EFFECTIVE INDOOR ^{222}RN RADIATION DOSE FROM CONCENTRATION ON FILTERED AIR SAMPLE

By

Temesgen Terefe Heda

A THESIS PRESENTED TO

THE DEPARTMENT OF PHYSICS
ADDIS ABABA UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE

MASTER OF SCIENCE in PHYSICS

ADDIS ABABA, ETHIOPIA

JUNE, 2017

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

EFFECTIVE INDOOR ^{222}RN RADIATION DOSE FROM CONCENTRATION ON FILTERED AIR SAMPLE

By

Temesgen Terefe Heda

Deaprment of Physics

Addis Ababa University

Approved by the Examining Board:

Dr. Tilahun Tesfaye — Signature _____
Advisor

_____ — Signature _____
Examiner

_____ — Examiner _____
Examiner

Dated: June, 2017

ADDIS ABABA UNIVERSITY

Date: **June, 2017**

Author: **Temesgen Terefe Heda**

Title: **Effective Indoor ^{222}Rn Radiation Dose from Concentration on Filtered Air Sample**

Department: **Deaprment of Physics**

Degree: **M.Sc.** Convocation: **July** Year: **2017**

Permission is herewith granted to Addis Ababa University to circulate and to have copied for non-commercial purposes, at its discretion, the above title upon the request of individuals or institutions.

Signature of Author

This Work is Dedicated to Men and Women of Science who labored for the welbeing of all humanity.

Table of Contents

List of Tables

List of Figures

Acknowledgements

First, I would like to gratitude my God who crucified and sacrificed on the cross to heal me and won my death. Next, I would like to express my appreciation to my advisor and instructor Dr. Tilahun Tesfaye , for formulating this thesis project, critical comment and guidance to my work. Finally, I would like to thank my family and Addis Ababa University for sponsoring my Msc. studies.

Addis Ababa University Temesgen Terefe Heda

Acronyms and Abbreviations Used

IAEA	≡	International Atomic Energy Agency
NCRP	≡	National Council on Radiation Protection
NORM	≡	Naturally Occurring Radioactive Material
WNA	≡	World Nucear Association
UNSCEAR	≡	United Nation Scientific Committee on the Effects of Atomic Radiations
SSNTD	≡	Solid State Nuclear Detector
US EPA	≡	United State Environmental Protection Agency
WHO	≡	World Health Organization
IAR	≡	International Agency for Research on Cancer;
ICRP	≡	International Commission For Radiological Protection
CEC	≡	Commission of Europian Committee
EPA	≡	environmental protection agency
IARP	≡	International Agency For Research on Cancer

IARC -

Abstract

Instantaneous measurements of equilibrium equivalent concentration of radon (EEC_{Rn}) Counting system were taken over a period of 21 days in Nuclear physics laboratory located in the first floor of the physics building, Addis Ababa University. The method is based on grab sampling of known volume of air on a glass fiber filter of more than 99% retention followed by gross beta counting of the filtered air sample and counted over large number of successive time intervals using an end-window Geiger-Müller (GM) counter.

The gross beta count was canalized using a mathematical model based on Bateman differential equations (Papp & Daróczy, 1997) and the experimental count rate was fitted to the mathematical method to determine Equilibrium Equivalent Concentrations of Radon isotopes.

The indoor effective dose was estimated from the EECs. The values of annual effective doses in Nuclear physics laboratory first floor of closed indoor building for radon were found to vary in the range 0.39 mSv/y - 1.93 mSv/y, with a mean of 0.99 mSv/y. These results are lower than the value 1.15 mSv/y recommended by (ICRP-60, 1990). In addition to environmental value of the present survey, the results are considered to be essential in analyzing any data for future activities in this field.

CHAPTER 1

Introduction

Radioactive decay is a process which an unstable atom releases particulate radiation or electromagnetic radiation. The radioactive decay of a naturally occurring isotope changes the number of protons in a nucleus by doing alpha and beta decays. If the decay is a one step process, it means that a stable atom is formed, but on the other hand; nucleus of the decay product, which is called its daughter, might be unstable and this result in other decay till the daughter nuclei is stable. This multiple step is called a decay series. The decay of ^{238}U to ^{206}Pb is a decay series which involves 14 steps and includes several α and β decays (Krane, 1987).

Uranium is a radioactive isotope that spontaneously decays to lighter "daughter" elements by losing high-energy.Uranium decays to radium through a long series of steps with a half-life of 4.5 billion years. Radon-222 (^{222}Rn) is also radioactive and it decays with a half-life of 3.82 days, producing daughter products of polonium, bismuth, and lead. ^{222}Rn can be measured with active or passive methods.In 1900 Friedrich Ernst Dorn reported some experiments in which he noticed that radium compounds emanate a radioactive gas he named Radium Emanation (Ra Em). Before that, in 1899, Pierre and Marie Curie observed that the gas emitted by radium remained radioactive for a month.

Radon (^{222}Rn) is a naturally occurring radioactive gas that originates from the decay of radium (^{226}Ra) in the primordial uranium (^{238}U) decay series. Half-life of ^{222}Rn is long enough that it can migrate even to quite long distances from the place of its decay into buildings raised in a certain area. According to (Nazaroff, 1988), this distance in soil and rocks can be as long as a few meters. Numerous worldwide studies of radiation exposure show that inhalation of radon (^{222}Rn) and its progeny is the dominating contributor to the total collective radiation exposure of world's population (UNSCEAR, 2000).

^{222}Rn is produced continuously from the decay of radium in the ground. It dissolves in groundwater, which often carries it in high concentrations and releases it to areas

inhabited by humans. An important characteristic of radon is that it gives more radiological significance than other United States, Canada, and the United Kingdom members of uranium decay series. ^{222}Rn is the most important radon isotope in uranium decay chain, because it has the longest half-life that makes it easier for radon to travel in air before it decays. Other important characteristic of radon is that its decay products are also chemically active radionuclides and relatively short-lived (Nagda, 1994).

Currently in Ethiopia, there is no radon concentration standard in air for indoor houses. Considering this circumstance measuring radon indoor house is necessary. In order to examine measurement methods that can be used in houses and deduce improvement plans for this study investigated radon measurement protocols used in the United States, Japan, Germany, the United Kingdom and compared them to that used in Ethiopia, Addis Ababa University in the physics laboratory room in the first floor.

1.1 THE DISCOVERY OF RADON ^{222}Rn

While investigating fluorescence phenomena of various materials, in 1896, Becquerel reported that crystals of uranous salts emitted radiation which even blackened photographic plates wrapped in black paper or covered with glass or other substances. The rays emitted were concluded to be an atomic phenomenon characteristic of the element and for this the name 'radio activity' was introduced. The element of Radon(^{222}Rn) was discovered in 1900 by Dorn, who called it radium emanation. At first, the element was named Nit on (Nitens comes from the Latin meaning shining), but after about 1920 the name radon began to appear in the literature. Twenty isotopes of the element radon are known. The most abundant are ^{222}Rn(radon), ^{220}Rn (thoron) and ^{219}Rn(action). These three isotopes originate from the radioactive decay of the radium, of which the isotopes are members of the naturally occurring decay series starting with ^{238}U, ^{232}Th and ^{235}U, respectively. All radon isotopes are radioactive. The half-life of ^{222}Rn is long enough to allow much of the gas to escape from the upper layer of the soil and reach the atmosphere. Substantially less of the ^{220}Rn and ^{219}Rn reaches the air because of their short half-lives (55.6 sec and 3.96 sec,respectively). Only the radon isotope ^{222}Rn were considered in this study.

It is essentially inert and occupies the last place in the zero groups of gases in the Periodic table. Since 1923, it has been called Radon. Due to its gaseous nature, radon

may be released from the solid material to the environment and is therefore present, not only in soil and rock, but also in air and in water. It is estimated that every square mile of soil to a depth of 6 inches contains about 1 gram of radium, which releases Radon in tiny amounts into the atmosphere. The main hazard is from inhalation of the element and its solid daughters which are collected on dust in the air (Nabil & Hamed, 1995).

1.2 PHYSICAL PROPERTIES

Radon is a colorless, odorless, and tasteless gas and therefore not detectable by human senses alone. At standard temperature and pressure, radon forms a monatomic gas with a density of 9.73 kg/m^3, about 8 times the density of the Earth's atmosphere at sea level, 1.217 kg/m^3 (David, 2003).

Radon is one of the densest gases at room temperature. Although colorless at standard temperature and pressure, when cooled below its freezing point of 202 K radon emits a brilliant radio luminescence that turns from yellow to orange-red as the temperature lowers. Upon condensation, radon glows because of the intense radiation it produces. Radon is sparingly soluble in water, but more soluble than lighter noble gases. Radon is appreciably more soluble in organic liquids than in water.

1.3 RADON DECAY CHAINS

As radon itself decays, it produces other radioactive elements called radon progeny (also known as radon daughters) or decay products. If the decay time is short the radon isotope will not be able to escape from its place of origin before decay. When radon decays it goes from the gaseous state into being metallic particles. These particles can attach aerosols in the air, which humans can inhale. The inhaled particles stick to the respiratory tract (Marsh & Bailey, 2013).

The short lived radon daughters have half-lives ranging from 300 ns to 10.6 h for the thorium decay series and between 164 micro seconds to 26.8 min for the uranium decay series. In addition to an isotope's radiological half-life it also has a biological half-life, the time for half of the amount of the substance to be expelled from the body. The biological half-life can for some isotopes be shorter than the radiological half-life. This means that the nuclides will be expelled from the body before the majority of the nuclides can decay, however this is not the case of the short lived

radon daughters which decay before they can be removed from the lung tissue. Lead-210 on the other hand has a long enough radiological half-life to be removed from the lung tissue before it decays. Thorium and uranium is present in rocks but due to thoron's short half-life only a small fraction is able to diffuse from its place of origin before it decays into a metal particle. Because of radon's longer half-life it is therefore more likely to inhale the radon daughters instead of thoron daughters.

Daughters of Radon (^{222}Rn)

- ^{222}Rn 3.82 days, alpha decaying to
- ^{218}Po 3.10 minutes, alpha decaying to
- ^{214}Pb 26.8 minutes, beta decaying to
- ^{214}Bi 19.9 minutes, beta decaying to
- ^{214}Po 0.1643 ms, alpha decaying to
- ^{210}Pb which has a much longer half-life of 22.3 years, beta decaying to
- ^{210}Po 138.376 days, alpha decaying to ^{206}Pb, stable.

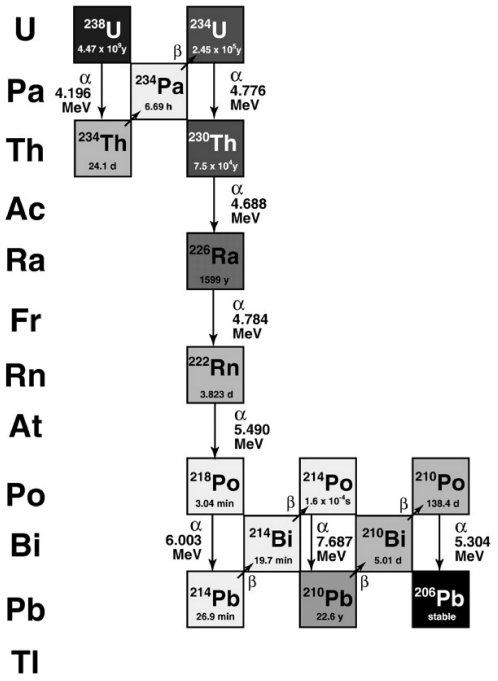

Figure 1.1: Radioactive decay chain of Uranium-238

The decay process of $^{238}Uranium$ can be summarized as shown in Figure 1.2. This process will continue until the formation of Lead-206, which is a stable element.

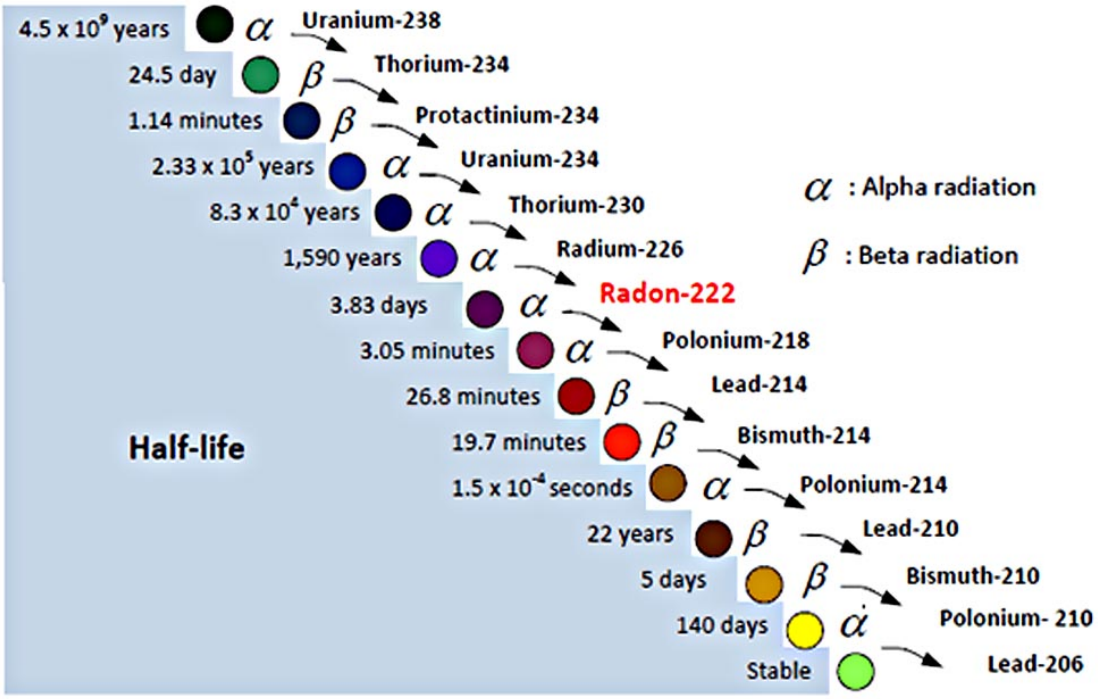

Figure 1.2: Uranium-238 decay chain

1.4 RADON IN AMBIENT AIR

The United Nation Scientific Committee on the Effects of Atomic Radiations has made a very simple model to try to estimate the relative contribution of these sources: for a "typical" house, with a radon concentration of 50 Bq/m^3 at ground floor, the contributions of soil, building materials and outdoor air are, respectively, 60 percent, 20 percent and 20 percent, while for the upper floors in high rise buildings, where the radon concentration-is estimated to be "typically" 20 Bq/m^3, these values become 0 percent, 50 percent and 50 percent. For those who live close to the ground, e.g. in detached houses or on the ground floor of apartment buildings without cellars, the most important radon source is radium in the ground. The radium concentration in soil usually lies in the range 10 Bq/kg to 50 Bq/kg, but it can reach values of hundreds Bq/kg, with an estimated average of 40 Bq/kg (UNSCEAR, 1993).

Since radon is a colorless, odorless gas the only way to know how much is present in the air or water is to perform tests. In the United States radon test kits are available to the public at retail stores, such as hardware stores, for home use and testing is

available through licensed professionals, who are often home inspectors. Efforts to reduce indoor radon levels are called radon mitigation. In the U.S. the Environmental Protection Agency recommends all houses be tested for radon.

1.4.1 Radon entry into the atmosphere

The study showed on a seasonal variation with higher radon concentration levels for saps, tunnels and basements during the summer and lower levels during the winter. The summer -winter ratio for tunnels which had the highest ratio was 2.41. A comparison between closed and open tunnels was made pointing at that the ratio was 2.82 for closed tunnels and 1.27 for open tunnels. This phenomenon is also found in a study from. The radon concentration level was about the same in the winter for both closed and open tunnels but the closed tunnels had much greater levels during the summer (Li et al., 2006). Radon concentration can differ widely from place to place. In the open air, it ranges from 1 to 100 Bq/m^3, even less (0.1 Bq/m^3) above the ocean. In caves or aerated mines, or ill-aerated houses, its concentration climbs to 20 - 2,000 Bq/m^3.

1.4.2 Radon in mines

Mining is an ancient, multi-disciplinary industry, long recognized as being arduous and liable to injury and disease. (Anon, 1995), The industry employs a labor force of several hundred thousand miners, both in South Africa and in the rest of the world. Studies of underground miners have consistently shown an increased risk of lung cancer with cumulative exposure to ^{222}Rn and its decay products. Working with natural raw radioactive materials increases exposure to radiation.

(Evans et al., 1981), ^{222}Rn and its progeny form 54.8 percent of the effective dose of natural radiation received by the U.S population. Exposure occurs through the inhalation of the radioactive ^{222}Rn gas and the inhalation of radioactive particles produced by mining and milling. (Gulson BL, 2005)The inhalation of high cumulative levels of ^{222}Rn and its alpha-particle emitting decay products has been linked to an increased risk of lung cancer among underground miners. Short lived radon progenies have been established as causative agents of lung cancer. The main carcinogens formed by the decay of ^{222}Rn are the short-lived progeny Polonium-218 and Polonium-214, both alpha-particle emitting elements (Yamada, 2003).

The decay products of ^{222}Rn are all solids and are readily deposited on the bronchial airways and inside the alveoli of the lungs during breathing (Mahur et al., 2008).

The exposure to ^{222}Rn and ^{222}Rn progeny only exhibits effects on the lung and bronchial epithelium, because of the weak penetrating power of alpha-particles and the proximity of the ^{222}Rn gas and progeny with the epithelium cells in the lungs and bronchi, and thus ^{222}Rn does not affect any other organ or system. (Stanton et al., 2007) The radiation dose from ^{222}Rn gas itself is very low in comparison with its decay daughters, as the ^{222}Rn decay daughters deposit and accumulate on the airway surfaces, increasing the received dose through increased retention time.

1.4.3 Radon in outdoor

Outdoor air usually acts as a diluting factor, due to its normally low radon concentration, but in some cases, as in high rise apartments built with materials having very low radium content, it can act as a real source. The radon concentration in outdoor air is mainly related to atmospheric pressure, and (in case of non-perturbation weather) it shows a typical oscillating time pattern, with higher values during night. Until a few years ago the average level of radon gas concentration in the atmosphere at ground level was usually assumed to be of the order of few Bq/m^3: e.g. in the range of 4 Bq/m^3 to 15 Bq/m^3 in USA.

The way for the radon to get into the air besides diffusing out of the rock is by water. It is observed that radon can be transported by water (Richon et al., 2005). Ambient air over oceans has very low values (approximately 0.1 Bq/m^3) of radon concentration, due to the minimum presence of radium in the sea water and the high solubility of radon in water at low temperatures. Therefore, radon concentration in outdoor air of islands and coastal regions is generally lower than in continental countries, e.g. United Kingdom and Japan have an average outdoor air value of approximately 4 Bq/m^3. Some level of radon will be found in all buildings. Radon mostly enters a building directly from the soil through the lowest level in the building that is in contact with the ground.

1.4.4 Radon indoor

High levels of radon in the water supply can also increase indoor radon air levels. Typical entry points of radon into buildings are cracks in solid foundations, construction joints, cracks in walls, gaps in suspended floors, gaps around service pipes, cavities inside walls, and the water supply. Radon concentrations in the same location may differ by a factor of two over a period of 1 hour. Also, the concentration in one room of a building may be significantly different from the concentration in an

adjoining room.

The Swedish Radiation Safety Authority has estimated that out of the annual 3000 cases of lung cancer, around 450 of the cases were caused by inhalation of radon and its short-lived daughters in dwellings in conjuncture with smoking and around 50 cases without conjunction with smoking. There have been studies conducted on radon concentrations in rock shelters and tunnels with different focuses. The radon concentration level depends on the geological material in the cave also in addition to the underlying rocks. The air flow and ventilation influence the radon concentration levels mainly depending on changes in the outside temperature and the ratio between the temperature inside and outside the cave as long as the rock shelter does not have a mechanical ventilation system (Thinova & Rovenska, 2011).

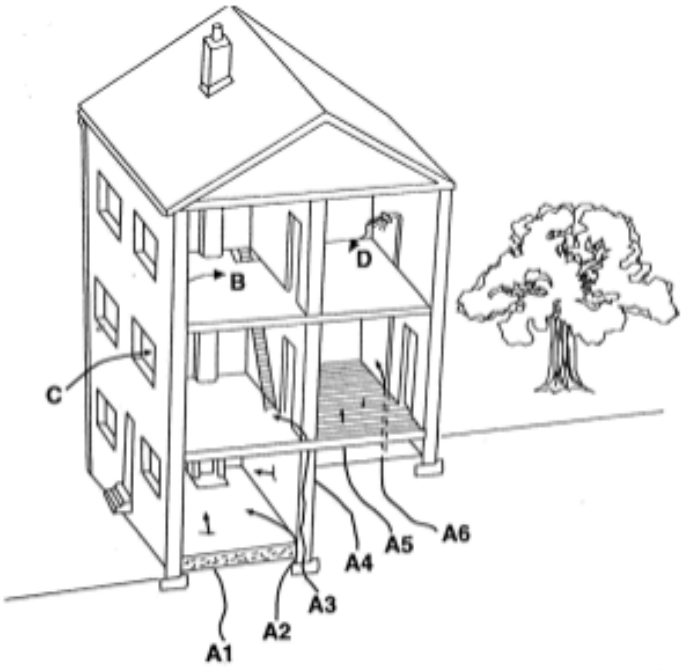

Figure 1.3: Typical radon sources and entry routes

where

- entry of radon from the soil through
- A1-cracks in solid floors
- A2-construction joints
- A3-Cracks and cavities in wall

- A4-Cracks in walls below ground level
- A5-Gaps in suspended floors
- A6-Gaps around service pipes
- B-Radon exhalation from building materials
- C-Entry of Radon with out door air
- D-Radon released from water

1.4.5 Radon in water

The applications of radon span many research fields. The importance of the knowledge regarding radon in water is not only confined to radiation protection issues but also in its use for studying geological and hydrogeological characteristics of the environment (Somlai et al., 2007). The study of submarine ground water discharge involves the use of radon as a natural tracer (Waska et al., 2008). Since the ground waters are rich in radon as compared to surface waters (Burnett et al., 2010), the discharge of ground waters into open water bodies like oceans, lakes and rivers can be noted by high concentration of radon in water.

The expanding concern about the radiological health risks posed by water borne Radon progenies attracts many researchers to this field of research, as does the use of radon as a fresh water tracer (Burnett et al., 2010) in ground water discharge.

The radium in groundwater, which decayed from ^{238}U in rocks (Schmidt et al., 2008) ultimately reaches houses with groundwater (Aghamiri et al., 2006) when water is pumped from boreholes for household activities. Radon also diffuses from the soils and enters houses through foundation cracks. Its radiations are the main cause of radiological risk indoors. The exposure to high radon radiation has a carcinogenic effect to human organs thus radon dissolved in ground waters brings concern to the residents (Waska et al., 2008) since it delivers both inhalation and ingestion radiological risks. The radiation from radon and radon progenies pose the largest radiation exposure to the population in the world among all the naturally existing radiation sources (Prasad et al., 2008).

In a study from Hong Kong radon levels in tunnels with high groundwater ingress was compared to radon levels in other tunnel projects. The study of Radon level found that the tunnels with high groundwater ingress had higher levels of radon (Li & Chan, 2004).

The indoor radon concentration in Finland and Maine (USA) regions may already be high due to high rates of radon entry from the ground. The world average radon concentration in all types of water supplies is assumed to be 10 KBq/m^3 (UNSCEAR, 1993).

As well as being ingested through drinking water, radon is also released from water when temperature is increased, pressure is decreased and when water is aerated. Optimum conditions for radon release and exposure occur during showering. Water with a radon concentration of 104 pCi/L can increase the indoor airborne radon concentration by 1 pCi/L under normal conditions. High concentrations of radon can be found in some spring waters and hot springs.

1.5 HEALTH HAZARDS DUE TO RADON

1.5.1 Discovery

The main exposure of radiation comes from inhalation of the short-lived radon daughters. The inhalation of the daughter-nuclides will lead to an inhomogeneous dose distribution within the respiratory tract. When the radon gas itself is inhaled it is often also exhaled before depositing energy through radiation. That is because radon is a noble gas which is not very reactive, it does not chemically bind to the body's tissue or dust particles present in air. The radon daughters however are more reactive and attach themselves to condensation nuclei and dust particles present in air, which, when inhaled, can bind to the respiratory tract. This is why the radon daughters contribute mainly to the dose and not the radon gas itself. Because the progenies have short half-lives they deposit most of their dose in the bronchial epithelium, except for Pb-210, which has a longer radiological half-life as well as biological half-life of 18 days (Chamberlain, 1991).

Swedish studies also support the theory of a synergistic effect for radon daughters and smoking leading to respiratory cancer Damber & Larsson (1982).

Pooled analysis from Europe, North America and China suggest a relative risk of developing lung cancer of at least 16 percent per 100 Bq/m^3 of residential radon exposure. The study also estimated that the risk for smokers versus non-smokers is 25 times higher (ICRP, 2010). The contribution made by thoron to the human exposures in indoor environments is usually small compared with that due to radon, due to the much shorter half-life (55 seconds versus 3.82 days). It should be noted that exposure to radon is not a new phenomenon and documentary evidence from as far back as

the 16^{th} century indicates that elevated radon exposure was probably responsible for excess lung cancer mortality of miners in some Central European mines, such as the silver mines in Bohemia (Jacobi, 1993).

Radon is one of a very small number of substances which have been established to be human carcinogen on the basis of human studies. As such it is a Group 1 and Group A carcinogen, according to the classification used by the World Health Organization (WHO/IARC, 1988) and by the US Environmental Protection Agency (EPA, 1987) respectively. The principal adverse health effect arising from the inhalation of radon and mainly its decay products is lung cancer. The gas radon decays to produce a series of decay or daughter products. From a health perspective the daughter products of most significance are the four short-lived ones polonium-218 to polonium-214 inclusive, which are referred to in various ways: radon daughters, radon progeny, radon decay products. These elements, unlike radon, shortly after their formation attach themselves to aerosol particles; only a small fraction of them remain in unattached form, depending on aerosol size and concentration and on ventilation (Nazaroff, 1988). Based on national and worldwide investigations, several agencies have concluded that radon is a known cancer causing agent in humans and is the second most common cause of lung, skin, and leukemia cancers after smoking (Alghamdi & Aleissa, 2014).

However, an increase in lung cancer risk has been observed even with exposure levels below 200 Bq/m^3. In view of such scientific data, World Health Organization (WHO, 2009) proposed a reference level of 100 Bq/m^3 to minimize health hazards due to indoor ^{222}Rn exposure. It is recommended to set a national reference level as low as reasonably achievable. In view of the scientific data on health effects of indoor radon a reference level of 100 Bq/m^3 is justified from a public health perspective because an effective reduction of radon-associated health hazards for a population is herewith expected. However, if this level cannot be implemented under the prevailing country specific conditions, the chosen reference level should not exceed 300 Bq/m^3 which represents approximately 10 mSv per year according to calculations by the ICRP. Radon is a human health risk, as long-term exposure to high radon concentrations through inhalation is the second leading cause of lung cancer after smoking (WHO, 2005). Radon soil gas, and radon in indoor air has been studied worldwide, where it was recognized as an important and significant area of research.

Since the 1950s epidemiological studies have shown a significantly higher incidence of lung cancer amongst miners in uranium and zinc mines. This increased risk

for lung cancer is due to exposure of airborne radon isotopes and their short-lived progenies also called radon daughters. Radon and its daughters are present in the atmospheric air and inhalation of these radionuclides contributes to the exposure from natural radiation sources. Present studies have concluded that miners exposed to radon have a higher incidence of lung cancer which cannot be explained by other factors (ICRP, 1987).

1.5.2 Effects of radon on the body

The United States estimated that there are 7000-10000 cases of lung cancer caused by indoor radon annually. Radon is the second largest factor, which can cause lung cancer. The first factor is smoking. But now people do not have enough awareness of the pollutions, which are caused by radon.

Long term exposures to radon via inhalation in closed rooms or caves or open air saturated with radon gas are the cause of about 10 percent of all deaths from lung cancer (Truta-Popa et al., 2011).

The indoor exposure ICRP recommends the action level for radon and Thoron and its progeny concentration is about 200 Bq/m^3 and also the annual inhalation dose is about 3 mSv/y - 10 mSv/y.

1.6 RATIONALE OF THE STUDY

Currently in Ethiopia, there is no radon concentration standard in air for indoor houses. Considering this circumstance, examination of official methods for measuring radon in houses is necessary. In order to examine measurement methods that can be used in houses and deduce improvement plans for this study investigated radon measurement protocols used in the United States, Japan, and the United Kingdom, and compared them to the nuclear physics laboratory room of the first floor. It is an established fact that high concentration of radon is carcinogenic. So one must be aware of his/her environs radon concentrations take the necessary steps for the reductions. It is also necessary to measure radon and thoron levels of a given locale as part of accumulations of environmental radiation data. Future generations may use the data for possible nuclear activates.

CHAPTER 2

Review of Radon Related Literature

The Concentration of Rn, in various air environments, has been measured and documented around the world. Special interest has been in the indoor and in mining environments to assess possible health hazards.

Radon inhalation especially is associated with lung cancer risk. Varying indoor radon works have been carried out in different types of regions, old and new setting, different building types, different building functions, varying seasons and climatic zones.

In Chattisgarh, India, the geometric mean of indoor radon concentrations in the urban dwellings have been measured to vary from 20.20 Bq/m^3 to 30.31 Bq/m^3, while in rural dwellings it measures from 15.50 Bq/m^3 to 36.05 Bq/m^3.

Chattisgarh's annual geometric mean value of inhalation dose is found to vary from 0.39 mSv/y to 1.36 mSv/y, in the urban dwellings, and its overall mean value is 0.60 mSv/y. In its rural area the annual inhalation dose is varying from 0.39 mSv/y to 1.46 mSv/y, with a geometric mean value of 0.74 mSv/y (Khokhar et al., 2008).

In the new region of Adapazari, Turkey, average radon concentration (arithmetic mean) measured a minimum value of 24.0 Bq/m^3, a maximum value of 108.5 Bq/m^3, with a mean of 63.5 Bq/m^3. In the old region of Adapazari, on the other hand, dwelling average radon concentration measured a minimum 16.2 Bq/m^3, a maximum 155.0 Bq/m^3, with a mean of 59.9 Bq/m^3 (Kapdan & Altinsoy, 2012).

^{222}Rn-mostly referred to simply as radon-and its short-lived decay products in the atmosphere are the major contributors to human exposure from natural sources, producing an average effective dose to the population of 1.15 mSv/y (UNSCEAR, 2008). The average annual effective dose due to ^{220}Rn usually referred to as thoron, the radon isotope belonging to the decay chain of ^{232}Th and its progeny is estimated to be over 10 times smaller than that due to radon: 0.1 mSv/y (UNSCEAR, 2008). For this reason, exposure to thoron and its decay products has often been neglected in

the past. However, several studies have shown that in some cases doses from thoron and its progeny can be comparable to those from radon and its short-lived decay products, or even larger.

2.1 DOSIMETRY AND RADIOLOGICAL RISKS

The ultimate reason for all works on indoor radon is the potential for exposures to radon decay products to cause ill effects among humans. A basis for this concern has been the increased incidence of lung cancer among mine workers exposed to higher than average levels of ^{222}Rn decay products. This led to some estimation of the risk of lung cancer from indoor exposures and of the importance of this radiological risk relative to other environmental insults. Inhalation dose imparted by radon and its short lived progeny can be as high as 59 percent of the total dose in the natural background radiation areas. It is a health concern especially true for regions where concentration of radon is high, or possible accumulation of radon and its progeny is high.

World average of annual effective dose to a human by natural radiation is 2.4 mSv/y and about half of which is due to indoor radioactivity, and indoor structures are places of long term human exposure to high concentrations of radon, thoron and their progenies. There are two types of biological effects due to radiation exposure: stochastic effect and deterministic effect. In stochastic effect, the chance of the effect occurring, is statistical in nature and is a function of dose, without any threshold. Examples are cancer and genetic effects. For Deterministic effects, groups of cells or tissues are extensively damaged due to exposure to very high radiation doses and the biological effects may appear, within a few hours to a few weeks, after exposure to ionizing radiation. The effect has a threshold and the severity of the effect, is proportional to the dose received (UNSCEAR, 1993) and (UNSCEAR, 2000).

2.1.1 Ionizing radiation and its source

Ionizing radiation is energy in the form of particles or waves that is sufficient to remove electrons from the shells of atoms. The nuclei of unstable atoms are one of the sources of radiation. As these radioisotopes seek to become more stable, their nuclei give out particles and high-energy waves in a process termed as radioactive decay. The major types of radiation emitted during radioactive decay are alpha and beta particles, including gamma rays. Radiation can come from natural sources or man-made radionuclides. Some radioisotopes, such as radium, uranium, and

thorium, have been there since the creation of planet earth. The radioactive gas radon is one type of NORM produced as these radioactive materials decay and add over 50 percent of radiation exposure to public from Figure below. Regardless of how they are generated, all radioisotopes emit radiation.

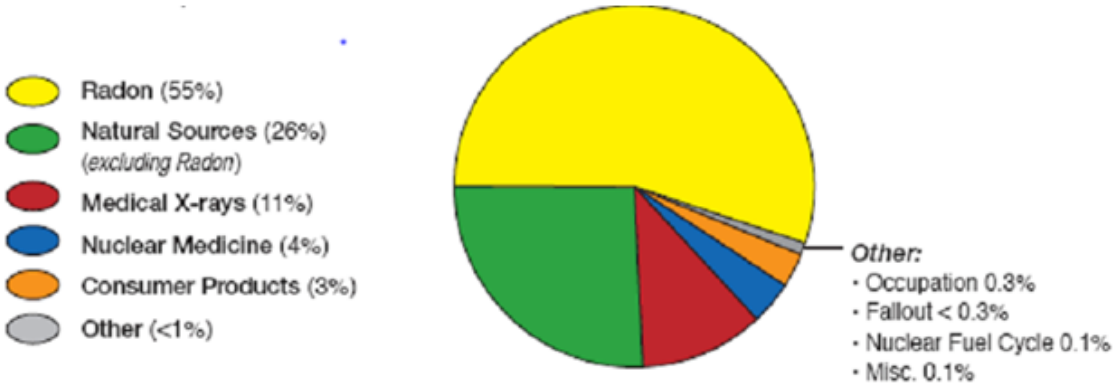

Figure 2.1: Sources of radiation exposure [UNSCEAR, 2000; USEPA, 2007]

2.2 Radon measurement Methods

Most methods of measuring radon (Rn-222) and its decay products (RnD) are based on the detection of the alpha emitted by these radionuclides during their radioactive decay. A small number of methods are based on the detection of emitted gamma rays and some techniques exist which detect beta decays.

It is important to distinguish between methods which measure the concentration of the gas radon and those which measure the concentrations or other characteristics of airborne radon decay products. In Rn and RnD measurement the techniques may be classified as being active or passive. Active techniques are those which require electric power and/or the use of air pumps to collect activity from the air.

Passive techniques are those where the detector while installed at the sampling location does not require electric power. The air containing Rn and RnD usually enters such passive detectors by free diffusion and the radiation detecting medium itself does not require any power supply (i.e. alpha track plastics or activated charcoal). Passive techniques are usually simple, cost effective and easy to use. They are suited admirably for survey work and for long term measurements. Some instruments are available where the detector requires a low level of power supplied by a battery but no pump is used. This fall into a class of detection technique intermediate between passive and active.

2.2.1 Active measuring methods

Grab sampling

Here the activity of Rn or RnD in a discrete sample of air taken at a single location in a short period of time (from about 1 sec to about 20 min) is measured. This approach is at best useful for initial screening purposes or for spot-checking of the effectiveness of remedial actions. It is of very limited use for determinations of average indoor air radon concentrations which are more appropriately determined on the basis of long-term measurements.

Continuous sampling

Here air is drawn either continuously (or semi-continuously) for long periods of time through a Rn or RnD detecting instrument. This type of approach gives information on the time dependence of the airborne activities in a building. Information which may be obtained using continuous sampling include the ratio between day-time and night-time concentrations in a building, diurnal variations etc. Such information is quite useful in deciding on strategies used to reduce occupational exposures where occupancy factors are much less than in dwellings.

Time integrating sampling

Techniques using time integration consist of using a device which will yield a single determination of airborne activity averaged over some chosen period from a few days to a year or longer. In reaching a decision on the necessity of remedial action it is generally considered in European Community countries that integrating measurements of minimum duration 3 months should be made.

In countries such as the US, where real-estate transactions may require urgent evidence of the indoor radon concentration in a building short-term integrating techniques of a few days duration may be recommended providing they are carried out according to a recognized measurement protocol.

Double-filter method

Two-filter method is the instantaneous measurement of radon which belongs to active sampling method. It can measure radon and radon daughters at same time. This is a mature method of measuring radon which can exclude interference of radon progeny and improve the measurement accuracy. This method is in high sensitive. The measurement time is short and with simple operation. Backward is the device

heavy and large noise when we sampling. Thedetection limit was 3.3 Bq/m^3.

Balloon method

method is the most instantaneous measurement of radon with active sampling. It can also measure radon and radon daughters. The balloon method and two-filter method have same elements to work. One different is the balloon instead of a decay tube. Radon and its daughters in the detection limits were 2.2 Bq/m^3.

Scintillation cells

This is one of the oldest and most reliable type of device for measuring the concentration of radon gas. It exists in 'a number of forms and can be used for grab-sampling or for continuous long term measurements.

Electronic monitors

A range of electronic detectors are available in which the common feature is the detection of alpha particles from radon and its decay products by surface barrier or similar solid state detectors and associated electronics. These devices are either mains power and/or battery operated. They are usually equipped with a small battery operated pump and can be used to identify the routes of radon entry into a building.

Geiger-Müller counter

This is another method of grab sampling which is based on direct beta counting of filtered aerosol sample over successive time intervals by end window Geiger- Müller counter. This method can be used for simultaneous measurement of radon and thoron decay products.

2.2.2 Passive measuring method

Track etching

Track etch method is a cumulative radon measurement method. It is belongs to passive sampling method. Radon concentration in the environment can be a cumulative measured. Annual average data in the measured place can be obtained directly, which avoid influence factors such as the time, season and weather. It has the characters of high sensitive, good reproducibility, simple operation and easy to preserve the data. The sample taking time of is 3 months, at least not less than 30 days.

Activated charcoal method

The adsorption of radon by activated charcoal has been used for many years as a detection method. The method is very simple. The gamma radiation emitted by radon and its ingrown decay products in the charcoal is measured by means of a gamma ray detector such as Sodium Iodide (NaI(T1)). Activated charcoal method is a commonly used passive cumulative measurement method for indoor radon detection. The activated charcoal method has priorities of low cost, easy operation, measuring result accurate and small volume, etc. However it is not suitable used for outdoor and humidity place. Timely analysis is needed after sampling (less than 7 days) otherwise the radon will decay. The detection limit was 6 Bq/m^3.

Alpha track detectors

A number of plastic or polymeric materials are available which have the property that the primary damage caused in them by the passage of alpha particles remains fixed in them and may be made visible as tracks by means of a suitable etching procedure. These materials are often called Solid State Nuclear Track Detectors (SSNTDs).

Electret detectors

An electret is a material such as some types of aluminised Teflon which when charged will generally retain the charge and associated electric potential for a period of a year or longer. Such charged electrets have been used as electrostatic collectors of charged radon decay products from the air which can then be measured by a scintillation detector, surface barrier detector or other alpha particle detector.

Table Most common modes of operation of radon detectors

Detector	Grab	Integrating	continuous	Active	Passive
Scintillation cell	Yes	-	Yes	Yes	Yes
Alpha Track	-	Yes	-	-	Yes
Charcoal Detectors	-	Yes	-	-	Yes
Electret	-	Yes	-	-	Yes
Electronic	Yes	-	Yes	Yes	-

Figure 2.2: Most common modes of operation of radon detectors

CHAPTER 3

Experimental Method

3.1 THE SAMPLING SITE

Addis Ababa University province is located between 38^0 42'E longitude and 9^0, 02' N latitude in the central part of Ethiopia. It is a state university, originally called the University College of Addis Ababa its establishment in 1950. It has climate of hot and dry summers, and cold winters. Since the establishment of the university, it has experienced a remarkable growth in enrollment and a significant expansion of faculty and its administrative staff. At present the university encompasses 13 colleges both for male and female students.

The selected site of this University has different climatic conditions and somewhat different geological characteristics and there were different types of weather condition in different days. Around the laboratory bricks, cemented blocks and electronics materials are the main materials found in the room. Also there are different types of materials inside the room. The present work deals with the measurement of radon concentration in closed room physics laboratory first floor of Addis Ababa University College of Natural science by using beta counting detector in order to see if the students, teachers, employees are at any risk from radon related health hazards. Moreover, mean annual effective dose due to radon will also calculate and compared with the maximum permissible level of the world recommended value.

3.2 DATA GATHERING METHODS

High volume grab sampling method was employed for the determination of radon progeny concentrations in air. This method is based on gross beta counting of a filtered aerosol sample over successive time intervals by an end-window Geiger-Müller (GM) counter. The evaluation of the activity concentrations was based on the following procedure:

1. Sampling known volume of air on a sampling head using filter paper.
2. Placing, the filtered air sample under an end-window GM counting system, with in a minute or two after the end of sampling.
3. Record the gross count in successive intervals of time for sufficiently large number of intervals (more than 100) over a period of 9 to 10 hrs.
4. Analysis of the count rate versus time and fitting of experimental points with the mathematical model.
5. Determination of EECs from the best-fit of experimental points and the mathematical model.

3.2.1 Sampling the Air

The door and windows of the sampling site, on each day that we took measurement were closed for at least 12 hours before sampling of air. Each morning, air was sampled, using a suction pump fitted with a sampling head designed for this purpose, for 15 minutes in the morning hours (between 6:00 am and 7:00 pm) of the 21 sampling days.

A suction pump with air flow rate of 0.18 m^3/minute was used to suck air on a Whatman®-glass fiber filter paper that has more than 99% retention of aerosols. The filter paper deposit the aerosols while allowing air to pass through. To this effect the filter was fitted between two "O"-rings in the sampling head and its base was supported by a wire mesh to stand the pressure of air pumping during sampling. The effective filter surface, available for the passage of air was 3 cm in diameter.

The sampling head was kept in each case at the center of the room and at a height of approximately 1 m to 1.5 m above the floor and the height of nuclear physics laboratory first floor room approximately about 5 m from the ground. Air sucked through by a built in pump was passed through the air suction pump to the beta counting detector for the measurement of radon concentration.

At the end of the 15 minutes sampling time the filter paper was carefully removed from the sampling head and placed under the GM tube for counting.

3.2.2 Counting the Activity on the Filtered Samples

Within one or two minutes after sampling is ended, the filter was placed below GM tube on a shelf. Counting of the activity, on the filtered air samples, was done using

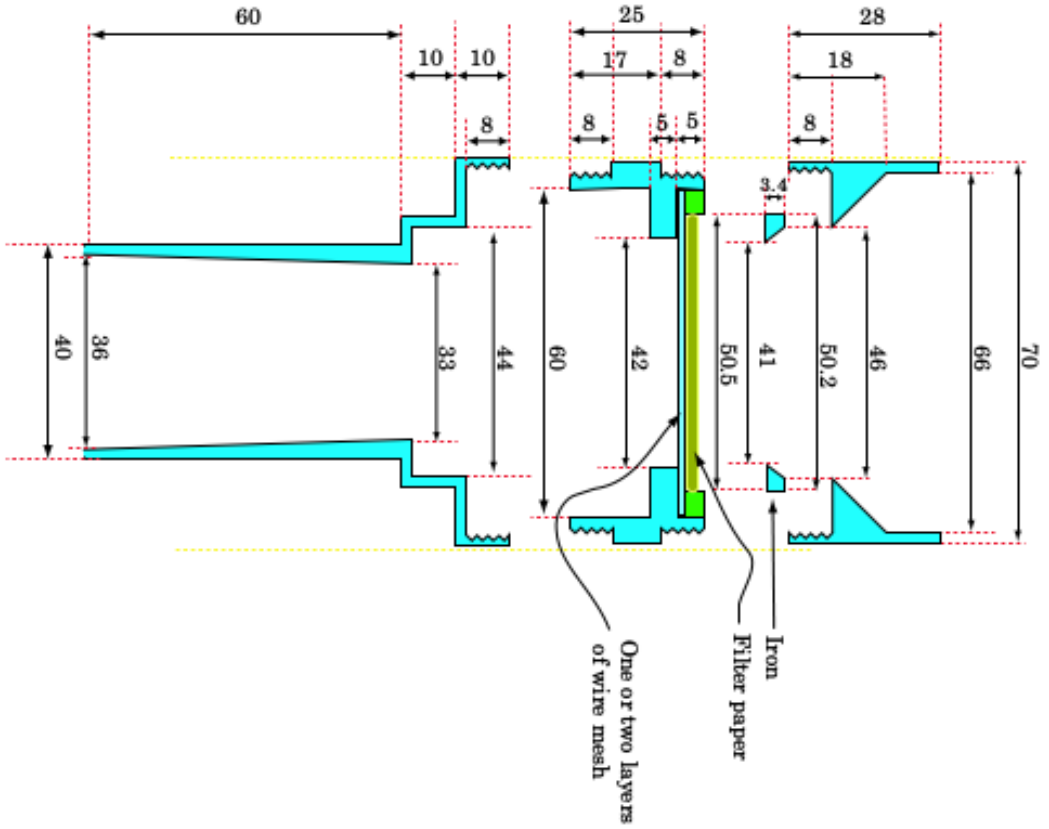

Figure 3.1: Blue print of the sampling Head (lengths are in millimeter)

a GM tube (window thickness of 2×10^{-3} g/cm^2 and a diameter of 3 cm) counting system. The operating voltage the GM tube was determined to be 500 V.

Gross beta counts were recorded over successive time intervals of 0.5 min, 1 min , 5 min, 8 min, 17 minutes duration for each of 21 sampling days for 8-10 hours.

The back ground counting rate was also measured by using clean filter before and after measurements.

GM Counting System

Materials used in the experimental method of this work are listed and described in the following paragraphs.

- entry of radon from the soil through
- A- Beta detector
- B-Gm-counter
- C-Sampling head

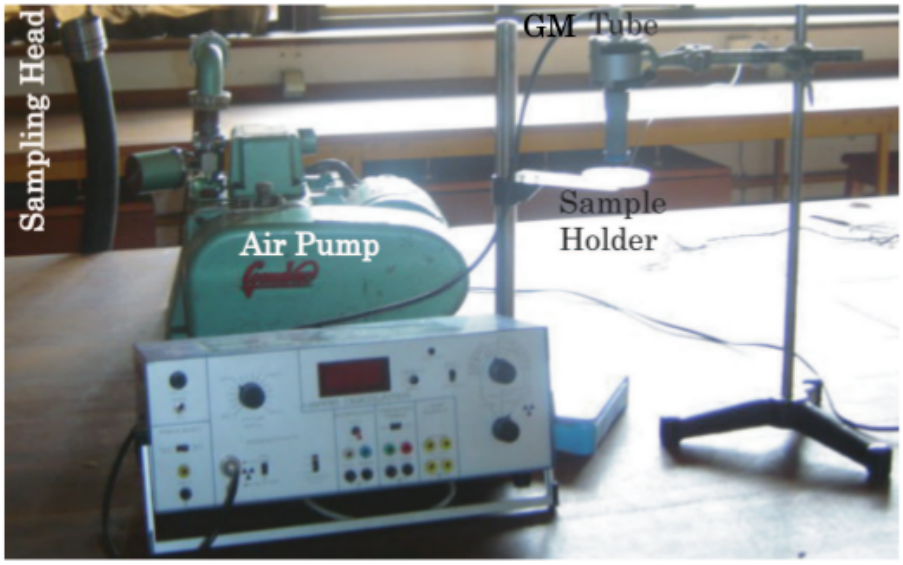

Figure 3.2: The suction pump (seen at the back of the power supply)

- D-Glass fiber filter
- E-End window Gm tube
- F-Stop watch
- G-Shielded (leads)
- H-Filter holder(shelve)
- I-GM tube system beta counter containing high voltage supply(500 V).

Air suction pump: is an equipment used for sucking air through the filter paper. It is operated with the main voltage supply (230 V)

Power Supply unit: supplies voltage needed for the correct operation of the GM tube (500 V).

Glass fiber filter: used to filter and deposit aerosols and radon progeny in air. It is placed on the sampling head during sampling.

GM Counting system: has two parts. The first is GM tube while the second is the counter. The GM tube is filled with argon to be ionized by the incoming radiation while the counter collects electrons and reports through its window screen. The GM tube type: GM 125 (LND72314) wide window GM detector was used.

Figure 3.3: Disassembled parts of the Sampling Head

Figure 3.4: The GM Counting System at the nuclear and radiation physics lab, AAU

Sampling head: the sampling head has the following longitudinal cross section view which was also used by Z.Papp. The design details of the sampling head are shown in figure below. This design is the same as that used by Z Pap petal. Sampling head was crafted by Abaya mechanical Engineering firm in Addis Ababa (Papp & Dezsó, 2006).

Counting Geometry

The shelve was used to hold the tube, facing downward, inside a thick, cylindrical lead shield. The filter was fixed on the shelve sample holder plate with a circular opening at its center. This opening in the plate was in order to avoid any back scattering of beta particles emitted from the filter, which otherwise may create difficulties while evaluating their exact contribution to the count-rate. The clean side of the filter faced downward. The distance between the filter and the window was 0.9 cm. A plastic sheet was used to cover the detector window to absorb alpha particles. The number of counts was corrected for coincidence loss and the background events.

The detector was housed in a thick lead shield that is internally lined with aluminium sheet.

3.2.3 Analysis of the Gross Count

Defined Solid Angle Absolute Beta Counting (DSAABC) method has been used to measure the activities of the filtered air samples. Some of the features are outlined below (Papp & Daróczy, 1997).

Mathematical Modeling of the Counts

Nomenclature:

Subscripts i and j:

$$
\begin{aligned}
&1 \Leftrightarrow^{218} \text{Po},\\
&2 \Leftrightarrow^{214} \text{Pb}, \qquad (\text{radon decay products})\\
&3 \Leftrightarrow^{214} \text{Bi},
\end{aligned}
$$

$$
\begin{aligned}
&4 \Leftrightarrow^{212} \text{Pb},\\
&5 \Leftrightarrow^{212} \text{Bi}, \qquad (\text{thoron decay products})\\
&6 \Leftrightarrow^{208} \text{Tl}
\end{aligned}
$$

$$7 \Leftrightarrow \text{U}, (\text{unknown} \beta - \text{emitter with long half life}).$$

Constants:

T = air sampling time.

k = air sampling flow rate.

t_b = time at the beginning of a counting interval.

t_e = time at the end of a counting interval.

C = total β counts over the interval (t_b, t_e)

M = number of counting intervals.

$\mathcal{E}_i$ = β counting efficiency of the detector for the i^{th} $\beta -$ emitting radionuclide $(i = 2, 3 \ldots 7)$.

λ_i = decay constant of the i^{th} radionuclide, $\quad (i = 1, 2, \ldots 7)$.

$\lambda_{ij} = \lambda_i - \lambda_j, \quad (i, j = 1, 2, \ldots 7.)$

$e_{Tij} = \exp(-\lambda_i T) - \exp(-\lambda_j T), \quad (i, j = 1, 2, \ldots 7).$

$\hat{e_i} = \exp(-\lambda_i t_b) - \exp(-\lambda_i t_e), \quad (i = 1, 2, \ldots 7).$

$e_{Toj} = 1 - \exp(-\lambda_j T), \quad (j = 1, 2, \ldots 7).$

Variables

n_i = number of atoms per unit volume of sampled air, $\quad (i, = 1, 2, \ldots 7.)$

a_i = activity of the i^{th}radionuclide per unit volume of the sampled air, $\quad (i = 1, 2, \ldots 7.)$

N_{Ti} = number of atoms of the i^{th}radionuclide in the filter at the end of sampling $(i = 1, 2, \ldots 7)$

t = time elapsed since the end of sampling. t = 0 at the end of sampling.

CR = total β count rate

$e_i = \exp(-\lambda_i t), \quad (i = 1, 2, \ldots 7).$

$e_{ij} = \exp(-\lambda_i t) - \exp(-\lambda_j t), \quad (i, j = 1, 2, \ldots 7.)$

$e_{0j} = 1 - \exp(-\lambda_j t), \quad (j = 1, 2, \ldots 7.)$

Buildup during Sampling.

Assuming the sampling flow rate, k and the number density (n_i) of the radionuclides in the sampled air are constant during the sampling period, the solutions of the

equations for the number of radionuclides at the end of sampling will be:

$$n_1 = \frac{N_{T1}\lambda_1}{k e_{T01}} \tag{3.1a}$$

$$n_2 = \frac{\lambda_2 N_{T2}}{k e_{T02}} - n_1\left[1 - \frac{\lambda_2 e_{T21}}{e_{T02}\lambda_{12}}\right] \tag{3.1b}$$

$$n_3 = \frac{\lambda_3 N_{T3}}{k e_{T03}} - n_1\left[1 - \frac{\lambda_3 e_{T23}}{\lambda_{32} e_{T03}} - \frac{\lambda_3\lambda_2 e_{T23}}{\lambda_{32}\lambda_{12} e_{T03}} + \frac{\lambda_3\lambda_2 e_{T31}}{\lambda_{13}\lambda_{12} e_{T03}}\right] - n_2\left[1 - \frac{\lambda_3 e_{T23}}{\lambda_{32} e_{T03}}\right] \tag{3.1c}$$

$$n_4 = \frac{N_{T4}\lambda_4}{k e_{T04}} \tag{3.1d}$$

$$n_5 = \frac{\lambda_5 N_{T5}}{k e_{T05}} - n_4\left[1 - \frac{\lambda_5 e_{T54}}{e_{T03}\lambda_{45}}\right] \tag{3.1e}$$

$$n_6 = \frac{\lambda_6 N_{T6}}{k e_{T06}} - 0.36 n_4\left[1 - \frac{\lambda_6 e_{T56}}{\lambda_{65} e_{T06}} - \frac{\lambda_6\lambda_5 e_{T56}}{\lambda_{65}\lambda_{45} e_{T06}} + \frac{\lambda_6\lambda_5 e_{T64}}{\lambda_{46}\lambda_{45} e_{T06}}\right] - 0.36 n_5\left[1 - \frac{\lambda_6 e_{T56}}{\lambda_{65} e_{T06}}\right] \tag{3.1f}$$

$$n_7 = \frac{N_{T7}\lambda_7}{k e_{T07}} \tag{3.1g}$$

Decay After Sampling

After the end of sampling the differential equations, describing the decay and build up of each radionuclide, are solved with known boundary conditions: $N_i(t) = N_{Ti}$, at $t = 0$ and the decay parameters of the deposited radionuclides to obtain the number of radionuclides $N_i(t)$ on the filter at any latter time t. In the case of $N_6(t)$, due to the fact that only 36% of ^{212}Bi ($i = 5$) and therefore ^{212}Pb($i = 4$) decay via ^{208}Tl, we introduce a factor of 0.36 in the expressions derived. Thus:

$$N_1(t) = N_{T1} e_1 \tag{3.2a}$$

$$N_2(t) = N_{T2} e_2 + N_{T1}\left[\frac{\lambda_1 e_{12}}{\lambda_{21}}\right] \tag{3.2b}$$

$$N_3(t) = N_{T3} e_3 + N_{T2}\left[\frac{\lambda_2 e_{23}}{\lambda_{32}}\right] + N_{T1}\left[\frac{\lambda_2\lambda_1 e_{32}}{\lambda_{32}\lambda_{21}} + \frac{\lambda_2\lambda_1 e_{13}}{\lambda_{31}\lambda_{21}}\right] \tag{3.2c}$$

$$N_4(t) = N_{T4} e_4 \tag{3.2d}$$

$$N_5(t) = N_{T5} e_5 + N_{T4}\left[\frac{\lambda_4 e_{45}}{\lambda_{54}}\right] \tag{3.2e}$$

$$N_6(t) = N_{T6} e_6 + 0.36 N_{T5}\left[\frac{\lambda_5 e_{56}}{\lambda_{65}}\right] + 0.36 N_{T4}\left[\frac{\lambda_4\lambda_5 e_{46}}{\lambda_{54}\lambda_{64}} + \frac{\lambda_4\lambda_5 e_{65}}{\lambda_{54}\lambda_{65}}\right] \tag{3.2f}$$

$$N_7(t) = N_{T7} e_7 \tag{3.2g}$$

The β-count Rate (CR)

The α-particles emitted by the members of the two decay series are absorbed by the absorber, of thickness 0.012 gcm^{-2} (deliberately introduced to this effect), and by the window of the GM tube. Therefore the gross β-count, at a given time interval is the sum of the contribution by each beta emitter in the series and by an unknown beta emitter(if any) deposited on the filter paper. Therefore the count rate at a given time t is given by:

$$CR = \sum_{i=2}^{7} \mathcal{E}_i \lambda_i N_i(t) \tag{3.3}$$

where $\mathcal{E}_i$ is the absolute detection efficiency of the detection system for the β-particle emitted by radionuclide i.

Substituting equations (3.2a) to (3.2g) in equation (3.3) and integrating with respect to time t between the beginning t_b and end t_e of a counting interval, we obtain

$$C = \sum_{i=1}^{7} N_{Ti} X_i \tag{3.4}$$

where

$$\begin{aligned}
X_1 &= \frac{\mathcal{E}_1\lambda_2\hat{e}_1}{\lambda_{21}} - \frac{\mathcal{E}_2\lambda_1\hat{e}_2}{\lambda_{21}} + \frac{\mathcal{E}_3\lambda_2\lambda_3\hat{e}_1}{\lambda_{21}\lambda_{31}} - \frac{\mathcal{E}_3\lambda_1\lambda_3\hat{e}_2}{\lambda_{21}\lambda_{32}} + \frac{\mathcal{E}_3\lambda_1\lambda_2\hat{e}_3}{\lambda_{32}\lambda_{31}},\\
X_2 &= \mathcal{E}_2\hat{e}_2 + \frac{\mathcal{E}_3\lambda_3\hat{e}_2}{\lambda_{32}} - \frac{\mathcal{E}_3\lambda_2\hat{e}_3}{\lambda_{32}},\\
X_3 &= \mathcal{E}\hat{e}_3,\\
X_4 &= \mathcal{E}_4\hat{e}_4 + \frac{\mathcal{E}_5\lambda_5\hat{e}_4}{\lambda_{54}} - \frac{\mathcal{E}_5\lambda_4\hat{e}_5}{\lambda_{54}} + \frac{0.36\mathcal{E}_6\lambda_5\lambda_6\hat{e}_4}{\lambda_{54}\lambda_{64}} - \frac{0.36\mathcal{E}_6\lambda_4\lambda_6\hat{e}_5}{\lambda_{54}\lambda_{65}} + \frac{0.36\mathcal{E}_6\lambda_4\lambda_5\hat{e}_6}{\lambda_{65}\lambda_{64}},\\
X_5 &= \mathcal{E}_5\hat{e}_5 + \frac{0.36\mathcal{E}_6\lambda_6\hat{e}_5}{\lambda_{65}} - \frac{0.36\mathcal{E}_6\lambda_5\hat{e}_6}{\lambda_{65}},\\
X_6 &= \mathcal{E}_6\hat{e}_6,\\
X_7 &= \mathcal{E}_7\hat{e}_7
\end{aligned}$$

Assuming that total β-counts were measured over M (M>7) successive time intervals, these series of measurements can be described by a series of linear equations of the type equation (3.4):

$$C_m = \sum_{i=1}^{7} N_{Ti} X_{mi} \qquad (m = 1, 2, \ldots M), \tag{3.5}$$

where C_m are the measured total β-counts, corrected for background and coincidence loses, and X_{mi} are the values of X_i for the different time intervals, respectively.

A system of M equations, of seven unknowns, generated from each interval of measurement were used to determine the air concentration of the daughter products. Counting was made for a large number of intervals (ranging from 100 to 180 in this case), to make full use of the statistical nature of the decay process in the determination of air concentration of daughters.

A weighted least square regression analysis was performed to determine air concentration of daughter products that best fit the decrease of the count rate with time. Parameters that provide less than 10% systematic error were taken. One example of a curve fitted with this procedure is shown in fig 4.1.

Determination of Activity Concentration (EECs)

If $M > 7$ and the columns of the matrix, generated by each counting interval by the use of equation (3.5), $X_{mi}(m = 1, 2, \cdots 7)$ were linearly independent then unknowns N_{Ti} could be estimated using the weighted least squares fitting method. If N_{Ti} were known n_i could be computed according to equations (3.1a) to (3.1g) (Papp & Daróczy, 1997).

The six β emitting daughters of ^{222}Rn and ^{220}Rn denoted by subscripts i & j: (i, j =1,2,...7). i.e. 1 $\rightarrow^{218}$Po; 2 $\rightarrow^{214}$Pb; 3 $\rightarrow^{214}$Bi; 4 $\rightarrow^{212}$Pb; 5 $\rightarrow^{212}$Bi; and 6 $\rightarrow^{208}$Tl and 7 $\rightarrow$U. The last one is to take care of the existence of “unknown" long-lived β emitting radionuclide in air.

Aerosols are collected on a filter paper. Air sampling flow rate (k) and concentration of radionuclides (n_i) are assumed to be constant during sampling time.

Determination of Effective Dose

Equilibrium factor between radon and short lived progenies is very important for dose assessment from inhalation of radon and it must be determined in each radon monitoring. According to the ICRP recommendations (ICRP, 1991), for a factor of equilibrium can be assumed value of 0.4, however, since this factor depends largely on environmental conditions (hours and mode of ventilation and humidity). It is necessary to develop a method of measuring the progeny concentrations in order to calculate equilibrium factor according to the formula (Leung et al., 2006)

$$\mathrm{EEC_{Rn}} = 0.105\,\mathrm{C_1} + 0.515\,\mathrm{C_2} + 0.380\,\mathrm{C_3} \tag{3.6}$$

where EEC_{Rn} is radon equilibrium equivalent concentration; C_{Rn}, C_1, C_2 and C_3 are the activity concentrations (in Bq/m^3) for ^{222}Rn, ^{218}Po, ^{214}Pb and ^{214}Bi, respectively.

3.2.4 Average Annual Effective Dose

Effective dose is the sum of the products obtained by multiplying the equivalents doses to various organs and tissues by the appropriate risk weighting factor for each. This quantity is considered to be proportional to the total probability of stochastic effects. Its SI unit is the Sievert (Sv), as for equivalent dose.

$$1\,\mathrm{Sv} = 100\,\mathrm{rem}(\mathrm{oldunit}).$$

The annual effective dose due to exposure of radon progeny has been calculated by the relation given by UNSEAR:

$$\text{Effective Dose}(\tfrac{msv}{y}) = (\tfrac{Bq}{m^3}) \times 24\,\mathrm{h} \times 365.25 \times 0.8/\mathrm{y} \times 10^{-5}\left(\tfrac{\mathrm{mSv/Bqh}}{m^3}\right) \tag{3.7}$$

$$= EEC_{Rn} \times 7 \times 10^{-5}\,\mathrm{Sv/y} \tag{3.8}$$

where EEC_{Rn} is Radon equilibrium equivalent concentration

CHAPTER 4

Data and Data Analysis

4.1 RESULTS

The major objectives of this study is to investigate effective radon concentration Dose radiation in air samples by using beta counting detector. In order to achieve the above listed objectives of the study, active method of technique has been employed. For the air sample a GM counter was used for indoor air sample make in situ actual measurement.

Measurements were taken in the nuclear physics laboratory located on the first floor of physics building. Air was sampled once in a day Morning about 6:30 to 16:30 A.M. A total of 21 measurements were made.

Data for each measurement was recorded for more than 9 hrs in successively increasing intervals of time. The data recorded is given serial number and label. The time intervals, on which the decay is recorded, were computed in columns five and six of table 4.1.

The length of the measuring time interval and the gross count obtained were fed in a computer programmer, that computes the concentration of progeny and the equilibrium equivalent concentration for the two isotopes, from the observed decline in the observed count rates. This computation is based on the mathematical model developed in chapter 3.

Equilibrium equivalent concentration of Rn was computed by the computer program using equation (3.6) so as to determine the annual effective dose from the computed Equilibrium Equivalent Concentration (EEC) of Radodn.

A typical measurement procedure is indicated in table 4.1

	Label:	LabTZ22		Intervals				
Start	Sampling	6:30:00		0:00:30		Room	Indoor	
	Sampling Stop	6:45:00		0:01:00				
	Samp t (min)	0:15:00		0:05:00				
	Sampling Date	22-05-2017		0:08:00		Back g.	23.2/min	
				0:17:00		Rem: door&windows closed overnight		
No	observe time	disply cnt	Interval time	start	stop time	time(mi	delta time	Count rate
1	6:47:00	0	1	6:47:00	6:47:30	2	0.5	1025
2	6:47:30	1025	2	6:47:30	6:48:00	2.5	0.5	972
3	6:48:00	1997	3	6:48:00	6:48:30	3	0.5	935
4	6:48:30	2932	4	6:48:30	6:49:00	3.5	0.5	921
5	6:49:00	3853	5	6:49:00	6:49:30	4	0.5	935
6	6:49:30	4788	6	6:49:30	6:50:00	4.5	0.5	924
7	6:50:00	5712	7	6:50:00	6:50:30	5	0.5	894
8	6:50:30	6606	8	6:50:30	6:51:00	5.5	0.5	906
9	6:51:00	7512	9	6:51:00	6:51:30	6	0.5	927
10	6:51:30	8439	10	6:51:30	6:52:00	6.5	0.5	843
11	6:52:00	9282	11	6:52:00	6:52:30	7	0.5	1039
12	6:52:30	10321	12	6:52:30	6:53:00	7.5	0.5	703
13	6:53:00	11024	13	6:53:00	6:53:30	8	0.5	1107
14	6:53:30	12131	14	6:53:30	6:54:00	8.5	0.5	664
15	6:54:00	12795	15	6:54:00	6:54:30	9	0.5	840
16	6:54:30	13635	16	6:54:30	6:55:00	9.5	0.5	901
17	6:55:00	14536	17	6:55:00	6:55:30	10	0.5	883
18	6:55:30	15419	18	6:55:30	6:56:00	10.5	0.5	1113
19	6:56:00	16532	19	6:56:00	6:56:30	11	0.5	568
20	6:56:30	17100	20	6:56:30	6:57:00	11.5	0.5	782
21	6:57:00	17882	21	6:57:00	6:57:30	12	0.5	809
22	6:57:30	18691	22	6:57:30	6:58:00	12.5	0.5	748
23	6:58:00	19439	23	6:58:00	6:58:30	13	0.5	806
24	6:58:30	20245	24	6:58:30	6:59:00	13.5	0.5	900
25	6:59:00	21145	25	6:59:00	6:59:30	14	0.5	702
26	6:59:30	21847	26	6:59:30	7:00:00	14.5	0.5	781
27	7:00:00	22628	27	7:00:00	7:00:30	15	0.5	817
28	7:00:30	23445	28	7:00:30	7:01:00	15.5	0.5	831
29	7:01:00	24276	29	7:01:00	7:01:30	16	0.5	1155
30	7:01:30	25431	30	7:01:30	7:02:00	16.5	0.5	560
31	7:02:00	25991	31	7:02:00	7:02:30	17	0.5	670
32	7:02:30	26661	32	7:02:30	7:03:00	17.5	0.5	714
33	7:03:00	27375	33	7:03:00	7:03:30	18	0.5	757
34	7:03:30	28132	34	7:03:30	7:04:00	18.5	0.5	1301
35	7:04:00	29433	35	7:04:30	7:05:00	19.5	0.5	794
36	7:04:30	0	36	7:05:00	7:05:30	20	0.5	707
37	7:05:00	794	37	7:05:30	7:06:00	20.5	0.5	841
38	7:05:30	1501	38	7:06:00	7:06:30	21	0.5	601
39	7:06:00	2342	39	7:06:30	7:07:00	21.5	0.5	690
40	7:06:30	2943	40	7:07:00	7:07:30	22	0.5	701

Table 4.1: Measurement procedure in beta counting system (partly shown)

The data shown in table 4.1 was fed into a computer program to obtain the best fit between the experimental gross beta count (indicated by + and – in figure 4.1).

The best fit curve shown in figure 4.1 displays all the information about the measurement. This includes the label of the measurement and Name:, the type of detector used, the sampling time, the air flow rate and the total number of intervals that are used in the computation.

Further the concentration of each daughter product with the associated experimental error is displayed in the right top corner of the display.

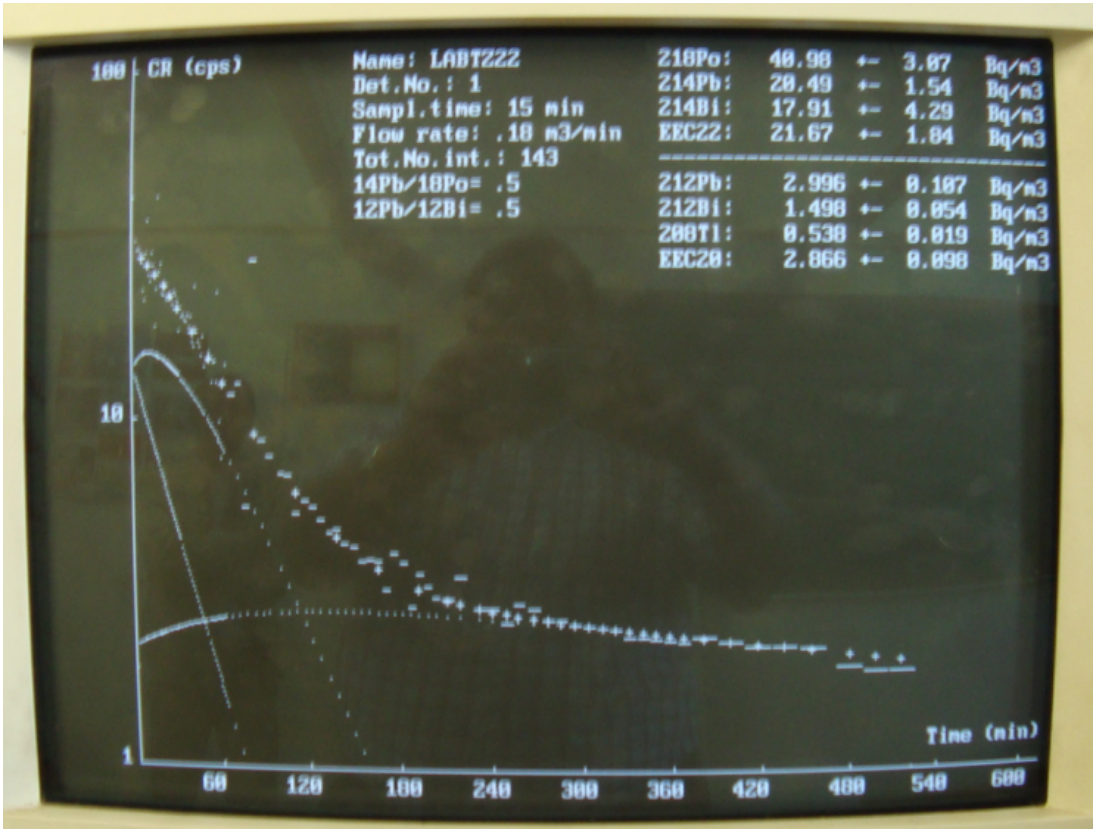

Figure 4.1: One of the data plotes measurement procedure in beta counting system

Measurement results of all the 21 sets of measurements are displayed in table 4.2.

CODE	DATE	218Po		214Pb		214Bi		EEC222		212Pb		212Bi		208Tl		EEC220	
		conc	±	conc	±	conc	±	conc	±	conc	±	conc	±	conc	±	conc	±
LabTZ-01	4/24/2017	22.44	0.58	11.22	0.29	12.56	0.79	12.91	0.34	1.977	0.022	0.989	0.011	0.355	0.004	1.891	0.02
LabTZ-02	4/25/2017	38.65	0.59	19.32	0.3	16.01	0.8	20.1	0.34	2.707	0.02	1.354	0.01	0.486	0.004	2.589	0.018
LabTZ-03	4/26/2017	28.29	2.6	14.15	1.3	7.9	3.49	13.26	1.51	1.393	0.087	0.696	0.043	0.25	0.016	1.332	0.079
LabTZ-04	4/27/2017	29.78	1.11	14.89	0.56	10.86	1.49	14.93	0.64	2.034	0.038	1.017	0.019	0.365	0.007	1.946	0.035
LabTZ-05	4/28/2017	32.01	1.83	16	0.92	15.63	2.39	17.54	1.04	2.292	0.088	1.146	0.044	0.412	0.016	2.193	0.081
LabTZ-06	5/1/2017	28.75	1.98	14.38	0.99	5.26	2.59	12.43	1.12	1.942	0.077	0.971	0.038	0.349	0.014	1.857	0.07
LabTZ-07	5/2/2017	21.07	0.74	10.53	0.37	9.2	0.97	11.13	0.42	1.703	0.027	0.852	0.013	0.306	0.005	1.629	0.025
LabTZ-08	5/3/2017	35.94	2.11	17.97	1.06	16.32	2.92	19.23	1.25	3.01	0.078	1.505	0.039	0.541	0.014	2.879	0.071
LabTZ-09	5/4/2017	24.91	1.74	12.46	0.87	6.72	2.27	11.59	0.99	1.596	0.071	0.798	0.036	0.287	0.013	1.527	0.065
LabTZ-10	5/5/2017	15.25	1.73	7.62	0.86	9.42	2.3	9.11	1	1.372	0.076	0.686	0.038	0.246	0.014	1.312	0.069
LabTZ-11	5/8/2017	10.99	0.32	5.49	0.16	4.24	0.41	5.6	0.18	1.086	0.016	0.543	0.008	0.195	0.003	1.039	0.015
LabTZ-12	5/10/2017	12.1	1.59	6.05	0.8	4.8	2.17	6.21	0.93	0.974	0.066	0.487	0.033	0.175	0.012	0.931	0.06
LabTZ-13	5/11/2017	30.31	0.67	15.15	0.33	11.33	0.9	15.3	0.39	2.173	0.026	1.087	0.013	0.39	0.005	2.079	0.023
LabTZ-14	5/12/2017	14.21	0.87	7.1	0.44	3.3	1.15	6.41	0.5	0.89	0.034	0.445	0.017	0.16	0.006	0.852	0.032
LabTZ-15	5/18/2017	11.25	1.23	5.63	0.62	3.96	1.67	5.59	0.72	1.043	0.049	0.521	0.024	0.187	0.009	0.998	0.045
LabTZ-16	5/19/2017	15.84	13.04	7.92	6.52	57.47	20.17	27.53	8.46	2.12	0.537	1.06	0.268	0.381	0.096	2.028	0.491
LabTZ-17	5/22/2017	37.45	1.94	18.73	0.97	21.93	2.72	21.91	1.16	3.007	0.069	1.504	0.034	0.54	0.012	2.876	0.063
LabTZ-19	5/24/2017	31.32	1.83	15.66	0.92	12.9	2.43	16.26	1.05	2.353	0.078	1.176	0.039	0.423	0.014	2.25	0.071
LabTZ-20	5/25/2017	23.42	1.24	11.71	0.62	7.19	1.67	11.23	0.72	1.749	0.047	0.874	0.023	0.314	0.008	1.673	0.043
LabTZ-21	5/26/2017	24.37	2.55	12.18	1.28	22.21	3.51	17.26	1.51	2.51	0.1	1.255	0.05	0.451	0.018	2.401	0.091
LabTZ-22	5/27/2017	40.98	3.07	20.49	1.54	17.91	4.29	21.67	1.84	2.996	0.107	1.498	0.054	0.538	0.019	2.866	0.098

Table 4.2: Computed Values of Rn and Thoron progeny, and EEC

From Table 4.2 In the computation the program assumes the following points: The concentration of long lived beta-emitter was assumed to be zero. "The daughter products of ^{222}Rn verses ^{218}Po (half-life = 3.05 min) and ^{214}Pb (half-life = 26.8 min) are linked together by the ratio

The ratio of activity concentration of ^{214}Pb to activity concentration of ^{218}Po is 0.5.

The daughter products of ^{220}Rn namely ^{212}Bi (half-life = 61 min) and ^{208}Tl (half-life =

3 min) are linked together when the graph is plotted. This stems from the fact that the activities of these two isotopes are very small as compared to that of ^{222}Rn daughters. From the plot using the program the following results was observed "Activities of isotopes in a unit volume of sampled air " The beta count rate measured over the time interval specified for all the counting intervals as a function of time " Contribution of the individual decay products for all the counting intervals, as a function of time. "The Equilibrium Equivalent Concentration (EEC) of ^{222}Rn and ^{220}Rn based on the data of table 4.5 the results observed is shown in figure above. From the above figure the short halfe-life of Radon daughter products are decays in short period of time. But,which have long half-life are decays in long period of time.

The results show that the highest activity of radon concentration was 27.53 Bq/m^3 and minimum value of radon concentration was 5.59 Bq/m^3 in Nuclear physics laboratory. With mean value of Radon-222 is 14.2 Bq/m^3. The results were below the action level recommended by WHO (WHO2008) of 100 Bq/m^3.

EEC values obtained from table 4.2 are used to calculate the annual effective dose based on each measurement. The results of this calculation are tabulated in table 4.3.

Annual effective Dose is given by equation (3.7):

$$\begin{aligned}\text{Effective Dose}(\tfrac{\text{msv}}{\text{y}}) &= (\tfrac{\text{Bq}}{\text{m}^3}) \times 24\,\text{h} \times 365.25 \times 0.8/\text{y} \times 10^{-5}\left(\tfrac{\text{mSv/Bqh}}{\text{m}^3}\right)\\ &= \text{EEC}_{\text{Rn}} \times 7 \times 10^{-5}\,\text{Sv/y}\end{aligned}$$

Table 4.3 gives a summary of the results of the indoor radon concentration levels and the annual effective dose in 21 different days in nuclear physics laboratory for the present study where the measurement were taken from April 24, 2017 to May, 27, 2017. The present experimental laboratory show that the indoor radon concentration obtained varied from 5.59 Bq/m^3 to 27.53 Bq/m^3 an overall mean value 14.2 Bq/m^3 and standard error of 14.2 ± 1.2 Bq/m^3 which is within the recommended ICRP action level of 200 Bq/m^3 - 600 Bq/m^3 (ICRP, 1993).

The lowest value of radon concentration was found to be 5.59 Bq/m^3; this is due high diffusion from indoor air to outdoor air since in the outdoor air there is heavy rain which dissolves the outdoor radon atoms. The annual effective dose from the corresponding measured radon concentration in the different days has been calculated using the Equation of annual effective dose which varies from (0.39 mSv/y to 1.93 mSv/y with a mean value of 0.99 mSv/y which is within the recommended ICRP intervention level of (3-10) mSv/y (ICRP, 1993).

No	Sample Code	Radon-222 concentration Bq/m^3	Annual effective Dose (msv/y)
1	LabTZ01	12.91±0.34	0.90
2	LabTZ02	20.1±0.34	1.41
3	LabTZ03	13.26±1.51	0.93
4	LabTZ04	14.93±0.64	1.05
5	LabTZ05	17.54±1.04	1.23
6	LabTZ06	12.43±1.12	0.87
7	LabTZ07	11.13±0.42	0.78
8	LabTZ08	19.23±1.25	1.35
9	LabTZ09	11.59±0.99	0.81
10	LabTZ10	9.11±1.00	0.64
11	LabTZ11	5.6±0.18	0.39
12	LabTZ12	6.21±0.93	0.43
13	LabTZ13	15.3±0.39	1.07
14	LabTZ14	6.41±0.50	0.45
15	LabTZ15	5.59±0.72	0.39
16	LabTZ16	27.53±8.46	1.93
17	LabTZ17	21.91±1.16	1.53
18	LabTZ19	16.26±1.05	1.14
19	LabTZ20	11.23±0.72	0.78
20	LabTZ21	17.26±1.51	1.20
21	LabTZ22	21.67±1.84	1.52
Min	-	5.59	0.39
Max	-	27.59	1.93
Mean	-	14.2	0.99

Table 4.3: Indoor Radon-222 Concentration, Annual effective Dose

The annual effective dose in nuclear physics laboratory first floor building is less than ICRP intervention level of (ICRP, 1993). The highest value was observed in the day of 19-05-2017 with an indoor radon concentration of 27.53 Bq/m^3 and an annual effective dose rate of 1.93 mSv/y. This result was measured high because of early in the morning it was recorded.

4.2 Comparison With other areas of the world

The indoor radon concentration determined in nuclear physics laboratory in the first floor building is 14.2 Bq/m^3. The Global average 39 Bq/m^3 reported by WHO (WHO, 2005).

Region	Country	Population In 1996 (10^6)	Mean Radon concentration (Bqm^{-3})
Africa	Algeria	28.78	30
	Egypt	63.27	9
	Ghana	17.83	
America	Canada	29.68	34
	United States	269.4	46
	Argentina	35.22	37
	Chile	14.42	25
	Paraguay	4.96	28
Asia	China	1232	24
	Honk Kong	6.19	41
	India	944.6	57
	Indonesia	200.45	12
	Japan	125.4	16
	Iran	69.98	82
	Kuwait	1.69	14
	Syria	14.57	44
Europe	Denmark	5.24	53
	Estonia	1.47	120
	Finland	5.13	120
	Belgium	10.16	48
	France	58.33	62
	Germany	81.92	50 9
	Ireland	3.55	
	Czech Republic	10.25	140
	Hungary	10.05	107
	Albania	3.4	120
	Croatia	4.5	35
	Slovenia	1.92	87
	Spain	39.67	86

Table 4.4: Comparison of Indoor Radon Concentration

Table 4-3 shows percentage contribution to average concentration ^{222}Rn by location. It is clear that the detected concentration values of ^{222}Rn in the Addis Ababa University is lower than those values reported in other worldwide locations, see table 4.3 and also lower than the mean values 46 Bq/m^3, reported by (UNSCEAR, 2000). On the other hand, it was found that the detected concentration values of ^{222}Rn in the Addis Ababa University are in agreement with those reported in some other countries such as Egypt, Japan, Indonesia and Kuwait. The variation in the indoor radon concentration due to many reasons such as different nature of the building materials, source of radiation in the room, types of materials in the closed air, location of the room and the weather condition of the environment.

No level of radon is considered safe. In fact, many countries set their national exposure levels based on their own studies. The American Environmental Protection Agency (Garawi M.S. & Alenezy, 2004) limits radon action level of 148 Bq/m^3.

This reference represents the acceptable indoor radon level in order to limit the risk to individuals and alert them when action should be taken. In Europe, the reference

level varies depending on the age of the building. Some European countries have more than one reference level, but in general it does not exceed 400 Bq/m^3. The Commission of the European Communities (CEC, 1990) has recommended two action levels, 200 Bq/m^3 for new homes and 400 Bq/m^3 for old and existing homes. In the meanwhile, some countries that have not determined a national reference level, such as Ghana, Ireland have adopted WHO action reference levels of 100 Bq/m^3 to minimize health hazards due to indoor radon exposure (Alghamdi & Aleissa, 2014).

In addition to this the indoor radon concentration determined in Addis Ababa university physics lab in three researchers were average concentration 19.12 Bq/m^3 and 23.9 Bq/m^3. Also in this work the average radon concentration in same place is 14.2 Bq/m^3. It is less than the global average 39 Bq/m^3 reported by WHO (WHO, 2005). The reason the lower value is due to weather variation, and due to the time of measurement.

Source of exposure	Average effective dose (mSv) Average	Typical range
Cosmic radiation		
Directly ionizing and photon component	0.28	
Neutron component	0.1	
Cosmogenic radionuclides	0.01	
Total cosmic and cosmogenic	**0.39**	**0.3-1.0**
External terrestrial radiation		
Outdoors	0.07	
Indoor	0.41	
Total external terrestrial radiation	**0.48**	**0.3-0.6**
Inhalation exposure		
Uranium and thorium series	0.006	
Radon (^{222}Rn)	1.15	
Thoron (^{220}Rn)	0.1	
Total inhalation exposure	**1.26**	**0.2-10**
Ingestion exposure		
^{40}K	0.17	
Uranium and thorium series	0.12	
Total ingestion exposure	0.29	0.2-0.8
Total	**2.4**	**1-10**

Table 4.5: Average Worldwide exposure to Natural Radiation [UNSCEAR2000]

From table 4.5 the radon(^{222}Rn) average effective dose Worldwide exposure to Natural Radiation (UNSCEAR, 2000) was 1.15 (msv/y). Then, the average effective dose of radon in nuclear physics laboratory first floor building is less than the Radon(^{222}Rn) average effective dose Worldwide exposure to Natural Radiation (UNSCEAR, 2000).

CHAPTER 5

Conclusions and Recommendations

5.1 CONCLUSIONS

The most important radon isotope from a health viewpoint is ^{222}Rn. Its decay products, especially ^{218}Po and ^{214}Po, can have a pronounced adverse effect on lung tissues, leading to lung cancer in many cases. Radon entry into the room usually occurs through cracks, joints, pipe fittings in walls, cracks in solid floors, through windows, and so on. ^{222}Rn was measured inside nuclear physics laboratory in the first floor building. Radon levels ranged from 5.59 Bq/m^3 to 27.53 Bq/m^3 a mean value of 14.2 Bq/m^3. The results were below the action level recommended by WHO (WHO2008) of 100 Bq/m^3. The annual effective dose ranged for Radon-222 between 0.39 msv/y to 1.93 mSv/y(Radon), with a mean value 0.99 mSv/y. The result of 0.99 mSv/y is lower than the value 1.15 mSv/y recommended by (Hasan et al., 2011) and (ICRP-60, 1990). On the basis of the current results, we may conclude that in the physics laboratory first floor building room, the levels of indoor radon are well within acceptable values.

5.2 RECOMMENDATION

Recommendation Based on the research findings the following recommendations have been made: The main perspectives for future work are:-

- Investigation of radon concentration indoor air, by taking a very detail sampling of radon inventory i.e. spatial and temporal inventory, it will be easy to understand and quantify the level of radon and other natural radioactive materials.
- In order to get a precise experimental result all the parameters can be controlled Measurement can be designed and set up, to improve the indoor radon concentration result the measurements shall take based on seasonal variation,

Bibliography

Aghamiri, S., Ghorbani, Z., Darafsheh, A., Torabzadeh, H., Fathivand, A., Minuchehr, A., & Jalinoos, A. (89(2006)). Ra-226 concentration in the teeth of habitants of areas with high level of natural radioactivity in ramsar. *Journal of Environmental Radioactivity*, 212–218.

Alghamdi, A. S. & Aleissa, K. A. (2014). Influences on indoor radon concentrations in riyadh, saudi arabia. *Radiation Measurements*, *62*(35-40).

Anon (1995). An insidious hazard, western deep levels - a clean bill of health. *SA Mining, coal, gold & base minerals*, (15-16).

Burnett, W., Peterson, R., Santos, I., & Hicks, R. (2010). Use of automated radon measurements for rapid assessment of groundwater flow into florida streams. *Journal of Hydrology*, *380*, 298 – 304.

CEC (1990). Commission recommendation of 1990 on the protection of the public against indoor exposure to radon. *European Community*, *80*(26-28).

Chamberlain, A. (1991). Radioactive aerosols. *Cambridge: Cambridge University Press*.

Damber, L. & Larsson, L. G. (1982). Combined effects of mining and smoking in the causation of lung carcinoma. *Acta Radiologica Oncology*, *21*(5).

David (2003). Atomic, Molecular, and Optical Physics; Ionization Potentials of Atoms and Atomic Ions. CRC Handbook of Chemistry and Physics (84th)ed Boca Raton, Florida: CRC Press.

EPA (1987). Iarc report:"the risk assessment guidelines of 1986". *Office of Health and Enviromental Assessment*.

Evans, R. D., Harley, J. H, ., Jacobi, W., Mclean, A. S., Mills, W. A., & Stewart, C. (1981). Estimate of risk from environmental exposure to radon-222 and its decay products. *Pergamon Press, Oxford*, *290(5802)*(98-100).

Garawi M.S., Baig, M. & Alenezy, M. (2004). Indoor radon distribution inside different rooms of residential buildings in riyadh, saudi arabia. *Science International (Lahore)*, *6*(18-82).

Gulson BL, Mizon KJ, D. B. . K. M. (2005). The effect of exposure to employees form mining and milling operations in a uranium mine on lead isotopes a pilot study. *Science of the Total Environment*, *339*(267-272.3 14).

Hasan, A., Subber, A. R., & Shaltakh, A. (2011). Measurement of radon concentration in soil gas using rad7 in the environs of al-najaf al-ashraf city-iraq. *Advances in Applied Science Research*, *2*(273-278).

ICRP (1987). Icrp publication 50 - lung cancer risk from indoor exposures to. radon daughters.oxford. *New York, Toronto, Sydney, Frankfurt,Pergamon Press*.

ICRP (1991). Recommendations of the international commission on radiological protection. *ICRP Publication 60 Anals of the ICRP*, *2*.

ICRP (1993). Protection against rn-222 at home and at work, icrp publication 65. *Annals of ICRP*, 23.

ICRP (2010). Icrp publication 115 -lung cancer risk from radon and progeny and statement on radon. *International Commission on Radiological Protection*.

ICRP-60 (1990). *Radiation Protection Recommendations of the International Commission on Radiological Protection*. Pergamon Press, Oxford.

Jacobi, W. (1993). The history of the radon problem in mines and homesannals of the icrp. *Pergamon Press, Oxford*, *23*.

Kapdan, E. & Altinsoy, N. (2012). A comparative study of indoor radon concentrations between dwellings and schools. *Radiation Physics and Chemistry*, *81*(4), 383–386.

Khokhar, M., Kher, R., Rathore, V. S., & Pandey, T. (2008). Ramachandranecomparison of indoor radon and thoron concentrations in the urban and rural dwellings of chhattisgarh state of indiaradiat. *Radiation Measurements*, *43*, s405 – s409.

Krane, K. S. (1987). *Introductory Nuclear Physics*. John Wiley and Sons.

Leung, S., Nikezic, D., & Yu, K. (2006). Passive monitoring of the equilibrium factor inside a radon exposure chamber using bare lr 115 ssntds. *Nuclear Inst. and Methods in Physics Research A*, *564*(319-323), 161–189.

Li, K. & Chan, A. (2004). Management of radon in tunnel drilling. *Journal of Construction Engineering and Management, 130*, 699–707.

Li, X., Zheng, B., Wang, Y., & Wang, X. (2006). A study of daily and seasonal variations of radon concentrations in underground bildings. *Journal of Environmental Radioactivity, 87*(101-106).

Mahur, A. K., Kumar, R., G., S. R., Sengupta, D., & Prasad, R. (2008). Measurement of natural radioactivity and radon exhalation rate from rock samples of jaduguda uranium mines and its radiological implications. *Nuclear Instruments and Methods in Physics Research, 266*(1591-1597).

Marsh, J. W. & Bailey, M. R. (2013). A review of lung-to-blood absorption rates for radon progeny. *Radiation Protection Dosimetry, 157 (4)*(499-514).

Nabil & Hamed (1995). Measurement of radon concentration in soil at north gaza "radon". *University of Athens - Greece, 41*.

Nagda (1994). Radon: Prevalence, measurements, health risks and control. *Astm Intl*.

Nazaroff, W. W., N. A. V. E. (1988). Radon and its decay products in indoorair. *New York: Wiley Interscience*.

Papp & Dezsó (2006). Measuring radon and thoron progeny in air by absolute beta counting subsequent to grab sampling. *Radiation Measurements, 41*.

Papp, Z. & Daróczy, S. (1997). Measurement of radon decay products and thoron decay products in air by beta counting using end-window Geiger-Müller counter. *Health Physics, 72*(4), 601.

Prasad, G., Prasad, Y., Gusain, G., & Ramola, R. (2008). Measurement of radon and thoron levels in soil, water and indoor atmosphere of budhakedar in garhwal himalaya. *Radiation Measurements, 43*, S375 – S379.

Richon, P., Perrier, F., Sabroux, J., Trique, M., Ferry, C., & Voisin, V. (2005). Spatial and time variations of radon-222 concentration in the atmosphere of a dead-end horizontal tunnel. *Journal of Environmental Radioactivity, 78*(179-198).

Schmidt, A., Schlueter, M., Melles, M., & Schubert, M. (2008). Continuous and discrete on-site detection of 222rn in ground- and surface waters by means of an extraction module. *Journal of Applied Radiation and Isotopes, 66*(2), 1939 – 1944.

Somlai, K., Tokonami, S., Ishikawa, T., Vancsura, P., Gaspar, M., Jobbagy, V., Somlai, J., & Kovacs, T. (2007). Rn-222 concentrations of water in the balaton highland and in the southern part of hungary, and the assessment of the resulting dose. *Radiation Measurements, 42*, 491 – 495.

Stanton, D. W., Kielblock, J., Schoeman, J., & Johnston, J. R. (2007). Handbook on Mine Occupational Hygiene Measurements. Johannesburg. Mine Health and Safety Council.

Thinova, L. & Rovenska, K. (2011). Rdaon dose calculation methodology for underground workers in the czech republic. *Radiation Protection Dosimetry*.

Truta-Popa, L., Hofmann, W., & Cosma (2011). Prediction of lung cancer risk for radon exposures based on cellular alpha particle hits. *Radiation Protection Dosometry, 145*(218-223).

UNSCEAR (1993). Unscear report:sources and effects of ionizing radiation.report to the general assembly,. *United Nations, New York*.

UNSCEAR (2000). United nations scientific committee on the effects of atomic radiation (2000) annex b. *UNSCEAR Report to the General Assembly. UN, New York*.

UNSCEAR (2008). Sources and effects of ionizing radiation. *United Nations ed., NY*.

Waska, H., Kim, S., Kim, G., Peterson, R., & Burnett, W. (2008). An efficient and simple method for measuring ra-226 using the scintillation cell in a delayed coincidence counting system (radecc). *Journal of Environmental Radioactivity, 99*, 1859 – 62.

WHO (2009). Who handbook on indoor radon: A public health perspective. *WHO Press, Geneva*.

WHO (June 2005.). The world health organization, fact sheet no. 291: Radon and cancer. *Available*.

WHO/IARC (1988). Who/iarc report: Iarc monograph on the evaluation of carcinogenic risks to humans. *Man-made mineral fibres and Radon, IARC Monograph,Lyon, France, 43*.

Yamada (2003). Radon exposure and its health effects. *Journal of Health Science, 49(6)*(417-422).

DECLARATION

ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES
DEPARTMENT OF PHYSICS

MSc Thesis

Effective Indoor ^{222}Rn Radiation Dose from Concentration on Filtered Air Sample

Name of Candidate: Temesgen Terefe Heda

I the under signed declare that the thesis is my original work and no part of it can be claimed as an intellectual property of anybody else except me and my advisors.

Signature: _____