

**ASSESSMENT OF INDOOR RADON ACTIVITY CONCENTRATION
LEVELS IN TWO DISTRICTS OF THE UPPER WEST REGION OF GHANA**

BY

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**THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA SCHOOL OF
NUCLEAR AND ALLIED SCIENCES DEPARTMENT OF NUCLEAR SAFETY
AND SECURITY IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR
THE AWARD OF MPhil RADIATION PROTECTION DEGREE**

JUNE, 2014

DECLARATION

This thesis is the result of research work undertaken by Anthony Babategremine Yuoni in the Department Of Nuclear Safety And Security, University Of Ghana, under the supervision of Prof. Aba Bentil Andam and, Prof. E.O. Darko.

Sign

(Anthony Babategremine Yuoni)

Date.....

Sign.....

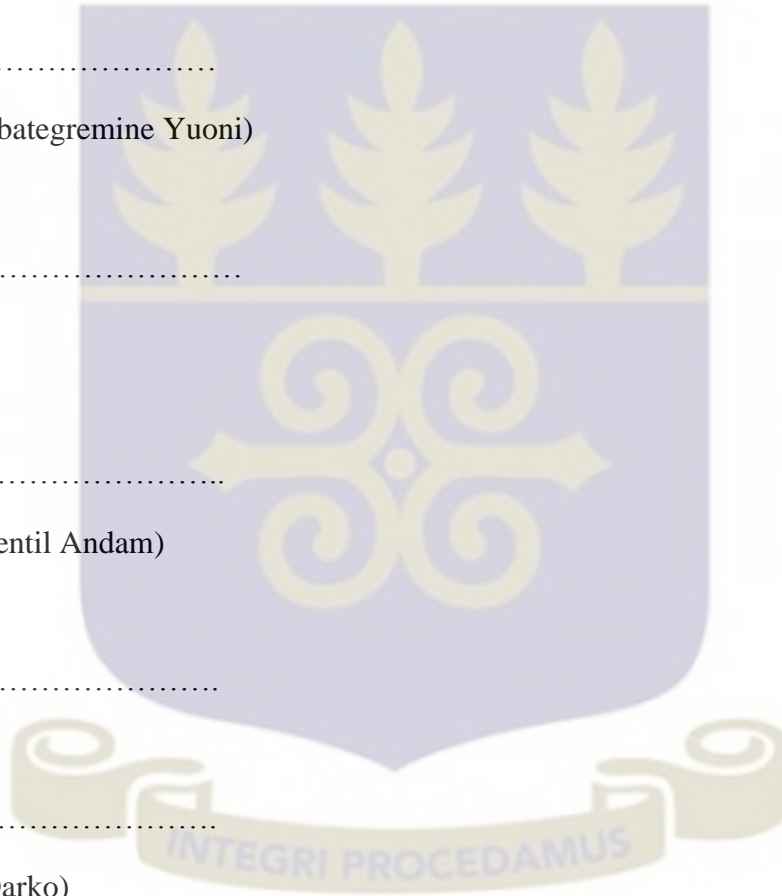
(Prof. Aba Bentil Andam)

Date.....

Sign.....

(Prof. E.O. Darko)

Date.....



DEDICATION

This work is dedicated to my late parents Mr. Matthew Yuoni and Madam Benedicta Nankpi, my siblings, all friends and relatives.



ACKNOWLEDGEMENTS

I am indebted to my supervisors: Prof. Aba Bentil Andam, and Prof. E.O. Darko for their hard work, patience and unflinching support. I also thank my H.O.D, Dr Augustine Faanu for his great support.

I am most thankful to the Head of Physics Department, Kwame Nkrumah University of Science and Technology, Kumasi, for permitting me to use their 1029 Continuous Radon Monitor. I am indebted to Mr. Addison who transported the device to Accra for me and also for training me on how to use the monitor.

I am thankful to Madam Irene Nsiah-Akoto, Mr. O.C. Oppon for their pieces of advice and encouragement. I also thank Mr. Peter Der, Mr. Issaka Swalah and all the teachers in the Science Department of St. Francis Girls' Senior High School-Jirapa for always being at my service. To all the students of St. Francis Girls' Senior High School-Jirapa, I say thank you. I am most grateful to Madam Rosemary Nyekpieng for her motherly concern.

I also thank Mr. Cypran Basing and his wife, Madam Suzana, for their great support for the past two years. To Felicia Kangbirinye, may the Good Lord favour you in all that you do for your financial support. I appreciate the contributions of Rev. Fr. Sylvester Nankpi and Rev.Fr. John-Bosco Eledi. I also appreciate the contributions of Rev.Sisters:Amuh Suzana, Leticia, and Marther. I am equally grateful to my course mates for their moral support and to all who have contributed in diverse ways to this work.

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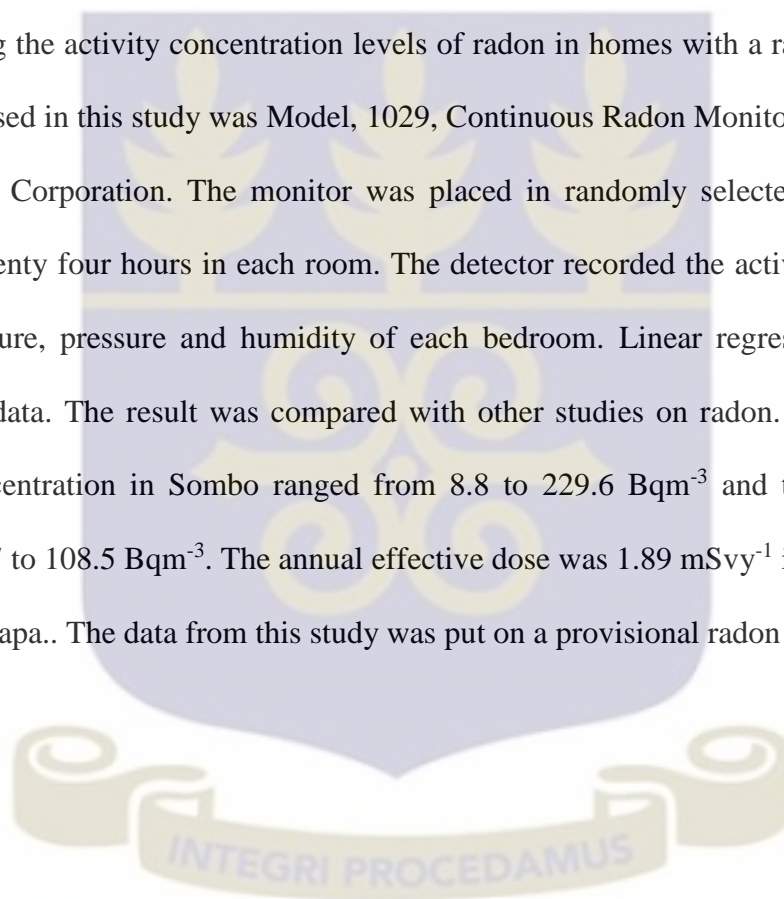


LIST OF ABBREVIATIONS

ACD	Activated Adsorption Detector
ATD	Alpha Track Detector
CRM	Continuous Radon Monitor
CSIR	Centre for Scientific and Industrial Research
EER	Equilibrium Equivalent Concentration of Radon
EID	Electronic Integrating Devices
EPA	Environmental Protection Authority
GAEC	Ghana Atomic Energy Commission
IAEA	International Atomic Energy Agency
IARC	International Agency for Cancer Research
KNUST	Kwame Nkrumah University of Science and Technology
KNUST	Kwame Nkrumah University of Science and Technology
NCRP	National Council on Radiation Protection and Measurement
NGO	Non-Governmental Organisation
NRC	National Research Council
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organisation
WL	Working Level
WLM	Working Level Month

ABSTRACT

The current study has estimated indoor radon activity concentration and annual effective dose in thirty eight bedrooms in Sombo and Jirapa in the Upper West Region of Ghana where no known studies on indoor radon has been carried out. The period of the study was from January 2014 to April 2014. Radon and its progenies have the propensity to cause lung cancer. The incident of lung cancer attributable to indoor radon exposure can be minimised by measuring the activity concentration levels of radon in homes with a radon detector. The instrument used in this study was Model, 1029, Continuous Radon Monitor manufactured by Sun Nuclear Corporation. The monitor was placed in randomly selected bedrooms for a period of twenty four hours in each room. The detector recorded the activity concentration, the temperature, pressure and humidity of each bedroom. Linear regression was used to analyse the data. The result was compared with other studies on radon. The indoor radon activity concentration in Sombo ranged from 8.8 to 229.6 Bqm⁻³ and that of Jirapa was between 11.7 to 108.5 Bqm⁻³. The annual effective dose was 1.89 mSvy⁻¹ in Sombo and 1.52 mSvy⁻¹ in Jirapa.. The data from this study was put on a provisional radon map of Ghana.



CHAPTER ONE

INTRODUCTION

1.1 Background

People are exposed to natural radiation from both terrestrial and cosmic sources. The cosmic rays come from outer space and the radionuclide in the earth crust are responsible for the terrestrial radiation. Radiation from some natural radioactive sources are almost the same throughout the world but others vary due to the difference in geological parameters and geographic locations.

Each person in the world may be exposed to a greater dose of radiation from indoor radon than from other sources; both natural and man-made, (UNSCEAR, 2000). Studies have shown that more than fifty percent (50%) of the global radiation from natural radioactive sources in the universe that the public are exposed to comes from radon. Most of the exposure to the populace occur indoors but some other people are exposed to radon at their work places. Workers occupationally exposed to radon at various levels include uranium and vanadium miners, workers remediating radioactive contaminated sites, workers at underground nuclear waste storage sites, employees of natural caves, oil refinery workers, and power plant workers. The global individual annual effective dose from background radiation is 2.4 mSv. The annual average individual effective dose from radon is 1.15 mSv. The collective dose may vary from place to place depending on local geology, building construction practices and environmental factors.

Radon is a progeny from the uranium, thorium and the actinium decay series all of which are primordial elements (Otton, 1995) found in soil and rocks. When radon is allowed to accumulate in an enclosed space, it becomes hazardous to the health of occupants of such dwelling.

The International Agency for Cancer Research in 1988 identified radon as a category one human carcinogen and it was placed in the same group as asbestos, tobacco and benzene (IARC, 1988). The main health hazard associated with inhalation of radon and its daughter products is lung cancer (Field et al, 2000, Darby et al., 2005, Lubin et al., 1997). The commonly diagnosed cancers worldwide are lung, breast, and colorectum cancers. Lung cancer constitutes about 13% of all cancers diagnosed, followed by breast cancer, 11.9 % and colorectum cancer, 9.7 %. Lung cancer has the highest mortality rate of 19.4 % compared with liver cancer whose death rate is 9.1 % and stomach cancer, 8.8 % globally (Felay et al, 2013).

The chances of one developing lung cancer depend on the concentration of radon in the home, the time spent in the home and the smoking habit of the inhabitant. It has been estimated that of all lung cancer cases in the US, about 3% to 14% are attributable to radon gas inhalation (WHO, 2009).

Radon gas is continuously produced inside the rock strata and then seeps through the earth's crust to the atmosphere. Indoor radon exposure of late has become a serious global health concern and many countries in the world including Ghana are working hard to mitigate the effect of radon on the general public. Several studies on radon concentrations in soil, water,

dwellings have been carried out in Ghana for more than 20 years now (Nsiah-Akoto et al., 2011; Quashie et al., 2010; Darko et al., 2010,; Andam, 1992).

The United States of America has declared the month of January every year as a National Radon Month (www.radonmonth.org/ 11/01/14) to educate her citizens on the need to test their homes for radon gas concentrations.

Often the greater percentage of radon gas that infiltrate into homes comes from the soil directly in contact with the building or underneath the basement of a building. Water, especially ground water, contains some amount of radon. The public is exposed to radon from water when they ingest or use the water for bathing and laundry. Radon gas is slightly soluble in water. The solubility of radon in water increases with decreasing temperature of the water. The coefficient of solubility of radon varies with temperature. At 20 °C the coefficient of solubility of radon in water is 0.254.

Meteorological factors have a great influence on the infiltration of radon from the soil. Pressure, temperature and the speed of the wind affect radon emanation. But humidity and rainfall have no direct effect.

Due to the debilitating effect of radon some countries have established action or reference levels; some of which are legally binding while others are advisory in nature. Countries such as Sweden, Switzerland and Czech Republic have made it mandatory for radon levels in homes to be within their national reference levels (Synnott and Fenton, 2005). In Sweden for instance, the Swedish Commission for radiation protection in 1980 issued a mandatory radon limits of 400 Bqm⁻³ equilibrium equivalent ²²²Rn concentration (EER) for existing buildings and 70 Bqm⁻³ EER as the value for newly constructed homes. These values were

revised in 1994 and expressed as annual radon gas concentration. The compulsory limit for existing dwellings was then 400 Bqm^{-3} and that of new construction was 200 Bqm^{-3} . Also, in Switzerland, the radiological protection ordinance sets the limit for radon at 1000 Bqm^{-3} for homes and 3000 Bqm^{-3} for work places.

A national reference level for radon is the maximum accepted radon concentration beyond which remedial action may be advised or required. It does not serve as a stiff limit between safety and vulnerability but stands for the annual average radon concentration above which remedial action is recommended or required. All nations are encouraged to establish their own action levels (WHO, 2009). In setting a national reference level, many factors such as distribution of radon levels in a country and incidence of smoking should be taken into account. The World Health Organization (WHO, 2009) recommends 100 Bqm^{-3} but depending on the country's prevailing circumstance if the attainment of this value is not feasible, the chosen national reference value should not exceed 300 Bqm^{-3} . This is to ensure that the general public is protected from the hazard of radon.

1.2 Statement of the Problem

Radon is the primary cause of lung cancer for non-smokers. The only way of determining radon levels is by testing for it using appropriate detectors. However, there has not been known research on radon in the study area. In addition, inhabitants of Nadowli and Jirapa Districts know little or nothing about radon and its health hazards. Some of the homes have small windows most of which are hardly opened during the day. People living in this area leave early in the morning for their work and come late in the evening. It is likely that some

people may be exposed to unacceptable levels of radon. This work is to assess the radon activity concentration levels in both districts.

1.3 Rationale

Epidemiological studies have given strong evidence of a link between indoor radon and lung cancer. There is no known threshold concentration of radon and its progeny below which it cannot cause lung cancer. This points to the fact that any level of radon; whether low or high is capable of causing lung cancer. This work is therefore aimed at estimating the concentration of radon in the study area. The results from this work will add to previous radon data in Ghana to help develop a national radon map which is currently absent. A radon prone area is an area where a good number of the homes have radon concentration beyond the reference level. Not only is Ghana going to develop a national radon map but also a national reference level will be established. A national reference level will assist home owners, real estate developers, building designers and contractors to make informed decisions regarding radon exposure. The government of Ghana will be able to formulate radon policies based on this research and data from other researchers.

1.4 Objectives

1.4.1 Primary Objectives

The main objective of this project is to determine the indoor radon activity concentration levels in Jirapa and Sombo in the Upper West Region of Ghana and to calculate the annual effective dose likely to be incurred by people in these communities.

1.4.2 Specific Objectives

The specific objective is to come out with recommendations based on the findings of this study and other studies in Ghana to the District Assemblies and the scientific community.

1.5 Relevance

This study will provide initial data on radon activity concentration levels in Jirapa and Sombo. The stochastic effect of radon on lung cancer can be determined. The information from this research may be useful to the Nadowli and Jirapa District Assemblies. The outcome of this project could motivate the scientific community to conduct more radon studies in many parts of the Upper West Region of Ghana.

1.6 Scope and Limitation

The work covers only indoor radon activity concentration and measurements are taken from only bedrooms of participants. Indoor facilities such as halls, study rooms bath rooms are not considered. Occupational and outdoor exposures to radon are excluded in this particular study. Also two towns are considered for this study. These towns are Jirapa and Sombo in the Upper West Region of Ghana.



CHAPTER TWO

LITERATURE REVIEW

To overcome the debilitating effect of radon, it is important to understand some fundamental concepts such as: the nature of radon, sources of radon, radon emanation, the health risk of radon and radon measuring instruments. This chapter reviews basic concepts on radon.

2.1 Properties of Radon

Radon has three naturally occurring isotopes: ^{222}Rn from the uranium decay series, ^{220}Rn a daughter product of the thorium decay series and ^{219}Rn a member of the actinium decay series. ^{220}Rn is commonly called thoron and ^{219}Rn is mostly referred to as actinium. The half-life of ^{219}Rn is 3.98 s and it has a low activity concentration as compared to ^{222}Rn in nature. Hence, it does not pose any significant health risk as compared to ^{222}Rn . The radiological impact posed by ^{220}Rn is minimal, since it has a half-life of 55.6 s and a higher activity concentration than ^{219}Rn but a much lower activity concentration when compared with ^{222}Rn . Radon-222, decay product of U-238, is a naturally occurring radioactive inert gas with a half-life of 3.8 days. It has no colour, taste, odour and cannot be seen with the eye.

Table 2.1 shows some physicochemical properties of ^{222}Rn , ^{220}Rn and ^{219}Rn (IAEA, 2013).

Uranium decay products are also shown in Tables 2.2 and 2.3.

Table 2.1: Some physical and chemical properties of three isotopes of radon

Parameter	Symbol	^{222}Rn	^{220}Rn	^{219}Rn
Half-life	$T_{\frac{1}{2}}$	3.8 d	55.8 s	4.0 s
Decay constant	λ	$2.0984 \times 10^{-6}\text{s}^{-1}$	$1.242 \times 10^{-2}\text{s}^{-1}$	$1.74 \times 10^{-1}\text{s}^{-1}$
Diffusion coefficient in air	D_{MA}	$1 \times 10^{-5} \text{m}^2\text{s}^{-1}$		
Diffusion coefficient in water	D_{Mw}	$1 \times 10^{-7} \text{m}^2\text{s}^{-1}$		



Table 2.2: ^{238}U decay products

Element	Half-life	Radiation emitted
^{238}U	4.47×10^9 y	Alpha
^{234}Th	21.1 d	Beta
^{234}U	2.46×10^5 y	Alpha
^{230}Th	7.45×10^4 y	Alpha
^{226}Ra	1600 y	Alpha
^{222}Rn	3.82 d	Alpha
^{218}Po	3.07 min	Alpha
^{214}Pb	26.9 min	Beta
^{214}Bi	198 min	Beta
^{214}Po	162 μs	Alpha
^{210}Pb	22.2 y	Beta
^{210}Bi	5.01 d	Beta
^{210}Po	138 d	Alpha
^{206}Pb	Stable	

Table 2.3: Thorium-232 decay products

Element	Half-life	Radiation emitted
^{232}Th	5.75 y	Alpha
^{228}Ra	6.15 h	Beta
^{228}Ac	1.91 y	Beta
^{228}Th	3.63 d	Alpha
^{224}Ra	55.8 s	Alpha
^{216}Po	0.148 s	Alpha
^{212}Pb	10.6 h	Alpha
^{212}Bi	60.5 min	Beta
^{208}Tl	3.06 min	Alpha
^{208}Pb	Stable	

2.2 Sources of Radon

Radon is found in soil, rocks, water, building materials among others. Since radon is a decay product of ^{238}U , the amount of radon present in the soil or rocks will depend on the quantity of ^{238}U in the soil or rocks. Table 2.4 below shows the worldwide atmospheric radon sources (Ludin al. 1971). From the table, radon infiltration from the soil is the major source of atmospheric radon.

Table 2.4: Global sources of atmospheric radon (Ludin et al., 1971)

Source	Bq/a
Emanation from soil	7.4×10^{13}
Ground water	1.85×10^{13}
Emanation from oceans	1.11×10^{12}
Phosphate residues	1.11×10^{11}
Uranium tailings	7.4×10^9

Radon atoms found in solid grains have very low diffusion coefficient and would scarcely be released to the atmosphere. On the other hand radon atoms situated in the interstitial space between grains are likely to diffuse to the surface. Radon gases released from the ground to the atmosphere follow a series of processes (Moed et al., 1988) such as emanation, transport and exhalation. Emanation is the process whereby radon gas decay outflow from the grains into the interstitial space amid the grains. The emanation of radon is influenced by the amount of ^{226}Ra and the size of the mineral grains in the soil or rock. Transport of radon gas to the surface of the ground is mostly due to diffusion and advective flow. The transportation of radon in the earth is subject to geochemical and geophysical boundaries. The transported radon gases are exhaled to the atmosphere. Exhalation of radon gas is governed by hydrometeorological factors (Etiope and Martinelli, 2002). Figure 2.1 shows the processes involved in the release of radon from the ground to the atmosphere (IAEA, 2013)

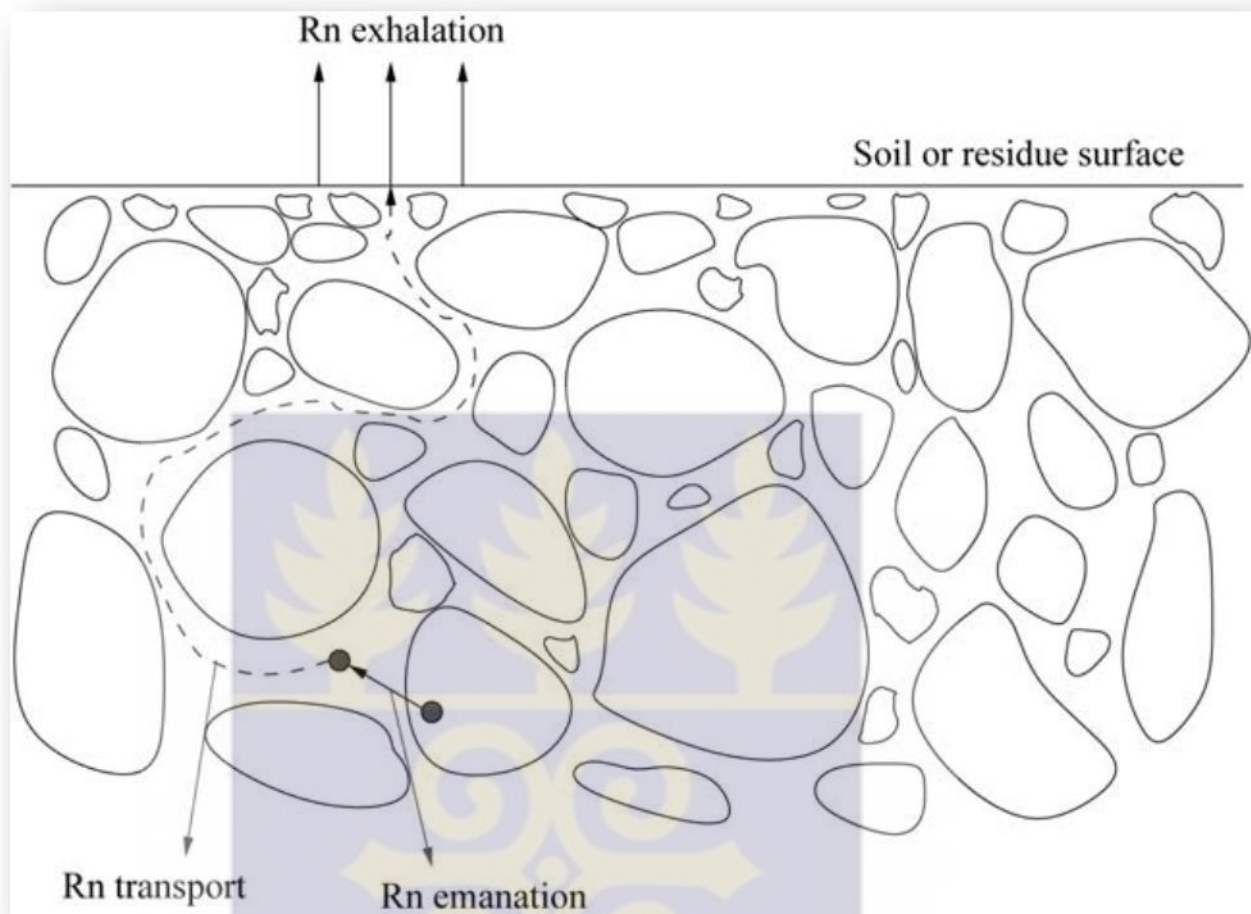


Figure 2.1: The route of radon from the ground to the atmosphere

2.3 Radon in Buildings

The most common source of radon in buildings is through soil gas infiltration. Radon gas easily moves into buildings due to pressure difference between the soil and the rooms. The gas seeps into the rooms through cracks in floors, openings in suspended floors, cavities in walls, joints in construction materials and gaps created due to plumbing and electrical wiring activities.

The quantity of radon present in the ground to be transported to the surface of the atmosphere is determined by the radon production rate. The radon production rate (P) gives the volume of radon produced per unit time. Its unit is $\text{Bqm}^{-1}\text{s}^{-1}$.

$$p = \lambda ER\rho_b \quad (2.1)$$

Where:

P = radon production rate ($\text{Bqm}^{-1}\text{s}^{-1}$)

λ = decay constant for radon (s^{-1})

E = emanation coefficient

R = radium activity concentration in the soil or rocks (BqKg^{-1})

ρ_b = the bulk density (Kgm^{-1})

The solubility of radon in water among other factors depends on the temperature of the water. The solubility of radon increases with decreasing temperature and decreases with increasing temperature.

Ground water may contain much radon than surface water. The radon in surface water easily escapes into the atmosphere but the radon in the ground water are somewhat constrained. The exposure of radon to the public as a result of drinking water may not pose any significant health hazard. The major exposure incurred by the public is through inhalation as a result of activities such as bathing, and washing.

2.4 Radon Emanation Coefficient

Emanation coefficient is defined as the ratio of radon atoms produced that seep from the solid state in which they were generated and are liberated to infiltrate through the bulk medium.

It is a well-established fact that when radium in a solid grain decays to radon, the radon seeps from the grain due to recoil. The recoil range of solids is less than 0.05 μm . As a result of the very small recoil range, majority of the recoiling atoms stay within the crystal lattice of the solid. Even if the recoil distance between the atoms and lattice is increased, the radon emanation will still be small due to the very small diffusion coefficient of solids, 10^{-25} to 10^{-27} m^2/s (Semkow, 1991; Ziegler et al., 1985). When the recoil ends outside of the grain, then, the radon will be able to escape. The recoil range of radon is different in different media such as air, water, and quartz (SiO_2). When the density of air is 1.58×10^3 g/cm^3 , the projected recoil ranges for ^{222}Rn and ^{220}Rn are respectively 53×10^3 nm and 60×10^3 nm. Also the recoil ranges for ^{222}Rn and ^{220}Rn in water of density 1.0 g/cm^3 are 77 nm and 87 nm respectively. With quartz of density 2.65 g/cm^3 ^{222}Rn has a projected recoil range of 34 nm while ^{220}Rn has a recoil range of 38 nm.

2.5 Factors Affecting Radon Emanation

The difference in emanation coefficients compounded with the complex influence of bed rock and uranium mineralogy, particle size and moisture content have been qualitatively studied (Fleischter, 1983; Sasaki et. al., 2004; Barillon et.al., 2005).

2.5.1 Particle Size and Shape

The quantity of uranium and radium closer to the surface of the grain from which radon seeps into the interstitial pores is partly influenced by particle size and shape. When the particle size is greater than 0.1 μm and radium is evenly distributed throughout the grain, then the emanation coefficient will apparently be inversely proportional to the particle size.

Radium distributed on the surface of the grain will result in a constant emanation coefficient independent of the particle size as shown in Figure 2 below (IAEA, 2013)

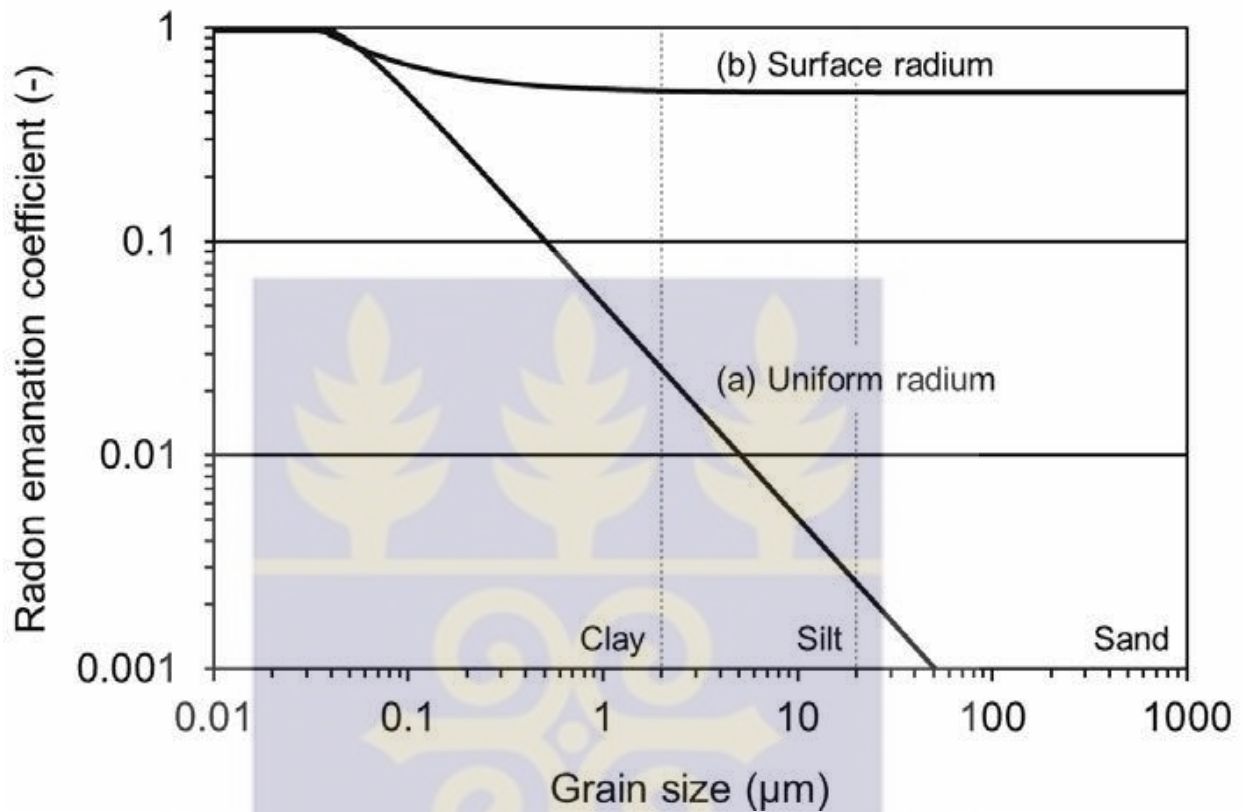


Figure 2.2: Radon emanation in a single grain model

2.5.2 Moisture Content

Studies have revealed that moisture content has a powerful effect on the emanation coefficient (Markkanen and Arvela, 1992; Breitner et al., 2010; Barton and Ziemer, 1986; Rogers et al, 1983; Bossew, 2003). The powerful effect of moisture content on emanation coefficient is due to the fact that the recoil range of water is very small compared to that of air; hence the stoppage of radon atoms within the pore space is much more efficient in water than in air; hence the stoppage of radon atoms within the pore space is much more efficient in water than in air.

The emanation coefficient in dry materials is comparatively low in that, majority of the radon atoms seeping from particles conceal themselves in neighbouring particles. A recoiling atom will probably end its recoil in the pore if the water content in the pore is increasing. For greater moisture content (above 5% per volume) a smaller number of atoms will be able to move through nearby particles. The emanation coefficient is fairly constant at saturation point. The emanation coefficient in saturated conditions is 2-6 times greater than in dry conditions.

2.5.3 Mineralogy

The physical and chemical properties of minerals such as lattice structure, porosity, grain shape and the components of the element strongly affect the emanation coefficient of radon. Soil is made from different kinds of mineral grains from varied rocks; therefore the emanation coefficient of soil differs considerably.

2.5.4 Diffusion Coefficient

Fick's first law of particle diffusion best describes the molecular diffusion coefficient of radon. The law can be defined for radon as that, the radon flux density is directly proportional to its concentration gradient.

$$f = -D_M \nabla C \quad (2.2)$$

Where:

f = the radon flux density ($\text{Bqm}^{-2}\text{s}^{-1}$)

D_M = molecular diffusion coefficient (m^2s^{-1})

∇C = the gradient of radon activity concentration

The significance of the negative sign is that radon diffuses from a higher concentration to a lower concentration. Radon molecular coefficient in air (D_{MA}) is $1 \times 10^{-5} \text{ m}^2\text{s}^{-1}$ and in water (D_{MW}) is about $1 \times 10^{-9} \text{ m}^2\text{s}^{-1}$. Radon diffuses in pore space between particles in permeable medium such as soil. The rate of diffusion in an inhomogeneous medium may be slower than in a homogeneous medium such as water or air. Two reasons account for this phenomenon; porosity and tortuosity of the medium. Tortuosity is equal to one for a pure solution and is less than one in soils. For example, the tortuosity of closely pack uniform spheres is 0.66. Equation 2.2 can be rewritten as:

$$f = -n_s \tau D_M \nabla C \quad (2.3)$$

Where:

f = the radon flux density ($\text{Bqm}^{-2}\text{s}^{-1}$)

n_s = the porosity of the soil

τ = tortuosity factor

D_M = molecular diffusion coefficient (m^2s^{-1})

∇C = gradient of radon activity concentration in the pore space (Bqm^{-4})

The diffusion coefficient of the pore fluid (D) is defined as:

$$D = \tau D_M \quad (2.4)$$

Substitution eqn (4) into eqn (3), we have:

$$f = -nD \nabla C \quad (2.5)$$

Let $nD = D_e$

Where

D_e = effective bulk diffusion coefficient of soil.

In a homogeneous medium the flux density depends on the diffusion coefficient of the pore fluid (D) since n is equal to unity.

The diffusion coefficient of radon in soil more often than not depends on the type of soil, pore size, moisture content and the level of compaction (Schumann and Gundersen, 1996; Rogers and Nielson, 1991). Among these factors moisture content invariably overshadows the other physical factors. This is due to the large difference between the molecular diffusion coefficient of air and water. Studies on radon diffusion coefficient with regard to moisture content and different soil types abound. These studies have revealed that radon diffusion is hindered when water content goes beyond a certain value. The diffusion coefficient for dry soil can be calculated using the relation

$$D = \tau D_{MA} \quad (2.6)$$

2.6 Health Risk Attributed to Radon

Radon is the primary cause of lung cancer for non- smokers and the second leading cause of lung cancer for smokers (WHO, 2009). The effect of radon takes a long time before it begins to show. Higher exposure to radon and its progeny combined with smoking has a multiplicative effect. Radon is a gas but its progeny like ^{218}Po , ^{214}Po among others are particles and easily attach themselves to aerosol and particulates. The decay of ^{222}Ra results in the emission of alpha particles. Alpha particles are helium nuclei least penetrating but

most ionising as compared to beta and gamma radiation. When these particles are breathed in, some attach themselves to the bronchial epithelium while others are breathed out. Alpha particles deposited in the lungs may emit ionizing radiation. This high ionizing energy from alpha particles can interfere with the genes of their immediate surroundings and cause lung cancer.

The bronchial epithelium is the most affected part of the body when exposed to alpha radiation due to inhalation of radon gas. The skin and the thoracic airways are exposed to significant doses from radon and its progeny but do not suffer the same fate as the bronchial epithelium. The kidney and bone marrow receive low doses as well. The debate as to whether radon causes other cancers other than lung cancer still lingers on. Currently there is no empirical evidence to the fact that radon could cause other cancers other than lung cancer. A study on the effect of radon on other cancers other than lung cancer concluded that there was no significant impact of radon progeny on other cancers (Darby et al., 1995). A parallel study on radon and the risk of death from cancer and heart diseases in the German uranium miners' cohort study confirmed that radon can cause lung cancer. This investigation did not find any correlation between the increase risk in coronary heart diseases and cerebrovascular diseases, and radon exposure (Kreuzer et al., 2010). A similar work on radon exposure mortality among white and American Indians uranium miners did not find any association between radon products and chronic lymphocytic leukemia (Schubauer-Berigan et al., 2009). In all, the potential for radon to cause other cancers other than lung cancer is not conclusive.

2.7 Units for Measurement of Radon

The S.I. unit for measuring radon is Bequerels per cubic meter (Bq/m^3). Radon progeny concentrations are often expressed in terms of working levels (WL). A working level is defined as any combination of the short-lived progeny in one litre of air that results in the ultimate release of 1.3×10^5 MeV of potential alpha particle energy. Exposure to radon over a period of one month (170 hours) is termed as working level month (WLM).

2.8 Radon Measurement

Radon measurement is the only surest way of determining the concentrations of radon and its progeny. The use of appropriate devices and protocols are vital to the reliability of the data. The test for radon gas may be described as short or long term depending on the duration for which the measurement was taken (Quindoes et al., 1991). Activated charcoal, electrets ion chamber and continuous radon monitor detectors may be used as short-term detectors to estimate average long-term radon levels in dwellings. The only challenge with short term test is that it may give misleading results. For instance, a poorly ventilated room will give a high radon concentration when tested. This value may not be representative of the actual average radon concentration in that home. Due to diurnal and seasonal variations the long-term radon measurement is most often desirable. It is worth noting that yearly concentration of radon could change.

Devices employed in the measurement of radon gas concentration are said to be either passive or active. Active devices need electricity to function and can track the variation of radon gas within the time of measurement. Examples are electronic integrating devices (EIDs) and continuous radon monitor. Passive devices do not need electricity or a pump to operate. They are used for long term radon test in homes and work places.

2.9 Measurement Devices

2.9.1 Alpha- Track Detector (ATD)

Alpha- track detectors are plastic substrates put within a filter-covered diffusion chamber that does not allow entry of radon daughter products. The plastics are polyallyl diglycol carbonate (PADC or CR-39), cellulose nitrate (LR-115), or polycarbon materials. Alpha particles produced from radon decay in the vicinity of the plastic; strike it producing microscopic damage known as latent tracks. These latent tracks are revealed by means of either chemical or electrochemical etching of the plastic material. The tracks are magnified and counted manually using a light microscope or electronically. The track density is proportional to the radon concentration in Bq h/m^3 when the background count is subtracted. The track density is converted to radon concentration with the aid of a conversion factor derived at a calibration facility. The period for which alpha track detectors are deployed range from 1 month to 1 year. Humidity, temperature and background beta and gamma radiation do not affect alpha track detectors. They can therefore be used in any part of the world. Alpha particles though most ionizing travel the least distances compared with beta and gamma radiation; hence measurement about 2000 m above sea level may need some little adjustment. To prevent cross-sensitivity to thoron, a diffusion chamber with a large resistance to gas entry is used. Table 2.5 summaries radon gas measuring devices and their characteristics (WHO, 2009).

Table 2.5: Radon gas measurement devices and their characteristics

Detector type	Passive/active	Typical uncertainty (%)	Typical sampling period	Cost
Alpha-track detector	Passive	10-25	1-12 months	Low
Activated charcoal detector	Passive	10-30	2-7 days	Low
Electrets-ion chamber	Passive	8-15	5 days -1 year	Medium
Electronic integrating device	Active	~ 25	2 days- year(s)	Medium
Continuous radon monitor	Active	~10	1 hour – year(s)	High

2.9.2 Activated Charcoal Adsorption Detector

Activated charcoal adsorption detectors are deployed between one and seven days to measure indoor radon. They operate on the principle of radon adsorption on the active site of the activated charcoal. The detectors after exposure are sealed and the progeny of radon are allowed to attain equilibrium after three hours. The performance of the activated charcoal adsorption detectors are affected by humidity. There is therefore the need to calibrate it under various conditions of humidity. It is advisable to also calibrate the ACD over the period of exposure and the temperatures likely to be experienced on the field. ACD gives a good approximation of the mean radon concentration of an area based on the premise that there is a small change in radon concentration. For a standard ACD a minimum concentration of 20 Bqm^{-3} has been calculated. Many people have used the ACD for various studies (Iimoto et al., 2004, 2008).

2.9.3 Electret Ion Chamber

Like the activated charcoal adsorption detectors, electrets ion chambers are passive devices that operate as integrating detectors used for the measurement of mean radon gas concentration within a specified period of time. The electret plays two important functions in the chamber. It serves as a source of electric field and also acts as a sensor. Radon gas move into the chamber by passive diffusion. Radon progeny are filtered at the inlet; hence they (progeny such as ^{218}Po , ^{214}Po among others) are prevented from entering the chamber. The air in the chamber is ionized due to the radiation emitted by the radon gas and its daughter products. The positive electrets found at the base of the chamber collect the negative ions. The electrets discharge over a specified period of time is a measure of time-integrated ionization. This is somewhat related to the concentration of radon. A remote electric reader which may be powered by a battery reads the electric discharge in volts. The value obtained from the device, combined with the time of measurement and the calibration factor gives the concentration of radon in appropriate units. Electrets ion chambers may be design for long or short term radon monitoring. The short term devices are deployed between 2 to 15 days at 150 Bqm^{-3} concentrations and the long term devices measure radon concentration between 3 to 12 months at 150 Bqm^{-3} concentrations. Electrets ion chambers are good detectors and have been used in several countries. They have exhibited great accuracy and precision under standard operating conditions.

2.9.4 Electronic Integration Devices (ELD)

Many electronic integration devices (EIDs) make use of a solid-state silicon detector that has a diffusion chamber for detecting alpha particles discharged by radon progeny. The diffusion chamber is small, thus it takes more than two days in order to obtain a statistically stable reading. The sensitivity of the EIDs could be improved by applying a high voltage to electrostatically collect charged radon progeny by contact by the detector. Electronic integration devices are affected by high humidity. For a period of a week's exposure, EIDs has a minimum detectable concentration of 20 Bqm^{-3} . Many EIDs cannot be routinely calibrated.

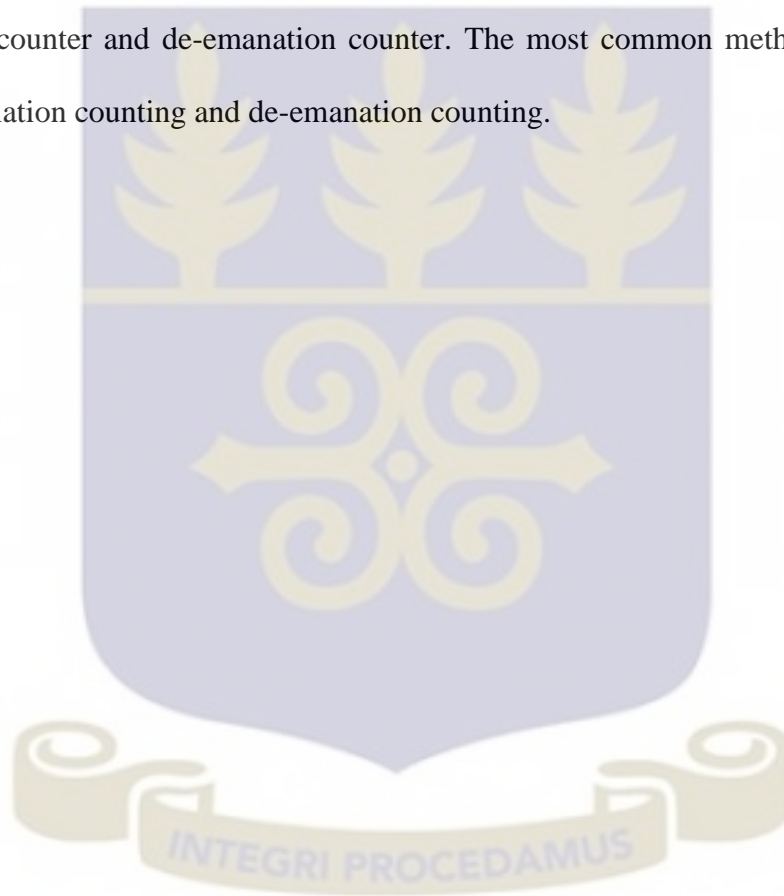
2.9.5 Continuous Radon Monitors (CRM)

The continuous radon monitors use different types of sensors such as scintillation cells, current or pulse ionization chambers, and solid state silicon detectors. Every continuous radon monitor has electrical circuitry that gives a brief report of the radon concentration within a specified period of time. This report could be used to calculate the average radon concentration for a known period of time. The variety of sensors used play different important roles in the detection of radon and its progeny. For instance, when a solid state silicon detector is used, alpha spectrometry is likely. This permits the detection of radon and thoron separately. On the whole, the minimum detectable concentration calculated for CRMs using standard methods is 5 Bqm^{-3} .

2.9.6 Radon Monitoring Devices in Water

The incidence of radon in ground water is mostly caused by radium decay in rock and soil that dissolve in the water. The general public is exposed to radon from water sources

through inhalation of the radon gas and ingestion of water that may have significant amount of radon. The cancer risk from inhalation of radon is much greater than the risk of ingestion of water containing radon. In many instances radon released from water to the indoor air is much less than radon seeping from the soil into the houses. There are many standard methods for sampling and measurement of radon in water. Some of the techniques of monitoring radon in water are direct gamma counting, electrets ion chambers, liquid scintillation counter and de-emanation counter. The most common methods employed are liquid scintillation counting and de-emanation counting.



CHAPTER THREE

MATERIALS AND METHODS

This chapter examines the materials and methods used in this study. A description of the study area is also presented. Details of sampling and measurement have been described.

3.1 Materials

The following materials were used in the study:

- 1029 continuous radon monitor, manufacture by Sun Nuclear Corporation
- Builder's tape measure
- Portable print
- GPS

3.2 Study Area

3.2.1 Nadowli District

The Nadowli District is located in the centre of the Upper West Region of Ghana. The total land mass is about 2,742.5 square kilometers. To the west of the district is Burkina Faso, to the south the Wa municipality, to the north is the Jirapa District and to the east is the Sissala West District as shown in Figure 3.1. The black circle on the map shows Sombo. The GPS coordinates showing the sample points is in Appendix A6

The 2010 population and housing census reveals that, the district has a total population of 94,388 with 44,724 being males and 49,664 being females. The population between the ages of 0-14 constitute about 45%, the productive population is 49% while 6% is the aged. The district has a growth rate of 1.9% per annum.

It lies between latitude 11°30' and 10°20'. The landscape is somewhat flat but slightly undulating at altitude between 150 m to 300 m above sea level. The 'Bakpong' is the principal stream and many other transient streams flow into the Black Volta. The mean monthly temperature ranges from 32° C in March to 27° C in August. The average yearly temperature is about 36° C. The annual rainfall is about 1100 mm with the maximum rainfall in the month of August. The dry season spans from October to March. During the dry season the northeasterly harmattan winds blow through the area. Relative humidity is between 70% to 90% during the rainy season, but below 20% during the dry season.

There are three main types of rocks found in the district. To the west and some parts of the east of the district are birimian and granite and to the east has basement complex. Birimian rock formation is thought to have some traces of gold and has the capacity to hold large amount of ground water. Laterite, sandy and sandy loam (savanna ochrosols) are the soil types in this part of the country. The soil is infertile as a result of bush fires, overgrazing, erosion and poor farming practices.



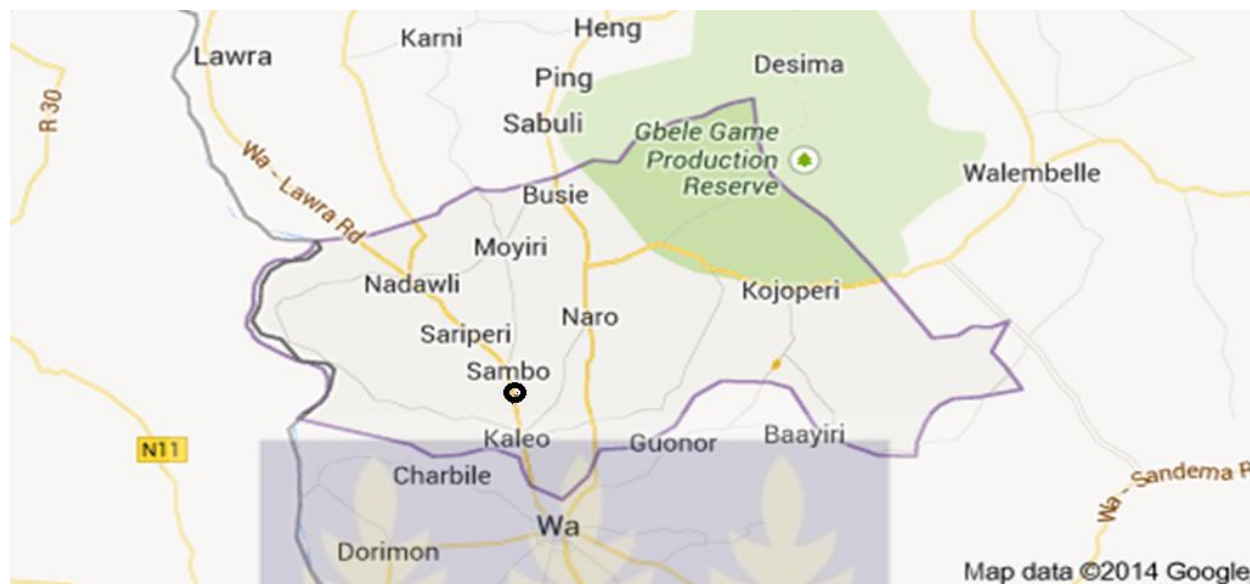


Figure 3.1: Geographical map of Nadowli District showing the sample point, Sombo

3.2.2 Jirapa District

It has a total area of 1667 square kilometers. It is bounded to the south by the Nadowli District, to the north by Lambussie-Karni District to the west by Lawra District, east by Sissala West District. It is about 62 Km from the regional capital, Wa.

The topography of the land is flat and low lying with the mean height of 300 m above sea level. The soil type is sandy-loam with underlying hard iron pans. There are narrow belts of alluvial soils along the tributaries of the Black Volta. Just like the rock types in the Nadowli District, the Jirapa District has Birimian formation having granite rocks that store significant amount of water. Sheet and gully erosions are common in the district.

The vegetation zone is guinea savanna woodland and trees dotted in the area. The main types of trees are shea, dawadawa, baobab and neem. The district is situated in the tropical continental climatic zone. The average annual temperature is between 28 °C to 31 °C. The rains start in June and end in October. These rains are induced by the moist monsoon winds.

The annual rainfall is between 1000 mm to 1100 mm. The continental air mass blowing from the Sahara is cold, dry and dusty between the months of November and March.

Figure 3.2 is the map of the Upper West Region showing all the districts in the region. The thick black circle shows the location of Jirapa in the Upper West Region of Ghana (http://en.wikipedia.org/wiki/Jirapa,_Ghana#mediaviewer/File:Upper_West_Ghana_districts.png 11/07/14). Appendix A7 illustrates the GPS location and the sampling points of the area.

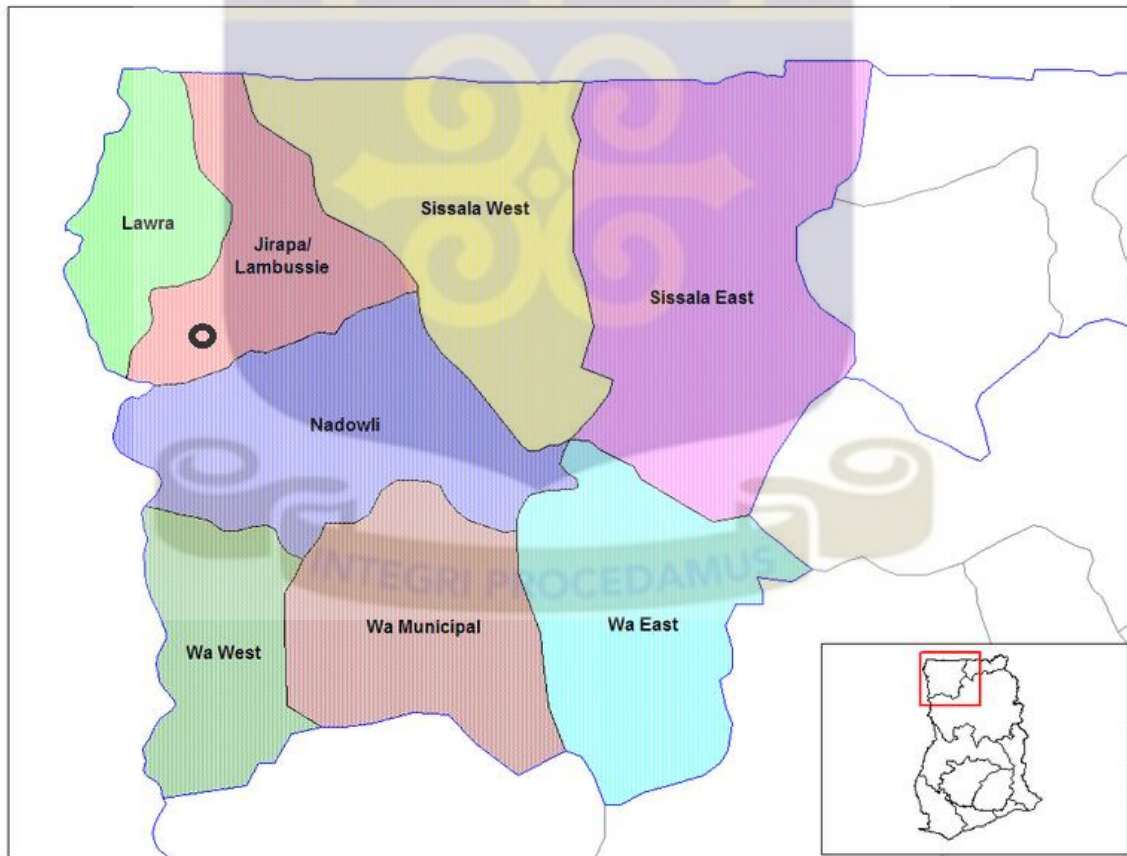


Figure 3.2: Map of Upper West Region of Ghana showing the Jirapa District

3.3 Method

3.3.1 Sampling

Before the sampling was done at Jirapa and Sombo, permission was sought from the Assembly Members of the areas and the Jirapa District Director of Health. The houses were randomly selected and the rationale of the project was explained to participants in the language that they best understood (Dagaare). Fifty houses were chosen from Jirapa but five people did not show interest and were subsequently left out. In Sombo, twenty houses were selected. All those from whom we sought consent agreed to take part in the project and were highly enthusiastic about learning more about radon.

Prior to the measurement, the houses were divided into old and new houses. An old house is defined as any house that is more than five years after its construction. This definition was chosen not based on the materials used but was arbitrarily selected. On smoking, only two houses had smokers (male smokers). No female smoker was found. The people were asked to declare their smoking status because cigarette has been found to be the major cause of lung cancer for smokers and even for partial smokers. The effect of cigarette and radon with regard to inducing lung cancer is multiplicative. It is exciting to note that many people in the study area either have never smoked or have completely stopped smoking. In addition, the volume of the bedrooms of participants were estimated using the builders' tape measure. Most of the rooms were rectangular in shape. The length, breadth and height of the rooms were taken and volume computed using the formula in equation 3.1.

$$V_R = L * B * H \quad (3.1)$$

Where:

V_R = volume of bedroom

L = length of bedroom

B = breadth of bedroom

H = height of bedroom

3.3.2 Description of the Continuous Radon Monitor (CRM) Model 1029

The 1029 continuous radon monitor was used to collect data from the Jirapa and Nadowli Districts. This instrument was manufactured by the Sun Nuclear Corporation to measure radon concentrations in the environment. It was designed to be used by home inspectors and building professionals. The model 1029 continuous radon monitor is very sensitive and has an inbuilt temperature, pressure and humidity sensors unlike its predecessors' models, 1027 and 1028, which lack these sensors.

This active device requires a standard 9 V battery to operate. An alkaline battery alone can support its operation for 100 hours. An AC adaptor could also be used but this must be supported with a battery source. Additionally, it can be operated on a lithium-ion battery for about 300 hours. The 1029 CRM has a 16-character display screen that shows the instructions on how to operate the device and also displays the results of the measurement. By the push of buttons data can be entered, parameters set, and report printed with the aid of a portable printer or a computer. This unit can be connected to the computer via USB or serial cable.

The device when in use is placed in a bed room or structure whose radon concentration is to be monitored. It is then left unattended to for a period of 24 hours. The surrounding air loaded with radon, diffuses into the chamber of the radon monitor. The space between the

base and the cover permits air to freely circulate in the monitor. The daughter products of radon progeny emit alpha particles. These alpha particles emitted are detected by photo diodes in the unit and then counted. In the process of the testing, the counts are stored in the memory of the monitor and converted to radon concentration in pCi/l with the aid of a stored calibration factor. When the test is over the concentration is displayed on the screen. This could be printed using a portable printer or a computer printer. The 1028 and 1029 monitors are shown in Figure 3.1.

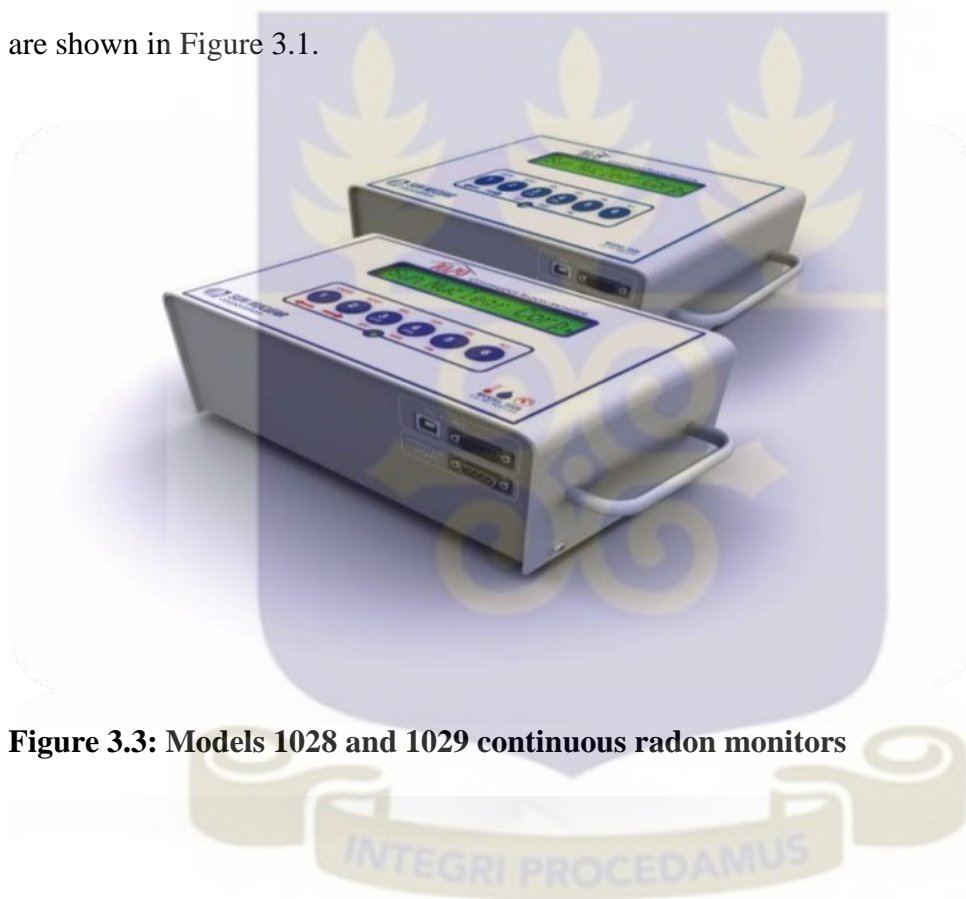


Figure 3.3: Models 1028 and 1029 continuous radon monitors

3.3.3 Measurement of Radon Activity Concentration

The radon monitor before it was used to collect data for this work was placed on a table about a meter high from the floor for a period of 24 hours. In the same room and the same time duration, the device was placed at two different positions. When the results were printed, it was realized that the concentration on the table top was less than the concentrations on the floor of the room at varied positions. Comparing placing the detector

on the floor with placing it a meter above the ground, putting it on the floor would be most appropriate. The reason is that occupants of the bedrooms are likely to be exposed more to radon at the floor level.

3.4 Comparison of Data

Radon activity concentration in old houses (houses that were five years and above) were compared with radon concentration in new houses. Also the amount of radon in cement block houses was also compared with the radon concentration in houses constructed from laterite blocks.

The 1029 continuous radon monitor recorded the time, temperature, humidity, pressure and the concentration of the bedrooms where it was placed. The detector measured the above parameters on an hourly interval for a period of twenty four hours and was calibrated with correction factors of 1.784 and 2.820. The arithmetic mean for the one day period was considered as the estimated concentration of radon, temperature, humidity and pressure for each bedroom.

The radon activity concentrations in some rooms were recorded for a period less than 24 hours. Only reading periods between 18 hours to 24 hours were accepted. Any other reading below the above range was rejected.

The monitor measured the radon activity concentration in Ci/l, the temperature in degree Fahrenheit, the pressure in inHg. All these units were converted to standard unit using the ICRP 65 dose conversion factors.

The annual equivalent dose was estimated using the relation in equation 3.2a

$$H_{RN} = C_{RN} * D * F * T \quad (3.2a)$$

Where:

H_{RN} = annual equivalent dose

C_{RN} = measured radon activity concentration in Bqm^{-3}

F = the radon equilibrium factor indoors (0.4)

T = the indoor occupancy time (80%) = 7000 h/y

H = indoor occupancy factor (0.8)

D = the dose conversion factor ($9.0 * 10^{-6}$ mSv/h per Bqm^{-3})

3.4.1 Sample Calculation of Annual Equivalent Dose

The average radon activity concentration for Jirapa was $32.3 Bqm^{-3}$.

Therefore from equation 3.2a, the annual equivalent dose will be:

$$H_{RN} = 32.3 * 9.0 * 10^{-6} * 7000 * 0.4 * 0.8 \quad (3.2b)$$

$$= 0.651168 \text{ mSvy}^{-1}$$

$$= 0.65 \text{ mSvy}^{-1}$$

$$H_{RN} = 0.65 \text{ mSvy}^{-1}$$

Therefore the annual equivalent dose estimated from Jirapa was 0.65 mSvy^{-1}

The arithmetic mean of the radon activity concentration calculated from Sombo was 39.2

Bqm^{-3}

$$H_{RN} = C_{RN} * D * F * T \quad (3.2c)$$

Substituting the parameters into equation 3.2c

We have:

$$H_{RN} = 39.2 * 0.4 * 7000 * 0.8 * 0.000009 \quad (3.2d)$$

$$= 0.790272 \text{ mSvy}^{-1}$$

$$= 0.79 \text{ mSvy}^{-1}$$

$$\therefore H_{RN} = 0.79 \text{ mSvy}^{-1}$$

The effective dose E, was also estimated with the help of equation 3.3

$$E = H_{RN} * W_R * W_T \quad (3.3)$$

Where:

E= annual effective dose

H_{RN} = annual equivalent dose

W_R = radiation weighting factor for alpha particle (20)

W_T = tissue weighting factor for lung (0.12)

3.4.2 Sample Calculation of Annual Effective Dose

Equation 3.3 was used to estimate the equivalent dose as:

$$E = H_{RN} * W_R * W_T$$

But H_{RN} for Jirapa is 0.65 mSvy^{-1}

Then,

$$E = 0.65 * 20 * 0.12$$

$$= 1.56 \text{ mSvy}^{-1}$$

$$\therefore E = 1.56 \text{ mSvy}^{-1}$$

Also, in Sombo the H is 0.79 mSvy^{-1}

$$E = 0.79 * 20 * 0.12$$

$$= 1.89 \text{ mSvy}^{-1}$$

$$\therefore E = 1.9 \text{ mSvy}^{-1}$$

3.5 Statistical Analysis of Data

The square of the coefficient of correlation also known as the linear coefficient of determination was used to compare the effect of temperature and humidity on radon infiltration in each room. The term coefficient of determination will be used throughout this work.

The coefficient of determination (r^2) is the square of the correlation coefficient, r . It explains the extent to which y varies from the regression line using x as the predicting element. For example if $r = 0.95$, then $r^2 = 0.90$ is the coefficient of determination. It can therefore be said that about 90 % of the variation of y can be explained by the behaviour of x using linear regression as the statistical tool and the remaining 10 % of the variation is due to chance or

other factors besides x that may be affecting y . The formula for r and r^2 are illustrated in equations 3.3 and 3.4

$$r = \frac{n(\sum xy - (\sum x)(\sum y))}{\sqrt{n(\sum x^2) - (\sum x)^2} \sqrt{n(\sum y^2) - (\sum y)^2}} \quad (3.3)$$

$$\text{Let } z = \frac{n(\sum xy - (\sum x)(\sum y))}{\sqrt{n(\sum x^2) - (\sum x)^2} \sqrt{n(\sum y^2) - (\sum y)^2}}$$

$$\text{Then, } r^2 = z^2 \quad (3.4)$$

Where:

r = linear correlation coefficient for sample data

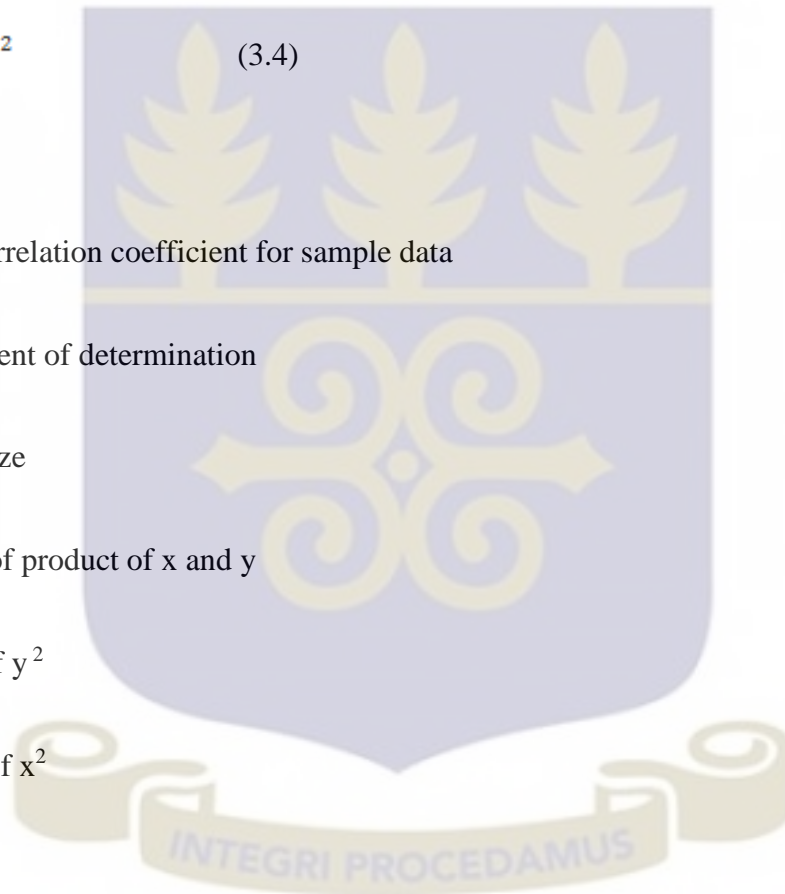
r^2 = coefficient of determination

n = sample size

$\sum xy$ = sum of product of x and y

$\sum y^2$ = sum of y^2

$\sum x^2$ = sum of x^2



CHAPTER FOUR

RESULTS AND DISCUSION

This chapter discusses the radon levels in Jirapa and Sombo and also the effect of temperature, humidity, pressure and volume of the rooms on indoor radon infiltration.

The result from Jirapa town is shown on Table 4.1.

4.1 Radon Concentration

4.1.1 Radon Activity Concentration in Jirapa

From Table 4.1 the mean radon concentration for Jirapa was 32.3 ± 7.2 Bqm⁻³, with a standard deviation of 22.7 Bqm⁻³. The average temperature was 29.3 ± 6.5 °C and humidity of 22.8 %.

Table 4.1: Radon activity concentration, temperature, humidity and pressure from Jirapa

CODE	CONCENTRATION (Bqm ⁻³)	TEMPERATURE (°C)	HUMIDITY (%)	PRESSURE (mmHg)
JMS	43.1 ± 4.9	30.4 ± 0.5	16.0 ± 0.3	735.8±0.2
JLT	18.8 ± 2.6	25.8 ± 0.3	11.8 ± 0.5	736.5±0.2
JEP	33.7 ± 3.6	30.2 ± 0.6	20.6 ± 0.9	737.0±0.3
JAL	11.7 ± 1.7	30.5 ± 0.3	35.7 ± 2.4	736.1±0.9
JSA	19.7 ± 2.4	29.2 ± 1.6	14.3 ± 0.3	736.6±0.0
JBC	27.0 ± 2.7	29.7 ± 0.2	29.4 ± 1.3	736.1±0.2
JPR	25.3 ± 3.2	26.8 ± 1.3	18.2 ± 0.7	737.4 ±0.3
JTA	18.8 ± 1.9	28.9 ± 0.2	29.5 ± 0.4	737.8±0.6
JTO	43.3 ± 4.9	28.4±0.3	30.4±2.2	737.6±0.3
JFR	12.0 ± 1.4	27.6 ± 0.2	13.6 ± 0.3	738.1±0.3
JMR	12.0 ± 1.8	29.6 ± 0.2	9.2 ± 0.3	735.2±0.3
JFE	70.0 ± 8.9	29.8 ± 0.2	14.7 ± 0.5	736.4±0.2
JLA	40.7 ± 4.5	30.4 ± 0.5	14.3 ± 0.3	736.0±0.2
JMO	25.6 ± 3.3	30.6 ± 0.3	24.6 ± 0.8	736.8±0.3
JKB	39.9 ± 3.7	32.4 ± 0.2	28 ± 2.3	734.7±0.3
JAM	27.7 ± 4.8	31.4 ± 0.8	11.9 ± 1.0	733.7±0.2
JNA	25.2 ± 4.3	30.4 ± 0.4	25.0 ± 0.7	737.5±0.3
JHU	21.0 ± 3.1	29.0 ± 0.3	24.0 ± 0.8	736.5±0.5
JLW	108.5 ± 10.3	28.3 ± 0.2	25.9 ± 1.2	736.7±0.2
JDC	22.2 ± 3.1	27.4 ± 0.1	56.4 ± 1.0	739.7±0.3

The bedroom JLW registered the highest radon concentration in Jirapa town of 108.5 ± 10.3 Bqm⁻³. This bedroom was constructed with landcrete blocks, it had one small window and was seven years old at the time of this study. The walls were neither rendered nor plastered and four people were living in the room. There was a cigarette smoker in the household.

The high level of radon in this room could be attributed to poor ventilation. Not only was the window small but also the room was congested with household materials, thereby impeding the free circulation of fresh air into the room. Radon from the building materials (landcrete blocks) might have also added to the radon activity concentration in this room, since the walls were neither rendered nor plastered. Another plausible reason could be that the soil on which the foundation of the house was laid may be having large amount of U-238 or Ra-226. These elements contribute significantly to radon production when they decay. However, limited time could not permit the investigator to study radon levels in the soil. The smoker could increase the risk of members of his household to developing lung cancer since cigarette smoke has a high probability of causing lung cancer.

The least radon concentration was observed from the bedroom with code JAL. Room JAL was build using sandcrete blocks, it was plastered, rendered and its volume was 37.5 m³. The house was about ten years old at the time of this research. It had two large windows and only one occupant. The low concentration of 11.7 Bqm⁻³ may be due to good ventilation. The rendering and plastering of the building could have reduced radon emanation from the building materials. It could be inferred that the sandcrete blocks contained small amount of radium or U-238. The absence of cracks on the walls and the floor prevented radon from infiltrating from the ground. The radon level in this bedroom is about ten times less than the radon activity concentration of room JLW.

Room JFE had a radon activity concentration value of 70.0 Bqm^{-3} . The radon values for the rest of the rooms ranged from 12.0 Bqm^{-3} to 43.3 Bqm^{-3} . These values are far below the action level of 100 Bqm^{-3} recommended by the World Health Organisation (WHO, 2009).

Figure 4.1 shows a graph of radon concentration against bedroom codes.

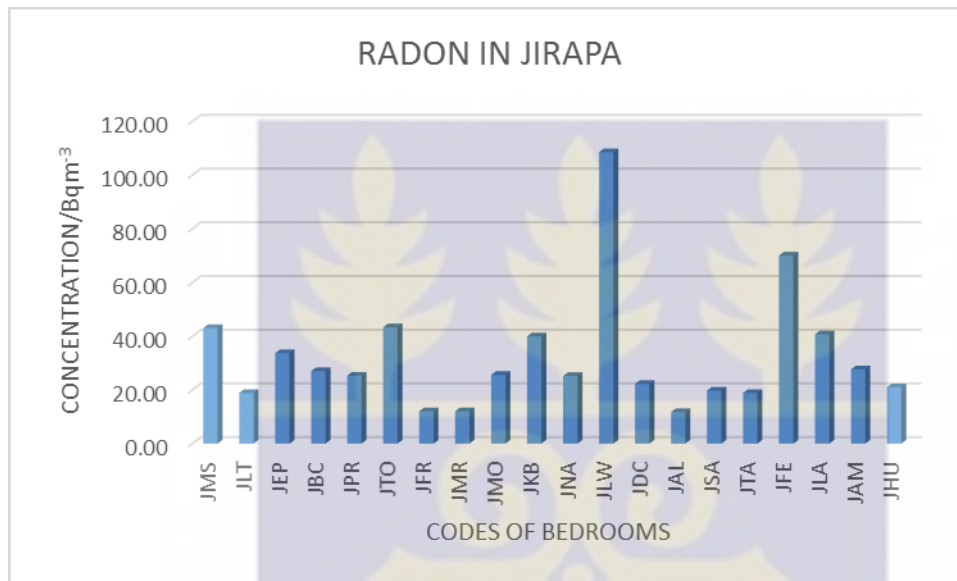


Figure 4.1: Radon concentration against bedroom codes in Jirapa



4.1.2 Radon Concentration in Sombo

Table 4.2: Radon concentration, temperature, humidity and pressure from Sombo

CODE	CONCENTRATION (Bqm ⁻³)	TEMPERATURE (°C)	HUMIDITY (%)	PRESSURE (mmHg)
SAA	38.2 ± 2.0	31.2 ± 0.4	34.0 ± 1.1	736.4 ± 0.3
SVI	36.4 ± 4.3	31.5 ± 0.4	45.9 ± 1.2	735.3 ± 0.3
SKY	229.6 ± 15.2	28.1 ± 0.2	58.9 ± 0.5	737.4 ± 0.3
SRA	23.5 ± 3.3	32.4 ± 0.3	33.8 ± 3.0	735.6 ± 0.3
SNY	35.2 ± 5.6	32.9 ± 0.6	21.8 ± 1.2	735.4 ± 0.3
SGA	16.4 ± 3.1	32.4 ± 0.3	48.7 ± 1.3	736.6 ± 0.4
SSA	10.2 ± 1.4	30.9 ± 0.7	52.0 ± 1.4	736.4 ± 1.0
SFR	19.9 ± 4.1	32.3 ± 0.2	52.6 ± 0.5	734.1 ± 0.9
SSI	15.3 ± 3.2	30.3 ± 6.3	56.5 ± 11.8	735.6 ± 0.3
SGB	32.2 ± 6.6	30.7 ± 6.3	52.9 ± 10.8	736.3 ± 0.3
SFA	24.2 ± 4.9	32.6 ± 6.7	48.9 ± 10.0	735.8 ± 0.3
SFD	23.0 ± 4.2	32.3 ± 0.2	52.2 ± 0.5	734.1 ± 0.3
SVT	37.9 ± 7.7	30.7 ± 6.3	13.9 ± 2.8	734.9 ± 0.2
SKG	35.3 ± 2.9	33.0 ± 0.4	50.3 ± 0.8	735.3 ± 0.3
SSO	8.8 ± 1.8	31.0 ± 6.3	49.1 ± 10.0	737.2 ± 0.3
SCH	28.4 ± 5.8	31.4 ± 6.4	49.0 ± 10.0	736.0 ± 0.3
SNA	31.5 ± 6.5	27.6 ± 5.6	66.2 ± 13.5	735.1 ± 0.3
SSU	60.0 ± 8.5	31.4 ± 0.3	17.3 ± 1.1	735.6 ± 0.4

Eighteen homes were monitored in Sombo as shown in Table 4.2. The mean radon activity concentration was 39.2 Bqm⁻³. Home SKY was found to have had the highest radon concentration of 229.2 Bqm⁻³. This dwelling was constructed from landcrete blocks, the building was old (that is the building was more than five years) and had four people living in it. The volume of the room was 39.34 m³. The average temperature of this room was 28.1 °C and its humidity was 58.9 %. The only window to this room was somewhat small compared to the volume of the room. There are a myriad of factors that could have accounted for this high radon value. For instance, the composition of the sub-soil could be one of the factors, and the soil adsorptivity and permeability could be another. The design and construction of the home, cracks on the structure, wind velocity and even the radon content of the

bedroom's natural gas may be the rest of the factors that could impact on radon level in this room.

The remaining bedrooms have their radon levels between 8.8 Bqm⁻³ and 38.2 Bqm⁻³. Home SSO had the least radon value of 8.8 Bqm⁻³. This is surprising because SSO is an adobe bedroom. Naturally, adobe houses are expected to have elevated levels of radon due to the design and construction and also the building materials employed. The low radon concentration in SSO may be due to low content of U-238 or Ra-266 in the soil because, the soil on which the foundation of the house was laid was the same soil used to mould the landcrete blocks. Also the room was larger than the normal bedroom volume, this might have improved the ventilation in the room. In addition, the logs used as pillars and part of the ceiling materials did not contribute any significant radon levels to this room. The value is twenty-six times less than the value of the highest radon concentration. Figure 4.2 shows radon concentration verses bedroom codes.

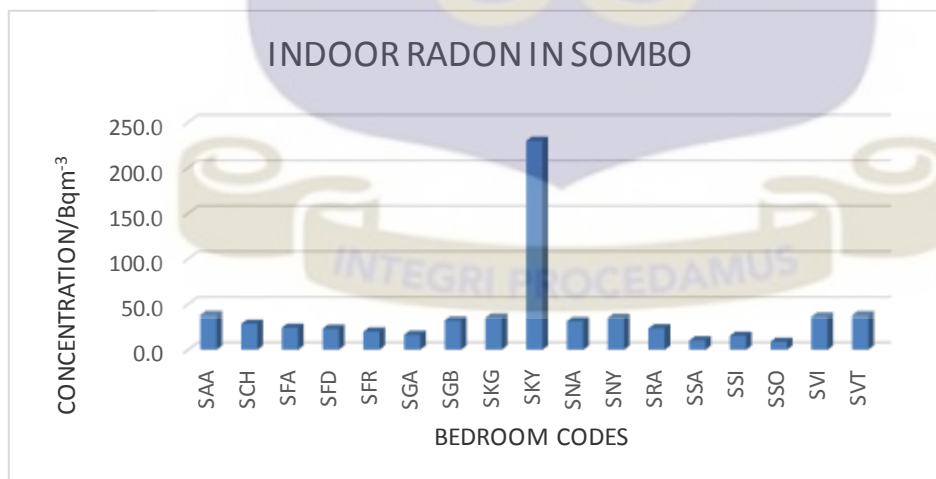


Figure 4.2: A bar chart of radon concentration against bedroom codes in Sombo

4.2 Effect of Temperature on Indoor Radon Concentration

Studies on the effect of temperature and radon infiltration abound (Girault, et al., 2011; Gregoric et al., 2011). All these investigations corroborate the effect of temperature on radon emanation. Likewise, in this study, the temperature coefficient of determination (r^2) was computed using Microsoft excel, and used to compare the extent to which indoor radon level depended on temperature.

Table 4.3 illustrates the coefficient of determination for concentration and temperature for each room studied in Jirapa.

Room JLT has r^2 value of 0.42; the implication is that 42% of the radon recorded in this room depended on temperature and the remaining 58 % depended on other factors. In other words, there is a moderate negative correlation between the seeping of radon into the room and the temperature of the room as shown in Figure 4.3.

Also, JHU has a coefficient of determination of 0.38 and hence a moderate correlation coefficient of 0.65. Rooms JAM, JLA, JTA and JBC have coefficient of determinations ranging from 0.19 to 0.25. This means that the influence of temperature on indoor radon in these rooms varied from 19 % to 25 %. However, the radon activity in JTO and JMO are almost independent of their rooms' temperatures. Factors other than temperature determined the radon levels in these rooms.

In Sombo, the largest coefficient of determination for radon activity concentration due to temperature was 0.46 as shown in Table 4.4. This value was recorded in room SNY. The radon concentration in this room was 35.2 Bqm^{-3} and 46 % of this value was due to the ambient temperature of the room. The coefficient of correlation in this room was 0.68 and a graph of radon activity concentration against temperature is shown in Figure 4.3. The graph

has a slope of $-6.2 \text{ Bqm}^{-3} \text{ }^{\circ}\text{C}^{-1}$. The negative sign indicates that indoor radon activity concentration is inversely proportional to the room's temperature. The higher the temperature the lower the radon accumulation in the room. Room SCH has the second highest coefficient of determination of 0.37 and a negative moderate coefficient of correlation of 0.61. The r^2 value of room SKY was 6×10^{-6} and hence the effect of temperature on the indoor radon levels in this room could be ignored. The other remaining rooms did not show any strong effect of temperature on the radon activity concentration.

Table 4.3: Coefficient of determination for radon activity concentration due to temperature in Jirapa

CODE	CONCENTRATION (Bqm^{-3})	TEMPERATURE ($^{\circ}\text{C}$)	COEFFICIENT OF DETERMINATION (r^2)
JMS	43.1	30.4	0.1384
JLT	18.8	25.8	0.3643
JEP	33.7	30.2	0.2685
JAL	11.7	30.5	0.0117
JSA	19.7	29.2	0.0104
JBC	27.0	29.7	0.0150
JPR	25.3	26.8	0.5165
JTA	18.8	28.9	0.2890
JTO	43.3	28.4	0.3335
JFR	12.0	27.6	0.0208
JMR	12.0	29.6	0.1899
JFE	70.0	29.8	0.1036
JLA	40.7	30.4	0.0104
JMO	25.6	30.6	0.0582
JKB	39.9	32.4	0.0515
JAM	27.7	31.4	0.2166
JNA	25.2	30.4	0.0984
JHU	21.0	29.0	0.2828
JLW	108.5	28.3	0.2815
JDC	22.2	27.4	0.0490

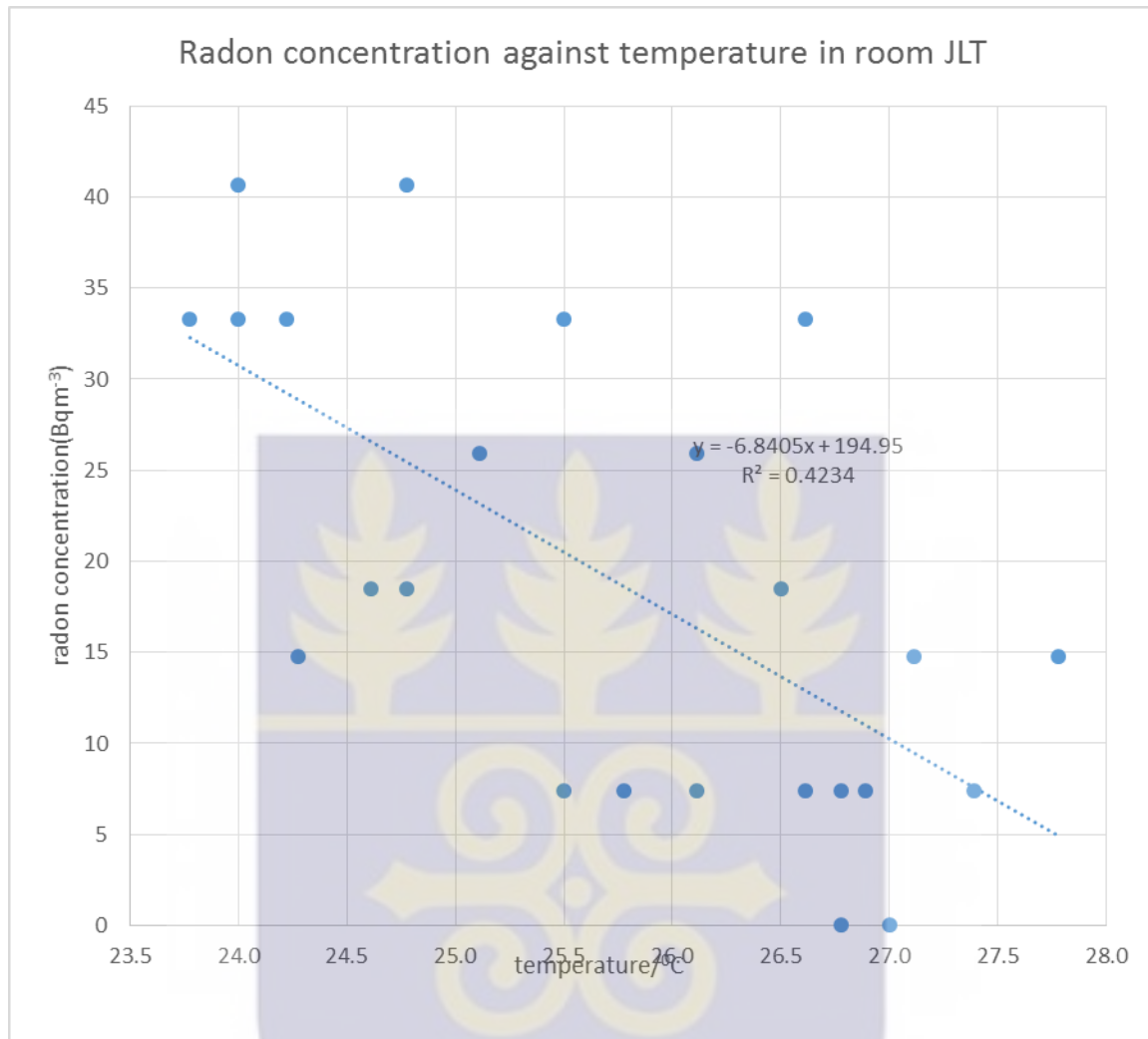
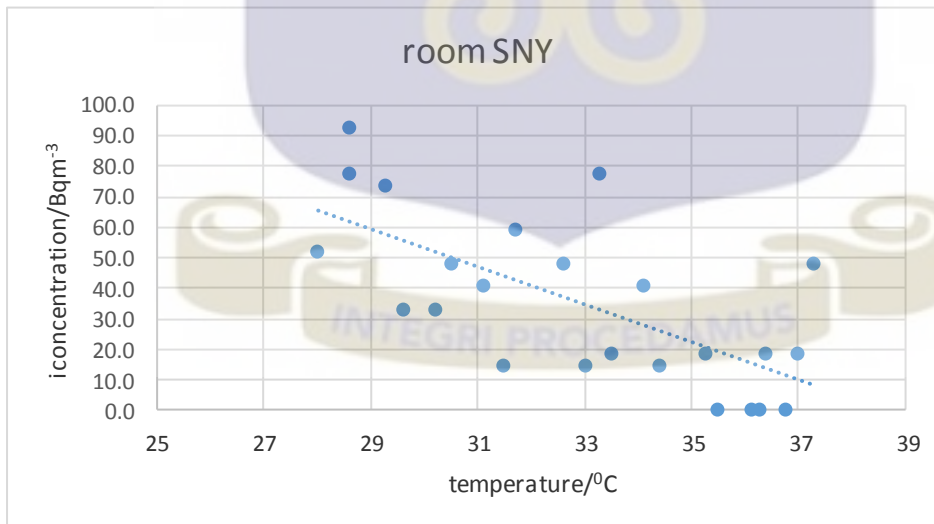


Figure 4.3: Radon concentration against temperature in bedroom JLT



Figure 4.4: Coefficient of determination of radon activity concentration due to temperature in Sombo

CODE	RADON CONCENTRATION (Bqm ⁻³)	TEMPERATURE (°C)	COEFFICIENT OF DETERMINATION
SAA	38.2 ± 2.0	31.2 ± 0.4	0.0219
SVI	36.4 ± 4.3	31.5 ± 0.4	0.0347
SKY	229.6 ± 15.2	28.1 ± 0.2	0.0241
SRA	23.5 ± 3.3	32.4 ± 0.3	0.2082
SNY	35.2 ± 5.6	32.9 ± 0.6	0.4590
SGA	16.4 ± 3.1	32.4 ± 0.3	0.0307
SSA	10.2 ± 1.4	30.9 ± 0.7	0.0356
SFR	19.9 ± 4.1	32.3 ± 0.2	0.0091
SSI	15.3 ± 3.2	30.3 ± 6.3	0.1865
SGB	32.2 ± 6.6	30.7 ± 6.3	0.0315
SFA	24.2 ± 4.9	32.6 ± 6.7	0.2420
SFD	23.0 ± 4.2	32.3 ± 0.2	0.0352
SVT	37.9 ± 7.7	30.7 ± 6.3	0.0538
SKG	35.3 ± 2.9	33.0 ± 0.4	0.0000
SSO	8.8 ± 1.8	31.0 ± 6.3	0.2359
SCH	28.4 ± 5.8	31.4 ± 6.4	0.3734
SNA	31.5 ± 6.5	27.6 ± 5.6	0.0215
SSU	60.0 ± 8.5	31.4 ± 0.3	0.0283

**Figure 4.4 radon concentration against temperature in room SNY (Sombo)**

4.3 Effect of Humidity on Radon Emanation

Relative humidity may have some effect on radon infiltration. Table 4.4 below shows the coefficients of determination for radon concentration and humidity for Jirapa. From the table, the highest coefficient of determination is 0.52 and this was recorded in room JPR. What this means is that, 51% of the radon concentration (25.3 Bqm^{-3}) in room JPR may be caused by the humidity in the room. A graph of radon activity concentration plotted against humidity is shown in Figure 4.4. Following room JPR is JTL with r^2 value of 0.36; indicating that 36 % of the radon activity in room JTL was as a result of the room's relative humidity. But the radon activity in rooms JSA and JLA which have the same r^2 value of 0.0104 was almost independent of the humidity. That is, there is little or no correlation between relative humidity and radon concentrations in these rooms. A graph of the coefficient of determination of radon concentration against humidity is shown on Figure 4.5. The result from Sombo did not show any significant effect of humidity on radon infiltration as shown in Table 4.6. This is understandable because the study was conducted in the dry season. During the dry season the humidity of the area does not change significantly.



Table 4.4: Coefficient of determination for radon activity concentration due to humidity in Jirapa

CODE	CONCENTRATION (Bqm ⁻³)	HUMIDITY (%)	COEFFICIENT OF DETERMINATION (r ²)
JMS	43.1	30.4	0.1384
JLT	18.8	25.8	0.3643
JEP	33.7	30.2	0.2685
JAL	11.7	30.5	0.0117
JSA	19.7	29.2	0.0104
JBC	27.0	29.7	0.015
JPR	25.3	26.8	0.5165
JTA	18.8	28.9	0.289
JTO	43.3	28.4	0.3335
JFR	12.0	27.6	0.0208
JMR	12.0	29.6	0.1899
JFE	70.0	29.8	0.1036
JLA	40.7	30.4	0.0104
JMO	25.6	30.6	0.00582
JKB	39.9	32.4	0.0515
JAM	27.7	31.4	0.2166
JNA	25.2	30.4	0.0984
JHU	21.0	29.0	0.2828
JLW	108.5	28.3	0.2815
JDC	22.2	27.4	0.049

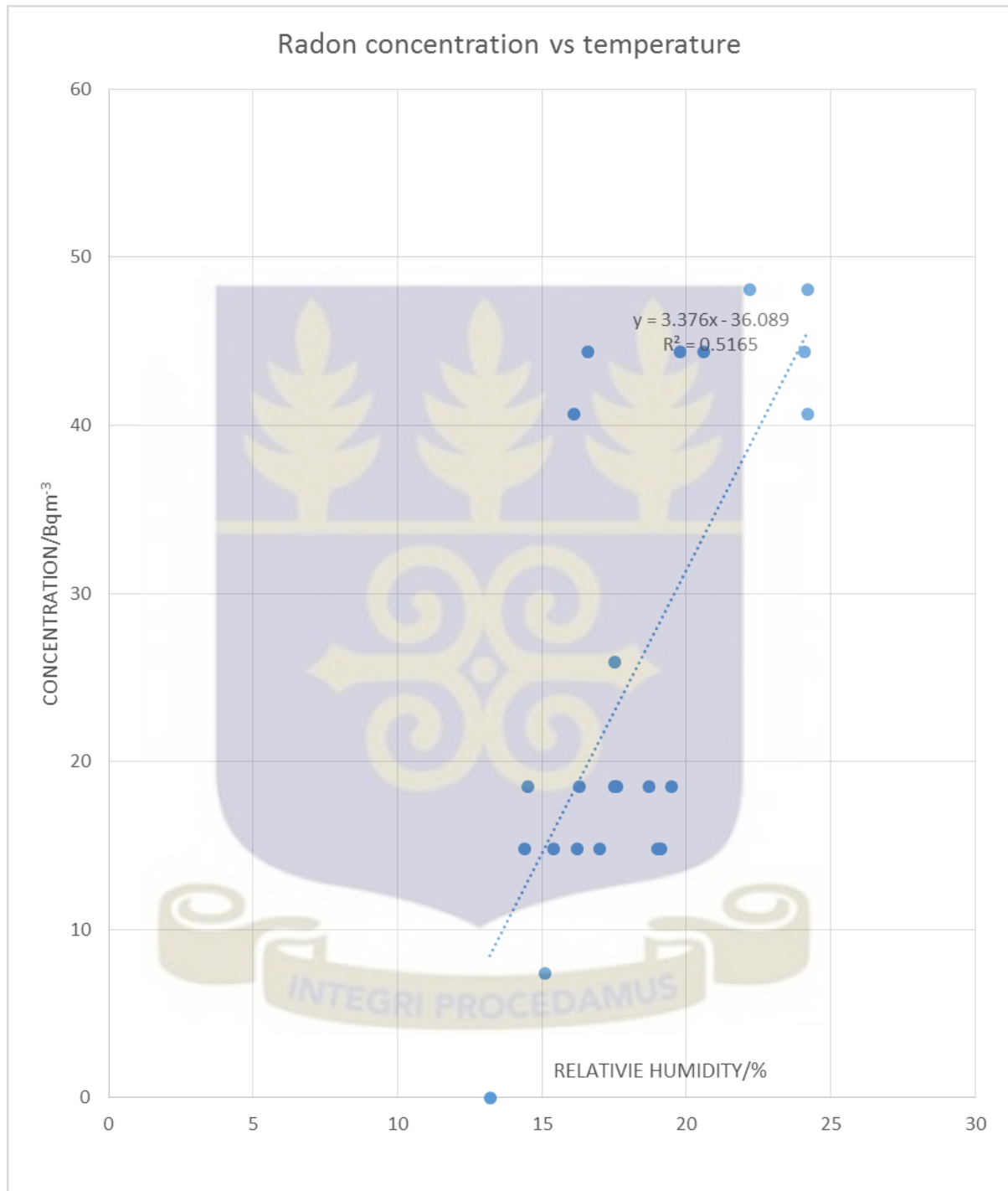


Figure 4.5: Radon concentration against humidity in bedroom JPR

Table 4.5: Coefficient of determination for radon activity concentration due to humidity in Sombo

CODE	RADON CONCENTRATION (Bqm ⁻³)	HUMIDITY (%)	COEFFICIENT OF DETERMINATION
SAA	38.2 ± 2.0	34.0 ± 1.1	0.0081
SVI	36.4 ± 4.3	45.9 ± 1.2	0.0025
SKY	229.6 ± 15.2	58.9 ± 0.5	0.0033
SRA	23.5 ± 3.3	33.8 ± 3.0	0.0068
SNY	35.2 ± 5.6	21.8 ± 1.2	0.0150
SGA	16.4 ± 3.1	48.7 ± 1.3	0.1902
SSA	10.2 ± 1.4	52.0 ± 1.4	0.0024
SFR	19.9 ± 4.1	52.6 ± 0.5	0.0288
SSI	15.3 ± 3.2	56.5 ± 11.8	0.0008
SGB	32.2 ± 6.6	52.9 ± 10.8	0.2184
SFA	24.2 ± 4.9	48.9 ± 10.0	0.2577
SFD	23.0 ± 4.2	52.2 ± 0.5	0.0115
SVT	37.9 ± 7.7	13.9 ± 2.8	0.0032
SKG	35.3 ± 2.9	50.3 ± 0.8	0.0000
SSO	8.8 ± 1.8	49.1 ± 10.0	0.1953
SCH	28.4 ± 5.8	49.0 ± 10.0	0.1730
SNA	31.5 ± 6.5	66.2 ± 13.5	0.0260
SSU	60.0 ± 8.5	17.3±1.1	0.0639

4.4. Combined effect of Temperature and Humidity on Indoor Radon Levels

The effect of only temperature or humidity on indoor radon activity may be negligible but the combined effect of these two parameters could contribute greatly to residential radon. For example the sum of the coefficients of determination for both humidity and temperature in room JLT was 0.79 as shown in Table 4.7. Thus, 78.8 % of the radon in this room could be attributed to the temperature and the humidity in the room. The total r^2 value for temperature and humidity for room JPR was 0.67; hence 67 % of the radon value in this room was also due to temperature and humidity.

Table 4.6: Sum of the coefficient of determination of radon due temperature and humidity in Jirapa

CODE	r ² due to radon concentration (Bqm ⁻³) and temperature(°C)	r ² due to radon concentration and relative humidity (%)	Sum of r ² values
JPR	0.1510	0.5165	0.6675
JLT	0.4234	0.3643	0.7877
JTO	0.0001	0.3335	0.3336
JTA	0.2152	0.2890	0.5042
JHU	0.3783	0.2828	0.6611
JLW	0.0740	0.2815	0.3555
JEP	0.0078	0.2685	0.2763
JAM	0.2493	0.2166	0.4659
JMR	0.0227	0.1899	0.2126
JMS	0.0026	0.1384	0.1410
JFE	0.0992	0.1036	0.2028
JNA	0.0952	0.0984	0.1936
JMO	0.0000	0.0582	0.0582
JKB	0.0534	0.0515	0.1049
JDC	0.1066	0.0490	0.1556
JFR	0.0032	0.0208	0.0240
JBC	0.1944	0.0150	0.2094
JAL	0.0468	0.0117	0.0585
JLA	0.2283	0.0104	0.2387
JSA	0.0154	0.0104	0.0258

4.4.1 Effect of Pressure on Radon Infiltration

A mean pressure of 736.6±0.9 mmHg was registered in Jirapa area. The rooms recorded 735.8 mmHg as the highest pressure and 733.7 mmHg as the least pressure. The pressure observed in Sombo ranged from 734.1 to 737.3 mmHg, with an average pressure of 735.7±0.9 mmHg. The research was conducted in the dry season (from January to April) and during the dry season significant changes of pressure do not normally occur in Sombo and Jirapa. It is therefore not surprising that the pressure has no significant effect on the radon activity concentration in the rooms. Appendices A4 and A5 show the coefficient of determination due to pressure in Jirapa and Sombo respectively.

4.5 Effect of Volume of Rooms on Radon Emanation

A study on the spatial and volumetric variations of radon conducted by Sathish in Bangalore, a city in India, concluded that radon concentration is inversely proportional to the volume of the room (Sathish et al., 2010). A similar investigation on the environmental safety of natural and manufactured building materials in Egypt seems to corroborate Sathish's findings (Kamal et al, 2011).

Similarly in this study, the radon concentration of room JFR is almost four times its volume, that of room JMR is approximately three times its volume and the radon activity of room JLT is also about three times the volume of the room. Additionally, the volume of room JLW is thrice its radon activity.

In Sombo, the volume of SKY was six times less than its radon concentration and that of SGA was about thrice its radon activity. Room SSA's radon concentration was four times less than its volume and the volume of SSI was twice its radon concentration. This trend agrees with Sathish's result. Thus the radon concentration of a bedroom and its volume has an inverse relation. Tables 4.7 and 4.8 show the codes, radon activity and volumes of bedrooms in Jirapa and Sombo respectively. Figures 4.6 and 4.7 are bar charts that give a pictorial view of the relationship between radon accumulation in a room and the volume of the room in Jirapa and Sombo respectively.

Table 4.7: Radon activity concentration and volume of bedrooms in Jirapa

CODE	RADON CONCENTRATION (Bqm ⁻³)	VOLUME(m ³)
JMS	43.1	41.2
JLT	18.81	48.8
JEP	33.7	24.7
JBC	27.0	41.2
JPR	25.3	32.4
JTO	43.3	28.4
JFR	12.0	43.9
JMR	12.0	38.8
JMO	25.6	31.0
JKB	40.0	46.6
JNA	25.2	14.1
JLW	108.5	38.4
JDC	22.2	37.2

Table 4.8: Radon activity Concentration and volume of Bedrooms in Sombo

CODE	RADON CONCENTRATION/Bq ⁻³	ACTIVITY Volume/m ³
SAA	38.2±2.0	37.9
SSU	60.0±8.5	48.3
SVI	36.4±4.3	41.3
SSA	10.2±1.4	43.1
SSI	15.3±3.2	37.1
SGA	16.4±3.1	6.5
SKY	229.6±15.2	39.4

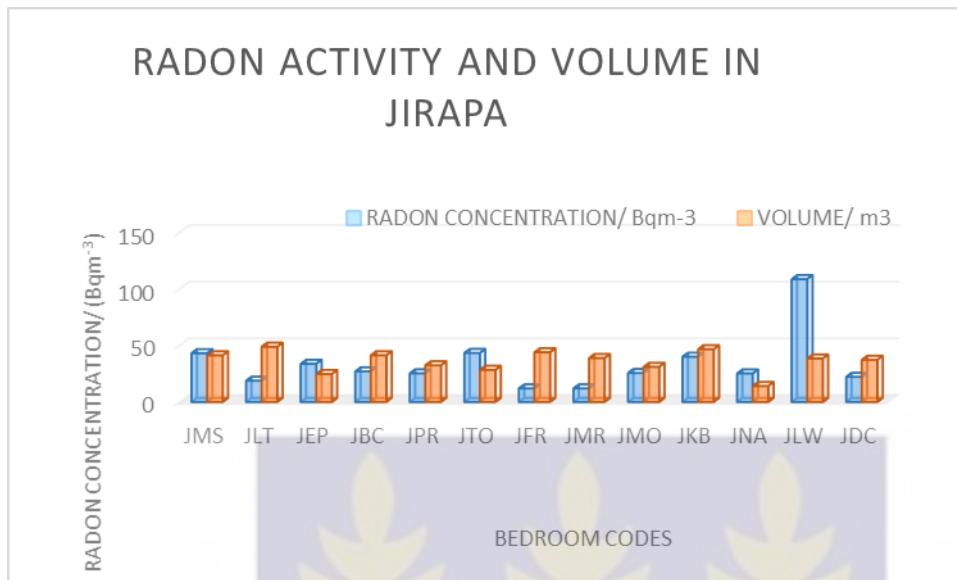


Figure 4.6: A bar chart on indoor radon activity concentration and volume of bedrooms in Jirapa

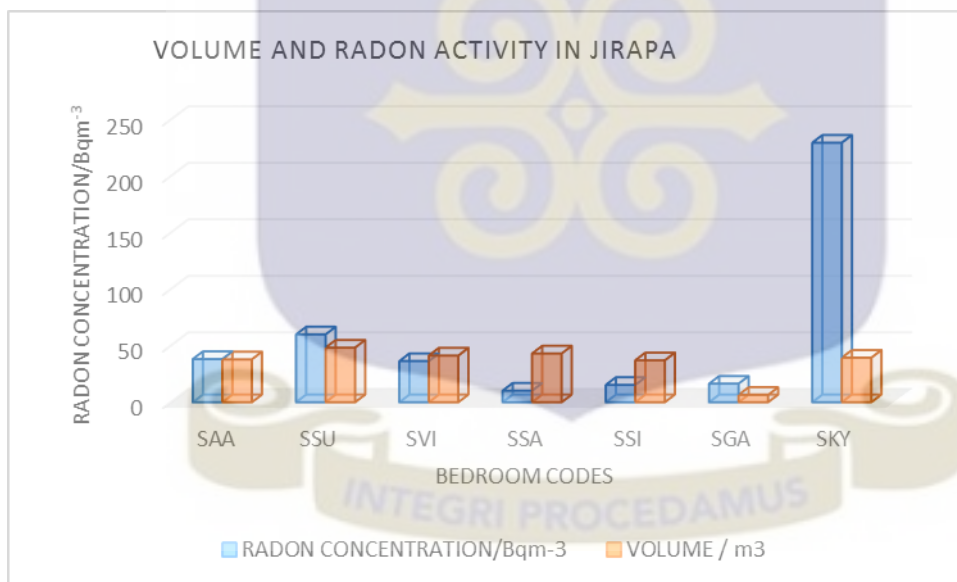


Figure 4.7: A bar chart on indoor radon activity concentration and volume of bedrooms in Sombo

4.6 Annual Effective Dose

The annual effective dose in Jirapa ranged from 0.06 to 5.26 mSvy⁻¹ with the overall average of 1.5 mSvy⁻¹. The NCRP (2009) report number 116 recommends 1.0 mSvy⁻¹ for the general public. This shows that the effective dose in Jirapa is slightly above the recommended 1.0 mSvy⁻¹ but may not pose any serious health hazards. However, JLW and JFE need immediate remedial measures because their values are far beyond the 1.0 mSvy⁻¹ as given in Appendix A1.

The mean annual effective dose in Sombo was 1.9 mSvy⁻¹ with the range between 0.40 to 11.12 mSvy⁻¹ as shown in Appendix A2. Bedroom SKY requires urgent action to apply appropriate mitigation to reduce radon activity concentration in the room.

4.7. Some Radon Studies in Ghana

Many studies on radon have been conducted in Ghana. Residential radon, soil radon and radon in water are some of the areas studied. Most of these studies were done in the southern part of Ghana with very little or no studies in some parts of the North. A study on the radon levels in adobe houses is one of the classic radon investigations in the Kassena Nankana area of the Upper East Region of Ghana. This study revealed that the radon concentration in the area ranged from 35.28 to 244.22 Bqm⁻³ with an arithmetic mean of 130.03 Bqm⁻³ (Quashie et al., 2011). These values are higher than the mean concentrations of Sombo and Jirapa. The current study area recorded 35.5 Bqm⁻³ for the mean radon concentration. Though the Kassena Nankana area may have similar geological parameters, the meteorological conditions could vary sharply. Also, the investigation in the Upper East Region was based on adobe houses only but this study considered all manner of houses; therefore the vast difference in the radon concentrations of the two studies is to be expected. The detectors used in the monitoring and the period of the monitoring could contribute to the great

difference in the mean radon values. In the Kassena Nankana District, the passive L115 nuclear track detectors were used and the detectors were put in the rooms for about three months. However, in this study the model 1029 continuous radon monitor was used and the detector was placed in bedrooms for a period of twenty four hours. A similar study in Dome reported a mean radon concentration of 466.9 Bqm^{-3} (Nsaih-Akoto et al., 2011). The radon levels in Dome is also higher than the mean radon concentration of the current study. The Dome's value is about thirteen times higher than the radon levels in Sombo and Jirapa. It is obvious that the geological and meteorological conditions in Dome-Accra are not similar to the conditions in Jirapa and Sombo. Therefore, the large difference in the radon concentration is not surprising. In addition the settlement in Jirapa and Sombo are dispersed while that of Dome is closed. Close settlements are most likely to experience challenges in ventilation, which could be a fertile ground for indoor radon accumulation than in dispersed settlements.

Parallel studies conducted in Biakpa registered radon activity of 80.4 Bqm^{-3} and 144.4 Bqm^{-3} in Prestea. Other research work in the South Eastern part of Ghana and Sakumono reported 518.7 and 10.78 Bqm^{-3} respectively (Nsiah- Akoto, 2010).

4.8 Provisional Radon Map of Ghana

This radon map, is a tentative radon map of Ghana based on some studies on radon done in Ghana and it covers six out of the ten regions of Ghana. Table 4.8 shows some radon studies in Ghana. The mean radon concentration studied in a region was taken as a representation of the regional average. Much work on indoor radon is still needed to complete this map as shown in Figure 4.9.

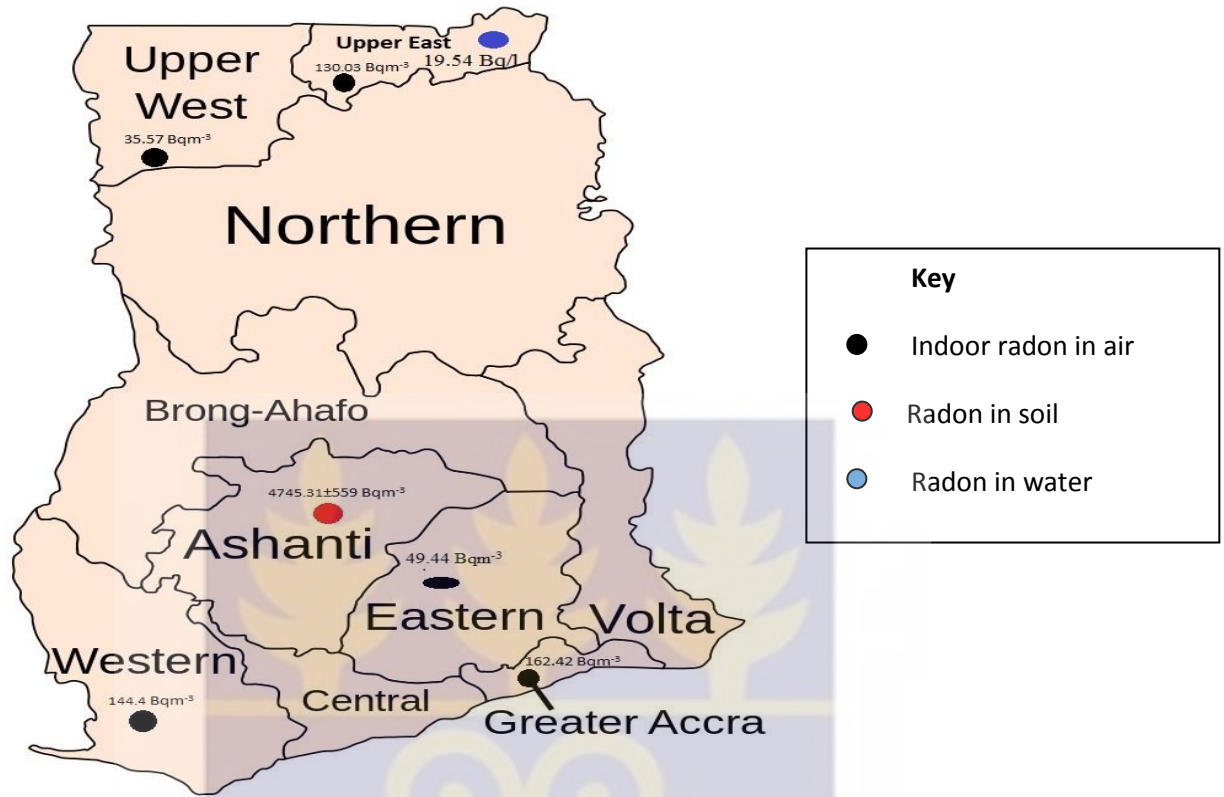


Figure 4.8: Provisional radon map of Ghana



Table 4.9: Some previous radon studies in Ghana

AREA	CONCENTRATION (Bqm ⁻³)	REFERENCES	NATURE OF SAMPLE
KASSENA NANKANA	19.54 Bq/l	Asumadu et al.;2012	Water
KASSENA NANKANA	130.03	Quashie et al., 2011	Gas
SAKUMONO ESTATE	10.18	Akortia, (2008)	Gas
Maccarthy Hill and GAEC	27.94	Amoah et al., 2012	Soil
DOME	466.9	Nsiah-Akoto et al.; 2011	Gas
Aburi	49.77	Yeboah, 2014	Gas
KNUST	1673.51	Ahenkorah-Duodu, 2013	Soil
KNUST	2.77	Bediako, 2013	Gas
Ashanti Region	3841.51	Apraku, 2013	Soil
Kumasi	100338.34	Owusu, 2013	Water



CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study was conducted in Sombo and Jirapa in the Upper West Region of Ghana. The study period was from January to April 2014. The radon concentration, temperature, humidity and pressure of the area were estimated using 1029 continuous radon monitor. The radon levels in Sombo ranged from 8.8 to 229.6 Bqm⁻³ with a mean concentration of 39.2 Bqm⁻³. Jirapa recorded an arithmetic mean radon concentration of 32.3 Bqm⁻³, with the radon activity between 11.7 to 108.5 Bqm⁻³. The overall average radon concentration for both towns was 35.8 Bqm⁻³. These values are below the WHO indoor radon levels limit and hence may not pose any serious radiological hazard.

Indoor radon emanation was compared with the ambient temperature and it was realised that temperature has an inverse relation with indoor radon activity. The effect of humidity on radon infiltration was not conclusive and needs further investigation. It can be concluded from this study that, unless there is a significant change in the pressure of the rooms, pressure has no direct effect on indoor radon levels in the current study.

The volumes of the rooms were computed using builders' tape measure and compared with the amount of radon in the rooms. This shows that the rooms' volumes were inversely proportional to radon accumulation.

The annual equivalent dose estimated from Sombo was 0.80 mSvy⁻¹ and the annual effective dose was 1.87 mSvy⁻¹. In Jirapa, the annual equivalent dose was 0.65 mSvy⁻¹ and the annual effective dose was 1.52 mSvy⁻¹.

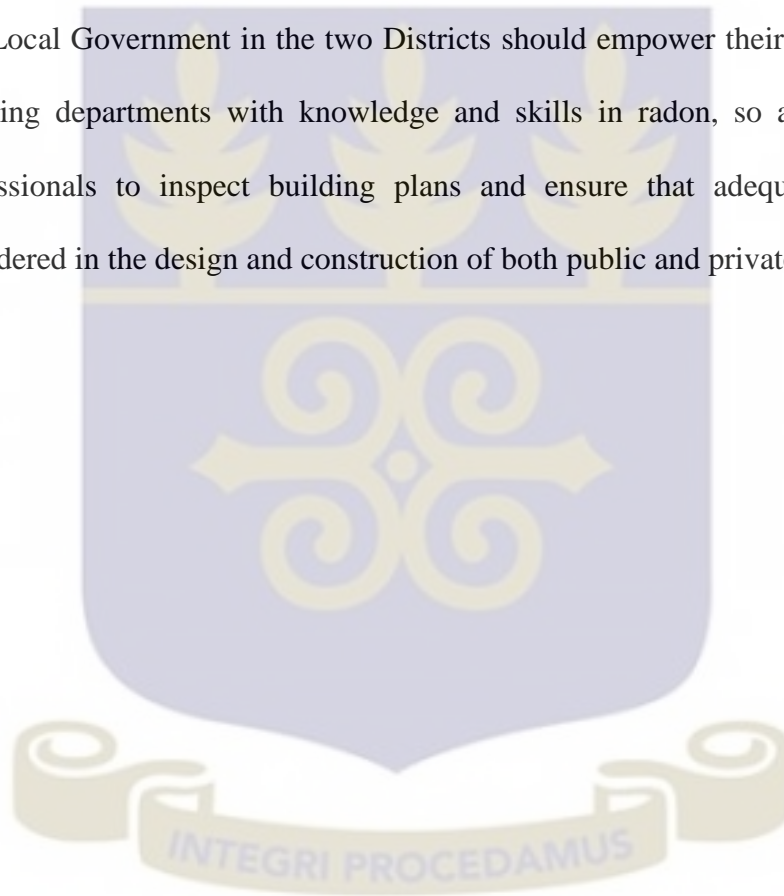
This work has provided these communities with some knowledge of radon and its health implications. It is hoped that the knowledge acquired will reduce the anxiety of those who have low levels of radon in their rooms and will motivate people with elevated levels of radon to take immediate action. The overall effect is the reduction of lung cancer risk in the area. The ability to minimise the event of lung cancer will not only save money that would have been used to treat the disease but will prevent the discomfort of hospitalisation and the undesirable side effect of cancer drugs.

It must be emphasised that the observations made in this study are tentative. Further studies on this subject will be required to confirm or otherwise of the results and deductions made in this investigation.

5.2 Recommendations

1. A long term indoor radon monitoring studies in these towns should be conducted by research institution such as GAEC and the School of Nuclear and Allied Sciences University of Ghana-Legon. Data from the long term studies and this current study will better position the people of Jirapa and Sombo to make informed decisions regarding indoor radon.
2. Much awareness on radon should be created in these communities by EPA, the Radiation Protection Board and NGOs interested in protecting the populace against the debilitating effect of radon.
3. Borehole water in the study area should be tested by research institutions such as the Centre for Scientific and Industrial Research (CSIR) to ensure that people are not over exposed to radon through the ingestion of water.

4. Radio Upper West and Radio Progress should devote part of their airtime on sensitising the public on the benefits of adequate ventilation in dwellings with regard to indoor radon and lung cancer risk reduction.
5. More studies on radon by Universities and the Ghana Atomic Energy Commission (GAEC) should be encouraged in the region so that a regional average could be obtained.
6. The Local Government in the two Districts should empower their town and country planning departments with knowledge and skills in radon, so as to enable these professionals to inspect building plans and ensure that adequate ventilation is considered in the design and construction of both public and private dwellings



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APPENDICES

APPENDEX A1

TABLE 1: Estimated annual equivalent and effective doses from Jirapa

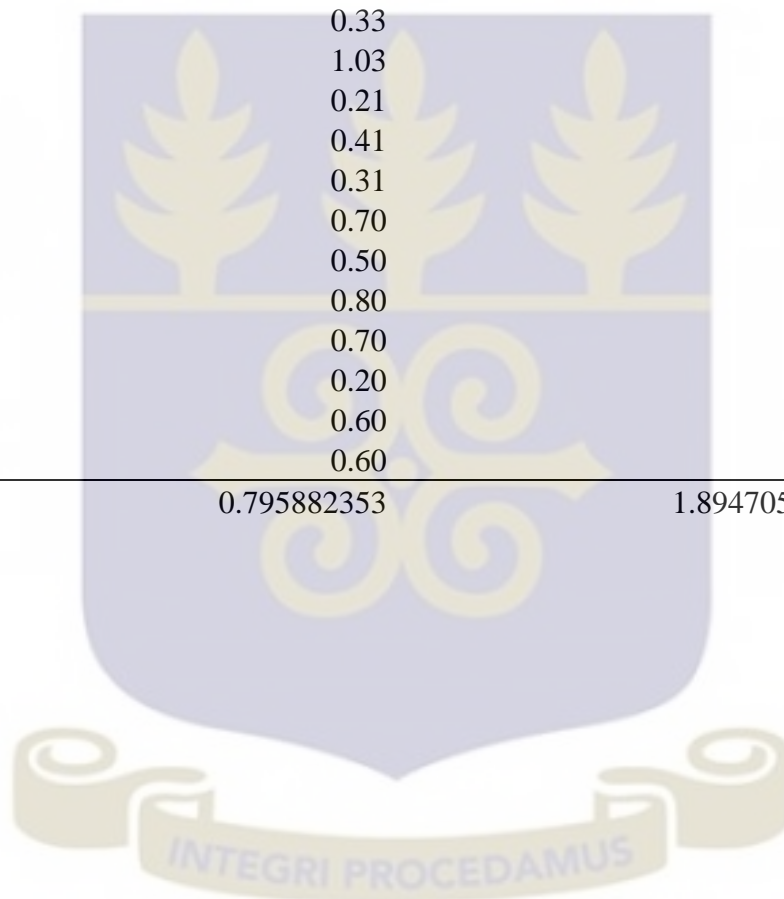
CODE	ANNUAL EQUIVALENT DOSE DOSE/mSvy ⁻¹	ANNUAL EFFECTIVE DOSE/mSvy ⁻¹
JMS	0.87	2.08
JLT	0.38	0.91
JEP	0.68	1.63
JAL	0.24	0.57
JSA	0.4	0.96
JBA	0.54	1.31
JPR	0.51	1.22
JTA	0.38	0.91
JTO	0.87	2.10
JFR	0.24	0.58
JMR	0.24	0.58
JFE	1.41	3.39
JLA	0.82	1.97
JMO	0.52	1.24
JKB	0.81	1.93
JAM	0.55	1.32
JNA	0.51	1.22
JHU	0.42	0.06
JLW	2.19	5.26
JDC	0.45	1.08
MEAN	0.6515	1.516



APENDIX A2

TABLE 2: Estimated annual equivalent and effective doses from Sombo

CODE	ANNUAL EQUIVALENT DOSE/mSvy ⁻¹	ANNUAL EFFECTIVE DOSE/mSvy ⁻¹
SAA	0.77	1.85
SVI	0.73	1.76
SKY	4.63	11.12
SRA	0.30	0.72
SNY	0.71	1.70
SGA	0.33	0.79
SSU	1.03	2.47
SSA	0.21	0.49
SFR	0.41	0.97
SSI	0.31	0.74
SGB	0.70	1.60
SFA	0.50	1.20
SVT	0.80	1.80
SKG	0.70	1.70
SSO	0.20	0.40
SCH	0.60	1.40
SNA	0.60	1.50
MEAN	0.795882353	1.894705882



APPENDIX A3

TABLE 3: Information provided by participants from Jirapa

CODE	MAJOR BUILDING MATERIAL	AGE OF HOME (OLD/NEW)	NUMBER IN BEDROOM	SMOKING (Y/N)
JMS	LATERITE	OLD (11 YEARS)	4	N
JLT	SANDCERETE	NEW (3 YEARS)	3	N
JEP	SANDCERETE	OLD (10 YEARS)	3	N
JAL	SANDCERETE	OLD (10YEARS)	1	N
JSA	LATERITE	OLD (7 YEARS)	1	N
JBC	LATERITE	OLD (12 YEARS)	3	N
JPR	SANDCERETE	OLD (10 YEARS)	1	N
JTA	SANDCERETE	OLD (12 YEARS)	2	N
JTO	SANDCERETE	OLD (10 YEARS)	2	N
JFR	SANDCERETE	OLD (8 YEARS)	1	N
JMR	SANDCERETE	OLD (6 YEARS)	2	Y
JFE	LATERITE	OLD (9 YEARS)	1	N
JLA	LATERITE	OLD (10 YEARS)	3	N
JMO	LATERITE	OLD (7 YEARS)	2	N
JKB	LATERITE	OLD (8 YEARS)	3	N
JAM	LATERITE	OLD (13 YEARS)	3	N
JNA	LATERITE	OLD (8 YEARS)	5	N
JHU	SANDCERETE	OLD (15 YEARS)	1	N
JLW	LATERITE	OLD (7 YEARS)	2	Y
JDC	SANDCERETE	NEW (4 YEARS)	2	N

APPENDIX 3

TABLE 3.1: Information provided by participants from Jirapa

CODE	MAJOR BUILDING MATERIAL	AGE OF HOME (OLD/NEW)	NUMBER IN BEDROOM	SMOKING (Y/N)
SAA	LATERITE	OLD	2	N
SVI	LATERITE	OLD	2	N
SKY	LATERITE	OLD	4	N
SRA	SANDCERETE	OLD	1	N
SNY	SANDCERETE	OLD	3	N
SGA	LATERITE	NEW	1	N
SSA	LATERITE	OLD	2	N
SFR	LATERITE	OLD	2	N
SSI	LATERITE	OLD	2	N
SGB	LATERITE	OLD	2	N
SFA	LATERITE	OLD	3	N
SFD	LATERITE	OLD	2	N
SVT	LATERITE	OLD	3	N
SKG	LATERITE	OLD	4	N
SSO	LATERITE (ADOBE)	OLD	2	N
SCH	LATERITE	OLD	4	N
SNA	LATERITE	OLD	4	N
SSU	LATERITE	OLD	2	N

APPENDIX 4

TABLE 4: Coefficient of determination for radon concentration in Jirapa due to pressure

CODE	ACTIVITY CONCENTRATION (BqM ⁻³)	PRESSURE (mmHg)	COEFFICIENT OF DETERMINATION (R ²)
JMS	43.1 ± 4.9	735.8 ± 0.2	0.10000
JLT	18.8 ± 2.6	736.5 ± 0.2	0.12516
JEP	33.7 ± 3.6	737.0 ± 0.3	0.02876
JAL	11.7 ± 1.7	736.1 ± 0.9	0.26411
JSA	19.7 ± 2.4	736.6 ± 0.0	9.95 E-29
JBC	27.0 ± 2.7	736.1 ± 0.2	0.11810
JPR	25.3 ± 3.2	737.4 ± 0.3	0.00702
JTA	18.8 ± 1.9	737.8 ± 0.6	0.02141
JTO	43.3 ± 4.9	737.6 ± 0.3	0.08577
JFR	12.0 ± 1.4	738.1 ± 0.3	0.12380
JMR	12.0 ± 1.8	735.2 ± 0.3	0.01380
JFE	70.0 ± 8.9	736.4 ± 0.2	0.07060
JLA	40.7 ± 4.5	736.0 ± 0.2	0.13557
JMO	25.6 ± 3.3	736.8 ± 0.3	0.03887
JKB	39.9 ± 3.7	734.7 ± 0.3	0.00140
JAM	27.7 ± 4.8	733.7 ± 0.2	0.00561
JNA	25.2 ± 4.3	737.5 ± 0.3	0.00047
JHU	21.0 ± 3.1	736.5 ± 0.5	0.13422
JLW	108.5 ± 10.3	736.7 ± 0.2	0.07859
JDC	22.2 ± 3.1	739.7 ± 0.3	0.08893

APPENDIX A5

TABLE 5: Coefficient of determination for radon activity concentration in Sombo due to pressure

CODE	CONCENTRATION (Bqm ⁻³)	PRESSURE (mmHg)	COEFFICIENT OF DETERMINATION (R ²)
SAA	38.2 ± 2.0	736.4 ± 0.3	0.01235
SVI	36.4 ± 4.3	735.3 ± 0.3	0.00359
SKY	229.6 ± 15.2	737.4 ± 0.3	0.04511
SRA	23.5 ± 3.3	735.6 ± 0.3	0.16487
SNY	35.2 ± 5.6	735.4 ± 0.3	0.07403
SGA	16.4 ± 3.1	736.6 ± 0.4	0.00017
SSA	10.2 ± 1.4	736.4 ± 1.0	0.02929
SFR	19.9 ± 4.1	734.1 ± 0.9	0.07236
SSI	15.3 ± 3.2	735.6 ± 0.3	0.05178
SGB	32.2 ± 6.6	736.3 ± 0.3	0.01504
SFA	24.2 ± 4.9	735.8 ± 0.3	0.36289
SFD	23.0 ± 4.2	734.1 ± 0.3	0.16391
SVT	37.9 ± 7.7	734.9 ± 0.2	0.40858
SKG	35.3 ± 2.9	735.3 ± 0.3	0.03242
SSO	8.8 ± 1.8	737.2 ± 0.3	0.00620
SCH	28.4 ± 5.8	736.0 ± 0.3	0.30838
SNA	31.5 ± 6.5	735.1 ± 0.3	0.00119
SSU	60.0 ± 8.5	735.6 ± 0.4	0.01085

APPENDIX 6: GPS Coordinates of Jirapa



APPENDIX 7: GPS Coordinates of Sombo

