SOIL RADON MAPPING IN SELECTED AREAS OF THE ASHANTI REGION OF GHANA

By

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DECLARATION

This thesis entitled "Soil Radon Mapping in selected areas of the Ashanti Region of Ghana" has been carefully conducted and apart from references made to other writers all other information, results and deductions are from experiments conducted by me.

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DEDICATION

For all the love and well wishes, I am indebted to you greatly.

This work is dedicated to my Dad and Mum

VEN. DOMINIC OHENE APRAKU

AND

MRS. MARGARET MMIENU APRAKU

ABSTRACT

Radon is a radioactive gas found in soils, water, homes or schools and/or offices. Radon concentrations in these areas have been determined severally, and other mitigating measures to control its effects have been devised. Radon concentrations in soil gases are done in most parts of Ghana. Experiments were carried out in nine (9) selected sites in the Ashanti region of Ghana to find Radon map for the Ashanti region, which covers 24389 km^2 of Ghana using the grab sample method. Twenty (20) holes were dug in grids to a depth of 65 cm at an interval of 50 m in each sampling site. Soil radon concentrations were recorded in Agogo, Akropong, Ayeduase, Bosomtwe, Konongo, Mankranso, Mampong, Nkrumah and Obuasi after which a Radon Map was drawn for the Ashanti Region. The Radon concentration varies from 149.11 Bq/m^3 – 18.58 kBq/m^3 with Bosomtwe recording the lowest and Obuasi having the highest. The permissible soil radon level of 740 – 7400 Bq/m^3 is recommended by the U.S Environmental Agency and 600 – 800 Bq/m^3 for Canada. Agogo, Akropong, Ayeduase, Mampong and Mankranso are within the U.S. EPA standard whilst Obuasi and Konongo have the average radon concentration of 18.58 kBq/m^3 and 10.74 kBq/m^3 respectively. Other works done in Ghana using different techniques recorded average radon levels between 11.03 – 22.01 kBq/m^3.

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CHAPTER ONE

INTRODUCTION

1.1 Properties of Radon

Radon is a chemical element with symbol Rn and atomic number 86. It is a radioactive, colorless, odorless, noble gas, occurring naturally as the decay product of uranium or thorium. Radon gas occurs in three isotopic forms with all of them emitting alpha particles in their decay series. The three isotopes of radon gas are Radon-222 (^{222}Rn, $T_{1/2}$ = 3.82days) produced in the uranium-238 decay chain, Radon-219 (known as Actinon, ^{219}An, $T_{1/2}$ =3.92sec.) which is also produced from the decay of Uranium-235 (^{235}U) and Radon-220 (also called Thoron, ^{220}Th, $T_{1/2}$ =54sec). The half-life of Radon-220 is thus much less than that of Radon gas-222 and hence there is greater likelihood that larger proportion of Radon gas-220 will disintegrate while still trapped deep in the soil than in case of Radon gas-222. Consequently, the quantity of Radon-220 that may be exhaled into the atmosphere will be far less than that Radon-222 gas. Radon gas is soluble in water as well as in other liquids. Unlike most substances, however, the solubility of Radon gas in water varies inversely with temperature (Onwona-Agyemang, 1993). The coefficient of solubility of radon gas for some liquids at atmospheric pressure is given in table 1.1. The coefficient of solubility of a substance in a liquid is defined as the ratio of the concentration of that substance in that liquid to that in air.

Table 1.1: Coefficient of solubility of Radon in liquid

Liquid	Coefficient of Solubility		
	$-18\ ^0C$	$0\ ^0C$	$+18\ ^0C$
Water	–	0.597	0.285
Ether	–	0.597	0.285
Petroleum	29.700	20.090	15.080
Hexane	35.400	33.400	23.140
Ethylene	13.600	9.400	7.350

Radon is a colorless and odorless gas, and therefore not detectable by human senses alone. At standard temperature and pressure, radon forms a monoatomic gas with a density of 9.73 kg/m^3, about 8 times the density of the Earth's atmosphere at sea level, 1.217 kg/m^3. Radon is one of the heaviest gases at room temperature and is the heaviest of the noble gases. Although colorless at standard temperature and pressure, when cooled below its freezing point of 202 K (-71 °C; -96 °F), radon has a brilliant phosphorescence which turns from yellow to orange-red as the temperature is lowered. Upon condensation, radon glows because of the intense radiation it produces. Being a noble gas, radon is chemically not very reactive. However, the 3.82 days half-life of radon-222 makes it useful in physical sciences as a natural tracer. In the consideration of natural radiation dose, the forerunner of Radon-219, Uranium-235, is relatively a rare isotope; Radon-219 has a relatively short half-life of about four seconds (Kharamadoust, 1989; Mueller et al., 1988). Due to the relatively short half-life of Radon-219 almost all the Radon-219 may decay before it can escape from the ground into the environment. Radon is related to lung cancer, and is a threat to health because it tends to collect in homes, sometimes to very high concentrations. As a result, radon is the largest source of exposure to naturally occurring radiation. The German chemist Friedrich E. Dorn discovered radon-222 in 1900, and called it radium emanation. However, a scarcer isotope, radon-220, was actually observed first, in 1899, by the British scientist, R.B. Owens, and the New

Zealand scientist, Ernest Rutherford. The medical community nationwide became aware of the possible extent of a radon problem in 1984. That year a nuclear plant worker in Pennsylvania discovered radioactivity on his clothing while exiting his place of work through the radiation detectors. The source of the radiation was determined to be radon decay products on his clothing originating from his home.

1.1.1 Sources of Radon

Radon-222 is the decay product of radium-226. Radon-222 and its parent, radium-226, are part of the long decay chain for uranium-238. Since uranium is essentially ubiquitous in the earth's crust, radium-226 and radon-222 are present in almost all rocks and all soils and water. The first four decay products of Radon are relatively short-lived with half-lives of less than 30 minutes. These short-lived decay products are responsible for almost the entire dose of alpha particles to the lungs. The long-lived daughters will be expelled from the lungs before any appreciable number of disintegration of these isotopes can take place. The main terrestrial sources of Radon gas are soil and rock. The concentration of Radon gas in a given soil sample is influenced by the distribution of Uranium in the earth's upper crust. Building materials fabricated from soil and rocks contain radioactive nuclides that occur naturally in the earth's crust. The dominant isotope which diffuses from building materials is Radon gas-222. Furthermore, in certain cases, industrial by products that are rich in Radon have been used in the production of concrete that was later found to emit significant amounts of Radon gas in buildings (Woods, 1993). Groundwater can be another source of Radon gas. Radon gas generated in the earth's crust accumulates in underground water. As a result, high Radon gas concentrations have been detected in certain potable water supplies, especially supplies where the storage or hold-up time is too short for Radon gas decay.

1.1.2 Effects of Radon on the environment

Tiny amounts of uranium and radium are naturally present in rocks and soils. These elements produce Radon when they decay, and the miniscule amounts of radon gas thus produced can escape into the air. Indoor accumulation of the gas poses a serious health hazard. When radon decays, it produces charged particles that adhere to dust and other fine matter that can be inhaled by people. It has been found that the inhalation of this radioactive gas increases one's chance of developing lung cancer. According to the Environmental Protection Agency (EPA) of U.S, radon may cause up to 21,800 deaths from lung cancer each year in the United States. Radon passes through the ground and settles in surface waters. However, most of the radon will remain in the soil. Radon has a radioactive half-life of 3.82 days, meaning that half a given amount of radon will disintegrate into other compounds, usually harmful compounds every four days. Radon enters the soil from uranium deposits. It also enters the soil through uranium and phosphate mines and through coal combustion. It is noted that radon gas emits very little gamma radiation. Radiation exposure or radiation sicknesses due to exposure through soil are unlikely, but radon decay products may enter the food chain if they become attached to plants or animals within the soil. These particles have been linked to lung cancer when inhaled and their effects on other organs when ingested are also known. Just as radon can move up through soil to the air above, it can sink into groundwater or enter water systems such as lakes and rivers. The effects of radon and radon decay products on aquatic life is worth knowing, as well as the effects of ingesting fish contaminated with radon decay products. The greater danger of radon in water systems is its potential to enter buildings through tap water before breaking down. Radon gas is generally dispersed harmlessly as it enters the atmosphere, (Nevada Radon Education Program, University of Nevada Cooperative Extension). However, it can enter indoor air systems through cracks in a building's foundation. Within the building, radon poses some health risks. Over years of exposure, alpha particles from radon and its daughter can significantly impact on the health of your lungs. In

view of this, radon gas is classified as a Group A carcinogen, and is considered to cause lung cancer and other lung diseases. Scientists, however, are increasingly suspicious that Radon may be linked to disease in other parts of the body as well. When inhaled, radon gas accumulates in lipid tissue throughout the body with the highest concentration in the brain, bone marrow, and nervous system. Additionally, one-third of the inhaled Radon decay products pass from the lungs into the blood stream indicating that the gas does not flow quickly in and out of the lungs, but lingers in the body. Radon is rapidly absorbed into the body lungs and it accumulates in the cranium resulting in increased gamma ray emissions from bismuth-214 (one of the radioactive radon decay products) and altered Electro-encephalograph (EEG) signals (Darko et. al., 2009).

1.2 Radon Gas Hazard: Ghana in perspective

The United State of America and other developed countries have identified the health risk radon gas poses to humans and are developing mitigating measures to keep most of their citizens alive; unfortunately this story is different on our side of the world. Radon is only known to a few physicists, chemist and other areas of study but not all of these fields even see the need for such a detailed research into this radon problem. Radon is harmful at higher levels and since most lung cancers are initiated by radon exposures there is the need to know how vulnerable someone is. Most part of the Ashanti region of Ghana has few records of its radon emanation levels. This challenge justifies the project as an important research area in Ghana.

1.3 Project Objectives

The subject of radioactive contamination gained considerable public importance because of the Chernobyl accident and the recent accident in Japan. Naturally occurring radionuclides are the largest contributors to radiation doses received by human beings. Because of increased public concern and awareness about radioactive pollution, this study is being carried out to plot Radon

mapping in Ghana which will help determine their concentrations and the associated occupational and public exposures in selected towns in the Ashanti region of Ghana. Radon and therefore thoron gas pose a major radiation hazard as far as the exposure of the general public to the natural background radiation is concerned. It is important that an extensive nationwide monitoring research on Radon (Uranium and Thorium) gas be carried out so as to acquire a reliable database on background radiation from the parent of Radon gas and its daughters. Such a database would be vital for any national policy on radiation control and safety (Andam, 1985). The main Objective for this project is to measure and analyse Radon levels in the soil.

Other objectives for this work are:

1. To provide data on the concentration of radon gas in soil samples of various school campuses in Ashanti Region.
2. To understand the conditions required to ensure minimum levels of radon in the soil.
3. To have soil background check on radon levels.

CHAPTER TWO

LITERATURE REVIEW

2.1 Some Radon level measurement in Ghana

In the year 2001, Radon research conducted at the Lake Bosomtwi area was more of Geophysics research even though it still made use of the changing concentration of radon gas emanation from the soil. Radon gas samples were collected from a depth of 10 cm and 20 cm with the corresponding average concentrations of 167.2 pCi/l or 6.19 kBq/m^3 and 195.5 pCi/l or 7.23 kBq/m^3 respectively. Research work in 2002 was mainly to find out how radon emanation from the soil is affected by depth, for this reason soil samples were collected from different depths and analyzed using the Radon Degassing Unit-200 (RDU-200) and the Radon Detector Analyzer-200 (RDA-200) for degassing and analysis. Samples were collected in a village named Abonu. Table 2.2 is a summary of 2002 results converted to pCi/l.

Table 2.2: Variation of soil Radon Concentration at Abonu with depth.

DEPTH/cm	**RADON CONCENTRATION/pCil^{-1}.**		
	MINIMUM	MAXIMUM	AVERAGE
10	104.7	240.9	150.59
20	106.5	250.1	201.3
30	140.8	250.2	195.8
40	135.0	294.5	204.1
50	190.2	298.9	203.2

The average soil radon concentration at Abonu was found to be 150.59 pCi/l or 5.572 kBq/m^3. In 2003 the sample area was widened to help monitor accurately the emanation of radon to help predict the possible occurrence of an earthquake. Samples were collected from six different areas namely Adwafo Town, Tepaso Village, Momorontuo Village, Ataa Junction, Tumiabu Atonbisi Village and Duasi Village. The minimum radon concentration was 3.91 pCi/l or 144.67 Bq/m^3 and maximum radon concentration of 335.14 pCi/l or 12.4 kBq/m^3 was also recorded. The average radon concentration for these sites is 106.02 pCi/l or 3.92 kBqm^{-3}. In 2006 confirmation analysis was done on the results obtained in 2003, so four of the six villages which recorded high values in 2003 were sampled again. Of all the villages, a minimum value of 31.90 pCi/l or 1.18 kBq/m^3 was recorded by Adwafo village and Duasi got the maximum value of 191.39 pCi/l or 7.3 kBq/m^3. Overall calculated average was 99.9 pCi/l or 3.7 kB/m^3. In 2010, a Preliminary Studies on Geological Fault Location Using Solid state Nuclear Track Detection in Ghana, Alpha track (LR-115 type II) detectors were used for the soil radon gas measurement in forty two (42) sample pits on 70 m × 100 m of land behind National Radioactive Waste Management Centre (NRWMC), Ghana Atomic Energy Commission (GAEC) and fifteen (15) sample pits on about 300 m × 200 m of land at Dunkonah. Comparison method for the determination of uranium content of the soil with track-etch detectors was used in both studied areas. At Dunkonah, the average soil radon gas concentrations calculated ranged from 10.2±0.5 to 23.0±0.7 kBq/m^3 with seven (7) sample pits having very high concentration levels. The average soil radon gas concentrations obtained at NRWMC, GAEC ranged from 6.4±0.4 to 27.5±0.8 kBq/m^3 with 20 sample pits having very high concentration levels. The area of high soil radon gas concentration at NRWMC coincided with the fault lines discovered.

2.2.1 Radon Measurement in Deep Mines in Ghana

There is a report of measurement of radon gas concentration in two deep gold mines in Ghana; Tarkwa Goldfields and Prestea Goldfields. Radon concentration measured underground at Tarkwa were in the range of 56 Bq/ m^3 to 268 Bq/m^3 . Corresponding values for Prestea were 43 Bq/m^3 to 878 Bq/m^3.These results represent the first published data on underground radon concentration in deep gold mines in Ghana. Measurement of the radon gas was done by means of the solid state nuclear track technique, with CR–39 plastic recording medium for the alpha particles from radon decay (Badoe et al., 2007).

2.2.2 Monitoring of natural background radiation in some Ghanaian homes.

The average radon concentration for the modern sand Crete building was found to be 2.0 Bq/m^3. This is at the threshold of detection for the seven months exposure period. The mean for the nine single unit houses was 3.0 Bq/m^3 which was the same for the one storey buildings. The fourth storey of the block of flats had an average value of 1.0 Bq/m^3, this shows the thinning out of radon concentration with height above ground level. For the traditionally constructed houses, the mean radon concentration was 121.0 Bq/m^3 with a standard error of the mean being 15.0 Bq/m^3 for all the measurements during the nine months exposure period. The test house monitored continuously for a year period had a mean value of 28.0 Bq/m^3. During the period from March to June nine houses exceeded the remedial action limit of 150.0 Bq/m^3 with three of these exceeding the immediate level of 400.0 Bq/m^3set by the Environmental Protection Agency (EPA) of the United State of America. The mean for this period was 171.0 Bq/m^3 with error of 34.0 Bq/m^3. The radon concentrations range from below 5.0 Bq/m^3 to 580.0 Bq/m^3.

2.2.3 In-Situ Radon level measurement for some other tropical countries

In December, 2011, Radon concentrations for in situ measurements in soil gases were done in Northern Malaysia Peninsular (NMP) by B. A. Almayahi, A. A. Tajuddin and M. S. Jaafar. A ^{222}Rn concentration varies from 2.23 kBq/m^3 to 375.42 kBq/m^3. The ^{222}Rn concentrations in Perlis state lower than Penang, Kedah and Perak states. This is the first time such documentation has been made in radon area monitoring by using CR-39 NTDs in Northern Malaysia Peninsular. The study area (NMP) is geologically divided into the following major regions: Triassic, Quaternary, Tertiary Cambrian, Silurian to Devonian, Carboniferous Intermediate Grad, Ordovician to Silurian, Jurassic to Cretaceous and Permian. NPM includes the northern states of Penang, Kedah, Perlis and upper portion of North Perak. The detector chamber is placed inside a PVC pipe 8 cm in diameter 50 cm in length. The cylinder is buried in the soil at a 50 cm depth by using an earth drill (AUGER DZ500). The soil ^{222}Rn gas concentrations at a 50 cm depth for all 13 measurement sites were recorded. In NMP found lowest and higher ^{222}Rn concentrations at Kedah and Perak, respectively as 2.23 kBq/m^3 and 375.4 kBq/m^3. Radon concentrations were recorded very high at 375kBq/m^3, which is exceptionally high as an outdoor value. The ^{222}Rn concentrations in Kedah state lower than Penang, Perlis and Perak states. Experiments were carried out at Jordan in 2001 by K.M. Abumurad and M. Al-Tamimi to determine emanation power and radon levels in different kinds of soil and bedrocks. Seven stations were selected in the investigated district, which covers an area of about 2300 km^2 in the northern and western part of Jordan. Five holes were dug in each station at different depths. Two to three passive dosimeters using plastic detectors (CR-39) were put in each hole. Two weeks later, the dosimeters were collected and chemically etched. Some soil and rock samples from the study area were collected and analyzed for radioactive nuclides using γ-ray spectroscopy. The correspondence between radon levels in the soil gas and its precursor concentrations was not clear. However, the study confirms the exponential increase in radon level with depth. In general, Al-Hisa phosphate limestone showed the highest radon concentration while

Amman silicified limestone showed the lowest concentration. The highest radon level recorded was about 40 kBq/m^3at depth of 100 cm in Al-Hisa phosphate limestone (AHP), which form 7% of the studied area; while the lowest (at the same depth) was about 1.6 k Bq/m^3 in (WG), which form 30% of the studied area.

2.3 Radon Gas as a seismic precursor

Radon gas concentration in soil can be a signal of an imminent seismic activity. According to the Increased Reactive Surface Area (IRSA) model, microfracturing prior to major seismic events is responsible for precursory increases in radon gas concentration (Furlan and Tommasino, 1993). Shiratoi (Bella and Shiratoi, 1990) in 1927, on the basis of some experiment on hot water springs in Japan propounded a hypothesis that a correlation may exist between radon gas content variations in the ground and seismic phenomenon. Before the Tomankai (UNESCO, 1984) earthquake which occurred in Japan in 1944, Hatuda had detected an anomalous change in the radon gas level near an active fault in Japan. Okabe continued these researches ten years later by daily sampling of the radon gas content in the air near the soil (Okabe, 1956). His work showed a direct correlation between radon gas variations and local seismic at Tattori and hence attributed the radon gas exhalation increase to seismic vibrations. Soviet researchers (Mavashev and Ulomov, 1967) started work on measurement of radon gas levels in the Tashkent hydrological basin fifteen years before the earthquake. Between the period 1961 and 1964 the radon gas content apparently increased. These results heightened the curiosity of other scientists. More measurements were taken at frequent intervals and finally it was discovered that there was a direct correlation between increase in radon gas levels and seismic activities. Sultankhodzhayev et al. (Sultankhodzhayev, 1979), in the U.S.S.R., reported an increase in radon gas concentration in a thermal spring four days before the Gazli earthquake (measuring 7.3 on the Richter scale) in May, 1976 at an epicentral distance of 500 km. The Department of Physics, University of La Sapienza in rome, periodically sampled the

water in an artesian well located at Mentana (near Rome) and the Peschiera springs (near Rieti). The researchers noticed a marked increase in the radon gas content from the beginning of June to the end of October. This was followed by a rapid decrease in a few days prior to the Irpinia earthquake (Rikitake and Kato, 1984) of November 23, 1980 (measuring 6.6 on the Richter scale). Kato (1984) measured radon gas concentration at different locations in the eastern part of North Anatolian fault zone (Rikitake and Kato, 1984). He found out that where a peak in the track density was observed corresponds to the vicinity of a fault line. Currently research programmes are underway in many countries to investigate further, the possibility of using radon gas as a seismic precursor.

2.3.1 Record of seismic Activity in Ghana

In 1967 a petroleum exploration corporation, Union Cabide (Adams et al., 1986), undertook an extensive seismological survey across an area of the continental shelf extending from the southern part of Accra to the Volta River. The result of this survey indicated that the area was seismically active. Adams and Ambrasseys (1986) noted in one of their researches that an area near Accra, between 20 W and 27 E, is the most seismically active zone along the coast of West Africa (Adams et al., 1986). In the remote past, earthquakes of various magnitudes have been experienced in Accra and its surroundings. These include 1862, 1906, 1939, and 1969 earthquake events. Although most of these activities centered around Accra, strong after effects have been reported along the coast eastward to Lome, which experienced tidal wave as a result of an earthquake in 1911 (Adams et al., 1986). The earthquake which hit Accra in 1939 was closely monitored and recorded (Junner, 1941). Much of the havoc caused by this earthquake was mostly to the west fissures, causing up to 5m wide opening in the alluvium bordering the Akwapim scarp near Weija. The epicentre was located at about 40 km out to the sea, south of Accra. In 1964 an earthquake which measured 4.0 on the Richter scale was recorded at a location close to the Akwapim

escarpment near Akropong. Since 1973 the seismic observatory of the Geological survey Department, Accra, (with observatories at Kukurantumi, Weija, Winneba and the Shai Hills) has been in operational. In recent years it has recorded a number of seismic events including the June 27, 1991, the August 23, 1991 and the October 23, 1991 earthquakes, measuring 3.0, 3.9 and 2.4 respectively on the Richter scale. Other earthquake events are the February 2, 1996 (measuring 3.6), the January 8, 1997 (measuring 4.5) and the March 6, 1997 earthquake event, measuring 4.8 on the Richter scale, which is by far the highest registered in recent times. This earthquake had its epicentre 5 km North-East of Weija (Adams et al., 1986). As far as records show, there is enough evidence to prove that the Akwapim fault zone, and to a lesser extent, the great boundary fault are still seismically active (Adams et al., 1986).

CHAPTER THREE

THEORETICAL BACKGROUND

3.1 Hypothesis of Radon

Radon is a radioactive gas found in nature. Its source is from uranium, a very heavy silvery-white radioactive metal. For many centuries it was used as a pigment for glass. Now it is used as a fuel in nuclear reactors and in nuclear bombs. Depleted Uranium is used in casings of armor piercing arterial shells, armor plating on tanks and as ballast in the wings of some large aircraft and shielding for radioactive materials. A typical example is the shielding of Cobalt−60 machine used for the treatment of cancer. As the uranium molecule decays to form stable lead, a process taking many, many years, it changes from one radioactive element to another in a sequence known as the Uranium Decay Cycle. Parthway through this cycle, the element radium decays to radon which as a gas moves up through the soil to atmosphere. Radon, Rn-222 ($T_{1/2}$= 3.82 days), is a daughter product of radium, Ra-226, which in turn is derived from the longer-lived antecedent, U-238. Thoron, Rn-220 ($T_{1/2}$ = 56 seconds) is a daughter of thorium, Th-232, which is present in larger amount in the earth's crust than radon. Because of thoron's short half-life, it leaves the ground very fast, and is of no significant radiobiological consequence. These radionuclide series are present in slowly decreasing amounts in the environment, due to radioactive decay of their parents, which has been known and understood since the end of the 20th century. Widely varying radon levels exist in different regions related to geological circumstances. New concern regarding radon exposures is traceable to the discovery that there are more houses with high radon levels than previously realized and to the use of a new method of expressing and summing doses from partial body exposures, such as the lung dose from radon daughters. This method of expressing dose was

promulgated by the International Commission on Radiological Protection (ICRP) and National Council on Radiation Protection (NCRP) based on defined weighting factors which make it possible to sum partial body doses and thereby estimate a total body dose which would have a quantifiable risk. This quantity is defined as the Effective Dose (ED). Thus, the previously estimated partial body environmental radon dose to the tracheobronchial epithelium (TBE) (2500 Sv/year.) was not included in whole body dose calculations because that exposure was limited to a small fraction of the body. The new method of calculation multiplies the 2500Sv/year. dose to the TBE by a weighting factor (WF) which allows the dose to the TBE to be included in the ED from environmental radiation exposure Different WFs have been proposed, including 0.12 (EPA), 0.08 (NCRP) and (NAS-NRC BEIR V), and 0.06 (ICRP). These WFs raise the radon contribution to the whole body from 0 Sv to 300, 200, and 150 Sv respectively. NCRP quotes an uncertainty of +/- 50% in these numbers. Based on these estimates, radon in equilibrium with its daughters delivers 2 times more dose than previously accepted as the total dose received from all sources of natural background exposure (approx. 100 Sv/year on the average in the United States). Thus, it is not surprising that adoption of the effective dose notion by many radiation protection groups (including the NCRP and the EPA in the United States), has led to increased concern regarding the potential health effects of radon. It should be noted that lung cancer risk coefficients from radon are not increased. There are no new cases of lung cancer that led to the increased dose estimate. In fact, the new estimates of radiation dose imply a lower risk coefficient. That is, when the same numbers of lung cancer cases that occur are attributed to the higher doses (ED), the risk per unit exposure is decreased. The major health effect associated with Radon gas inhalation and its daughters is lung cancer. Lung cancer problems have been identified with mine workers exposed to Radon gas and its decay products. The historical review of the subject for four instances where both medical and environmental information was available has been given by Holaday (Monat et al., 1983). The Radon gas, once inhaled, circulates uniformly throughout the whole body via the blood stream. Solubility of Radon gas in the body tissue is found to be low and therefore the

Effective Dose Equivalent from inhalation of Radon gas is normally small compared with Radon gas daughters. For this reason the estimation of the dose delivered to the lung is mainly based on the contribution from the alpha-emitting daughters of Radon gas.

3.1.2 Medical effect of Radon inhalation

Natural sources contribute significant quantities of radiation toward the total radiation exposure that humans receive. Some of these natural radiations are harmless to humans in the ambient environment. However, radon, a large component of the natural alpha radiation expose to human (greater than sixty per cent), posing a threat to the public health when radon gas accumulates in poorly ventilated residential and occupational settings.

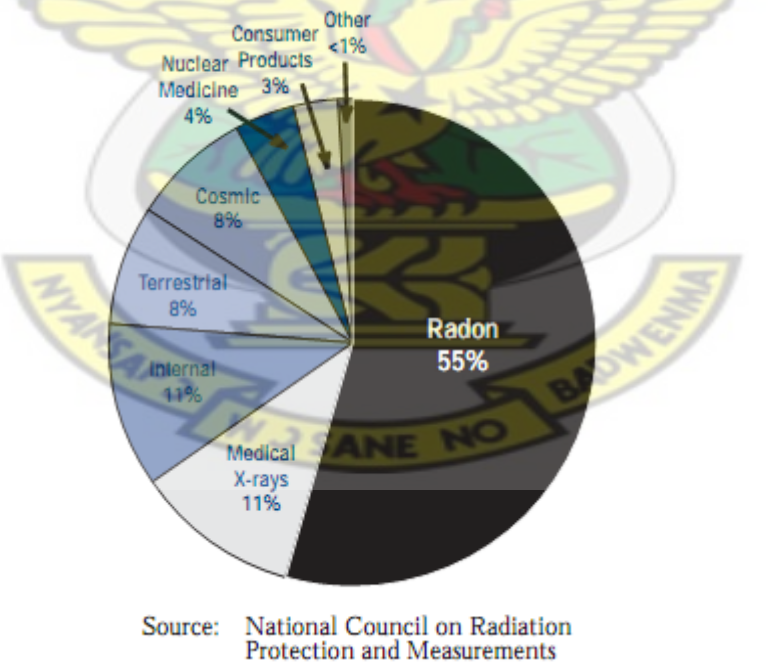


Figure 3.1: Sources of Radiation Exposure

According to the Office of the Surgeon General: "Indoor radon gas is a serious health problem in our nation which can be addressed by individual action, unless people become aware of the danger

radon poses, they will not act. 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 200 of 360 Sv per year. Radon, although not always publicized as a tremendous public health concern, ranks highly among other preventable causes of death, including drunk driving, drowning, and fires. Additionally, the death risk to the average person from radon gas at home is 1,000 times higher than the risk from any other carcinogen or toxin regulated by the Environmental Protection Agency (EPA). For these reasons, research must be conducted to evaluate certain subgroups that have elevated risks and technology must be developed and implemented in order to limit exposure to dangerous levels of radon and its harmful progeny. The most recent National Academy of Science (NAS) report on radon, The Health Effects of Exposure to Radon estimated that about 14 per cent of the 164,100 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. 160 of these deaths have been attributed to radon dissolution exposure in ingested water, and 700 deaths from exposure in outdoor air (mostly exposure from mines). The majority of the radon caused deaths occur from inhalation of radon and radon progeny. The average number of years of life expectancy lost per death from lung cancer is about fifteen. In a second National Academy of Science (NAS) report published in 1999 on radon in drinking water, the NAS estimated that about 89 per cent 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 per cent were due to stomach cancer from consuming water containing radon. Certain characteristics of the residence and environmental factors will play a role in determining the indoor radon concentrations. 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 (winter) rather than in more mild temperatures (summer and spring). The risk of lung cancer is

associated with lifetime inhalation of radon in air at a concentration of 1 Bqm^{-3} (0.027 pCi/l) and this was estimated on the basis of studies of underground miners. The values were based on risk projections from three follow-up studies. These three reports used data from 4 to 11 cohorts of underground miners in seven countries and developed risk projections of 1.0 x 10^{-4}, 1.2 x 10^{-4}, and 1.3 x 10^{-4} per unit concentration in air (1 Bqm^{-3}), respectively. The three values were for a mixed population of smokers and non-smokers. The risk of lung cancer (discussed in two reports of the National Research Council and one of the National Institutes of Health) posed by lifetime exposure to radon (^{222}Rn) in water at 1Bqm^{-3} was calculated to be 1.3 x 10^{-8}. As already stated, an increase in the number of radiation particles that pass through the human body corresponds to an increase in the chance of developing cancer. Therefore, 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, like for miners, because more lung cells are killed off by the radiation rather than becoming cancerous and some radiation is wasted on the already killed cells (the "inverse exposure-rate effect"). But at lower concentrations, like in residences, every emitted particle will have an impact.

3.1.3 Risk for Smokers

Apart from the results of very limited in-vitro and animal experiments, the only source of evidence on the combined effect of the two carcinogens (cigarette smoke and radon) was the National Academy of Science (NAS) data collected from six miner studies. Analysis of that data indicated a synergistic effect of the two exposures acting together, which was characterized as sub multiplicative (i.e., less than the anticipated effect if the joint effect were the product of the risks from the two agents individually, but more than if the joint effect were the sum of the individual risks). The risk of lung cancer from radon exposure is estimated to be approximately 10 -15 times greater for persons who smoke cigarettes in comparison with those who have never smoked.

According to the NAS Committee on the Biological Effects of Ionizing Radiation, a breakdown of the contribution of smoking and radon exposure to lung cancer deaths in the United States illustrates that of every 100 persons who died of lung cancer, approximately 93 were current or former smokers, whereas 7 had never smoked. However, it is important to remember that the lung cancer incidence among non-smokers is much lower than among smokers. Radon in homes causes 23% of lung cancer deaths among ever-smokers, but 11% among never-smokers. Therefore, increasing the radon levels presents a much higher relative risk to non-smokers. For example, increasing the radon concentration from 1.5 pCi/l or 55.5 Bq/m^3 to 4 pCi/l or 148 Bq/m^3 , the cancer risk for a smoker increase 100%, but only 42% for a non-smoker. Although there is no sure explanation for the synergistic effect of radon exposure and smoking, the predominant hypothesis is that smokers have a higher potential retention of deposited radon progeny due to increased mucus production and iterations in mucociliaryclearance. Figure 3.2 shows Radon and the risk of lung cancer between smokers and non-smokers.

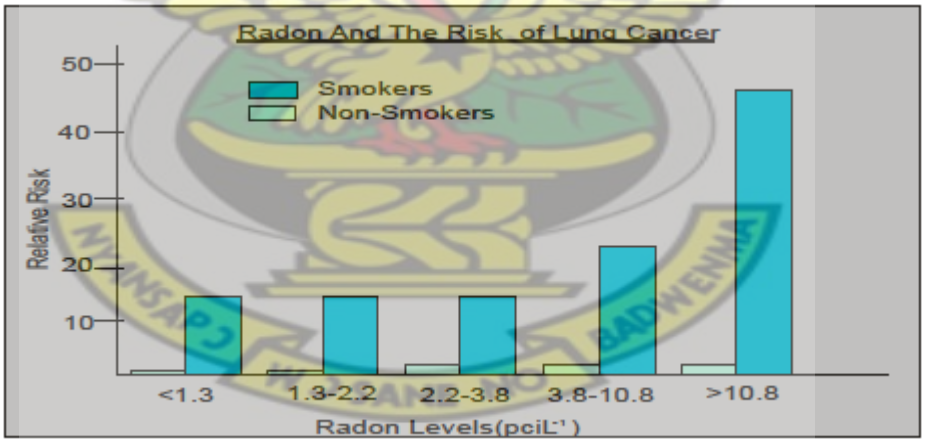


Figure 3.2 Radon and the Risk of Lung Cancer between Smokers and Non- smokers.

3.1.4 Risk for Children and Elderly

Data on the effects of radiation in children is rather limited, however, several studies have shown that children are more susceptible to radon exposure than adults. Children have different lung architecture and breathing patterns, resulting in a somewhat larger dose of radiation to the respiratory tract. Children also have longer latency periods in which to develop cancer. Hofmann reported that the radon dose was strongly dependent on age, with a maximum value reached at about the age of 6 years. Despite these findings, no conclusive data exists on whether children are at greater risk than adults from radon. Because of the latency time for cancer to develop and the cumulative nature of radon risk through time, there is very little possibility that someone could get lung cancer from radon before age 35, although exposures before that age contribute to the risk at later ages. The relative risk from domestic radon exposure is also higher for children because they spend more time at home and/or the basement. On average, children spend 70% more time in the house than adults. The rates of translocation in a person show that there exists an exponential increase in the number of translocation with an increase in age. It has been hypothesized that decreased efficiency in DNA repair mechanisms is a function of age. Therefore, as a person gets older, their DNA becomes more unstable and abnormalities persist through the cell cycling process because of a lack of repair capabilities. For this reason, alpha particle exposure at later life stages can have greater potential for causing genomic changes. However, individuals of this age are probably too old to die of the associated tumour progression (cancer end-points take many years [usually >15] to manifest themselves).

3.1.5 Risk for Women and Men

The effect of radon exposure on lung cancer risk in women might be different from that in men because of differing lung dosimetry or other factors related to gender (the risk model was

developed using epidemiological studies in male miners). Women have displayed lower rates of lung cancer incidence than males, even after stratifying the analysis to control for smoking history. In 1999, the National Academy of Sciences calculated the lifetime risks of exposure to Radon-222 at home for each Bq/m^3(0.007 pCi/L) in air. The result obtained is in table 3.1 below;

Table 3.1: Lung cancer risks from exposure to Radon-222 at 1x 10^{-4}Bq/m^3

	Ever Smokers	Never Smokers
Men	3.1	0.59
Women	2.0	0.40

3.2 Geographic and Residential Risks

The amount of radon emanating from the earth and concentrating inside homes varies considerably by region and locality, and is greatly affected by the residential structure as well as soil and atmospheric conditions. Nearly every state in the United States has dwellings with measured radon levels above acceptable limits. The Environmental Protection Agency (EPA) estimates that 6% of American homes (approximately 6 million) have concentrations of radon above 4 pCi/l or 148 Bq/m^3. Areas of the country that are likely to have homes with elevated radon levels are those with significant deposits of granite, uranium, shale, and phosphate, which are all high in radium content and, therefore, potential sources of radon gas. However, due to the many determinants of indoor radon levels, local geology alone is an inadequate predictor of risk. The only way to determine indoor radon concentration is by testing. Other factors that predispose homes to elevated levels of radon include soil porosity, foundation type, location, building materials used, entry points for soil

gas, building ventilation rates, and source of water supply. Further research is being conducted on ways to predict which homes are most likely to have significant levels of radon. The Radon gas once inhaled circulates uniformly throughout the whole body via the blood stream. For this reason the estimation of the dose delivered to the lung is mainly based on the contribution from the alpha-emitting daughters of Radon gas. While radon is a lipid-soluble gas that can move freely in and out of the brain despite the blood-brain barrier, none of the transmuted heavy metal radon daughters are soluble in lipids, meaning they remain trapped in the brain where they emit gamma radiation and alpha particles resulting in both radiation and chemical injury to the brain cells. Of keen interest was the unexpected discovery that the radioactivity selectively accrues to the brain proteins in the Alzheimer's victims and to the brain lipids in the Parkinson's victims. Other studies have indicated the astrocytes may be involved in Alzheimer's disease and amyloid deposits and neurofibrillatory tangling observed with Alzheimer's may well reflect the response to radiation injury of the astrocytes. An estimated 4.5 million Americans have Alzheimer's disease, the number having doubled in the last 25 years. An estimated 1.5 million Americans have Parkinson's disease with 60,000 new cases diagnosed each year. Other hazardous effects from the alpha particles emitted from radon gas and its daughters are bone and gastrointestinal cancers etc. Non-cancerous effects such as excess of liver cirrhosis, slight increase in various kidney diseases, excess of cataracts, growth retardation, and increase in benign cartilaginous tumours of bone, spinal cord defects and chromosomal aberrations have also been found to be caused by radon gas and its daughters (Wagnor et al., 1971; UNSCEAR, 1982). Plasma, the liquid component of blood, is mainly composed of water which has a relatively low solubility coefficient for radon gas at ordinary temperatures. On the other hand a study of Radon gas exhalation from the ground has been used to determine the location of uranium ores, geothermal sources, underground water movement etc., the possibility of predicting earthquakes from environmental radon gas monitoring is also being researched into.

3.3 Guidelines for mitigating High levels of radon in the home

Currently there are no Ghanaian statutory limits covering naturally occurring radioactive materials such as radon and its progeny. However, both the NCRP and EPA of U.S.A. have published guidelines for acceptable levels of radon in the home. The NCRP recommends that in single family homes remedial action be taken to reduce radon levels if the average annual exposure exceeds 2 WLM/year (equal to 8 pCi/l or 296 Bq/m^3assuming radon daughters are in 50% equilibrium with Rn-222). EPA recommendations are based on average airborne radon levels in the home, and they recommend a graded scale of actions. Their recommendations suggest action at a lower dose (factor of 2) than NCRP, but otherwise there is no major difference. The recently passed radon act 51 poses a long term goal of remediation to outdoor levels of $0.2 - 0.7$ pCi/l or $7.4{-}25.9$ Bq/m^3 , which would require many billions of dollars to accomplish. The urgency of recommended actions depends on the average radon levels in the living areas of individual homes, and not simply on the highest level in an uninhabited portion of the house. The amount of time spent in the home and where one spends most of that time needs to be considered when making decisions on corrective actions. If high levels are found in high occupancy areas, remedial action should be considered and advice obtained from experts. Radiation control officials at the state or local level can suggest additional kinds of measurements, as well as recommend remedial actions, if indicated.

3.3.1 EPA Recommendations

3.3.1.1 Action Plan

In considering whether and how quickly to take action based on test results, the following guidelines may prove useful. The EPA believes that radon levels should try to be permanently reduced as much as possible. Based on currently available information, the EPA believes that levels in most homes can be reduced to about 0.02 WL (4 pCi/liter or 148 Bq/m^3)

3.3.1.2 Radon levels between 1.0 WL (200 pCi/l) or higher:

Exposures in the range are among the highest observed in homes. Residents should undertake action to reduce levels as far below 1.0 WL (200 pCi/liter or 7.4 kBq/m^3) as possible. It is recommended that action should be taken within several weeks. If this is not possible, consultation with appropriate state or local health or radiation protection officials can determine if temporary relocation is appropriate until the levels can be reduced.

3.3.1.3 Radon level between 0.1 WL (20 pCi/l) to 1 WL (200 pCi/l):

Exposures in the range are considered greatly above average for residential structures. Action should be undertaken to reduce levels as far below 0.1 WL (20 pCi/l or 740 Bq/m^3) as possible within several months.

3.3.1.4 Radon level between 0.02 WL (4 pCi/l) to 0.1 WL (20 pCi/l):

Exposures in this range are considered above average for residential structures. Action should be undertaken to lower levels to about 0.02 WL (4 pCi/liter or 148 Bq/m^3) or below within a few years, sooner if levels are at the upper end of this range.

3.3.1.5 Radon level between 0.02 WL (4 pCi/l) or lower:

Exposures in this range are considered average or slightly above average for residential structures. Although exposures in this range do present some risk of lung cancer, reduction of levels this low may be difficult, and sometimes impossible, to achieve.

There is increasing urgency for action at higher concentrations of radon. The higher the radon level in a home, the faster action should be taken to reduce exposure.

3.4 Radioactive decay processes

All naturally occurring radioactive nuclides decay by emitting either alpha or negative beta particles. Therefore, each transformation in the radioactive series changes the mass number by either 4 or 0 and changes the atomic number by -2 or +1. There are four decay chains of importance when considering naturally occurring radioactive materials and each is defined by its heaviest natural (not man-made) element. These are the U-235 series (also called the Actinium Series), the thorium-232 series (the Thorium Series), the U-238 series (the Uranium Series) and the Np-237 series (the Neptunium Series). Three of the series namely, the Uranium Series, the Thorium Series and the Actinium series decay to produce radon of which U-238 series is the longest half life of radon. The series of most interest to us is the decay chain that includes radon-222, namely the U-238 series. All the three series undergo alpha and beta decay with gamma de-excitation emission occurring in most steps. The Actinium series decayed to produce radon-219 with half-life of 3.96 seconds (Figure 3.4b). Thoron, ^{220}Rn with half-life of 56 seconds is a daughter product of the thorium-Series (Figure 3.4c), which is present in larger amount in the earth's crust than radon. Because of thoron's short half-life, it eventually disappeared before it leaves the ground and is of no importance in radiobiology. From the U-238 series, the element radium decayed to form radon-222 which moves up from the soil to the atmosphere. The U-238 series is the one that produces radon-222 as shown in (Figure 3.4a). From this series, radon is the only element which is gaseous at STP. This is the root of the problem for as the uranium-238 decays into its decay products. All the solids remain within the earth or seawater and the radon, being gaseous, has the mobility to percolate up through the earth and into the atmosphere, or into a house which may be above the percolating radon. If we consider the radioactive decay series shown in the (Figure 3.4a), which begins with U-238, the important radionuclide in that decay chain is radon-222.When radon-222 decays it does so by giving off an alpha particle, leaving behind a polonium-218 atom, which then decays further to At-218 or Pb-214. In this case, it has

two routes by which it can decay; one by alpha decay, the other by beta decay. The route which is called "alpha decay" is because the Po-218, or for that matter the Rn-222, emits an alpha particle, which consists of two protons and two neutrons held tightly together. (This alpha particle is also the nucleus of the helium atom). The route called "beta decay" occurs because the Po-218 can decay when one of its neutrons, within the nucleus, breaks up into a proton and an electron, emitting the electron immediately. So the net result in this case is that an electron is shot out from the nucleus. This is not one of the electrons that have been orbiting the nucleus, but a new one made up from the neutron that decayed. One must note that is not the electron from the orbiting ones but the electron from the nucleus called "beta" particle. It is identical to all electrons in all regards, but is called a beta particle to remind us of its origin, the nucleus. Furthermore, it is not possible for an electron to exist inside a nucleus, the result of an interesting quantum mechanical phenomenon, so that when it's created, it must immediately exit the nucleus. The neutron that decayed cannot decay simply into an electron for a host of reasons, so it decays into a proton and emitted electron. The proton, however, is free to remain in the nucleus, which then increases the number of proton and changes the element itself. In gamma de-excitation process for instance the process involves a nucleus in an excited state that de-excites to the ground state but does not change the nuclear species, whereas alpha and beta decay alter the mass number of the nucleus (Krane, 1988). The energy released from gamma-ray decay is usually in the form of a photon. The energies of the gamma-ray range from thousands of electron volts (keV) to a few million electron volts (MeV). Different radioactive nuclei emit characteristic gamma radiation, and so these energies can be identified through X-ray spectroscopy. Radon gas might escape the soil particle by recoil and then by the processes of diffusion and advection, could be transported to the surface of soil (Speelman, 2004). The properties that enhance these processes will be expatiated in the following sections as well as the processes by which radioactive nuclei transform to form other decay species.

3.4.1 The Radioactive Decay Law

All radioactive nuclides decay stochastically by processes like alpha and/or beta decay. A radioactive element will not release all particles at once. The decay process is statistical in nature; early researches came to the realisation that it was impossible to predict when a specific atom would disintegrate to form another. This led to the following deductions. If there exist a number, N of radioactive nuclei at a certain time t, and no new nuclei are being formed in that sample, then the decay (dN) in the sample in a certain time (dt), would be proportional to the total number of nuclei N in the following way (Speelman, 2004).

$$\frac{dN}{dt} = \lambda N \qquad (3.1)$$

Where λ is called the decay constant of a specific radioactive species. Equation (3.1) can be written as;

$$\lambda = -\frac{dN/dt}{N} \qquad (3.2)$$

The above equation explains the nature of which is the probability per unit time for the decay of an atom. The value of λ differs for each nuclide. The solution of this equation is called the exponential law of radioactive decay (speelman, 2004). It is

$$N_{(t)} = N_0 e^{-\lambda t} \qquad (3.3)$$

3.4.2 Decay of Alpha

Alpha decay and emission occurs naturally in heavy nuclei in the radioactive series. In the early 20th century, Rutherford's work on a particle scattering led to the realization that atom consisted of largely empty space while the nucleus is a relatively large mass in the centre of the atom (Speelman, 2004). He also concludes from his experiments with alpha particles entering a thin-

walled chamber, that the particles were in fact helium nuclei (Krane, 1988). The alpha (α) emission takes place, because the nucleus gains binding energy from a decrease in mass of the system. Since the alpha particle is very stable and relatively tightly bound structure and its mass is relatively small compared to the remaining parts of the nucleus, it is favoured to be emitted from the system together with the release of kinetic energy. The emission of a particle in these cases is spontaneous and can be stated in the following way;

$$ {}^{A}_{Z}X_{\mathrm{N}} \longrightarrow {}^{A-4}_{Z-2}Y_{\mathrm{N-2}} + {}^{4}_{2}\alpha \qquad (3.4) $$

Where A is the mass number of the nuclear species, Z is the atomic number of the species and N is the number of neutrons. N is not usually indicated in the equation, but could readily be obtained by A−Z. X is the initial decaying nucleus, whereas Y is the final state, and an alpha particle is emitted (Speelman, 2004). Alpha emission is evident in the 238U nucleus and as an example can be written as;

$$ {}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha \qquad (3.5) $$

The final species in equation (3.5) is thorium-234 accompanied with the release of kinetic energy.

3.4.3 Decay Series of U-238

Radon gas is formed in the ^{238}U decay series. It undergoes a series of 14 decays to ultimately form a stable nucleus, of ^{206}Pb. The Radon gas formed in the series is only radioactive gas in the series and has the longest half-life (3.825days) relative to its decay products up to the long-lived ^{210}Pb (Speelman, 2004). Since the radon gas in this instance is contained in a porous material like soil, the time is long enough for the radon gas that is closer to the surface of the soil to be transported

there and exhaled to the surrounding atmosphere (Nero, 1988). The distance it is transported to reach the surface is widely debated and ranges from 1 m for some soils to about $1.6 - 1.9$ metres (Sqgaard-Hansen and Damkjer, 1987; Nero, 1988). One other point to notice in the 238U series is the radionuclides that radon gas decays to. These have relatively short half-lives and are chemically active. They can attach to airborne particles like dust and indoor surfaces and respiratory tracts (James, 1988; Hadler et al., 2002). From the above relation, it is evident that most of the decay products decay via alpha emission and in some cases by beta emission.

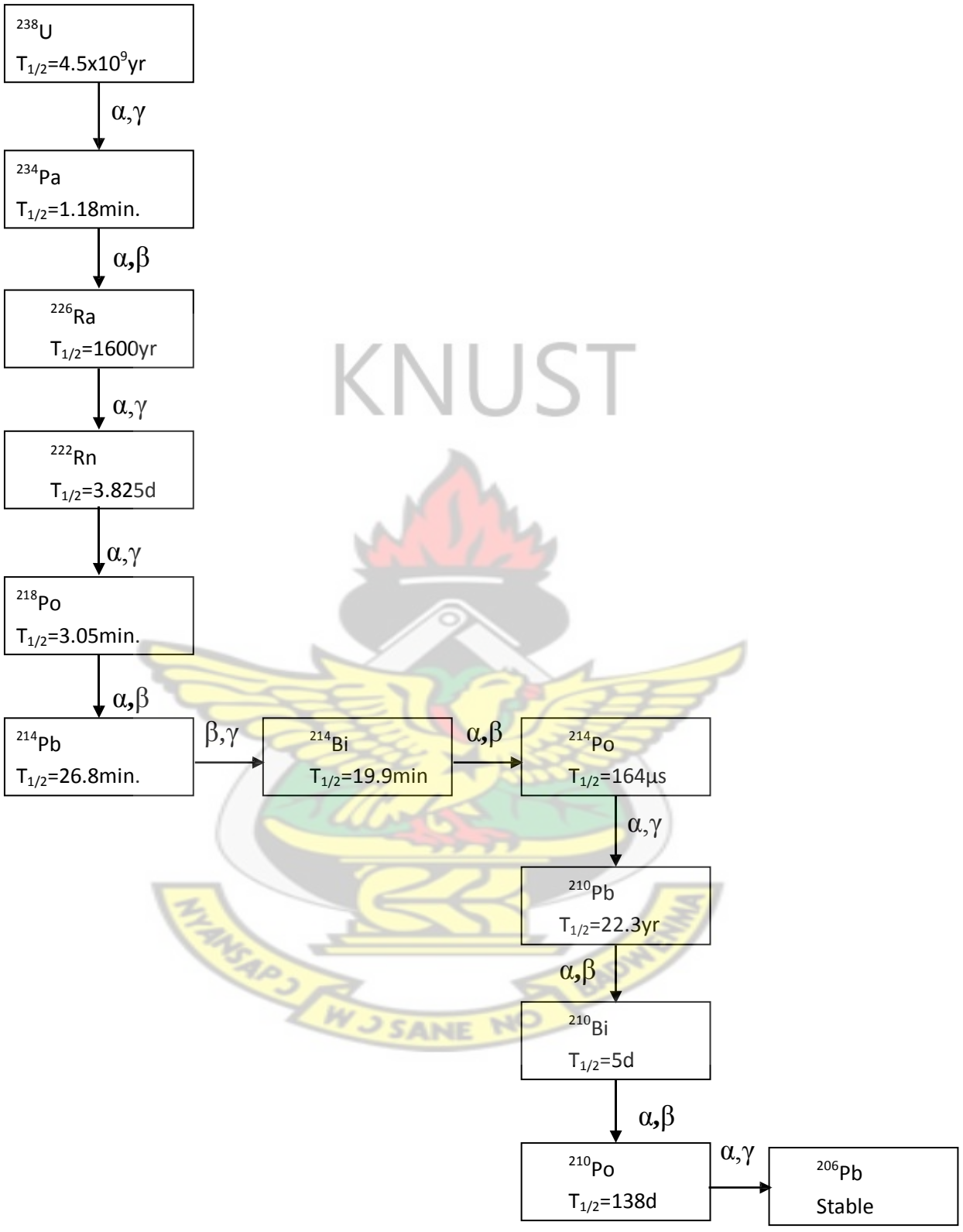


Figure 3.4 (a) Uranium-238 decay series

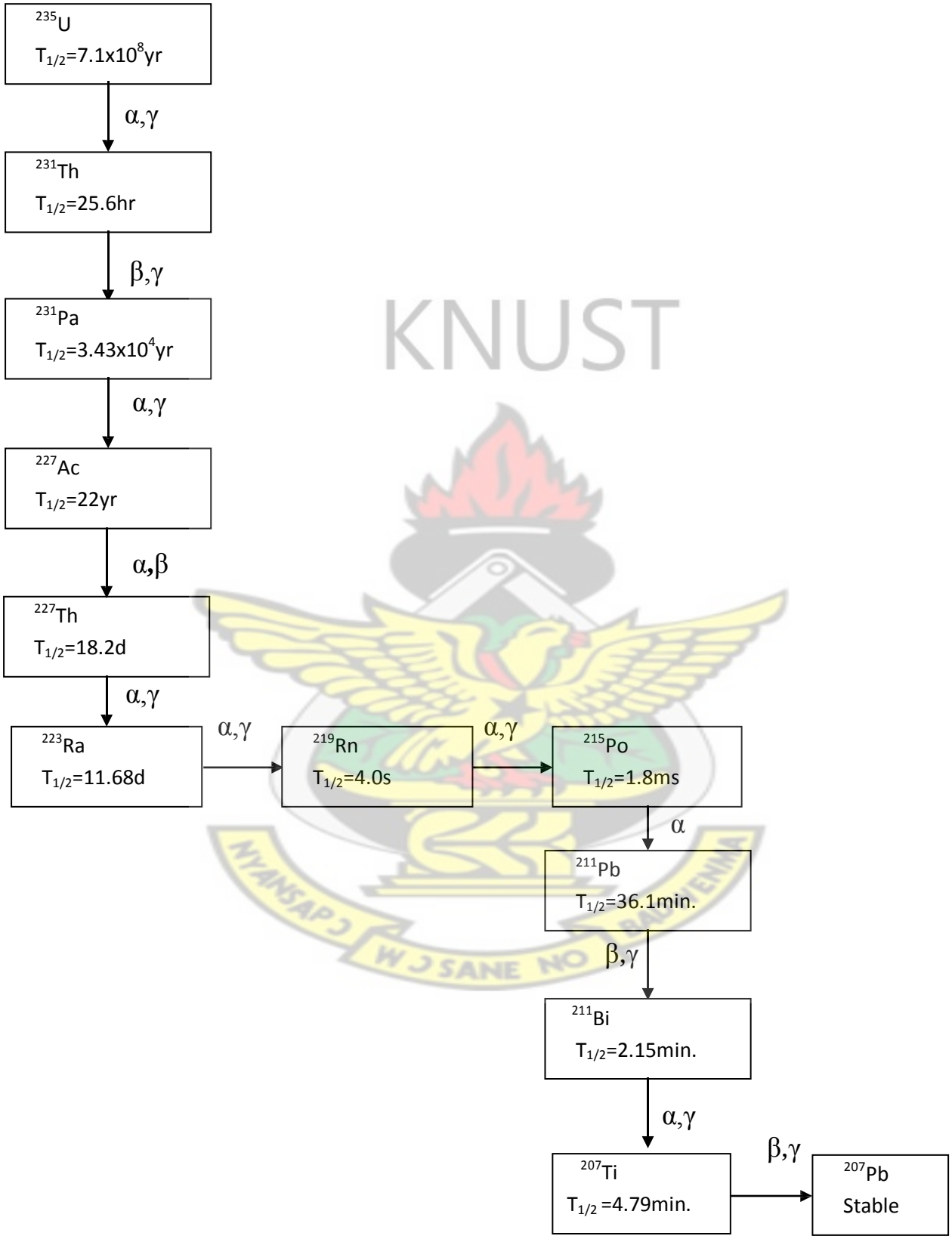


Figure 3.4 (b) Uranium-235 decay series

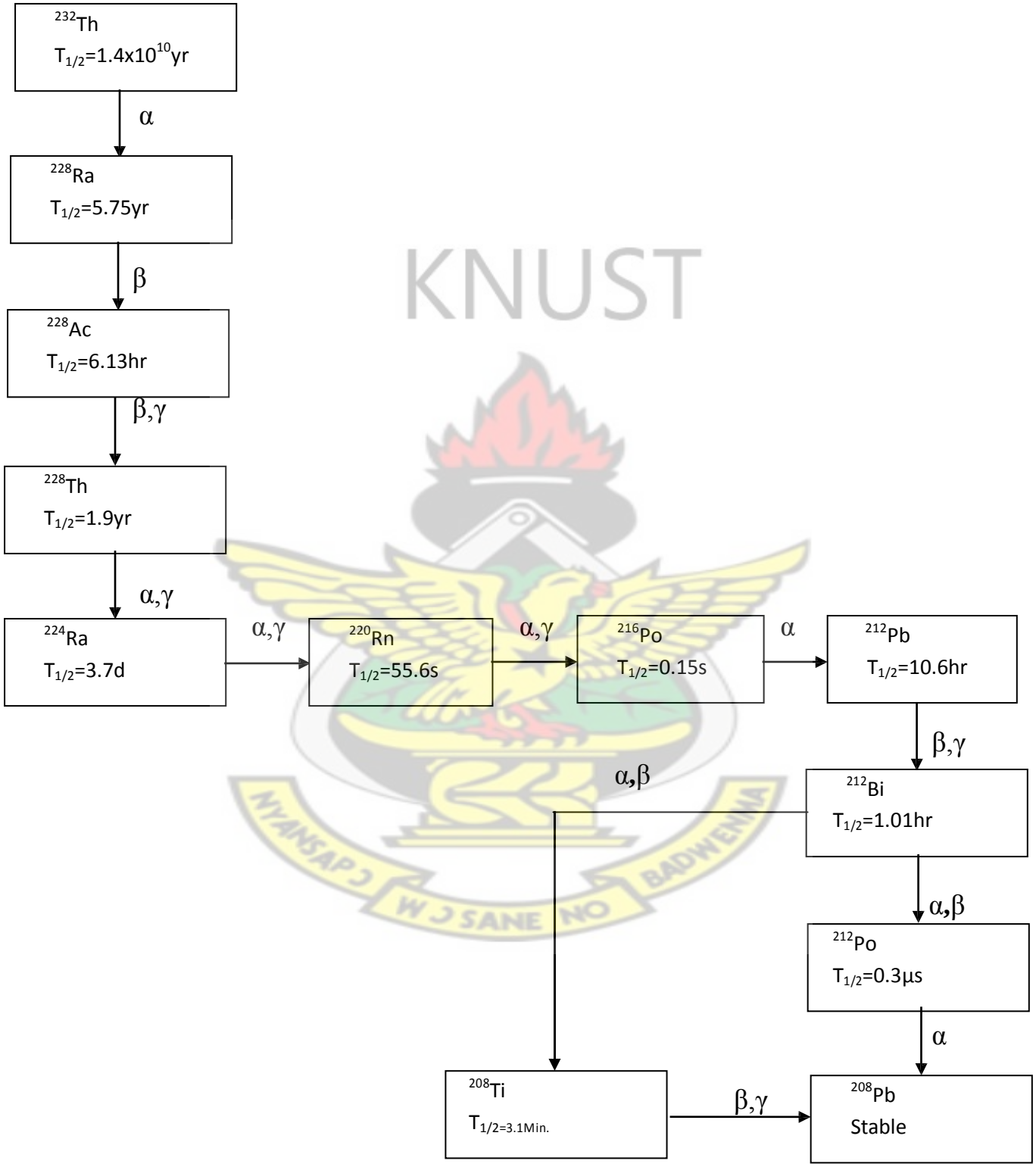


Figure 3.4 (c) Thorium-232 decay series

3.5 Radon Emanation process

Radon is created from the disintegration of the solid radium. Being a gas, it migrates through pores and faults in the soil to the surface of the earth by means of three mechanisms namely; diffusion, convection and by gas carriers. The first process, diffusion, is a spontaneous movement of radon gas from higher concentrations to lower concentrations. This process is rather slow and can only account for a migration of a few meters, due to the short half-life of radon. When the soil is subjected to a steep temperature gradient the gas is transported by convection (transfer of heat). The last mechanism is transportation with gas carriers. This process predominates during volcanic activities, where large fluxes of radon gases associated with the eruptive phases move from the soil into the atmosphere. The amount of radon that reaches the soil pores is described by the emanation fraction. For typical soils or bedrocks, the emanation fraction can range from 5% to 50% (review of Nazaroff 1992). How easily a gas can penetrate a substance (the soil/rock) is measured in permeability, for which the substance's porosity is of major importance. This physical geological parameters account for spatial variations of radon content in soil air. On the other hand, temporal changes in the emanation process are also due to meteorological conditions. Porous soil is probably less affected by groundwater levels than more impermeable soil types, such as clay. Very low water solubility also enables a small horizontal transportation within the groundwater.

3.6 Evaluating Radon Potential of an Area

Scientists can evaluate the radon potential of rocks and soils at housing sites and other areas of interest by evaluating the geology in that area. The factors listed below can increase the probability that an area will have high levels of radon, when

1. probably uranium-rich rocks underlie the area.

2. the site is located on a hill or slope.

3. soils are well drained or dry most of the time.

4. soils form deep cracks during dry time of the year.

5. highly permeable soils are present.

6. the soils are thin and bedrock is close to the surface.

7. the underlying rocks are fractured.

8. the underlying rock contains limestone caverns.

3.6.1 Characteristics of Soil

One of the properties of soil that influence the production and transport of radon gas is the porosity of the soil (Speelman, 2004). It is defined as the ratio of the pore volume to the total volume of the soil. It gives a measure of the storage capacity of the material. According to Nazaroff et al., there are two very important components; the textural pore space and the structural pore space (Nazaroff, 1988). The textural pore space is referred to as the result of random packing of the soil particles whereas the structural pore space is evident in well-aggravated soils. Common porosity values for uniformly sized particle grains fluctuate between 0.25−0.5µm, whereas poorly sorted soils, with a wide variety of grain sizes, possess a porosity value of about 0.3µm.

3.6.2 Grain- Size Sparseness

Soil samples usually consist of a distribution of grain-sizes. This distribution makes up the soil texture and structure which is integral to radon gas transport. Soils have been classified in major divisions, such as sand, silt or clay. Typical particle sizes for the major divisions are; sand with a typical range of about 60 – 200 µm and clays being that of less than 2 µm (Nazaroff, 1988). Soil types form in different situations. Larger particles are formed by the physical processes of

mechanical weathering, whereas the soil formations for clays are determined by chemical processes. Clays and other metals, together with carbonates often form complexes with uranium and radium which leads to the distributions of radionuclides in the soil (Gundersen et al., 1994). Changes in the grain-size distributions and the control of the extent thereof, together with the presence of grain cements, are due to the redistribution of the earlier mentioned complexes that formed. This would change the permeability of soil (Speelman, 2004). The permeability of the soil is defined as how readily something, a gas in this case, would flow through the soil. Soil permeability is determined by the number, size and degree of interconnection of the pore spaces.

CHAPTER FOUR

MATERIALS AND METHODS

4.1 Experimental Sites

In all, nine (9) study areas were considered in the Ashanti Region of Ghana. This region occupies 24389 sq. Km of Ghana, which is 10 per cent of the total land of Ghana. Northern, southern, eastern, western and central parts of this region were considered. In order to define the scope of work some schools within each of the towns were selected; Mampong (St. Monica's college of education), Obuasi (Obuasi Sec. Tech. School), Agogo (Agogo Women's college of Education), Konongo (Konongo Odumase SHS), Akropong (Osei Tutu SHS), Mankranso (Mankranso SHS), Bosomtwe (St. George's Sec. Tech. School), Nkrumah (Nkrumah D/A Prim & JHS), Ayiduase (in and outside KNUST). Fig 4.1 shows the sampling sites on the map of Ashanti region whilst fig. 4.2 shows the geology of the sampling sites. The areas selected are characterised as typical tropics located in the southern sector of Ghana. These sites were selected to investigate the soil-gas radon concentrations. All the sites were strongly associated with already existing structures and new developments for dwellings.

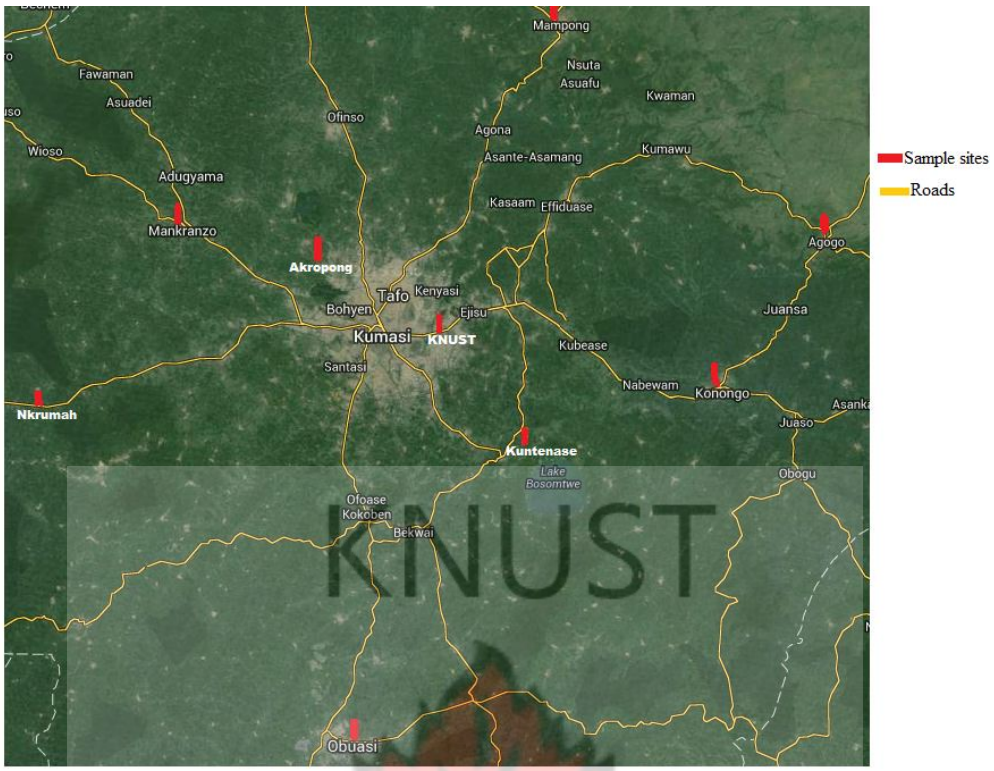


Figure 4.1: Geographical map of the sampling sites

4.2 Geology of the sampling area

The lithology of the studied domain consists mainly of different types of sedimentary rock units which are cropping out in the vicinity of this region and covered occasionally by other metamorphic rocks containing minerals like quartz, feldspar and amphibole which form the metavolcanics. The Tarkwaian formation consists mainly of Gold and Manganese. More of these sediments contain phosphate which has about 10– 20 ppm uranium. Different locations were chosen in order to measure the radon emission of each of the eight different lithologies, which build the geology of the region.

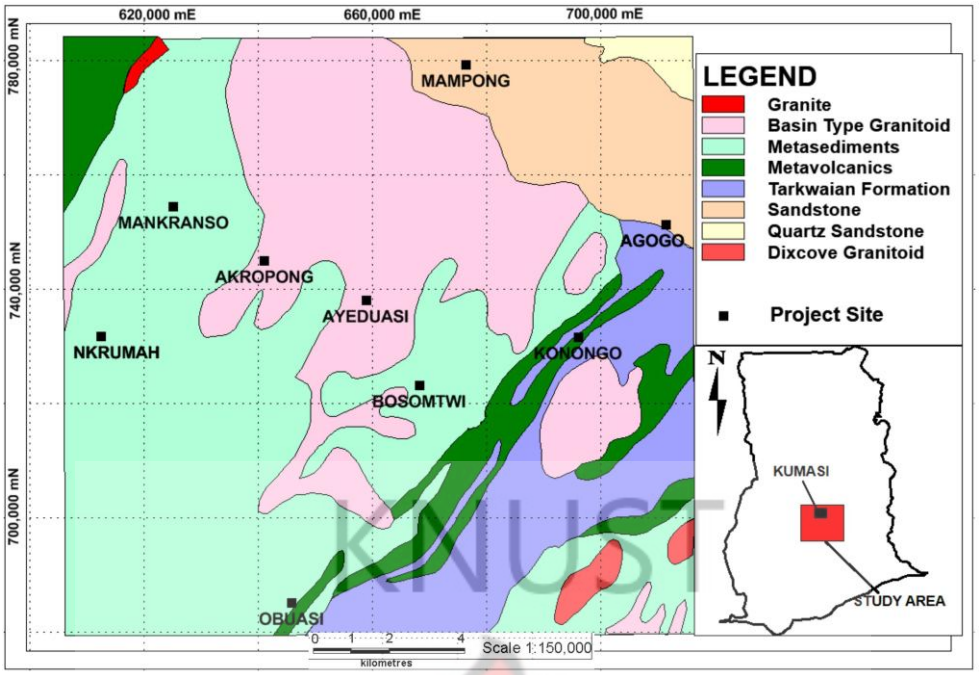


Figure 4.2 Geological map of Ashanti region and sampling sites

4.3 Apparatus

The under listed Materials and Equipment were used in the sample collection

1. Hollow stainless steel metal rod approximately 3.4 cm in diameter
2. Pylon Model 300A, Lucas cell (Scintillation Cell)
3. Pylon Model AB-5 Radiation Monitor
4. Pylon Model 154 vacuum soil probe assembly
5. Garmin GPS 76
6. Vacuum Hand pump
7. Hammer
8. Cotton wool and aerosol filter

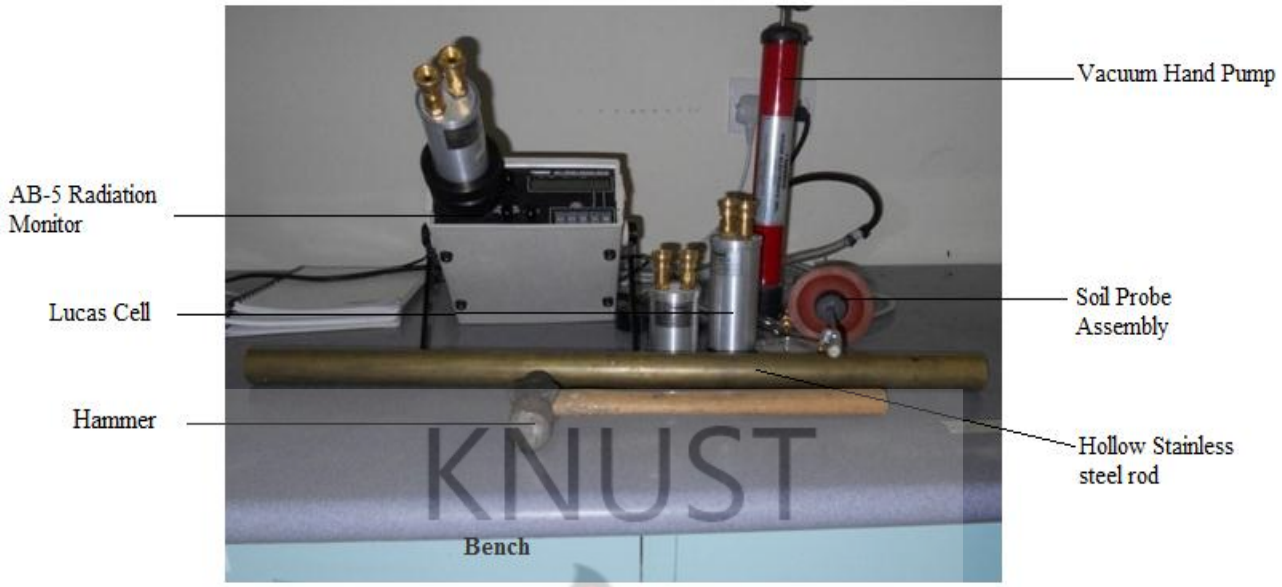


Figure 4.3: Experimental set up for soil radon gas determination

4.4 Experimental Procedure

4.4.1 Sample Preparation

On each site, twenty (20) profiles were made in grid using the GPS with each profile points of 50 metres apart. Soil radon gas samples of about 272 ml were collected at a depth of 0.65 metres (65 cm) and analysis were made using the grab sampling measurement method. Fig. 4.4 shows how 65 cm depth was made on each site.

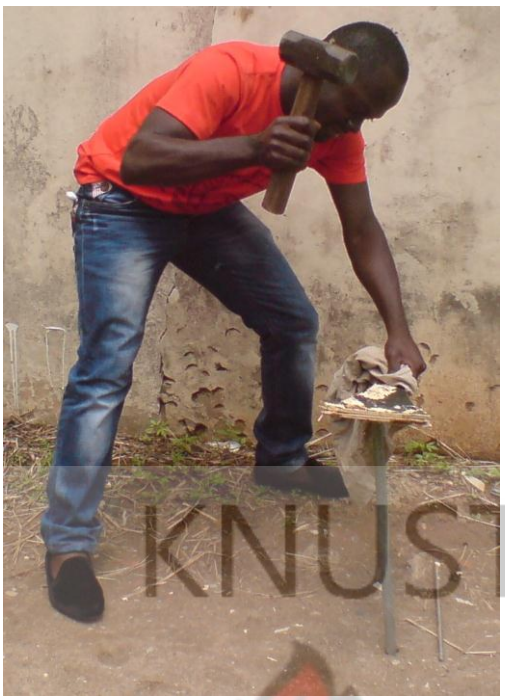


Figure 4.4: Digging to a depth of 65 cm into the soil.

4.4.2 System Background Measurement

Twenty cells were used for taking radon gas sample on each site. Before each cell was used, the following degassing processes were followed:

Compressed nitrogen gas was used to flush the cells with the aid of two tube connectors connected firmly to the cell's valves. One of the tubes leads to the outdoor whiles the other connects from the nitrogen gas source. The cells were flushed for about 20 minutes with a pressure of about 0.5 kg/cm^2 (or 3.01 pm) after which all tubing and tube connectors were disconnected. After each sample collection, the processes were repeated. The radon gas can be removed by flushing the cell repeatedly.

The AB-5 was switched off, the cap was removed and the scintillation cell was mounted to the AB-5. After 30 seconds of mounting the cell to the AB-5, the AB-5 was turned on. In the Continuous mode, the AB-5 was programmed for an interval length of 30 minutes. The AB-5 was allowed to count for four full intervals for a period of 2 hours. The

counting was stopped and the values for the counts were recorded for the intervals. The average count per minute value was determined and recorded. This gave the current background level of the system.

4.4.3 Grab sample Acquisition

The scintillation cell was evacuated to at least 25 inches of mercury using the vacuum pump, and the soil probe. With the scintillation cell mounted on the AB-5, 272 ml of gas was drawn from a depth of 65 cm using the soil probe. The gas was filtered with the filter holder on the soil probe containing aerosol filter. Fiqure 4.5 shows how the radon gas was drawn from the depth of 65 cm at Akropong using the grab method. The gas was tested for radon by the grab sample measurement.

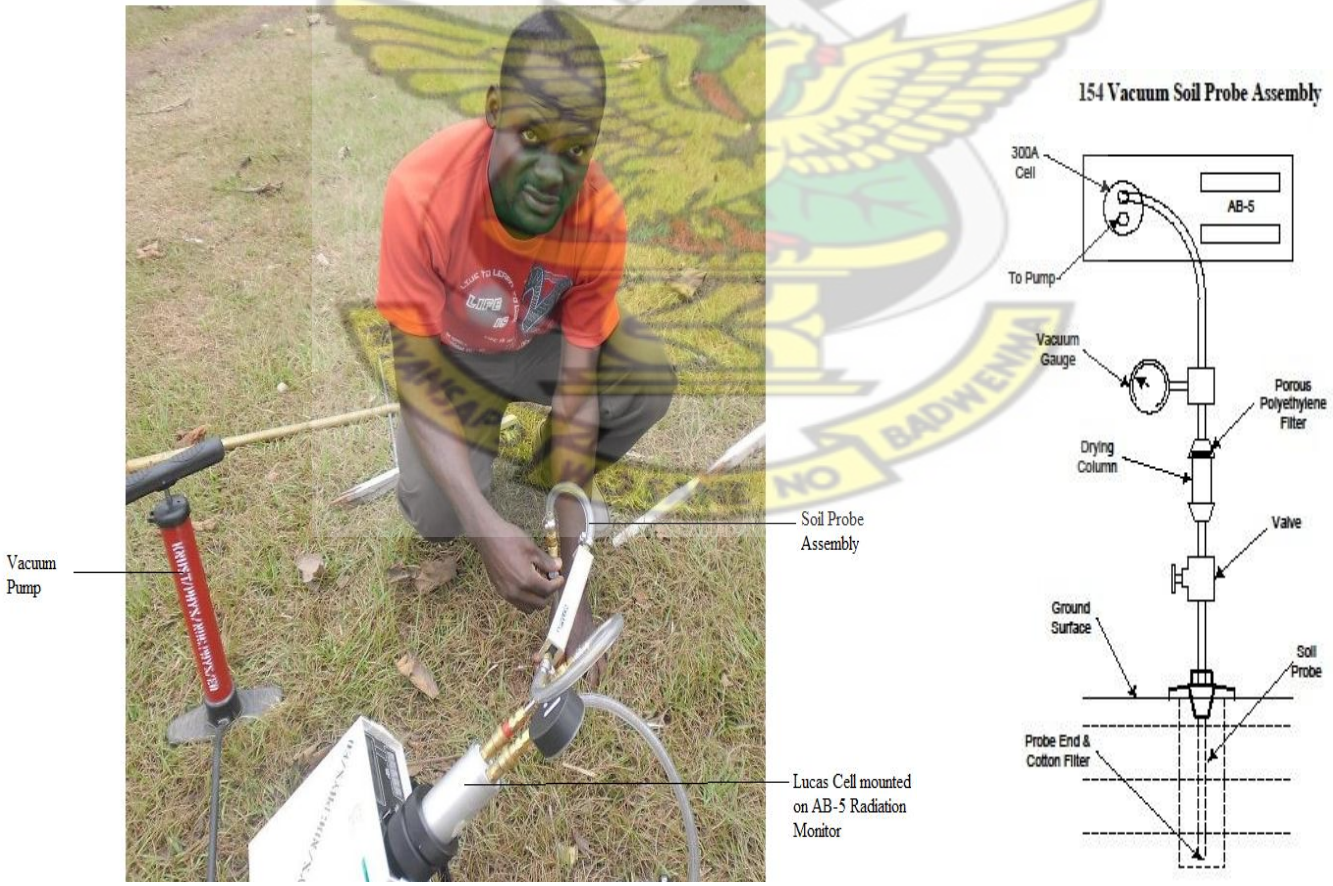


Figure 4.5: Radon gas collection from the soil by the grab method

Most work on soil Radon conducted in Ghana used the Integrative sampling technique. The fact is that Ghana can boast of only one Soil Probe assembly which is in the Nuclear Physics Laboratory of the Kwame Nkrumah University of Science and Technology (KNUST). With the help from the Engineering Department of KNUST, a new soil probe was fabricated and calibrated based on the original soil probe by Pylon Electronics Inc. Fig. 4.6 shows the comparison of the original soil and the fabricated one constructed during my work.

Fig 4.6 (a) Original Soil Probe Assembly Fig4.6(a) Fabricated Soil Probe Assembly

Figure 4.6: Comparison of the Original Soil Probe by Pylon Electronics and the Fabricated Soil Probe.

4.4.4 Grab Sample Measurement

The AB-5 was switched off and the cap or other accessory mounted on the AB-5 was removed. The cell was mounted on the AB-5 and Waited for at least 30 seconds. In the Continuous mode, the AB-5 was programmed for an interval length of 5 minutes for a period of 30 minutes. The start of the count time (t) was noted and counted for six (6) full intervals after which the values were recorded. The AB-5 was turned off and the cell was removed and mounted the cap back to the AB-5 to protect the Photo-multiplier tube

(PMT) from light exposure. The cells were flushed for about 30 minutes after the counts to make it available for use at different site.

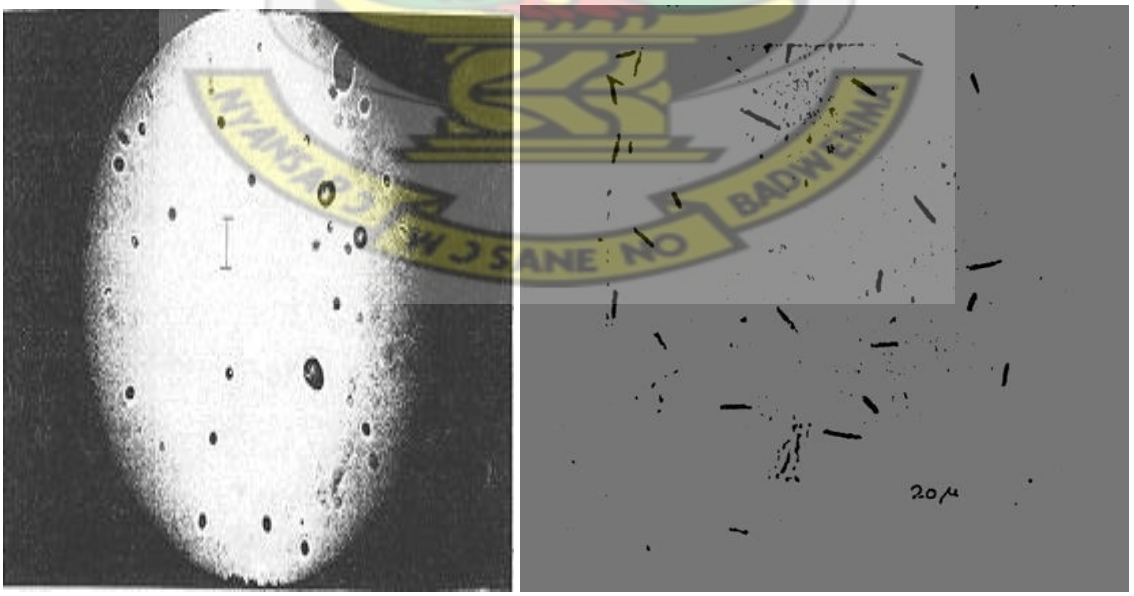
4.5 Radon Measurement Techniques

Radon measurements are performed for different applications. These include mineral prospecting, detection of volcanic eruption and earthquake predictions. When carrying out radon measurement, the first step is to determine whether to measure radon itself or its progeny. In each case, beta, alpha and gamma radioactivity are the detectable phenomenon. The measurement can be continuous or by carrying out by grab sampling. It can be active, which involves the pumping of soil gas into or through a detecting instrument, or passive when the radon concentration is measured in situation under natural conditions. Some of the measurement techniques are describe in details below;

4.5.1 Solid State Nuclear Track Detectors (SSNTDs) Method

Solid State Nuclear Track Detectors (SSNTDs) are insulating solids both naturally occurring and man-made. There are several types of these detectors including inorganic crystals, glasses and plastics, but the most popular used detector for radon measurement is the LR 115 because of its high sensitivity. For this method, detectors are put in a proper device and buried in the soil to a considerable depth to be exposed to radon gas. When a heavily ionizing charged particle passes through the detectors, it leaves a narrow trail of damage or latent track about 50Å in diameter along its path. This latent track cannot be seen with the naked eye. The exact nature of the physical and chemical changes occurring at the damage site depends on the charge (Z) and velocity (ß = v/c, where v is the particle velocity and c is the velocity of light) of the particle, on the chemical structure of the detector material and also on the environmental conditions like

temperature and pressure. After the detectors have been exposed for a period of 2-3 months, they are removed and etched with chemicals such as sodium hydroxide solution and hydrofluoric acid at a constant temperature for 3 hours to enlarge or develop the latent tracks. After the etching, the detectors are washed for about 30 minutes with cold water and then with distilled water and finally dry in air. The latent tracks are then viewed under an optical microscope. Only the charged particles which give up energy exceeding the critical value can produce etchable tracks. The number of tracks per area counted is used to calculate the radon concentration of the site tested .The advantage of SSNTDs CR-39 over other detectors is it integrating nature of the detectors which allows events to be accumulated over long periods of time. The stored information is preserved almost indefinitely under normal temperature and pressure and other environmental conditions. The recorded tracks can be examined any time after the experiment, even after several years. There is no radioactive decay or electronics breakdown. Some photographs of nuclear tracks developed and Lexan track detectors are shown in figure 4.7 below.



a. Fission fragment &alpha tracks in CR-39 b. Fission fragment tracks in Lexan

Figure 4.7: Photographs of nuclear tracks developed in CR-39 and Lexan track detectors

4.5.2 Electrets Ion Chamber Detector Method

In this radon detector method, an electrostatically charged disk detector (electrets) is situated within a small container (ion chamber). During the measurement period, radon diffuses through a filter-covered opening in the chamber, where the ionization resulting from the decay of radon and its progeny reduces the voltage on the electrets. A calibration factor relates the measured drop in voltage to the radon concentration. The variations in electrets design determine whether detectors are appropriate for making long-term or short-term measurements. Electrets ion chamber for long (EL) detectors may be deployed for 1 to 12 months. Since the electrets-ion chambers are true integrating detectors, the EL type can be exposed at shorter intervals if radon levels are sufficiently high. For short-term measurements, electrets ion chamber (ES) detectors are deployed for 2-7 days. Since the electrets-ion chambers are also true integrating detectors, the ES type can be exposed at longer intervals if radon levels are sufficiently low. This method is non-destructive and the electrets can be measured several times without having their charge value altered. After proper calibration, the electrets dosimeter can deliver a dose response curve. The electrets dosimeter offers several advantages. An example is its ability to store information over 27 relatively long periods. It is independent of the humidity in its environment and easy to take readings if it is well calibrated. But its response curve does not cover efficiently the very low or very high doses and also it is sensitive to gamma radiation background which in some case may induce significant error or even preclude their use.

4.5.3 Activated Charcoal Adsorption (AC) Method

For this method, an airtight container with activated charcoal is opened in the area to be sampled and radon in the air adsorbs onto the charcoal granules. At the end of the sampling period, the container is sealed and sent to a laboratory for analysis. The gamma emission from the radon adsorbed to the charcoal is counted on a scintillation detector and a calculation based on calibration information is used to calculate the radon concentration at the sample site. Charcoal adsorption detectors, depending on the design, are deployed from 2 to 7 days. Because charcoal allows continual adsorption and desorption of radon, the method does not give a true integrated measurement over the exposure time. Use of a diffusion barrier over the charcoal reduces the effects of drafts and high humidity.

4.5.4 Electrets detector Method

One of the most recent techniques for radon measurements and monitoring is the electrets radon monitor. Electrets is a piece of dielectric material that exhibits an almost permanent electrical charge if not otherwise perturbed, this charge produces a strong electric field which is able to collect ions of opposite signs and the total charge of the electrets decreases. The electrets radon monitor is basically made of steel can on the lower top of which the electrets dosimeter is fixed. At the bottom is a small inlet which allows the radon gas to enter the assembly through a filter. Decaying of radon produces ionizing particles that intend produce ions within the inner volume. These ions are collected and the total charge of electrets changes. After some time the surface potential of the electrets is measured by the shutter method using a battery operated, lightweight piece of equipment. This method is nondestructive and the electrets can be measured several times without having their charge value altered. After proper calibration, the

electrets dosimeter can deliver a dose response curve. The electrets dosimeter offers several advantages, an example is its ability to store information over relatively long period, and it is independent of the humidity in its environment and easy to take readings if it is well calibrated. But its response curve does not cover efficiently the very low or very high doses and also it is sensitive to gamma radiation background which in some case may induce significant error or even preclude their use.

CHAPTER FIVE

5.0 Results and Discussion

The result of this work is based on the equation (5.1) which determines the Radon concentration in pCi/l on each site. The graphs represent the variation in radon concentration and their specific locations for each profile or sample point chosen.

$$^{222}\text{Rn (pCi/l)} = \frac{CPM - BG}{G} \qquad (5.1)$$

Where:

CPM = The average of the 5 minute count converted to counts per minute (cpm) format.

BG = The average background count based on a 30 minute count converted to a counts per minute (cpm) format.

G = (Count Efficiency [0.73]) x (Conversion of cpm to pCi [2.22]) x (Approximate Number of Alpha Emitters [2]) x (Volume of Gas Sample in liters[0.257])

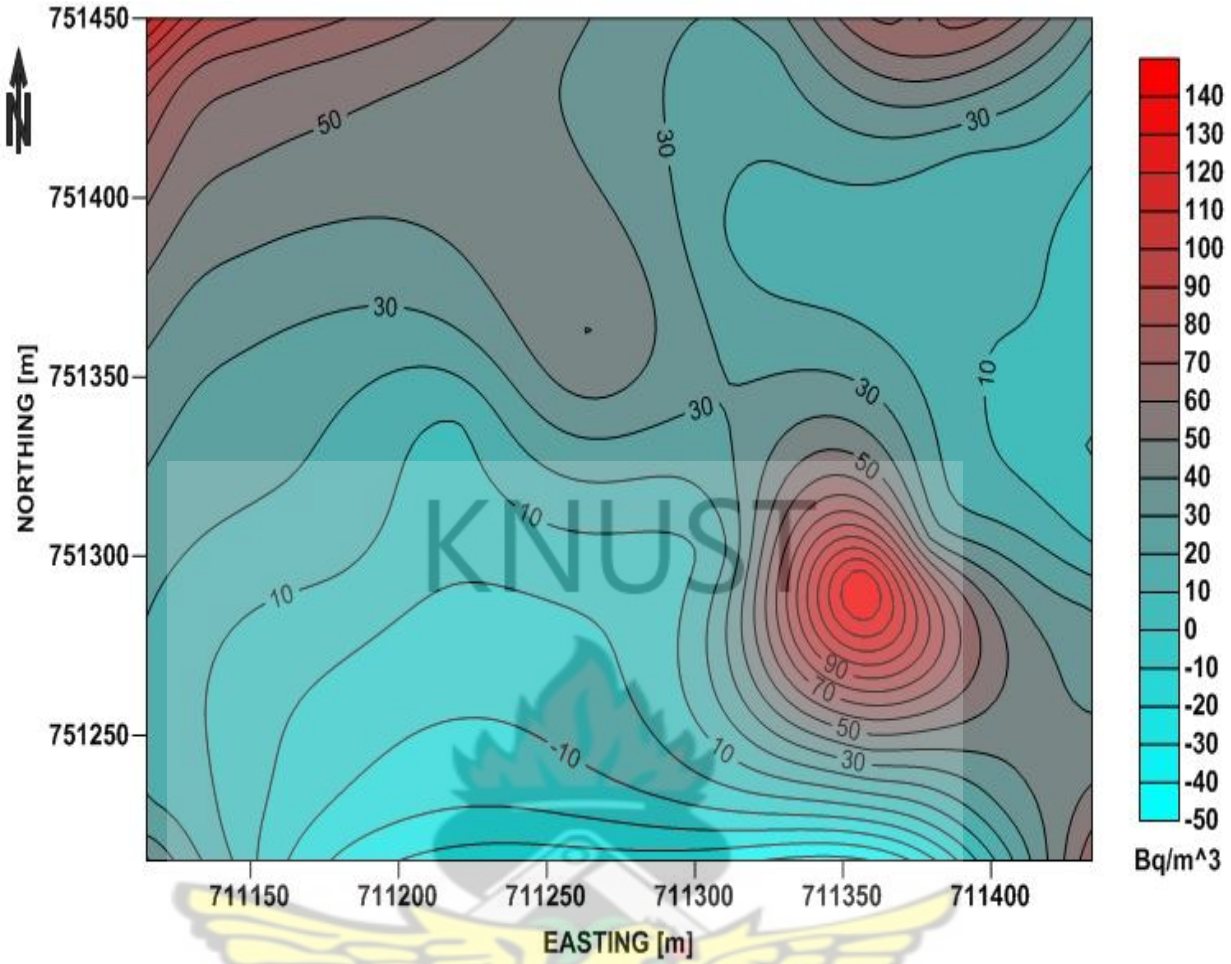


Figure 5.1: Soil Radon gas concentration in Agogo

The concentration of radon registered highest at about 140 pCi/l or 5.18 kBq/m^3 at the profile 14 whose elevation is 456 m. Sample 12 and sample 19 have the same elevation of 454 m but have different concentration levels of 40 pCi/l or 1.48 kBq/m^3 and 15 pCi/l or 555 Bq/m^3 respectively. The radon gas is found to concentrate much at the North-East part of the school compound in Agogo as shown in fig. 5.1.

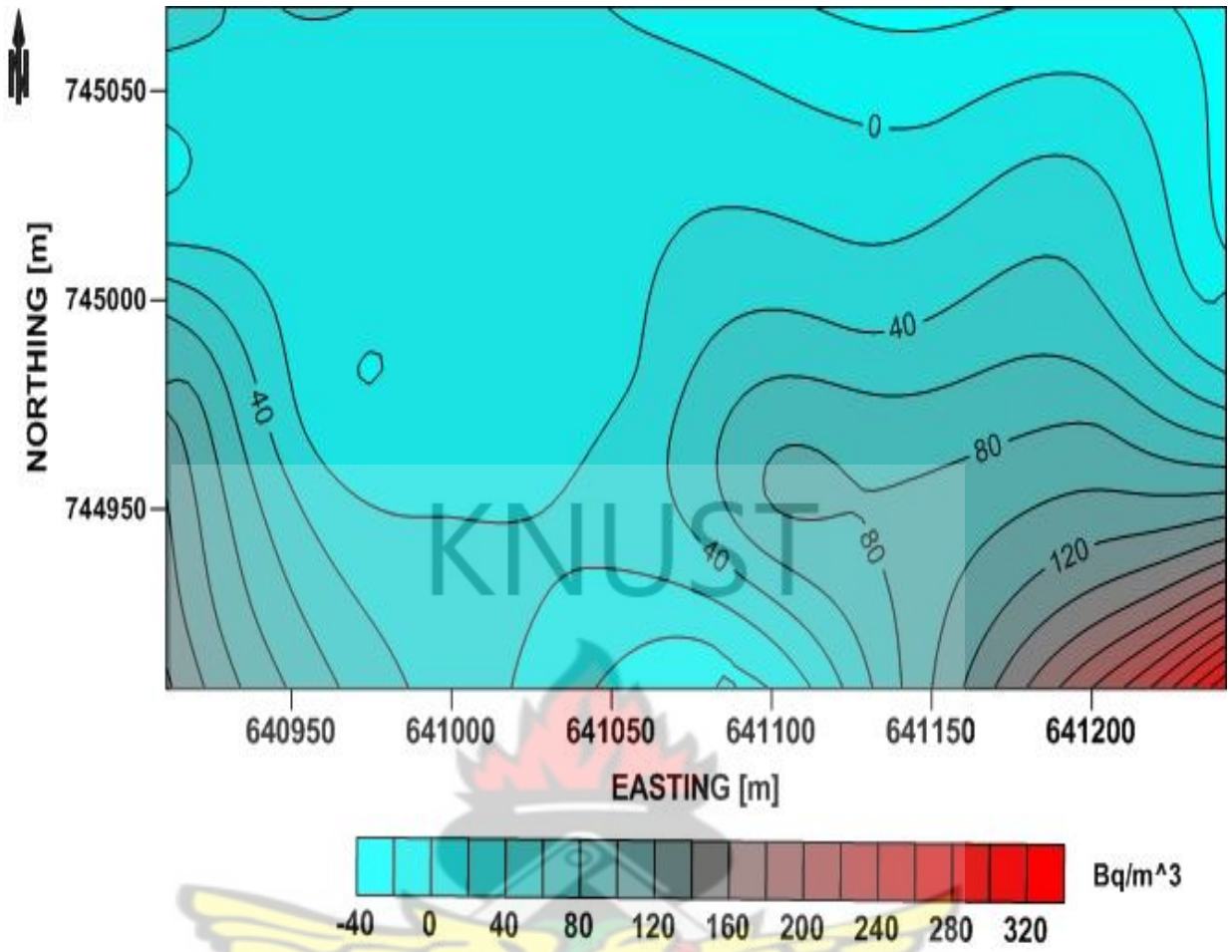


Figure 5.2: Soil Radon gas concentration in Akropong

The average height above sea level for Akropong lies between 250 m and 270 m. Radon concentrations is invariant to the elevation. Profiles 4, 19 and 20 have maximum radon levels of 83 pCi/l or 3.07 kBq/m^3, 80 pCi/l or 2.96 kBq/m^3 and 79 pCi/l or 2.92 kBq/m^3 respectively. The radon levels in Osei Tutu campus, Akropong is concentrated on South-Eastern part of the school as shown fig. 5.2 above.

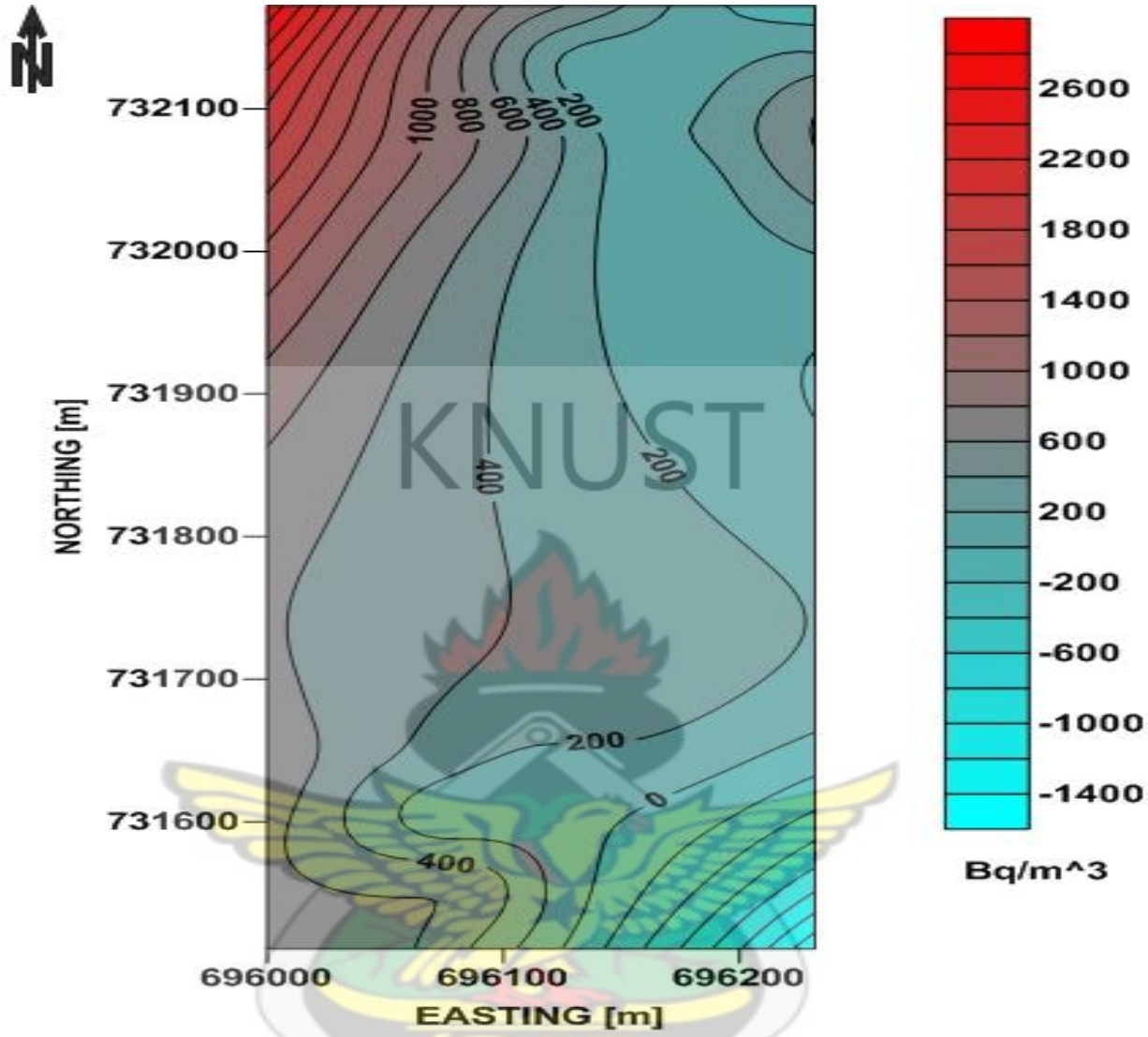


Figure 5.3 Soil Radon gas concentration in Konongo

The minimum radon concentration at Konongo-Odumasi school compound is 66.25 pCi/l or 2.45 kBq/m^3 and the highest 652.07 pCi/l or 24.13 kBq/m^3. The trend of the radon gas distribution is concentrated at the northing part of the school compound as in fig. 5.3. However, the radon concentration in the soil of Obuasi Sec. Tech. School compound is distributed evenly at Obuasi with the maximum radon levels concentrated at the northing part of the school compound in Obuasi as in fig. 5.4.

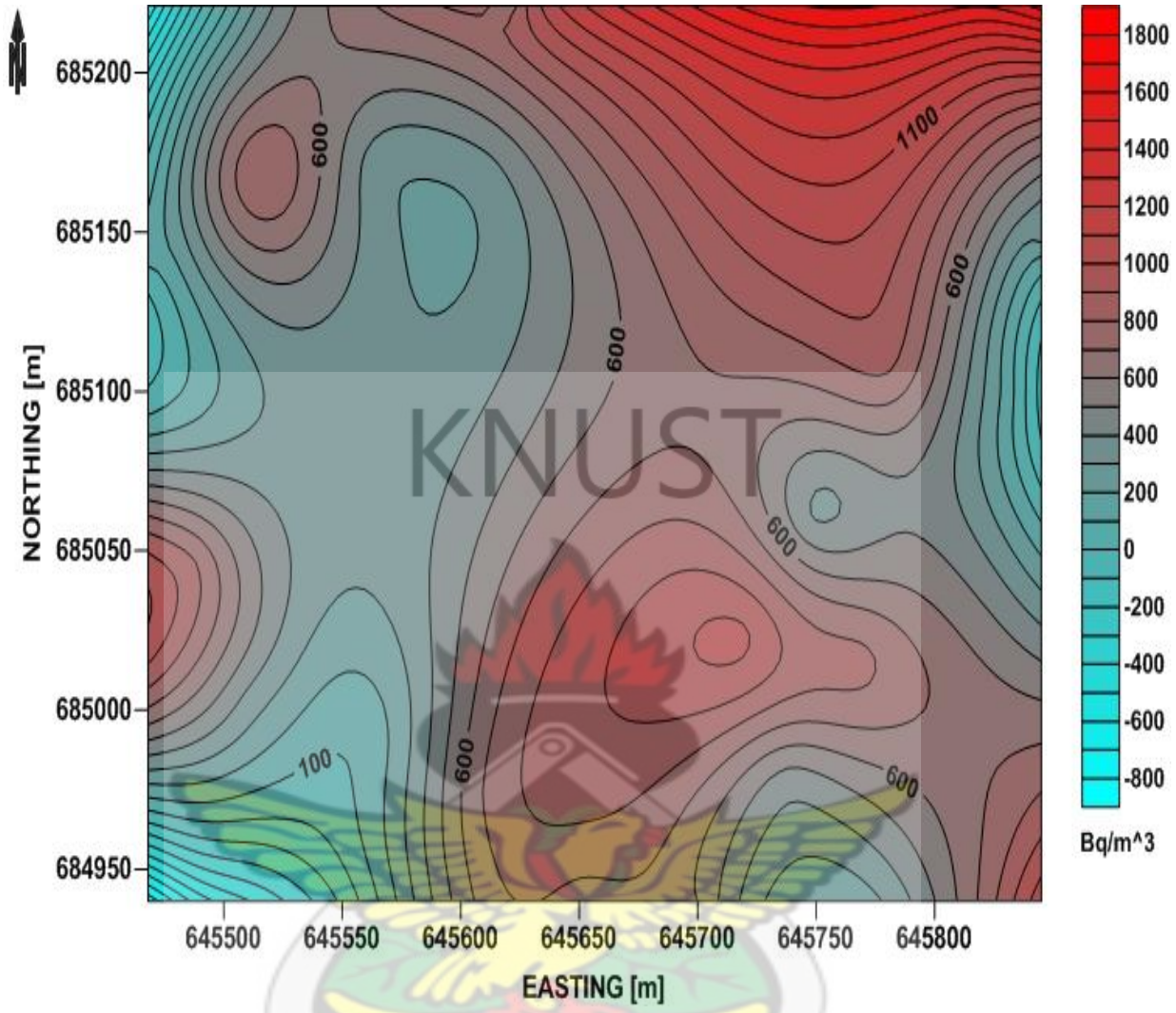


Figure 5.4: Soil Radon gas concentration in Obuasi

The combination of all radon concentration in the sites under study are shown in figure 5.5 below, which is an illustration of the Radon Map of the selected areas in the Ashanti region.

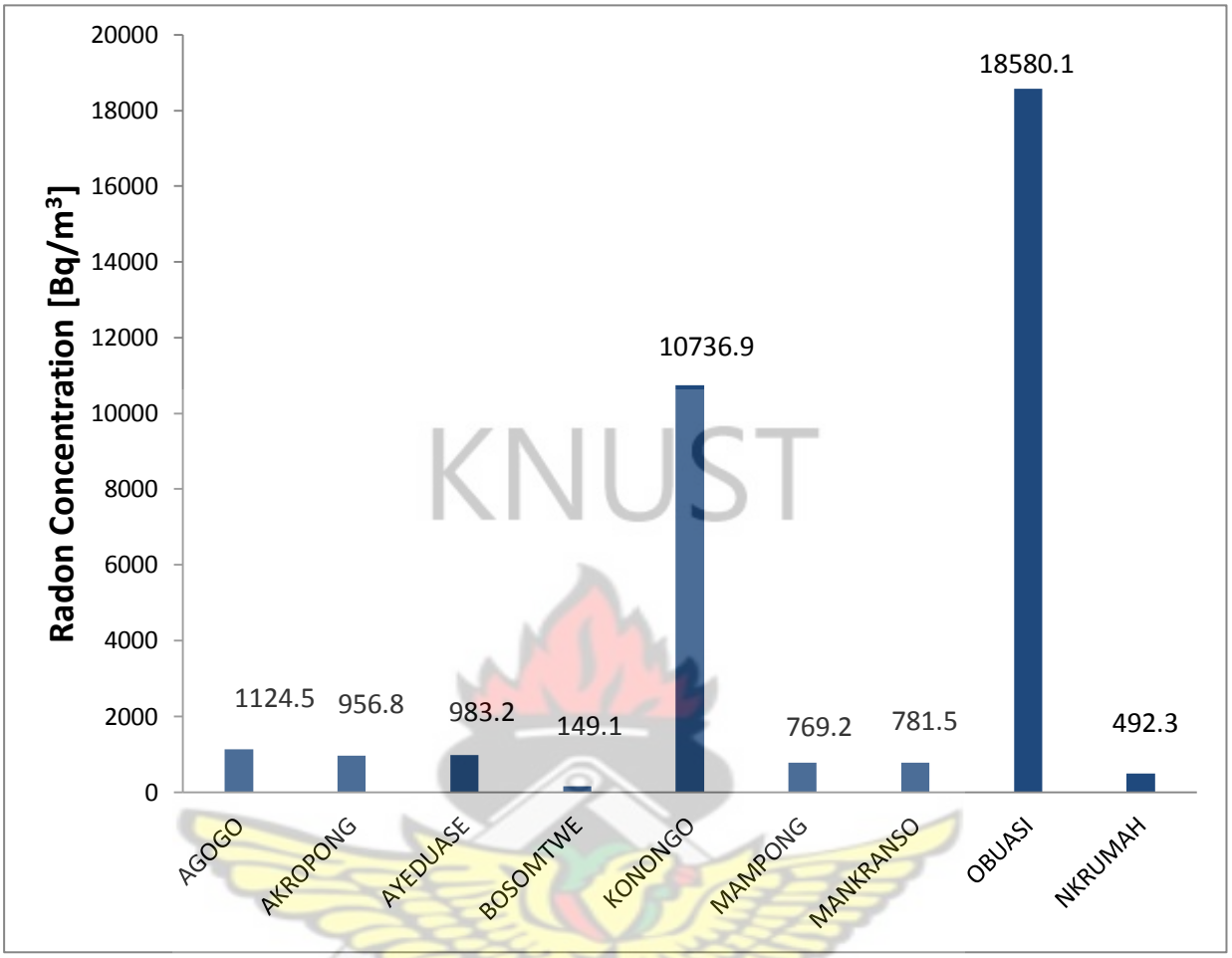


Figure 5.5: Comparison of radon levels in the selected areas of the Ashanti Region.

The average concentrations for the different sites are in table A.10 in the appendix. From figure 5.5 the radon levels in soils of Obuasi and Konongo are higher as compared to the radon levels in the other towns of Ashanti with Bosomtwi recording lowest. Works conducted between a period of 2001 through to 2006 in both Obuasi and Bosomtwi using different radon measurement technique showed that Obuasi has the highest radon gas concentration with an average of 20.10 kBq/m^3 and Bosomtwi with the lowest of average concentration of 3.69 kBq/m^3. The different concentrations are due to the following factors: uranium-rich rocks underlie the area or the site is located on a hill or slope as shown in fig 4.2. The underlying rock type in Agogo, Konongo and Obuasi is the Tarkwaian formation, which consist of mainly

Gold and Manganese. The underlying rock in Konongo and Obuasi occasionally have metavolcanics which is a metarmorphic rock containing minerals like quartz, feldspar and amphibole which are rich in uranium and hence maximum radon level in the soil of those areas. However, Bosomtwi recorded the lowest soil radon gas because of the metasediments which is a sedimentary rock (with little phosphate) that underly the area. The soil in Bosomtwi is also covered by evergreen vegetation that always keeps the soil moist and thus reduces the soil radon content.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

In conclusion this research work was a success. The results from this work indicate that radon risk is high in some areas of Ashanti. The high soil radon concentration of the areas is due to the high Uranium concentrations in the soil because radon is one of the decay products of Uranium. The minimum radon concentration obtained is 4.03 pCi/l or 149.11 Bq/m^3 at Bosomtwe and the maximum radon concentration of 502.16 pCi/l or 18.58 kBq/m^3 is obtained in Obuasi. A lot more findings and research tactics were developed after which the conclusions in table 6.1 were made;

Table 6.1: Radon concentrations for each sampling site in pCi/l and Bq/m^3

Sampling Site	Radon Concentration/pCi/l	Radon Concentration/Bq/m^3
Agogo	30.39	1124.43
Akropong	25.86	956.82
Ayeduase	26.57	983.09
Bosomtwe	4.03	149.11
Konongo	290.19	10737.03
Mampong	20.79	769.23
Mankranso	21.12	781.44
Obuasi	502.16	18579.92
Nkrumah	13.31	492.47

Other works done in Ghana using different techniques recorded average radon levels between 11.03 – 22.01 kBq/m^3. These results confirm the fact that Ghana is believed to be characterised with Uranium packets all over the country with Obuasi and Konongo having greater amount in

the Ashanti region. Obuasi and Konongo are both located on a hill with their soils been dry most of the time. The geology of Obuasi and Konongo are characterised with fractured rocks containing limestone caverns with thin and permeable soil close to its surface. Bosomtwe recorded the lowest soil radon concentration which is in conformity with other studies conducted in areas in the Bosomtwe area using other methods, because the soil at that area was with too much water at that time.

6.2 Recommendation

It is recommended that different methods of soil radon concentration measurement should be deployed in a similar project to check the accuracy of the results yielded by the grab and quick sampling method used in this work. It is suggested that the same or similar research should be carried out during one particular season (Wet or dry) because heavy rainfall and the moisture content of the soil might have effect on the soil radon concentration. Calibration of the radiation monitor must be done regularly to correct its sensitivity or counting efficiency.

6.2.1 Radon and EPA Policy

The major source of radon exposure is through inhalation, with background levels in ambient air ranging from 0.003 to 2.6 pCi/l or 0.11 to 96.2 Bq/m^3. Higher levels of radon are frequently present in indoor locations, such as homes, schools or office buildings. It is strongly recommended that the Environmental Protection Agency (EPA) in Ghana, should come out with policies regarding radon activity concentration and its hazardous exposure. Looking at the results of this work, it is also recommended that the selected schools and dwellings should maintain good ventilation since is the way to reduce ones exposure to radon. One is advised to

seal all cracks in the foundation of his building using Deep Seal Plus and ensure regular monitoring of radon invasion.

APPENDIX A

Table of results

Table A.1: Radon concentrations of each sampling point of the Akropong area

AKROPONG	LONGITUDE	LATITUDE	ELEVATION/m	CONCENTRATION/pCi/l
SAMPLE1	640997	744952	249	17.87326477
SAMPLE2	641038	744926	253	17.13042396
SAMPLE3	641085	744907	254	8.779900843
SAMPLE4	641102	744954	255	83.85772456
SAMPLE5	641129	744996	255	34.57724555
SAMPLE6	641055	744985	256	16.81482666
SAMPLE7	641073	745031	255	14.86655356
SAMPLE8	641010	744999	248	5.684886422
SAMPLE9	641033	745044	248	5.684886422
SAMPLE10	640986	745058	247	14.97953366
SAMPLE11	640936	745070	247	13.88868214
SAMPLE12	640916	745025	249	2.453949072
SAMPLE13	640976	745021	270	10.82448047
SAMPLE14	640961	744975	267	5.72903803
SAMPLE15	640911	744985	264	62.7751839
SAMPLE16	641151	745037	250	4.428899877
SAMPLE17	641197	745021	251	30.55851545
SAMPLE18	641242	745000	252	6.726517573
SAMPLE19	641203	744969	252	80.04233112
SAMPLE20	641125	744947	254	79.32616802

Table A.2: Radon concentrations of each sampling point of the Agogo area

AGOGO	LONGITUDE	LATITUDE	ELEVATION/m	CONCENTRATION/pCi/l
SAMPLE1	711115	751229	421	21.64816061
SAMPLE2	711141	751215	436	14.80946327
SAMPLE3	711146	751270	448	6.765733806
SAMPLE4	711180	751306	455	14.49519985
SAMPLE5	711220	751336	444	10.30719969
SAMPLE6	711265	751358	450	49.28826807
SAMPLE7	711314	751391	433	17.44762192
SAMPLE8	711328	751439	447	30.06497783
SAMPLE9	711375	751450	449	58.53342816
SAMPLE10	711392	751404	450	13.49225138
SAMPLE11	711388	751355	451	12.42807756
SAMPLE12	711379	751306	454	39.83608895
SAMPLE13	711307	751303	453	15.73317894
SAMPLE14	711357	751293	456	139.030881
SAMPLE15	711360	751244	457	35.59059833
SAMPLE16	711409	751235	458	37.45590375
SAMPLE17	711431	751280	457	33.99327049
SAMPLE18	711432	751286	455	30.4029844
SAMPLE19	711434	751330	454	14.9220432
SAMPLE20	711409	751372	353	11.59146461

Table A.3: Radon concentrations of each sampling point of the Ayiduase area

AYIDUASE	LONGITUDE	LATITUDE	ELEVATION/m	CONCENTRATION/pCi/l
SAMPLE1	658820	737887	273	25.75652781
SAMPLE2	658822	737887	273	9.307185764
SAMPLE3	658821	737888	271	8.626504016
SAMPLE4	658823	737888	274	5.511481312
SAMPLE5	658829	737886	274	35.59766792
SAMPLE6	658831	737895	276	43.27911409
SAMPLE7	658825	737895	265	37.97611908
SAMPLE8	658824	737904	263	34.36008899
SAMPLE9	658834	737902	262	19.73070026
SAMPLE10	658836	737930	264	35.65475822
SAMPLE11	658840	737959	266	29.84862161
SAMPLE12	658841	737980	269	13.35846267
SAMPLE13	658865	737985	267	1.133802637
SAMPLE14	658863	738016	268	46.92609031
SAMPLE15	658909	737994	270	49.15621341
SAMPLE16	658922	377949	270	12.2588075
SAMPLE17	658962	737898	262	48.56596909
SAMPLE18	658925	737882	258	34.03782227
SAMPLE19	658894	737879	258	25.7531931
SAMPLE20	658878	737905	265	14.60604573

Table A.4: Radon concentrations of each sampling point of the Konongo area

KONONGO	LONGITUDE	LATITUDE	ELEVATION/m	CONCENTRATION/pCi/l
SAMPLE1	696139	732172	252	447.2097558
SAMPLE2	696186	732161	250	65.54455962
SAMPLE3	696232	732141	247	206.1005764
SAMPLE4	696179	732084	248	200.6156203
SAMPLE5	696130	732130	240	90.32445409
SAMPLE6	696112	732085	241	570.0531885
SAMPLE7	696225	732096	249	535.9641662
SAMPLE8	696170	732050	251	77.78399152
SAMPLE9	696159	732007	253	121.3499152
SAMPLE10	696157	732091	252	66.23514361
SAMPLE11	696061	731642	257	365.052061
SAMPLE12	696110	731650	256	195.0213195
SAMPLE13	696153	731672	253	256.4724978
SAMPLE14	696118	731561	256	183.2119617
SAMPLE15	696074	731595	258	107.1781857
SAMPLE16	696085	731555	254	548.0943549
SAMPLE17	696096	731511	257	320.504737
SAMPLE18	696000	731631	261	652.0704251
SAMPLE19	696046	731614	261	279.4607537
SAMPLE20	696034	731681	262	515.5269587

Table A.5: Radon concentrations of each sampling point of the Mampong area

MAMPONG	LONGITUDE	LATITUDE	ELEVATION	CONCENTRATION
SAMPLE1	676443	779091	443	19.65400185
SAMPLE2	676397	779110	446	34.98448078
SAMPLE3	676353	779131	446	40.73979635
SAMPLE4	676372	779176	443	21.77821444
SAMPLE5	676414	779158	443	38.60557962
SAMPLE6	676463	779141	446	38.0236054
SAMPLE7	676505	779119	445	34.04782641
SAMPLE8	676548	779094	446	12.60441722
SAMPLE9	676598	779097	444	9.486459969
SAMPLE10	676645	779083	445	16.16002229
SAMPLE11	676616	779115	446	17.35678432
SAMPLE12	676579	779148	446	11.22424594
SAMPLE13	676522	779148	445	15.21963304
SAMPLE14	676548	779020	444	6.909526658
SAMPLE15	676568	778976	442	3.363925729
SAMPLE16	676557	778927	440	34.04782641
SAMPLE17	676522	778974	446	26.13668516
SAMPLE18	676483	779014	443	16.44387311
SAMPLE19	676430	778988	443	7.05878844
SAMPLE20	676392	779023	445	11.96495253

Table A.6: Radon concentrations of each sampling point of the Obuasi area

OBUASI	LONGITUDE	LATITUDE	ELEVATION/m	CONCENTRATION/pCi/l
SAMPLE1	645619	685221	216	703.5018807
SAMPLE2	645613	685173	225	382.8471811
SAMPLE3	645563	685172	227	353.3424439
SAMPLE4	645513	685168	230	787.1811021
SAMPLE5	645497	685214	229	147.7319685
SAMPLE6	645468	685145	233	202.5490168
SAMPLE7	645486	685098	230	132.4301737
SAMPLE8	645486	685045	227	813.0325358
SAMPLE9	645511	685004	227	382.4460162
SAMPLE10	645565	684993	227	152.9469122
SAMPLE11	645610	684973	226	698.2078036
SAMPLE12	645652	684942	227	677.1003212
SAMPLE13	645702	684940	224	597.7949997
SAMPLE14	645737	684979	227	450.5532317
SAMPLE15	645718	685022	228	1017.051259
SAMPLE16	645767	685015	227	826.9651676
SAMPLE17	645751	685063	229	383.4368239
SAMPLE18	645781	685106	228	811.5624316
SAMPLE19	645829	685100	227	169.2095022
SAMPLE20	645845	685147	227	353.3927653

Table A.7: Radon concentrations of each sampling point of the Bosomtwe area

KUNTENASE	LONGITUDE	LATITUDE	ELEVATION/m	CONCENTRATION/pCi/l
SAMPLE1	668157	723229	286	0.439381869
SAMPLE2	668198	723258	293	1.230509332
SAMPLE3	668237	723300	292	0.729902121
SAMPLE4	668276	723275	292	0.862890501
SAMPLE5	668230	723228	293	4.491459105
SAMPLE6	668255	723183	293	8.177918337
SAMPLE7	668191	723192	289	4.262164195
SAMPLE8	668216	723152	288	11.53063943
SAMPLE9	668222	723198	289	4.050876739
SAMPLE10	668193	723231	290	4.508532839

Table A.8: Radon concentrations of each sampling point of the Mankranso area

MANKRANSO	LONGITUDE	LATITUDE	ELEVATION/m	CONCENTRATION/pCi/l
SAMPLE1	625155	754405	225	42.33005459
SAMPLE2	625165	754454	231	65.91728448
SAMPLE3	625169	754504	231	16.60313904
SAMPLE4	625118	754507	234	23.89242289
SAMPLE5	625070	754522	234	31.34924275
SAMPLE6	625017	754532	235	29.21996139
SAMPLE7	625115	75446	233	14.22628855
SAMPLE8	625066	754461	233	17.96663675
SAMPLE9	625017	754470	235	23.21881073
SAMPLE10	624965	754473	234	21.38885327
SAMPLE11	624920	754494	235	16.82989957
SAMPLE12	624874	754514	235	11.83783325
SAMPLE13	624856	754468	233	10.79780276
SAMPLE14	624900	754445	234	14.48599604
SAMPLE15	624949	754433	239	15.08877888
SAMPLE16	624998	754422	233	13.89948661
SAMPLE17	625047	754410	234	10.89037441
SAMPLE18	625096	754405	236	18.08455222
SAMPLE19	625138	754383	236	17.2696816
SAMPLE20	625193	754383	239	7.116278903

Table A.9: Radon concentrations of each sampling point of the Nkrumah area

NKRUMAH	LONGITUDE	LATITUDE	ELEVATION/m	CONCENTRATION/pCi/l
SAMPLE1	612363	731614	196	8.396008609
SAMPLE2	612328	731579	197	8.400143654
SAMPLE3	612341	731531	190	12.06792849
SAMPLE4	612388	731522	192	23.33219099
SAMPLE5	612419	731563	194	20.92492791
SAMPLE6	612373	731582	195	15.24751125
SAMPLE7	612378	731534	195	11.9653527
SAMPLE8	612395	731608	201	18.26009155
SAMPLE9	612392	731668	203	7.665706322
SAMPLE10	612393	731729	205	8.390139513
SAMPLE11	612443	731723	205	27.12749528
SAMPLE12	612343	731731	201	13.49185121
SAMPLE13	612300	731756	200	26.71772567
SAMPLE14	612268	731796	201	10.89784417
SAMPLE15	612228	731920	203	3.017115511
SAMPLE16	612178	731913	203	9.877821961
SAMPLE17	612130	731931	202	18.76696802
SAMPLE18	612090	731961	201	5.966202864
SAMPLE19	612050	731992	201	8.419351605
SAMPLE20	609375	730147	175	7.189642604

Table A.10:Comparison of the average radon concentration of all the sites in Ashanti.

SAMPLESITE	AVERAGE RADON CONCENTRATION/pCi/l
AGOGO	30.39183979
AKROPONG	25.8606309
AYEDUASE	26.57225879
BOSOMTWE	4.028427447
KONONGO	290.1887314
MAMPONG	20.79053228
MANKRANSO	21.12066893
OBUASI	502.1641768
NKRUMAH	13.30610099

APPENDIX B

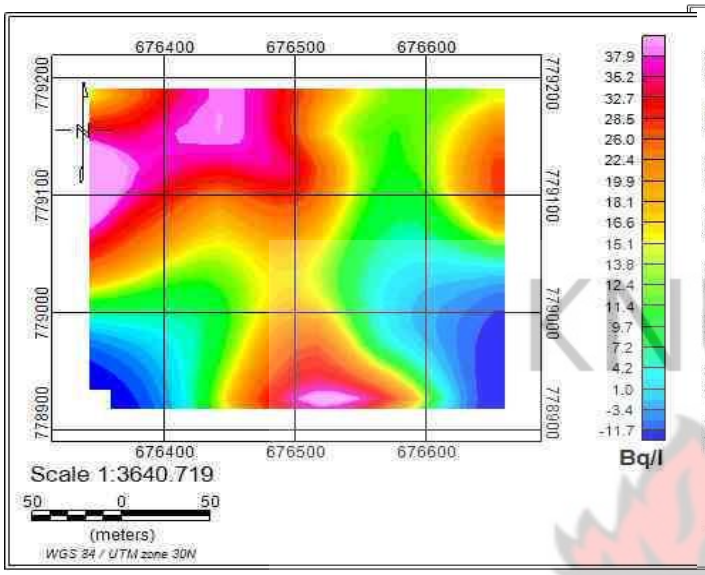


Fig.B1: Radon concentration in Mampong

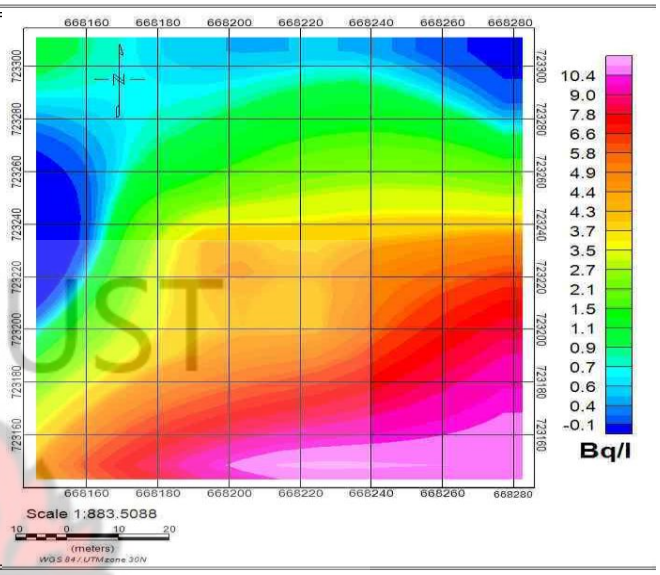


Fig.B2: Radon concentration in Bosomtwi

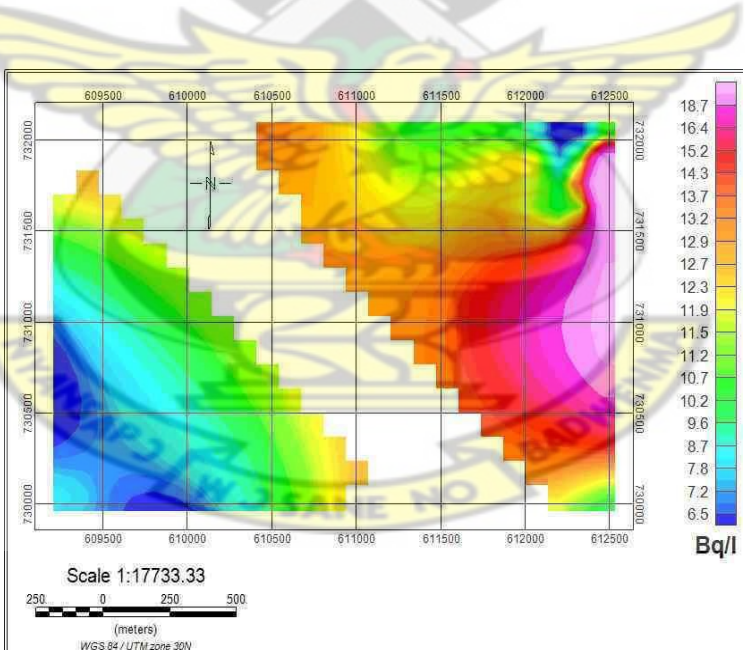


Fig.B3: Radon concentration in Nkrumah

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