INDOOR RADON IN SELECTED HOMES IN ABURI MUNICIPALITY: MEASUREMENT UNCERTAINTY, DECISION ANALYSIS AND REMEDIATION STRATEGY

BY

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DECLARATION

This Thesis is the result of research work undertaken by Sandra Manu Yeboah in the Department of Nuclear Safety and Security, Graduate School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Prof. E.O. Darko and Prof. Aba Bentil Andam.

To the best of my knowledge, this work or any part of it has not been submitted elsewhere for the award of any degree, except references to previous works which have been duly acknowledged.

Sign………………….. Sign…………………………….

(Sandra Manu Yeboah) (Prof E.O. Darko)

Date…………………… Date………………………

Sign………………………

(Prof Aba Bentil Andam)

Date……………………

DEDICATION

This Thesis is dedicated to my beloved father, Nana Batafo Akyeampong Nti II and mother Georgina Duker (of blessed memory), who have made me who I am today. The Thesis is also dedicated to all my brothers and sisters for their love, care and support.

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TABLE OF CONTENTS

LIST TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACD_S	Activated Charcoal Detectors
ATD_S	Alpha Track Detectors
BEIR	Biological Effects of Ionizing Radiations
Bqm^{-3}	Becquerel per meter cubed
CI	Confidence Interval
ECE	Electrochemical Etching
EEC	Equilibrium Equivalent Concentration
EIC_S	Electret Ion Chambers
EPA	Environmental Protection Agency
EU	European Union
GAEC	Ghana Atomic Energy Commission
HSE	Health and Safety Executive
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
LET	Linear Energy Transfer

mSv	millisievert
NAS	National Academy of Science
NCRP	National Council on Radiation Protection and Measurements
NNRI	National Nuclear Research Institute
NRC	National Research Council
NTD	Nuclear Track Detection
PAEC	Potential Alpha Energy Concentration
PADC	Polyallyldiglycol Carbonate
REL	Restricted Energy Loss
SSNTD$_S$	Solid State Nuclear Track Detections
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USEPA	United States Environmental Protection Agency
WLM	Working Level Month
WHO	World Health Organisation

ABSTRACT

The main source of natural internal irradiation of man is radon and its decay products. In this study, the radon concentration levels in selected homes in Aburi of the Akuapim North Municipal Assembly in Eastern Region, Ghana were estimated using time-integrated passive radon detector; LR-115 Type II solid state nuclear track detector (SSNTD) technique. The primary objective of the study was to measure radon levels in 30 selected homes in the Aburi municipality and determine the uncertainties associated with the measured radon concentrations in order to take a decision on remedial actions to be adopted in case of any abnormality using simple qualitative decision analysis method. Measurements were carried out from December, 2013 to March, 2014. After each month of exposure for a period of three months, the detectors were subjected to chemical etching in a 2.5M analytical grade of sodium hydroxide solution at $(60 \pm 1)^{o}$C, for 90mins in a constant temperature water bath to enlarge the latent tracks produced by alpha particles from the decay of radon. The etched tracks were magnified using the microfiche reader and counted with a tally counter. The results obtained from the study revealed that concentration of radon in most of the selected homes in the Aburi municipality is low and it is within the internationally accepted action level of 100Bqm^{-3} set by WHO (2009). The analysis of the results established that the average radon concentrations vary in the range 23.72-92.24Bqm^{-3}, 19.07- 124.36 Bqm^{-3} and 31.63-123.87 Bqm^{-3} for month 1, month 2 and month 3 respectively. The corresponding mean values are 46.77, 45.92 and 56.66 Bqm^{-3} respectively with standard deviations of ±2.18, ±2.38 and ±2.76. These gave a mean of 49.78 ±12.50 for the three months. Two (2) of the rooms investigated had values above 20 % of the remedial action level of 100Bqm^{-3} in two of the months but with their average values slightly lower than the remedial action level. From the uncertainty evaluation and decision analysis it is clear that the rather low

values of radon indicates that there is no need for any remediation action in almost all the rooms with the exception of room A26 and perhaps A29, which may require a relatively inexpensive mitigation action by improving ventilation in these rooms. The radon activity has not only been found to vary with the construction mode of the houses but also with the ventilation conditions, the climatic conditions, the geology and topography among others.

CHAPTER ONE

INTRODUCTION

Radon, a naturally occurring analogue of the uranium-thorium series is a carcinogenic gas and one of the ubiquitous and inexhaustible natural elements of the earth’s crust. The quest for effective control of radon to improve its adverse health effects has been a subject of much concern worldwide in recent years. However, the health effects of radon depend on duration of exposure, gender, physical conditions, and geographical location, among others. This chapter provides the background and explains the reason for the study, the objectives, and the importance as previous studies have focused on different areas in the country.

1.1 Background

The health risk posed by ionizing radiation to humans are well known. Radon because of its short lived progeny, is becoming an increasingly social and scientific issue since its inhalation may results in lung cancer. More than 55% of the global radiation dose delivered to human kind on this earth from all natural sources come from radon alone [Walia et al., 2003].

Radon-222 is an odourless, colourless, radioactive gas which is a progeny of the naturally occurring radioactive decay of uranium-238. Radon-222 is a noble gas (chemically unreactive) that can readily migrate through permeable rocks and soils and eventually seep into buildings or released into the atmosphere. Although it is generally assumed to be an inert gas, in actuality it is a "metalloid". It lies on the diagonal of the Periodic Table between the true metals and nonmetals and therefore demonstrates some of the properties of both.

All isotopes of radon are radioactive. Radon's atomic number, 86, places it in the noble gas column and for this investigation it will be assumed inert. There are three known isotopes of radon, ^{219}Rn, ^{220}Rn, and ^{222}Rn. All the three isotopes of radon are radioactive, but each belongs to a different radionuclide series. Both ^{219}Rn and ^{220}Rn have short half-lives of less than one minute, whereas the half-life of ^{222}Rn is about 3.8 days. It takes time for radon gas to diffuse out of soil and enter living spaces, so the major contributor to doses to the general public is ^{222}Rn. For radiation safety reasons, radon-222 is the most important isotope to consider.

Radon further decays into radioactive chemical reactive particles which can attach themselves to other airborne particles such as dust in homes and the environment. If inhaled, these new radioactive particles, may cause damage to lung tissues and increase the risk of lung cancer. It is these decay products which pose the real health threat from radon in homes. When the decay products of the trapped radon in the lung undergo further radioactive decay, the surrounding lung tissue can be damaged.

Radon-222 is an alpha emitter that decays with a half-life of 3.8 days into short lived series of progeny such as ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb and ^{210}Bi which emit high energy alpha particles that are highly effective in damaging tissues. These can be deposited in the lung through inhalation. Over a period of time, this may lead to malignant transformation and the formation of lung cancer. Since even a single alpha particle can cause major damage to a cell, it is possible that radon-related DNA damage can occur at any level of exposure. The USA National Academy of Sciences [NAS, 1999] estimated that radon causes between 15,000 and 20,000 deaths in the USA annually. In January, 2004 a national radon action was declared in the USA. A lot of research are also ongoing to map out regions of high natural background radiation through the monitoring of radon gas in some homes and mining centres. Most of the time is spent within buildings; therefore the measurement and evaluation of radon concentration is necessary [Risica, 1998; Hamori et al., 2004].

The main source of indoor radon is its immediate parent radium-226 in the ground of the site and in building materials (sand, rock cement, etc), tap water, natural energy sources used for cooking like (gas, coal, etc) which contain traces of ^{238}U [Nero,1988; 1989]. The outdoor air also contributes to the radon concentration indoors, via the ventilation air. Tap-water and the domestic gas supply are usually radon sources of minor importance. In most situations it appears that elevated indoor radon levels originate from radon in the underlying rocks and soils [Castren et al., 1985]

Radon is also found in well water and will enters a home whenever it is used. In many situations such as showering, washing clothes, and flushing toilets, radon is released from the water and contributes to the total inhalation risk associated with radon in indoor air. Risk assessment of radon both in mines and in dwellings has given clear insight into the health risk due to radon. For the general public, exposure to radon is now recognized as the second leading cause of lung cancer after smoking.

The decision to apply a given mitigation strategy to reduce radon concentration in a particular location depends on many factors including the uncertainties associated with measurement of radon, and comparison with a given reference level. Reference level represents a level at which one should consider taking actions to reduce the radon concentration. It represents the maximum accepted radon concentrations in a dwelling and it is not a rigid boundary between safety and danger.

In Ghana, there are no specific regulations relating to indoor radon levels in either home or workplace. Therefore, a national radon map is necessary to help identify the geological areas where the population is most at risk of exposure above the reference levels established by the WHO (2009) and other international organizations [ICRP, 1993]. Different countries have established regulations and reference levels for the control of indoor radon levels. Some of the countries and their action levels are: The action level for workplaces in Hungary is 1000Bq.m$^{-3.}$[Kavasi et al., 2006]; in the UK the Health and Safety Executive (HSE) has adopted a radon action level of 400Bq.m^{-3} for workplaces [Kendall et al., 2005], the USA uses a reference level of 148Bq.m^{-3} for dwellings and a level of 400Bq.m^{-3} for workplaces [USEPA, 2004], the European Union (EU) accepts the recommended action levels included in the ICRP-65 of between 500 and 1500 Bqm^{-3} [ICRP, 1993], Israel uses a mandatory reference level of 200Bq.m-^{3} for existing schools and day care centers [Akerblom,1999] and the new reference level above which an action should be taken is now 100Bq.m^{-3} [WHO, 2009].

In this study, the uncertainty associated with the measured concentration of radon was determined using standard statistical methods. Remediation measures that need to be undertaken was determined using simple qualitative decision analysis method. The equivalent dose per unit radon exposure was also determined using a conversion factor [Chen, 2005]. Radon concentration is normally given in the units of Bq.m-^{3}, while radon dose is expressed in the unit of mSv (milliSievert), which could be a radiation weighted and/or tissue weighted quantity.

1.2 Problem Statement

Exposure to radon in homes and workplaces is one of the main sources of risk associated with ionizing radiations causing tens of thousands of deaths from lung cancer each year globally. On 22 September, 2009, the World Health Organization released a comprehensive global initiative on radon that recommended a reference level of $100 Bq.m^{-3}$ for indoor radon. The WHO has urged all member states to strengthen or establish radon measurement and mitigation programmes and also establish a national reference level [WHO, 2009].

Studies have shown that virtually much have not been done in Ghana. The public is unaware of the potential hazards associated with radon inhalation. Investigation have so far not been conducted in the Aburi Municipality regarding the concentrations of radon in dwellings, the uncertainties associated with the measured radon concentration, and the necessary remediation measures to be adopted in case of any abnormality and informed policy decisions on the need to take issues on radon seriously.

Though there are many previous studies done elsewhere whose results have been considered, this work focused only in Aburi due to location and the short-time frame of the work, among others. The quality of work would have improved if long-term studies on population lung cancer risk due to indoor radon had been estimated using epidemiological.

1.3 Objectives

The primary objective of the study is to measure radon levels in selected homes in Aburi municipality and determine the uncertainties associated with the measured radon concentrations in order to take decision on remedial actions to be adopted in case of any abnormality using simple qualitative decision analysis method.

The specific objectives of the study are:

- Determine radon concentrations in some selected homes in the Aburi municipality;
- Determine and analyse the uncertainties associated with the measured radon concentrations;
- Use simple qualitative decision analysis method to determine remediation measures to be adopted in case there is high values of radon concentration above reference levels;
- Compare the results with data from work done in other environments in Ghana and elsewhere; and
- Make appropriate recommendations to address any remedial actions to stakeholder institutions and individual households involved in this study.

1.4 Justification and Relevance of the Study

A number of studies have been carried out on indoor radon levels in homes in many countries including Ghana. Data available from these studies show that there may be the need to undertake remediation measures to restore the quality of life in the affected areas. A number of studies have been carried out in Ghana in some households, but data available on the radon levels in homes at Aburi and the neighbouring areas have not been addressed since no similar work has been done in this study area. It is therefore considered imperative to measure the activity concentration of indoor radon in selected homes in this area. Studies on indoor radon distribution in homes will therefore provide essential radiological information and the necessary remediation measures.

Similarly, the data generated in this study will provide reference values of indoor radon in the area and may be useful for relevant authorities (construction companies and the regulatory body) in the development and implementation of radiation protection guidelines and standards for the public in the country, as well as to conduct further studies on this subject in schools, churches, cells, etc. It will also engender interest for further research into radon in other homes from all the regions of the country.

1.5 Scope and limitation

The work is intended to cover measurement of indoor radon levels in selected homes in Aburi municipality using solid state nuclear track detectors. Though there are many previous studies carried out in other areas in Ghana, this work is focused on Aburi due to the short duration of the work, geological considerations, topography, meteorology, accessibility to equipment and the closeness of the study area to the laboratory where data analysis was carried out. The time frame for this work is three months and therefore focuses on few selected homes in the Aburi Municipality.

1.6 Structure of Thesis

This Thesis is presented in five chapters. Chapter 1 deals with background to the study, research problem, relevance of work, objectives, scope and limitations. Chapter 2 deals with the Literature review. Chapter 3 covers Materials and Methods. Results and Discussions are presented in Chapter 4, and Conclusion and Recommendations from the study are covered under Chapter 5 respectively.

CHAPTER TWO

LITERATURE REVIEW

This section reviews work done by other researchers on radon in homes and other media. Some important facts about indoor radon and contribution of radon-222 to health have been addressed. Assessment and classification of radon, and the necessity of undertaking these investigations are also discussed. The uncertainties associated with the measurement of radon, decision analysis methods and remediation strategies are also discussed. Methods and instrumentations for the measurement of radon concentration in various media are also presented.

2.1 Overview of Radon and its Progeny

Radon is a naturally occurring radioactive gas which is colorless, odorless, tasteless, and imperceptible to senses and chemically inert gas which is produced continuously from the natural decay of U-238; U-235 and Th-323. Radon is a gas which seeps out of rocks and soil. Radon flows from the soil into outdoor air and also into the air in homes from the movement of gases in the soil beneath homes. Outdoor air contains typically low levels of radon, but it builds up to higher concentrations indoors when it is unable to disperse [UNSCEAR, 2000].

Radon further decays into radioactive, chemically reactive particles, which can attach themselves to other airborne particles such as dust in a home environment. If inhaled, these now radioactive particles may cause damage to lung tissues and increase the risk of lung cancer. It is this decay products which poses the real health threat from radon in our homes. When the trapped radon decay products in lung tissues undergo further radioactive decay, the surrounding lung tissues may be damaged. The deposited atoms decay by emitting a type of radiation called alpha radiation, which has the potential to damage cells in the lung. This radiation can disturb the DNA of these lung cells which can lead to cancer. Alpha radiations travel only extremely short distances in the body. Thus, alpha radiations from decay of radon progeny in the lungs cannot reach cells in any other organs, so it is likely that lung-cancer is the only potentially important cancer hazard posed by radon in indoor air.

The most significant pathway for human exposure is through the permeation of underlying soil gas into buildings, although indoor radon can also come from water, outdoor air, or building materials containing radium. Radon-222 decays with a half-life of 3.82 days into a series of short lived radioisotopes collectively referred to as radon daughters or progeny. Most inhaled radon-222 is exhaled since it is chemically inert.

Two other radon isotopes are radon-219 (actinon) and radon-220 (thoron), which occur in nature and produce radioactive radon daughters. Environmental concentrations of actinon and thoron and its daughters are extremely low so their contribution to human exposure is negligible due to its short half -life of (3.7s) and (56s) respectively. As a result, they are thought to pose less of a problem than radon-222. Following common usage, the term radon in some cases refers simply to radon-222, but sometimes to radon-222 plus its progeny. For example, one may talk about “radon risk” when most of that risk is actually conferred by inhaled decay products [Nelson et al., 2001]. A list of the progeny of radon gas is given in Table 2.1 in the order of appearance. Each radioactive element on the list gives off either alpha radiation or beta radiation and sometimes gamma radiation too thereby transforming itself into the next element on the list. The last element on the list is not radioactive, lead-206, it does not decay, and therefore has no half-life.

Table 2.1: The Decay Products of Radon-222

Isotopes	Atomic number	Half-Life	Radiation Emitted	α particle decay energy (MeV)
^{226}Ra	88	1600y	α	4.78
^{222}Rn	86	3.825d	α	5.49
^{218}Po	84	3.05min	α	6.00
^{214}Pb	82	26.8min	β, γ	-
^{214}Bi	83	19.9min	β, γ	-
^{214}Po	84	164μs	α	7.69
^{210}Pb	82	22.3y	β, α	-
^{210}Bi	83	5.01d	β	-
		$+3.0\times10^{6}$y	α	4.95
^{210}Po	84	138.4d	α	5.30
^{206}Pb	82	Stable	-	-

A chain form of the decay series of Radon and its Progeny with their half-life is given below:

Rn-222 → Po-218 → Pb-214 → Bi-210 → Pb-210 → Pb-206.

2.1.1 Chemical and physical Characteristics of Radon

The following are the physical and chemical characteristics of radon:

- Radon is soluble in water and some other liquids. Its solubility in water is about 28% at 18°C and varies inversely with temperature.

- Radon melts at about -110℃ and it has a boiling point of -65℃
- Radon is the heaviest of the noble gases on the periodic table
- Radon is chemically inert
- Radon has a density of 9.72g/litre at 0℃ and standard atmospheric pressure(mmHg) making it about seven times denser than air
- Radon is a radioactive gas, colourless, odourless and tasteless
- Radon decays by alpha particle emission with a half-life of 3.8 days.

2.1.2 Radon Entry into Homes

Many factors contribute to the entry of radon gas into a building. Radon from rocks and soil under homes or buildings is the largest source of indoor radon in air. The radon gas rises through soil and enters a home through cracks and other openings. It is most concentrated in the lowest level of a home or building because of the proximity to the ground. Houses in nearby areas can have significantly different radon levels from one another. As a result, landlords cannot know if elevated levels of radon are present without testing. The movement of radon into houses is controlled largely by the soil permeability under a foundation and access to the interior of the house through openings in the foundation. Radon-222 gas can also seep into a house through cracks in the foundation, openings around drainage pipes caused by shrinkage of concrete, plumbing penetrations in slabs or any other openings in foundations or walls [Nero, 1988; 1989]. The following factors determine why some homes have elevated radon levels and others do not:

1. The concentration of radon in the soil gas (source strength) and permeability of the soil (gas mobility) under the home;
2. The structure and construction of the home building; and

3. The type, operation, and maintenance of the heating, ventilation, and air conditioning (HVAC)

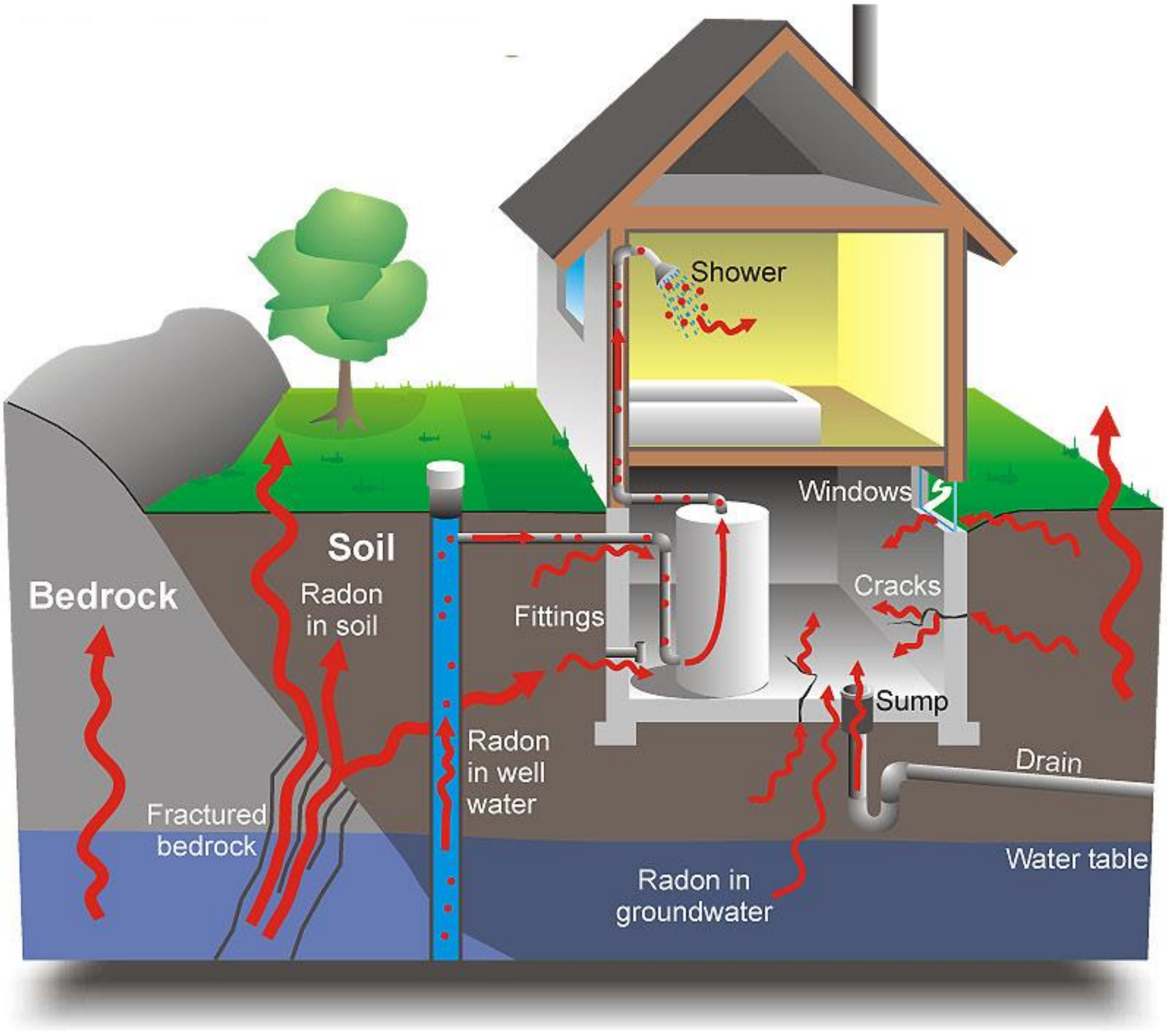

Figure 2.1: Major Radon Entry Routes (WHO, 2009)

Radon concentration can vary within a home from hour-to-hour and day-to-day. Due to these fluctuations, estimating the annual mean concentration of radon in indoor air requires measurements of mean radon concentrations for at least three (3) months.

2.2 Sources of radon

According to Nero (1988, 1989) the main source of indoor radon is its immediate parent radium-226 in the ground of the site and in the building materials. It appears in most situations that elevated indoor radon levels originate from radon in the underlying rocks and soils [Castren et al., 1985]. This radon may enter living spaces in dwellings by diffusion or pressure driven flow if suitable pathways between the soil and living spaces are present.

2.2.1 Soil

The most important radon source is radium in the ground for those who live close to the ground, e.g. in detached houses or on the ground floor of apartment's buildings without cellars. 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].

The ingress of radon from the soil is predominantly one of pressure-driven flow, with diffusion playing a minor role [de Meijer et al., 1992]. The magnitude of the inflow varies with several parameters, the most important being the air pressure difference between soil air and indoor air, the tightness of the surfaces in contact with the soil on the site, and the radon exhalation rate of the underlying soil is also another parameter. The under pressure indoors causes radon to be drawn in from the ground under the building if there are no airtight layer between the basement and the ground.

2.2.2 Building materials

The second main source of indoor radon is building materials, while in the seventies they were considered the principal one [UNSCEAR, 1977]. Exhalation of radon from building materials depends not only on the radium concentration, but also on factors such as the fraction of radon produced which is released from the material, the porosity of the material, the surface preparation and the finish of the walls. The main source of radon-220 (also called "thoron") in indoor air is building material. Due to its short half- life (55 s), thoron originating in soil in effect is usually prevented from entering buildings and therefore makes negligible contribution to indoor thoron levels. It is difficult measuring thoron and its progeny due to its short half-life unlike radon.

2.2.3 Outdoor air

The concentration of radon in outdoor air is mainly related to pressure in the atmosphere, and it shows a typical oscillating time pattern, with higher values during the night. 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.

2.2.4 Sources of Indoor Radon

Radon from soil and rocks under homes or buildings is the biggest source of indoor air. Radon gas rises through soil and seeps into homes or building through cracks and other opening. Once it enters the room, it can become trapped and concentrated. Radon is most concentrated in the lowest level of a home or building because of the proximity to the ground. The concentration of radon in a home depends on [UNSCEAR, 1993; 2000]:

- The exchange rate between indoor air and outdoor air, this depend on the ventilation habit of the inhabitants and the sealing of window as well as the construction of the house
- The amount of uranium in the underlying soils and rocks
- The routes available for passage of radon into homes.

The following are ways by which openings allow easy flow of radon into our homes or into buildings:

- cavities in walls
- crawl spaces that open directly into buildings
- Gaps in suspended floor
- Cracks in floors and walls
- Openings around sump pumps and drains
- Joints in construction materials.

2.2.5 Tap-water

The radon concentration in water may be high in drilled wells in rocks. Many rural dwellers obtain their drinking water from untreated water sources and they are used for domestic activities such as drinking, bathing, washing of cloths and dishes, cooling and recreation, etc. Radon is soluble in water, its solubility decreases rapidly with increase in temperature (510cm^3/kg, 230cm^3/kg and 169cm^3/kg at 0^{o}C, 20^{o}C and 30^{o}C respectively. When such water is used in the household, radon will be partially released into the indoor air, causing an increase in the average radon concentration. According to UNSCEAR (1988), radon concentrations in tap-water from deep wells can range from 100 kBq/m^3 to 100 MBq/m^3. The indoor radon concentration may 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].

Table 2.2: Sources of Global Atmospheric Radon [Ludin et al., 1971]

Source	**Ci per year (x 10^6)**	**Bq/year**
Human Exhalation	0.00001	3.7E+4
Coal Combustion	0.0009	3.33E+5
Natural Gas	0.01	3.7E+7
Coal Residue	0.02	7.4E+7
Uranium Mill Tailings	2	7.4E+9
Phosphate Residues	3	1.11E+11
Emanation from Oceans	30	1.11E+12
Ground Water	500	1.85E+13
Emanation from Soil	2000	7.4E+13

Dissolved radon in ground water is the second most important potential source of atmospheric radon. Tailings from both residues from phosphate mines and uranium mines contribution to the global radon is estimated to be 2 to $3x10^6$ Ci of radon-222 per year. Earlier research has estimated that 20% of the radon formed in tailings is released and that emanation rates can be as high as 1,000pCi radon/m^2/s. Fly ash, combustion and natural gas which are coal residues also add to the atmospheric radon levels, however, only in negligible quantities.

2.3 Emanation of Radon

The process by which radon gas is transported from a solid to a gas or liquid medium is known as emanation [Michel, 1987] .The mechanism by which this process occurs is primarily through alpha recoil. This transportation of radon throughout soil is primarily accomplished through alpha recoil and the mechanical flow of air and water throughout the soil. Alpha recoil is defined as the process by which an atom recoils in the reverse or opposite direction from the path of particle ejection following the radioactive decay of its parent atom (radium). The transportation within these pores is also facilitated by diffusion and convection. The diffusion constants for radon in water and air, $10^{-5}cm^2/sec$ and $10^{-2}cm^2/sec$, respectively, show that diffusion of radon is a relatively slow process and the movement of radon is therefore not significantly affected by this mechanism.

2.4 Exhalation of Radon

The actual release of radon from the pore space or soil-gas to ambient air is called exhalation, whiles its release from water is called evaporation. The rates of these processes are functions of many variables including [Michel, 1987]:

- Variations in atmospheric pressure
- Meteorological factors, including temperature and precipitation
- Soil porosity
- The concentration of radon in the soil-gas or water.

The dispersion of radon is primarily determined by atmospheric stability, including direction of wind’s force, and turbulence and vertical temperature gradients following the release into ambient air. Once radon reaches a height of one meter approximately above the soil surface, its dispersion is predominately determined by atmospheric stability. Temperature inversions in the early morning act to produce a stable atmosphere which keeps radon in the soil or near the ground or water surface. Generally, radon levels in air decreases exponentially with altitude since solar radiation breaks up inversion leading to upward dispersion of radon which reverses with radiant cooling in the afternoon.

2.5 Comparison Radon to other Sources of Radiation

Natural and artificial or man-made alpha emitting radionuclides in the environment can pose a risk to human health, but the natural sources currently make the largest contribution to human exposure. According to NCRP (1984), inhaled radon and radon decay products which are part of natural sources are the largest contributors to population exposure and might be responsible for a large number of cancers each year (Figure 2.2).

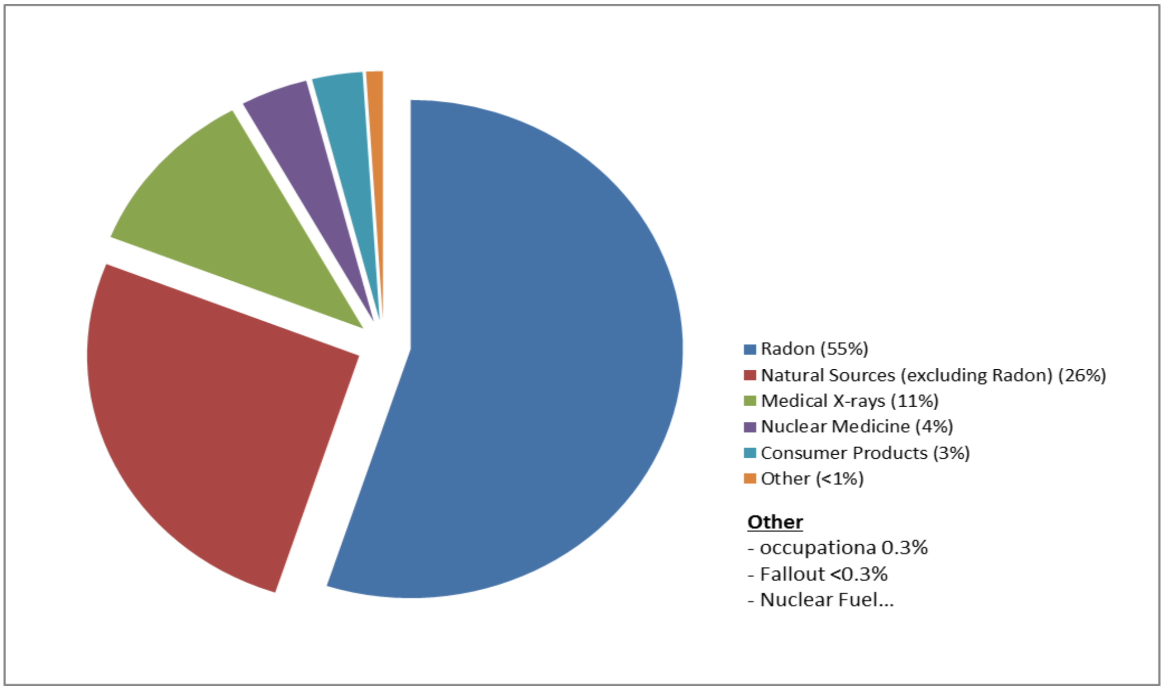

Figure 2.2: Comparison of percentage for radon exposure to sources of radiation [NCRP, 1993]

2.6 Health Effects of Radon

Natural radiation is harmless to humans in ambient environment but contributes significant quantities of radiation towards the total radiation exposure that humans receive. Radon is one of the very small number of substances which have been established to be human carcinogen on the basis of human studies. Radon can pose a threat to the public health when it accumulates in poorly ventilated homes as well as workplaces since it contributes more than sixty percent (60%) of the natural radiation. Unless people become aware of the dangers radon poses, nothing could be done about it. Indoor radon gas is a serious health problem in many countries that can be addressed by individual action. Millions of homes are estimated to have elevated radon levels. Fortunately, the solution to this problem is straight- forward. Like the hazards from smoking, the health risks of radon can be reduced". Radon accounts for more than half of the total average annual exposure to radiation, about 2 of 3.6 mSv per year.

The National Research Council in its report (BEIR VI) on the Health Effects of Exposure to Radon [NRC, 1999] estimated that about 14% of the 164,000 lung cancer deaths in the United States each year are attributable to exposure to radon- correlating to approximately 15,000 to 22,000 lung cancer deaths each year in the most recent National Academy of Science (NAS) report on radon. Seven hundred (700) deaths are attributed to exposure in outdoor air mostly from mines and 160 of these deaths have been attributed to radon dissolution exposure in ingested water. Inhalation of radon and its progeny causes majority of deaths. In a second NAS report published in 1999 on radon in drinking water, the NAS estimated that about 89% of the fatal cancers caused by radon in drinking water were due to lung cancer from inhalation of radon released to indoor air, and about 11% were due to stomach cancer from consuming water containing radon [NAS, 1999].

Henshaw et al. (1990, 1992) recently suggested that elevated levels of indoor radon exposure may be implicated in the occurrence of other cancers such as childhood leukemia. Clearance of radon from the bloodstream is relatively rapid, with a half-time of the order of minutes [Underwood et al., 1941]. Hursh et al. (1965) demonstrated that radon is removed from the body primarily through exhalation via the lung. Studies have revealed that radon is removed from the body with a base half-life of between 30 and 70 minutes, with a smaller component having a half- life of the order of several hours [Crawford-Brown, 1991]. According to Gosink et al. (1990) the rate of radon elimination from a resting person appears to be slower than that of a physically active person. Indoor radon air mostly inhaled is exhaled and remains in the lungs for only a short time. Pollonium -218 (^{218}Po) which is a daughter of radon is very reactive and electrostatically attracted to tiny particulates in air. These particulates are inhaled and deposited in the lungs. Radon daughters then decay sequentially, releasing damaging alpha and beta particles. Therefore, it is radon progeny, not radon, that actually cause the damage to the bronchial epithelium, because only the progeny remain in the lungs long enough to decay significantly [Cothern, 1987]. Some researchers have suggested that there might be a synergistic effect between radon and cigarette whilst others have suggested that smoking may cause a thicker layer of mucus in the lungs, which may actually protect the lungs from alpha particles [Cothern, 1987].

According to NCRP Report (1988), several national and international organizations have developed inhalation risk models based on epidemiological and radiobiological data for radon. Risk projections have been made using three of these models. The BEIR IV [NRC, 1988] suggest that the average lifetime risk from inhalation exposure to radon daughters is likely to be of the order of less than 100 cases per million WLM to perhaps 500 cases per million WLM, with the lower value being applicable to females and non-smoking males and the higher values being applicable to a mixed population of females and smoking and non-smoking males [SENES, 1990].

Comparatively, few epidemiological studies have investigated the exposure to natural background radon levels, and those that are available show no significant increase in lung cancer death rate from inhalation exposure to normally occurring levels of radon and radon progeny [Létourneau et al., 1994]. Animal studies, involving the inhalation of radon and its progeny have provided considerable data confirming human epidemiology studies. Although there have been some attempts to estimate the risk to animals from ingestion of radon and radon progeny, it has generally been concluded that the risk from ingestion is significant compared with the risk from inhalation [Cothern, 1987].

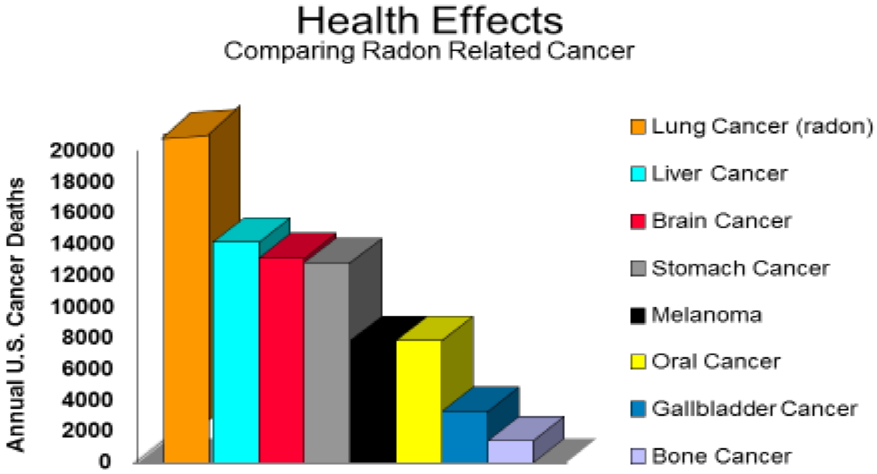

Figure 2.3: Comparison of radon health related cancer risk

2.7 Risk Estimates

There are different models used to estimate the lung cancer risk. These include the model in the BEIR III report. The BEIR III report [NRC, 1980] gives an elaborate age dependent risk factors of 10×10^{-6} per WLM.y for ages 35-45, 20×10^{-6} WLM.y for ages 45-65, and 50×10^{-6} per WLM.y for ages above 65 and latency period of 10 years.

The EPA (USA) recommends 4pCi/L ($148 Bq.L^{-1}$) as the action level for a lifetime exposure to indoor radon. Depending on whether a person is a smoker, non-smoker or former-smoker the EPA (USA) estimates that the risk of developing lung cancer is 1 to 5 percent. The National Research Council (NRC) estimates the risk as 0.8% to 1.4%. The overall risk of radon exposure is related not only to its average level in the home, but also to the occupants and their lifestyles [USEPA, 1984].

Factors that influence the Risk of Lung Cancer from Radon Exposure are as follows: age, duration of exposure, gender, physical condition, geographic location, other carcinogenic exposure, cigarette smoking, time since initiation of exposure and genetic tendency either to resist or be affected by internal radiation exposure.

The highest radon levels are typically found in the lowest level of the house. If well water is the major source of radon, upper floors can be affected more than lower floors because of dissolution of radon from the water. Radon levels are elevated in colder climates rather than in more mild temperatures (summer and spring). The risk to people is proportional to the length of exposure and the radon concentration in air (linear, no-threshold hypothesis). However, the radon risk begins to level off for extremely high concentrations, such as in the mines, because more lung cells are killed off by the radiation and some radiation is wasted on the already killed cells (inverse exposure-rate effect). But at lower concentrations, like in residences, every emitted particle will have an impact.

The risk of lung cancer associated with a lifetime inhalation of airborne radon at a concentration of 1 Bqm^{-3} was estimated on the basis of studies of underground miners. The values were based on risk projections from three follow-up studies: NIH (1994), BEIR IV [NRC, 1988]; BEIR VI [NRC, 1998]. Data from 4 to 11 cohorts of underground miners in seven countries were obtained from the three reports and developed risk projections of 1.0×10^{-4}, 1.2×10^{-4}, 1.3×10^{-4} per unit concentration in air (1.0 Bq.m^{-3}), respectively. The three values were for a mixed population of smokers and non-smokers.

As the number of radiation particles increase in the body, there is an increase in the chance of getting cancer and the risk to people is proportional to the length of exposure and the radon concentration in air (linear, no-threshold hypothesis).

2.8 Risk Assessment

Risk assessment has been defined by the National Research Council (NRC) of USA as “the characterization of the potential adverse health effects of human exposures to environmental hazards” [NRC, 1983]. A way of examining risks that they may be better avoided, reduced, or managed is presented as risk assessment. Assessments of radiological hazards and all other types of hazard require some of the following components or all components:

1. Exposure or dose assessment, which is the determination of the extent to which human will be exposed to the hazard.
2. Dose-response assessment, in which the relation between the magnitude of the dose and probability that the health effect will occur is determined.

3. Hazard identification which is investigated to determine whether a particular hazard has a corresponding health effect
4. Risk characteristics, which describes the magnitude and nature including uncertainties surrounding that risk [NRC, 1983]. It is the last component of risk characterization that integrates the results of the previous three components into risk model that includes one or more quantities estimates.

2.8.1 Radon Concentrations in Air

Concentrations of radon in the outdoor environment are affected not only by the magnitude of the exhalation rates in the general area but also by atmospheric mixing phenomena [Blaauboer et al., 1997]. Because lung cancer has been observed and studied extensively in miners exposed to radon-222, a conversion adopted by the ICRP for radon exposures that is based on equality of detriments from epidemiological determinations. As stated in ICRP publication 65, a conversion from radon exposure to effective dose was obtained by a direct comparison of the detriment associated with a unit effective dose and a unit radon exposure. The detriment per unit effective dose for the general public is 7.3×10^{-5} per mSv. This is based mainly on studies of A-bomb survivors [ICRP, 1993]. The detriment per units exposure to radon progeny is 8.0×10^{-5} per m J h m^{-3}(1mJ h m^{-3} =0.282 WLM, where WLM is the exposure unit of Working Level Month commonly used in workplaces) [ICRP, 1993]. An exposure to radon progeny of 1 mJ h m^{-3} in terms of detriment is equivalent to an effective dose of 1.10 mSv for members of the public. ($8.0\times10^{-5}/ 7.3\times10^{-5}= 1.10$)

Direct measurement of the concentrations of all short-lived decay products of Rn-222 and Rn-220 are difficult and limited. They are estimated from consideration of equilibrium or disequilibrium between these nuclides and their respective decay products. An equilibrium factor, F, is defined such that it permits the exposure to be estimated in terms of the potential alpha energy concentration (PAEC) from the measurement of radon gas concentration. This equilibrium factor is defined as the ration of the actual PAEC to the PAEC that would prevail if all the decay products in each series were in equilibrium with the parent radon. However, it is simpler to evaluate this factor in terms of an equilibrium equivalent radon concentration, $C_{eq,}$ as follows:

$$F= C_{eq} /C_m \tag{2.1}$$

$$C_{eq} = 0.105\ C_1 + 0.515\ C_2 + 0.380\ C_3 \tag{2.2}$$

$$C_{eq} = 0.913\ C_1 + 0.087\ C_2 \tag{2.3}$$

Where, the symbols $C_{1,}$ C_2 and C_3 are the activity concentrations of the decay progeny, namely $^{218}P_{O,}$ ^{214}Pb and ^{214}Bi respectively, for the radon-222 series, and ^{212}Pb and ^{212}Bi (C_1 and C_2) for the thoron series. The constants are fractional contributions of each decay product to the total potential alpha energy from the decay of unit activity of the gas. The equilibrium equivalent radon concentration is directly proportional to the Potential Alpha Energy Concentration (PAEC) as follows:

1 $Bq.m^{-3}$ (EEC) = $5.56\times10^{-6}mJ.m^{-3}$ (PAEC) = 0.27mWL (Working Level).

In the UNSCEAR (2000) Report, a value of 9.0×10^{-6} $mSv.h^{-1}$ per $Bq.m^{-3}$ was used for the conversion factor, 0.4 for the equilibrium factor of Rn-222 indoors and 0.8 for the indoor occupancy factor. Hence, the annual equivalent dose indoors in units of $mSv.y^{-1}$, H_E, is calculated as:

$$H_E\ (mSv.y^{-1}) = C_{Rn}\ F.T.D \tag{2.4}$$

Where, C_{Rn} is the measured Rn-222 concentration in $Bq.m^{-3}$, F is the Rn-222 equilibrium factor indoors (0.4), T is the indoor occupancy time (0.8×24 h×356 =7000 $h.y^{-1}$) and D is the dose conversion factor ($9.0 \times 10^{-6} mSv.h^{-1}$ per $Bq.m^{-3}$).

2.8.2 Radon concentration in water

Radon is soluble in water, its solubility decreases rapidly with an increase in temperature (510 cm^3/kg, $230 cm^3/kg$ and $169 cm^3/kg$ at 0℃, 20℃ and 30℃, respectively (NCRP Report No. 97). Radon is extremely volatile and is readily released from water. Drinking water contaminated by radon may increase ones chance of developing stomach cancer [Mays et al., 1985]

Radon gas rise generally from where it is trapped at high pressure under a home, into the lowest level of the home. It can also enter homes through well water. The radon gas can be released from the water into the air as one takes the bath or use it for other house hold task like laundry or dish washing. When you take a shower with water that seeps through granite rock or granite sands, it can have dissolved radon gas in it. The radon gas in the water can become dispersed in the air and you may breathe it in. Most of the time, there will not be enough radon in the water to cause health problems, but if the radon concentration is great enough, it could be a course of concern.

2.8.3 Dose Equivalent to the Lung due to Inhalation of Radon Gas

The annual dose equivalent in soft tissues other than the lung is given by:

$$H_{\text{soft tissues}} (Sv) = 0.9 \times 10^{-10} C_{Rn,\, air} (Bqm^{3}) \qquad (2.5)$$

Where, $C_{Rn,\ air}$ is the concentration of radon in the air where the inhalation occurs. In the case of lungs, the radon content of the lung air has also to be taken into account,

$$H_{lung}\,(Sv) = 8\times10^{-10}C_{Rn,\ air}\,(Bqm^{3}) \tag{2.6}$$

Applying the weighting factor of 0.12 for the lungs and of 0.88 for the other tissues, the annual effective dose equivalent rate is given by

$$H_{E}\,(Sv) = 1.77\times10^{-10}C_{Rn,\ air}\,(Bqm^{3}) \tag{2.7}$$

2.9 Measurement Techniques and Detection of Radon Gas

The assessment and control of radiation exposure to the general public is obtained by quantitative measurements of radon and its daughter products concentration. Measurement techniques can be divided into three broad categories: Grab Sampling, Continuous and Active Sampling and Integrated Sampling. Selection between these categories depends on time over which an instrument can be devoted to the measurements, the kind of information required, the cost involved and the desired accuracy with which measurements can be related to an estimate of risk [CEC, 1990].

Grab Sampling method is used in industrial monitoring since it provides instantaneous measure of radon and its progeny in air. The Grab approach is best useful when first screening purposes or for spot- checking of the efficacy of remedial actions. In the determination of average indoor radon air concentrations, it is limitedly used since values fluctuate widely depend on various factors. Grab sampling or short-term integrating sampling of a few days are considered inadequate for making accurate estimates of long term exposure of occupants of a building to radon.

Continuous sampling and Active Sampling involves multiple measurements at closely spaced time intervals for long period. It gives information on the time dependence of the airborne activities in a building. The results is a series of measurements which can give information on the pattern with which the concentration varied throughout the measurement interval. It is recommended when other measures indicate a problem and the source of radon entry needs to be pinpointed exactly since it is costly.

Integrating Sampling uses device which yield a single determination of airborne activity averaged over some chosen period from few days to a year or longer. The results from integrating devices which are passive is an estimate of the approximate average concentration through the environment interval exclusively carried out with inexpensive passive detectors. It is the preferred approach in survey work. 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. The recommendations of the Commission of the European Communities (CEC) of February 1990 stress the need and desirability of making long-term(generally one year) integrating measurements in order to determine if indoor air is above or below the appropriate radon reference or actions levels [CEC, 1990]. The method and choice used for measurement depends on the particular information required, the type of radon survey and cost of apparatus involved [Seitz, 1949].

2.9.1 Monitoring of Radon in Homes

Radon is easy to find yet it cannot be seen in our homes. Testing of radon in homes is easy and only takes few days to months and this depends on the kind of test. Short-term testing and long-term testing are the two main ways to test for radon in homes.

2.9.1.1 Short- Term Testing

This is the fastest or quickest way to test for radon in homes. For this type of test remain in homes for two to 90 days, depending on the type of device used. Charcoal canister, electrets ion chamber, charcoal liquid scintillation, Alpha track detectors and continuous monitors are some of the detectors used for short-term indoor radon testing. According to USEPA (1987, 1992) and White et al. (1994), the results of short-term measurements cannot be used to accurately estimate the long-term average value.

2.9.1.2 Long-term Testing

This type of test remains in homes for a year or some months, in other words more than 90 days. These measurements give the best estimates of the average value. In particular the one-year is the most appropriate, except in cases in which the dwelling is not lived in for a long period of the year. Some of the detectors that are used for long term-testing are electrets ion chamber and Alpha track detectors. This study considers short- term measurements of three (3) months due to time constraint.

2.9.2 Measurements of Radon in Air

One of the earliest methods for measuring radon concentrations in air is the scintillation cell, which is used as a grab sample. The inside wall of the cell is coated with zinc sulphide (ZnS), except one end which is covered with a transparent window for coupling to a photomultiplier tube. A flash of light is emitted from the ZnS coating when an alpha particle strikes the wall of the cell. The light is translated into an electrical signal when it is being detected by the photomultiplier tube. The background rates are low in a typical Lucas cell and it is about 0.1 or 0.2 counts per minute (cpm) and has an efficiency of 70% to 80%.

The two-filter method is also another method used in measurement of radon and its daughter concentrations. In this method, air is passed through the first filter where daughter products are removed. Then the air is passed through a long decay chamber, where daughter products are allowed to grow in and are collected on a second filter. The filters can be counted separately to determine the concentration of radon.

Another way by which alpha particles from the decay of radon and its daughters can also be detected is by the use of ionization chambers. Ionization counters can be used either to count electrical pulses from individual decay events or to measure currents resulting from the integrated effects of all decays. Ionization chamber is not widely used as scintillation counters since it is more expensive to construct than Lucas cells and for measurements of radon, they do not appear to have a major advantage over Lucas cells.

2.9.3 Residential Testing Devices

Different measurement techniques have been developed to determine the radon concentration in air. These include thermoluminiscent detectors (TLDs) [George and Breslin, 1977], solid state nuclear track detectors [Urban et al., 1985], electrets detectors [Kotrappa et al., 1988] and devices based on the absorption of radon gas by activated charcoal [Cohen and Cohen, 1983].

2.9.3.1 Electret Ion Chamber

A passive device that functions as integrating detectors for measuring the average radon gas concentration during the measurement period is an electrets- ion chamber (EICs). The electrets serves both as the source of an electric field and as a sensor in the ion chamber. Radon gas enter the chamber by passive diffusion through a filtered inlet. Inside the chamber, radiation emitted by radon and its decay products ionizes the air within the chamber volume. The positive electrets located at the bottom of the chamber collects the negative ions. The radon concentration is related to the discharge of the electrets over a known time interval. The electrets discharge in volts is measured using a non-contact battery operated electrets reader. This value, in conjunction with a duration and calibration factor, yields the radon concentration in desired units.

2.9.3.2 Activated Charcoal Detectors

A passive device deployed for one to seven (1-7) days to measure indoor radon is the activated charcoal detectors (ATDs). The detection principle is radon adsorption on the active sites of the activated carbon. The detector is sealed after sampling and the radon decay products equilibrate with collected radon. The collectors can be directly counted with gamma or analytically prepared for liquid scintillation counting techniques after a three (3) hour waiting period. With the alpha counting method, 20ml liquid scintillation vials containing 2-3 g of activated carbon are used. While with gamma counting method, the charcoal canisters contain 25-90 g of activated carbon. The canisters can be equipped with a diffusion barrier to extend the measurement period to seven (7) days.

2.9.3.3 Solid State Nuclear Track Detectors and their Advantages.

A Solid State Nuclear Track Detector also known as Alpha Track Detector (ATDs) is a small piece of specially produced plastic substrate enclosed within a filter-covered diffusion chamber that excludes the entry of radon decay products. The plastic is usually a cellulose nitrate (LR-

115), polyallyldiglycol carbonate (PADC or CR-39) or polycarbonate (Makrofol) material. Chemical or electro-chemical etching of the plastic detector material enlarges the size of the alpha tracks, making them observable by light microscopy so that they can be counted by an automated counting device or manually. The number of tracks per unit surface area, after subtracting background counts, is directly proportional to the integrated radon concentration in Bqh.m^{-3}. A conversion factor obtained by controlled exposures at a calibration facility allows conversion from track density to radon concentration.

The Solid State Nuclear Track Detectors (SSNTDs) have become important tools in every investigation regarding the presence of radon gas. SSNTDs [Fleischer et al., 1975] are insulating solids both naturally occurring and man-made. There are several types of these detectors including inorganic crystals, glasses and plastics. When a heavily ionising charged particle passes through such insulating solids, it leaves a narrow trail of damage along its path. This is called' Latent Track' as it cannot be seen with the naked eye. In addition, they may be revealed and become visible under an ordinary optical microscope when treated with a properly chosen chemical reagent.

The medium of detection often used in the field of Solid State Nuclear Track Detectors application fall into two categories namely polymeric or plastic detectors and natural mineral crystals. The second category of detectors which is natural mineral crystals and glasses that have, imprinted within them, a record of their radiation history over the years can be applied in fields such as geology, planetary sciences as well as oil exploration. Some of these minerals e.g. sheets of mica can be used as custom-made detectors of heavy-ion or induced-fission bombardment. They can be used for instance inside reactor cores since they do not record neutron-recoils and can withstand high temperatures and gamma-ray exposures.

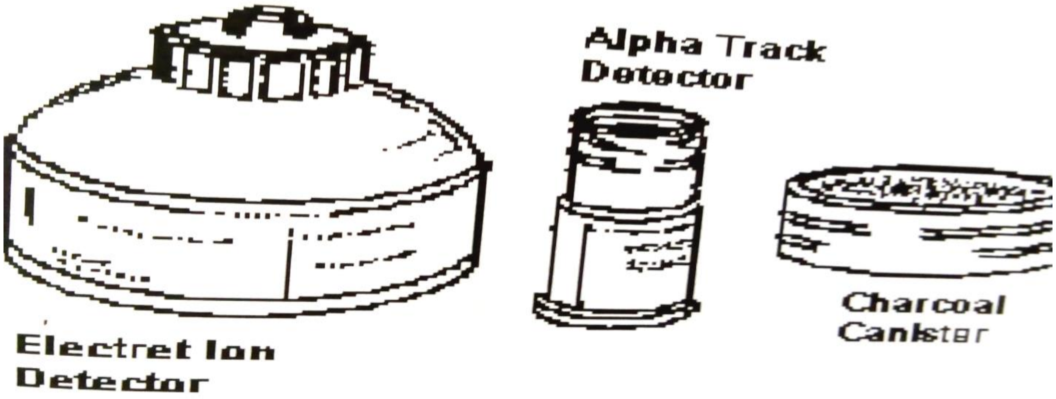

Figure 2.4: Different types of detectors used for radon monitoring

The other category is the use of polymeric or plastic detectors. These are most widely used not only for radiation monitoring and measurements, e.g. in health physics or radiation protection, or in environmental research and applications such as measuring of radon levels in dwellings or on the field, but can also be used in many other fields involving nuclear physics and radioactivity. A CR-39 is one of the commonly used nuclear track detectors discovered by Cartwright et al. (1978). It is based on polyallyldiglycol carbonate. Cellulose nitrate is also another commonly used nuclear track material. Makrofol detector which is based on polycarbonate is also another kind of detectors used. Apatite, olivine, mica etc. are some natural materials which show the track effect and are used for fission or fossil track studies.

Solid State Nuclear Track Detectors are very sensitive, are not fogged by exposure to light or is affected by moderate degree of heating and poses no great handling problems. It is durable and simple, and particularly valuable for remote use, such as in high altitude balloon exposure to cosmic rays. Their robustness enables them to be used in personnel dosimetry.

Basic simplicity of its methodology the low cost of its materials is the reason for its widespread use. Other important factors include the small geometry of the detectors, and their ability in certain cases to preserve their track record for almost infinite lengths of time.

2.9.3.4 Applications of Solid State Nuclear Track Detectors (SSNTDs)

There are many applications found by solid-state nuclear track detectors in various fields of physics and other branches of science particularly in nuclear science and technology. Some other application apart from measurements of indoor radon and its progeny concentrations include geophysics and radiography.

Radon measurements are one of the widely used applications of SSNTDs today which is predominantly existing in all rocks. Granites, dark shales, volcanic rocks, sedimentary and metamorphic rocks are examples of rocks which contain uranium. Other factors which affect indoor radon levels are radon in groundwater, soil and outdoor air.

2.9.3.5 Applications related to radon measurements

1. Volcanic studies: The radon flux increases before volcanic eruption

2. Radon emanation and exhalation from soil and building materials: This is useful to classify building materials and soils as radon sources

3. Measurements of radon in tap water, natural water and soil: This measurement is useful in uranium and thorium prospecting. Knowledge of radon levels in soil is important for classifying different areas for construction purposes and for planning of new buildings.

4. Radon monitoring in mines and other underground places: This is useful for radiological protection of miners, as well as in epidemiological studies involving miners.

5. Earthquake predictions: Concentrations of radon in underground water and deep wells have been observed to increase significantly before earthquake.

2.9.3.6 Other applications other than radon measurements

1. Biology and medicine: Novel application of track detectors have been found in the investigation of the effects of alpha particles on living cells which are cultured on the detectors themselves.

2. For identification of products from some reactions in high and low energy physics

3. Fission track dating. Spontaneous fission of U-238 occurs with a small probability. As the number of tracks grows with the age of the minerals, the latter can be determined based on the known U-238 concentrations.

4. After collision of a neutron with a proton in the detector material, a recoil proton is formed which may leave latent track in the detector. This is the basis for neutron measurements with the track detectors.

5. Neutrinos are neutral particle with very small mass created in beta decays, and are very difficult to detect. The solar neutrinos and other neutrinos are readily measured by a stack of large detectors.

2.10 Etching Mechanisms of the Track Detectors

The process of subjecting the exposed detectors to a polymer degrader rather than solvent (etchant) for latent track to be visible under optical microscope is etching. Etching rate is the speed at which the dissolved plastic material is removed from the remaining plastic sheet. For a track detector there are two kinds of etching rate. They are bulk or material etching rate V_B (μmh^{-1}) for the undamaged material and the track etching rate V_T (μmh^{-1}) at which the etching solution proceeds along the latent track. If the rate of etching along the track $V_{T,}$ exceeds the rate at which the surface is etched, V_B then the track will obviously be enlarged by etching. The track etching rate depends strongly on the energy loss of ion. Chemical etching and electrochemical etching are the two forms of etching.

2.10.1 Chemical Etching

Chemical etching is usually done in a thermostatically controlled bath. Aqueous solution of sodium hydroxide (NaOH) or potassium hydroxide (KOH) with concentrations ranging from a molarity of 1-12 (~ 6 M being used frequently) is frequently used etchant for plastics. The temperature usually used ranges from ~ 40°C to 70 °C. Sometimes ethyl alcohol is added to the etchant to increase sensitivity and speeding of etching. A large beaker is usually placed inside the temperature controlled bath, and it is this beaker which contains the etching solution. Several detectors that are to be etched simultaneously are suspended by means of strings or wires making sure that they do not touch each other. The beaker is covered to reduce evaporation. The detectors can be classified into two categories according to different properties of the etched tracks. They are thin detectors where majority of etched tracks are etched through holes and thick detectors where the residual foil thickness is greater than the etched-track depth [Enge, 1980; L' Annunziata, 1998; Kase et al, 1985].

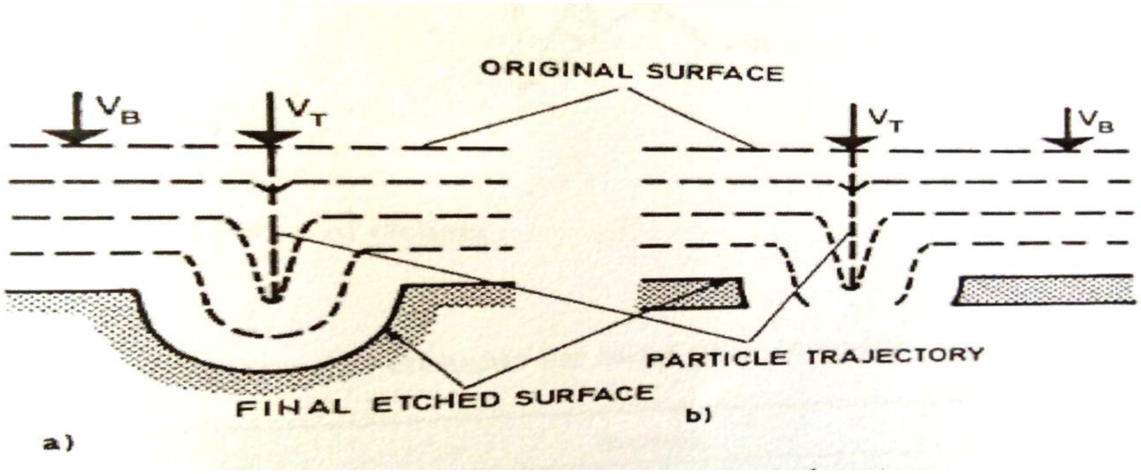

Figure 2.5: **Schematic diagram of thin and thick detector: (a) represents the thin detector, and (b) thick detector.**

2.10.2 Electrochemical Etching

This type of etching is helpful to enlarge the tracks to ease counting when the track density is not too high that is less than ~10^3 tracks cm^{-2}. It enlarges the chemically etched tracks a hundred fold or so. The principle of the ECE method is to apply a high frequency electric field across two component of an etching cell, (~ 30 -50 $KVcm^{-1}$) filled with a conducting etchable solution, e.g. NaOH, and separated by plastic detectors containing etchable tracks on its surface. After a period of chemical pre- etching, which produce sharp tipped tracks, the electric field at the tip builds up to a value equaling the breakdown limit of the dielectric medium. “Treeing” takes place giving rise to large Lichtenberg- type surrounding the track-tip. The stages that occur in Electrochemical Etching is represented in the figure below.

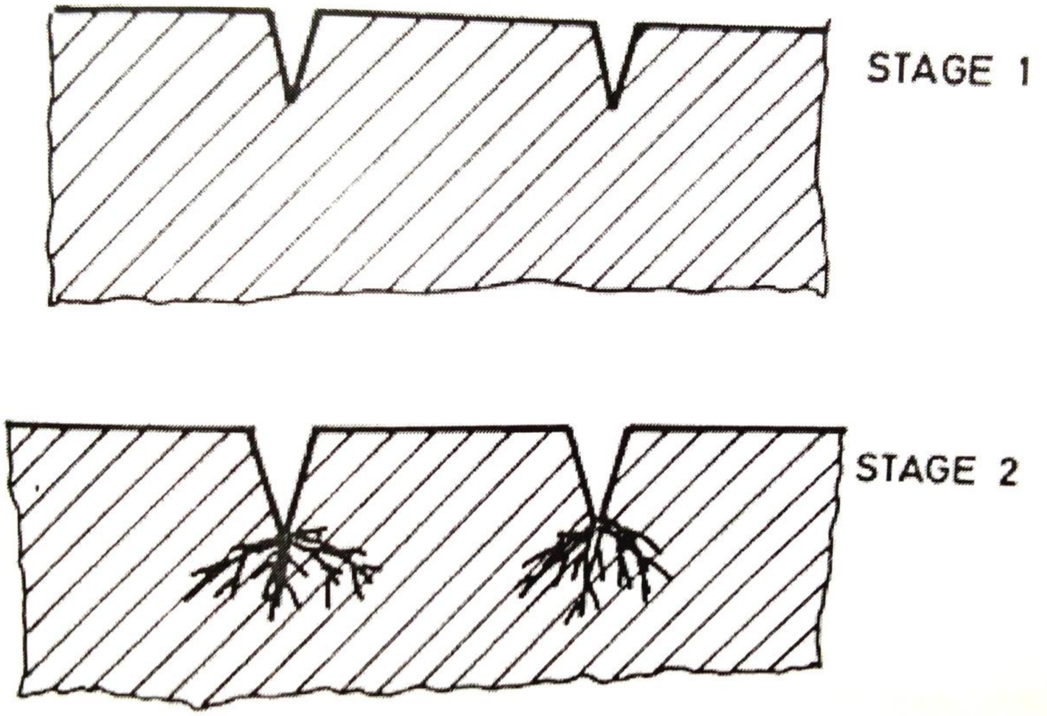

Figure 2.6: Stages in electrochemical etching

2.11 Evaluation and Track Counting

Various methods are used in evaluation of Solid State Nuclear Track Detectors for track diameter and track density. These include ocular or manual counting, spark counting and analysis with image analyzers, etc.

2.11.1 Ocular or manual counting

The easiest and most preferred counting tool is the ocular method. When proper magnification is used, the difference in refractive index between the track detector material and air gives subsurface track a high contrast. Tracks differ in shapes and size and this depends on the particle to be detected, the angle of entrance in relation to the detector surface, its energy, the etching conditions and the detector material. The objective mostly used for counting purposes are 20 or (25) X and 40 (45) X. The most common magnification for fission fragments track counting are 200 X and 400- X. Most track range in length from less than 1µm to perhaps 10 or 15µm therefore the microscope must have an overall magnification in the range of 100 X to 1000 X. Placing a glass disk with a scribed square, circle or other reference marking of a known image area in the microscopic eyepiece is the way to obtain the track density practically. The number of tracks within the pattern divided by the pattern area yields the track density. To reduce the statistical uncertainty for a particular measurement, a number of locations of fields on the sample may be counted. To attain accuracy, it is necessary to develop a consistent convention for treating tracks that touch or lay across the reticule border. Track size and orientation can also be obtained by an optical microscope other than track density. To reduce eye strain the image can be projected on a video monitor for easy counting [L'Annunziata, 1998; Eghang et al., 2007].

2.11.2 Spark counting technique

A semi-automatic device used to count low track densities (10^2- 10^3 cm) is a spark counter. Plastic detectors foil mainly LR-115 Type II containing etched through- holes produced by etching of the film exposed to alpha particles is placed on the electrode, and covered by another plastic foil ~ 100µm thick support backing, which is thinly aluminized on the lower face to offer a conducting path. The potential across the capacitor is raised when the switch is closed and a voltage is applied. Sparks jump through different holes in the detector foil in random sequence but only once per through-hole. The sparks are counted by scalar through a discriminator. The capacitor needs to be charged by the applied voltage to provide sufficient potential for the next spark after each spark. When a detector has been sparked counted, the replica tracks on the foil can be counted with ease using a low magnification optical system such as microfiche reader. This is necessary when the film is damaged. The counts obtained are used to calculate the track densities based on the area of the electrode used and finally the concentration of the heavily charged particles which interacts with solid state detectors is calculated (L'Annunziata, 1998)

2.11.3 Image analyzers

Many automatic systems for track evaluation are now on the market. The main components of such a system are an optical microscope equipped with auto focus and an X-Y moving stage, a personal computer, a CCD video camera and a digitizer. The image of the detector surface is obtained by conventional optical microscope and transmitted by the CCD camera to the computer.

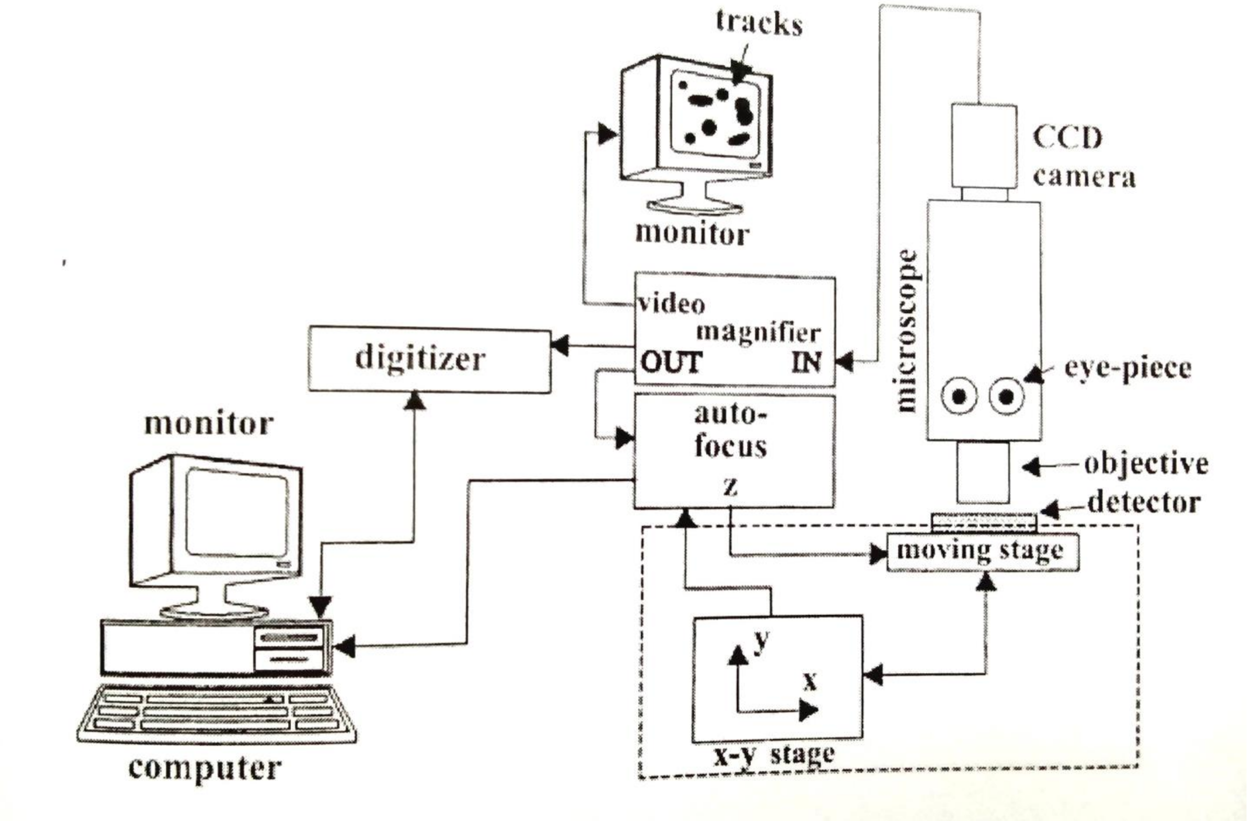

Figure 2.7: An automatic image analyzer for track counting and evaluation

Generally the principle used is that, as the video signal sweeps, a track or other objects results in change of signal level. The contrast of the object is related to the degree of change. The complexity of information processing unit and its ultimately reflected in a system cost depends on the amount of information obtained. The detector foil can be usually scanned at a rate of up to four frames per second. The X-Y stage is capable of moving over a large area in steps of about 1µm. In particular, a magnification of 0.5µm/pixel is used giving a resolution of 0.2µm by interpolation along a line of pixel. According to L'Annunziata (1998) automatic system are not only used for route in work but also contributing to the possibility of more advanced research work in fields such as high-energy heavy-ion interaction, exotic decays, cosmic ray and monopole investigations due to their speed.

2.12 Exposure Uncertainties

The exposure uncertainties are due not only to measurement techniques, but also to the method used to estimate personal exposure. Actually no "personal dosemeters" are used, but "environment measurements" and occupancy factors are utilized to obtain person exposure, especially for long periods of time. A tentative study to compare "personal monitoring" with "environmental monitoring" has recently been published [Litt et al., 1990], but it refers to an exposure of few days. The summary of uncertainties in exposure is as follows

Sampling location: Radon detectors are usually positioned in one room of the house, preferably in bedrooms where most time is spent. This introduces a bias in those cases where the radon concentration varies appreciably from room to room, as it could happen in multistory dwellings, where significant variations could exist between the ground and upper floors.

Occupancy factor: In practice, the occupancy factor is very difficult to measure. Personal judgment is often the only way for its estimation, especially in case of long periods. This factor differs among persons, as it is strictly linked with age, occupation, state of health, etc. Also, the occupancy factor could differ significantly during weekends and holidays. However, when averaged over the general population, it is relatively constant. It still depends on climate, being usually higher in cold climate countries. Most authorities for a first approximation assume an occupancy factor of 0.8, being made up of about 0.6 at home and 0.2 in other indoor situations [ICRP, 1993; UNSCEAR, 1993].

Retrospective assessment: In case–control epidemiological studies retrospective assessment of exposure is required in case-control epidemiological studies. Usually this assessment is made measuring at present the radon concentration in all dwellings used in the period under study. This procedure could introduce a high bias, that can be tentatively limited if a strict protocol for case and control selection is used. According to Samuelsson (1988), other experimental techniques for retrospective assessment of radon exposure based on the build-up of polonium-210 on glass surfaces in dwellings is under development. A similar approach is also now under development in which the buildup of ^{210}Po in porous materials (volume trap) in dwellings is measured as an aid to retrospective assessment of radon exposure.

Measurement period: One-year integrated measurements are usually performed to get good estimates of the mean radon concentration. The results however could differ from year to year, for instance due to strong climate changes. According to Martz et al. (1991), measurements carried out for 5 year period in 40 residences by the United States of America Department of Energy (DOE) Radon Laboratory of Colorado show a mean coefficient of variation of approximately 22%. Moreover, dosemeters continue to measure even when persons are not at home, and this could introduce a bias in case of significant difference in radon concentration with respect to the period of the day when persons are at home or at work.

Measurement technique: Alpha particles emitted by radon and its progeny produce tracks that are subsequently counted using passive track dosimeters. They are usually utilized for long-term measurements. The overall uncertainty measurement due both to reproducibility and calibration usually ranges from 10% to 30% (one standard deviation), depending on the actual radon concentration and other factors.

2.12.1 Basic Statistics

Uncertainty in measurements is the doubt that exists about the results of any measurements. There is always a margin of doubt in every measurement and due to that doubt, there is the need to ask how big is the margin and how bad the doubt. Error is the difference between the measured value and the true value of the quantity being measured whiles uncertainty is a quantification of the doubt about the measured results. Any error whose value is not known is a source of uncertainty. Uncertainty in measurements enable good quality measurements to be made and to understand the results obtained. It is also needed to know which decision to make. To reduce the risk of making mistakes in the work, one can check measurements a second or third time before proceeding.

2.12.1.1 Arithmetic Mean and Standard Deviation

To maximize the information one get from measurements, a number of readings and basic statistical calculations are needed. The two most important statistical parameters are the arithmetic mean or average and the standard deviation of the set of numbers or counts. Sometimes, it is enough to know the range between the highest and lowest value but for a small set of values, it may not give you useful information about the spread of readings. The usual way to quantify is by determining or calculating the standard deviation. It tells how different the individual readings are from the average of the set. Normally two thirds (2/3) of all readings will fall between ±1 standard deviation of the average and 95% of the readings will fall within two (2) standard deviation as a "rule of thumb". The process of calculating the mean (μ) and the standard deviation (S) for a series of measurements can be expressed mathematically as follows:

$$\bar{x} = \sum \frac{x_i}{N} \qquad (2.9)$$

$$S = \sqrt{\frac{\sum N(x-\bar{x})}{N}} \tag{2.10}$$

Many factors can undermine a measurement because real measurements are never made under perfect conditions, errors and uncertainty can come from the environments, measuring instruments, the item being measured, measurement process as well as operator error.

2.12.1.2 Measurement Uncertainty and Confidence Interval

To determine the uncertainty of a measurement, the source of uncertainty in the measurement and the estimation of the size of the uncertainty from each source must be identified. Uncertainty can be estimated using statistics usually from repeated readings or from other information from past experience of measurements, from calibration certificates, from calculations and from common sense [UKAS, 1997]. Standard uncertainty is the margin whose size can be thought of ±1 standard deviation (ie ± δ). It tells us about the uncertainty of an average. To calculate standard uncertainty using statistics, the mean and estimated standard deviation can be calculated from the set and the estimated standard uncertainty of the mean is calculated from the following expression:

$$\mu = \frac{S}{\sqrt{N}} \tag{2.11}$$

Where, N is the number of measurements in the set, S, is the standard deviation and μ is the mean.

In a series of repeated measurements of a quantity; A_1, A_2 …A_N, the combined uncertainty in the measured data, ΔA, is calculated as a function of the uncertainties in the individual quantities, i.e. ΔA_1, ΔA_2… ΔA_N, from statistics and for repeated measurements, and other information from calibration certificates and other factors involved in the measurements. Thus, the combined uncertainty is given by:

$$\Delta A = A\sqrt{\sum(\Delta A_i)^2} \tag{2.12}$$

Where, $(\Delta A_i)^2$ is the variance of the distribution (i = 1, 2,…,N), $\bar{A}$ is the mean of the measured quantity and ΔA is the combined uncertainty.

When the results of an experimental measurements is quoted, whatever the technique used, it is essential that it is accompanied by a realistic estimate of the uncertainty of the measurement (i.e. $X=\bar{A}\pm\Delta A$).

If reference is made to the Normal distribution of all possible results of the measurement then the uncertainty in the measurement must be related to the width of the distribution, P(x), with a mean value of μ, given by the following relation (See Figure 2.8):

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(\mu-x)^2}{2\sigma^2}\right] \tag{2.13}$$

Suppose a given measured quantity, A, is found to be valid, then the results may be quoted as a value with appropriate confidence limit represented by a statistical coverage factor, k standard deviations of A. The intention is to state that the average value, A, lies within a defined degree of confidence, i.e., between the upper limit and the lower limit; $A-k\sigma_N$ and $A+k\sigma_N$. In this case the factor for the two-tailed probability distribution should be used (see Table 2.1). For 95% confidence interval the results is represented by $A\pm1.96\sigma_N$. Often a more relaxed one standard deviation confidence limit is quoted. Table 2.3 shows the statistical coverage factor for various confidence intervals.

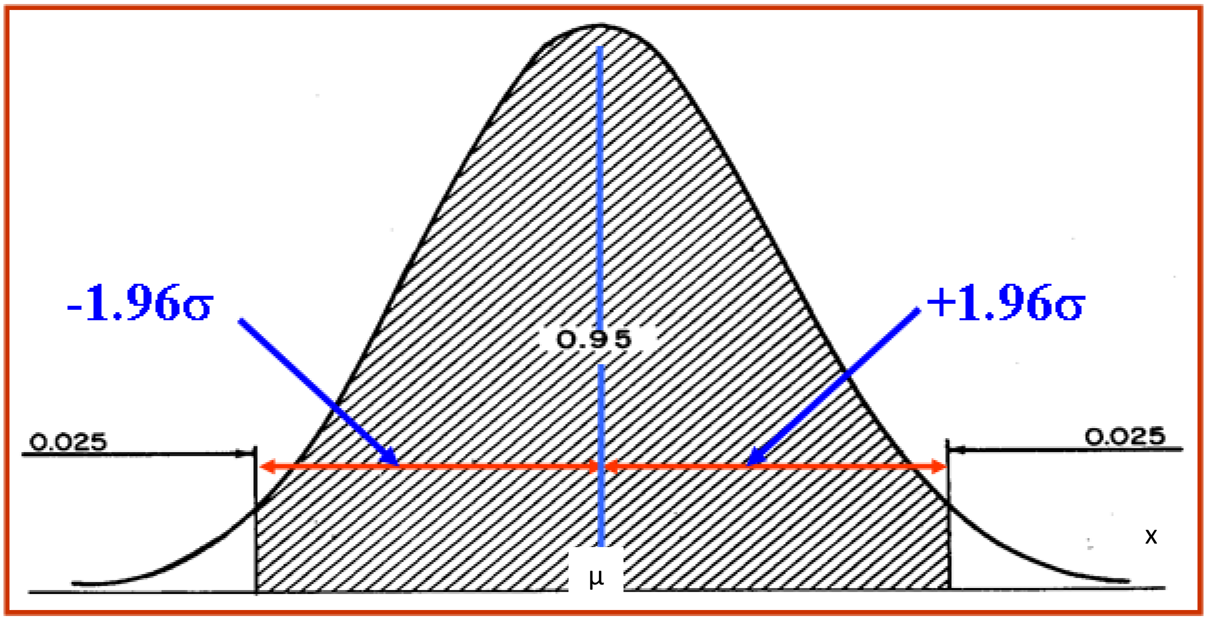

Figure 2.8: Two-Tailed Distribution at 95% Confidence Limit

Table 2.3: Statistical coverage factor for various confidence intervals

Confident Interval	Probability within region (%)	Probability outside region (%)	k-factor
μ±σ	68.3	31.0	1.0
	90.0	10.0	1.645
	95.0	5.0	1.96
μ±2σ	95.5	4.5	2.0
	98.0	2.0	2.326
	99.0	1.0	2.576

μ±3σ	99.9	0.1	3.0

2.13 Decision Analysis

A logical and systematic way to address a wide variety of problems involving decision-making in an uncertain environment is decision analysis. It is a systematic way of organizing and representing the various decisions and uncertainties that a decision-maker faces. As a decision-making process, decision analysis provides a step-by-step procedure that has proved practical in tackling even the most complex problems in an efficient and orderly way. One of the fundamental benefits of decision analysis is that it can distinguish good decisions from bad ones. Furthermore, it provides a criterion for establishing whether a decision is good or bad.

Decision analysis clearly lays out four elements of rational decision-making. The first element is information. An important component of this knowledge is an assessment of uncertainty or "What one *doesn't* know"). The second element is alternatives, (or "What courses of action are open to the person"). The third element is values, (or "What do the person want?"). Finally, there is logic, (or "How does one put knowledge, alternatives, and values together to arrive at a decision?").

Any decision analysis process is based on three main rules;

Consistency: The decision analysis process for similar kinds of problems and opportunities must be standardize to enable consistent decision making over time.

Comprehensiveness: Decision analysis processes should include a comprehensive assessment and analysis of the business situation. Missing information or incomplete information can lead to incorrect decisions.

Continuity: Decision analysis is a continuous process of making and refining decisions during a course of a project. The value of the analysis of the decision will significantly diminish if it is done only in discrete situations.

Decision analysis models are usually used in decision making processes. They are a general decision support methodology aimed at the classification of options that occur in decision making processes. They are important for analysis, simulations and explanation of options. Decision models are typically developed through decomposition of complex decision sub-problems. The results of the decomposition are a hierarchical structure that consists of attributes and utility functions. Such hierarchical decision models can be discovered from retrospective analysis of measured data [Bohance et al., 2000].

In general, a hierarchical decision model is composed of attributes Xi and utility functions Fi, as shown in Figure 2.9. The attributes, sometimes called the performance variables or parameters, are variables that represent the decision sub-problems. They are organized hierarchically so that the attributes that occur on higher levels depend on the lower levels.

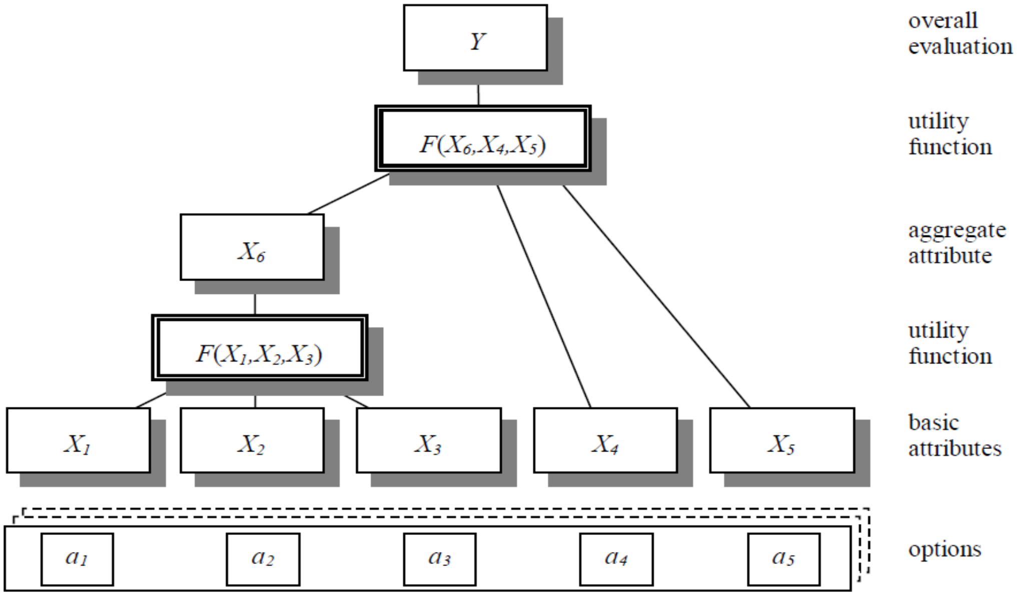

Figure 2.9: Components of a hierarchical decision model

In complex real-life situation, decision making problems of choice can be extremely challenging and difficult, mainly because of complex interrelated or even conflicting objectives. To support the decision maker, a decision model is designed to evaluate options. In practice, this approach has been most often used for technical or economic decision problems such as project or investment evaluations, portfolio management, strategic planning and personal management. Applications of qualitative hierarchical decision model are presented. In particular, the various knowledge representations and options analysis emphasize the importance for practical decision making process [Henschel and Scott, 1987; Prill et al, 1990, Turk et al, 1991; Bohance et al., 2000].

2.14 Radon Mitigation Strategies in Homes

Several radon control measures have been developed, tested and implemented in the United States [Henschel and Scott, 1983; Henschel, 1983; Prill et al., 1990] and long-term performance of these systems are reported [Turk et al., 1991]. These studies suggest that almost all homes can be remediated to below the recommended action level of 148 Bq.L^{-1} (4pCi.L^{-1}). Recommendations for radon remediation vary by country, with Sweden setting an action level of 370 Bq.L^{-1} (10 pCi.L^{-1}) and that of Canada is 740 Bq.L^{-1} (20 pCi), compared to U.S. level of 148 Bq.L^{-l} (4 pCi).

In certain countries the inclusion of protective measures in new buildings has become a routine process and it has become a mandatory procedure in the United States of America, Europe, Sweden and Canada. Most countries have adopted an indoor radon air concentration of 200-400 Bq/m^3 as a reference level above which mitigation measures should be taken [ICRP, 1993]. The

World Health Organisation released a comprehensive global initiative on radon that recommended a reference level of 100Bq.m^{-3} for indoor radon on 22 September, 2009 [WHO, 2009]. As a result, W H O advised that countries implements national programmes to reduce the population's risks for individuals exposed to high radon levels. A national reference level of 100Bq/m^{3} is recommended but should not exceed 300Bq/m^{3}.

Radon levels in homes can be reduced by the following:

- sealing floors and walls;
- installing a radon sump system in the basement;
- avoiding the passage of radon from the basement into living rooms;
- improving the ventilation of the house;
- installing a ventilation system or positive pressurization; and,
- increasing under-floor ventilation.

CHARPTER THREE

MATERIALS AND METHODS

This chapter looks at the materials and methods used in the assessment of radon in the selected homes at the Aburi Municipality. The uncertainties in the measurement of radon levels have been described and simple qualitative decision analysis method used to determine the type of remediation required. Pearson's rank correlation coefficient was also used to determine the relationship between the various variables involved in the measurements.

3.1 Materials

In this study, cellulose nitrate LR 115 Type II nuclear track detectors were used in the measurement of radon concentration. The detectors were manufactured by KODAK Pathe of France. Balplan microscope from Bausch and Lomp Scientific Optical Product division of the United States and Tally Counter made by Compass of Japan were used in counting the tracks created by the interaction of alpha particles from the decay of radon and progeny. A thermostatically controlled etching bath, volumetric flask and sodium hydroxide (NaOH) pellets from BDH Laboratory Supplies in England were used in processing the exposed detectors. Installation of the detectors in the selected homes was carried out with the aid of masking tape, glue and cardboard.

3.2 The Study Area

The present study is located in the southern part of Ghana and its north east of Accra, precisely Eastern Region of Ghana, in the Akwapim South municipality, Aburi constituency. Selection of Aburi for the study is based on the topography, geology, climate and ease of accessibility. Aburi area was also chosen because the houses there are representative of typical Ghanaian homes. The population of this town is about 18701[Ghana Statistical Service, 2013]. It is located at latitude 5^{o}84’802” North and longitude 0^{o}17’449” East. The average elevation of Aburi, Ghana is 289 meters and 1000 meters above sea level.

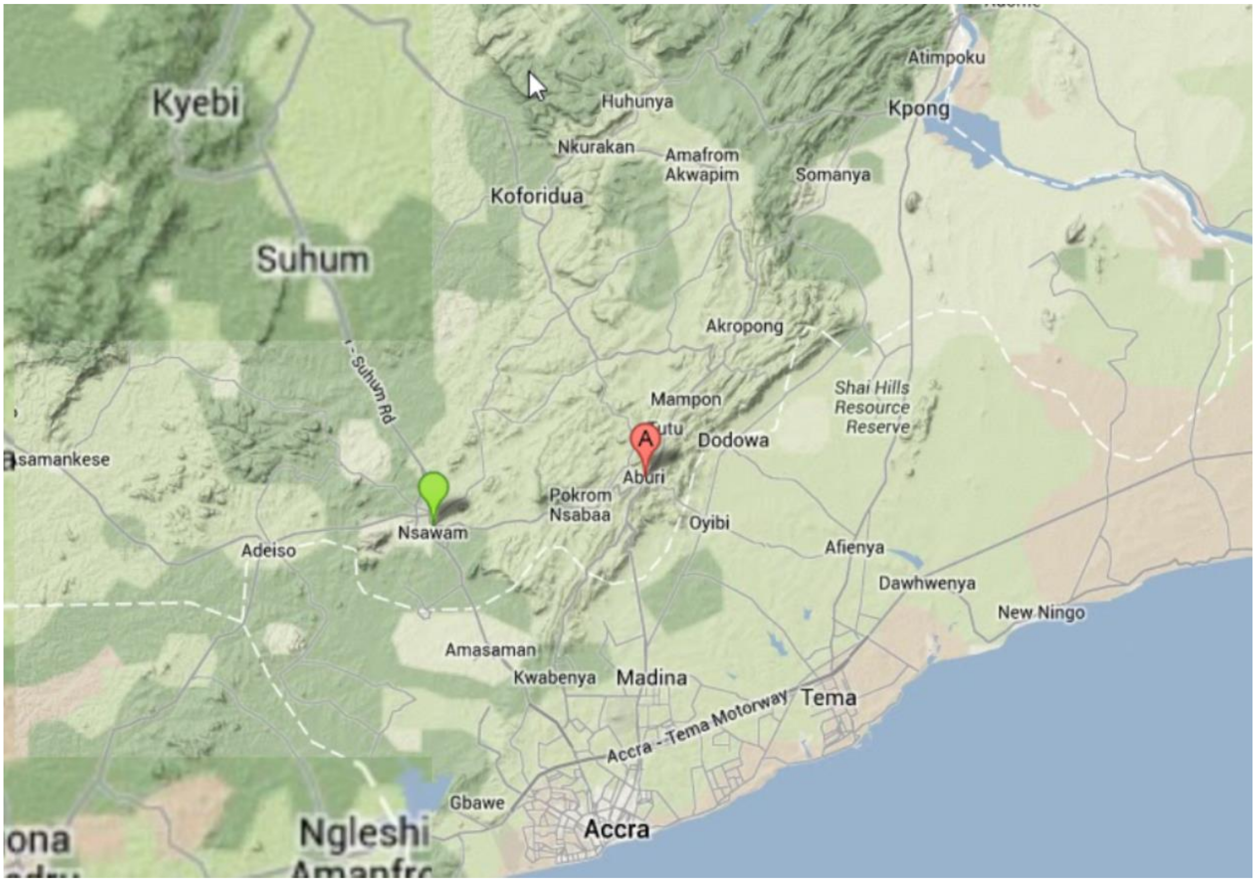

Fig 3.1 Map of the study area.

3.2.1 Geology of Aburi and Surrounding Area

The Precambrian Guinea Shield of West Africa is the geology in which Ghana falls. The main rock units existing in Ghana are the metamorphosed and folded Birimian, Tarkwanian, Dahomeyan Formation, the Togo Formation and the Buem Formations. About two-thirds of Ghana is dominated by Paleoproterozoic Birimian rocks consisting of five evenly spaced volcanic belts trending northeast-southwest. The intervening basins between the volcanic belts are filled by sediments. The remaining one-third is made up of post-Birimian rocks [Amedoful et al., 2008; Kesse., 1985]. Aburi- Akuapim is made up of the Togo and the Dahomeyan Formation shown in Fig1.1

3.2.2 Climate and Vegetation

Geographically, the district lies in the west semi- equatorial climate which experiences double maximum annual rainfall. It also lies in the savannah zone. Rainfall occurs in two raining seasons and the mean annual rainfall is about 800mm. The first season accounts for about 67% of the annual rainfall which begins in March and ends in mid -July. The second begins in August and ends in October [Nsawam Adoagire Municipal Assembly, 2006].

The most semi-Deciduous forest and the coastal savannah grassland are the two types of vegetation found in the Akwapim south district of which Aburi forms part. Sunshine duration for most part of the year averages 6.6hours per day. The south west monsoon and the dry northeast trade winds popularly known as Hammartan are the main winds that affect the study area with an average wind speed of 3m/s. Visibility is poor in the morning because of the tall trees. The mean temperature ranges between 24^{o}C and 30^{o}C in the day and 13^{o}C and 24^{o}C in the night.

Farming is the leading occupation of the people cultivating vegetables, tubers, cash crops such as pineapple and orange. Economic tree like timber is produced for export but due to uncontrolled felling of trees for the sawmill industry and the need for fuel wood, only a few trees are found concentrated on the ridge at present. In recent times, most part of the rich forest has been reduced to secondary forest through increased human activities.

3.2.3 Topography and Drainage

The Akwapim North Municipal Assembly is made up of densu plains, the pompan narrow land and the Akwapim Togo mountain range which rises over 1000 feet above sea- level at Aburi. The Densu River and its tributary rivers and streams drain through the Municipality. The Densu is approximately 115.8 km long and its source is the Atiwa mountain range near Kibi in the Eastern region.

The population of Aburi is 18701 [Ghana Statistical Service, 2013] and the main soil type is forest ochrosoil geological resources rock boulders.

3.2.4 The Togo Formation

The Togo Formation are rocks forming the Akwapim range of hills trending northeast wards from the coast West of Accra through Kpong, Anum into the Republic of Togo. Mostly found rocks in Togo are schists, quartzite and phyllites. Nevertheless, unaltered shale and sandstone are common in some places.

3.2.5 Type of Dwellings and Materials Used for Building

Cement, sand and stones are materials used for construction for the dwellings under study. Most of the houses in the study areas are sandcrete houses and are poorly ventilated. Each house has four to six rooms. Most of the ceilings in the houses are made of wood and roofed with corrugated sheets and are at a height of about 2.5m-4m from the ground. Cement, sand and stones were generally used as the construction materials for dwellings. Several of these materials are expected to contribute significantly as sources of indoor radon.round. The floor spaces of the room are approximately 4 x 3 m^2 with two windows and a door.

3.3 Methodology

The passive technique of using the Solid State Nuclear Track Detectors (SSNTDs) was utilized for the study of indoor radon level in dwellings of Aburi at the Akwapim South Municipality in the Eastern Region. Nuclear track detection technique based on LR-115(type II) detector was used during the study because of its simplicity and long term integrated read-out, high sensitivity to alpha particle radiation, ruggedness, availability, and in ease of handling and low-cost. The measured track density was then converted into radon concentration.

3.3.1 Sampling

The indoor radon concentration in the Aburi municipality was studied in thirty (30) homes in the present investigation. The houses were carefully selected using the random sampling method so that the operation and construction do not vary significantly. Each house has five to seven rooms. The ceilings of the houses are mostly made of wood and roofed with corrugated sheets that are at a height of about 2.5m -4m from the ground. The floor spaces of the rooms are approximately 4 × 3 m^2 with two windows and a door.

3.3.2 Measurement of Radon Concentration

The Solid States Nuclear Track Detectors which are sensitive to alpha particles emitted by radon were utilized in this investigation. Cellulose nitrate LR- 115 type II alpha particle detectors with a thickness of 13 µm on a 100 µm polycarbonate backing and produced by Kodak Pathé of France were used. The choice of LR-115 Type II alpha detector was preferred to the LR-115 Type I because the Type II can be stripped off its sensitive part and can be analyzed easily by a spark counter. The Type I detector can only be analyzed with a microscope which is tedious. The LR-115 Type II plastic track detectors each with a size of about (3.0 cm × 2.5cm) and fixed at the center of a specially designed cardboard measuring (11cm× 12cm) with the aid of a cellutape. It was fixed at the top of each dwellers bedroom inside a specially made envelope. The sensitive upper surface of the detector was freely exposed to the emergent radon so that it was capable of recording the alpha- particles resulting from the decay of radon in the room. In Aburi municipality, thirty (30) LR-115 Type II detectors were distributed inside the houses. In each house, at least two detectors were placed in different bedrooms at a height of about 3m above the floor with the help of a masking tape. The exposure time used for all houses was from December 2013 to March 2014.

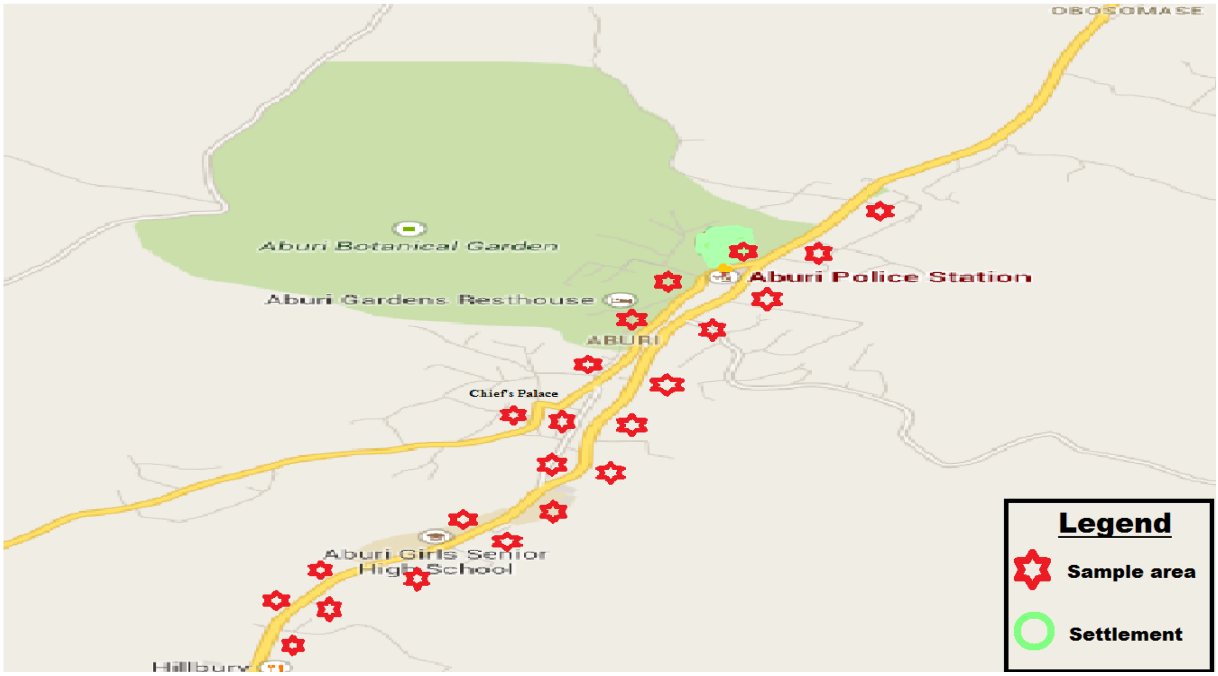

Fig 3.2 Map of study area showing sampling sites

3.3.3 Processing of the LR-115 Detector

A weighed 100 grams of sodium hydroxide pellets is put in a beaker with an electronic balance at the weighing room in the Chemistry Department, National Nuclear Research Institute (NNRI), Ghana Atomic Energy Commission (GAEC). The NaOH pellets are completely dissolved with about 100cm^3 of distilled water. The solution was transferred into a 1 Liter volumetric flask. The beaker was rinsed thoroughly and all the water that was used to rinse the beaker was added to the solution in the volumetric flask. The solution was topped up to 1 Liter mark with distilled water. The detectors were removed from the specially made envelope after three (3) months of exposure and subjected to chemical etching in the 2.5 M analytical grade sodium hydroxide (NaOH) solution at (60 ± 1) ^{o}C, for one and half hours in a constant temperature water bath to enlarge the latent tracks produced by alpha particles from the decay of radon. Beakers of different sizes contained the etched solution. The beakers were immersed in a bath containing water. The detectors were chemically etched by suspending them in the 2.5 M analytical grade NaOH solution at a temperature of (60 ± 1) °C and also hanged on copper. To reduce evaporation which may increase solute concentration, the beakers were covered with lids. The detectors were washed with running water after etching. After few minutes of drying in air, the detectors were ready for track counting.

3.3.4 Counting of the Track Densities and Calculation of Radon Concentration

The etched track detectors were sparked using a spark counter after drying. The detectors were pre- sparked at 1200 V and sparked at 700 V thrice. The replica sparks on the aluminized Mylar were counted using a microfiche reader and tally counter after sparking. The tracks were counted thrice for each detector and the average was calculated. The average number of tracks per unit area was taken from the mean of the individual number of tracks per unit area. The track densities determined on the analyzed detectors were converted into radon concentrations (Bqm^{-3}) using the calibration factor of 1 (track cm^{-2} Bq^{-1} m^{3} h^{-1}) for the Type II LR-115 bare detectors.

The track densities were determined using the following expression in equation (3.1):

Track Density (ρ) = Average number of Tracks / Area of electrode (3.1)

Concentration of indoor radon gas in Bqm^{-3} was calculated using the formula shown in equation (3.2):

$$\text{Concentration } (kBqm^{-3}) = C_{Rn} = \frac{\rho - \rho_b}{\varepsilon T\,(hrs)} \tag{3.2}$$

Where, ρ is the track density, ρ_b is the background track density, ε is the calibration factor ($Tracks.m^3/cm^2kBq.h$) of the LR-115 (Type II) and T (hrs) is the exposure time in hours.

Sample calculations

Average number of sparks (Exposed) = 861

Average number of sparks (Background) = 161

Diameter of electrode = 0.8 cm

Area of electrode = πr^2, Area of electrode = $3.142\times (0.4\ \text{cm})^2 = 0.5\ \text{cm}^2$

Calibration factor (ε) = 1 (Track.m^3 / cm^2kBq.h)

Track Density (Exposed) = 861/ 0.5 cm^2 = 1722 cm^{-2}

Track Density (Background) = 161/ 0.5 cm^2 =322 cm^{-2}

Track Density = 1722 cm^{-2} – 322 cm^{-2} = 1400cm^{-2}

Exposure Time (h) = 2160 hours

$$\text{Radon concentration } (kBqm^{-3}) = \frac{1400cm^{-2}}{1(Track.m^3/cm^2kBq.m^{-3}.h)\,x\,2208\,h}0.634\,kB.m^{-3}$$

Radon concentration ($kBqm^{-3}$) = 0.634 × 1000 = 634Bqm^{-3}

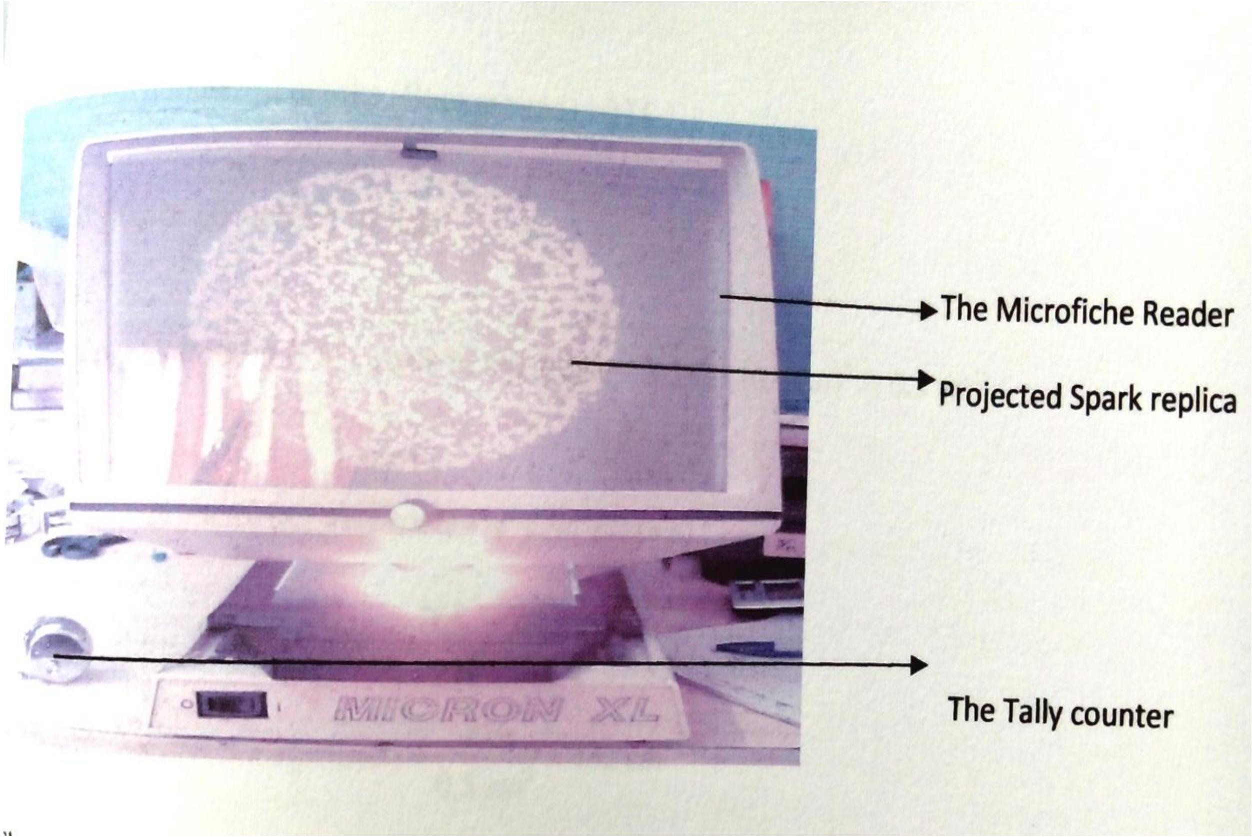

Figure 3.3: Spark counter used for the analysis of the track detectors

3.3.5 Determination of Indoor Annual Effective Dose

To determine the annual effective dose indoors, the conversion coefficient from absorbed dose in air to effective dose and the indoor occupancy factor was taken into account. According to UNSCEAR (2000) a value of 9.0×10^{-6} $\mathrm{mSvh^{-1}}$ per $\mathrm{Bq.m^{-3}}$ is used as the conversion factor, 0.4 for equilibrium factor of ^{222}Rn indoors and 0.8 for the indoor occupancy factor. The annual equivalent dose, H_{Rn}, is given by equation (3.3):

$$H_{Rn}\ (\mathrm{mSv.y^{-1}}) = C_{Rn}.\ D.F.T \qquad (3.3)$$

Where, F is the Rn-222 equilibrium factor indoors (0.4), T is the indoor occupancy time (0.8×24 h $\times 365 = 7008$ $\mathrm{h.y^{-1}}$), C_{Rn} is the measured ^{222}Rn concentration (in $\mathrm{Bq.m^{-3}}$) and D is the dose conversion factor (9.0×10^{-6} $\mathrm{mSv.h^{-1}}$ per $\mathrm{Bq.m^{-3}}$).

According to ICRP (991), to calculate the annual equivalent dose and effective dose, a tissue and radiation weighting factors needs to be applied. The radiation weighting factor (W_R) for alpha particles is 20. The ICRP recommended tissue weighting factor for lung is 0.12. To calculate the annual effective dose (E) the equation (3.4) below is used:

$$E\,(mSv.y^{-1}) = H_{Rn}.\,W_R\,.W_T \qquad (3.4)$$

Where, H_{Rn} is the Annual Equivalent Dose to the lungs, W_R is the Radiation Weighting Factor which is 20 for alpha particles, W_T is the Tissue Weighting Factor for the Lung (0.12).

In the temperate regions, people spend most of their time in open air and only go indoors to sleep at night. The occupancy factor of 0.4 is used for the annual radon dose calculation in this study since dwellers spend only about nine (9) hours indoors out of the 24 hours in a day, thus $9 / 24 = 0.375 \approx 0.4$

To determine the annual dose equivalent received by the lung due to inhalation of radon gas, the solubility factor for soft tissues 0.4, a quality factor for alpha particles, and assuming that the short lived daughter atoms produced decay in the tissue as a radon gas, the annual dose equivalent in tissue other than the lung is given by equation (3.5):

$$H_{soft\ tissue}\,(Sv) = 0.9 \times 10^{-10} C_{Rn,air}\,(Bqm^{-3}) \qquad (3.5)$$

Where, $C_{Rn,\,air}$ is the concentration of radon in the air where the inhalation occurs.

In the case of lungs, the radon content of the lung has to be taken into account, which results in the equation (3.6) below:

$$H_{lung}\,(Sv) = 8\times10^{-10} C_{Rn,\,air}\,(Bqm^{-3}) \qquad (3.6)$$

When a weighting factor of 0.12 is applied for the lungs and 0.88 for the other tissues, the annual equivalent dose is given by equation (3.7);

$$H_E(Sv) = 1.77 \times 10^{-10}\, C_{Rn,\,air}(Bqm^{-3}) \qquad (3.7)$$

In this work attempt was not made to calculate the dose and the risk but radon concentration was compared with reference levels set by the WHO.

3.3.6 Risk Assessment From Radon Exposure

Life time risk from exposure to indoor radon can be determined by calculating the whole body annual effective dose and applying radiation weighting factor (W_R) for alpha particles. An exposure time of 70 years can be used as well as a risk factor of 0.05 for fatal cancer, 0.01 for both non-fatal cancers and hereditary effect to whole body for stochastic effect. This is based on recent results from combined analysis of epidemiological studies of miners. A life time excess absolute risk of 5×10^{-4} per WLM (14×10^{-5}/ m J h / mm) is now used as the nominal probability coefficient for radon and radon progeny induced lung cancer replacing previous ICRP 65.

The life time cancer risk can be calculated as follows:

$$\text{Life time risk} = H_{RN} \times T \times R \qquad (38)$$

Where H_{RN} is Annual Equivalent Dose

T is the exposure time

R is the risk factor

3.3.7 Measurement Uncertainties

Several factors contribute to uncertainties in the measured data. These include variation in sampling, efficiency calibration, exposure time, errors in counting, etc. Within the time constraint of this study only short-term measurements were made. The combined uncertainty, ΔR, in the measurements is represented by equation (3.9):

$$\Delta R = R_C \sqrt{\sigma_N{}^2 + \sigma_\varepsilon{}^2 + \sigma_T{}^2} \tag{3.9}$$

Where, σ_ε^2 is the variance in the determination of the efficiency calibration (ε), σ_T^2 is the variance in the measurement of the counting time (T), σ_N^2 is the variance in the measurement of the track density, R_c is the average radon concentration and ΔR is the overall uncertainty in the measured radon concentration.

The, σ_i (i=1, 2, ……, N) is the standard deviation given by equation (3.10):

$$\sigma_i = S.D. = \sqrt{\frac{\sum N(x-\bar{x})^2}{\sum N}} \tag{3.10}$$

The value of the radon concentration was then quoted as R±ΔR at the 95% confidence interval.

3.3.8 Correlation Analysis between radon concentration and other measured variables

The correlation between temperature, pressure, humidity and rainfall, volume of each room and the concentration of radon were determined by plotting the values for the various parameters against radon concentration. This is because only few measurements were made in the short-term study. For relatively long-term studies Pearson's correlation function could be used to determine the relationship between the various parameters by determining the correlation coefficient. Pearson's correlation functions are illustrated in equations (3.11) and (3.12).

For a given population, correlation function (ρ) is given as:

$$\rho_{x,y} = \frac{\operatorname{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E\left[(X-\mu_X)(Y-\mu_Y)\right]}{\sigma_X \sigma_Y} \tag{3.11}$$

Where, cov is the covariance, σ_X is the standard deviation of X, μ_X is the mean of X, and E is the expectation value of X [David, 2009].

For a given sample or measurement, correlation function (r) is by equation (3.12):

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \tag{3.12}$$

Where, $\bar{X}$ and $\bar{Y}$ are sample mean of X and Y respectively.

Correlation is a measure of the linear dependence between two variables X and Y, giving a value between +1 and −1 inclusive, where 1 is perfect positive correlation, 0 is no correlation, and −1 is perfect negative correlation [David, 2009].

3.3.9 Decision Analysis and Remediation

The uncertainties associated with the measurements were evaluated and the necessary decision and remedial action suggested on the basis of WHO recommendation [WHO, 2009] and UNSCEAR guidelines [UNSCEAR, 1993; 2000]. Comparison of the results with recommended remedial action levels set by the WHO was used as a basis for simple qualitative decision making process to determine the remedial action.

Decision to remediate was represented mathematically by the following:

Let y_o (radon action level = Ract) be the point at which one chooses to remediate, and y the measured quantity, then the radon remediation will depend on the concentration level measured as follows:

(a) Remediate without monitoring; if $y>y_o$

(b) Do not remediate or do nothing; if $y<y_o$

(c) Remediate and monitor; from the normal distribution $\exp(y) > \exp(y_o)$

On the basis of the above relations, the houses were categorized into groups and decision taken as to remediate a particular group of house or not. Decision strategies considered and evaluation criteria were as follows:

1. Perform short-term measurements on all houses and remediate those for which the uncorrected measurement exceeds the action level. i.e. $R_{meas} > R_{action}$
2. Perform short-term measurements on all homes and then remediate those for which the bias corrected measurements exceeds the action level: $R_{meas}/b > R_{action}$, where b is a correction factor for long-term measurements and seasonal variation due to meteorological conditions.
3. Perform long-term measurements on all houses and then remediate those for which the measurement exceeds the action level: $R_{meas} > R_{action}$
4. Follow recommended strategy by monitoring homes with prior mean estimates above a given level and remediate those with high values.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Indoor Radon Concentrations

The present database includes more women than men. Majority of the study subjects are farmers. Eighty percent (80%) of the inhabitants used their rooms as both living and bedrooms and normally windows are closed in these dwellings because of low temperature. Figures 4.1 to 4.3 give summaries of the results of indoor radon concentration levels for each month measured in the 30 different houses in the Municipality. The average values are provided in Figure 4.4. The houses were selected at random situated at different areas, at least a half kilometer away from each other.

The survey indicates that the radon concentration obtained for the period varies from (23.72 to 92.24) Bqm^{-3} for the first month, (19.07 to 124.36) Bqm^{-3}for the second month and (31.63 to 123.87) Bqm^{-3} for the third month respectively, with the overall mean value 49.78±12.50 Bqm^{-3}. These values are within the action level of 200-600Bq.m^{-3} set by the ICRP (1993), but some homes may require some mitigation when compared with the WHO reference value of 100 Bq.m^{-3}

The lowest value for the indoor radon concentration was found to be 19.07Bqm^{-3}, whereas the highest concentration was found to be 124.36Bqm^{-3}. The highest value was recorded in house A26 for month 2 followed by A28 with average concentration of 104.54Bqm^{-3} for month 3. The high radon concentration levels in house A26 may be attributed to the poor ventilation, the type of building materials used, the age and dust accumulation in the room (which are usually considered as important sources of radon in buildings). The lowest value was found in house A8 with an indoor radon concentration of 19.07Bqm^{-3} for month 2, which is probably due to adequate ventilation. All the values obtained are below the ICRP action level and also within the reference level of 148 Bq.m^{-3} set by the USEPA for the USA [USEPA, 2004]. Comparison with the WHO recommended value of 100 Bq.m^{-3}[WHO, 2009] indicate higher average values for two of the rooms in house number A26 and A29 respectively. However, the mean value of 49.78 Bq.m^{-3} for the period is a little higher than the world average radon concentration of 40Bq.m^{-3} [UNSCEAR, 2000].

The indoor radon concentrations in the present study indicate that most of the rooms investigated had values which are significantly low. Only two rooms had concentrations values of about 20% above the recommended action level of 100Bqm^{-3} set by the WHO [WHO, 2009]. These houses are constructed mainly from the same skeletal building materials (sandcrete blocks, stones and Portland cement) and the finishing materials used are basically the same from room to room. Other factors which affected the low readings include the fact that the area is highly ventilated and thus the radon gas emitted is diluted and only small amount of radon may enter a room.

Since the aforementioned factors contributed to the low results for most of rooms investigated and only two rooms had concentrations values above 20% of the remedial action level, attention must be focused on these houses.

In Figure 4.6, comparison is made with work done in different parts of Ghana. It is observed that the value obtained in this study is less than the values obtained in published articles with the exception of Kwabenya which had a relatively smaller value. The low concentration recorded for the Aburi area may be attributed to geological, meteorological and other considerations such as the topography.

4.2. Comparison of radon concentrations with meteorological conditions and volumes of the rooms considered in the study

Figures 4.7 to 4.11 show comparison of the concentrations with meteorological parameters, namely; temperature, humidity, pressure and rainfall pattern, as well as the volumes of the rooms investigated.

Comparison of the radon concentration with the volumes of the rooms shows an inverse relationship. The bigger the room sizes the smaller the radon concentration (Figure 4.8). It was also observed that temperature has a significant influence on the radon concentration. The higher the temperature the higher the radon concentration (Figure 4.9). The temperature in the area is also usually low and does not allow easy outflow of the radon gas. Rainfall also has a significant influence in reducing the amount of radon gas ingress into the rooms as can be observed from Figure 4.7. Humidity and pressure show similar trend with the values decreasing with decreasing concentration and then increasing with increase in concentration as shown in Figures 4.10 and 4.11. The high humidity in the area may contribute to the low concentration by the soil pores closing and not allowing easy flow of the gas.

Further, the underlying rock formation in the area are mainly made of sedimentary type of rock which has low concentrations of the parent nuclide Ra(U). Furthermore, the area is at high altitude and the weather conditions are quite cold most times of the year. The radon gas may therefore be absorbed by water droplets in the atmosphere thus reducing the entry of the gas into the rooms from outside the rooms.

4.3 Estimation of Lung Doses and Risk Assesments

Indoor radon concentration was estimated using indirect methods for population lung cancer risk. Estimates of life time cancer risk to individual from radon were based on knowledge from miners experience. Table 4.2 and 4.3 shows the annual effective dose to the lungs and soft tissues as well as the estimated life time cancer risk in the municipality. For A8 an effective dose of 4.55×10^{-6} and a risk of 7.1932×10^{-5} and 1.4386×10^{-4} for fatal cancer, non -fatal cancer and hereditary effect respectively were recorded and 17.65×10^{-6} and a risk of 2.7922×10^{-4} for fatal cancer and 5.5843×10^{-5} for non- fatal cancer and hereditary effects respectively for A26. These results indicated that the lower the concentration, the lower the dose and risk and vice versa.

4.4 Measurement uncertainties

The mean concentrations, median values and the standard deviations are provided in Table 4.1. The percentage above or below the mean are also presented. The overall mean concentration of radon for all the participating houses is (49.87.36±12.50) Bq.m^{-3} in the range 25.69 – 99.72 Bq.m^{-3}. The average values is less than the WHO recommended action level of 100 Bq.m^{-3} even considering 3σ and therefore need not be of any concern. However, two of the rooms in houses A26 and A29 had values which are significant and need to be considered to determine whether they would need any remediation. Room number A29 had an average value of 91.45±9.6 Bq.m^{-3} in the range 89.88-92.24 Bq.m^{-3} with median value of 92.24 Bq.m^{-3}. The upper limit of this value is 91.45+9.6=101.84 Bq.m^{-3} which is within the recommended level set by the WHO. For the 95% and 99% confidence intervals, the values are above the level set by the WHO.

For A26 the average value is 99.72±10 Bq.m^{-3} in the 50.94-124.36 Bq.m^{-3}. This means that the average value for room A26 lies in the range 99.72-σ = 89.72 Bq.m^{-3} and 99.72+σ = 109.72

Bq.m^{-3}. The median value for A26 is 123.87 Bq.m^{-3}. For two standard deviations, i.e. 99.72.78±2σ, the minimum value would be 99.72-2σ which is below the action level. The upper limit of this value will be 99.72+2σ = 119.72 Bq.m^{-3}. For three standard deviations, i.e. the values is 99.72±3σ, the minimum value is 99.72-3σ = 69.72 Bq.m^{-3}, which is below the action level and the maximum value is 99.72+3σ = 129.72 Bq.m^{-3}. The maximum values for house A29 and A26 have values which are significantly above the recommended level in the 99.9% confidence interval. This means that there is still some risk of exposure to radon. Therefore attention should be focused on these houses to determine whether they warrant any action.

The median value for A29 is less than the recommended level whiles that of A26 is about 30% above the recommended level. This means that attention should be focused more on A26 than that of A29

4.5 Decision process

The levels of radon measured are associated with decision making process whether to remediate in order to reduce the risk or do nothing. The decision could be made by the individual occupying a room or at the household level and would require estimate of the cancer risk from radon. In case there is the need to remediate then the cost of remediation would have to be taken into consideration.

The cost of remediation could be determined for those houses (A26 and A29) with levels above the recommended action levels depending on the level of risk. The essence of radon remediation is a tradeoff between the costs in monetary terms and lives. Once a decision has been taken to remediate, the cost of remediation can be calculated. The cost of remediation can be evaluated by setting up a decision tree with three branches. In each branch, the expected loss in monetary terms can be evaluated. The radon equivalent dose can be converted into the equivalent cost per Bq.L^{-1} for additional home remediation. For any given household, the equivalent cost per Bq.L^{-1} can be computed as a function of the risk and the individual parameters and the cost of reduction in the probability from cancer death.

The decision to apply appropriate remedial action in order to reduce radon levels to the recommended action level was based on appropriate analysis of the situation and taking relatively inexpensive methods due to the fact that the levels for the two rooms (A26 and A29) are not significantly above the action levels within the measurement uncertainties determined. Based on the decision and remediation strategies to be adopted, recommendations are given as to whether to remediate or not to remediate.

4.6 Remedial Actions

A conservative comparison was made between the results and the WHO standard, and it was observed that two of the houses A26 and A29 had values above the recommended remedial action level of 100Bq.m^{-3} for long term remediation [WHO, 2009]. Within the time constraint of the study, only short-term measurements were made as compared to long-term measurements applied in the case of the WHO.

On the basis of the risks assessment, the houses can be partitioned into groups, i.e. those requiring remediation and those that do not need any remediation. The remedial action needed could be determined according to whether they fall into any of the following categories:

- Radon levels<action levels-no action needed

- Radon levels>action levels-remedial actions
- Radon levels still high after remedial actions-radiation protection program needed.

Judging from the rather low values of radon, it is clear that there is no need for remediation in almost all the rooms with the exception of room A26 and perhaps A29, which may require a relatively inexpensive mitigation action by improving ventilation in the room.

From the study, the type of remediation required is simply increasing the size of the windows or opening of the windows during both day and night in order to increase air circulation, while at the same time providing for security.

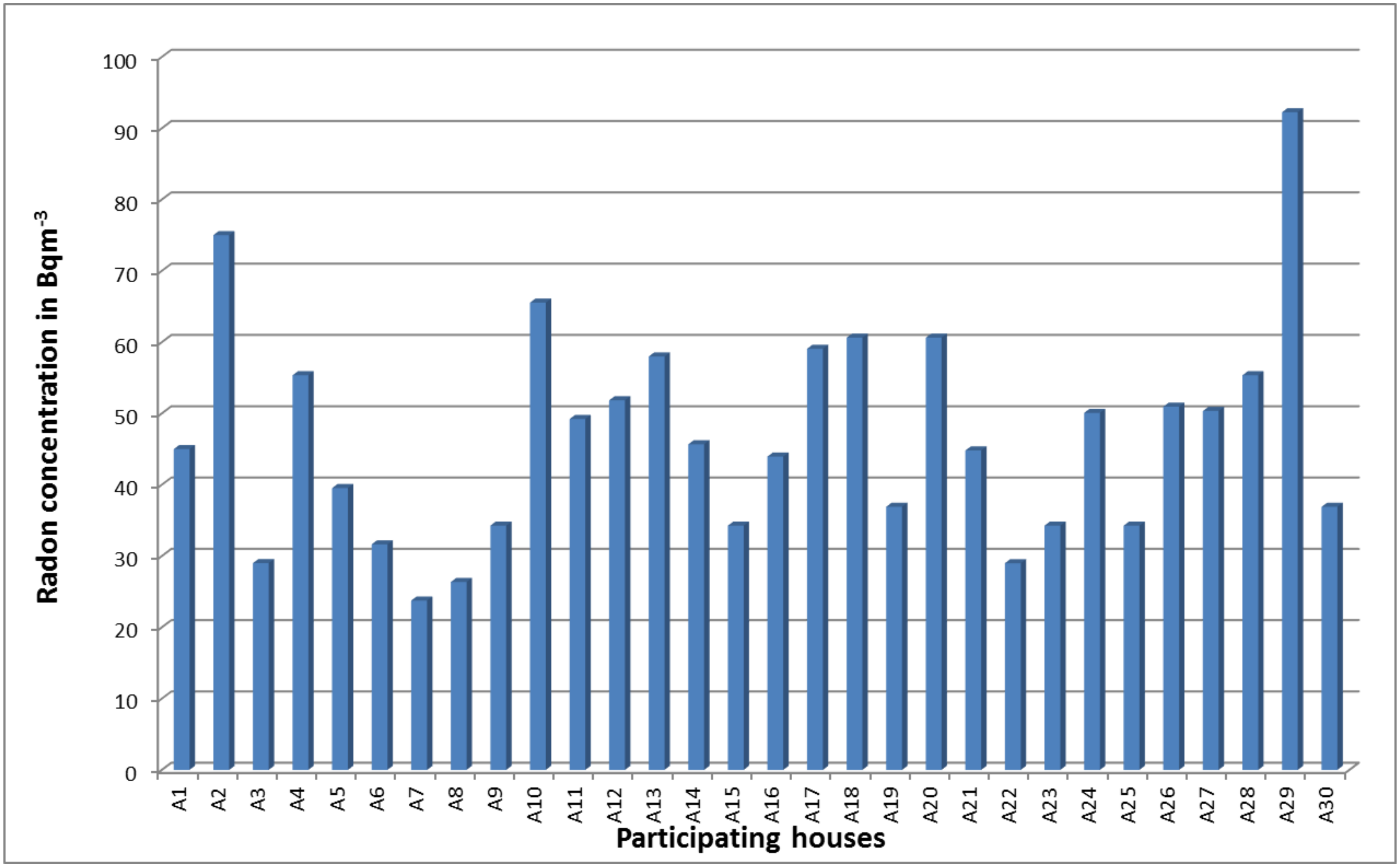

Figure 4.1 Participating Houses and the corresponding radon concentration for month one

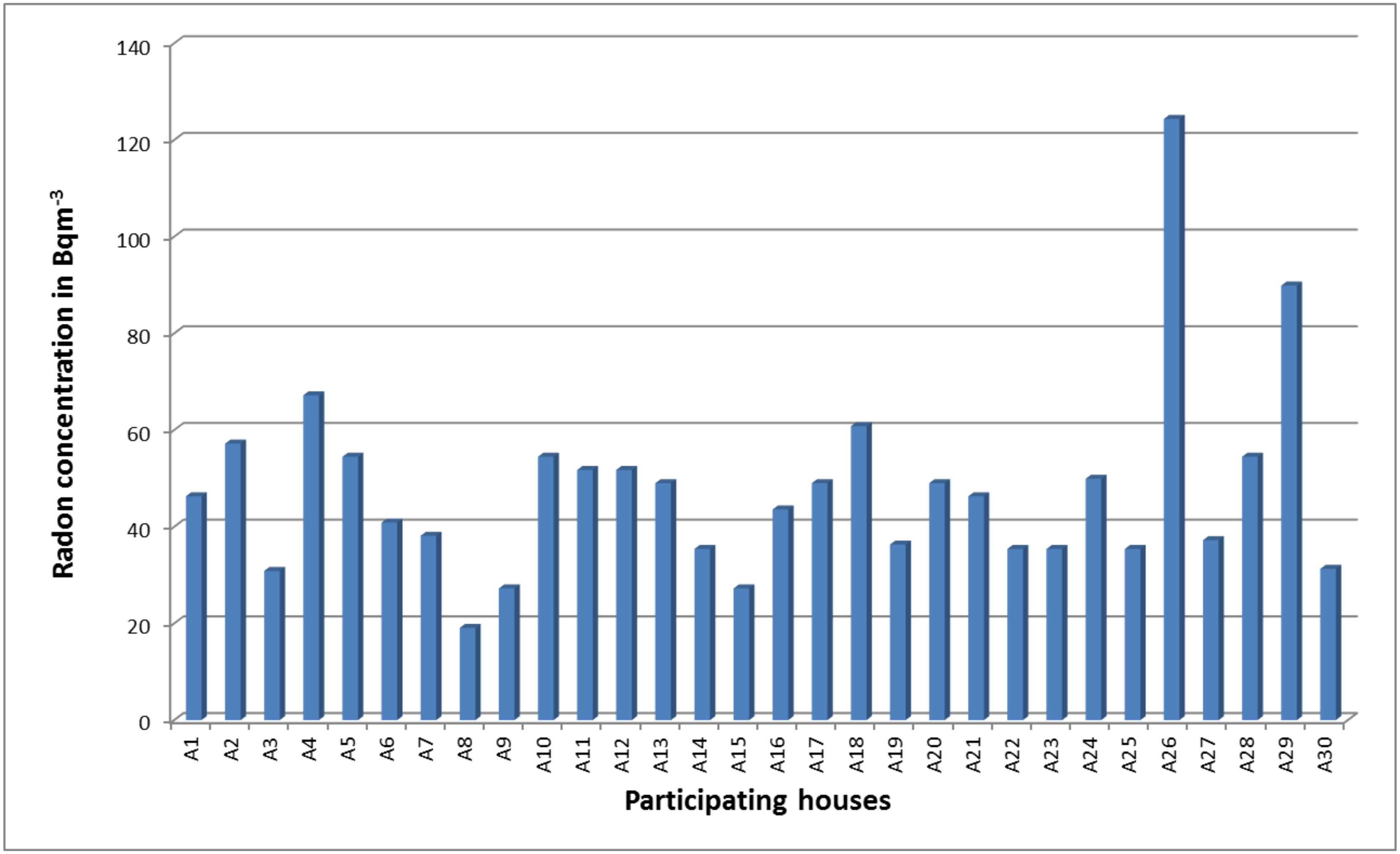

Figure 4.2 Participating Houses and the corresponding radon concentration for month two

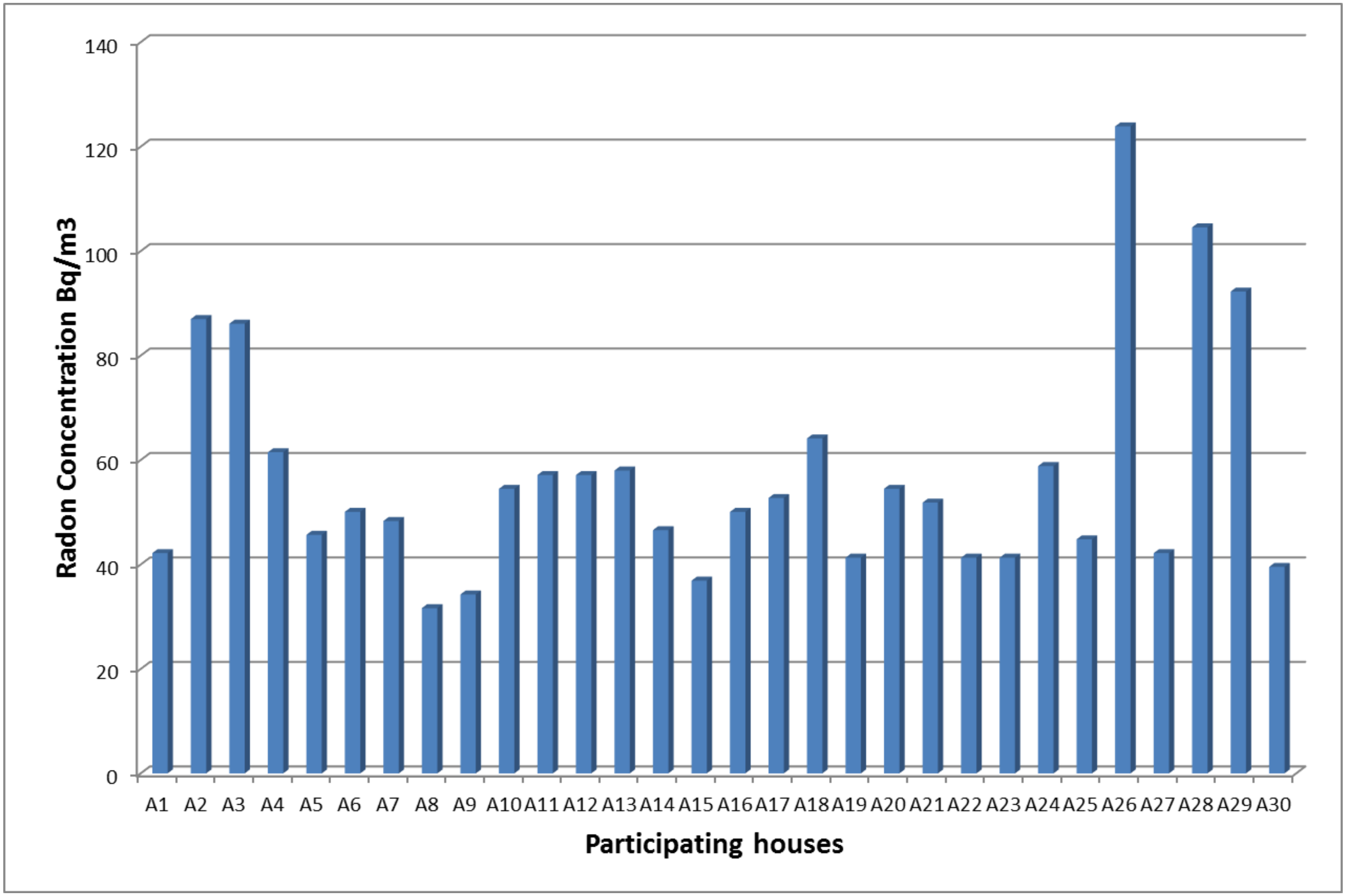

Figure 4.3: Participating Houses and the corresponding radon concentration for month three

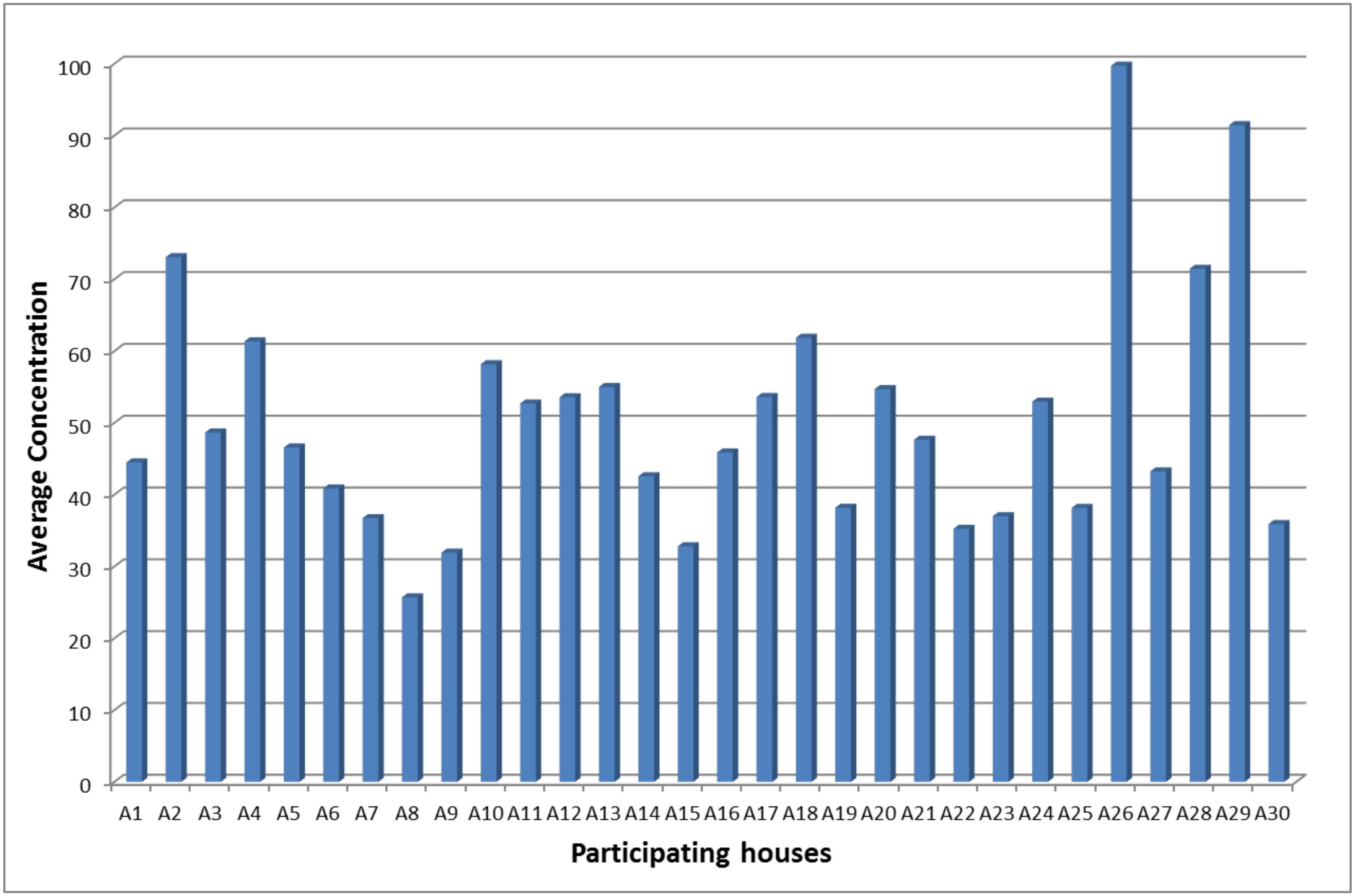

Figure 4.4: Overall average concentration as a function of participating houses

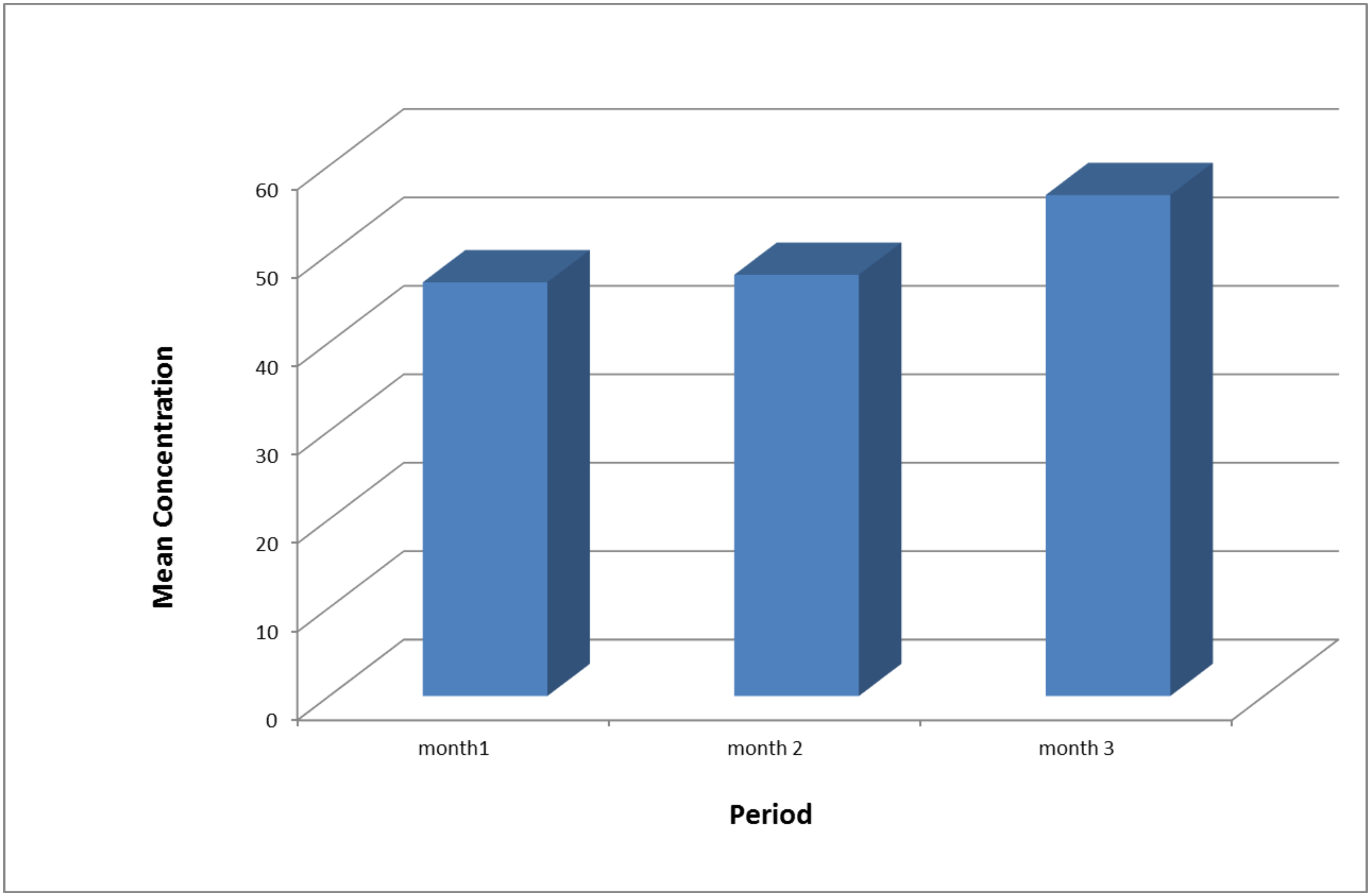

Figure 4.5: Mean concentration for the study period

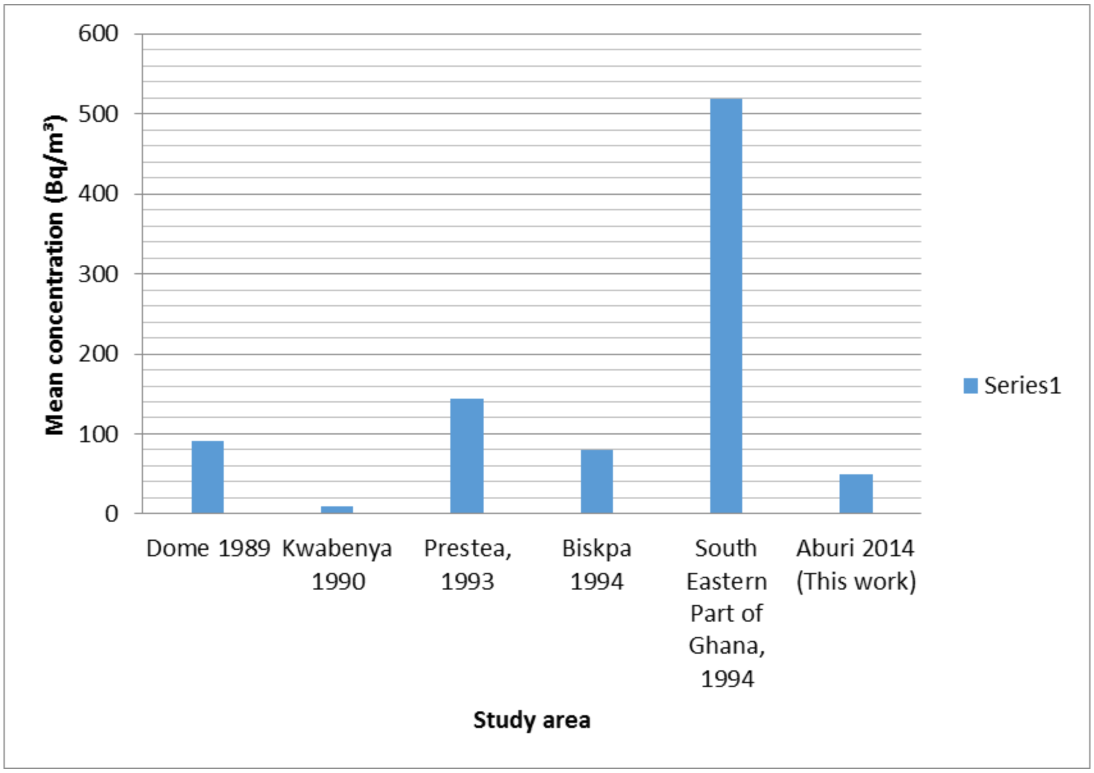

Figure 4.6: Comparison of radon concentrations from previous study areas with this work

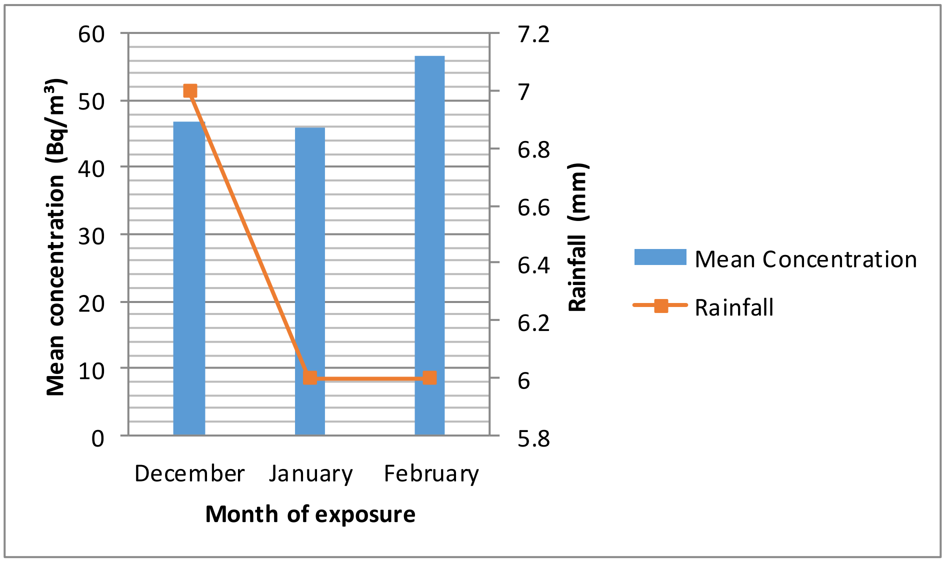

Figure 4.7: A bar chart of mean concentration and rainfall against months of exposure

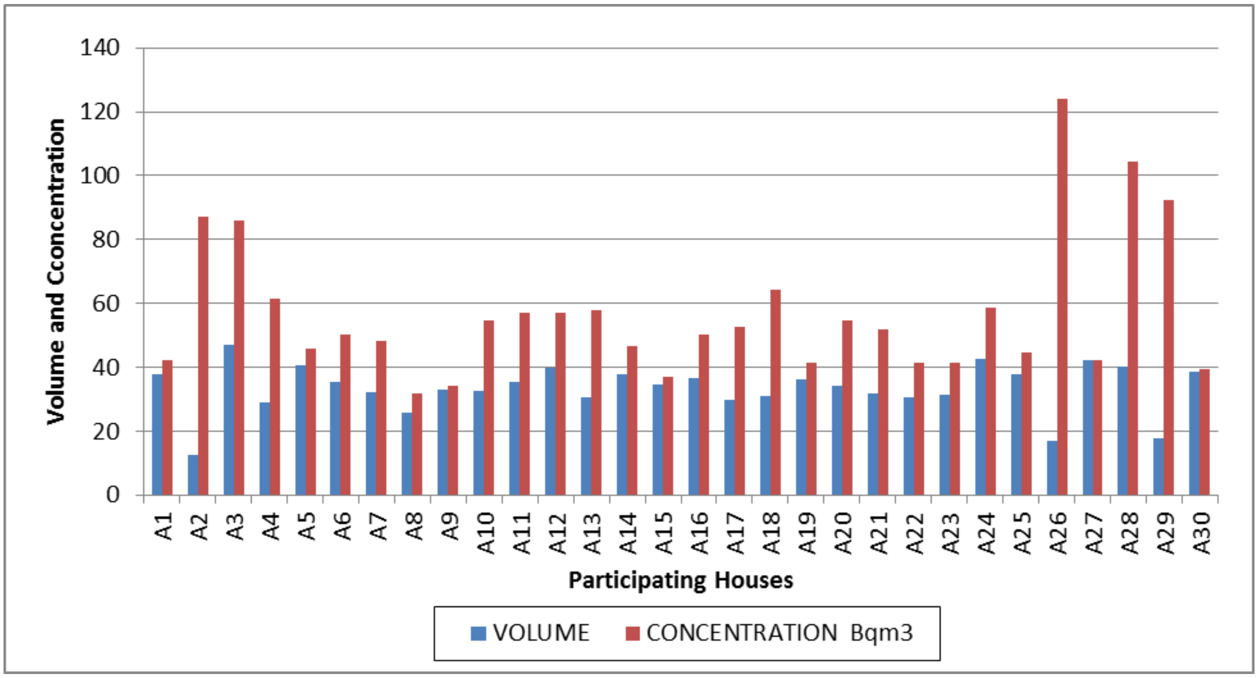

Figure 4.8: Participating Houses and their corresponding volume and concentration.

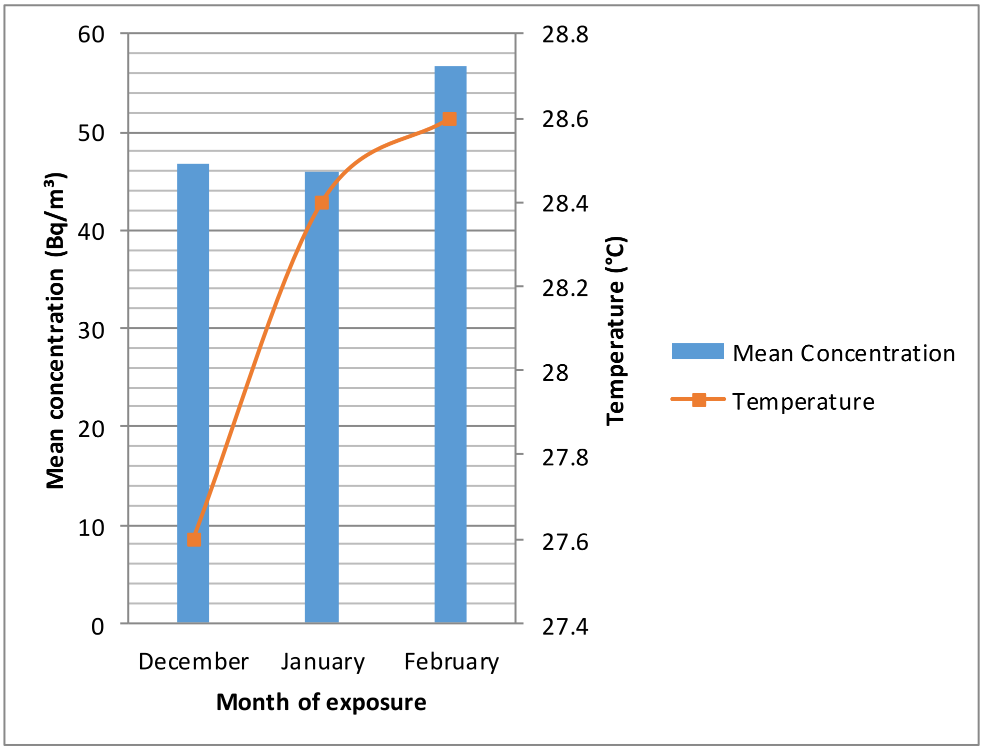

Figure 4.9: Month of exposure against mean concentration and Temperature

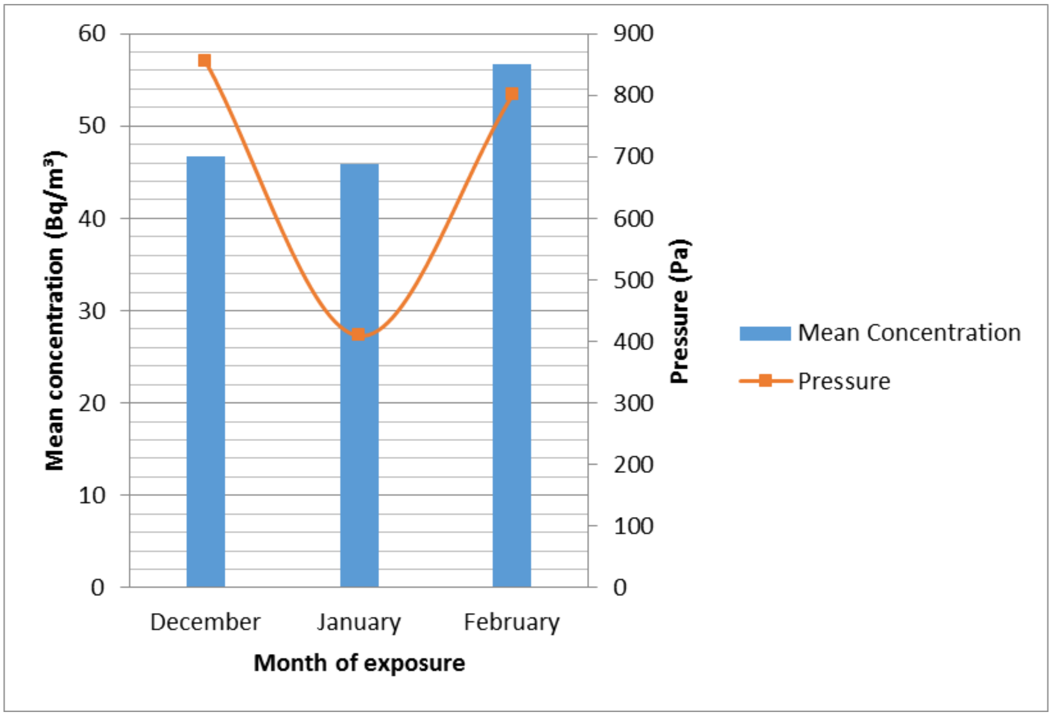

Figure 4.10: Month of Exposure against Concentration and Pressure

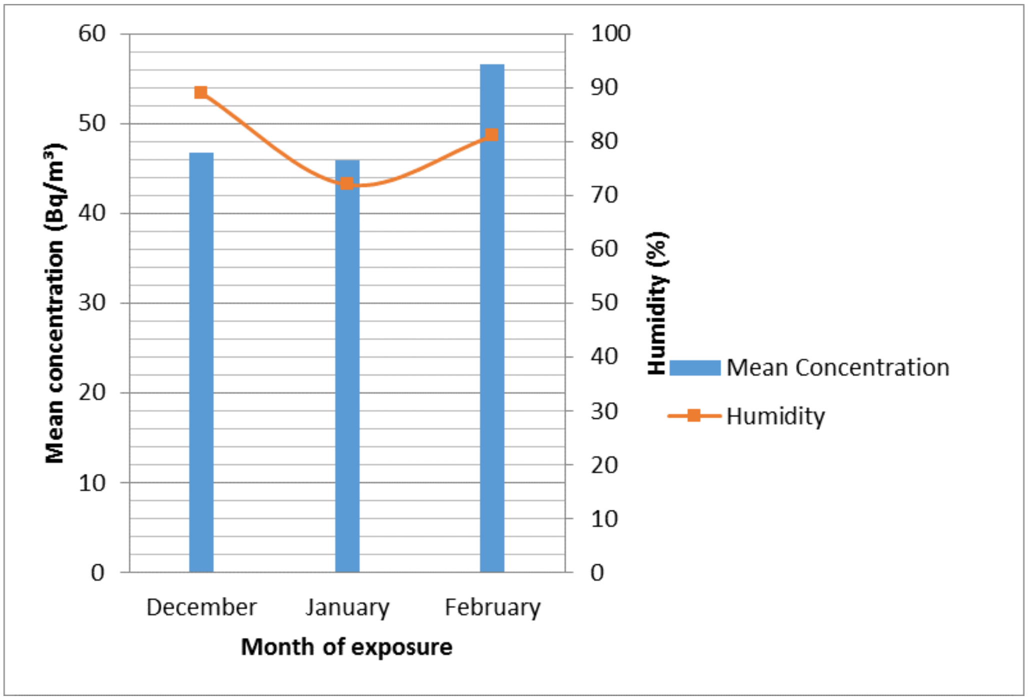

Figure 4.11: Month of Exposure against Concentration and Humidity

Table 4.1: Mean, Median value and the standard deviation of the distribution for the rooms investigated

ROOM I D	MEDIAN VALUE (Bq.m^{-3})	MEAN RADON CONC. (Bq.m^{-3})	% ABOVE ACTION LEVEL	STANDARD DEVIATION (Bq.m^{-3})
A1	45	44.48	-55.52	6.66
A2	75	73.06	-27	8.54
A3	30.86	48.65	-51.35	6.97
A4	61.49	61.34	-38.66	7.83
A5	45.67	46.56	-53.44	6.82
A6	40.85	40.85	-59.15	6.39
A7	38.13	36.72	-63.28	6.06
A8	26.36	25.69	-74.31	5.07
A9	34.26	31.95	-68.05	5.65
A10	54.48	58.16	-41.84	7.63
A11	51.74	52.69	-47.31	7.26
A12	51.84	53.56	-46.44	7.32
A13	57.98	54.99	-45.01	7.42
A14	45.67	42.55	-57.45	6.52
A15	34.26	32.8	-67.2	5.73
A16	43.94	45.86	-54.14	6.77
A17	52.72	53.59	-46.41	7.32
A18	60.81	61.85	-38.15	7.86
A19	36.31	38.17	-61.83	6.18
A20	54.48	54.7	-45.3	7.39
A21	46.29	47.64	-52.36	6.9
A22	35.4	35.23	-64.77	5.94
A23	35.4	36.99	-63.01	6.08
A24	50.07	52.94	-47.06	7.28
A25	35.4	38.15	-61.85	6.18
A26	123.89	99.72	-0.28	9.99
A27	42.16	43.24	-56.76	6.58
A28	55.35	71.45	-28.55	8.45
A29	92.24	91.45	-8.55	9.56
A30	36.9	35.91	-64.09	5.99

Table 4.2: Annual Effective Dose to the Lungs and Soft Tissues

Room ID	Average Conc. Bq/m^3	Whole Body Annual Equivalent Dose, H_{RN} (mSv/y)	Whole Body Annual Effective Dose (mSv/y)	Equivalent Dose in soft tissue other than Radon (RN) nSv/y	Equivalent Dose in the lung µSv/y	Annual Effective Dose to the lung (µSv/y)
A1	44.48	1122	2693	40.032	35.584	7.8730
A2	73.06	1827	4385	65.754	58.448	12.932
A3	48.64	1216	2918	43.776	38.912	8.6093
A4	61.34	1544	3701	55.206	49.072	1.0857
A5	46.56	1164	2794	41.904	37.248	8.2411
A6	40.85	1021	2450	37.65	32.680	7.2305
A7	36.72	918	2203	33.048	29.376	6.4994
A8	25.69	642	1541	23.121	20.552	4.5471
A9	31.95	799	1918	28.755	25.560	5.6552
A10	58.16	1454	3470	52.344	46.528	10.294
A11	52.69	1317	3161	47.421	42.152	9.3261
A12	53.56	1339	3214	48.204	42.848	9.4801
A13	54.99	1374	3298	49.491	43.992	9.7332
A14	42.55	1063	2551	38.295	34.040	7.5314
A15	32.80	820	1968	29.520	26.240	5.8056
A16	45.86	1147	2753	41.274	36.688	8.1172
A17	53.59	1340	3216	48.231	42872	9.4854
A18	61.85	1546	3710	55.665	49.480	1.0947
A19	38.17	954	2290	34.353	30.536	67.561
A20	54.70	1368	3283	49.230	43.760	9.6819
A21	47.64	1191	2858	42.876	38.112	8.4323
A22	35.23	881	2114	31.707	28.184	6.2357
A23	36.99	925	2220	33.291	29.592	6.5472
A24	52.94	1324	3178	47.646	42.352	9.3704
A25	38.15	954	2290	34.335	30.520	6.7526
A26	99.72	2493	5983	89.748	79.776	17.650
A27	43.24	1081	2594	38.916	34.592	7.6535
A28	71.45	1786	4286	64.305	57.160	12.647
A29	91.45	2286	5486	82.305	73.160	16.187
A30	35.91	898	2155	32.319	28.728	6.3561

Table 4.3: Estimated Life Time Cancer Risk in Aburi Municipaility

Room ID	AVE. Concentration	Whole Body Annual Equ. Dose H_{RN}(mSv/y)	Equivalent Dose to the lung mSv/y	Estimated Life Time Cancer Risk			
				Fatal Cancer	Non-fatal Cancer	Hereditary Effect	Total Risk
A1	44.48	1122	3.5584E-05	1.2454E-04	2.4909E-05	2.4909E-05	1.7436E-04
A2	73.06	1827	5.8448E-05	2.0457E-04	4.0914E-05	4.0914E-05	2.8640E-04
A3	48.64	1216	3.8912E-05	1.3619E-04	2.7238E-05	2.7238E-05	1.9067E-04
A4	61.34	1544	4.9072E-05	1.7175E-04	3.4350E-05	3.4350E-05	2.4045E-04
A5	46.56	1164	3.7248E-05	1.3037E-04	2.6074E-05	2.6074E-05	1.8252E-04
A6	40.85	1021	3.2680E-05	1.1438E-04	2.2876E-05	2.2876E-05	1.6013E-04
A7	36.72	918	2.9376E-05	1.0282E-04	2.0563E-05	2.0563E-05	1.4394E-04
A8	25.69	642	2.0552E-05	7.1932E-05	1.4386E-05	1.4386E-05	1.0070E-04
A9	31.95	799	2.5560E-05	8.9460E-05	1.7892E-05	1.7892E-05	1.2524E-04
A10	58.16	1454	4.6528E-05	1.6285E-04	3.2570E-05	3.2570E-05	2.2799E-04
A11	52.69	1317	4.2152E-05	1.4753E-04	2.9506E-05	2.9506E-05	2.0654E-04
A12	53.56	1339	4.2848E-05	1.4997E-04	2.9994E-05	2.9994E-05	2.0996E-04
A13	54.99	1374	4.3992E-05	1.5397E-04	3.0794E-05	3.0794E-05	2.1556E-04
A14	42.55	1063	3.4040E-05	1.1914E-04	2.3828E-05	2.3828E-05	1.6680E-04
A15	32.8	820	2.6240E-05	9.1840E-05	1.8368E-05	1.8368E-05	1.2858E-04
A16	45.86	1147	3.6688E-05	1.2841E-04	2.5682E-05	2.5682E-05	1.7977E-04
A17	53.59	1340	4.2872E-05	1.5005E-04	3.0010E-05	3.0010E-05	2.1007E-04
A18	61.85	1546	4.9480E-05	1.7318E-04	3.4636E-05	3.4636E-05	2.4245E-04
A19	38.17	954	3.0536E-05	1.0688E-04	2.1375E-05	2.1375E-05	1.4963E-04
A20	54.7	1368	4.3760E-05	1.5316E-04	3.0632E-05	3.0632E-05	2.1442E-04
A21	47.64	1191	3.8112E-05	1.3339E-04	2.6678E-05	2.6678E-05	1.8675E-04
A22	35.23	881	2.8184E-05	9.8644E-05	1.9729E-05	1.9729E-05	1.3810E-04
A23	36.99	925	2.9592E-05	1.0357E-04	2.0714E-05	2.0714E-05	1.4500E-04
A24	52.94	1324	4.2352E-05	1.4823E-04	2.9646E-05	2.9646E-05	2.0752E-04
A25	38.15	954	3.0520E-05	1.0682E-04	2.1364E-05	2.1364E-05	1.4955E-04

A26	99.72	2493	7.9776E-05	2.7922E-04	5.5843E-05	5.5843E-05	3.9090E-04
A27	43.24	1081	3.4592E-05	1.2107E-04	2.4214E-05	2.4214E-05	1.6950E-04
A28	71.45	1786	5.7160E-05	2.0006E-04	4.0012E-05	4.0012E-05	2.8008E-04
A29	91.45	2286	7.3160E-05	2.5606E-04	5.1212E-05	5.1212E-05	3.5848E-04
A30	35.91	898	2.8728E-05	1.0055E-04	2.0110E-05	2.0110E-05	1.4077E-04

CHARPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The concentration of radon-222 (222Rn) has been measured in thirty (30) homes in Aburi over a period of three months using LR 115 type II detectors placed inside the rooms of participating houses. The mean radon concentration for the three months study period was (49.78.36 ± 12.50) Bqm-^{3} in a range of (25.69- 99.72) Bqm-^{3}. One house (A26) recorded concentrations of 124.36 Bqm-^{3} in the second month and 123.87 Bqm-^{3} in the third month respectively during the study period. These values are about 24% higher than the recommended action level of 100Bqm-^{3} set by the WHO. The average value for this house is 99.72 Bqm-^{3} which is about 0.28% less than the recommended level.

The effective dose to the lungs ranged from 4.55×10^{-6} to 17.65×10^{-6} from room A8 and A26 respectively. This is an indication that the life time risk to indoor radon exposure is relatively low due to low radon concentrations recorded. The lowest value for the estimated life time lung cancer risk was found to be 7.1932×10^{-5} for fatal cancer and 1.4386×10^{-5} for both non-cancer and hereditary effect and was recorded in room A8. The fatal cancer risk and the non-fatal cancer risks were respectively 2.7922×10^{-4} and 5.5843×10^{-5}. These values were high for the fatal cancer, non-fatal and hereditary effect for A26. These values are comparatively low for rests of the rooms as a result of low concentration of radon recorded in the various homes.

Results from the study have shown that radon levels in about 93% of the rooms investigated in the Aburi Municipality are below the action level of 100Bqm^{-3} recommended by the WHO, while the remaining 6.7% are quite below the level requiring control All the values are however much lower than the ICRP level of 200- 600 Bqm^{-3} for indoor radon.

The low radon concentration in the present study could be attributed to the following environmental factors:

1. The area is highly ventilated and thus the radon gas emitted is diluted and only small concentration will enter the room.
2. There is high humidity in the area and therefore the soil pores are closed and do not allow easy entry of the radon gas.
3. The underlying rock formation are mainly of sedimentary type of rock which is known to have low concentration of the parent nuclide of Ra (U- Series) .
4. The temperature in the area is usually low and does not allow easy outflow of the gas
5. The area is at high humidity in an elevated ground and is usually cold, due to the topography. The radon gas is therefore absorbed by water droplets in the atmosphere thus reducing the ingressof the gas into the room.

Since the aforementioned factors contributed to the low measurements, only two of the rooms had value above 20% of the remedial action level in two of the months considered in the study and need some attention.

5.2 Recommendations

5.2.1 Occupants of Room A26 and A29

1. The occupants of these two rooms are advised to ensure good ventilation practices as cost effective means of mitigation of indoor radon gas level in the area. The occupants are advised to open their windows for fresh air from outside whenever they are at home.
2. The occupants are advised to increase the size of their relatively small windows to allow the entry of fresh air from outside.
3. Any crack within or outside the house must be carefully sealed to prevent the entry of the gas in the rooms.
4. Occupants are encouraged to seal large opening through floor assembles in contact with soil such as spaces around bathtub, shower or toilet drains with materials that provide permanent air tight seal such as non- shrink mortar, grouts expanding foam or similar material designed for such purposes.

5.2.2 Research Institution

1. Further studies in other parts of the country should be encouraged to collate more data to enhance the development of radon map for Ghana to assist the identification of the radon-prone areas in the country and also to help build or establish a national reference level.
2. A national radon database that monitors the measurements results over time can be used to evaluate the effectiveness of a national radon programme.
3. Further studies are needed to confirm radon levels in Aburi Municipality and extension of the study to other areas.

5.2.3 Regulatory Authorities

1. Regulatory Authourities are encouraged to consider the need for national policy and regulations on radon mitigation measures which will allow assessment of radon levels in homes, offices, schools etc. Radon safety should be considered when new houses are built, particularly in high radon areas. Homes under construction should be implemented with building codes to reduce radon levels.
2. The Environmental Protection Agency (EPA, Ghana), Ghana Health Service and Radiation Protection Board of the Ghana Atomic Energy Commission (GAEC) should work hand in hand to organize public forums to sensitize the general public about the associated health risk to indoor radon exposure.
3. Other governmental agencies concerned with radiological health and the Environmental Protection Agency should encourage and fund additional research by competent qualified scientists to improve the understanding of the risk of radiation and the means to mitigate that risk.
4. Decision makers should consider enacting building regulations and building codes requiring radon protection measures in all new buildings under constructions and existing ones.

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APPENDIX

Table A1: Average Net Count, Average Track Density and Radon Concentration for Month One

ROOM ID	COUNT1	COUNT2	COUNT3	AVE COUNT	BKGD COUNT	AVE NET COUNT	TRACK DENSITY ρ	CONCENTRATION Bqm3
A1	19	19	19	19.00	2	17	33.33	45
A2	31	30	30	30.33	2	28.33	55.55	75
A3	13	13	13	13.00	2	11.8	21.57	29
A4	23	23	23	23.00	2	21	41.18	55.35
A5	17	17	17	17.00	2	15	29.41	39.53
A6	14	14	14	14.00	2	12	23.53	31.63
A7	11	11	11	11.00	2	9	17.65	23.75
A8	12	12	12	12.00	2	10	19.61	26.36
A9	15	15	15	15.00	2	13	25.49	34.26
A10	27	29	29	28.33	2	26.33	48.76	65.54
A11	20	21	21	20.67	2	18.67	36.61	49.21
A12	23	21	21	21.67	2	19.67	38.57	51.84
A13	24	24	24	24.00	2	22	43.14	57.98
A14	19	20	19	19.33	2	17.33	33.98	45.67
A15	15	15	15	15.00	2	13	25.49	34.26
A16	18	19	19	18.67	2	16.67	32.69	43.94
A17	24	24	24	24.00	2	22	43.14	59.06
A18	24	26	25	25.00	2	23	45.1	60.62
A19	16	16	16	16.00	2	14	27.45	36.9
A20	25	25	25	25.00	2	23	45.1	60.62
A21	19	19	19	19.00	2	17	33.33	44.8
A22	13	13	13	13.00	2	11	21.57	28.99

A23	15	15	15	15.00	2	13	25.49	34.26
A24	21	21	21	21.00	2	19	37.25	50.07
A25	15	15	15	15.00	2	13	25.49	34.26
A26	21	21	21	21.00	2	19.33	37.9	50.94
A27	16	16	16	16.00	2	14	27.45	50.34
A28	23	23	23	23.00	2	21	41.18	55.35
A29	37	36	37	36.67	2	35	68.63	92.24
A30	16	16	16	16.00	2	14	27.45	36.9
								46.79

Table A2: Average Net Count, Average Track Density and Radon Concentration for Month Two

ROOM ID	COUNT1	COUNT2	COUNT3	AVE COUNT	BKGD COUNT	AVE NET COUNT	TRACK DENSITY ρ	CONCENTRATION Bqm3
A1	20	20	20	20.00	3	17	33.33	46.29
A2	24	24	24	24.00	3	21	41.18	57.19
A3	14	15	14	14.33	3	11.33	22.22	30.86
A4	28	27	28	27.67	3	24.67	48.37	67.18
A5	23	23	23	23.00	3	20	39.22	54.47
A6	18	18	18	18.00	3	15	29.41	40.85
A7	17	17	17	17.00	3	14	27.45	38.13
A8	10	10	11	10.33	3	7	13.73	19.07
A9	13	13	13	13.00	3	10	19.61	27.24
A10	23	23	23	23.00	3	20	39.22	54.47
A11	22	22	22	22.00	3	19	37.25	51.74
A12	22	22	22	22.00	3	19	37.25	51.74
A13	21	21	21	21.00	3	18	35.29	49.01
A14	16	16	16	16.00	3	13	25.49	35.4
A15	13	13	13	13.00	3	10	19.61	27.24
A16	19	19	19	19.00	3	16	31.37	43.57
A17	21	21	21	21.00	3	18	35.29	49.01
A18	26	26	24	25.33	3	22.33	43.78	60.81
A19	15	17	17	16.33	3	13.33	26.14	36.31
A20	21	21	21	21.00	3	18	35.29	49.01
A21	20	20	20	20.00	3	17	33.33	46.29
A22	16	16	16	16.00	3	13	25.49	35.4
A23	14	18	16	16.00	3	13	25.49	35.4
A24	20	23	21	21.33	3	18.33	35.94	49.92
A25	17	15	16	16.00	3	13	25.49	35.4
A26	50	48	48	48.67	3	45	89.54	124.36
A27	15	18	17	16.67	3	13.67	26.8	37.22

A28	24	22	23	23.00	3	20	39.22	54.47
A29	38	36	34	36.00	3	33	64.71	89.88
A30	15	15	15	15.00	3	12	22.57	31.29
								47.64

Table A3: Average Net Count, Average Track Density and Radon Concentration for Month Three

ROOM ID	COUNT1	COUNT2	COUNT3	AVE COUNT	BKGD COUNT	AVE NET COUNT	TRACK DENSITY ρ	CONCENTRATION Bqm3
A1	17	18	16	17.00	1	16	31.37	42.16
A2	32	34	35	33.67	1	33	64.71	86.98
A3	36	32	33	33.67	1	32.67	64.06	86.1
A4	28	19	26	24.33	1	23.33	45.75	61.49
A5	18	19	18	18.33	1	17.33	33.98	45.67
A6	20	18	22	20.00	1	19	37.25	50.07
A7	23	16	19	19.33	1	18.33	35.94	48.31
A8	13	12	14	13.00	1	12	23.53	31.63
A9	15	14	13	14.00	1	13	25.49	34.26
A10	21	24	20	21.67	1	20.67	40.53	54.48
A11	25	22	24	23.67	1	23.67	42.49	57.11
A12	26	23	22	23.67	1	23.67	42.49	57.11
A13	25	26	21	24.00	1	24	43.14	57.98
A14	18	19	22	19.67	1	19.67	34.65	46.57
A15	16	17	15	16.00	1	16	27.45	36.9
A16	20	20	20	20.00	1	19	37.25	50.07
A17	19	21	23	21.00	1	20	39.22	52.72
A18	25	26	25	25.33	1	24.33	47.71	64.13
A19	17	18	15	16.67	1	15.67	30.73	41.3
A20	20	24	21	21.67	1	20.67	40.53	54.48
A21	23	20	19	20.67	1	19.67	38.57	51.84
A22	15	18	17	16.67	1	15.67	30.73	41.3
A23	19	14	17	16.67	1	15.67	30.73	41.3
A24	23	24	23	23.33	1	22.33	43.78	58.84
A25	18	17	19	18.00	1	17	33.33	44.8
A26	49	47	48	48.00	1	47	92.16	123.87
A27	17	20	14	17.00	1	16	31.37	42.16

A28	41	39	42	40.67	1	39.67	77.78	104.54
A29	37	38	33	36.00	1	35	68.63	92.24
A30	16	14	18	16.00	1	15	29.41	39.53

Table A4: Average Deviation, Average Concentration and Uncertainty for the Study Period.

Deviation for Month 1	Deviation for Month 2	Deviation for Month 3	Average Deviation	Standard Deviation	Avg Radon Conc	Uncertainty
0.00	0.00	1.00	0.58	0.61	44.48	27.24
0.58	0.00	1.53	0.94	0.96	73.06	70.48
0.00	0.58	2.08	1.25	1.26	48.65	61.48
0.00	0.58	4.73	2.75	2.76	61.34	169.07
0.00	0.00	0.58	0.33	0.39	46.56	18.19
0.00	0.00	2.00	1.15	1.17	40.85	47.90
0.00	0.00	3.51	2.03	2.04	36.72	74.83
0.00	0.58	1.00	0.67	0.70	25.69	17.91
0.00	0.00	1.00	0.58	0.61	31.92	19.55
1.15	0.00	2.08	1.37	1.39	58.16	80.81
0.58	0.00	1.53	0.94	0.96	52.69	50.83
1.15	0.00	2.08	1.37	1.39	53.56	74.42
0.00	0.00	2.65	1.53	1.54	54.99	84.74
0.58	0.00	2.08	1.25	1.26	42.55	53.77
0.00	0.00	1.00	0.58	0.61	32.80	20.08
0.58	0.00	0.00	0.33	0.39	45.86	17.92
0.00	0.00	2.00	1.15	1.17	53.59	62.84
1.00	1.15	0.58	0.94	0.96	61.85	59.66
0.00	1.15	1.53	1.11	1.12	38.17	42.91
0.00	0.00	2.08	1.20	1.22	54.70	66.68
0.00	0.00	2.08	1.20	1.22	47.64	58.07
0.00	0.00	1.53	0.88	0.91	35.23	31.89
0.00	2.00	2.52	1.86	1.87	36.99	69.06
0.00	1.53	0.58	0.94	0.96	52.94	51.07
0.00	1.00	1.00	0.82	0.84	38.15	32.11
0.00	1.15	1.00	0.88	0.91	99.72	90.27
0.00	1.53	3.00	1.94	1.95	43.24	84.50
0.00	1.00	1.53	1.05	1.07	71.45	76.71
0.58	2.00	2.65	1.94	1.95	91.45	178.72
0.00	0.00	2.00	1.15	1.17	35.91	42.11

Table A5: Average radon concentration for the study period and the standard deviation from the Distribution

Room ID	Radon Concentration (Bq.m^{-3})				Standard deviation ±(Bq.m^{-3})
	Month 1	Month 2	Month 3	Average	
A1	45.00	46.29	42.16	44.48	6.66
A2	75.00	57.19	86.98	73.06	8.54
A3	29.00	30.86	86.1	48.65	6.97
A4	55.35	67.18	61.49	61.34	7.83
A5	39.53	54.47	45.67	46.56	6.82
A6	31.63	40.85	50.07	40.85	6.39
A7	23.75	38.13	48.31	36.72	6.06
A8	26.36	19.07	31.63	25.69	5.07
A9	34.26	27.24	34.26	31.95	5.65
A10	65.54	54.47	54.48	58.16	7.63
A11	49.21	51.74	57.11	52.69	7.26
A12	51.84	51.74	57.11	53.56	7.32
A13	57.98	49.01	57.98	54.99	7.42
A14	45.67	35.4	46.57	42.55	6.52
A15	34.26	27.24	36.9	32.8	5.73
A16	43.94	43.57	50.07	45.86	6.77
A17	59.06	49.01	52.72	53.59	7.32
A18	60.62	60.81	64.13	61.85	7.86
A19	36.90	36.31	41.3	38.17	6.18
A20	60.62	49.01	54.48	54.7	7.39
A21	44.80	46.29	51.84	47.64	6.9
A22	28.99	35.4	41.3	35.23	5.94
A23	34.26	35.4	41.3	36.99	6.08
A24	50.07	49.92	58.84	52.94	7.28
A25	34.26	35.4	44.8	38.15	6.18
A26	50.94	124.36	123.87	99.72	9.99
A27	50.34	37.22	42.16	43.24	6.58
A28	55.35	54.47	104.54	71.45	8.45
A29	92.24	89.88	92.24	91.45	9.56
A30	36.90	31.29	39.53	35.91	5.99

Table A6: Studied Area, Number of Houses, Average Radon Concentration, Range and Number of Houses with Concentration above 200 and 400 Bqm^{-3}in the Last two Columns.

Area	Number of Houses	Average Concentration	Range Bqm	>200Bqm 3	>400Bqm 3
Aburi (2014)	30	49.78	19.07 - 124.36		
Dome (1989)	26	91.8	5.2 - 336.4	2(8%)	
Kwabenya	20	9.4	5.0 -34		
Biakpa	14	80.4	31 - 194		
South Eastern part of Ghana	20	518.7	169.3 - 2047.7	7(35%)	11(55%)
Prestea	39	118.9	0.4 -909.1	2(5%)	4(10%)
Kassenna- Nakana	45	132.7	35.3 - 244.2	5(11%)	

Table A7: Average Temperature, Humidity, Pressure and Rainfall for the study period.

Period	Temperature	Humidity	Pressure	Rainfall
13-Sep	26.55	95	797.1	2.3
13-Oct	30.8	92	846.5	5.4
13-Nov	27.95	88	839.6	1.6
13-Dec	27.6	89	855.9	0.7
14-Jan	28.35	72	409.6	0.6
14-Feb	28.6	81	801	6
14-Mar	28.6	92	887.3	4.8

Table A8: Participating Rooms with Volume and Average Concentration

ROOM	VOLUME	Radon CONCENTRATION Bqm-3
A1	37.629	42.16
A2	12.64329	86.98
A3	46.9455	86.1
A4	28.899	61.49
A5	40.71	45.67
A6	35.4177	50.07
A7	32.28096	48.31
A8	25.9308	31.63
A9	32.9448	34.26
A10	32.75255	54.48
A11	35.4177	57.11
A12	39.6936	57.11
A13	30.47316	57.98
A14	37.8609	46.57
A15	34.40598	36.9
A16	36.6234	50.07
A17	29.75525	52.72
A18	31.14825	64.13
A19	36.0693	41.3
A20	34.2378	54.48
A21	31.8915	51.84
A22	30.73035	41.3
A23	31.464	41.3
A24	42.4116	58.84
A25	37.62	44.8
A26	16.744	123.87
A27	42.1668	42.16
A28	40.09824	104.54
A29	17.55	92.24
A30	38.62879	39.53