>
<td>408.2</td>
<td>Nasik</td>
<td>34.4</td>
<td>18.6</td>
<td>290.6</td>
</tr>
<tr>
<td>Coimbatore</td>
<td>10.1</td>
<td>10.2</td>
<td>266.9</td>
<td>Ooty</td>
<td>3.4</td>
<td>2.5</td>
<td>87.8</td>
</tr>
<tr>
<td>Cuttack</td>
<td>61.7</td>
<td>15.3</td>
<td>722.2</td>
<td>Poona</td>
<td>4.2</td>
<td>3.0</td>
<td>87.9</td>
</tr>
<tr>
<td>Darjeeling</td>
<td>24.8</td>
<td>2417</td>
<td>678.2</td>
<td>Ranchi</td>
<td>22.4</td>
<td>24.4</td>
<td>1055.0</td>
</tr>
<tr>
<td>Dehradun</td>
<td>22.6</td>
<td>25.9</td>
<td>803.8</td>
<td>Shillong</td>
<td>23.9</td>
<td>15.5</td>
<td>323.2</td>
</tr>
<tr>
<td>Delhi</td>
<td>19.9</td>
<td>19.2</td>
<td>536.9</td>
<td>Srinagar</td>
<td>18.6</td>
<td>14.8</td>
<td>615.4</td>
</tr>
<tr>
<td>Dhanbad</td>
<td>37.1</td>
<td>53.0</td>
<td>345.4</td>
<td>Tehri</td>
<td>136.2</td>
<td>81.6</td>
<td>328.2</td>
</tr>
<tr>
<td>Gangtok</td>
<td>23.9</td>
<td>26.1</td>
<td>854.1</td>
<td>Thiruvalla</td>
<td>74.3</td>
<td>19.8</td>
<td>25.1</td>
</tr>
</tbody>
</table>
Table 1.4 gives the estimated ranges of radon entry rate from different sources in typical houses (ICRP, 1986). It is evident that soil has the highest entry rates followed by brick or concrete.

### Table 1.4: Volume Specific Entry Rate and indoor Radon Levels from Various Sources (ICRP, 1986)

<table>
<thead>
<tr>
<th>Source</th>
<th>Specific entry rate (Bqm⁻³h⁻¹)</th>
<th>Indoor radon* (Bqm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick or concrete</td>
<td>Estimated mean: 2-20, Range: 1-50</td>
<td>Estimated mean: 3-30, Range: 0.7-100</td>
</tr>
<tr>
<td>Wooden Houses</td>
<td>Estimated mean: &lt; 1, Range: 0.05-1</td>
<td>Estimated mean: &lt; 1, Range: 0.03-2</td>
</tr>
<tr>
<td>Soil</td>
<td>Estimated mean: 1-40, Range: 0.5-200</td>
<td>Estimated mean: 2-60, Range: 0.5-500</td>
</tr>
<tr>
<td>Outdoor air</td>
<td>Estimated mean: 2-5, Range: 0.3-15</td>
<td>Estimated mean: 3-7, Range: 1-10</td>
</tr>
<tr>
<td>Others (walls, natural gas)</td>
<td>Estimated mean: &lt; 0.1, Range: 0.01-10</td>
<td>Estimated mean: &lt;0.1, Range: 0.01-10</td>
</tr>
<tr>
<td>All sources</td>
<td>Estimated mean: 6-60, Range: 2-200</td>
<td>Estimated mean: 10-1000, Range: 2-500</td>
</tr>
</tbody>
</table>

* Mean ventilation rate used is 0.7 h⁻¹ (normal range 0.3 – 1.5 h⁻¹)

Environmental measurements of radon were mostly confined to outdoor air earlier. Since 1970, indoor radon levels were measured with keen interest, and several large-scale surveys have been carried out by several agencies all over the world (Campos-Venuti et al., 1994; Hopke and Moghissi, 1996; UNSCEAR, 2000). Typical worldwide indoor and outdoor levels of radon are about 45 Bqm⁻³ and 7 Bqm⁻³ respectively and that of outdoor thoron level is estimated as 0.2 Bqm⁻³ (Mettler and Upton, 1995). An initial survey in Indian houses indicates that the indoor radon concentration varied between 2.2 and 56 Bqm⁻³ with a geometric mean of 15.1 Bqm⁻³.
Table 1.5: Reported Indoor Radon Levels Around the World (UNSCEAR, 2000)

<table>
<thead>
<tr>
<th>Region</th>
<th>Country</th>
<th>Concentration (Bqm$^{-3}$)</th>
<th>AM</th>
<th>GM</th>
<th>Max</th>
<th>GSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>Algeria</td>
<td>30 - 140</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Egypt</td>
<td>9 - 24</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td>Ghana</td>
<td>- 340</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>North America</td>
<td>Canada</td>
<td>34 14 1720</td>
<td>3.6</td>
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<td></td>
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<tr>
<td></td>
<td>United States</td>
<td>46 25 -</td>
<td>3.1</td>
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<tr>
<td>South America</td>
<td>Argentina</td>
<td>37 26 211</td>
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<tr>
<td></td>
<td>Chile</td>
<td>25 - 86</td>
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<td></td>
<td>Paraguay</td>
<td>28 - 51</td>
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<td></td>
<td>Belgium</td>
<td>48 38 12000</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>France</td>
<td>62 41 4690</td>
<td>2.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Germany</td>
<td>50 40 &gt;10000</td>
<td>1.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ireland</td>
<td>- 37 1700</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Luxemburg</td>
<td>110 70 2500</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Netherlands</td>
<td>23 18 380</td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switzerland</td>
<td>70 50 10000</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>U. K.</td>
<td>20 - 10000</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Europe</td>
<td>Bulgaria</td>
<td>- 22 250</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Czech Republic</td>
<td>140 20000</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hungary</td>
<td>107 82 1990</td>
<td>2.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poland</td>
<td>41 32 432</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Romania</td>
<td>45 - 1025</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slovakia</td>
<td>87 - 3750</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Europe</td>
<td>Albania</td>
<td>120 105 270</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Croatia</td>
<td>35 32 92</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cyprus</td>
<td>7 7 78</td>
<td>2.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Greece</td>
<td>73 52 490</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td>75 57 1040</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Portugal</td>
<td>62 45 2700</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slovenia</td>
<td>87 60 1330</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The reported indoor radon and thoron levels in about 35 countries world over are given in Tables 1.5 and 1.6 respectively (UNSCEAR, 2000). Table 1.5 shows that the population weighted worldwide average radon concentration is 39 Bqm$^{-3}$; while the geometric mean calculated for the data is 30 Bqm$^{-3}$ with a geometric standard deviation of 2.3. The average EECs of indoor thoron levels (Table 1.6) range between 0.2 Bqm$^{-3}$ and 12 Bqm$^{-3}$; while the ratio of $^{222}$Rn/$^{220}$Rn EEC varied from 0.01 to 0.5 worldwide.

Table 1.6: Outdoor and Indoor Thoron Levels around the World (UNSCEAR, 2000)

<table>
<thead>
<tr>
<th>Country</th>
<th>Equilibrium equivalent concentration (Bqm$^{-3}$)</th>
<th>$^{220}$Rn/$^{222}$Rn EEC ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outdoor</td>
<td>Indoor</td>
</tr>
<tr>
<td>North America</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>United States of America</td>
<td>0.09</td>
<td>(0.03-0.3)</td>
</tr>
<tr>
<td>China</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>0.3</td>
<td>(0.1-0.5)</td>
</tr>
<tr>
<td>Japan</td>
<td>0.09</td>
<td>(0.03-0.12)</td>
</tr>
<tr>
<td>Malaysia</td>
<td>0.5</td>
<td>(0.3-1.8)</td>
</tr>
<tr>
<td>France</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Germany</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Republic of Moldova</td>
<td>0.2</td>
<td>(0.1-0.6)</td>
</tr>
<tr>
<td>Romania</td>
<td>0.3</td>
<td>(0.1-0.6)</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>-</td>
<td>(1.1-7.1)</td>
</tr>
<tr>
<td>Italy</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>Slovenija</td>
<td>0.12</td>
<td>(0.05-0.37)</td>
</tr>
<tr>
<td>Range</td>
<td>(0.09 - 0.5)</td>
<td>(0.2 -12)</td>
</tr>
</tbody>
</table>

All this information facilitated the understanding of many environmental processes, which affect the distribution of radon and thoron levels in indoors and outdoors and the related radiation exposure to man.
However, there still exist many problems associated with the accurate assessment of exposures and radiation doses to general population due to radon, thoron and their progeny.

1.3 EPIDEMIOLOGICAL STUDIES

Historically, the awareness about the carcinogenic nature of radon came during the study of uranium miners beginning with the earliest observations Nagaratnam, 1994; Jacobi, 1993, followed by several observational studies carried by others all over the world (Ludewig and Lorenzer, 1924; Bale and Shapito, 1956). The most extensive epidemiological study of radon exposures is the joint analyses of the 11 underground miner cohorts (Lubin et al., 1994; Samet et al., 1991; ICRP, 1984). The database included populations across countries such as China, Europe, USA and Canada. A total of about 2736 lung cancer deaths were observed in a database of 1151315 Person Years (PY) with exposures ranging from 8 to 800 WLM. This yielded a statistically significant Expected Risk Ratio (ERR) of 0.5 % per WLM (ICRP, 1991; 1993; Muirhead, 1997). Based on these estimates, it has been surmised that indoor radon, which is present in high concentrations in many countries, may contribute significantly to lung cancer risks. This resulted in residential epidemiological studies in many countries (Blot et al., 1990; Lubin et al., 1990; Schoenberg et al., 1990; Pershagen et al., 1992; Schoenberg et al., 1992; Alavanja et al., 1994; Letoumeau et al., 1994; Pershagen et al., 1994; Lubin et al., 1994). However, these studies have not shown any definite association between residential radon exposure and lung cancer risk (Lubin et al., 1995).

The above finding has been interpreted as evidence to show that (i) exposure to radon progeny at the levels typically found in houses does not cause lung cancer, (ii) exposure to radon progeny in houses causes lung cancer but not to the extent estimated from risk models based on underground miners, or (iii) risk among miners, roughly confounded by smoking or by other exposures in mines, and risk models based on miners are therefore not applicable to residential exposures. This has led to claims that indoor radon may not pose a significant health hazard to the general population and that current approaches to risk management cannot be justified (Alderson, 1994). However, the studies carried out by Lubin et al., (1995) showed that the data from published case control studies support a wide range of risks of residential exposure to radon progeny, from as low as no effect at all to an effect greater than predicted by miner studies. This wide range is attributed to the uncertainties associated with information on population mobility and cumulative radon exposure.

Concern has also developed about possible associations of indoor radon exposure with other cancers (Lucie, 1989; Alexander et al., 1990; Henshaw et al., 1990; James, 1992; Richardson et al., 1991; Lubin et al., 1997; Harley and Robbins, 1992; Allen et al., 1995). However, several other studies oppose this concept based on many uncertainties (Sternfeld et al., 1987; Lubin et al., 1998; Paintadose et al., 1988; Brenner et al., 1992; Greenland, 1992).
In spite of all these limitations, epidemiological methods are the only options available for assessing the risk due to radiation exposure in humans. Outstanding issue now is the health effects of low levels of chronic radiation exposures. So far, no definite trends are observed in the available studies and there exists a large variability in the effects obtained in different facilities and cohorts. Results of continuing studies would eventually lead to a definite picture of the corresponding dose response relationships and the risk estimates.

1.4 OBJECTIVES OF THE PRESENT STUDY

The external gamma dose rates have been more or less well mapped in India by several studies. A countrywide survey of outdoor natural gamma radiation levels using Thermo Luminescent Dosimeters (TLD) covering about 214 locations scattered all over India revealed that the average external gamma radiation dose for the country is about 775 nGy\(^{-1}\) (Nambi et al., 1987). Mishra and Sadasivan (1971) have projected a national average value of 707 nGy\(^{-1}\) based on natural radioactivity analysis of undisturbed soil samples from more than 30 different locations, all over the country, assuming a uniform cosmic ray component of 287 nGy\(^{-1}\). Of the terrestrial component, 48.7% of the contribution is from \(^{40}\)K and the remainder is by the thorium (33.6%) and uranium series (17.7%) (Sadasivan et al., 2003).

A good database on the countrywide concentration levels of \(^{238}\)U, \(^{232}\)Th and \(^{40}\)K in geological materials as shown in Table 1.7.

### Table 1.7: Uranium, Thorium and Potassium Content in Indian Rocks

<table>
<thead>
<tr>
<th>State</th>
<th>(^{238})U (Bqkg(^{-1}))</th>
<th>(^{232})Th (Bqkg(^{-1}))</th>
<th>Potassium (%)</th>
<th>(^{40})K (Bqkg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andaman &amp; Nicobar</td>
<td>31.5</td>
<td>27.4</td>
<td>1.22</td>
<td>378.2</td>
</tr>
<tr>
<td>Andhra Pradesh</td>
<td>33.2</td>
<td>40.9</td>
<td>1.65</td>
<td>511.5</td>
</tr>
<tr>
<td>Arunachal Pradesh</td>
<td>34.9</td>
<td>98.2</td>
<td>2.00</td>
<td>620.0</td>
</tr>
<tr>
<td>Assam</td>
<td>63.0</td>
<td>129.3</td>
<td>2.41</td>
<td>747.1</td>
</tr>
<tr>
<td>Bihar</td>
<td>40.9</td>
<td>36.9</td>
<td>1.62</td>
<td>502.2</td>
</tr>
<tr>
<td>Daman &amp; Diu</td>
<td>55.7</td>
<td>24.5</td>
<td>1.63</td>
<td>412.3</td>
</tr>
<tr>
<td>Delhi</td>
<td>32.6</td>
<td>30.4</td>
<td>1.87</td>
<td>579.7</td>
</tr>
<tr>
<td>Goa</td>
<td>33.0</td>
<td>30.5</td>
<td>1.33</td>
<td>412.3</td>
</tr>
<tr>
<td>Gujarat</td>
<td>55.7</td>
<td>24.5</td>
<td>1.63</td>
<td>505.3</td>
</tr>
<tr>
<td>Haryana</td>
<td>32.6</td>
<td>30.4</td>
<td>1.87</td>
<td>579.7</td>
</tr>
<tr>
<td>Himachal Pradesh</td>
<td>32.6</td>
<td>30.4</td>
<td>1.87</td>
<td>579.7</td>
</tr>
<tr>
<td>Jammu &amp; Kashmir</td>
<td>43.4</td>
<td>29.0</td>
<td>1.76</td>
<td>545.6</td>
</tr>
<tr>
<td>Karnataka</td>
<td>33.0</td>
<td>30.5</td>
<td>1.33</td>
<td>412.3</td>
</tr>
<tr>
<td>Kerala</td>
<td>45.1</td>
<td>47.6</td>
<td>1.80</td>
<td>558.0</td>
</tr>
<tr>
<td>Madhya Pradesh</td>
<td>44.0</td>
<td>31.6</td>
<td>1.48</td>
<td>458.8</td>
</tr>
<tr>
<td>Maharashtra</td>
<td>31.7</td>
<td>33.4</td>
<td>1.64</td>
<td>508.4</td>
</tr>
<tr>
<td>Manipur</td>
<td>95.2</td>
<td>36.2</td>
<td>1.63</td>
<td>505.3</td>
</tr>
<tr>
<td>Meghalaya</td>
<td>66.7</td>
<td>32.0</td>
<td>1.67</td>
<td>517.7</td>
</tr>
<tr>
<td>Mizoram</td>
<td>35.5</td>
<td>28.8</td>
<td>1.87</td>
<td>579.7</td>
</tr>
<tr>
<td>Nagaland</td>
<td>89.1</td>
<td>39.5</td>
<td>2.00</td>
<td>620.0</td>
</tr>
</tbody>
</table>
Thus, there exists a good knowledge on the total external radiation levels across the country. Since it is estimated that nearly 50% of the total radiation dose to the population is contributed by the inhalation dose due to radon and its progeny (UNSCEAR, 2000), there is a need to supplement the external exposure data with the inhalation component.

Although some information about radon is available, there is a need to delineate the contribution of thoron and its progeny to the inhalation dose. This scientifically spirited concern has been voiced in many for a consisting of several research institutions and universities on many occasions. A resolution to this concern finally emerged in the present research work.

Realizing the scientific significance of the project, the research funding council for the major research project, university grants commission, New Delhi, India agreed to sponsor the project with a total outlay of Rs. 10.00 Lakh for the period of three years.

Earlier work for the environment of Bangalore city reveals that, the activity concentrations of $^{226}$Ra in soil varied in the range of 7.7–111.6 Bqkg$^{-1}$ with a mean value of 26.2 Bqkg$^{-1}$. The concentration of $^{232}$Th varied in the range 16.7–98.7 Bqkg$^{-1}$ with a mean value of 53.1 Bqkg$^{-1}$ and that of $^{40}$K in the range 151.8–1424.2 Bqkg$^{-1}$ with a mean value of 635.1 Bqkg$^{-1}$ (Shiva Prasad et al., 2008). It may be noted that the concentrations of $^{226}$Ra and $^{232}$Th observed in some regions are significantly higher when compared to the other sampling stations.

It is interesting to note that the soil collected at some locations showed a $^{226}$Ra concentration of 111.6 Bqkg$^{-1}$, which is more than 3 times higher than the worldwide average value of 32.0 Bqkg$^{-1}$ and also other regions of India. In about 67% of the samples from Bangalore region the $^{232}$Th concentrations were more than the world average of 40.0 Bqkg$^{-1}$. In five samples the concentrations were more than two-fold of that of the world average. In these five samples, the concentration was around 90.0 Bqkg$^{-1}$ (Shiva Prasad et al., 2008).
Further, the concentration levels of $^{222}\text{Rn}$ in ground water samples of Bangalore Metropolitan showed the analytical results of several groundwater samples collected from the gneissic and granitic rocks were above the permissible limit of 11.8 BqL$^{-1}$ and at places the concentration is as high as hundred times. The radon gas is occurring in the groundwater of the area ranging from 55.9 BqL$^{-1}$ to 1189.3 BqL$^{-1}$ plus or minus error values (Hunse et al., 2010). In view of this it was thought that is highly essential to know the possible health hazards due to the exposure of radon to the inhabitants of Bangalore city and an attempt has been made to study the variation of $^{222}\text{Rn}$, $^{220}\text{Rn}$, their progeny and their dose rates to the inhabitants of Bangalore metropolitan and the impact on health.

The proposed research work envisages the environmental radioactivity in Bangalore city with the specific attention to the measurements of indoor radon, thoron and their progeny levels in dwellings of Bangalore city and their impact on health. The major objectives of the present research work are:

- To study the background radiation for the environment of Bangalore
- To study the seasonal variations of indoor radon and thoron levels
- To study the variations of radon, thoron in dwellings of different features
- To study the correlation between $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{222}\text{Rn}$, $^{220}\text{Rn}$

In view of the above aims, the dosimeters have been deployed since April 2007 to 2011 for the measurement of seasonal variations of indoor radon, thoron and their progeny levels, different rooms of the same houses and different type of houses with respect to different floorings, ventilation, volume and walls.

The experimental methodology is as per the standard protocol provided by the Environmental Assessment Division, Department of Atomic Energy, Bhabha Atomic Research Center, Government of India, Mumbai for radon groups working in the country.

1.5 AREA OF PRESENT STUDY
The area of present study is Bangalore Metropolitan, India and the locative map is shown in Fig. 1.6.

![Locative map of Bangalore Metropolitan, India](image)

The district lies between the latitudes 12°39' to 13°13' N and longitudes 77°22' to 77°52' E. The climate is having four distinct seasons, viz., summer season, rainy season, autumn season and winter season. April is usually the hottest month with the mean daily maximum temperature of 30-35 °C and mean daily minimum at 20-24 °C. The geology of this part forms predominantly a granite terrain with numerous varieties of granites, granitic gneiss, pegmatite, charnockites and so on. The rocks around the
study area are called Closepet granites (Ningappa et al., 2008). These rocks are younger than the peninsular gneiss, made up of several types of potassium granites with variable color, texture and multiple intrusion relationship.

The common rocks are pink, grey and porphyrite gneisses with large feldspars, black dolerite. These rocks form geological band of a width 15–25 km. The radioactivity reported for the building materials collected from this region is higher compared with soil radioactivity (Ramachandran et al., 2011). However, major quantity of bricks used for the construction of the buildings are brought from places in the city out skirts called Nelamangala, Magadi etc. and a small portion from Hoskote, Ramanagara and Channapattana of radial distance 60 km. The average activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K in the soils of Nelamangala and Magadi are reported as $31.3 \pm 0.6$, $52.6 \pm 0.9$ and $303.1 \pm 6.1$ Bqkg$^{-1}$ and $16.9 \pm 0.6$, $57.5 \pm 1.1$ and $1073.0 \pm 15.6$ Bqkg$^{-1}$ respectively (Shiva Prasad et al., 2008).

The reported values of radon concentration occurring in the groundwater of the study area ranging from $55.9$ BqL$^{-1}$ to $1189.3$ BqL$^{-1}$ (Hunse et al., 2010). The authors have also reported that the radon concentration is above the permissible limit of $11.8$ BqL$^{-1}$ and at places the concentration is as high as hundred times (Hunse et al., 2010).

### 1.6 GEOLOGY AND GEOMORPHOLOGY

Bangalore city lies over a hard and moderately dense gneissic basement dated back to the Archean era (2500–3500mya). A large granitic intrusion in the south central part of the city extends from the Golf Course in the north central to Vasantpur in the south of the city (almost 13 km in length) and on an average 4 km from east to west along the way. A magmatite intrusion formed within the granitic one extends for approximately 7.3 km running parallel with Krishna Rajendra road/Kanakpura road from Puttanna Chetty road in Chamrajpet till Bikaspura road in the south. These basic intrusions which mark the close of the Archean era (Lower Proterozoic; 1600–2500 mya) mainly constitute hard massive rocks such as Gabbro, Dolerite, Norite and Pyroxenite.
Bangalore city lies within the south pennar basin. The Vrishabhavathi, a minor tributary of the Arkavati leaves the city almost diagonally from the southwest (Kengeri). On entering, it branches off giving rise to the Nagarbhavi Thorai at the intersection of the Mysore Road and the Bangalore University Road.

The river Arkavati branches north from Cauvery, most probably due to some structural control imposed by presently active faults and other north-south trending lineaments in its course.

![Geomorphology of Bangalore area](image)

*Fig. 1.7. Geomorphology of Bangalore area (Anbazhagan and Sitharam, 2008)*

The river Ponnaiyar enters the city from the southeast and branches into two, one stream terminates in the Bellandur Lake, whereas the other continues towards
northwest. The basic geomorphology of the city comprises of a central denudational plateau and pediment (towards the west) with flat valleys that are formed by the present drainage patterns shown in Fig. 1.7.

The central denudational plateau is almost void of any topology and the erosion and transportation of sediments carried out by the drainage network gives rise to the lateritic clayey alluvium seen throughout the central area of the city. The pediment/pediplain is a low relief area that abruptly joins the plateau. The area might have uplifted along active lineaments and may have been eroded by the river Arkavati and its subtributaries. The resulting alluvial fan deposits have been deposited or transported along the waterways. (Anbazhagan and Sitharam, 2008)

All the monitored houses were on the ground floor. About twenty-houses of different construction types were chosen each in all the monitored locations. The details are presented in different chapters.
This chapter describes the extensive studies and surveys carried out for measurement of $^{222}\text{Rn}/^{220}\text{Rn}$ and their progeny levels, the source of $^{222}\text{Rn}/^{220}\text{Rn}$ ($^{226}\text{Ra}/^{232}\text{Th}$), radon in water and the background gamma radiation levels of the different environs of the world up to date.

Elham Bavarnegin et al., (2012) have done the analytical study of radionuclide concentration and $^{222}\text{Rn}$ exhalation rate in market available building materials of Ramsar a northern city of Iran, using an active radon gas analyzer with an emanation container and reported that the $^{222}\text{Rn}$ exhalation rate varied from below the minimum detection limit of 0.01 to 0.31 Bqm$^{-2}$h$^{-1}$ with an average of 0.08 Bqm$^{-2}$h$^{-1}$. The $^{226}\text{Ra}$, $^{232}\text{Th}$, and $^{40}\text{K}$ contents were also measured using a high-resolution HPGe gamma-ray spectrometer system. The radio nuclide contents varied from below the minimum detectable activity up to 73.5, 169.0 and 1.350 Bqkg$^{-1}$, with the average value of 16 ± 6, 25 ± 11, and 280 ± 101 Bqkg$^{-1}$, respectively.

Khan et al., (2012) have done the studies on preliminary measurements of $^{222}\text{Rn}$ radiations in bare mode in Rampur district of western UP (India) in 32 dwellings using solid-state nuclear track detectors (LR-115 Type II) in a bare mode. They reported, the indoor $^{222}\text{Rn}$ concentrations were found to vary from 30.0 Bqm$^{-3}$ to 85.4 Bqm$^{-3}$ with an average value of 62.36 Bqm$^{-3}$. This value is lower than the ICRP recommended values of 200 Bqm$^{-3}$. They also found that, in general, the radon level in lower floors is higher than that in upper ones in all houses.

Sathish et al., (2012) have done the studies indoor radon and reported that the measured geometric mean concentration values of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ levels were found to be 32.2±1.6 and 21.4±1.0 Bqm$^{-3}$, respectively. Whereas the dose rate received by the population of Bangalore ranged between 0.2 and 3.5 mSvy$^{-1}$ with an average and the geometric mean of 1.14±0.05 and 1.06 mSvy$^{-1}$ respectively.

Sathish et al., (2012) have done the studies on radon and thoron and reported that the estimated concentration of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ varied from 17.2 ±1.2 to 85.8 ±2.3 Bqm$^{-3}$ and 8.3 ±1.2 to 38.3 ±5.4 Bqm$^{-3}$ with a mean of 32.2 ±1.6 and 21.4 ±1.0 Bqm$^{-3}$ respectively.
Barooah et al., (2011) have done the studies on study of $^{222}\text{Rn}$ exhalation rates using LR-115 nuclear track detectors in coal–mining area of the foothills of Mokakchung district, Nagaland and reported that the mass and surface exhalation rates from coal samples varied in the range 9.7-16.2 mBqkg$^{-1}$h$^{-1}$ and 323.5-538.6 mBqm$^{-2}$h$^{-1}$ respectively. The mass and surface exhalation rates from soil samples varied in the range 11.1-15.2 mBqkg$^{-1}$h$^{-1}$ and 368.3-507.6 mBqm$^{-2}$h$^{-1}$, respectively.

Binesh et al., (2011) have done the studies on radioactivity and dose assessment of heavy radioactive pollution, $^{222}\text{Ra}$ and $^{226}\text{Ra}$ from water sources of three northern regions in Iran. The reported $^{222}\text{Ra}$ levels were higher than 11 BqL$^{-1}$ as normal level. Further, $^{226}\text{Ra}$ concentrations were higher than 0.185 BqL$^{-1}$. Study also reveals, according to the advice of WHO and EU Council, $^{222}\text{Ra}$ induced the total annual effective dose is greater than 0.1 mSvy$^{-1}$ in 2 samples and in 12 samples the annual effective dose is induced by $^{226}\text{Ra}$ was greater than 0.1 mSvy$^{-1}$.

Gupta and Chauhan (2011) have done the studies on estimating radiation dose from building materials. They have measured the radioactivity using $\gamma$-ray spectrometry in naturally occurring radionuclide in the soil, stone and sand samples used as building materials in North-Eastern Haryana state of India and the reported activity concentrations of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ varied from $18 \pm 1.5$ to $156 \pm 6$ Bqkg$^{-1}$, $23 \pm 1$ to $300 \pm 5$ Bqkg$^{-1}$ and $32 \pm 0.5$ to $1705 \pm 14$ Bqkg$^{-1}$ respectively. They have also investigated the absorbed dose rate, $^{226}\text{Ra}$ equivalents, Internal and external hazard indices in soil, sand and stone samples.

Jibiri et al., (2011) have done the studies on terrestrial gamma dose rates and physical-chemical properties of farm soils from ex- tin mining locations in Jos-Plateau, Nigeria. The reported activity concentrations of the radionuclides in the farm soils were higher than world average values for normal background radiation areas.

Shashi kumar et al., (2011) have done the studies on radon in soil gas and Natural radionuclides in soil, rock and ground water samples around Mysore city and reports that the GM activity concentrations of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ in soil and rock
samples were 20.3, 64.0 and 396.7 Bqkg$^{-1}$, 46.4, 68.7 and 634.9 Bqkg$^{-1}$. Reported activity concentration is low compared with the values of world activity concentration, whereas the highest $^{226}$Ra and $^{222}$Rn activity concentration in bore well water sample were found in Chamundi hills, and were 189.10 mBqL$^{-1}$ and 434.60 BqL$^{-1}$ respectively.

Kant et al., (2010) have done the studies on radon activity and exhalation rates in Indian fly ash samples and reported that $^{238}$U, $^{226}$Ra and $^{40}$K varied from 99 ± 2 to 203 ± 4Bqkg$^{-1}$, 145 ± 2 to 288 ± 4 Bqkg$^{-1}$ and 355 ± 5 to 516 ± 6 Bqkg$^{-1}$ respectively, the reported radon exhalation rate varied from 7.8 to 21.6 mBqkg$^{-1}$h$^{-1}$ and absorbed dose rate were 143 to 277nGyh$^{-1}$.

Dainius and Aloyzas (2008) have done the studies on natural Radionuclide distribution and radon exhalation from soil in Vilnius City and reported that the activities of natural radionuclides $^{226}$Ra, $^{232}$Th and $^{40}$K, their results revealed the higher activities of $^{40}$K (263 Bqkg$^{-1}$) and the lower activity concentrations for $^{232}$Th (5 Bqkg$^{-1}$), the average $^{226}$Ra value were 13 Bqkg$^{-1}$ respectively.

Oktay et al., (2011) have done the extensive studies on assessments of natural radioactivity and radiological hazards in construction materials used in Elazig, Turkey and reported that, the specific concentrations of $^{238}$U, $^{232}$Th and $^{40}$K from selected building materials, ranged from 3.5 to 114.1 Bqkg$^{-1}$, 1.6 to 20.7 Bqkg$^{-1}$ and 201.4 to 4928.0 Bqkg$^{-1}$, respectively. The lowest of Ra$_{eq}$ is 36.5 ± 1.8 Bqkg$^{-1}$ calculated in bricks while the highest value was 405.2 ± 20.9 Bqkg$^{-1}$ in gas concrete. The reported average indoor radon concentration was 364.3 Bqm$^{-3}$, which is higher than the global mean value, in newly constructed floor.

Chauhan (2011) has done the studies on $^{222}$Rn exhalation rates from stone and soil samples of Aravalli hills in India using LR -115 alpha sensitive plastic track detector and reported the $^{222}$Rn concentration in stone samples collected from Aravalli range of hills varied from 729 to 1958 Bqm$^{-3}$ with an average of 1440±134 Bqm$^{-3}$ whereas, in case of soil samples it varied from 806 to 1325 Bqm$^{-3}$ with an average of 1040 ± 101 Bqm$^{-3}$. The measurements also indicate normal to some higher levels of
$^{222}$Rn concentration emanated from the samples collected from Aravali range of hills of North India.

Mahur et al., (2011) have done the Comparative study of indoor $^{222}$Rn, $^{220}$Rn with $^{222}$Rn exhalation rate in soil samples in some historical places at Jaipur, Rajasthan using Solid State Nuclear Track Detectors based twin chamber dosimeters and the reported $^{222}$Rn concentrations were found to vary from $18.4 \pm 3.1 \text{ Bqm}^{-3}$ to $62.1 \pm 5.7 \text{ Bqm}^{-3}$, whereas $^{220}$Rn concentrations vary from $5.9 \pm 0.6 \text{ Bqm}^{-3}$ to $22.0 \pm 2.6 \text{ Bqm}^{-3}$. $^{222}$Rn activity and $^{222}$Rn exhalation rates in the soil samples were also measured by using Sealed can technique using LR 115-type II nuclear track detectors. $^{222}$Rn activities are found to vary from 294.2 to 868.4 Bqm$^{-3}$ with an average value of 566.0 Bqm$^{-3}$. $^{222}$Rn exhalation rates in these samples vary from 146.8 to 312.2 mBqm$^{-2}$h$^{-1}$ with an average value of 203.4 mBqm$^{-2}$h$^{-1}$.

Ramachandran et al., (2011) have done the studies indoor thoron and reported that the $^{220}$Rn concentration varied from 5.7 to 42.2 Bqm$^{-3}$ with a GM of 12.2 Bq m$^{-3}$ whereas Inhalation dose rate due to $^{220}$Rn and its progeny varied from 0.047 to 0.39 mSvy$^{-1}$ with GM of 0.14 mSvy$^{-1}$.

Sathish et al., (2011) have done the studies indoor radon and reported that the radon and thoron concentration varied from 4.0 to 93.0 Bqm$^{-3}$ and their daughters concentrations ranged from 0.01–2.5 mWL. Whereas the annual effective exposure dose rate ranged from 0.1–0.4 mSvy$^{-1}$ with a mean of 0.2±0.1 mSvy$^{-1}$. The authors concluded that the concentrations of radon were higher in rooms with lower volumes and the levels of indoor radon were well within the acceptable values.

Shakir Khan et al., (2011) have done the studies on $^{226}$Ra and $^{222}$Rn exhalation studies of soil using LR-115 plastic track detectors in urban area of Elah district of Uttar Pradesh province in Northern India and the values of effective $^{226}$Ra content are found to vary from 27.87 to 45.14 Bqkg$^{-1}$ with a mean value of 34.98 Bqkg$^{-1}$. The mass exhalation rates of $^{222}$Rn vary from $2.38 \times 10^{-6}$ to $3.86 \times 10^{-6}$ Bqkg$^{-1}$d$^{-1}$ with a mean value of $2.99 \times 10^{-6}$ Bqkg$^{-1}$d$^{-1}$. The surface exhalation rates of $^{222}$Rn vary from $6.19 \times 10^{-5}$ to $10.03 \times 10^{-5}$ Bqm$^{-2}$d$^{-1}$ with a mean value of $7.77 \times 10^{-5}$ Bqm$^{-2}$d$^{-1}$. 
Sroor et al., (2011) have done the studies on natural radioactivity and $^{222}$Rn exhalation rate of soil in southern Egypt. The soil of 30 mining samples from six locations in southern Egypt, were analyzed for concentrations of radio nuclides in samples by gamma-ray spectrometer using HPGe detector with a specially designed shield. A solid state nuclear track detector SSNTD was used to measure the $^{222}$Rn concentration as well as exhalation rate for these samples. The radon concentrations were found to vary from 1.54 to 5.37 Bq kg$^{-1}$. The exhalation rates were found to vary from 338.81 to 1426.47 Bq m$^{-2}$ d$^{-1}$. They also concluded that the knowledge of the uranium concentrations is sufficient to estimate the $^{222}$Rn concentrations from the soil samples and its escape into the atmosphere.

Balakrishna et al., (2010) have done the studies on indoor radon and thoron and reported that the radon and thoron concentration were found to be 23.78 and 14.69 Bq m$^{-3}$, whereas their progeny concentrations were 0.082 and 0.044 mWL respectively. The authors concluded that the concentrations were higher during winter season, in bath rooms, in concrete walls and in granite flooring houses.

Binesh et al., (2010) have done studies on evaluation of the radiation dose from radon ingestion and inhalation in drinking water and reports that about 75% of the water samples had radon concentration greater than 10 Bq L$^{-1}$, which is advised Environmental Protection Agency’s (EPA) normal level. According to their measurements, the arithmetic means (AM) of radon concentration for all samples were 16.238 ± 9.322 Bq L$^{-1}$. Similarly, the annual effective dose in stomach and lung per person has been evaluated and 2 samples induced the total annual effective dose greater than 0.1 mSv y$^{-1}$.

Chen et al., (2010) have done the studies on $^{226}$Rn exhalation from building materials for decorative use. The results showed that slate and granite generally had higher $^{222}$Rn exhalation rates than other decorative materials. In slate and granite, $^{222}$Rn exhalation rates varied widely from non-detectable to about 300 Bq m$^{-2}$ d$^{-1}$. The average $^{222}$Rn exhalation rates were 30±16 Bq m$^{-2}$ d$^{-1}$ for slate and 42±63 Bq m$^{-2}$ d$^{-1}$ for granite respectively. The analysis also showed that granite countertops contribute very little to
the $^{222}\text{Rn}$ concentration in a kitchen. If an entire floor were covered with granite slabs of the radon exhalation rate of 300 $\text{Bqm}^{-2}\text{d}^{-1}$, it adds only 18 $\text{Bqm}^{-3}$ to indoor radon provided an air exchange system was operated properly.

Griffiths et al., (2010) have constructed a time-dependent map of radon-222 flux density at the Australian land surface with a spatial resolution of 0.05 and temporal resolution of one month and found the mean flux density was 23.4±2.0 $\text{mBqm}^{-2}\text{s}^{-1}$.

Hunse et al., (2010) have done the studies on radon in groundwater and found that the high levels of $^{222}\text{Rn}$ gas from groundwater in Bangalore and also analysed the groundwater samples from bore wells and a dug well. The authors concluded that the analytical results of all the 30 groundwater samples collected from the gneissic and granitic rocks shows radon concentration is above the permissible limit of 11.83 Bq L$^{-1}$ and the radon gas in the groundwater of the area ranged from 55.96 Bq L$^{-1}$ to 1189.30 Bq L$^{-1}$.

Kant et al., (2010) have done the studies on measurement of radium activity and radon exhalation rate and the reported activity concentration of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ in various fly ash samples varied from 99±2 to 203±4, 145±2 to 288±4, and 355±5 to 516±6 Bq kg$^{-1}$ respectively. The radium equivalent activity varied from 317 to 614 Bq kg$^{-1}$ with radon activity varied between 214 and 590 Bq m$^{-3}$. The radon mass exhalation and surface exhalation varied from 7.8 to 21.6 mBq kg$^{-1}$h$^{-1}$ and 138 to 3816 mBq m$^{-2}$h$^{-1}$. The absorbed dose varied from 143 to 277 nGy h$^{-1}$. The indoor annual effective dose varied from 0.7 to 1.36 mSv and the outdoor annual effective dose varied from 0.17 to 0.34 mSv. The authors also reports that the activity concentration of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ are below the permissible levels.

Kakali Bhuyan et al., (2010) have done the studies on distribution pattern of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in dwellings and reported that the differences between mean and median in each case, high standard deviation, significant kurtosis and skewness indicate that $^{222}\text{Rn}$ and $^{220}\text{Rn}$ emission in the study area exhibit unsymmetrical distribution with a long asymmetric tail, extending either towards higher or lower values with respect to the median.
Nagaraja et al., (2010) have done the studies on outdoor radon and reported that the average value of radon concentration of 17.50 Bqm\(^{-3}\) and the effective dose equivalent from radon and its progeny was found to be 0.55 mSv y\(^{-1}\).

Rashmi et al., (2010) have done an extensive study on activity measurement and dependence of radon exhalation rate on physical parameters in soil samples and reported that the mass exhalation and surface exhalation for grain size of 75µm and of mass 0.05Kg were 8.7±1.3 mBqkg\(^{-1}\)h\(^{-1}\) and is 185±15 mBqm\(^{-2}\)h\(^{-1}\) respectively. It also accounted that the radon exhalation rate strongly depend on physical parameters.

Sathish et al., (2010) have done the studies indoor radon and reported that the radon and thoron concentration varied from 33.4±6.1 and 21.6±2.5 Bqm\(^{-3}\) respectively. Whereas the dose rate ranged from 0.1 - 0.5 mSv y\(^{-1}\). The authors have also concluded that the concentrations of radon were higher in rooms with poorly ventilated houses.

Sivakumar et al., (2010) have done the studies on indoor radon and reported that the annual average \(^{222}\)Rn and \(^{220}\)Rn progeny levels in indoor air in Gudalore ranged between 0.99 to 7.29 and 0.84 to 5.72 mWL respectively. The authors found maximum values 3.93 mWL and 3.10 mWL during winter and minimum 3.14 mWL and 2.20 mWL during summer for \(^{222}\)Rn and \(^{220}\)Rn respectively and also observed that the ambient \(^{222}\)Rn and \(^{220}\)Rn progenies attained minima in the afternoons between 12.00 - 14.00 hrs (IST) and the highest values in the morning hours before sunrise i.e. between 3.00 - 5.00 hrs (IST) and the correlation coefficient between radon and thoron progenies was found to be 0.77.

Yang et al., (2003) have measured the exhalation of radon and its carrier gases, the reported average value of \(^{222}\)Rn concentration at Chung-lun area was 16800 Bqm\(^{-3}\), while for Yan-chao location it is 5200 Bqm\(^{-3}\). The reported activity concentration of \(^{40}\)K, \(^{232}\)Th and \(^{238}\)U for Yan-chao and Chung-lun were found to vary from 526±3 to 559±3, 28±2 to 33±7, 17±6 to 19±6 Bqkg\(^{-1}\) and 477±3 to 561±3, 34±5 to 35±5 and 16±7 to 18±6 Bqkg\(^{-1}\) respectively.
Sathish et al., (2010) have done the studies thoron and observed that the higher concentrations were at the wall, ceiling, and flooring of the room and the concentration was reduced as the detector was moved away from them.

Sathish et al., (2010) have done the studies indoor radon and reported that the average value of radon and thoron were found to be 33.4±6.1 and 21.6±2.5 Bq m⁻³ respectively and the dose rate due to radon, thoron, and their progenies ranged between 0.1–0.5 mSv⁻¹. The arithmetic and geometric mean concentrations were found to be 0.2±0.03 and 0.2 mSv⁻¹, respectively. The authors concluded that the concentrations of indoor radon, thoron and their progeny levels are more in poor ventilated houses.

Shivaram et al., (2010) have done the studies on correlation between radon and their progenies and reported that the average annual dose of radon daughters were found to be 1.98 mSv⁻¹. The authors were observed strong correlation between radon and their progenies. The authors concluded that the radon, thoron and their progeny levels vary with ventilations conditions, types of flooring and building materials and high concentration was observed in poorly ventilated and granite flooring houses.

Singh et al., (2010) have done the studies on \(^{226}\)Ra and \(^{222}\)Rn exhalation rate in some solid samples of some area of santhal pargana, Jharkhand using LR-115 Type II solid state nuclear track detector. They reported that the values of \(^{226}\)Ra concentration and \(^{222}\)Rn exhalation rate were found to be maximum in Jamatara district and minimum in Godda district. It is also observed that values were found to be more in soil compared with rock and sand samples.

Ajayi and Adesida (2009) have done the studies on radioactivity in some sachet drinking water samples produced in Nigeria and measured activity concentration values varied from 0.57 ± 0.21 to 34.08 ± 5.61 Bq L⁻¹, 2.22 ± 0.97 to 15.50 ± 4.51 Bq L⁻¹ and 0.04 ± 0.01 to 7.04 ± 1.16 Bq L⁻¹ for the radio nuclides respectively. Estimated total annual effective doses varied from 4.73 to 49.13, 1.21 to 12.26, 0.86 to 8.54, 1.22 to 11.66, 3.40 to 28.98 and 0.68 to 5.04 mSv y⁻¹ for different age groups respectively.
Kant et al., (2009) have done the studies on radon activity and radiation dose and reported that the radon activity and the annual inhalation dose in the environment of various slate stone mines in Haryana varied from 21 to 113 Bq m\(^{-3}\) with an average of 38.5 ± 5.8 Bq m\(^{-3}\) and 0.37 to 1.94 mSv with an average of 0.66 ± 0.10 mSv respectively.

Kant et al., (2009) have done the studies on radon activity and reported that the average indoor and outdoor concentrations of radon in pCi L\(^{-1}\) as 30.16±2.52 and 39.21±4.73 respectively at Botshabelo 46.06±5.21 and 47.64±5.29 for Midvaal respectively and found the indoor exposure for radon was 120.66±10.08 to 184.24±20.87 and the build-up of radon indoors and outdoors was obtained as 0.74±0.06 and 0.96±0.11 respectively for Botshabelo and 1.13±0.13 and 1.17±0.13 for Midvaal.

Michael et al., (2009) have done the studies on gamma-ray emissions from natural and manmade decorative stone and found that the activity concentrations of the radioisotopes varied by more than two orders of magnitude across the stone samples, with maximal levels of 3380, 850, and 2130 Bq kg\(^{-1}\), for \(^{238}\)U, \(^{232}\)Th, and \(^{40}\)K, respectively.

Michael et al., (2009) have done the studies on emanation of radon from granites and reported that the values of radon exhalation rate varied from 2 to 3106 mBq m\(^{-2}\) s\(^{-1}\) whereas the concentration of radon varied from 0.01 to 11 Bq kg\(^{-1}\) by alpha scintillation method and 0.01 to 40 Bq kg\(^{-1}\) by continuous radon monitor. The authors concluded that due to low porosity of granites radon emanates from surface of the granites.

Michael et al., (2009) have done the studies on assessment of gamma-ray emissions from natural and manmade decorative stones and the reported gamma-ray activities for \(^{40}\)K and radioisotopes from the \(^{238}\)U and \(^{232}\)Th-decay series in 55 samples of decorative stones used in the US. The majority of activity concentrations were similar to values reported elsewhere, but some granites contained radioisotopes from the \(^{238}\)U and \(^{232}\)Th-decay series at levels up to 3380 and 850 Bq kg\(^{-1}\), respectively.
Morales et al., (2009) have done the studies on Indoor radon levels and gamma-radiation in dwellings of the Metropolitan Zone of Guadalajara and the results showed a lognormal distribution of annual concentrations and seasonal variations. The reported mean annual concentrations of radon were lower than US EPA and EEC action values, whereas the $^{220}$Rn levels were higher than the typical value determined by the UNSCEAR Reports.

Sathish et al., (2009) have done the studies on concentration of radon and their progenies and reported that the presence of radon in houses is the effect of several aspects such as the activity concentrations of uranium, radium and thorium in the local soil, building materials, ventilation of houses. The authors concluded that the concentrations of radon are relatively higher in granite than in concrete, cement and bricks.

Sathish et al., (2009) have done the studies on concentration of indoor radon and reported that the arithmetic mean values of $^{222}$Rn and $^{220}$Rn were found to be 35.0 and 21.5 Bqm$^{-3}$ respectively. Whereas the effective dose rate received by the population in the study area ranged between 0.1–0.5 mSv y$^{-1}$ with the arithmetic mean concentration 0.2±0.03mSvy$^{-1}$. The authors concluded that the higher concentrations in poorly ventilated houses.

Sathish et al., (2009) have done the studies on radon and reported that the concentration of radon were found to be 33.38 Bqm$^{-3}$. The authors concluded that the concentrations of indoor radon, thoron and their progeny levels are more in poor ventilated houses as well as smaller volume of the room.

Sathish et al., (2009) have done the studies radon and reported that the radon concentration varied from 4-93 Bqm$^{-3}$ whereas their progeny concentrations ranged from 0.012-2.45 mWL and the annual effective dose due to radon, thoron and their progenies ranged between 0.105 and 0.457mSvy$^{-1}$. The authors concluded that the concentrations are more in smaller volume rooms and low in larger volume rooms.
Sathish et al., (2009) have done the studies on indoor radon and reported that the radon, thoron and their progeny levels in different types of floorings, wall, room and building material are well within the admissible limit. The authors summarized that the concentration level of $^{222}$Rn and $^{220}$Rn in dwellings depend on soil beneath, local geology, the house construction materials and microclimatic parameters.

Jing chen et al., (2008) have done the studies on radon exhalation rate in building materials and found that the values of radon exhalation rate varied from non detectable to 312±19 Bqm$^{-2}$d$^{-1}$ with an average of 30±16 and 42±63 Bqm$^{-2}$d$^{-1}$ in slate tiles granites respectively.

Mahur et al., (2008) have done the extensive studies on measurement of natural radioactivity and radon exhalation rate and the reported $^{238}$U and $^{40}$K concentration vary from 123±7 to 40858±174 Bqkg$^{-1}$ and 162±11 to 9024±189 Bqkg$^{-1}$ respectively. Whereas the radon exhalation rate varied from 4.2±0.05 to 13.7±0.08 Bqm$^{-2}$h$^{-1}$ and the absorbed dose were ranged between 63.6 to 18876.4 nGyh$^{-1}$ with an average value 7054.2 nGyh$^{-1}$ and the annual external effective dose rate varied from 0.7 to 23.2 mSv$^{-1}$. The radium equivalent (Ra$_{eq}$) activities varied from 134.3 to 40858.0 Bqkg$^{-1}$. The value of external hazard index (H$_{ex}$) varied from 0.4 to 110.4 with an average value of 41.2. The authors concluded that the computed radiological data indicates the region is not safe and may pose significant radiological threat to the population.

Munazza Faheem et al., (2008) have done the studies on radon exhalation rate in soil and building materials and found that the values of radon exhalation rate varied from 122±19 to 681±10 mBqm$^{-2}$h$^{-1}$ with an average of 376±147 mBqm$^{-2}$h$^{-1}$ in soil where as an average of 212±34, 195±25, 231±30 and 292±35 mBqm$^{-2}$h$^{-1}$ in bricks, sand, cement and marbles respectively and the values are well below the world average value of 57600 mBqm$^{-2}$h$^{-1}$ (0.016Bqm$^{-2}$s$^{-1}$). The authors concluded that the radon exhalation increases with the increase in water content to some extent and then starts decreasing with further increase in water content and the effect of moisture content in soil and building materials; hence ply an important role in the temporal variability of radon concentration.
Saad et al., (2008) have done the studies on $^{222}$Rn exhalation rate from building materials used on the Garyounis University campus, Benghazi, Libya using the can technique, containing CR-39 and reported that, $^{222}$Rn concentration from brick walls, marble ledges, and ceramic floors were found to vary from $107.8 \pm 3.6$ to $277.9 \pm 9.3$ Bqm$^{-3}$ with a mean of $172 \pm 5.8$ Bqm$^{-3}$, $100.0 \pm 3.3$ to $298.7 \pm 10.0$ Bqm$^{-3}$ with a mean of $174.5 \pm 5.8$ Bqm$^{-3}$, and $87.0 \pm 2.9$ to $275.3 \pm 9.2$ Bqm$^{-3}$ with a mean of $145.1 \pm 4.9$ Bqm$^{-3}$, respectively. The authors presented that these building materials do not pose a significant radiation hazard, and thus the use of these materials in the construction of the university campus is considered to be safe for staff and students.

Sathish et al., (2008) have done the studies on activity of radio nuclides and reported that the activity of radium is maximum in granites and minimum in sand compared to cement, concrete and brick. Whereas the activity of thorium is more in granite and sand and in other materials such as cement, concrete and brick it appears to be more or less same. The authors concluded that the higher amount of $^{226}$Ra in soil depends to a large extent on the mineral composition of the host rocks and granite has large amount of radium than other rocks.

Sriharsha et al., (2008) have done the studies on gamma radiation and reported that the gamma dose rate inside the temples varied from 122.7 to 231.4 nGyh$^{-1}$ with a median of 130.1 nGyh$^{-1}$ outside the temples it was 141.8 to 340.2 nGyh$^{-1}$ with a median of 216.2 nGyh$^{-1}$ and in different types of buildings in indoor atmosphere it is varied between 112.2 to 197.5 nGyh$^{-1}$ with a median of 127.0 nGyh$^{-1}$ and in outdoor atmosphere it was 140.9 to 298.4 nGyh$^{-1}$ with a median of 216.2 nGyh$^{-1}$.

Shiva Prasad et al., (2008) have done the studies on Concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K in the soil of Bangalore region, India and the estimated concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K in the soils of Bangalore region vary in a wide range. The $^{226}$Ra is in the range of 7.7 - 111.6 Bqkg$^{-1}$ with a mean value of 26.2 Bqkg$^{-1}$, the $^{232}$Th has 16.7 - 98.7 Bqkg$^{-1}$ with a mean value of 53.1 Bqkg$^{-1}$ and $^{40}$K varies between 151.8 to 1424.2 Bqkg$^{-1}$ with a mean of 635.1 Bqkg$^{-1}$. 
Karpinska *et al.*, (2007) have done the measurement of indoor radon concentration and found that the value of radon concentration in brick house as $41 \text{ Bq m}^{-3}$ whereas, in concrete slab house it was $33 \text{ Bq m}^{-3}$ and in Green Hills estate $35 \text{ Bq m}^{-3}$. The authors concluded that the values are below the annual mean value ($\text{AM}=48 \text{ Bq m}^{-3}$) established for Poland.

El-Arabi *et al.*, (2006) have done the measurement of radon concentration and radon exhalation rate for different types of rocks and building materials and reported that the values of $^{222}\text{Rn}$ activity concentration ranged between $36.1\pm2$ to $96.4$, $17.8\pm3$ to $73.6\pm4$ and $18.0\pm2$ to $188.1\pm15\text{ Bq m}^{-3}$ whereas the values of radon exhalation rates varied from $0.0012$ to $0.004$, $0.005$ to $0.015$ and $0.007$ to $0.0069 \text{ Bq g}^{-1}\text{s}^{-1}$ for samples collected from Bir Elsid, Wadi El-Gemal and Germany respectively. The authors concluded that the samples of granite and acid dyke rock showed the maximum values of radon concentration and radon exhalation rate while minimum in basic dykes and amphibolites it is concluded that the radon concentration in building materials were minimum with $24\pm5.2 \text{ Bq m}^{-3}$ while maximum in soil with $250\pm16 \text{ Bq m}^{-3}$.

Marcus and Luiza (2006) have analyzed radionuclide content in over 350 Brazilian groundwater samples in 22 of the 27 Brazilian states, involving areas with quite different geologies. The observed values of $^{228}\text{Ra}$, $^{226}\text{Ra}$, $^{222}\text{Ra}$, $^{210}\text{Pb}$ and $^{238}\text{U}$ content in ground water showed a lognormal distribution, whereas the geometric means were $0.045 \text{ Bq L}^{-1}$, $0.014 \text{ Bq L}^{-1}$, $57.7 \text{ Bq L}^{-1}$, $0.040 \text{ Bq L}^{-1}$ and $1.2 \mu \text{g L}^{-1}$ respectively. They have also revealed the origin of $^{210}\text{Pb}$ in ground water is the presence of dissolved $^{222}\text{Ra}$ in water. The reported ratios of $^{228}\text{Ra}/^{226}\text{Ra}$ activity concentration are higher than one reinforces the importance of $^{228}\text{Ra}$ in ingestion dose calculations.

Nain *et al.*, (2006) have done the studies on radioactivity in cement samples and reported that the radon and radium concentration in various brands varied between $333\pm9.9$ to $506\pm13.3 \text{ Bq m}^{-3}$ and $3.7\pm0.1$ to $5.6\pm0.2 \text{ Bq kg}^{-1}$ while in various cementations finishing materials it was found to be $378\pm19.7$ to $550\pm9.8 \text{ Bq m}^{-3}$ and $4.2\pm0.2$ to $6.1\pm0.1 \text{ Bq kg}^{-1}$ respectively. The authors concluded that there is marginal variation of the concentration of radium and radon in various brands of cement in India and the concentration levels are lower than that of average global values.
Popovic et al., (2006) have done the studies on indoor radon concentration and radio activity of radio nuclides in building materials and determined the mean effective dose equivalents of radon and its progenies in closed space were 0.074 and 1.22 mSv respectively.

Tuccimei et al., (2006) have done the studies on exhalation rate of $^{222}$Rn and $^{220}$Rn simultaneously and evaluated the effects of chamber leakage and back diffusion on $^{222}$Rn free exhalation rate and the influence of available exhalation surface, humidity content and precursors concentration on $^{222}$Rn and $^{220}$Rn exhalation rates. The authors suggested that the exhalation rate measurement should allow the evaluation of leakage and back diffusion phenomena which could take place during experiments in order to calculate the free exhalation rates of building materials and concluded that the exhalation rate are strongly variable and dependent on factors like grain size, sample humidity and air temperature.

Villalba et al., (2006) have done the studies on natural radioactivity in ground water, effective dose due to water ingestion in the state of Chihuahua (Mexico) and the activity concentration of $^{222}$Rn and $^{226}$Ra and total uranium on groundwater samples collected from wells distributed throughout the state of Chihuahua. Value obtained for the total uranium activity concentration in groundwater throughout the state varied from 0.03 to 1.34 BqL$^{-1}$. Radon activity concentration obtained throughout the state was 1.0 to 39.8 BqL$^{-1}$. A linear correlation between $^{238}$U and $^{222}$Rn dissolved in ground water of individual wells was observed near Chihuahua City.

Al-Jarallah et al., (2005) have done the studies on measurement of radon exhalation rate in granites and found the value of radon exhalation rates of 13.1 Bqm$^{-2}$h$^{-1}$ with an average of 1.5±1.9 Bqm$^{-2}$h$^{-1}$ whereas the radium content of 297Bqkg$^{-1}$ with an average of 83±73 Bqkg$^{-1}$.

Fournier et al., (2005) have done the studies on radon transport through building materials and influence of the water content on radon exhalation rate and reported that the radon transport in porous materials is strongly influenced by the presence of water.
and found that the presence of water does not involve in the concentration on the surface of the medium according to its porosity. The authors also reports that the emanation coefficient is high in materials with medium porosity (limestone, brick, cement) and low in materials with low porosity (concrete and granite). The authors concluded that the radon migration inside the building materials is mainly governed by molecular diffusion.

Fournier et al., (2005) have done studies on Simulation of Radon Transport through Building Materials: Influence of the Water Content on Radon Exhalation Rate and the results show that the effects of the presence of water in a material largely depend on the material’s porosity. An increase in the water content can lead to a large exhalation of radon atoms for small porous media.

Gillmore et al., (2005) have done the studies on potential risk of radon and reported that radon concentrations in this famous cave are very low by world standards.

Halina Pienkowska (2005) have studied radon exhalation from building materials and soil and reported that the concentration of radon ranged from 1-690 Bqm$^{-3}$ in the city of Olsztyn. The authors observed that the emanation and migration mechanism of radon into the atmosphere depends on various factors such as decrease of radon concentration in sea region, with altitude and seasonal fluctuation of radon concentration.

Ajay kumar and Surinder Singh (2004) have done the studies on $^{222}$Rn exhalation in building materials using LR-115 type-II solid state nuclear detector and reported the $^{222}$Rn exhalation rate in these samples varied from 4.75 mBq m$^{-2}$h$^{-1}$ (0.14 mBqKg$^{-1}$h$^{-1}$) for lime stone to 506.76 mBq m$^{-2}$h$^{-1}$ (15.24 mBqkg$^{-2}$h$^{-1}$) for soil.

Dadong Iskandar et al., (2004) have done the studies on quantification of the dependency of radon emanation power on soil temperature. The authors studied the emanation from dry soil at temperatures between -20 °C and 45 °C and developed formula to calculate the radon emanation power as a function of the temperatures.
Sannappa \textit{et al.}, (2003) have done the studies on background radiation and reported that the average concentrations of radon and thoron were found to be 23.17 and 22.19 Bq kg$^{-1}$ respectively. The authors concluded that the radon concentration, gamma radiation and activity of $^{226}$Ra and $^{232}$Th in the soils are lower than the global average value.

Georges Monchaux \textit{et al.}, (2002) have done the studies on radon dose rate and reported that the risk of lung cancer in rats decreases with decreasing PAEC, i.e., exposure rates and concluded that the induction of lung cancer results from a complex interplay between cumulative and exposure rate, with an optimal combination of these two parameters.

Levin \textit{et al.}, (2002) have done the studies on radon exhalation and reported that the radon exhalation range ranged from 3.3 to 7.9 Bqm$^{-2}$h$^{-1}$ at Fyodorovskoye.

Virk \textit{et al.}, (2002) have done the studies on indoor radon and reported that the indoor radon and thoron levels were found to vary from 17.4 to 140.3 Bqm$^{-3}$ and 5.2 to 131.9 Bqm$^{-3}$ respectively. Whereas the year average dose rate for the local population varied between 0.03 to 0.83 mSvh$^{-1}$. The authors concluded that the annual exposure dose to inhabitants in all the dwellings lies below the upper limit of 10 mSv given in ICRP-65.

Wafaa (2002) has done the studies on radon permeability through some membranes like aluminized polymers, polymers, papers and glass and reported that the permeability constant does not change in certain range of thickness of materials.

Mohammed Al-Jarallah (2001) has done the studies on measurement of radon exhalation rate in building materials and reported the value of radon exhalation rate as 10.6Bqm$^{-2}$h$^{-1}$ with an average of 1.3 Bqm$^{-2}$h$^{-1}$ and found the linear correlation coefficient between emanated radon and radium content was 0.92 and the normalized radon exhalation rate from 2.0cm thick granites samples varied from not detectable to 0.068 Bqm$^{-2}$h$^{-1}$/Bqkg$^{-1}$ with an average of 0.030 Bqm$^{-2}$h$^{-1}$/Bqkg$^{-1}$. 
Mohammed Al-Jarallah (2001) has done the studies on radon exhalation from granites used in Saudi Arabia using radon gas analyzer and it was found that the radon exhalation rates per unit area from granite samples varied from not detectable to 10.6 Bqm$^{-2}$h$^{-1}$ with an average of 1.3 Bqm$^{-2}$h$^{-1}$. The linear correlation coefficient between emanated radon and radium content was 0.92. The normalized radon exhalation rates from 2.0 cm thick granite samples varied from not detectable to 0.06 Bqm$^{-2}$h$^{-1}$/Bqkg$^{-1}$ with an average of 0.03 Bqm$^{-2}$h$^{-1}$/Bqkg$^{-1}$ and the average radon emanation of the granite samples was found to be 21% of the total radium concentration.

Petropoulos et al., (2001) have reported the intercomparison on the radon exhalation rate determination from a concrete slab, specially constructed to produce radon surface flux well below 10 mBqm$^{-2}$s$^{-1}$ from different countries. The authors concluded that the agreement between the participant’s data, with a few exceptions, is satisfactory. The results are fairly well within the precision expected for such measurements.

Walley et al., (2001) have done the studies on Measurement of radioactivity and radon exhalation rate in different kinds of marbles and granites. They analyzed 60 geological samples of marble and granite from both Egyptian and foreign locations and the concentrations in Bqkg$^{-1}$ dry weight of radioisotopes were determined by gamma-ray spectrometry using hyper-pure germanium (HPGe) detector in Bqkg$^{-1}$ dry weight and reported the absorbed dose rate due to the natural radioactivity in the samples ranged from 2.45±0.07 to 64.44±1.93 nGyh$^{-1}$ for marble and from 41.55±1.25 to 111.94±3.36 nGyh$^{-1}$ for granite. The radium equivalent activity varied from 5.46±0.16 to 150.52±4.52 Bqkg$^{-1}$ for marble samples and from 229.52±6.89 to 92.16±2.76 Bqkg$^{-1}$ for granite. The radon exhalation rates for marble and granite samples were also calculated by using solid state nuclear track detector (CR-39). The value of radium exhalation rate varied from 8.0±2.39 to 30.20±5.06 Bqm$^{-2}$d$^{-1}$ for marble and 6.89±1.72 to 25.9±4.38 Bqm$^{-2}$d$^{-1}$ for granite and the effective radium content was found to vary from 1.70±0.51 to 6.42±1.08 Bqkg$^{-1}$ for marble and 1.29±0.32 to 5.63±0.96 Bqkg$^{-1}$ for granite. They have also observed the values of radon exhalation rate and effective radium content were found to correspond with the values of uranium concentration measured by the HPGe detector in the sample.
Muhammad Iqbal et al., (2000) have done the studies on measurement of natural radio activity in marble and the reported activity concentration of $^{226}$Ra, $^{232}$Th and $^{40}$K vary from 4 to 63, 9 to 40 and 7 to 105 Bqkg$^{-1}$ respectively. The radium equivalent activity ranged from 25 to 99 Bqkg$^{-1}$ and the average values of external and internal hazards indices were 0.19 and 0.26 respectively. The authors concluded that the marble mined from the various geological sites in Pakistan is safe for use as a construction materials.

Sroor et al., (2000) have done the studies on measurement of radon exhalation rate and radon concentration in soil and reported the values ranged from 338.81 to 1426.47 Bqm$^{-2}$d$^{-1}$ and 1.54 to 5.37 Bqkg$^{-1}$ respectively. The author reports that the concentration of radio nuclides are within the natural background level and indoor radon concentration are much smaller than the global average value.

Singh et al., (2001) have reported the gamma activity near the wall in the dwellings of Kulu area, Himachal Pradesh, India as 10.5 $\mu$Rh$^{-1}$ to 28.5 $\mu$Rh$^{-1}$

Vaupotic et al., (2001) has reported the gamma radiation level in schools on the territory of the abandoned uranium mine Zirovski vrh as 39 to 172 $\mu$Svmonth$^{-1}$ indoors and from 52 to 89 $\mu$ Svmonth$^{-1}$ outdoors.

Peter (1999) has carried out the studies on radon exhalation rate and the reported value of radon exhalation rate is 185±15mBqm$^{-2}$s$^{-1}$ and on the areas rich with coal and coal ash high radon exhalation rate were determined during all periods.

Kojima et al., (1999) have done the studies on the influence of meteorological and soil parameters on radon exhalation and found that the main influencing factors on the variation of the hourly exhalation data were the water content in the soil and the pressure difference between the surface and the soil air.

Peter Jovanović (1999) has done the studies on radon exhalation rate and the reported values of radon exhalation rate varied between $9\times10^{-3}$ to $4\times10^{-1}$ Bqm$^{-2}$s$^{-1}$ and
also found that the areas rich with coal and coal ash, higher radon exhalation rates were high during all periods of the year and one location in the coal mine area was covered with soil and clay which decreased radon exhalation rates by one order of magnitude.

Avadhani et al., (1998) measured the gamma radiation level in Goa region using plastic scintillometer. The values were varied from 30 to 88 nGy\textsuperscript{-1}h\textsuperscript{-1} with a geometric mean (GM) of 70.3 nGy\textsuperscript{-1}h\textsuperscript{-1}. The cosmic radiation component was been reported as 33 nGy\textsuperscript{-1}h\textsuperscript{-1}. This is comparable to exposure rate of 971.3 nGy\textsuperscript{-1}h\textsuperscript{-1} estimated from concentrations of naturally occurring radionuclides measured using HPGe Spectrometer.

Robert Grasty (1997) have done the studies on radon and reported that the gamma-ray flux from the uranium decay series was highest in the spring when the ground was water saturated and even covered with snow and the difference between soil types was attributed to the lower radon emanation of the more coarse-grained sandy soils compared to finer-grained clay soils.

Shaheed et al., (1997) reported the mean gamma exposure rate in the Cauvery environs of Thiruchanappali, India using scintillometer as ranging from 70 to 158 nGy\textsuperscript{-1}h\textsuperscript{-1} for the entire region.

Yu et al., (1996) have done the studies on the Variation of \textsuperscript{222}Rn Exhalation Rates from Concrete Surfaces of Different Ages and observed that the \textsuperscript{222}Rn exhalation rate was decreased with the age of the concrete blocks and the rate increased after the blocks were immersed in water.

Yu et al., (1996) have done the studies on the reduction of indoor radon concentration by using lightweight concrete in high rise buildings and reported that the value of radon exhalation rate for lightweight concrete is smaller than that of ordinary concrete, because lightweight concrete does not contain the crushed granite of normal concrete.

Sathish et al., (2009) have done the studies on radon and reported that the mean annual inhalation dose rate due to \textsuperscript{222}Rn, \textsuperscript{220}Rn and their progeny in the dwellings was
0.97 mSv y\(^{-1}\) (GSD 2.49) and observed that the major contribution to the indoor inhalation dose is due to \(^{222}\)Rn and its progeny.

CHAPTER 3

NUCLEAR INSTRUMENTATION

INTRODUCTION

Measurements of radiation levels and the concentrations of radionuclides in the environment are accomplished employing appropriate nuclear instruments. In the present study the alpha activity was counted using scintillation based Alpha Counting System. The gamma activities were detected and analyzed employing HPGe spectrometer. The atmospheric radon concentrations were measured using Low Level Radon Detection System (LLRDS). Back ground gamma radiation levels were surveyed by RADOS. The radon, thoron and their progeny levels were determined using Solid State Nuclear Track Detectors (SSNTD) and the tracks formed in these films were counted by Spark Counter, A brief account of these nuclear instruments used in the present study and their salient features are discussed in this chapter.

3.1 ALPHA COUNTING SYSTEM

Alpha particles have very high specific ionization which generally exceeds that of most of the cosmic ray components, good counter discrimination against natural back ground radiation can be achieved simply by voltage bias adjustments or by choice of the physical dimensions of the detectors to preferentially absorb alpha particles. Low background in beta and gamma detectors cannot be obtained by these methods because the specific ionization is not always distinguishable for that of the cosmic radiation.

The fact that backgrounds for unshielded alpha counters can be made by factor of 10 to 100 times smaller than fully shielded beta or gamma counters demonstrates the effectiveness of the discrimination. Therefore massive shielding and anticoincidence systems are not considered essential to alpha counting.
Ionization chambers were used for measurement of alpha particles (Finney and Evans, 1935 and Evans and Goodman, 1944) and subsequently the proportional counters became popular and analyses of samples utilizing proportional counter system have been described. This technique applicable to measure total alpha activity present in the environmental samples and is called autoradiography, the alpha activity is measured by the observation of the image of alpha particles trajectories as recorded in alpha sensitive emulsions. A nuclear track plate consisting of a layer of nuclear emulsion is placed in connect with a thin section or a polished section of a rock or mineral and exposed for sufficient time. The plate is then developed and observed under a microscope. However, this method of total alpha detection compares unfavorably with the other total alpha counting techniques and detection of low activities requires and exposure time of the order of several months.

The scintillation counter with an activated phosphor is the best general purpose low level alpha detection instrument available and the device has been in used since the pioneering days in nuclear physics. Certain phosphors such as ZnS (Ar), NaI (Tl) produce scintillation when ionizing radiations travel through them. The advantage of this detector is the relatively high scintillation efficiency (about 25-30%) and its poor conversion efficiency for fast electrons, facilitating easy discriminations of heavy charged particles in an intense background of gamma rays and beta particles. Good sensitivity of these detectors are attributing to the inherently low background, large source area and long term stability, Mayneord et al., (1960), Cherry, (1964), Marsden, (1964) have employed ZnS scintillation counter for counting the alpha activities of a large number of natural samples. In the present work the alpha activities of $^{222}\text{Rn}$ and its daughters $^{210}\text{Po}$ were counted using a ZnS (Ag) scintillation counting system.

The block diagram of the alpha counting system used in the present investigation is shown in Fig 3.2. A solid state time counting equipment is used to detect and display alpha radioactivity with the specially designed alpha probe supplied with the unit. The main parts of the unit are EHT unit, preamplifier, linear amplifier, scalar and timer. The necessary voltage for the working of the photomultiplier is provided by EHT unit which consists of high and low voltage power supplies.
The low voltages +12 V, +24 V, -12 V and -24 V are obtained by different IC regulations. The high voltage power supply is electronically regulated with a sine wave class C oscillator with 24 hours as its power source.

The main purpose of the preamplifier is to amplify the pulses from the detectors without any distortion of its linearity. The preamplifier consists of three stages: input stage, gain stage and output stage. The output from the preamplifier is fed to the voltage sensitive nuclear pulse amplifier or linear amplifier to provide continuously adjustable linear gain over a wide range.

The front panel of the counting system is provided with rotator control to vary EHT output steps of 150 volts. Also there is fine control which is again a rotator type. The fine control is used to vary the voltage in steps of 15 volts.

The background was noted every day after the stabilization of the counting system and was found to be about 0.005 cps. The efficiency of the detector was determined using $^{239}$Pu standard source. The average efficiency was found to be 30%. The full view of alpha counting system used in the present work is shown in Plate 3.1
Fig. 3.1: Block Diagram of Alpha Counting System

[Diagram showing the block diagram with labeled components: EHT, Pre-Amplifier, Pulse Shaper, Scaler, Gate, Timer, Alpha Scintillation Detector]
Plate 3.1: Complete View of Alpha Counting System
3.2 GAMMA RAY SPECTROMETER

Gamma spectrometry offers a convenient, direct and non destructive method for the measurement of the activity of different radionuclides in environmental samples. Gamma spectrometry techniques offer high efficiency [NaI (Tl) detectors] and high resolution (semiconductors) detection. The technique enables the use of large quantity of samples for counting. It is also possible, in this method to reduce the extraneous to very low values using suitable shielding arrangement. These features together with appropriate competent software codes that have become available now has made the gamma spectrometry method one of the most accurate technique of determining the activity concentration in environmental samples.

In this method, gamma rays are detected by making use of interaction properties of gamma rays with the absorbing medium. Photoelectric effect, Compton scattering and pair production are the three major processes by which gamma rays interact with matter and there by deposit their energy in a medium.

The information carriers produced due to the interaction of gamma rays with the detector medium varies with the type of detectors. When gamma rays interact with a scintillation medium the energy of the incident gamma photons are converted into light energy. These packets of light energy called scintillations act as information carriers.

The production of scintillation is directly proportional to the energy of the incident gamma ray. Scintillations are then made to fall on photocathode of PMT which emit photo electrons. These photoelectrons are multiplied using a series of dynodes and are converted into electronic pulses. These pulses which are representatives of incoming gamma rays are then processed using a pulse height analyzer. The energy required to produce a photoelectron in NaI (Tl) detector is about 300eV. Because of this higher energy, required to produce the information carriers, the energy resolution is poor. However, the mechanism of scintillation production is very good and these detectors offer high efficiency of detection. The basic information carriers in a semiconductor gamma ray detector are electron-hole pairs.
The average energy required to produce this pair is of order of 3eV only. As result the number of information carriers will increase providing higher energy resolution. The availability of germanium in its very high state of purity has lead to the fabrication of High Purity Germanium (HPGe) detectors. The HPGe detector posses’ reasonably high density and stopping power which make it possible to achieve complete absorption of the incident gamma radiation. Compact size, fast timing characteristics and effective thickness which can be varied to match the requirement of the applications are other important advantages. In addition HPGe have the advantage that they can be stored at room temperature. Liquid nitrogen cooling is required only when the detectors are in use. Hence, HPGe gamma ray spectrometer was employed in the present work to determine the activity concentration of radionuclides in environmental soil samples.

### 3.3 HPGe Spectrometer

A high resolution HPGe gamma ray spectrometer system was set up to carry out the present study. The block diagram of the HPGe spectrometer set up is shown in Fig.3.4. The HPGe detector is a p-type coaxial detector IGC 15190; it has a dimension of 5.05m diameter and 4.9 cm length providing an active volume of 90 cm$^3$. The full width at half maximum of the detector is 2keV at 1332keV and 0.8 keV at 122 keV. The relative efficiency is 18% relative to a 3×3 NaI (Tl) crystal measured at 25 cm source detector distance. The ratio of peak height to Compton plateau height for $^{60}$Co source is 50:1. The operating voltage of the detector is $\pm 2500$ V. The high voltage is supplied from a single width NIM module (Model 314) high voltage bias supply with protection circuitry to prevent detector damage. It supplies a low noise stable bias from 0 to $\pm 5KV$.

The detector is coupled to a high vacuum cryostat Dewar system. The Dewar serves as a reservoir of liquid nitrogen, while the cryostat provides a path via the copper cold finger for heat transfer from the detector element to the liquid nitrogen reservoir. The detector was housed inside a 7.5 cm thick lead shield consisting of graded shielding to reduce the characteristic X-ray from the lead with 15 cm free space between the detector and the shield to minimize the back scattering of gamma rays.
Fig. 3.4: Block Diagram of Hyper Pure Germanium Detector
The output pulses from the detector are amplified using a built in preamplifier. The HPGe detector IGC 15190 which has a built in RGHBC PGT FET cooled charge sensitive preamplifier with charge sensitivity of 100 mV/MeV provides a unipolar output pulse with negative polarity at 100 ns rise time and 50 ms delay time constant.

The output impedance of the preamplifier is 93 W and noise is $\leq 450$ eV. The gain is 1 V/MeV with a stability of $\pm 0.01 \%$ over 24 hours after 3 hours warm up. The integral nonlinearity of the preamplifier is $\pm 0.05 \%$ for $\pm 8$V swing. In addition to the amplifier, the major role of preamplifier is to convert the weak (high impedance) pulses produced by the detector system into strong (low impedance) pulses capable of being conducted through a cable to the spectroscopy amplifier.

The purpose of having spectroscopy amplifier is to amplify the signals from preamplifier linearly and shape them to become suitable for pulse height analysis. A Canberra spectroscopy amplifier (Model 2021) provided in a double with NIM module with gated active baseline restorer is used to amplify and process the signals from preamplifier. The amplifiers excellent DC stability, ultra low noise, broad gain range and wide choice of shaping time constant makes it ideally suited for the HPGe detector.

The amplifier has improved pulse symmetry, minimum sensitivity of output amplitude to variations in detector rise time and maximum signal-to-noise ratio. For a given shaping-time constant, the improved pulse symmetry minimizes the pulse dwell-time by tucking in the trailing skirt of the unipolar pulse-shape. This allows a faster return to the baseline. The result is superior energy resolution, count rate and throughout performance. Unipolar shaping is achieved with one differentiator and two active filter integrators. The amplifier offers 12 front switch selectable pulse shaping time constants of 0.25, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, 10.0 and 12ms and allows optimum resolution/count rate performance. A front panel adjustable pole/zero can be user trimmed to match the preamplifier fall-time constant and minimize undershoot following the first differentiator for improved overload and count rate performance.
Simultaneously unipolar and bipolar outputs are available at both front and rear panel BNC connectors. The unipolar output includes a baseline restorer which sample the output signal and maintains the baseline at references ground. The baseline restorer allows the unipolar output to appear DC coupled by imposing the unipolar output signal on a corrected DC level ±5 mV DC. The gated DC restorer offers automatic features on both restorer threshold and restorer rate, assuming the best possible low and high count rate performance.

The pulses from the Canberra spectroscopy amplifier are analyzed using NORLAND 5000 Multi Channel Analyzer (MCA). NORLAND is a 4096 channel system contained on one card usable with PC, XT or AT. In this MCA all the functions such as system timing, display generation, computation and data processing are provided by microprocessor. The MCA includes built in preamplifier/amplifier, pulse height analysis, data processing and I/O modes with option for simultaneous data acquisition and computer operation.

The MCA has a built advanced Analogue to Digital Convertor (ADC). The ADC is capable of producing highly accurate data transformation and categorization. The MCA is designed for a high resolution processing of amplitude modulated signals of the type encountered when measuring fast, random phenomena. The full scale input and upper level discriminators and ZERO control to suppress the unwanted pulses and shift the spectrum.

Each channel in the MCA is defined as an arbitrary interval of time, ranging from 10 ms to 1 second per channel. During each time interval, the scalar counts pulses of either fixed or random rates up to 10 million counts per seconds. The maximum dead time between channels is 700 ns.

The system automatically computers and displays the elapsed, real and live times, the total counts and total counts minus background counts in each channel. The MCA has the option to select region of interest (ROI), which is very useful for precise analysis of spectral data.
The MCA is also provided with an option of two point energy calibration and option to take the spectral output. The output was taken using a high speed printer. A full view of HPGe gamma spectrometer set up used in the present study is shown in Plate 3.4.

The spectrometer was calibrated using different standards. The standards for uranium, thorium, potassium and cesium were procured from international Atomic Energy Agency, Vienna. These standards are RG-U, RG-Th, RG-K and Soil-6 respectively for uranium, thorium, potassium and cesium. $^{238}$U and $^{232}$Th are in equilibrium with their daughters in both uranium and thorium standards.

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The standards were prepared in 300 ml top hat containers. Containers were sealed carefully with a vacuum seal to avoid loss of gaseous daughters produced from thorium and uranium. The efficiency of the detector for different gamma lines of various radionuclides was calculated using the following relation (Sannappa et al 2003):

$$E(\%) = \frac{N \times 100}{C} \times \frac{100}{a}$$

Where

$E$ is the efficiency of the system for that particular gamma energy
$N$ is the background subtracted count per second under the photo peak
$C$ is the activity of the standard (Bq) and
$a$ is the percentage abundance of the gamma rays

The minimum detectable activity (MDA) of radionuclides is then determined by using the following relation (Sannappa et al 2003):

$$MDA = CL \times \frac{B^{1/2}}{T} \times \frac{100}{E} \times \frac{100}{a} \times \frac{1000}{W} \text{ Bq kg}^{-1}$$

Where,

$CL$ is the confidence level, $B$ is the background counts in the peak region, $T$ is the time in seconds, $E$ is the efficiency of the detector for that particular energy, $a$ is the percentage abundance of the gamma ray and $W$ is the weight of the sample (kg). The
MDA at 95% confidence level for 20 hours of counting time and 275 g sample weight were found to be 1.7 Bqkg⁻¹ for ²²⁶Ra.

Plate 3.4: Complete View of Hyper Pure Germanium Detector
3.4 LOW LEVEL RADON DETECTIONS SYSTEM (LLRDS)

Many techniques have been established for measuring the concentration of radon and its decay products in air. These techniques are based on the detection of emissions from radioactive decay of radon and its daughter products. Most of the methods are based on detection of alpha particles, some on detection of gamma emission while a few utilize beta decays. In case of decay products either the individual decay products concentration or PAEC is measured. Due to low concentrations of environmental radon and its decay products, the precision and accuracy and detecting efficiency of the techniques are the important issues.

The radon measurements may be carried out for a variety of purposes and in a mill of uranium, laboratories and hospitals handling radium compounds needs to be carried out. For the assessment of population dose, the measurements have to be done in dwellings, office buildings and the outdoors as well. The concentrations of $^{222}\text{Rn}$ and its progeny in atmosphere air can be measured employing both active and passive detectors. In order to study the diurnal variation of radon and its progeny concentration in atmosphere sampling duration should be very small and the activity should be determined immediately. In such cases active devices are helpful. In the present work in order to determine the diurnal behavior of $^{222}\text{Rn}$ and its progeny concentration active devices techniques was employed.

The most simple convenient and easy to handle in the field measurements is the LLRDS. As the name signifies, this system can measure very low radon concentrations of the orders prevailing in atmospheric air. The block diagram of LLRDS is shown in Fig 3.5.

Radon concentration in atmosphere has been carried out using LLRDS. Radon decays to $^{218}\text{Po}$ atom which on formation is positively charged. It continues to carry +Ve charge for a small while after formation until neutralized by free electrons or until it plates out on condensation nuclei or nearby surfaces. The life span of the free or unattached atom may vary a few seconds to several minutes, depending on the airborne
concentration of nuclei and availability of surfaces nearby to plate on. This property of the born atoms of radon decay products is made use of in the LLRDS.

![Block Diagram of Low Level Radon Detection System](image)

**Fig.3.5: Block Diagram of Low Level Radon Detection System**

The LLRDS consists of sample collection chamber of 24 cm in diameter and 11.5 cm in height and a volume ~ 8 liters and is provided with an air inlet and outlet. It can be evacuated for collecting samples by vacuum transfer. The electrostatic field can be applied externally to the metallic plate which is an integral part of the chamber cover. After collection of a filtered air sample in the chamber at least 10 min delay is allowed for complete decay of thoron which may be present.

A negative voltage is then applied generally for about 90 minutes for the saturation of radon daughter atoms on the collection plate. At the end of this period the plate is removed and alpha counted during the interval $T_1$ and $T_2$ minutes, post
sampling. The complete view of the LLRDS used in the present study is shown in Plate 3.5.

Plate 3.5: Complete View of Low Level Radon Detection System
3.5 EXPRESSION FOR $^{222}$Rn CONCENTRATION IN SAMPLE AIR

Assuming that a sample of air having $^{222}$Rn concentration of $R_c$ (Bqm$^{-3}$) is collected in the chamber, if volume of the chamber is $V$ (m$^3$), the total $^{222}$Rn in the chamber will be $R_c \times V$ (Bq). The rate of production of RaA in the chamber is $R_c \times V$ atoms per sec. These freshly formed RaA atoms are attracted towards the disc maintained at negative potential. If the efficiency of collection under the electric field is $F$ the rate of collection on the disc is $R_c \times V \times F$ atom per sec. After collection under electric field for $t$ sec counting is done from 1 minute to $T_2$ minutes delay.

Total alphas emitted in the above period is given by

$$C = R_c \times V \times Z \times F$$

Here $Z$ is the alpha emission factor which is given by

$$Z = \left[ 270.22399\left(1-e^{-\lambda_a \theta}\right)\left(e^{-\lambda_a T} - e^{-\lambda_a T}\right) + 988.1663\left(1-e^{-\lambda_b \theta}\right) \right]$$

$$\left[\left(e^{-\lambda_b t} - e^{-\lambda_b T}\right) - 5598.24475\left(1-e^{-\lambda_c \theta}\left(e^{-\lambda_c t} - e^{-\lambda_c T}\right)\right) \right]$$

Where, $\lambda_a$ is the decay constant of RaA ($^{218}$Po) ($= 3.7877 \times 10^{-3}$ s$^{-1}$), $\lambda_b$ the decay constant of RaB ($^{214}$Pb) ($= 4.310 \times 10^{-4}$ s$^{-1}$), $\lambda_c$ is the decay constant of RaC ($^{214}$Bi) ($= 5.865 \times 10^{-4}$ s$^{-1}$), $t$ is the delay in starting the count using the charge plate (1min) and $T$ is the end of counting period (76min). The value of $Z$ worked out for 5000 sec is 3000. If the efficiency of the alpha counter is $E$ (fraction) then the total expected counts $C$ is

$$C = R_c \times V \times Z \times F \times E$$

Hence the $^{222}$Rn concentration in the air sample is given by
The collection efficiency $F$ is a function of the electrostatic field which in turn depends on the chamber dimensions. Another influencing factor is the relative humidity $H$. For a specific field the dependence of $F$ on the relative humidity $H$ can be described by the following empirical relationship

$$F = 0.9 \left(1 - e^{0.039H - 4.118}\right)$$

The minimum detectable level of $^{222}\text{Rn}$ concentration using this technique is about 1.7 to 8.8 Bqm$^{-3}$ depending on the relative humidity $H$ of the sampled air.

### 3.6 SOLID STATE NUCLEAR TRACK DETECTORS

Solid State Nuclear Track Detectors (SSNTDs) are thin sheets of dielectric materials such as cellulose nitrate and poly carbonates which are insulating materials. They are sensitive to alpha but not to beta and gamma radiation. An alpha particle which are heavily ionizing radiation passing through such insulating media leave narrow (3 - 10 nm) trails of damage. This damage produces broken molecular chains, free radical etc. These damaged regions can dissolve at a much higher rate than the undamaged material in certain chemical agents called etchants. The dissolved portion appears as a track in the film. Number of such tracks gives the number of alpha particles. Dosimeters are constructed using SSNTDs. Dosimeter system used is a cylindrical plastic cup divided into two components having a provision for holding the SSNTD films in specific concentration.

SSNTD in a cup with a suitable membrane like thin latex rubber sheet that determines the $^{222}\text{Rn}$ concentration alone since $^{220}\text{Rn}$ gas is trapped to less than 1% and the SSNTD inside the cup with a Whatman 41 filter paper determines the sum of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentrations in air. The system used for these measurements is called double chamber dosimeter. Bare mode exposure film can be fixed conveniently on the surface of the chamber. Size of the films used in the three different modes of exposure is $2.5 \text{ cm} \times 2.5 \text{ cm}$. 
The dosimeter with the films as described above was exposed for a period of about 90 days in four quarters of the year. About 150 houses of different features such as different types of floorings, rooms, walls and room of different volumes were randomly selected in Bangalore Metropolitan, India for exposing the dosimeters. The dosimeter cups were designed, fabricated and supplied by Bhabha Atomic Research Center, Mumbai, India. The schematic and complete view of dosimeter is shown in Fig. 3.7 and Plate 3.7.

Fig.3.7: Block Diagram of Solid State Nuclear Track Detectors based Dosimeter
3.7 SPARK COUNTER

Evaluation of etched tracks in SSNTDs by an optical microscope is difficult and time consuming and expensive task. 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) and developed and discussed in number of publications (Samyogi et al., 1978; Tommasino et al., and Durrani and Bull, 1987). The block diagram of the spark counter is shown in Fig.3.8. The complete view of the Spark counter used in the present work is as shown in the Plate 3.8. The basic principle involved in the spark counter is that sparks created across each of the tracks of the cellulose nitrate film due to high voltage discharge are converted as electrical pulses and are counted in the counter for a known set time.

In the present work an advanced fully programmable microprocessor based Spark counter was used for counting the SSNTDs. In a spark counter a very thin (~20
µm) plastic detector foil, irradiated with an \( \alpha \)-particles was first etched through holes along the charged particles tracks. This etched thin plastic track detector is placed between the two electrodes forming a capacitor and the spark through the holes is produced along the tracks.
Fig. 3.8: Block Diagram of Spark Counter
A pre-sparking step is then interposed to punch out such holes that were originally not quite etched through by applying an electric field across the thickness of the foil. Finally, the holes are counted by spark counting device. This is done by placing an aluminized Mylar on the top of the etched detector film and applying a high electric field across the thickness of the foil (say 500 v across 20 µm = 250 kVcm⁻¹). The aluminized layer (with metal face in contact with the detector film) provides a conducting path, and short-circuits the field, containing a capacitance. In doing so, the electric current burns off the aluminum directly above the hole, so that the spark cannot form through that particular hole again. The spark thus jumps through all the holes one by one in random sequence. A scalar which is incorporated into the circuit automatically counts the spark as they occur. The efficiency of hole-counting by this method is usually ~95% ± 5% compared to optical counting. The Mylar film retains a
vivid replica of the counted holes. Spark counting can be used to count relatively small ($\leq 10^{-3} \text{ cm}^2$) track densities.

Spark counter is a compact unit designed to count the number of tracks formed on the Cellulose Nitrate film (LR 115 Type II) of thickness of about 10-20 $\mu$m. Counting of the tracks by this method is most convenient and efficient. It consists of spark head, EHT circuit, pulse shaping circuits, stop/start circuit and switch etc. The different parts of spark counter are discussed below.

### 3.7.1 SPARK HEAD

The spark head assembly of the spark counter has two electrodes fitted into a circular cylindrical base, made of acrylic material. One of the electrodes called the Spark Head has an area of exactly 1 cm$^2$ and the other electrode has a spring loaded contact which is grounded. High voltage is applied across the spark head and the ground. The etched LR 115 film is placed on the electrode. An aluminized Mylar film is placed covering both the electrodes, such that conducting side is facing the film and also makes contact with the ground electrode. A cylindrical weight with transparent window for viewing the sparks when placed on the spark head ensures intimate contact between the surfaces.

### 3.7.2 OPERATION AND WORKING

#### 3.7.2.1 CALIBRATION

The spark counter has to be stabilized for 30 to 45 min, before it is used to measure the sparking counts. After high voltage was put on and was increased slowly to 250V, the chemically etched film was placed on the round electrode on spark head. The aluminized Mylar film was placed on the LR 115 film such that the counting surface was in contact with the LR 115 film and the ground electrode.

The weight was placed on Mylar gently, without disturbing the film. The start switch was then pressed to begin counting. At this stage an internal relay gets
actuated and high voltage will be applied across the film. At each hole there will be a discharge and is counted as one count and will not be counted again because of evaporation of the aluminum at the spot. The cumulative count will be displayed on the digital counter. After some time when the duration between two consecutive pulses exceeds a preset time interval, the counting will stop. Next the voltage is increased by 5 volt.

The counter weight and the Mylar film were carefully removed without disturbing the LR 115 film and that is cleaned with soft tissue paper without disturbing the sparked area. A fresh Mylar foil was kept along with the counter weight as was done earlier. Thus by taking counts in steps of 5 volts, the optimum counting voltage of the spark counter was determined from the plateau obtained from a plot track count against sparking voltages. The midpoint of the plateau was chosen as the optimum counting voltage as shown in the Figure 3.8.2.1. The sensitivity of the track counting can be improved by pre sparking the etched films at a higher voltage of 750 volts. With this some of the tracks, which are partially developed during etching are converted into holes. Regular counting of tracks in exposed films was carried out at the optimized voltage.

![Fig. 3.8.2.1: Plateau of Spark Counter](image-url)
3.8 DETERMINATION OF $^{222}\text{Rn}$ BY BUBBLER METHOD

Water samples for $^{222}\text{Rn}$ analyses were collected with the radon bubbler. Analyses of water sample in Bubbler method are by direct de emanations and alpha scintillation counting. The schematic of Radon bubbler and the complete view of Radon Bubbler are shown in Fig. 3.9 and Plate 3.9.

Radon bubbler and stand is a specially designed set up for the measurements of Radium as well as Radon in liquid samples. While Radon can be directly estimated by degassing from the sample, it is indirectly estimated through Radon build up by Emanometry technique. Radon bubblers are made of corning glass with airtight joints and stop cocks. Leak proof couplings for gassing and degassing of samples as well.

Radon sampling to Lucas cells are provided in the system. The bubblers can be mounted on a stand specially designed to hold 10 bubblers in one stand. A bearing coupled central rod and the bubbler holding arrangements make Emanometry sampling process very convenient with the system.
Fig. 3.9: Schematic of Radon Bubbler (Emanometry method)
Plate 3.9: Complete View of Radon Bubbler
3.9 RADIATION SURVEY METER

Employing the nuclear instruments described above the activity concentration of natural and artificial radionuclides in atmospheric and aquatic environment were measured by following the appropriate methods outlined in the next chapter.

Extensive study on background gamma radiation levels in and around Bangalore city is been carried out by using the new RDS-31S/R Multipurpose survey meter, (MIRION Technologies, Health Physics Division, Germany) continues the line of RADOS (Trade Name) survey meters offering modern design and approach to radiation monitoring. It is a battery operated instrument using an energy compensated GM tube as primary detector. This instrument detects the gamma radiation ranged between 48 KeV and 3 MeV. The complete view of the survey meter is shown in Plate 3.10.

Fig. 3.10: Complete View of Radiation Survey Meter
CHAPTER 4

METHODS OF MEASUREMENTS

4.1 INTRODUCTION

Environmental samples contain a number of radio nuclides originating from both natural and manmade sources. Distribution of radio nuclides varies from place to place. Activity concentration of some of the radio nuclides such as $^{226}\text{Ra}$ and $^{232}\text{Th}$ can be determined by direct counting methods employing the nuclear instruments.

4.2 BACKGROUND GAMMA LEVEL

Extensive study on background gamma radiation levels in and around Bangalore city is been carried out by using the new RDS-31S/R Multipurpose survey meter, (MIRION Technologies, Health Physics Division, Germany) continues the line of RADOS (Trade Name) survey meters offering modern design and approach to radiation monitoring. It is a battery operated instrument using an energy compensated GM tube as primary detector. This instrument detects the gamma radiation ranged between 48 KeV and 3 MeV.

Measurements were carried out in indoor and outdoor during installation and retrieval of the dosimeter at all locations. All measurements were made one meter above the ground surface, as is the standard practice. The arithmetic mean (AM) of the readings was taken as representative value for the location. This procedure was aimed at reducing minor fluctuations of the exposure level within a site. The dosimeter data was recorded at all the selected locations during the same period.

Exposure rate ($\mu\text{Rh}^{-1}$) was converted into dose rate (nGyh$^{-1}$) using the conversion factor of $1\mu\text{Rh}^{-1} = 8.7$ nGyh$^{-1}$ which stems from the definition of Roentgen and Gray (Nambi, 1987).
4.3 SOLID STATE NUCLEAR TRACK DETECTORS

Solid State Nuclear Track Detector (SSNTD) based dosimeters (Nikolaeva and Ilic, 1999) were used for the survey. These are simple to use and less expensive as compared to some continuous measurement systems like the Alpha Guard. Latter is useful for occasional comparisons with the SSNTD based dosimeters. SSNTD based dosimeters, described in the following section, were developed and calibrated for the survey. Since the sampling is passive and integrated for long duration, the diurnal and seasonal variations in radon concentrations are being taken into account (Ilic and Sutej, 1997).

SSNTD based dosimeter system is a cylindrical plastic chamber divided into two equal compartments (Nambi et al., 1994), each having an inner volume of 135 cm³ and height 4.5 cm. Dimensions of the dosimeter are chosen based on the ratio of effective volume of the cup to its total volume to achieve maximum track registration for the cylindrical cup (Jha et al., 1982). Design of the dosimeter is well suited to discriminate $^{222}$Rn and $^{220}$Rn in mixed field situations, where both the gases are present as in the monazite deposited areas. Cellulose nitrate films of LR-115 type II manufactured by the Kodak Pathe are used as detectors.

The 12 µm thick film cut into 2.5 cm × 2.5 cm size is affixed at the bottom of each cup as well as on the outer surface of the dosimeter. 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 (Ward et al., 1977) sandwiched between two-glass fiber filter papers and is called the membrane cup.

This membrane has permeability constant in the range of $10^{-8} - 10^{-7}$ cm² s⁻¹ (Wafaa, 2002) and allow more than 95% of the $^{222}$Rn gas to diffuse while it suppress the entry of $^{220}$Rn gas almost completely. Thus, the SSNTD film inside the membrane cup registers tracks contributed by $^{222}$Rn only, while that in the filter cup records tracks due to $^{222}$Rn and $^{220}$Rn. The third SSNTD film exposed in the bare mode registers alpha tracks contributed by the concentrations of both the gases and their alpha emitting progeny.

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 $^{222}$Rn /$^{220}$Rn progeny fall within 10 cm distance.

After the exposure period of 90 days, the SSNTD films were retrieved and chemically etched in 2.5
N NaOH solutions at 60 °C for 60 minutes with mild agitation throughout (Ramachandran et al., 2011).

The complete view of etching bath is shown in Plate 4.3. The tracks recorded in all the three SSNTD films are counted using a spark counter. A methodology has been developed to derive the equilibrium factors separately for $^{222}$Rn and $^{220}$Rn using the track densities based on the ventilation rates in the dwellings (Mayya et al., 1998).

One may expect deposition of activity on the SSNTD film in the bare mode exposure, which may pose as an unknown parameter in the calibration factor. But it has been proved that the LR-115 (12 µm) film does not register tracks from deposited activity (Eappen and Mayya, 2004). This is because the $E_{max}$ for LR-115 film is 4 MeV and all the progeny isotopes of $^{222}$Rn and $^{220}$Rn emit alphas with energies greater than 5 MeV.
4.3.1 CALIBRATION FACILITY AND STANDARDIZATION OF DOSIMETER

Experiments were carried out at the Bhabha Atomic Research Centre, Mumbai, India to estimate the calibration factors (Ramachandran et al., 1995) separately for $^{222}$Rn and $^{220}$Rn, in a calibration chamber of stainless steel of 0.5 m$^3$ volume. $^{222}$Rn (or $^{220}$Rn) gas is introduced into the chamber from standard sources obtained from Pylon, Canada. The calibration chamber has provisions for imputing aerosols from an aerosol generator, which is a Sinclair LaMer type condensation aerosol generator. It gives a laminar flow of mono-dispersed aerosols of di-2-ethylhexyl sebacate condensed on NaCl nuclei. Temperature settings of the boiler and re-heater are adjusted to obtain mono-dispersed aerosols of 0.25 µm diameter, which is close to the activity median aerodynamic diameter of 0.2 µm reported for indoor aerosols.

Aerosol concentrations of the order of $10^4$ to $10^5$ particles per cm$^3$ of air were generated to simulate the indoor environment conditions. Depletion of the aerosols inside the chamber was studied and accordingly input of the aerosols was regulated to maintain a near constant particle concentrations. The chamber has provisions for coupling an on-line Lucas cell system in conjunction with an Alpha Guard for continuous measurement of $^{222}$Rn gas concentration. The Alpha Guard, kept inside the chamber recorded hourly averaged $^{222}$Rn concentrations.

The on-line Lucas cell system was coupled to an alpha counting setup and counts were taken synchronizing with the timing of the Alpha Guard. Comparison of $^{222}$Rn measured by the two systems for a wide range of concentrations showed very good correlation of regression coefficient 0.97 and has a slope equal to unity (Eappen et al., 2001). Calibration factors (concentration conversion factors) for $^{222}$Rn and $^{220}$Rn are required to convert the recorded tracks in the exposed SSNTD films into $^{222}$Rn and $^{220}$Rn concentrations. Calibration factors were estimated experimentally as well as theoretically for all the three modes of exposures.

Calibration factors (CFs) for $^{222}$Rn and $^{220}$Rn gases in the cup mode were determined through a series of experiments. CFs for $^{222}$Rn ($k_R$) and for $^{220}$Rn ($k_T$) in terms of trcm$^{-2}$/Bqdm$^3$ can be obtained as:

$$k_R = \frac{24T}{C_R H} \quad \text{and} \quad k_T = \frac{24T}{C_T H}$$
Where, $T$ is the tracks per unit area (trcm$^{-2}$), $C_R$ is concentration of the $^{222}\text{Rn}$ gas (Bqm$^{-3}$), $C_T$ is the concentration of $^{220}\text{Rn}$ gas (Bqm$^{-3}$) and $H$ is the exposure time (hours). Experimentally obtained calibration factors for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are given by Mayya et al., (1998) and Eappen and Mayya (2004) for cup mode exposure.

CFs for $^{222}\text{Rn}$ in the membrane compartment is found to be equal (0.019 trcm$^{-2}$/Bqdm$^{-3}$) to that in filter paper compartment (0.02 trcm$^{-2}$/Bqdm$^{-3}$). CFs for $^{220}\text{Rn}$ in the membrane cup is essentially zero and that in the filter paper cup is 0.017 trcm$^{-2}$/Bqdm$^{-3}$.

The definition of the CFs for the bare mode has certain ambiguities. In the earlier approach, the CFs for the bare detector was defined as the track density rate obtained per unit WL (Barillion and Chambraudet, 2000; Durrani and Ilic, 1997). In reality, track formation rate in the bare mode is not a unique function of WL, but would depend on the equilibrium factor ($F$). If one defines the bare detector calibration factor as $k_B$ (trcm$^{-2}$/Bqdm$^{-3}$) of each species, it may be easy to show that this quantity is independent of the equilibrium factor as well as the incident energy of the alpha particle. For a given track density rate $T$ (trcm$^{-2}$/d), working level ($W_R$ for $^{222}\text{Rn}$ and $W_T$ for $^{220}\text{Rn}$ in mWL units) and the corresponding equilibrium factors ($F_R$ and $F_T$), the calibration factors as defined above can be obtained for $^{222}\text{Rn}$ ($k_{BR}$) and $^{220}\text{Rn}$ ($k_{BT}$) respectively in terms of trcm$^{-2}$/Bqdm$^{-3}$ using the following equations.

$$k_{BR} = \left( \frac{T}{3.7W_R} \right) \left( \frac{F_R}{1+2F_R} \right)$$

$$k_{BT} = \left( \frac{T}{0.275W_T} \right) \left( \frac{F_T}{2 + F_T} \right)$$

Based on this concept CFs was derived for the species matrix for $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny concentrations. They were found to be nearly constant for a wide range of equilibrium factors (0.1 - 0.72) supporting the basic assumption of the new approach. Table 4.3a shows the results of the CFs for the bare mode exposure for $^{222}\text{Rn}$ and $^{220}\text{Rn}$.

**Table 4.3.1a: Calibration Factors (CFs) for the Cup Mode and Bare Mode Exposures**

(Eappen et al., 2001)
The CFs for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are estimated as $0.02 \text{ trcm}^{-2}/\text{Bqdm}^3$ and $0.019 \text{ trcm}^{-2}/\text{Bqdm}^3$, respectively and are nearly identical. This confirms the assumption that, the bare card calibration factors are same for the alpha emitters since they are functions of only the difference in the ranges and the lower and upper cut off energies of detector. Hence, for practical use, an average value $0.02 \text{ trcm}^{-2}/\text{Bqdm}^3$ may be used as the CF for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in the bare mode exposure.

A Theoretical model has been developed to derive the calibration factors for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ for all the exposure modes by Eappen and Mayya (2004). The theoretical model is based on certain parametric constants chosen after experimental verifications. These include the bulk-etching rate and the break down thickness for the spark counting technique. Present calculation uses bulk etching rate as $4.0 \mu \text{mh}^{-1}$ and break down thickness as $3.0 \mu \text{m}$.

In the model, the upper and lower cut off energies for normal incident alphas are translated as residual ranges using the range energy relationship. The sphere of influence for the upper and lower cut off energies from normal incidence angle to critical angle can be obtained from integrating for the total area covered under solid angle for residual length of alpha particles lying within those incident angles. With these considerations, the observable tracks per unit area on the film per unit exposure time can be computed using the following equation:

$$T_r = \frac{\eta C}{4\pi} \int_0^{2\pi} d\phi \int_0^{\theta_C} d\theta \int_{r=R_E-R_L(\theta)}^{R_E-R_U} \sin \theta \cos \theta dr$$

where $\eta$ is the efficiency of track registration, $C$ the activity concentration of the species, $\phi$ the solid angle suspending the area of influence, $\theta$ the angle of incidence ranging from normal incidence ($\theta_C$) to critical angle ($\theta_C$), $r$ the radial distance from the point of emission, $R_E$ the range of alpha particle corresponding to its max energy and $R_L$, $R_U$ are the lower and upper cut off ranges for track registration for an incident angle $\theta$.

The integration extends over a region of influence, which is constructed by using detailed track development model. Eappen and Mayya (2004) have discussed the typical regions of influence for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ and their progenies in bare mode exposure configuration. Authors have showed that the region of

<table>
<thead>
<tr>
<th>Mode of Exposure</th>
<th>$^{222}\text{Rn}$</th>
<th>$^{220}\text{Rn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Filter</td>
<td>Membrane</td>
</tr>
<tr>
<td><strong>Cup Mode Exposure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>0.02 ± 0.004</td>
<td>0.019 ± 0.003</td>
</tr>
<tr>
<td>Theoretical</td>
<td>0.021</td>
<td>-</td>
</tr>
<tr>
<td><strong>Bare Mode Exposure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>0.020 ± 0.002</td>
<td>0.019 ± 0.003</td>
</tr>
<tr>
<td>Theoretical</td>
<td>0.019</td>
<td>0.019</td>
</tr>
</tbody>
</table>
influence is located farther from the detector for \(^{220}\text{Rn}\) progeny as compared to \(^{222}\text{Rn}\) and its progeny concentrations. For the cup mode exposure, integrations over the regions of influence would also include surface deposited activity contributions from the inner walls of the dosimeter.

A computer code has been written in FORTRAN for calculating the calibration factors in different configurations using the theoretical model (Eappen and Mayya, 2001). Several experimental studies were carried out in the calibration facility to determine the calibration factors under various equilibrium factor and gas concentration conditions. Theoretical and the experimental CFs obtained for the cup mode and bare mode exposures show close agreement with each other.

### 4.3.2 DOSIMETRIC METHODOLOGY

Inter-laboratory standardization experiments for the etching characteristics were conducted using standard alpha source also showed a good agreements. A theoretical methodology has been developed for evaluating the progeny concentrations using the twin cup \(^{222}\text{Rn} -^{220}\text{Rn}\) dosimeter system (Mayya et al., 1998). Mathematical basis used is similar to that developed by Planinic and Faj (1990; 1991) for radon dosimetry in which an auxiliary parameter, ventilation rate, was extracted from the equations relating the bare detector track densities to the gas and progeny levels.

This approach is considered as most logical one for \(^{222}\text{Rn} -^{220}\text{Rn}\) dosimetry with bare and cup detector system. But this methodology is complicated in the mixed field situation by the fact that \(^{220}\text{Rn}\) contribution has to be given as its ventilation dependant spatial profile for which only limited information is available in literature. So, the data currently available in the literature are used for the parameters like wall loss rates, unattached fractions and indoor turbulence levels (Porstendorfer, 1994).

In this method, it is assumed that SSNTD kept in the bare mode responds only to the airborne alpha emitters and not to the alpha activity deposited on it. It is also assumed that the bare card calibration factors are same for alpha emitters since it is a function of only the difference in the ranges, lower and upper cut off energy of the detector. Let \(T_1, T_2\) and \(T_3\) be the track densities recorded in the membrane mode, filter mode and bare mode, respectively.
Let $k_R$ be the calibration factors for $222\text{Rn}$ gas in membrane compartment and filter compartment, respectively and $k_T$ be the calibration factor for $220\text{Rn}$ in the filter compartment. If $d$ is the duration of exposure (days), the gas concentrations of $222\text{Rn}$ (Bqm$^{-3}$) and $220\text{Rn}$ (Bqm$^{-3}$) in the vicinity of the dosimeter can be determined from the observed track densities $T_1$ and $T_2$ using the following equations:

$$C_R = \frac{T_1}{dk_R} \quad \text{and} \quad C_T = \frac{T_2 - dC_R k_R}{dk_T}$$

Since the $222\text{Rn}$ decay constant is far smaller than the usually encountered air change rates (ventilation rates), $220\text{Rn}$ may be assumed to be spatially uniform. The activity fractions of the progeny are governed by their wall loss rates for the fine and the coarse fractions and the ventilation rates. The bare track densities are also dependent on the ventilation rates, which represent the progeny fractions for both gases. However unlike $222\text{Rn}$, $220\text{Rn}$ is not uniformly distributed in the room due to its short half-life, but is expected to set up profiles (Doi and Kobayashi, 1994).

The concentration $C_T$ would be considerably lower than that present near the ground and the walls, which are the $220\text{Rn}$ emitting surfaces. On the other hand, the thoron decay products, $212\text{Pb}$ and $212\text{Bi}$, being longer lived would mix more or less uniformly in the room and their activities will be fractions of a representative average $220\text{Rn}$ concentration.

A turbulent-diffusive transport model developed by Mayya et al., (1998) was used to obtain the bare track densities in terms of this concentration and the indoor ventilation rates. This method, which is known as the root finding method (RFM), is theoretically the most satisfactory approach for determining $222\text{Rn}$, $220\text{Rn}$ concentrations and their progeny working levels using the tracks recorded on the three SSNTD films. The progeny working levels were evaluated using the following relations:

$$WL_R = \frac{C_R F_R}{3700} = \frac{C_R (0.104F_{RA} + 0.518F_{RB} + 0.37F_{RC})}{3700}$$

$$WL_T = \frac{C_T F_T}{275} = \frac{C_T (0.908F_{TB} + 0.092F_{TC})}{275}$$
Where, $F_R$ and $F_T$ are the equilibrium factors for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ progeny, respectively, which are related to the ventilation rate. However, in practice, it was found that small uncertainties in the recorded tracks propagate non-linearly leading occasionally to unacceptable solutions for the equilibrium factors.

Very rich experience in measurements is required to eliminate these uncertainties, which is expected to be realized in the coming few years. Until then, it was decided to estimate the progeny concentrations using the cup based gas concentrations and the universally accepted equilibrium factors published elsewhere (UNSCEAR, 2000).

Information obtained from the third SSNTD is being used in conjunction with the RFM for building a database on the equilibrium factors. At present, the effective dose rate due to inhalation was estimated from the $^{222}\text{Rn}$, $^{220}\text{Rn}$ and progeny concentrations using the UNSCEAR (2000) equilibrium factors as given in Table 4.3b.

Table 4.3.2a: Average concentration of $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny in air and corresponding annual effective doses (UNSCEAR, 2000)

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Location</th>
<th>Concentration (Bqm$^{-3}$)</th>
<th>Effective dose equivalent (mSv/Bqhm$^{3}$)</th>
<th>Annual effective dose (μSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas</td>
<td>EEC</td>
<td>Gas EEC</td>
<td>Gas EEC</td>
</tr>
<tr>
<td>Radon</td>
<td>Outdoor</td>
<td>10</td>
<td>6</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Indoor</td>
<td>40</td>
<td>16</td>
<td>0.17</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoron</td>
<td>Outdoor</td>
<td>10</td>
<td>0.1</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Indoor</td>
<td>10</td>
<td>0.3</td>
<td>0.11</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^*$ This is the equilibrium equivalent concentration (EEC) of $^{222}\text{Rn}/^{220}\text{Rn}$ and is the product of the concentration of $^{222}\text{Rn}^{220}\text{Rn}$ and the equilibrium factor between $^{222}\text{Rn}^{220}\text{Rn}$ and its decay products. The equilibrium factor has been taken as 0.6 for outdoor and 0.4 for indoor in the case of $^{222}\text{Rn}$. In the case of $^{220}\text{Rn}$ $F$ is taken as 0.01 for outdoor and 0.03 for indoor. These values are weighted for an occupancy factor of 0.2 for outdoor and 0.8 for indoor.

4.4 $^{222}\text{Rn}$ BY EMANOMETRY
The samples were collected from the selected locations around Bangalore City from manually operated bore wells. About 100ml of water sample was collected in airtight plastic bottles with minimum disturbance, the bottles were gently and completely filled so that zero headspace was present, care was taken so that no air bubble and aeration which may lead to out gassing (Raghavayya et al., 1980). The samples were brought to the laboratory within a short time and analyzed immediately.

Activity concentration of $^{222}$Rn in water was estimated by the emanometry (Strain and Watson 1979). About 40 - 60 ml of water is transferred in to the radon bubbler using vacuum transfer technique, a pre-evacuated, background counted scintillation cell is connected to the top end of the bubbler and the upper tap is slowly opened, effervescence is seen in the bubbler indicating the partial disruption of dissolved air. The tap at the bottom of the bubbler is opened slowly and carefully so that vigorous effervescence results. Since both the taps of the bubbler are open, room air with only background radon enters the bubbler through the side of the capillary and breaks up into tiny bubbles due to sintered disc and carries with it the radon dissolved in water into the scintillation cell.

Scintillation cell was stored for 180 minutes to allow radon to attain equilibrium with its daughters, and then it is coupled to a photomultiplier and alpha counting assembly. The efficiency of the scintillation cells used is found to be 74% and the MDL of the system was 0.041 BqL$^{-1}$.

The concentration is calculated using the relation given by Raghavayya et al., (1980)

$$\text{Activity (BqL}^{-1}) = \frac{6.97 \times 10^{-2} \times D}{V \times E \times e^{-\lambda \theta} \times (1 - e^{-\lambda \theta})}$$

Where, $D$ is the gross alpha counts above the background; $V$ is the volume of water in radon bubbler (ml); $E$ is the % efficiency of the scintillation cell; $\lambda$ is the decay constant of radon ($2.098 \times 10^{-6}$ s); T is the counting delay in seconds; $t$ is the counting duration (1000 s) and $\theta$ is the delay between water sampling and de emanation of radon from water sample to scintillation cell in seconds.
4.5 INHALATION DOSE

Absorbed dose rates to the critical cells of the respiratory track due to $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny can be estimated on the basis of aerosol characteristics, its size distribution, unattached fraction, breathing fraction, and fractional deposition in the airways, mucous clearance rate and location of the target cells in the airways. Several models have been developed to assess the inhalation dose rates to the population due to $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny (Jacobi, 1993; Subba Ramu et al., 1988). Lung dose distribution assessment carried out by different agencies from the year 1956 to 2000 show a large variation in dose conversion factors (UNSCEAR, 1993, 2000). The estimated dose conversion factors varied drastically based on the breathing rate as well as the target tissue mass. In the present study, the dose conversion factors reported by UNSCEAR (2000) have been used to estimate the indoor inhalation dose rates $D$ ($\mu$Sv h$^{-1}$) due to $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny as shown below:

$$D(\mu\text{Sv h}^{-1}) = 10^{-3}[(0.17+9F_R)C_R + (0.11+40F_T)C_T]$$

Numerical values given in the above relations are the dose conversion factors for gas and progeny concentrations.

4.6 ENVIRONMENTAL MEASUREMENTS
Measurement of environmental radioactivity consists of the collection of soil samples and estimation of activity therein. Samples were collected at different locations in and around Bangalore Metropolitan, India. Soil sampling was aimed at evaluating the:

a) Distribution of radio nuclides in the surface soil to correlate the same with radiation exposure level and

b) Availability of radio nuclides that can be picked up by vegetation growing on the soil at each location, 10-15 spots of 0.5 m² area were selected and separated from one another by at least 10-15 m were marked out. The top layers of each marked location were cleared of vegetation and roots. The marked spot was dug up to a depth of 20 cm and about 2.5 kg of soil was collected at each spot. The entire sample, each of about 2.5 kg were taken and mixed thoroughly and finally soil sample of about 2.5 kg was sealed in a polythene bag and kept for 30 days for the establishment of equilibrium. After this, the samples were transferred to a porcelain dish and oven dried overnight at 110 °C. The samples were powdered and sieved through 150 sieves (Sannappa et al 2003).

4.7 GAMMA SPECTROMETRY

With radiochemical analysis it is not possible to separate isotopes of the same element. Many nuclides present in environmental matrix, emit beta and alpha particles as well as gamma rays. Gamma ray spectrometry offers a convenient analytical method for the identification of isotopes due to discrete energy of gamma rays. The method is not only qualitative but also quantitative. In the present study HPGe gamma ray spectrometer was used for the identification and measurement of the activities of $^{226}$Ra and $^{232}$Th in rock and soil samples. The gamma spectrometric procedures adopted is as follows

4.7.1 SAMPLE COLLECTION

The collections of samples were carried out in a careful and systematic way for the studies on environmental radioactivity. Therefore, soil samples were collected with utmost care in the present work. The area covered in the present study and the samples collected at various locations are shown in the Fig. 1.6.
4.7.2 SAMPLE COUNTING CONFIGURATION

About 300-350g of oven dried soil sample was filled in a wide mouthed plastic bottle (7cm diameter and 9cm height) with threaded lids. The lids were screwed tightly. The lid sides of the bottles were then dipped in molten paraffin wax. When the wax gets solidified, it acts as an effective seal against leakage of $^{222}\text{Rn}$ from the samples in the bottles. The $^{226}\text{Ra}$ in the sample attained radioactive equilibrium with $^{222}\text{Rn}$ and its daughters in about 30 days.

Before making any measurement, it is necessary to calibrate the counting system with a standard source in the same geometry and composition as that of the sample. To prepare such a standard, a known quantity of standard $^{226}\text{Ra}$ solution was mixed homogeneously with finely powdered sodium oxalate having the same density as the soil. The standard mixture was filled in a container identical to the sample container making sure that the quantity was also the same as the samples. (IAEA standard obtained from, Environmental Survey Laboratory of Bhabha Atomic Research Centre, Mumbai).

4.7.3 ENERGY AND EFFICIENCY CALIBRATION

Using standard sources $^{137}\text{Cs}$ and $^{60}\text{Co}$, the gain of the spectrometer system was adjusted so as to achieve a resolution of 1 keV/channel before taking further readings, the linearity of the counting system was periodically checked using standard sources namely, $^{57}\text{Co}$, $^{133}\text{Ba}$, $^{137}\text{Cs}$, $^{55}\text{Mn}$, $^{65}\text{Zn}$, $^{22}\text{Na}$, and $^{60}\text{Co}$. Figure 4.7.3a shows a typical plot of the photo peak channel against the energy. Energy calibration of the counting system helps in identification of the unknown radio nuclides. An accurate determination of efficiency of the systems is essential for quantitative estimation of radio nuclides and the efficiency of the spectrometer at different energies was determined using standard sources of $^{238}\text{U}$, $^{232}\text{Th}$, $^{137}\text{Cs}$ and $^{40}\text{K}$. Standards were prepared by taking known quantities of analyzed $^{238}\text{U}$/$^{232}\text{Th}$ ores and mixing them well within 150 $\mu$m size of quartz powder for simulating the soil samples matrix.
The $^{40}$K standard was prepared with oven dried granular KCL powder. The standards were filled in 250 ml container having threaded lids and were sealed to avoid the escape of $^{222}$Rn, the efficiency of the detector for gamma ray energies of various radio nuclides were determined using the following relation:

$$E(\%) = \frac{N \times 100 \times 100}{C \times A}$$

Where, $E$ is the efficiency of the system for a given gamma ray energy, $N$ is the net
count per second under the photo-peak of interest, $C$ is the activity of the standard source (Bq) and $A$ is the percentage branching intensity (gamma abundance) of the particular energy of the gamma ray. The variation of efficiency with energy is shown in Fig. 4.6.3b.

![Fig. 4.7.3b: Variation of Efficiency with Energy](image)

The minimum detectable activity (MDA) is given by

$$MDA(Bqkg^{-1}) = \frac{CL \times 100 \times 100 \times 1000 \times \sqrt{B}}{T \times E \times A \times W}$$

Where, $CL$ is the confidence level coefficient, $T$ is the background counting time (seconds), $B$ is the background counts, $E$ is the efficiency of the detector (%), $A$ is the percentage of branching intensity of a gamma ray energy and $W$ is the mass of the sample taken for analysis (g). The minimum detectable activities of $^{226}$Ra and $^{232}$Th at 95%
confidence level (CL) were found to be 0.8 Bqkg\(^{-1}\) and 1.97 Bqkg\(^{-1}\) respectively for a counting period of 20000 seconds and samples mass of 275g. Humidity was controlled by air-condition in the laboratory.

### 4.7.4 SAMPLE MEASUREMENTS

Gamma spectra of the samples were obtained over periods 10000 to 50000 seconds depending on the expected activity. \(^{226}\)Ra emits gamma rays of energy 186.2 keV only, the branching intensity being 3.3%. \(^{235}\)U emits gamma peak at 185.7KeV, which interferes with the \(^{226}\)Ra gamma peak because, the two cannot be separated with this system. Therefore, gamma peak of energy 609.51keV (which is emitted by \(^{214}\)Bi, a decay product of \(^{226}\)Ra) with intensity of 46.1% was used as proxy for the quantitative determination of \(^{226}\)Ra by gamma spectrometry. Another advantage of using this energy line is its negligible variation in absorption coefficient with different samples. Activity of \(^{232}\)Th was estimated using the photo peaks of 583.19 keV with intensity 85.97% and 911.05 keV with intensity 27.7% The characteristic photo peak of \(^{40}\)K is at 1460.8 keV (with intensity 10.7%) and that of \(^{137}\)Cs is 661.5 keV with 85.2% photon intensity (UNSCEAR, 1988). The activity of radio nuclides was calculated using the following relation

\[
Activity\left(Bqkg^{-1}\right) = \frac{(S \pm \sigma) \times 100 \times 100 \times 1000}{E \times W \times A}
\]

Where, \(S\) is the net counts/sec under the photo-peak of interest, \(\sigma\) is the standard deviation of \(S\), \(E\) is the counting efficiency (%), \(A\) is the gamma abundance of the radio nuclides and \(W\) is the mass of the sample (g).

### 4.8 INDOOR \(^{222}\)Rn EXHALATION RATE AND CONCENTRATION

The collection chamber method has been used for the measurement of \(^{222}\)Rn from indoor floor of different surfaces. Measurements were made using Low Level Radon Detection System. The procedure for the measurement of \(^{222}\)Rn exhalation rate consists of the following steps.

1. Collecting the \(^{222}\)Rn exhaled from a known area \((L)\) of the indoor floor for a given time in a collection chamber
2. Transfer of a specific fraction of the air from the collection chamber to LLRDS
3. Estimation of $^{222}$Rn concentration in LLRDS
4. Calculation of $^{222}$Rn exhalation from the measured $^{222}$Rn concentration

The schematic and full view of collection chamber setup, for measuring $^{222}$Rn exhalation rate in indoor floor is shown in Fig. 4.8a and Plate 4.8b.
Fig. 4.8a: Block Diagram of Collection Chamber
Plate 4.8b: Complete View of Collection Chamber set up

The accumulation chamber is a dome shaped stainless steel vessel with the rim diameter of 440 mm and a height of 100 mm having an effective volume of 15 liters. On the top of the chamber, two openings are provided one for connecting a hard rubber bulb which is used for mixing the air uniformly into the collection chamber and the other for transferring air from collection chamber to the LLRDS. Any leakage of air through the sides at the bottom of the chamber is avoided by proper sealing by sealant. $^{222}\text{Rn}$ exhaled from the floor gets collected in the chamber. The time of collection of $^{222}\text{Rn}$ for transferring it to LLRDS has been standardized for one hour by repeating the collection
for different intervals and counting. The counts obtained in the LLRDS were plotted for a
different collection period is shown in Fig. 4.8c.

![Fig. 4.8c: Collection Period versus Counts](image)

Therefore one-hour collection was adopted in all subsequent measurements. The
\(^{222}\)Rn concentration can then be estimated by LLRDS method. \(^{222}\)Rn exhalation rate from
the different floor is calculated from the estimated \(^{222}\)Rn concentration are as follows,

The parameters required are,

- \(J \text{ (Bqm}^{-2}\text{s}^{-1}) = \) Exhalation rate
- \(A \text{ (m}^2\) = Exhalation area
- \(V \text{ (m}^3\) = Volume of the Accumulation Chamber
- \(v \text{ (m}^3\) = Volume of the LLRDS Chamber
- \(\lambda \text{ (Sec}^{-1}\) = Decay Constant of \(^{222}\)Rn
- \(R_f \text{ (Bqm}^{-3}\) = Concentration of \(^{222}\)Rn in the Collection Chamber
- \(R_v \text{ (Bqm}^{-3}\) = Concentration of \(^{222}\)Rn in LLRDS
\( t \) (Sec) = Duration of Accumulation of \(^{222}\text{Rn}\) gas in the Collection Chamber

Let \( N_o \) (assumed to be constant) is the number of \(^{222}\text{Rn}\) atoms entering the chamber per second and is given by

\[
N_o = \frac{JA}{\lambda}
\]

Let the number of \(^{222}\text{Rn}\) atoms inside the collection chamber at any subsequent time \( t \) be \( N \). The build up in the chamber is given by

\[
\frac{dN}{dT} = N_o - \lambda N
\]

Solving the above equation and applying the limits 0 to \( t \) we get

\[
N = \frac{N_o \left(1 - e^{-\lambda T}\right)}{\lambda}
\]

Therefore,

\[
\lambda N = N_o \left(1 - e^{-\lambda T}\right)
\]

In terms of concentration we have

\[
R_v \left( \text{Bqm}^{-3} \right) = \frac{\lambda N}{N} = \frac{JA \left(1 - e^{-\lambda t}\right)}{\lambda V}
\]

At this time a sample drawn into the LLRDS chamber to estimate the \(^{222}\text{Rn}\) concentration measured in LLRDS chamber is \( R_v \) (Bqm\(^{-3}\)).

\[
R_v = \frac{V}{v + V}
\]

\[
R_v = \frac{v + V}{V}
\]

\[
\frac{JA \left(1 - e^{-\lambda t}\right)}{\lambda V} = R_v \frac{v + V}{V}
\]

The \(^{222}\text{Rn}\) exhalation rate is given by,
\[
J A \left(1 - e^{-\lambda t}\right) R_v \left(B m^{-2} S^{-1}\right) = \frac{R_v \lambda (V + \nu)}{A \left(1 - e^{-\lambda t}\right)}
\]

### 4.9 LOW LEVEL RADON DETECTION SYSTEM METHOD

The Low Level $^{222}$Rn Detection System (LLRDS), is used for the $^{222}$Rn progeny measurements. It consists of collection of freshly formed $^{222}$Rn progeny on a disc type electrode, which is maintained at a high negative potential in the chamber having filtered air containing $^{222}$Rn.

#### 4.9.1 PROCEDURE

Air samples were collected in the sampling chamber with the collection plate in position by vacuum transfer. As long as the plate is not energized, deposition of RaA on it is negligible. A delay of at least 10 minutes is normally allowed for any $^{220}$Rn which may be present in the chamber to decay completely. To start collection of RaA atoms, the negative potential is switched on. Positively charged RaA atoms get attracted to the charged plate and deposit on it. The collection is continued for an appropriate period typically about 90 minutes and then the negative potential is switched off, sampling time is noted. Charged plate is removed as quickly as possible. It is then loaded into an alpha counting device and counted for 5000 sec.

#### 4.9.2 $^{222}$Rn/$^{220}$Rn AND THEIR PROGENY IN INDOOR

The method of measurement of $^{222}$Rn, $^{220}$Rn and their progeny in air may be based on an active technique, which involves the pumping of air containing the gases and their progeny into a detecting system, or a passive technique where the concentrations are measured under natural conditions by simply exposing SSNTD films. A number of techniques are available, some of which are Nuclear Emulsion, Adsorption, Solid Scintillation, Liquid Scintillation, Gamma Spectrometry, Beta monitor, Solid State Nuclear Track Detector (SSNTD), Ionization Chamber, Surface Barrier Detector, Electrets Detector, $^{222}$Rn daughter aerosol collection. While some of the above methods are
unsuitable for indoor atmosphere, a few can be used for measuring both the $^{222}$Rn, $^{220}$Rn and their progeny concentrations, the two techniques used in this study, where one is active and the other passive, for indoor measurements are (i) $^{222}$Rn daughter aerosol collection and (ii) the SSNTD techniques respectively.

The first one is an active technique wherein the air containing $^{222}$Rn, $^{220}$Rn and their progeny is collected in a container and the activity is measured in the case of $^{222}$Rn and $^{220}$Rn progeny, the atoms are in aerosol form or as primary particles are collected on a filter paper by sucking the air at a known flow rate using a pump.

In both the cases, this technique can be used to measure either only $^{222}$Rn or $^{220}$Rn or $^{222}$Rn and $^{220}$Rn progenies separately in terms of WL units. Methods are also available to measure them when they are present as a mixture.

4.9.3 KUSNETZ’S METHOD ($^{222}$RN PROGENY)

The $^{222}$Rn progeny concentration can be measured in terms of working level (WL) units using Kusnetz’s (1956) method or its modifications by Raghavayya (1998). The schematic and full view of Air flow meter is shown in Fig. 4.9.3a and Plate 4.9.3b respectively. Air was drawn through a glass fiber filter paper by means of a suction pump at a flow rate of 35 LPM for 30 minutes. The decay products of $^{222}$Rn in air get deposited on the filter paper. Filter paper was then alpha counted after a specific time delay. Count rate was determined at a post sampling delay of 40 to 90 minutes. $^{222}$Rn daughter concentration (WL) was calculated using the Kusnetz’s equation modified by Raghavayya (1998). The original equation was modified to include a correction factor F for the sampling time and counting period.

The WL concentration is calculated using the expression

$$Rd(WL) = \frac{C}{E \times L \times F}$$
Where, $C$ is the count rate, $E$ the efficiency of alpha counting system (26%), $L$ is Sampling rate in liter per minute (LPM) and $F(T, t)$ is Working level factor corresponding to a sampling time $T$ (min) and counting delay of $t$ (min).
4.9.4 THE $^{222}$Rn PROGENY WORKING LEVEL

The unit for concentration of $^{222}$Rn daughters in air is known as the working level (WL). Originally the working level was defined as equivalent to the total alpha energy released by a concentration of 3.7 BqL$^{-1}$ of the four short lived decay products of $^{222}$Rn viz RaA ($^{218}$Po), RaB ($^{214}$Pb), RaC ($^{214}$Bi) and RaC’ ($^{214}$Po) on ultimate decay or when all the atoms decay to $^{210}$Pb. The WL concept is mainly used in uranium mines. The total alpha energy released could be $1.3 \times 10^5$ MeV per liter. In reality 100% secular equilibrium is never found between $^{222}$Rn and its decay products or between the decay products themselves.
The definition of working level (WL) was therefore modified as any combination (concentration) of $^{222}\text{Rn}$ progeny such that the total alpha energy released in one liter of air equal to $1.3 \times 10^5$ MeV. The working level unit is also known as the Potential Alpha Energy Concentration (PAEC).

Exposure of an individual to $^{222}\text{Rn}$ progeny is the time integral of the PAEC and expressed as working level month (WLM). For the purpose of this definition the month corresponds to 170 hours. Thus 1 WLM corresponds to the exposure at 1 WL concentration for the duration of 170 hours.

Working level factor; $F(T, t) = \text{Working level factor corresponding to a sampling time } T \text{ min and counting delay time } t \text{ min is given by} \]

$$F(T, t) = \frac{1.2676 \times 10^5 \left[1.02352(P) + (4.25939 + 33.167)b,(Q) - \\
(3.28292 + 24.38057(b)) - 6.459(C)(R)\right]}{[13.68 + 67.483b + 49.605c]}$$

Where,

$$P = (e^{-\lambda aT})(1 - e^{-\lambda aT}), Q = (e^{-\lambda bT})(1 - e^{-\lambda bT})\text{ and } R = (e^{-\lambda cT})(1 - e^{-\lambda cT})$$

$a$, $b$, and $c$ are the equilibrium ratios for RaA, RaB and RaC respectively.
CHAPTER 5

RESULTS AND DISCUSSIONS

The studies on $^{222}$Rn, $^{220}$Rn and their progeny levels in the indoor atmosphere are useful for determining the radiological risk due to them to the general public. The atmospheric concentrations of $^{222}$Rn, $^{220}$Rn and their progenies at the ground levels are governed by its exhalation rate and atmospheric diffusion depending on meteorological parameters. Therefore in the present study extensive studies on $^{222}$Rn and $^{220}$Rn variations were carried out.

This chapter deals with the results and discussions of the obtained data viz., variations of indoor $^{222}$Rn, $^{220}$Rn and their progeny levels in different locations, dwellings of different ventilation, different seasons, dwellings of different floorings, dwellings of different walls, different rooms of a dwelling, different volume of the dwellings and distribution of $^{220}$Rn and its progeny levels in Bangalore Metropolitan, India.

Large numbers of measurements have been carried out during the period 2007 to 2011. About 300 dwellings of different types of construction in different locations of Bangalore city, India were chosen on the basis of structure, age of the building, nature of walls, floorings, rooms and different volume of dwellings for the present study to see the effective dose rates due to indoor $^{222}$Rn, $^{220}$Rn and their progeny levels during different seasons of the year. Further, dwellings were also categorized on the basis of ventilation that dependence available number of windows, doors and usage pattern (such as closed, open, partially open/close) to identify them as poor (0-window), partial (1-windows) moderate (2-windows), good (3-windows), very good (4-windows) and excellent (5-windows) ventilated houses.
5.1 LOCATION WISE SEASONAL VARIATIONS AND DOSE RATES

Location wise seasonal variations of indoor $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentrations in different place of Bangalore city are shown in Fig. 5.1.1 and Fig. 5.1.2. The measured $^{222}\text{Rn}$ concentration during winter season of the studied locations ranged between 12.2 and 100.0 Bqm$^{-3}$, the higher value of arithmetic mean concentrations with standard error during winter was $61.9 \pm 9.2$ Bqm$^{-3}$ and the winter minimum value was $24.9 \pm 2.7$ Bqm$^{-3}$, whereas during summer season the concentration ranged between 4.1 and 50.3 Bqm$^{-3}$. The higher value of arithmetic mean concentrations with standard error during summer was $26.3 \pm 3.8$ Bqm$^{-3}$ and the summer minimum concentration was $10.9 \pm 1.0$ Bqm$^{-3}$.
The $^{220}$Rn concentration during winter season of the studied locations ranged between 6.2 and 72.9 Bq m$^{-3}$, the maximum value of arithmetic mean concentrations with standard error during winter was $35.2 \pm 4.2$ Bq m$^{-3}$ and the winter minimum was $15.4 \pm 1.7$ Bq m$^{-3}$, whereas during summer season the concentration ranges between 2.8 - 40.9 Bq m$^{-3}$, the maximum value of arithmetic mean concentrations of $^{220}$Rn with standard error during summer was $18.7 \pm 3.6$ Bq m$^{-3}$ and the summer minimum was $12.3 \pm 2.0$ Bq m$^{-3}$.

The winter maximum concentration of $^{222}$Rn was observed in Vijayanagar area and the winter minimum was observed in Rajajinagar. The summer maximum concentrations of $^{222}$Rn is observed in Vijayanagar and the summer minimum concentrations of $^{222}$Rn is seen in Rajajinagar and it is true for rainy and autumn seasons for the same locations. The higher value of $^{220}$Rn concentrations during winter was seen in Padmanabhanagar area and the winter minimum was observed in Rajajinagar.
The higher value during summer was seen in Rajajinagar and the lower was observed in Srirampuram. The arithmetic mean value of the $^{222}\text{Rn}$ concentrations of all the studied locations during winter, summer, rainy and autumn seasons are 42.6, 16.2, 23.4 and 24.9 Bqm$^{-3}$ respectively, where as for $^{220}\text{Rn}$ they are 24.3, 15.0, 18.8 and 19.2 Bqm$^{-3}$ respectively and the annual average concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are shown in Fig.5.1.3.

Especially in the winters, most of the dwellings show $^{222}\text{Rn}$ concentrations on an average 43.0 Bqm$^{-3}$ otherwise the highest concentration during winter season was observed as 100.0 Bqm$^{-3}$. Whereas the average $^{220}\text{Rn}$ concentration during winter season was 24.0 Bqm$^{-3}$ and the highest was 34.0 Bqm$^{-3}$. These large variations of the indoor $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentration between different dwellings of the studied locations can be explained due to different ventilation rate, nature of the soil underneath and particularly due to the geological considerations.

Even it has been established that the radon activity in soil-gas is highly variable and it differ dramatically from place to place, takes value of 30 KBqm$^{-3}$ in one place to 900 KBqm$^{-3}$, 10 m away (Toth et al., 1997). The average indoor $^{222}\text{Rn}$ concentration published for dwellings of different cities around the world vary between 8.7 Bqm$^{-3}$ (Australia) and 190.0 Bqm$^{-3}$ (German states of Saxony and Turingia), with a weighed arithmetic mean, for all the cities considered, of 40 Bqm$^{-3}$ (UNSCEAR 1993).

Annual effective dose rates due to $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progenies during different seasons of the year are shown in Fig. 5.14. During winter season it was found to vary between 0.17 and 0.32 mSvy$^{-1}$, whereas during summer season it was 0.11 and 0.17 mSvy$^{-1}$. The arithmetic mean dose with standard error during winter and summer seasons were $0.27 \pm 0.01$ and $0.13 \pm 0.007$ mSvy$^{-1}$ respectively.

The geometric mean concentration of dose during the winter and summer seasons are 0.26 and 0.13 mSvy$^{-1}$ respectively. The higher dose rates were observed during winter seasons of all the locations. The higher concentration of dose during the winter and summer seasons were observed in Vijayanagar and the lower concentrations were seen in Rajajinagar.
Fig. 5.1.3: Variations of $^{222}\text{Rn}$, $^{220}\text{Rn}$

This may be due to the fact that, during winter season the radioactive gases are trapped near the surface because of temperature inversions. In summer, the higher rate
of vertical mixing and dispersions lifts the aerosols to higher altitudes resulting in a
decrease in the concentration near the ground level air (Sesana et al., 2003). Wilkening
(1990) has reported similar trend of variations for the environment of USA. Magalhaes
et al., (2003) have observed a two order of magnitude of variability, with a maximum
of 50.0 Bqm\(^{-3}\) in winter and a minimum of 0.5 Bqm\(^{-3}\) in the summer months. In
addition \(^{222}\)Rn exhalation rate also decreases during monsoon as soil pores get filled by
water and hence, resulting in lower concentration of \(^{222}\)Rn and \(^{220}\)Rn (Nagaraja et al.,
2003).

5.2 WALL WISE VARIATIONS AND DOSE RATES

The concentrations of \(^{222}\)Rn and \(^{220}\)Rn in different types of walls of the houses
in all the studied locations are shown in Fig. 5.2.1 and Fig. 5.2.2.

Fig. 5.2.1: Wall wise \(^{222}\)Rn concentrations

The \(^{222}\)Rn concentrations in concrete, cement, brick and mud wall houses in the
studied locations were found to vary between 9.2 – 17.9, 13.7 - 27.1, 19.6 – 40.5 and
The arithmetic mean concentrations were 12.5 ± 1.0, 13.7 ± 1.5, 19.5 ± 2.6 and 42.6 ± 6.8 Bq m\(^{-3}\) respectively whereas their geometric mean concentrations were 12.2, 18.4, 25.8 and 39.5 Bq m\(^{-3}\) respectively.

The higher concentrations of \(^{222}\)Rn and \(^{220}\)Rn were observed in mud wall houses and lower concentrations in houses with concrete walls of all the locations. The annual average concentrations of \(^{222}\)Rn and \(^{220}\)Rn in dwellings of different walls are shown in Fig. 5.2.3.
The concentrations are found to vary from wall to wall. The variation may be due to random distribution of radioactive rock species used ignorantly in the
construction of houses (Kumar et al., 1994). Most of the walls of the houses in the city and surrounding area are constructed with cement and brick, and some of the houses had mud walls. In general the $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentration was found higher in mud wall houses than that in cemented wall houses. The ground floor allows more radon to diffuse inside the house because of higher porosity of material used.

The emanation of radon is also higher from rocks and local stones. In addition, the mud wall houses have small doors and a small window, which remains closed for most of the time. Due to poor ventilation condition, the radon is accumulated inside the house and thus results in higher $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentration in mud wall houses than in concrete wall houses (Ramola et al., 1995).

The higher concentrations of dose were seen in the houses of mud walls of all the locations and the lower concentrations were observed in houses with concrete walls of all the studied locations.

The annual effective dose rate due to $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progenies in dwellings of concrete, cement, brick and mud walls are shown in Fig. 4.24 and they were found to vary between 0.03 – 0.15, 0.11 – 0.18, 0.13 – 0.26 and 0.18 – 0.42 mSv·y$^{-1}$ respectively. The arithmetic mean dose with standard error were 0.09 ± 0.01, 0.15 ± 0.01, 0.19 ± 0.01 and 0.27 ± 0.02 respectively. The geometric mean dose rates were 0.09, 0.14, 0.18 and 0.26 respectively.

5.3 FLOOR WISE VARIATIONS AND DOSE RATES

The concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in different type of floorings of the houses of different locations are shown in Fig. 5.3.1 and Fig. 5.3.2.
The higher concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ were observed in granite flooring houses and lower concentrations were observed in houses with mosaic flooring of all the locations.
The annual average concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in dwellings of different floorings are shown in Fig. 5.3.3. The variations of dose rate due to $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in different floorings are shown in Fig. 5.3.4.

The $^{222}\text{Rn}$ concentrations in granite, concrete, red oxide, stone and mosaic flooring houses were found to vary between 36.8 and 100.0, 22.8 and 82.7, 13.8 and 57.9, 14.3 and 46.8 and 4.0 and 37.8 Bqm$^{-3}$ respectively. The arithmetic mean concentrations of $^{222}\text{Rn}$ with standard error were 65.7 ± 8.4, 44.6 ± 5.6, 30.1 ± 3.9, 23.2 ± 2.9 and 15.3 ± 2.7 Bqm$^{-3}$ respectively whereas their geometric mean concentrations were 60.4, 42.6, 28.6, 22.2 and 14.1 Bqm$^{-3}$ respectively. The $^{220}\text{Rn}$ concentrations were found to vary from 6.2 – 72.9, 12.5 – 69.4, 1.4 – 61.1, 4.2 – 40.9 and 2.1 – 37.5 Bqm$^{-3}$ respectively.

The arithmetic mean concentrations with standard error were 30.3 ± 4.5, 25.8 ± 3.5, 21.6 ± 1.4, 16.0 ± 1 and 14.4 ± 1.6 Bqm$^{-3}$ respectively, whereas their geometric mean concentrations were 27.5, 24.4, 21.2, 15.7 and 13.8 Bqm$^{-3}$ respectively.

Granite is rich of radium and it may be the reason for higher concentration of radon in granite flooring houses. The materials used for construction of buildings are sufficiently porous and allow radon to enter into the indoor atmosphere (Gaso et al., 2005). The earlier studies have shown that there is a positive correlation between the exhalation rate and concentration in building materials (Sathish et al., 2001).
Granite samples show higher radon exhalation rate than marbles. There is a positive correlation between $^{226}$Ra content of granite with radon exhalation and its concentration. This trend is observed by several researchers (Al-Jarallah 2001 and 2004; Papastefanou et al., 2001 and Sannappa et al., 2003). Some of the huts had mud walls, bare flooring and the roof covered by the dry coconut leaves with poor ventilation. The exhalation from brick wall with cement plastering is high. It is observed that the Mosaic flooring houses show slightly less radon exhalation rate than cement flooring houses.

Radon concentration in huts is lower than in concrete and mosaic flooring houses even though radon exhalation from bare flooring is higher than other types of floorings. This may be attributed to the possibility of out flow of air from huts through the coconut dry leaves.

Further, the fumes emitted during cooking process either from the kerosene stove or fire wood will increase the air pressure inside dwellings. Radon exhalation in mud walls is less compared to the cemented walls.

High exhalation of radon from concrete walls may be responsible for enhancement of concentration in cement and mosaic flooring houses, due to large
extent of usage of these materials in construction. This may be due to the high radon concentration in the concrete floorings and also because of the existence of porous between the slabs that were sandwiched by cement for the floorings. Due to this radon could easily enter into the houses (Vaupotic et al., 2001). The cracks in the floor as a consequence of poor quality of materials used for construction favors the enhancement of radon concentration (Singh et al., 1991).

Sreenath Reddy et al., (2006) and Vinaya Kumar Reddy (2006) have observed that the dwellings with mud floors have relatively higher dose and reports that the sub surface soil may be predominating source of indoor $^{222}$Rn, $^{220}$Rn for the environment of Hyderabad, India. This may be attributed to the rich content of $^{226}$Ra and $^{232}$Th in the local soil used for construction of mud walls. The radon levels in mud houses may be high due to emanation from ground surfaces and poor ventilation of the dwellings. Radon concentrations in dwellings changes from place to place due to difference in geology and climate, construction materials and domestic customs. Although exposure for radon in tropical climates is unlikely to be of serious concern, keeping in view the radiological significance of radon, mapping of radon level in different parts of the country is helpful in defining the radon prone areas, if any, and evaluating the natural radiation exposures (Rajesh Kumar et al., 2006).

The annual effective dose due to $^{222}$Rn, $^{220}$Rn and their progenies in mosaic, stone, red oxide, concrete and granite floors of the houses of different locations were found to vary from 0.09 – 0.2, 0.1 – 0.2, 0.1 – 0.3, 0.1 – 0.4 and 0.1 – 0.5 mSv y$^{-1}$ respectively.

The arithmetic mean concentration of dose with the standard error were 0.1 ± 0.01, 0.2 ± 0.01, 0.2 ± 0.02, 0.3 ± 0.04 and 0.4 ± 0.3 mSv y$^{-1}$ respectively. The higher dose rates were observed in the granite floorings houses in all the studied locations and the lower concentrations were observed in mosaic floorings. The geometric mean concentrations were found to be 0.12, 0.16, 0.20, 0.27 and 0.35 mSv y$^{-1}$ respectively.

**5.4 ROOM WISE VARIATIONS AND DOSE RATES**

The concentrations of $^{222}$Rn and $^{220}$Rn in different rooms of the houses of different locations are shown in Fig. 5.4.1 and 5.4.2.
The $^{222}\text{Rn}$ concentrations in bath room, bed room, kitchen and living room of the monitored houses were found to vary from 29.2 – 81.3, 24.9 – 58.5, 18.1 – 43.3, and 5.8 – 27.5 Bqm$^{-3}$ respectively. The arithmetic mean concentrations with standard error were 52.2 ± 4.2, 38.6 ± 3.3, 28.9 ± 1.7 and 17.1 ± 1.4 Bqm$^{-3}$ respectively, whereas their geometric mean concentrations were 50.9, 37.6, 28.4 and 16.5 Bqm$^{-3}$ respectively.
The $^{220}\text{Rn}$ concentrations were found to vary between 13.9 – 63.9, 5.6 – 47.9, 6.2 – 61.1, and 6.1 – 31.9 Bqm$^{-3}$ respectively. The arithmetic mean concentrations with standard error were 31.5 ± 3.5, 21.0 ± 1.7, 18.7 ± 1.7 and 14.8± 2.1Bqm$^{-3}$ respectively, whereas their geometric mean concentrations were 30.0, 20.4, 18.2 and 13.7 Bqm$^{-3}$ respectively. The higher concentrations $^{222}\text{Rn}$ and $^{220}\text{Rn}$ were observed in bath room, bed room and lower concentrations were observed in living rooms of the houses of all the locations. One can clearly see in the Fig. 5.4.3, that there is relatively higher concentration in bathroom compared to the other rooms in the houses.

Bathroom was found to have higher $^{222}\text{Rn}$ concentration; kitchen positioned second, after that bed rooms and living room the least. Bed rooms might be probably to be least ventilated, on an average based upon limited use patterns and bath rooms may receive some additional $^{222}\text{Rn}$ due to $^{222}\text{Rn}$ dissolved in water (Sathish et al., 2006). The $^{222}\text{Rn}$ is shown to be released in spray from faucets (Wilkening, 1986). Air in living rooms on the other hand is most readily diluted due to outdoor air blow. This can be correlated with concentrations of $^{222}\text{Rn}$ in water and the activity of $^{226}\text{Ra}$. However, Yadagiri Reddy et al., (2006) have reported that the radon concentration varied from 17.0 to 311.0 Bqm$^{-3}$ and progeny concentration varied between 0.1 to 20 mWL with an average of 62.0 ± 45 Bqm$^{-3}$ and 4.7 ± 4.1 mWL, respectively.

![Fig. 5.4.3: $^{222}\text{Rn}$, $^{220}\text{Rn}$ in different rooms](image-url)
They have also reported the activity concentrations of $^{226}\text{Ra}$ from different zones and observed that the bed rooms have relatively higher concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ followed by kitchen, front room and hall. This may be due to less atmospheric pressure and less ventilation in the bed room and also depends on location of the houses for the environment of Hyderabad.

The variations of dose rate in different rooms of the houses are shown in Fig. 5.4.4. The annual effective dose rate due to $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progenies in living room, kitchen, bed room and bath room were found to vary from 0.009 – 0.2, 0.1- 0.3, 0.04 – 0.3 and 0.02 – 0.5 mSv$^{-1}$ respectively.

The arithmetic mean dose with standard deviations are 0.1 ± 0.02, 0.2 ± 0.01, 0.2 ± 0.02 and 0.3 ± 0.05 mSv$^{-1}$ respectively. The higher dose rates were observed in bed room and bath rooms of all the studies locations. The observed geometric means of dose rates were 0.16, 0.22, 0.25 and 0.31 mSv$^{-1}$ respectively.

The arithmetic value of $^{222}\text{Rn}$, $^{220}\text{Rn}$ and the dose rates in different locations are shown in Figure 5.4.5. The higher concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are observed in Government Science College of Gandhinagar area.
Fig. 5.4.5: Area wise arithmetic mean values of $^{222}$Rn, $^{220}$Rn and their dose rates

The indoor radon is influenced mainly by the ventilation condition of the house. In most of the class rooms of the government science college high radon concentration in summer is observed than in winter, this unusual variation observed in the college is may be due the fact that the class rooms will be closed for longer duration in summer holidays.

5.5 ROOM VOLUME WISE VARIATIONS AND DOSE RATES

The volumetric variations of $^{222}$Rn and $^{220}$Rn are shown in Fig. 5.5.1. The higher concentrations of $^{222}$Rn and $^{220}$Rn were observed in lower volume room than in the higher volume room. The $^{222}$Rn and $^{220}$Rn concentrations in a dwelling of volume 30-310 m$^3$ ranged from 4.0 to 93.0 and 5.0 to 69.0 Bq m$^{-3}$, respectively. However, their progeny concentrations ranged from 0.01 to 2.5 and 0.01 to 0.8 mWL, respectively. It is also observed that the enhancement of volume by almost ten-fold reduces the concentration of $^{222}$Rn to 23% and that of $^{220}$Rn to 13% provided the rest of condition remains unaltered.
Fig. 5.5.1: $^{222}\text{Rn}$, $^{220}\text{Rn}$ with volume

It is interesting to note that as the volume of room varies as geometric progression; there is no dependence on the concentrations in the same ratio. About 67% of monitored houses had volume 30.0 – 100.0 m$^3$, $^{222}\text{Rn}$ concentrations were above 30 with maximum 93.0 Bq m$^{-3}$.

Fig. 5.5.2: Variation of Dose rate with volume
Whereas 32% of the dwellings had the volume 110 - 310 m³ have shown the concentrations less than 20.0 Bq m⁻³. For thoron it is 12.0 to 69.0 and less than 11.5 Bq m⁻³ respectively.

This evidently indicates that, though the observations have been made almost for similar type of constructions, ventilation and lifetime of the houses, but as the volume of the room increases the concentrations reduces exponentially and it becomes almost constant above the volume of 150 cubic meters. The variation in the concentration follows the exponential drop with the regression coefficients for $^{222}$Rn and $^{220}$Rn are 0.99 and 0.98, respectively. The volumetric variations of dose rates are shown in Fig. 5.52. The present work reveals that the dwellers of lower volume houses will expose themselves to the higher dose rates and is 4.4 times of the dose received in higher volume houses. It is recommended that the lower volume houses should have good ventilation to reduce the effective dose rate due to $^{222}$Rn, $^{220}$Rn and their daughters.

5.6 VENTILATION WISE VARIATIONS

Houses were selected on the basis of ventilation conditions depending on the number windows available ranged from 0 to 5. Ventilation wise seasonal variations of $^{222}$Rn and $^{220}$Rn levels in different dwellings of Bangalore city are shown in Fig. 5.6.1.
Fig. 5.6.1: Variation of $^{222}$Rn and $^{220}$Rn with respect to ventilation

The results of seasonal variations of $^{222}$Rn and $^{220}$Rn reveal the maximum concentrations during winter season and minimum during summer. The typical variations of $^{222}$Rn and $^{220}$Rn levels in different dwellings covering all the four seasons of the calendar year are shown in Fig. 5.6.2. The concentration of $^{222}$Rn and $^{220}$Rn were high during winter.

Fig. 5.6.2: $^{222}$Rn and $^{220}$Rn in different seasons

This could be due to temperature inversion which can generally be expected to be in winter (Sathish et al., 2001) and also houses are closed during this season most of the time to conserve heat energy. This leads to poor ventilation. The concentration gradually decreases and is lowest in summer. Turbulent transfer during summer causes low concentration of radon at lower atmosphere. The decrease of radon concentration and also exhalation from soil in rainy season has been observed. During rainy season
soil becomes saturated with water hence, less concentration is exhaled (Sathish et al., 2001).

The maximum concentration was observed during the winter periods as observed elsewhere (Ramachandran et al., 1989). It may be essentially influenced by the temperature inversion and also because most of all the windows are closed during winter season. But in summer low concentrations of $^{222}$Rn and $^{220}$Rn were observed because of the vertical mixing and dispersion.

Further during summer fans are used and all windows are kept open. During the rainy and autumn seasons the $^{222}$Rn and $^{220}$Rn concentrations do not show much variation. The average value of $^{222}$Rn and $^{220}$Rn of all the studied dwellings during winter, summer, rainy and autumn seasons were found to be 36.8, 13.8, 23.2 Bqm$^{-3}$ and 24.5 and 20.0, 8.1, 13.2 and 14.4 Bqm$^{-3}$ respectively.

Dwellings were chosen on the basis of different floorings. The variations of $^{222}$Rn and $^{220}$Rn concentrations in dwellings of different floorings with respect to the number windows are shown in Fig. 5.6.3.

Fig. 5.6.3: Variation $^{222}$Rn and $^{220}$Rn with respect to floorings
The variations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ levels in dwellings of different floorings covering all the four seasons of the calendar year are shown in Fig. 5.6.4.

![Graph showing variations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in different floorings](image)

**Fig. 5.6.4: $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in different floorings**

The floorings of the houses are of different materials. They are sufficiently porous to allow radon to escape into the indoor atmosphere. The data shows the higher concentrations in granite flooring houses and lower in mosaic and stone flooring houses. Loose cement flooring houses show high $^{222}\text{Rn}$ exhalation rate than stone flooring houses. This may be due to low porosity and low diffusion coefficient in the stone flooring than in ordinary cement flooring houses.

The data also reveals that the houses with red oxide and concrete floorings have shown the concentrations less than the granite flooring houses. This is may be due to the fact that granite contains higher activity concentrations of $^{226}\text{Ra}$. The results reveal that the concentration increases linearly from mosaic to granite flooring with the regression coefficient greater than 0.95 for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ respectively in all the cases.
The concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in houses of different walls are shown in Fig. 5.6.5.

Fig. 5.6.5: Variation of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ with respect to walls

The concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ levels in houses of various types of walls of the different dwellings are shown in Fig. 5.66. The figure depicts that the concentrations were found to vary from wall to wall in all the studied houses. The difference is may be due to the arbitrary distribution of radioactive rock class used rudely while building the houses (Singh et al., 1991).
It is known that the $^{222}\text{Rn}$ and $^{220}\text{Rn}$ gases are continuously diffused into the indoor environment due to the radioactive decay of naturally occurring radionuclide present in the soil beneath the dwellings and the construction materials used to build the dwellings.

Since the soil beneath the dwellings in a given location is expected to be of same type (Virk et al., 2000). The average values of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ levels of all the studied dwellings reveal maximum in winter and minimum in summer season. The gradual decrease of radon in summer is due to high temperature and low pressure in summer. Still decrease in monsoon may be due to saturated water in the soil. Winter to rainy season ratio of measured radon concentration is slightly more than the winter to summer season ratio. The higher values in winter are mainly because of ventilation factor (Ramola et al., 1995).

The concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in different rooms of different dwellings are shown in Fig. 5.6.7.
Fig. 5.6.7: Variation of $^{222}$Rn and $^{220}$Rn with respect to rooms

The variations of $^{222}$Rn and $^{220}$Rn levels in dwellings of different rooms are shown in Fig. 5.6.5. The result shows that the concentrations reduce linearly from bath room to open room with the regression coefficient above 0.96 in all the studied dwellings for both $^{222}$Rn and $^{220}$Rn respectively. This may be due to the better air exchange rate in the living room than in the bath room and bed room of all houses.
Fig. 5.6.8: $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in different rooms

Fig. 5.6.6 reveals that there is a positive correlation between $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progenies. The results differ fairly from dwelling to dwelling, but, this may be mainly due to the differences in location and meteorological conditions. Generally, sites with such radon and its progeny concentrations, such as that studied here, could possibly be found in many countries and may become important sources of information regarding the effect on health of low doses due to natural radiation exposure outdoors.
On the other hand, theoretical modeling is necessary to help interpret the data and to make predictions beyond the observations (for example, regional deposition in the human lung). In addition, the dwellings of high indoor radon and thoron concentration are in accordance with the distribution maps of $^{226}\text{Ra}$ and $^{232}\text{Th}$ concentrations in surface soil, respectively, and granite (Field and Kross, 1996).

### 5.7 $^{220}\text{Rn}$ AND ITS PROGENY LEVELS

An attempt has been made to find an approximate mean and range of thoron and its progeny in buildings in order to assess the possible health hazards from thoron in indoors for the environment of Bangalore Metropolitan. Buildings were chosen regardless the natural $^{232}\text{Th}$ concentrations. All the measurements were made on the ground floor. Nine dosimeters were suspended at equidistant from the flooring and ceiling of the room and at a distance of 25, 50, 75, 100, 125, 150, 175, 200 and 225 cm
from north to south wall as well as south to north wall of test room of volume 31m$^3$ as shown in Fig. 5.7.1 and the dosimeters were also deployed in lower and upper parabolic fashion as shown in Figs. 5.7.2 and 5.7.3.

Due to the short half-life of $^{220}$Rn, it is assumed that the distribution of $^{220}$Rn may be quite different to that of $^{222}$Rn (Guo et al., 1995). The investigation revealed dependence of $^{220}$Rn concentration on the distance from the wall and on the flooring in

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Ceiling

North  South wall

Fig. 5.7.1: Deployment of Dosimeters in equidistant Fashion

Suspended twin cup Dosimeters

North  South wall

Fig. 5.7.2: Dosimeters in Lower Parabolic Fashion

Ceiling

Fig. 5.7.3: Dosimeters in Upper Parabolic Fashion
a controlled room with brick wall coated with cement plaster and mud flooring.

Keeping the dosimeters for 90 days and the procedure is continued for one complete calendar year to see the variation. The results of the measurements of variations of $^{220}$Rn concentrations with wall distance for the period of 2007 to 2011 are discussed.

Variations of $^{220}$Rn concentration with the distance from the walls are shown in Figs. 5.7.4 and 5.7.5. The results illustrates that the $^{220}$Rn concentration decrease exponentially with as a function of the distance from the wall and it may be due to its short half life (Guo et al., 1995, Yamasaki et al., 1995).

![Graph 1](image1)

![Graph 2](image2)

Fig. 5.7.4 & 5.7.5: Distribution of $^{220}$Rn concentration with distance of wall

This suggests that it is necessary to keep the distance from the wall when we measure indoor $^{220}$Rn concentration. The horizontal and vertical distributions of $^{220}$Rn concentrations in a dwelling are shown in Fig. 5.7.6.
The results show that, as the distance increases both from the wall and the floorings, the $^{220}\text{Rn}$ concentration decrease exponentially. During the measurement period with twin cup dosimeters, the distribution of $^{220}\text{Rn}$ progeny and $^{222}\text{Rn}$ concentration were also measured at the different distance from wall and floorings and the variation are shown in Fig. 5.7.7.

Fig. 5.7.6: Horizontal and Vertical distributions of $^{220}\text{Rn}$

Fig. 5.7.7: Distribution of $^{222}\text{Rn}$, $^{220}\text{Rn}$ and $^{220}\text{Rn}$ progeny
The $^{220}\text{Rn}$ progeny concentration was nearly independent of the distance from soil wall. The uniformity of $^{220}\text{Rn}$ progeny concentrations in a dwelling is may be because of their long half life (Guo et al., 1992) and this was also confirmed by a model calculation by elsewhere (Yamasaki et al., 1995). Thoron exhalation from the building material provokes a certain indoor thoron activity concentration. Due to the short half-life, the concentration is not homogeneous in the room but higher towards the walls, floor and ceiling of the room built from the exhaling material. The steep increase close to the wall is observed. The turbulent transport from the wall into the room center decreases the relative contribution of the thoron close the wall. However, the portion in the room center increases. This is important for dose assessment of the dwellers. Only at ventilation rates above the exhalation saturation the total activity declines (Tschiersch et al., 2007).

Frequency distribution of indoor $^{220}\text{Rn}$ concentration in dwellings of Bangalore Metropolitan are shown in Fig. 5.78, the results reveals that, about 85% of the dwellings have shown the concentrations below 30 Bqm$^{-3}$ and 5% of the dwellings showed the concentrations above 50 Bqm$^{-3}$.

![Frequency distribution of $^{220}\text{Rn}$ concentrations](image)

**Fig. 5.7.8: Frequency Distribution of $^{220}\text{Rn}$ concentrations**

The $^{220}\text{Rn}$ concentrations during winter season is $1.7 \pm 0.2$ times that of summer season, where as its progeny during winter is $2.7 \pm 0.7$ times that of summer season and
not much variations are observed between rain and autumn seasons. The winter to summer ratio of $^{220}\text{Rn}$ and its progeny of the studied locations vary between 1.1 and 2.5 Bqm$^{-3}$ and 1.2 and 6.6 mWL respectively.

A survey carried out in Guangdong province gives one of the limited data of thoron and its progeny in China. The concentrations of thoron and its progeny were measured by grab sampling method, both indoors and outdoors, the reported average concentrations of thoron were $48.1 \pm 20.0$ Bqm$^{-3}$ and $22.1 \pm 10.7$ Bqm$^{-3}$ for indoor and outdoor environment respectively. The average equilibrium-equivalent concentrations of thoron were $1.1 \pm 0.8$ Bqm$^{-3}$ and $0.5 \pm 0.3$ Bqm$^{-3}$ for indoor and outdoor environment respectively.

For different building materials of the walls, the house with soil/mud walls had the highest thoron concentration; the reported average value of this kind of house was 104.0 Bqm$^{-3}$. The ratio between the exposure from thoron and its progeny and that from radon and thoron as well as their progeny was reported to be 30.5% in Guangdong province. Martinez et al., (2004) have done the measurement on variation in indoor thoron levels in Mexico City dwellings and showed the general log–normal distribution of integrated indoor thoron concentration with annual arithmetic and geometric means of 82.0 and 55.0 Bqm$^{-3}$, respectively, with ranges from 8.0 to 234.0 Bqm$^{-3}$, higher than world average of 3.0 Bqm$^{-3}$. The seasonal variation shows the minimum mean values in the summer season that were 35% lower than in autumn. The $^{220}\text{Rn}$ concentrations in the study area vary between 1.4 – 72.9 Bqm$^{-3}$ where as its progeny ranged from 0.01 – 4.8 mWL respectively. The arithmetic mean concentrations of $^{220}\text{Rn}$ and its progeny were $20.5 \pm 0.7$ Bqm$^{-3}$ and $0.4 \pm 0.07$. Higher $^{220}\text{Rn}$ concentrations were observed in Sheshadripuram, lower in Srirampura area, where as the higher progeny were observed in Malleshwaram, lower in Banashankari area.

The average monthly variation of indoor $^{222}\text{Rn}$ and its progeny concentrations are shown in the Figs. 5.7.9 (a) and (b). It shows the general trend of variation in the $^{222}\text{Rn}$ concentrations in the houses. The set of behavior of $^{222}\text{Rn}$ and its daughter concentrations in indoor air of some of the dwellings of Bangalore Metropolitan, with a peak during winter period of December to January and it is well documented by several other
researchers (Subramanian et al., 1977; Vohra et al., 1984) and it may be essentially influenced by the intensive temperature inversion which occurs in winter, the vertical mixing and dispersion which occur in summer.

Fig. 5.7.9: Monthly variations of $^{222}$Rn and its progeny

Fig. 5.7.10: Monthly variations of $^{220}$Rn concentrations

Monthly variations of $^{220}$Rn and its progeny concentrations are shown in Figs. 5.7.10 and 5.7.11.
Fig. 5.7.11: Monthly variations of $^{220}$Rn progeny concentrations

The maximum concentrations of $^{220}$Rn and its progeny were observed during the month of December and the minimum concentrations $^{220}$Rn and its progeny were observed during the month of June for the calendar year 2008.

In the earlier studies (Ningappa et al., 2008) on indoor $^{222}$Rn and its progeny levels around Bangalore rural district and Bangalore city, it is reported that the geometrical mean value of $^{222}$Rn concentration levels in indoor atmosphere of granite quarries varies from 55.0 to 300.0 with a median of 152.5 Bq m$^{-3}$ and its progeny varies from 0.2 to 19.6 with a median of 8 mWL respectively, the concentration level of $^{222}$Rn varies from 18.4 to 104.0 with a median of 45 Bq m$^{-3}$ and its progeny varies from 1.6 to 11.2 with a median of 4.8 mWL respectively. Higher concentration of $^{222}$Rn and its progeny were observed in granite quarries compared to Bangalore city due to the mining activity and types of the bedrock in granite quarries. The present results are comparable with observations made elsewhere (Ramachandran et al., 2011).

5.8 CORRELATION STUDIES
5.8.1 DIFFERENT ROOMS

The correlation between \(^{222}\text{Rn}\), \(^{220}\text{Rn}\) and their progenies are shown in Fig. 5.8.1a, they show linear variations with the regression coefficient 0.74 and 0.94 respectively. The frequency distribution of \(^{222}\text{Rn}\) and \(^{220}\text{Rn}\) are plotted in Fig. 5.8.1b, higher concentrations are observed in least ventilated rooms and lower concentrations in well ventilated rooms of all the studied locations.

![Correlation graph](image)

Fig. 5.8.1a: Correlation between radon and progeny
5.8.2 DIFFERENT FLOORINGS:

The correlation between $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny levels and the frequency distributions are shown in Figs. 5.8.2a and 5.8.2b.
Higher positive correlations between average $^{222}\text{Rn}$ concentrations and the build-up of $^{222}\text{Rn}$ ($r=0.98$); and between indoor exposure and average $^{222}\text{Rn}$ concentrations ($r=0.98$) were observed. The low correlation might be due to the fact that many physical and meteorological factors affect the variation of the $^{222}\text{Rn}$ progeny in indoor as well as outdoor. Indoor and outdoor pressure difference, wind speed, wind direction and aerosol concentration in the air are main factors in this respect (Sahota et al., 2005).

**5.8.3 DIFFERENT WALL**

Correlations between $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny levels and the frequency distributions in different types of wall materials covering all the four seasons in a calendar year are shown in the Figs. 5.8.3a and 5.8.3b.
Fig. 5.8.3a: Correlation between radon and progenies

Fig. 5.8.3b: Frequency distribution of $^{222}\text{Rn}/^{220}\text{Rn}$
A strong correlation coefficient was observed between radon activity and mass exhalation rate (correlation coefficient 0.99), which may be due to the radium content (Ramachandran et al., 1989) and porosity (Folkerts et al., 1984) in the samples of the studied location.

**5.8.4 DIFFERENT SEASONS**

The correlations between $^{222}$Rn, $^{220}$Rn and their progenies and the frequency distributions in different seasons are shown in Figs. 5.8.4a and 5.8.4b.

![Correlation between radon and progenies](image)

**Fig. 5.8.4a:** Correlation between radon and progenies
Looking at the seasonal correlation coefficients, wind speed is important for radon variations in all seasons, with the highest correlation during spring (0.6 ± 0.03). Horizontal advection is, in principle, as important as vertical mixing for the dilution of surface atmospheric radon (Piero et al., 2009).

The correlations between $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their daughter products showed a good correlation of 0.97 and 0.77 between $^{222}\text{Rn}$ and its progeny and $^{220}\text{Rn}$ and its progeny respectively. Looking at the seasonal correlation coefficients, wind speed may plly a significant role for radon variations in all seasons and horizontal advection is, in principle, as important as vertical mixing for the dilution of surface atmospheric radon (Piero et al., 2009).

**5.8.5 DIFFERENT VOLUMES**

To provide a novel glow on radon level inside closed space with respect to room volume. Study is carried out for a large number of measurements for $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentrations using nuclear track detector based discriminating dosimeters. The obtained values were plotted against room volume and the results have shown the monotonically decrease in concentration as the room volume increases. The data also showed an inverse relationship between $^{222}\text{Rn}$, $^{220}\text{Rn}$ concentrations and volume of
rooms. The correlation between $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progenies and the frequency distributions are shown in Figs 5.8.5a and 5.8.5b.

![Figure 5.8.5a: Correlation between radon and progenies](image)

![Figure 5.8.5b: Frequency distribution of $^{222}\text{Rn}/^{220}\text{Rn}$](image)

No significant correlation was found between $^{220}\text{Rn}$ and its progenies. On the other hand, even though the direct correlation between the concentrations of indoor
220\(^{\text{Rn}}\) and its progeny was weak, a better correlation (R=0.77) was found by modified 220\(^{\text{Rn}}\) concentrations with the ratios of source areas to volumes of rooms. It suggests that indoor concentrations of 220\(^{\text{Rn}}\) progeny may be roughly estimated from the measurements of indoor 220\(^{\text{Rn}}\) (Wei et al., 2005).

5.8.6 CORRELATION BETWEEN 226\(^{\text{Ra}}, 222\(^{\text{Rn}}\) AND 232\(^{\text{Th}}, 220\(^{\text{Rn}}\)

Correlation between 226\(^{\text{Ra}}\) and 222\(^{\text{Rn}}\) and 232\(^{\text{Th}}\) and 220\(^{\text{Rn}}\) are plotted in Fig. 5.86. The obtained correlation coefficients were 0.91 and 0.84 respectively for 226\(^{\text{Ra}}\) and 222\(^{\text{Rn}}\) and 232\(^{\text{Th}}\) and 220\(^{\text{Rn}}\) and this indicate that the higher concentrations are mainly due the presence of the activity concentrations of primordial radionuclides.

![Fig. 5.8.6: Correlation between activity concentrations](image-url)

Correlation between 222\(^{\text{Rn}}\) and 220\(^{\text{Rn}}\) concentrations including the errors as weighted average is measured. The correlation coefficient for 222\(^{\text{Rn}}\) and 220\(^{\text{Rn}}\) in room wise, wall wise, flooring wise and season wise were 0.70, 0.75, 0.70 and 0.58 respectively. Higher correlation is observed in wall wise variations and the lower in season wise variations. Weak correlation may reflect differences in the interior and surface structures of the grains and pore spaces (Hassan et al., 2011).

In addition to parent nuclide concentrations and grain structure, the emanation coefficient may influence exhalation rates. Exhalation rates may be low even with...
higher concentrations of the parent nuclides are present, if the emanation coefficient of
the material has a low value (Hassan et al., 2011).

5.9 BACK GROUND GAMMA RADIATION LEVELS

Back ground gamma radiation levels were measured by using RADOS. Thirteen
different rooms of different features such as big room (700 m$^3$), small room (20m$^3$),
good ventilation (10 windows), and poor ventilation (nil windows) were selected in
Government Science College, Central part of Bangalore, India and the measurement of
back ground gamma dose rates were carried out for a period of five months. Further,
the measurements were also made in bio chemistry lab, organic chemistry lab,
inorganic chemistry lab and physical chemistry lab of Government Science College,
Bangalore, India. The volumes of the selected rooms were in the range of 20 to 700 m$^3$.
The results of indoor pressure, indoor temperature and relative humidity of the studied
rooms varied from 683.5 – 689.5 mm Hg, 19.2 – 29.8 °C and 32.5 – 64.8 %
respectively.

The outcome of the measurements of present study on back ground gamma dose
rates carried out on day wise of different months of 2011 are shown in Figure 5.9.1.
Linear fit of the variation of dose rates for the period of February to June 2011 have
shown the regression coefficient as 0.18, whereas the regression coefficient for the
exponential growth and decay were found to be 0.04 respectively. For the same set of
data normal distribution curve is plotted and the area of graph was 2.53 with R$^2$ as 0.25.
The arithmetic mean values of the dose rate for the environment of Bangalore
Metropolitan varied from 1.02 to 1.61 mSv y$^{-1}$ with AM and GM as 1.32 ± 0.01 and
1.31 ± 0.01 mSv y$^{-1}$ respectively.
Fig. 5.9.1: Variation of gamma dose rate on day wise

The results reveal that, the dose rates are at alarming level. The arithmetic mean values of dose rates for the five months are depicted in Figure 5.9.2.
Sriharsha et al., (2008) have done the similar type of measurement for the environment of Mysore city, India and reported that the dose rates in temples varied from 122.7 to 231.4 \( \text{h Gyh}^{-1} \) with a median of 130.1 \( \text{h Gyh}^{-1} \) outside the temples it varied from 141.8 to 340.2 \( \text{h Gyh}^{-1} \) with a median of 216.2 \( \text{h Gyh}^{-1} \). In different types of buildings in indoor atmosphere it varied from 112.2 to 197.5 \( \text{h Gyh}^{-1} \) with a median of \( \text{h Gyh}^{-1} \) and in outdoor atmosphere it varied from 140.9 to 298.4 \( \text{h Gyh}^{-1} \) with a median of 216.2 \( \text{h Gyh}^{-1} \).

The external gamma dose rates have been mapped in India by several studies. A countrywide survey on outdoor natural gamma radiation levels using Thermo Luminescent Dosimeters (TLD) covering about 214 locations scattered all over India revealed that the average external gamma radiation dose for the country is about 775 \( \text{h Gyy}^{-1} \).

National average value is projected as 707 \( \text{h Gyy}^{-1} \) based on natural radioactivity analysis of undisturbed soil samples from more than 30 different locations, all over the country, assuming a uniform
cosmic ray component of 287 nGy\(^{-1}\) (Mishra and Sadasivan 1971). Total contribution to the natural sources of radiation to the Indian population works out to be 2.3 mSv\(^{-1}\) as against the global value of 2.4 mSv\(^{-1}\) (Ramachandran et al., 2012).

For the month of February, 2012 the dose rates in sports room (40 m\(^3\)), NCC office (25 m\(^3\)) and accounts office (50 m\(^3\)) varied from 0.96 to 1.57 with an AM of 1.18 \pm 0.03 mSv\(^{-1}\), 0.96 to 2.63 with an AM of 1.49 \pm 0.06 mSv\(^{-1}\) and 1.05 to 1.66 with an AM of 1.33\pm0.03 mSv\(^{-1}\) respectively. In the month of March, 2012 the dose rate in NCC office (25 m\(^3\)), administration office (220 m\(^3\)), NCC store room (25 m\(^3\)) and Managers room (40 m\(^3\)) varied from 0.96 to 1.66 with an AM of 1.25 \pm 0.02 mSv\(^{-1}\), 1.05 to 1.75 with AM of 1.4 \pm 0.02 mSv\(^{-1}\), 1.05 to 1.92 with an AM of 1.52 \pm 0.03 mSv\(^{-1}\) and 1.22 to 1.84 with an AM of 1.4 \pm 0.03 mSv\(^{-1}\) respectively. In the month of April, 2012 the dose rate in office room (40m\(^3\)), auditorium (700m\(^3\)), chemistry store room 1 (95m\(^3\)), chemistry store room 2 (95m\(^3\)) varied from 1.05 to 1.66 with an AM of 1.39 \pm 0.09 mSv\(^{-1}\), 0.87 to 1.48 with an AM of 1.16 \pm 0.02 mSv\(^{-1}\), 0.96 to 1.66 with an AM of 1.25 \pm 0.02 mSv\(^{-1}\) and 1.05 to 2.10 with an AM of 1.25\pm0.02 mSv\(^{-1}\) respectively. In the month of May, 2012 the dose rates in new accounts office (20 m\(^3\)), principal’s anti chamber (20 m\(^3\)) and chemistry lab (320 m\(^3\)) varied from 0.87 to 1.75 with an AM of 1.3 \pm 0.03 mSv\(^{-1}\), 0.87 to 1.57 with an AM of 1.2 \pm 0.03 mSv\(^{-1}\) and 0.87 to 1.66 with an AM of 1.25 \pm 0.02 mSv\(^{-1}\) respectively. In the month of June, 2012 the dose rates in chemistry Lab (220 m\(^3\)), chemistry staff room (20 m\(^3\)) and NCC office (40 m\(^3\)) varied from 0.87 to 1.57 with an AM of 1.25 \pm 0.02 mSv\(^{-1}\), 1.05 to 1.84 with AM of 1.35 \pm 0.03 mSv\(^{-1}\), and 1.05 to 1.84 with an AM of 1.36 \pm 0.03 mSv\(^{-1}\) respectively.

Relatively higher values of dose rates were observed in the chemistry lab and chemistry staff room, this is may be due to the usage/storage of chemicals in the laboratory classes; chemistry staff room had no ventilation and the volume of the room was 20 m\(^3\).

The similar sets of variations were also observed in principal’s anti chamber of the college, this is because of the lack of ventilation. The lower values of dose rates
were observed in auditorium and administration office, which were well ventilated and the volume of these halls were 700 and 320 m$^3$ respectively.

Additionally majority of the chemistry labs consists of reagents required for semi micro qualitative analysis of acid and basic radicals. Each group of acid and basic radicals was being analyzed using group reagents. Confirmation test of acid and basic radicals is executed through flame tests, based on the color of the flame the basic radicals were identified as Sodium, Calcium, Barium and Strontium; these basic radicals have lower ionization energy. During this process the energy released in the form of light in the visible range with an energy ranging from 3.1 eV to 1.6 eV. During chemical reactions due to the release of pungent smell, due to the formation of new chemical elements, may also account for the variation in the dose rates. The detailed studies in this regard are in progress.

The correlation between the arithmetic mean values of dose rates and volume of the room, indoor pressure, indoor temperature and indoor relative humidity are depicted in Fig. 5.9.3.

![Fig. 5.9.3: Correlation between dose rate and volume, pressure, temperature, relative humidity](image)

Very weak correlation is observed, the correlation between the arithmetic mean values of dose rates and volume of the room, indoor pressure, indoor temperature and indoor relative humidity were -0.18, -0.39, 0.18 and 0.09 respectively. Weak negative
correlation is observed between the dose rate and the volume of the room and the pressure of the room; whereas weak positive correlation is observed between the dose rate and temperature and relative humidity of the room. As the volume of the room increases the dose rate reduces and it may be due to the higher diffusion rate.

The background gamma radiation dose mainly depends on the radioactivity content of the building materials and soil beneath the house. It also depends on the construction materials used such as granite, cement, brick and the wall paints. Ventilation may ply a little role in reduction of dose rates. Since the data is scanty to conclude the major parameter that influence the back ground gamma dose rate, more data is being planned to obtain on the radioactivity measurements and to give the correlation with respect to the radium content in the materials used for construction.

The detailed study on the radioactivity in soil/building materials, radon levels and the radon exhalation in these rooms are also in progress to assess the dose due to the radon and its progeny levels too.

Our results are comparable with the earlier reported values elsewhere. As human beings are in the midst of a radiation environment, however low it may be, and it is not possible to avoid radiation exposure from natural sources altogether. All what is needed and is possible is to be conscious of this fact with a constant endeavor to control the radiation from man-made sources to levels as low as is reasonably achievable. Periodic review of the dose values reported in this note is very essential.

CHAPTER 6

Conclusions

Following conclusions are drawn out of the study on environmental radioactivity for the environment of Bangalore metropolitan, India
It is observed that the concentrations of indoor $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny levels are higher in poor ventilated houses as well as smaller volume rooms than in well ventilated rooms and rooms of larger volume. The levels of concentrations experimentally seen for the environment of Bangalore are well within the limits of International Commission on Radiological Protection. The higher concentrations were may be due to the presence of radioactive nuclides in the building materials used for construction of the houses. It is suggested that the room should be well ventilated and building construction materials must be free from radioactive species to minimize the $^{222}\text{Rn}$, $^{220}\text{Rn}$ concentrations in the dwellings.

**Variation on room volume**

The concentrations in different volume of the room due to exposure to indoor radon gas are higher in smaller volume rooms and lower in larger volume rooms of all the monitored dwellings. This clearly indicates that though the observations have been made almost for similar type of constructions and age of the building, as the volume of the room enhances the concentrations drops exponentially and it becomes almost constant above the volume of 200 m$^3$. It emphasis that rooms of dimensions with an average height around 4m may have the dimensions 5m×6m or 5m×5m may pose higher risk compared to the rooms of larger volume. The correlation coefficient for exponential drop in concentration is more than 90% in all cases and envisages that there is a direct dependence of concentration with volume.

Normally big rooms, class rooms, conferences halls etc. are of higher dimensions will have less risk. It is suggested that the lower volume rooms should be well ventilated to reduce the radiation exposure due to radon. On the basis of the results obtained it may be conclude that the levels of indoor $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are well within the acceptable values for the population prescribed by UNSCEAR.

**$^{220}\text{Rn}$ concentration level**

The $^{220}\text{Rn}$ concentrations were higher near the walls and flooring of the room and the concentration drops exponentially with the distance from walls, ceiling and flooring of the room. Indoor $^{220}\text{Rn}$ progeny concentrations were uniform with the distance from
the wall. Detailed studies such as the diffusion of $^{220}\text{Rn}$ from each wall of the building materials used and other influencing factors of $^{220}\text{Rn}$ progeny levels in dwellings are necessary to assess the dose due to $^{220}\text{Rn}$ and its progeny. Further work and more detailed studies on the evaluation of the public exposure from natural radiation, especially the exposure from $^{220}\text{Rn}$ and its progeny should be planned and performed in the country.

- **Annual Effective Dose rate**

  The $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny concentrations in the indoor atmosphere vary with ventilation conditions, types of flooring and type of the materials used for construction of houses. The average concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are 23.8 Bqm$^{-3}$ and 14.7 Bqm$^{-3}$ for their progenies they are 0.08 mWL and 0.04 mWL respectively, the $^{222}\text{Rn}$ concentration is less than the global average (40 Bqm$^{-3}$) but $^{220}\text{Rn}$ concentration is higher than the global average (10 Bqm$^{-3}$).

  The annual inhalation dose due to $^{222}\text{Rn}$, $^{220}\text{Rn}$, their progeny and ambient gamma radiation in Bangalore city is slightly lower than the global average value. Higher concentration is observed in very poorly ventilated and loose-cemented flooring houses.

  The annual average dose to the population of Bangalore city due to the exposure of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ progeny works out to be 1.7 mSvy$^{-1}$. All India mean effective dose equivalent is 2.5 mSvy$^{-1}$ and the global effective dose equivalent is 2.4 mSvy$^{-1}$. Seasonal variations of indoor $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny concentrations reveal the higher values during winter and lower in summer months. Higher values of annual effective dose rates were observed in granite flooring house, bath room, mud wall houses and during winter season. Among the higher dose rates, the inhabitants of lower volume room and granite flooring house are exposed to higher dose than during winter season or mud wall houses or bath rooms of the studied locations. It is suggested to have well ventilated rooms and granite flooring free houses to reduce the dose effect.

- **Correlation studies**

  $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny levels vary with ventilation conditions, types of the flooring, types of the materials used for construction of houses. Correlations between $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progeny levels have been studied and a positive
correlation of 0.98 between average $^{222}\text{Rn}$ concentrations and its progeny and 0.81 between $^{220}\text{Rn}$ and its progeny concentrations were observed. The correlation between $^{226}\text{Ra}/^{222}\text{Rn}$ and $^{232}\text{Th}/^{220}\text{Rn}$ in the study locations were found to be 0.97 and 0.68 respectively, where as the correlation between $^{222}\text{Rn}$ in water and in air were found as 0.83.

❖ **Back ground gamma radiation levels**

The background gamma dose rates for the environment of Bangalore city varied from 1.1 to 1.7 mSv y$^{-1}$ with a mean as 1.32 ± 0.01 mSv y$^{-1}$. The results revealed that the dose rates are at alarming level and demand the proper control measures to minimize the health hazards and the detailed investigations on dose rates due to the radon in water and air should be initiated. Weak correlation is observed between the dose rate and volume, pressure, temperature and relative humidity. Further, thorough investigations on the dose rates due to the usage/storage of chemicals in the laboratories should be planed and performed.

❖ **Essence of Radon mapping**

It is evident from our studies that the concentration levels of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ in dwellings depend on various factors such as soil beneath, local geology, the house construction materials, and last but not the least life style in the dwelling since higher concentration in the poor ventilated rooms has been observed. Therefore it is suggested that the residential rooms must be well ventilated and free from radon rich materials to reduce the health hazard effects of radon.

Indoor concentration depends also on radon exhalation rate of the flooring and ventilation condition. Higher concentrations of both $^{222}\text{Rn}$ and $^{220}\text{Rn}$ have been observed where the exhalation rate is more. In conclusion, this work has posed the bases for the realization of a network that will allow to mapping the environmental radioactivity in Bangalore region and, more importantly, that will contribute to diffusion of a more complete scientific culture about radioactivity. Further, nationwide initiation has to be performed to create the radon mapping in this regard.

It is suggested that the lower volume rooms should be well ventilated to reduce the radiation exposure due to radon, thoron and their progeny. The results conclude that
the levels of indoor $^{222}$Rn and $^{220}$Rn are well within the acceptable values for the population prescribed by UNSCEAR. Further to assess the authentic effect of radon on human beings, a rigorous study pertaining to radioactivity in soil samples, building materials, radon in water etc. should be envisaged.

**Future study**

Following suggestions are provided to reduce the health effects due to radon exposure for the indoor environment.

- More detailed studies on the evaluation of public exposure from the natural radiation; particularly the exposure from $^{222}$Rn, $^{220}$Rn and their progeny should be planned and performed in the entire city.

- Detailed analysis of radon in ground water should be initiated

- Map of radioactivity and radon levels in Bangalore city should be planned and performed

- Indoor radon mapping for Bangalore Metropolitan

- Indoor Radon Model for dwellings of Bangalore Metropolitan

- Development of new methodology for the study of surface radon exhalation

- Precautionary measures for radon mitigation

**REFERENCES**


Elham, B. Masoud, V M, Asad, B & Nasrin, F 2012 ‘Analytical Study Of Radionuclide Concentration And Radon Exhalation Rate In Market Available Building


Marsden, E 1964 ‘Radioactivity of some rocks, soils, plants and bones’, in the (Eds), Natural Radiation Environment, The University of Chicago Press, Chicago, IL, pp.807-24


Tuccimei, P, Moroni, M & Norcia, D 2006 ‘Simultaneous determination of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ exhalation rates from building materials used in Central Italy with accumulation chambers and a continuous solid state alpha detector: Influence of particle size, humidity and precursors concentration’, *Applied Radiation and Isotopes*, Vol. 64, pp. 254–263.


LIST OF PUBLICATIONS

During the period of research work, a total of 22 research articles have been published in journals of good repute and several parts of the results and discussion (21 research papers) have been presented at various national and international conferences/symposium, which are based on the work presented in this thesis.

REVIEW ARTICLES:


**INTERNATIONAL JOURNALS:**


NATIONAL JOURNALS:


NATIONAL BULLETIN


PROCEEDINGS:

INTERNATIONAL


NATIONAL


PRESENTATIONS IN CONFERENCE, SEMINARS AND SYMPOSIUM

INTERNATIONAL:
27. LA Sathish, K. Nagaraja, Sundareshan.S and S. Shobha. Inhalation dose due to indoor $^{222}$Rn and $^{220}$Rn in Bangalore, India. 7th International Conference on High Levels of Natural Radiation and Radon Areas, Park Hotel, November 24 - 26, 2010, Nave Mumbai, India.

28. V Nagesh, LA Sathish, K. Nagaraja and Sundareshan.S. Diurnal variations of indoor radon progeny for Bangalore Metropolitan, India. 7th International Conference on High Levels of Natural Radiation and Radon Areas, Park Hotel, November 24 - 26, 2010, Nave Mumbai, India.


30. TV Ramachandran, LA Sathish and Sundareshan.S. Nation-wide $^{222}$Rn and $^{220}$Rn atlas for India. International Symposium on Radon’ 17 – 20 October 2010, Columbus, Ohio, USA.


34. LA Sathish, K. Nagaraja, Sundareshan.S and T.V. Ramachandran. Study of inhalation dose due to indoor $^{222}$Rn and $^{220}$Rn. 6th International Conference on Protection Against Radon at Home and at Work, September 13 – 17, 2010 Prague, Czech Republic

**NATIONAL:**


