

**INVESTIGATION OF RADON CONCENTRATION AND ANNUAL EFFECTIVE
DOSE IN SELECTED CAVES IN KAKUMIRO AND FORT PORTAL, WESTERN
UGANDA**

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**A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND
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DECLARATION

I, Tusiimire Anita do hereby declare that this research dissertation has been written by me under the guidance of my supervisors. The dissertation has not been presented to any University or Institution for an academic award.

Signature:

Date:

APPROVAL

This dissertation by Tusiimire Anita has been designed and produced under our supervision and is now ready for submission to the Graduate Board and the senate of Kyambogo University with our due approval.

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DEDICATION

I dedicate this dissertation to the Almighty God whose blessings enabled me to successfully write this dissertation.

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ABSTRACT

This study was conducted to determine radon concentration and annual effective dose in Amabere Ga Nyinamwiru cave and Semwama hill cave in Western Uganda using continuous radon monitor (Radon Sentinel model 1030). The radon concentration levels in Amabere caves for morning period (7:00-10:00), mid-morning period (10:00-1:00) and afternoon period (1:00-4:00) varied from $14.27 \pm 4.01 \text{ Bqm}^{-3}$ to $17.70 \pm 01 \text{ Bqm}^{-3}$ with mean value of $15.90 \pm 2.76 \text{ Bqm}^{-3}$. The radon concentration in Semwama hill cave for morning period (7:00-10:00), mid-morning period (10:00-1:00) and afternoon period (1:00- 4:00) was found to vary from $447.3 \pm 30.64 \text{ Bqm}^{-3}$ to $507.63 \pm 30.64 \text{ Bqm}^{-3}$ with a mean value of $480.56 \pm 30.64 \text{ Bqm}^{-3}$. The annual effective dose for Amabere caves varied from $0.36 \pm 0.10 \text{ mSvyr}^{-1}$ to $0.44 \pm 0.08 \text{ mSvyr}^{-1}$ with an average value of $0.40 \pm 0.07 \text{ mSvyr}^{-1}$. The annual effective doses for Semwama hill cave ranged from $11.27 \pm 0.77 \text{ mSvy}^{-1}$ to $12.27 \pm 77 \text{ mSvy}^{-1}$ with mean value of $12.11 \pm 0.77 \text{ mSvy}^{-1}$. The Semwama Hill Cave effective dose data show that there is evidence of radon health risk to the general public and workers, as most of the values of yearly effective doses determined are more than 1 mSvy^{-1} as advised by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), International Commission on Radiological Protection (ICRP), and World Health Organization (WHO). Semwama hill cave, which has limited ventilation, has higher radon concentrations than Amabere caves. Further studies should be carried out on Semwama hill cave to ascertain the exposure levels to ^{222}Rn gas as compared with a broad baseline measurement and future research should also look at the seasonal variations in the cave's radon concentration, equilibrium factor, and aerosol state, as well as an analysis of the tour guides' time spent there.

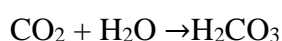
CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

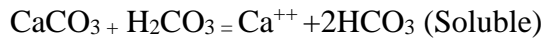
Humans are constantly exposed to ionizing radiations that have a natural source since they live in an environment with these sources (Hendry *et al.*, 2009). Cosmic radiations from space and terrestrial sources like soil and rocks that naturally contain radioactive materials are the two main sources of ionizing radiation in our environment. In varying amounts, all environmental media, including the human body, contain naturally occurring radionuclides of terrestrial origin, commonly known as primordial radionuclides. Only radionuclides whose decay products are present in substantial quantities and whose half-lives are comparable to those of the earth's atmosphere significantly increase population exposure (Hosmer *et al.*, 2010) .

Natural caves are known to be dwelling places of some people and often visited by tourists. There is a wealth of literature that examined radon distribution in caves and its effects on the health of both employees and visitors to the caves (Cuco *et al.*, 2017). The radioactive breakdown of Uranium-238 (^{238}U) or Radium-226 (^{226}Ra) in the host limestone or even in the rocks below the cave is the main source of radon (Gillmore *et al.*, 2000).

A cave is defined as any naturally created underground chamber large enough for a person to enter. For vertical passages, the term "pothole" is typically used instead of the phrase "cave" for horizontal passages. Most people think of caves as having a static atmosphere with total darkness (Cuezva *et al.*, 2009). The Caves are typical limestone caverns that include calcium carbonate (CaCO_3) deposits as a result of a chemical reaction of carbonic acid with rocks when rainwater and carbon dioxide from the air are combined.



Certain minerals and rocks, including limestone, are dissolved by carbonic acid.



Rain absorbs CO_2 from the air as it falls and more of it as it passes through the soil from plant roots. Complex organic acid dissolves into water together with decaying vegetable debris. Ground water cannot easily seep through the rock joints in the Cave's limestone rocks because those rocks have a finite number of pore spaces. As the rock fills the crevices between the rocks, pressure builds up and creates enormous chambers or three-dimensional formations. The water table is the area that is between the planes where air and water are both present in the pore spaces of rocks (Figure 1.1).

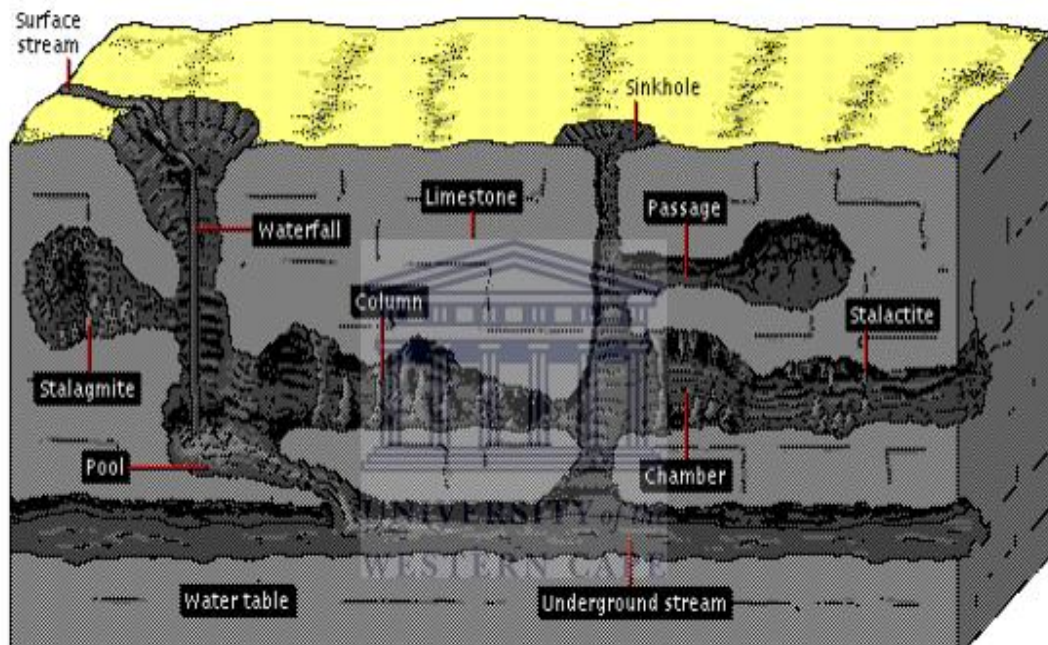


Figure 1. 1: Cave formations (Nemangwele and Lindsay 2005).

Radon is a naturally occurring radioactive noble gas. It is a uranium ^{238}U byproduct and thorium-232 (^{232}Th) natural decay sequence, which occurs in different concentrations in soils and rocks that contain these isotopes. The radon-222 (^{222}Rn) isotope is the result of ^{238}U decay while radon -220 (^{220}Rn) isotope is the result of ^{232}Th decay series. The radon -219 (^{219}Rn) isotope is the result of Uranium -235 (^{235}U) decay series. These three radon isotopes are found in soils and rocks that contain ^{238}U , ^{232}Th and ^{235}U isotopes. Given that it has a half-life of only

4 seconds, ^{219}Rn has little radiological relevance, and only a tiny fraction (0.3 percent) of the activity of naturally occurring uranium comes from ^{235}U (Biira, 2014). However, the solid disintegration products it produces have a strong affinity for the materials in their surroundings. These hazardous radon offspring include lead, polonium, bismuth, thallium, and bismuth. It's being known as the second to smoking through the aforementioned predecessors in terms of its danger to lung cancer risk (Little *et al.*, 2008).

In homes, there is ^{222}Rn produced by ^{238}U and its decay products and places of residence whether they are above ground or underground and poses the highest risk from ionizing radiation that occurs naturally in mines and caves (Becker, 2003). The primary environmental factor that is connected with lung cancer and bronchial tissue damage is radon and its offspring. Studies on the effects of radon on public health have mostly been conducted on a global level (Mancini *et al.*, 2021).

Natural uranium has three different radioisotopes of ^{238}U of percentage abundance of 99.276% and half life of 4.47×10^9 years, ^{235}U of percentage abundance of 0.718% and half life 7.1×10^8 years, and ^{234}U of percentage abundance of 0.0055% and half life 2.46×10^5 years. Although ^{234}U radioisotope is negligible in terms of its abundance, it is found to be dominant in ground water. Uranium (^{238}U) has an average crustal abundance of 2 – 3 ppm and decays by emitting alpha particles (Kumar *et al.*, 2014). Uranium is used in various applications such as in nuclear energy production, in production of protective shields of army tanks and also used in making armour piercing shells. Nuclear weapons, nuclear reactors, and enriched uranium are all utilized to power Navy vessels and submarines with nuclear propulsion (Nikolov *et al.*, 2012).

Natural radionuclides that are present in soil are what expose the people to background radiation. The amount of radiation that the world's population is exposed to in the environment is believed to be 80% provided by natural radionuclides and 20% by cosmic rays (Kolapo *et*

al., 2014). According to (Becker, 2003), the primary contributor to the population's overall effective radiation dose is exposure to naturally occurring radioactive elements. Internal exposure, mostly caused by ingesting, inhaling, or absorbing radioactive materials, and exterior exposure caused by gamma irradiation with radionuclides originating from primordial radionuclides of the earth's crust are the two main exposure pathways for these naturally occurring radionuclides. The primary contributors to the external sources of irradiation to the human population are naturally occurring radionuclides that date back to the origin of the earth (Marrow *et al.*, 2002). The amount of uranium in the rock and the presence of radon are only a couple of the variables that affect how much radiation miners are exposed to (Kreuzer *et al.*, 2015). Since radon is a byproduct of uranium's disintegration, soil with high uranium concentrations has higher concentrations of radon gas. In areas with large concentrations, ²²²Radon, a radioactive gas, is frequently detected (Papp and Dezs, 2006).

Thorium (²³²Th), also called thoria, is a slightly radioactive element. Most rocks and soils contain trace levels of thorium, which is four times more common there than in uranium. Gamma radiation is produced by certain of its offspring radionuclides. Thorium and its derivatives had some significant use prior to the realization of the inherent risks linked with its radiation. The production of toothpaste and gas mantles is the most well-known application of thorium. Thorium is still used to produce refractory materials for the metalworking industry, coat tungsten wire for electrical devices, regulate the size of the plutonium grains used in electric lighting, and alloy with magnesium. Thorium oxide is used to produce high-temperature laboratory crucibles for ore. It is combined with glass to create glasses that have a high refractive index and a low dispersion, which are used to construct lenses for cameras and scientific instruments. Nuclear energy can be produced using thorium, just like uranium (Kumar *et al.*, 2003).

Radiation exposure may result in a number of health issues. The radiation dose absorbed, the type of radiation, and the observed end goal are frequently factors that affect the nature and possibility of the created consequences. Kidney damage, mutagenic leukemia, and cancer are examples of biological impacts of radiation exposure. Thorium exposure can result in leukemia, lung, pancreatic, liver, hepatic, bone, and kidney malignancies (Avwiri *et al.*, 2014). Research has shown that cancer is associated with exposure to ionizing radiations of both of natural and artificial origin. Ionizing radiation can cause tissue damage by changing the chemical composition of the molecules within the tissue as a result of exposure. The majority of radiation damage is caused by a water molecule changing into a new form called a free radical. Free radicals can interact with the genetic material, or deoxyribonucleic acid (DNA), of the cell because of their high chemical activity. This may result in DNA damage, which is known as a deterministic impact of radiation exposure if it results in cell death. However, if DNA encoding causes other unfavorable alterations, this is known as a stochastic effect of radiation exposure resulting in cancer induction (Baverstock and Karotki, 2011).

Radon exposure has been linked to an increased risk of leukemia in addition to lung cancer (Turner *et al.*, 2011). Studies of the general population provide conflicting evidence; radon exposure and chronic lymphocytic leukemia have been linked, according to a study of uranium miners. Lung cancer is the health effect of radon that has received the greatest attention (Řeřicha *et al.*, 2006). In order to determine the radioactive threats to which cave employees are exposed, it is critical to continuously monitor radon gas and its decay products. Radiation protection guidelines state that understanding radon's distribution and where it comes from in caves is crucial. This research was conducted to investigate the concentration of radon and annual effective dose rates in the Semwama Hill and Amabere Ga Nyinamwiru caves. The information gathered will help to reduce worker exposure to radiation at work and to develop the regulatory criteria that should be followed to when visiting the caves.

1.2 Statement of the Problem

Caves are enclosed structures in which there is a potential of high concentrations of radon levels. In Uganda, people visit and stay in some of these caves without minding on the possible exposure to radiations in these natural caves. It is essential to understand the extent of radon radiation present in the Caves, as the dangers of exposure to this gas are well-established and genuine. Very little information is available about the radon levels in certain Ugandan caves (Biira, 2014). When such data is available, it will be easier to determine the annual effective dose rates and radon concentrations that employees in specific caves are exposed to and to take the necessary precautions to lessen exposure. By offering such details and statistics regarding the Amabere Ga Nyinamwiru caves and the Semwama Hill caves in Fortportal city and the Kakumiro area, western Uganda, this study makes a contribution in that respect.

1.3 Purpose of the Study

The purpose of the study was to investigate radon concentration and annual effective dose in selected caves in Kakumiro district and Fort portal, western Uganda.

1.4 Objectives of the Study

The objectives of the study were to:-

- i. measure the activity concentration of radon gas at different times and in different points of the caves.
- ii. determine the annual effective dose of radon gas levels in caves at different times and different points of the caves.
- iii. compare the activity concentrations and annual effective doses in the different caves.

1.5 Research Hypotheses

The objectives are meant to test the following null hypothesis

- i. The radon gas concentration in the caves does not depend on the time of the day.

- ii. The annual effective dose of radon will not be the same.
- iii. The radon gas exposure will not be greater than standard permissible level.

1.6 Scope of the Study

The study was carried out in Semwama hill cave and Amabere Ga NyinaMwiru cave, both found in western Uganda. The study was conducted on 108 samples from different parts and during different time intervals (Pre- selected time interval which was 30 minutes) of day time within the caves using Continuous Radon Monitor (Radon Sentinel). This was done between December 2022 to February 2023. The data obtained was analyzed using Origin 6.0 software; Excel spread sheets and ANOVA.

1.7 Significance of the Study

The information obtained showed the average radon concentration levels were 480.56 ± 30.64 Bqm⁻³ in Semwama Hill Cave compared to Amabere Ga Nyinamwiru cave whose average concentration was 15.90 ± 2.76 Bqm⁻³. This is to assist Ministry of Health, National Environment management Authority (NEMA), Ministry of Energy and Mineral Development Atomic Energy Council (AEC), and other policy making organs of Government to review its policy appropriate to the levels of radon dose likely absorbed general public who visit the caves. This work is in line with SDG number 3- Health and well-being.

CHAPTER TWO: REVIEW OF RELATED LITERATURE

2.1 Introduction

The review of the related literature of this study will cover topic of the study; radioactivity, radon and its origin, natural decay series, ionizing radiation and its effects on the human body, ionizing radiation quantities and units.

2.2 Radioactivity

All matter is made up of atoms. Atoms may be stable or unstable. Atoms with excess energy and nucleons are unstable or radioactive. Unstable or radioactive atoms decay by emitting nuclear particles such as alpha (α), beta (β) particles and gamma (γ) radiation and become more stable. Radioactivity can be artificial or natural.

Artificial radioactivity is the spontaneous decay of artificial radioisotopes made in a reactor or accelerator. Iodine-131, Cobalt-57, Cesium-137, Cobalt-60, Americium-241, Sodium-22 and Manganese-54 are some of the manmade radioisotopes. Artificial radioisotopes are used in medical procedures such as diagnosis and treatment of disease. They find applications in agriculture in production of new varieties of disease resistant grains and cereals, study of uptake of phosphate fertilizers in plants and also used in sterilizing food items. Some artificial radioisotopes are also used in pacemakers, smoke detectors, and industrial radiography, tracers, self-illuminating exit signs, nuclear energy generation and nuclear weapons production (Becker, 2003).

Natural radioactivity is the spontaneous decay of naturally existing radioactive materials, which is largely found in the crust of the earth. The two main sources of natural radioactivity are terrestrial and cosmic radiation. Cosmic radiation is made up of intense protons, electrons, gamma rays, and x-rays that come from space (Bartos and Kowalski, 2017). Primary cosmic rays are cosmic rays that have not yet interacted with material in the hydrosphere, lithosphere, or atmosphere of the earth. Protons make up the majority (about 85%) and the alpha particles

make up the majority (around 14%) of primary cosmic rays, with significantly lesser fluxes (1%) of heavier nuclei. Contrarily, secondary cosmic rays are mainly composed of subatomic particles including pions, muons, and electrons and are produced when the atmosphere is exposed to primary cosmic rays. Secondary cosmic rays account for about all of the cosmic radiation that has been observed at sea level, with muons and electrons each making up roughly 68% and 30% of the flow. The flux at sea level contains less than 1% protons. A high kinetic energy between 2 and 30 GeV is typical for positively charged primary cosmic rays. The energy of primary cosmic rays is so great that when they collide with the earth's atmosphere, they can almost rip apart atoms. The maximum cosmic ray strength is obtained at an altitude of roughly 20 km, where it sharply increases with altitude, latitude, and solar flare activity (Little et al., 2008). The intensity drops as the atmosphere's density rises from 20 km to the limit of the atmosphere (up to 50 km), which is caused by an increase in secondary cosmic ray generation. Numerous radionuclides, including sodium-22 (half-life 2.605 years) and carbon-14, are created when cosmic rays contact with the earth's atmosphere (half-life 5715 years). The contribution of these radionuclides to the radiation absorbed doses is not significant (Ramasamy *et al.*, 2011). At sea level, exposure to directly ionizing cosmic radiation results in an average absorbed dose rate of 31 nGy h^{-1} , which is equivalent to a yearly effective dosage rate of 0.270 mSvy^{-1} . At 41,000 feet (12.497 km) above the sea level, over the poles, the equivalent dose varies from $12 \text{ }\mu\text{Sv}$ to $100 \text{ }\mu\text{Sv}$ (Ramasamy *et al.*, 2011).

Terrestrial radiation. This is a result of terrestrial or primordial radionuclides in the crust of the earth. The half lifetimes of primordial radionuclides are on the order of 100 million years, which is equivalent to the age of the earth. They mostly consist of potassium-40, thorium-232, uranium-238, and radionuclides in their decay series. Both uranium and thorium start a chain of radioactive offspring, which are almost always present when the parent radionuclides are present. Even though many of the offspring radionuclides have short half-lives, they are still

present in the environment because their long-lived parent radionuclides continue to produce them. Primordial radionuclides are found in the earth, rocks, air, water, food, building supplies, and even the human body (Ramasamy et al., 2011). Radioactive substances in the human body irradiate different body tissues and are responsible for the internal radiation and contamination. These substances have a terrestrial and extraterrestrial origin since they are ingested with food and water, or inhaled with air e.g radon. They include mainly carbon-14, potassium-40, uranium, thorium and radium (Becker, 2003).

50% (Table 2.1) of the effective dose of natural radiation that American's experience comes from ²²²Radon and its offspring. People are exposed to radiation by the breathing of radioactive ²²²Radon gas as well as radioactive dust from mining and milling. Inhaling large cumulative levels of ²²²Radon and its decay products, which produce particles, has been associated with a greater incidence of lung cancer among underground miners. Lung cancer has been linked to radon progenies with short lifespans (Schoonhoven, 2012). The two short-lived, alpha-particle emitting descendants of ²²²Radon, ²¹⁸Polonium and ²¹⁴Polonium, are the primary carcinogens created by its decomposition. During inhalation and expiration, the solid decay products of ²²²Rn are conveniently deposited inside the lungs (Schoonhoven, 2012).

Table 2. 1:Natural sources of radiation exposure to the general public (Al-azmi et al., 2013).

Sources	Effective dose (mSvyr ⁻¹)	Typical range (mSvyr ⁻¹)
External exposure		
Cosmic rays	0.4	0.3-1.0
Gamma rays	0.5	0.3-0.6
Internal exposure		
Inhalation (Mainly radon)	1.2	0.2-10
Ingestion	0.3	0.2-0.8
Total	2.4	1-10

The natural radioactive decay of uranium in rocks and soils exposes people to radon (Faanu *et al.*, 2011). Additionally, employees in underground mining, particularly uranium mining, are exposed to a variety of radiation, including that produced by radon as uranium ore decays. The

radiation emitted harms the delicate lung tissues and may result into lung cancer. Lung cancer and smoking have been demonstrated to have the strongest mutually reinforcing impacts on human tissue. The amount of unattached progeny, radon activity concentration, potential alpha particle energy exposure, equilibrium factor, aerosol size distribution, breathing technique (nose or mouth breathing), fractional deposition in the airway, and breathing clearance are just a few of the factors that influence the doses of radon and its progeny to the lungs (Vogiannis and Nikolopoulos, 2015) . The Figure 2.1, shows the average world percentages of radiation exposure by different sources of radiation with the largest source being “natural radiation” arising from cosmic rays, earth gamma radiation, uranium in soil naturally decays to produce radon gas, water and rock while “man-made” radiation consists of x-rays used in medicine, agriculture and industry with nuclear weapons testing, nuclear power and some consumer goods.

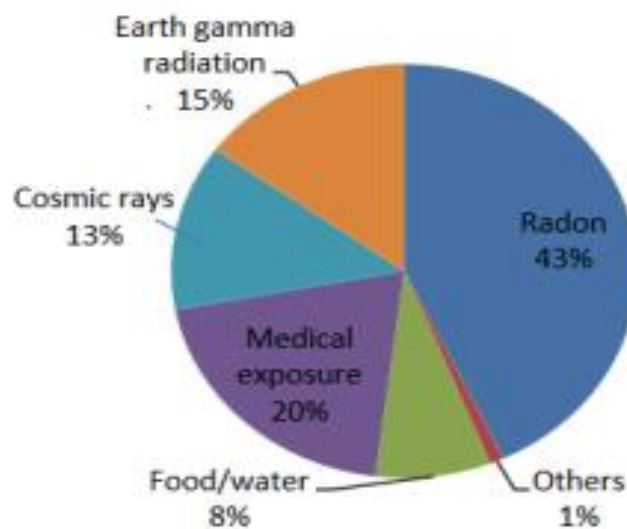


Figure 2. 1: Pie chart of average world percentage of radiation exposure by different sources of radiation (WHO, 2013).

The environment in underground mines is complex and unpredictable. Following exhalation, radon migrates along air currents as it produces the solid byproducts ^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po . In the air, these radionuclides bind to aerosol particles and produce what is known as attached radon progeny. The portion of the radon progeny that is not attached to the airborne

aerosol particle is known as the unattached state. Both attached and unattached radon offspring can be breathed in and can get up in the lungs, especially in the upper respiratory tract, where they can degrade and irradiate the lung tissue. Radioactive aerosols may penetrate the nasal cavity or respiratory system, depending on their size (Butterweek *et al.*, 2002).

Numerous nations have carried out indoor radon concentration measurement programs. According to ICRP, inhaling air with a volume of 300 Bqm⁻³ equates to a 5 mSv effective dosage. Depending on the country, the percentage of residences in Europe with 400 Bqm⁻³ or higher ranges from 0% to 10% for an effective dose of around 7 mSv. It was discovered that the average annual effective dose (including internal dose) was 6.4 mSv. Based on the annual dosage rate in their neighborhood, the population was split into three cumulative dose groups, and their risk was compared to that of people living in control zones. When all cancer fatalities were taken into account, there was no evidence that residing in the HNBR areas increased the risk of cancer mortality (Hendry *et al.*, 2009).

By releasing alpha particles, the ²²⁶Ra (half-life: 1622 years) decays to ²²²Rn. Following that, ²²²Rn undergoes a succession of alpha and beta decays that result in various isotopes of lead, astatine, bismuth, polonium, and astatine (Kappke *et al.*, 2013). When analyzing the impacts of exposure to a drug like radium, a number of factors affect both the likelihood that these effects would manifest and their severity. These variables include the person's exposure to dosages, duration, modes of exposure (contact, ingestion, or inhalation), and other substances. Other considerations include the person's age, sex, dietary needs, lifestyle, and health state.

The pace at which the number of unstable atoms decreases over time is expressed by radioactive decay. All radioactive decays follow an exponential law and are statistical. Considering a radioactive sample containing N unstable atoms, the decrease in the number, dN,

decaying in a time interval dt is directly proportional to N . This is shown in the relation to Equation (2.1)(Cuco *et al.*, 2017).

$$-\frac{dN}{dt} \propto N \quad (2.1)$$

where \propto is symbol of proportionality. The relation shown above can be written as a differential equation of the form (Ambrosino *et al.*, 2020).

$$-\frac{dN}{dt} = \lambda N \quad (2.2)$$

where λ is a constant of proportionality called decay constant of the radionuclide. The solution of Equation (2.2) called the Exponential Law is shown in the equation(Perrie *et al.*, 2018)

$$N_t = N_0 e^{-\lambda t} \quad (2.3)$$

where N_t is the number of unstable atoms present after a time interval t and N_0 is the number of original unstable atoms at $t = 0$. The decay constant expresses the probability per unit time that a radionuclide will decay and it is constant.

There are different types of radioactive decay which include: - Alpha (α) decay, beta (β) decay, gamma (γ) decay and spontaneous fission are the major radioactive schemes. An unstable atom can spontaneously emit excess energy or breakup to emit excess energy in order to become stable. When it does so, it is said to undergo radioactive decay.

In the α -decay of an unstable atom, an α -particle which is a nucleus of a helium atom that has lost two electrons is emitted from nuclei of heavy elements i.e. $Z \geq 83$ (Ramasamy *et al.*, 2011). An individual radionuclide's characteristic alpha particle energy is distinct and unique. Alpha particles have an extremely short range in air (approximately 10-2 m) and can be stopped by 10-5 m of rock, but they also lose the majority of their energy due to strong ionization. Additionally, a tiny piece of paper can stop alpha particles. Due to the lack of energy required for alpha particles to permeate the outer, dead layer of skin, external exposure (to the outside

of the body) is far less significant than internal exposure. Alpha particles can be exceedingly dangerous when ingested. It is possible for alpha emitters to cause deadly exposure to sensitive living tissue if they are swallowed, breathed, or absorbed into the bloodstream (Seo et al., 2019).

In β -decay of an unstable atom, β -particles which are fluxes of high energy electrons are emitted. According to the particular radionuclide that produces them, the beta particle energy spectrum is continuous up to a variable maximum energy. The initial speeds of beta particles may be very near to the speed of light. The beta particle's penetration depth depends on its initial energy. Bremsstrahlung is an electromagnetic radiation produced when beta radiation interacts with matter and loses energy through ionization (Appleton, 2013). When traveling the same distances, beta particles penetrate further than alpha particles but cause less harm. Although they fly far in the air, a layer of clothing or a few millimeters of aluminum can slow or stop them. Some beta particles have the power to harm skin and produce radiation injuries like skin burns. However, beta-emitters are more dangerous when breathed or swallowed, much like alpha-emitters are (Gillmore et al., 2000).

Gamma rays are electromagnetic radiations. They are released from some unstable atoms' nuclei as a result of alpha or beta decay. Gamma photons are very energetic particles that travel at the speed of light and can pass through air for hundreds to thousands of meters without experiencing any appreciable attenuation. Gamma rays can pass through rocks and soil and into the air, are more invasive than alpha or beta particles, and can be prevented by thick lead metal (Appleton, 2013). Potassium-40, a naturally occurring radioisotope that is prevalent in soil and water, are the main cause of gamma ray exposure. However, the increasing use of nuclear medicine (such as lung, thyroid, and bone scans) is contributing an increasing percentage of the total gamma radiation dosage for exposed individuals. Gamma rays are also

emitted by certain artificial radionuclides that have been dropped into the environment as a result of atomic bomb explosions and fallout from nuclear reactors. (Gillmore et al., 2001).

In spontaneous fission, the nucleus spontaneously breaks up without any apparent external cause. Spontaneous fission is the sole spontaneous source of energetic heavy charged particles with masses bigger than the alpha particle. Theoretically, every heavy nucleus can spontaneously split into two lighter pieces. The process is hampered for all nuclei save those that are exceedingly heavy, though, by the substantial potential obstacle that must be surmounted in order to distort the nucleus from its initial, nearly spherical shape. Due to this, spontaneous fission is not a significant process, with the exception of a few isotopes with extremely high mass numbers (Hendry et al., 2009).

2.3 Radon and its origin

Radon gas is inert, colorless, and odorless. It has no chemical reactions with other substances. With a half-life of 3.8 days, radon is relatively persistent which indicates how long it may linger in the air. With a high rate of dilution, radon released from soil into the air decays naturally in the atmosphere. As a result, outdoor habitats have very low radon concentrations. However, radon concentrations can increase to dangerous levels in an indoor space that isn't well aired. Groundwater, nearby soil, and rocks are the sources of radon indoors. Radon gas enters a building through fractures in the walls and floors, as well as through construction materials transported inside (Yoon et al., 2016).

Friedrich Ernst Dorn first identified radon in 1900 under the name Radium emission (Laughlin, 2012). Ramsay and Gray isolated the substance in 1908 and gave it the name Nitron. Dorn gave it the name radon in 1923 (Ramola, 2020). There are possibly 27 different radioactive isotopes of the element radon. There are 200 to 226 in a range of mass numbers. They are ^{219}Rn , ^{220}Rn ,

and ^{222}Rn , respectively. Due of its relatively lengthy 3.82-day half-life, ^{222}Rn is the most crucial element in radiological protection (Li *et al.*, 2020).

^{222}Rn and ^{220}Rn get through ground-air or building material-air interactions to enter the atmosphere. Other sources' contributions, such as those from the oceans, groundwater, and natural gas, are comparatively negligible. Mainly because the majority of building materials contain soil and the earth itself contains concentrations of soil. The abundance of ^{222}Rn and ^{220}Rn is shown to be up to 1×10^4 times greater than that of the atmosphere; there is a significant gradient in concentration between $^{222}\text{Rn}/^{220}\text{Rn}$ of the atmosphere and these minerals. The synthesis of radionuclides from the ^{238}U and ^{232}Th series continuously preserves this gradient and is in charge of maintaining a steady flow of the isotope ^{222}Rn and ^{220}Rn in the atmosphere. The $^{222}\text{Rn}/^{220}\text{Rn}$ the source term, which determines concentration in the atmosphere, is characterized by exhalation rate (the activity reported on the surface and in units of time) and atmospheric dilution processes that are influenced by weather. In addition to ^{222}Rn flux from soil, ^{226}Ra -containing construction components that include soil are potential sources of ^{222}Rn isotopes in the rooms (Miklyaev *et al.*, 2020).

There may be a variety of radioactive materials present in one environment as a result of the decay of $^{238}\text{Uranium}$ over thousands of years. $^{222}\text{Radon}$ is typically found in mines, however $^{220}\text{Radon}$, which is created when $^{232}\text{Thorium}$ decays, is also occasionally present. The amount of ventilation air that $^{222}\text{Radon}$ is disseminated in within the subsurface environment has a significant impact on its concentrations due to its gaseous nature. 54.8 percent of the effective dose of natural radiation that people receive comes from $^{222}\text{Radon}$ and its offspring of the people of the US. People are exposed to radiation when they breathe in radioactive $^{222}\text{Radon}$ gas and radioactive dust from mining and milling. The danger of getting lung cancer in underground miners has been linked to high cumulative exposure to the decay products of $^{222}\text{Radon}$ and its particles. Lung cancer has been linked to radon progenies, which have a short

lifespan. The two short-lived descendants of ^{222}Rn , ^{218}Po , ^{214}Po and ^{210}Po in Figure 2.2 both of which produce alpha particles, are the primary carcinogens created by the disintegration of that element (Schoonhoven, 2012).

Numerous researchers have examined radon's effects on health over the years. These researchers have made it easier to comprehend how crucial radon management is. Their key discovery is that lung cancer risk increases with prolonged exposure to radon levels above background levels. Other malignancies or fatal diseases have not been linked to radon exposure. People are at risk for health issues when exposed to radon's offspring, also known as radon decay products (RDPs), which are produced as radon decays. The decay products will float in the air if radon gas is present. Most of them will stick to dust or the surface of solid objects because they are electrically charged, but some might not. It is possible to breathe in linked and unattached portions. Radon emits alpha radiation once it has entered the lungs, which irritates and may harm the lung's live cells. Due to their short half-lives, RDPs largely breakdown in the lung (less than half an hour). Two of these short-lived substances' dosage to the lungs and related risk of lung cancer, ^{218}Po and ^{214}Po , are primarily influenced by the energy of the alpha particles they produce. There is very little radon gas in the open air, and it poses no health risks. However, radon can build up to relatively high levels and pose a health danger in some enclosed locations, like basements and underground mines (Xie et al., 2015).

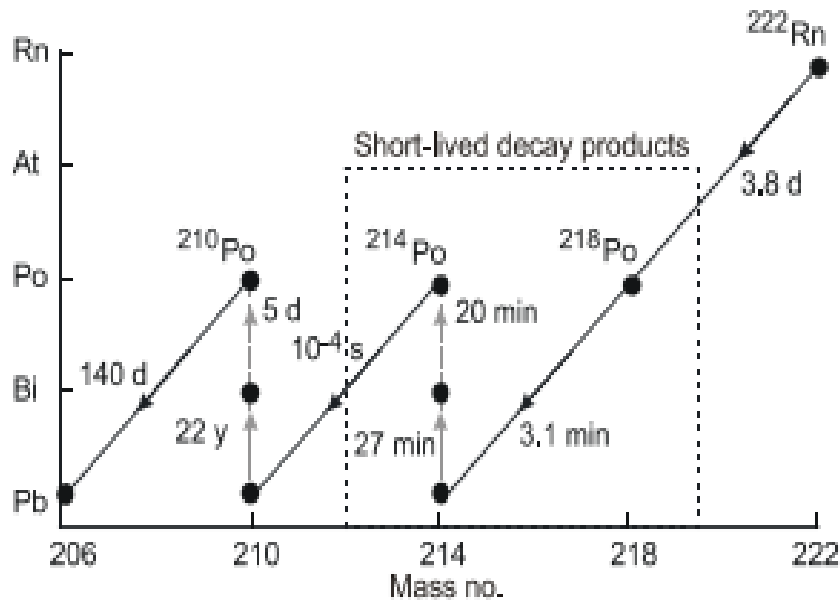


Figure 2. 2:The short-lived decay products ^{210}Pb to ^{206}Pb of ^{222}Rn (Laughlin, 2012).

A decay product of radon can be utilized for radiation therapy, flow rate measurements, radiography, leak detection, and some chemical laboratory studies. Other applications for radon can be; a tracer to find leaks and measure flow rates. As a tracer to detect subsurface contamination from non-aqueous phase liquids, It can also be used as a radiation standard for calibrating radon monitoring equipment in support of environmental assessments of homes and other buildings during the exploration of uranium or petroleum (Laughlin, 2012).

In order to address the risks of long-term radon exposure from any source, The European Union Council Directive 2013/59/EURATOM requires Member States to develop a national action plan including soil, construction materials, and water. Radon gas and carrier gases prefer to migrate through faults and cracks (CO_2 , N_2 , and many others) since they are more porous and permeable than the surrounding rock, gases can flow buoyantly from the deep layers of the crust to the surface. Radon gas emissions from faults and fractures in active fault zones might rise as a result of fault and earthquake activity. Radon concentration and flux surveys have been carried out in active fault zones for earthquake study and prediction because active fault

zones have consistently been demonstrated to have significant soil radon concentrations and fluxes (Miklyaev *et al.*, 2020).

2.4 Natural Decay Series

The series still present, which are uranium series, thorium series, and actinium series in Figure 2.3. A series is made up of a number of radionuclides that are all evenly divisible by four and are connected by decay. The originating radionuclide for this series is ^{232}Th , which has 100% abundance and an average half-life of years. The final nuclide in this decay chain is the stable ^{208}Pb . It takes stages to evolve from the first parent in this sequence, ^{232}Th , to the final product ^{208}Pb . Radium (^{226}Ra), an intermediate nuclide with a half-life of 6.7 years, is the long-living one.

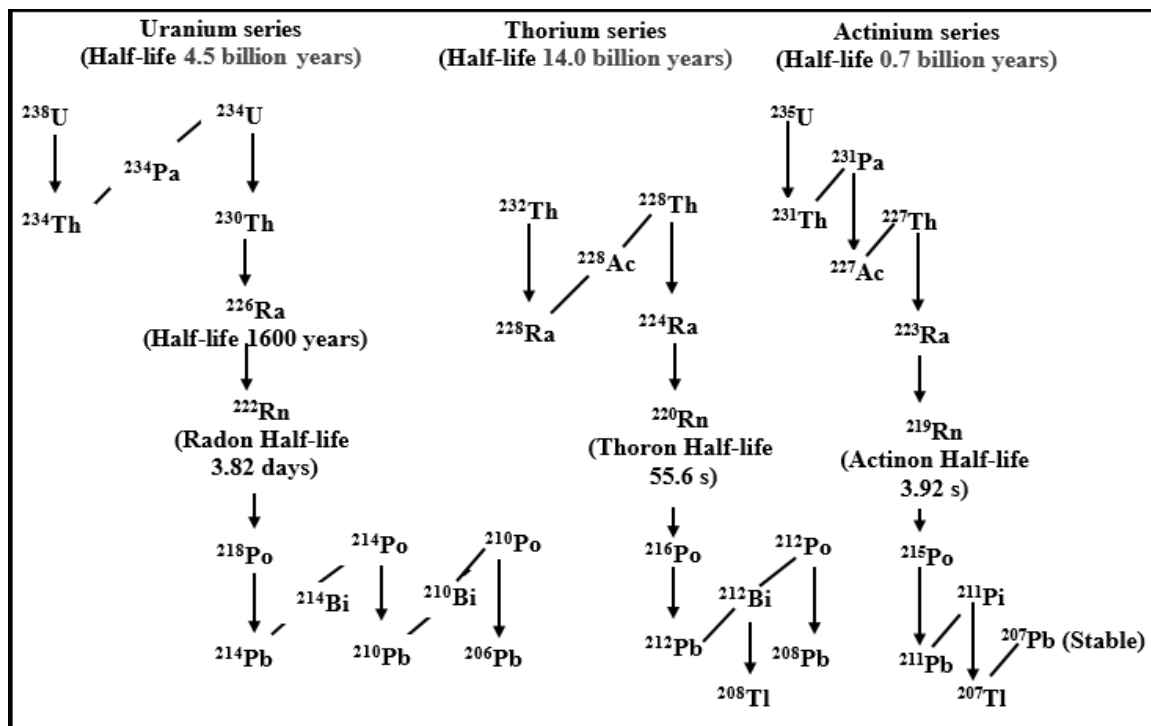


Figure 2. 3:Naturally occurring radioactive decay series (Marouli *et al.*, 2017).

The uranium (^{238}U) or $4n+2$ series is made up of several radionuclides that start with ^{238}U which has 99.27% abundance and an alpha decay with a years' worth of half-life. After and -decay steps, the uranium chain reaches its stable product, ^{206}Pb . Because it contains the most

significant isotopes of the elements radon, polonium, and radium, which may be extracted in significant quantities through the processing of uranium resources, this series is highly significant in nature. With an abundance of 0.72% and a half-life of years, ^{235}U , the first element in the actinium (^{235}U) or $4n+3$ series, decays by alpha emission. Each of the three natural radioactivity series contains a gaseous radioactive decay product with the most important being one in the decay scheme of radium (^{226}Ra) in Figure 2.4.

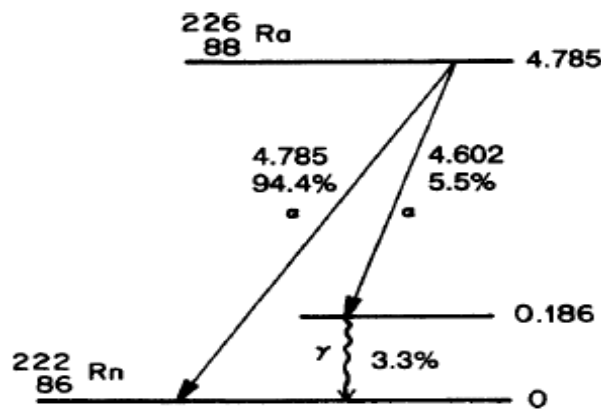


Figure 2. 4:Decay scheme of ^{226}Ra (Kozempel et al., 2015).

In Figure 2.4, the two downward-pointing arrows to the left display the energy and frequency of the two forms of alpha decay. Either one converts the nucleus from ^{226}Ra to ^{222}Rn . When the lower energy particle is ejected, the radon nucleus remains in an excited state (5.5%) with energy 186 keV above the ground state. The vertical wavy line depicts the succeeding 186 keV gamma ray, which is released practically immediately. The frequency of this photon emission, 3.3%, suggests that an internal-conversion electron is released in the remaining 2.2% of all disintegrations. A vacancy in the K or L shell of ^{222}Rn is left when an internal conversion electron is emitted. Consequently, distinctive X-rays are also released (Somlai et al., 2007).

2.5 Ionizing Radiation and its Effects on the Human Body

Inhalation, ingestion, and direct exposure are the three main ways that people are exposed to ionizing radiation. When someone inhales radioactive substances into their lungs, they are

exposed via the inhalation pathway. The main issues are radioactively contaminated dust, smoke, or gaseous radionuclides like radon (Little *et al.*, 2008). It is possible for radioactive particles to become lodged in the lungs and stay there for a long period. The radioactive particles must remain in the lungs and continue to decay there for the duration of the exposure. Inhalation is the main danger for radionuclides that emit alpha or beta particles. The energy that alpha and beta particles might impart on nearby tissue may cause DNA or other biological elements to become damaged. This damage has the potential to cause mutations and illnesses like cancer over time. According to (Appleton, 2013), the main causes of lung cancer in the US (United States of America) and UK (United Kingdom). It's estimated that radon exposure causes more than 15000 lung cancer deaths annually in the United States and more than 2500 fatalities in the United Kingdom. The primary cause of lung cancer in nonsmokers and the risk factor for lung cancer in smokers is exposure to radon and its offspring. Radon is thought to be a contributing factor in between 3 and 14% of all lung cancer cases, depending on the country's average level of radon exposure (Pisa *et al.*, 2001).

Radiation exposure in the mining sector varies widely, for example, based on the quantity of uranium and radon the rock contains. Radon is a byproduct of uranium decay (in this case mostly ²²²Radon) is more prevalent in soil that contains high levels of uranium. There may be a variety of radioactive compounds present in one environment since ²²²Radon is produced by the hundreds of years of decay of ²³⁸Uranium and its daughter atoms. Due to its gaseous nature, the amount of ventilation air used to disperse ²²²Radon around the mine greatly affects its concentrations, however ²²⁰Radon generated from the decay of ²³²Thorium may occasionally also be discovered. underground environment (Schoonhoven, 2012).

When someone ingests radioactive materials in radioactively contaminated water from contaminated subsurface water sources, or radioactively contaminated food from the soil and air, they are exposed through the ingestion pathway. Nuclear reactor accidents like Windscale

in 1957, Three Mile Island in 1979 and Chernobyl nuclear power plant in 1986 have caused widespread exposure and contamination of the members of the public and the surrounding environment with iodine-131, caesium-134 and caesium-137 radionuclides (Becker, 2003). Chernobyl nuclear power plant disaster alone resulted in widespread radioactive contamination of millions of people and the environment by iodine-131 and caesium-137 in three most affected countries of Belarus, the Russian Federation and Ukraine (Marsh et al., 2014). For ingested radioactive materials, alpha and beta emitting radionuclides represent the greatest danger since they release a lot of energy directly into tissue, harming DNA and other cells and putting the entire digestive system, kidneys, and other organs, as well as the bones at risk. Radionuclides in the body tend to concentrate in specific organs because of their chemical nature (Little et al., 2008). For instance, radioactive iodine tends to concentrate in the thyroid gland because the body needs iodine to function normally and cannot differentiate radioactive and non-radioactive iodine. Thus, radioiodine can cause the cancer of the thyroid gland. Radium (^{226}Ra) tends to concentrate in calcium rich areas such as the teeth and the bones. Thus radium may cause bone cancer due to its accumulation in the bones (Perrier et al., 2018).

External exposure is mainly due to gamma rays emitted by radionuclides from natural sources or fallout from atomic bomb tests and nuclear accidents (Little et al., 2008). Gamma rays can enter the skin and produce a dosage in numerous tissues because they are more invasive than alpha or beta particles. Although low penetrating ionizing radiations like alpha and beta particles are insulated by the skin, gamma rays are not. The consequences of ionizing radiation exposure depend on a number of factors, such as the radiation dose, its source (internal or external), how it is dispersed throughout the body, how long it is absorbed, and the exposed person's sensitivity, which can be influenced by both sex and age (Aguilera, 2011).

Ionizing radiation possesses sufficient energy to break chemical bonds or take an atom's electrons (Marsh et al., 2014). Ionizing radiation exposure may cause damage to body tissues

or organs. The immediate health impacts of this damage, which includes skin redness and blackening, hair loss, radiation burns, and radiation poisoning, may impede the functioning of tissues or organs. Depending on the radiation dose absorbed, the human body can be exposed to modest to severe health impacts. There are stochastic and non-stochastic variations of these health impacts (Mettler, 2012).

Ionizing radiation exposure at low levels and over time has stochastic effects (Baverstock *et al.*, 2011). If an irradiated cell is changed as opposed to killed, stochastic effects could result. After a long period of time, altered cells could turn cancerous. Without a threshold dose below which cancer cannot occur, the body's repair and defense mechanisms make this a very implausible consequence at low doses. Higher doses increase the likelihood of developing cancer, although the severity of any cancer brought on by irradiation is unaffected by dose. If the radiation-damaged cell is a germ cell, which is responsible for passing genetic information to descendants, then it is likely that a variety of hereditary effects could appear in the offspring of the exposed individual (Mettler, 2012). Without a dosage threshold, the probability of stochastic consequences increases linearly with dose. The cancer risk is higher for children and adolescents, as they are significantly more sensitive to ionizing radiation exposure than adults (Becker, 2003).

Other stochastic effects that occur include changes or mutations in DNA. In some cases, the body's natural repair mechanisms fall short or even worsen the mutations they are trying to fix. The mutations may be hereditary or teratogenic. Ionizing radiation exposure during pregnancy results in teratogenic alterations that exclusively harm the woman who was exposed. Severe mental retardation and congenital abnormalities of the fetus may result for exposure of the mother above specific threshold dosage values at specific stages of pregnancy (Mettler, 2012). Genetic mutations are passed on to off-springs (Al-Zoughool and Krewski, 2009).

Deterministic or non-stochastic effects are a result of a number of events, mostly cell death and delayed cell division, caused by prolonged exposure to high ionizing radiation doses. The functionality of the exposed tissue may be hampered if they are severe enough. With doses over the threshold for the occurrence of an effect, the severity of a certain deterministic consequence in an exposed individual increase. Radiation burns and radiation sickness are non-stochastic health effects of ionizing radiation exposure. Acute exposure to ionizing radiation is defined as a brief, high-dose exposure. Contrary to cancer, the health effects of acute ionizing radiation exposure typically manifest minutes, days, or months after exposure. Acute health consequences including radiation poi the health effects of acute exposure to ionizing radiation often appear minutes, soning and sickness (radiation burns) might result in early aging or even death. For doses of 3 to 5 Sv, death may happen minutes or hours later. Radiation illness symptoms include tiredness, drowsiness, hair loss, skin burns, and reduced organ function (Mettler, 2012).

2.6 Ionizing Radiation Quantities and Units

There are many quantities used in the measurement of ionizing radiation. Only quantities relevant to this study such as exposure, activity, specific activity, absorbed dose rate and dose equivalent rate have been discussed.

Activity is the measure of the amount of ionizing radiation being emitted or given off by a given radioactive source. The historical unit of measurement of activity is the curie (Ci) and the SI unit of measurement is the becquerel (Bq). One becquerel is equal to one radioactive decay per second. One curie (Ci) is equal to 3.7×10^{10} Bq.

When the radioactive material decays, the amount of its radioactivity per unit mass is the specific activity. The unit of the specific activity is the Becquerel per kilogram. The specific activity is used to describe the radionuclide content of soil, rocks, building materials etc (Turner

et al., 2012). The Specific Activity (S.A) of a radionuclide in a sample is determined by use of the Equation (2.4)(Marsh *et al.*, 2014).

$$S.A = \frac{\left(\frac{N_s}{t_s} - \frac{N_b}{t_b} \right)}{\eta \times k \times m} \text{ Bqkg}^{-1} \quad (2.4)$$

where N_s is the total number of counts of radionuclides in the sample, t_s is the duration of the sample counting in seconds, N_b is the total number of background counts obtained by collecting the background spectrum without the sample, t_b is the time in seconds of collecting the background spectrum, η is the detection efficiency of the spectrometer, k is the branching ratio (gamma radiation yield) of the radionuclide and m is the sample mass in kilograms. The branching ratio of a radionuclide is the probability that the decay of the radionuclide results in emission of the gamma ray (Hendry *et al.*, 2009).

The International Commission on Radiological Protection has chosen the values of radiation weighting factors for specific types and energies of radiations to be representative of values of the relative biological effectiveness of that radiation generating stochastic effects at low doses in Table 2.2 (Turner *et al.*, 2012).

Table 2. 2:Weighing factors for different kinds of ionising radiation (Ramola *et al.*, 2008).

Type of radiation	Radiation weighting factor WR
Photons (x-rays and gamma rays)	1
Electrons and muons	1
Protons and charged pions	2
Alpha particle, fission fragments and heavy ions	20

The irradiated organ or tissue is discovered to play a role in the link between the probability of stochastic effects and equivalent dose. Thus, a new dosimetric quantity called effective dose is

created and accounts for the radiological sensitivity of various tissues. A tissue weighting factor, W_T , represents the fractional contribution of each organ or tissue, T , to the overall harm resulting from radiation exposure if the entire body were uniformly exposed to radiation. Equation (2.5) yields the effective dosage, E , which is the total of the weighted equivalent doses in all tissues and organs.

$$E = \sum_T W_T \times H_T \quad (2.5)$$

The organ or tissue weighting factor, W_T , is a dimensionless quantity just like the radiation weighting factor, W_R . The effective dose and the equivalent dose have the same unit which is the sievert (Sv). The effective dose is expressed in millisievert (mSv) because the quantity is very small (Turner et al., 2012). For environmental gamma radiation, the effective dose is calculated using the Equation (2.6).

$$E = D'_a \times t \times 10^{-6} \times 0.7 \quad (2.6)$$

where E is the effective dose (mSv), D'_a is the dose rate (nGyh^{-1}), t is the exposure time (hours) and 0.7 SvGy^{-1} is the conversion factor for the human organs recommended in UNSCEAR (2000) report (Somlai *et al.*, 2007).

2.7 Radon Sentinel (Continuous Radon monitor)

Regular air sampling, radon etch track detectors, passive radon monitors, gamma-ray detectors, charcoal canisters, standard track etch detectors, liquid scintillation counts, sodium iodide detectors among others, are some of the radon monitoring methods. The Continuous Radon Monitor will serve as the detector for this investigation (Radon Sentinel). These methods are chosen based on the amount of time an instrument may be used for measurements at a particular site, the type of information needed, and the level of precision with which readings can be compared to a risk assessment (Nemangwele and Lindsay, 2005).

The Radon Sentinel is a detector that measures radon gas concentration. Professional inspectors can utilize the device in both homes and buildings. The Radon Sentinel is a continuous radon monitor that can be powered by four size C alkaline batteries or by an AC adaptor. Instructions and radon readings are displayed on the Radon Sentinel's 16-character display. Utilize the buttons on the display to enter data, define parameters, and view data values. After the radon sentinel has connected via USB to a computer, users can use the Continuous Radon Monitor software to download measurements, set parameters, and print reports.

2.8. Related Studies

Using alpha scintillation cells and etched track detectors, the air radon concentration was measured in the summer and winter at 11 locations along the tourist-guided trail in Kosovo's Gadime Cave. In the summer, there were two occurrences where values over 1700 Bqm^{-3} were observed; otherwise, the range was 400 to 1000 Bqm^{-3} . In the winter, values were lower. An individual receives an effective dose of 3.7 Sv during a 90-minute visit in the summer and 2.5 Sv during a 90-minute visit in the winter. A tour guide's annual effective dose is less than 3.5 mSv. Because radon has been found to cause cancer in miners at high levels of exposure, people who are exposed to lower amounts of radon in homes may be at risk for lung cancer. The findings of the 20 epidemiological studies on the connection between radon exposure in the house and the chance of developing lung cancer are conflicting, with some studies discovering a connection between the two diseases while others found none or results that were unclear. But seven recent extensive North American home case-control studies on radon and lung cancer showed a connection between radon exposure at home and lung cancer (Ruano-ravina *et al.*, 2014), use an exposure-response curve with a slope that is in line with the higher occupational exposures found in the miner studies.

Radon is thought to have a linear association with the risk of developing lung cancer (Choi and Mazzone, 2014). In other words, increasing the exposure by twofold increases the danger,

whereas decreasing it by half decreases the risk. The impact of doubling risk is far bigger for a smoker who is already at a high risk of lung cancer than it is for a non-smoker with a very low baseline risk. Even while the danger increases with radon concentration and exposure time, lung cancer development from home radon exposure is much less likely than it is from exposure in mines. According to estimates, exposure to radon at these levels increases the risk of lung cancer by 0.3% over the course of a lifetime of 20 Bqm⁻³(or 3 deaths in 1000 people). As opposed to this, 0.7% of home deaths are unintentional (or 7 in 1000) (Vilela *et al.*, 2019).

Radon and the byproducts of its breakdown, also known as radon daughters or radon progeny, release extremely ionizing alpha radiation. We breathe in the air that is suspended with the gaseous decomposition products. Despite the fact that radon in indoor air frequently makes up more than 50% of the ambient radiation, the risk is very negligible when it is diffused to extremely low concentrations outside (Al-Zoughool and Krewski, 2009). However, in locations like mines and tunnels, it can build up to harmful concentration levels and, with prolonged exposure, may cause cancer. Additionally, drinking water can contain radon, which can occasionally be dangerous. Radon is more likely to be present in granite and volcanic soils than other types of soil, as well as aluminous shales. Conversely, sedimentary rocks are predicted to have low quantities of this gas (Laughlin, 2012).

Since radon is a radioactive gas produced by the natural radioactive decay of uranium found in trace levels in the majority of rocks, soils, and water (Appleton, 2013) and given that the dangers of radon exposure are actual and have been well studied, in Uganda there need to know how much radiation are released in the caves to the cave tourists, dwellers and tour guides. Since radon concentrations are expected to be influenced by wind direction and air temperature, caves are an essential source of air (Russell and MacLean, 2008). Due to the fact that the geological constitution of caves contains uranium in various concentrations, Worker exposure to ²²²Radon and its decay products is a possibility in an underground cave setting. Studies have

proven that radon causes lung cancer and offers a health concern to anyone who are exposed to it because it tends to build up in areas where people congregate, such as mines and tunnels (Nemangwele and Lindsay, 2005).

CHAPTER THREE: METHODOLOGY OF THE STUDY

3.1 Study Area

The study was based on radon measurements to determine radon concentrations in the air in Semwama, cave and Amabere Ga Nyinamwiru cave.

Semwama Hill Caves is situated nearby a flat-topped rock in Kakumiro, in western Uganda. The compartments often house cattle, but they also have a traditional Bachwezi shrine where traditionalists, locals, and curious tourists go to make offerings, which involve use of seeds and leaves. Some locals think that the cave was originally a gathering place for elders. Tourists and visitors to the caves can discover more about the locals' culture. It is located on N00. 79914°, E 031.32170° and 1340 m high.

Amabere Ga Nyinamwiru is considered a historic cultural property situated in Fort Portal Town in western Uganda. Tourists enjoy the cultural tales associated with this cave. The cave in the rock was actually formed as a result of the stalagmites and stalactites. It is tucked up between a number of trees and a stunning waterfall. It is located at (N00.67733° and E030.22478°) of the Nyakasura Fort Portal volcanic field and scenic area. In Figure 3.1, is a map of western Uganda for the study area of Fort portal City and Kakumiro district.

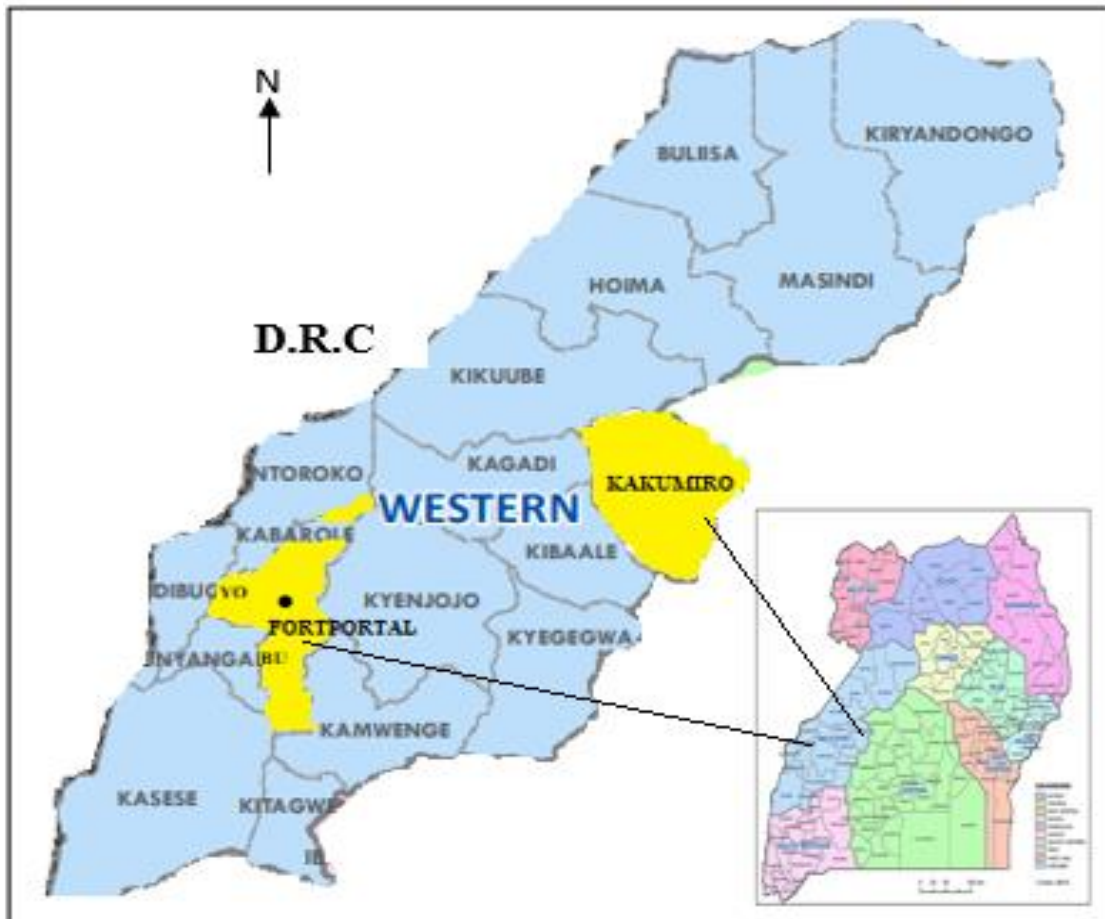


Figure 3. 1:Map of western Uganda for the study areas.

3.2 Research Design

A continuous radon monitor (Radon Sentinel) shown in Figure 3.2 was used to measure the radon concentrations inside Semamwa, and Amabere Ga Nyinamwiru caves. The Radon Sentinel readings were made throughout the day at various locations and times within the two caves. The placement of the instrument was determined using the cave's map as a guide. The study was to find out how radon concentration and annual effective dose varied in different caves.

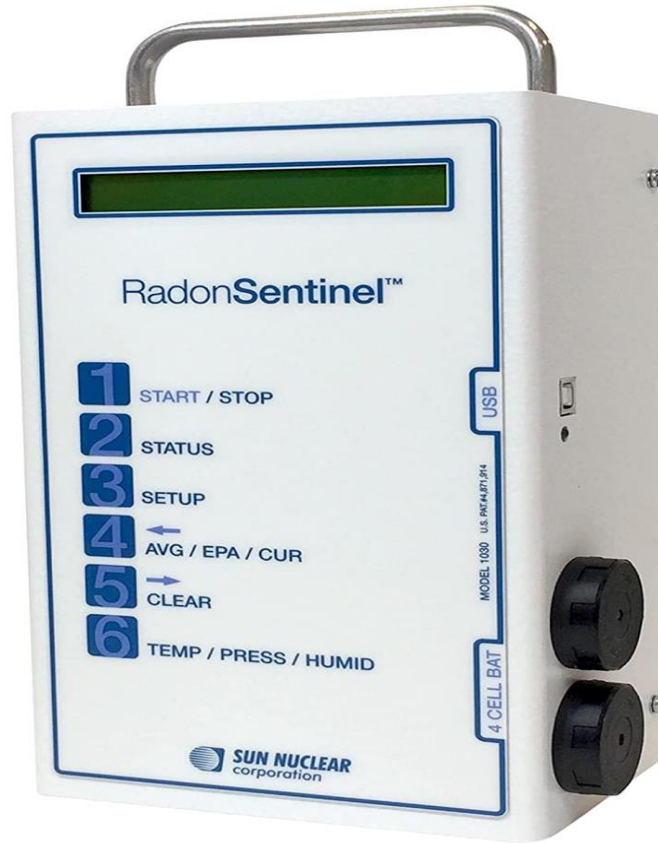


Figure 3. 2:Continuous Radon Monitor (Radon Sentinel) (Mocktar et al., 2020).

3.3 Experimental Setup

The measurements of ^{222}Rn concentration were done in Amabere Ga Nyinamwiru and Semwama hill cave inside the caves. This study was to investigate radon concentration and annual effective dose in selected caves in western Uganda. The continuous Radon Sentinel (1030) was used in this research to measure ^{222}Rn concentrations as shown in Figure 3.3. The radon monitor was placed at an open space inside the cave: - the entrance, middle part of the cave and the end part of the cave.

The test was set to start before 7.30 am every day in all the caves where the measurements were done, with interval of 0.5 hours with 12h of test duration and 0 hour of delay. After the stated period duration, the device was stopped and ^{222}Rn concentration readings were stored in the

radon device before being transfer to personal computer. The equipment registers possible errors as seen in Table 3.1.

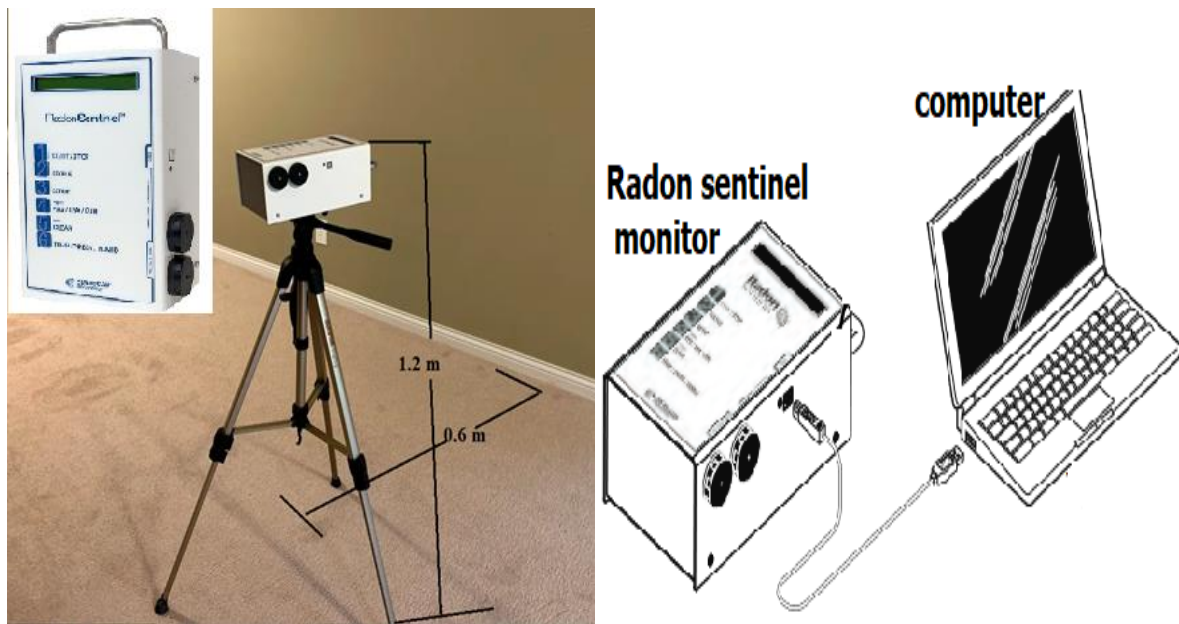


Figure 3. 3:Experimental setup for radon Sentinel (1030) (Jeli et al., 2016).

Table 3. 1:Troubleshooting the Radon Sentinel (1030).

Indication	Problem cause	Recommended action
Unit will not turn on	Power not connected and batteries are missing or discharged.	Connect power and/or insert four fully charged size C alkaline batteries.
Unit will not turn on with power connected or good batteries	Internal short or disconnection.	Contact Sun Nuclear Support. Unit will need to be returned.
System error message	Radon monitor experienced an abnormal condition.	See Radon system error codes on the user manual
Software not displaying the Radon Sentinel serial number	Radon monitor not detected by the software	Select Refresh Devices. Click. When the connection is discovered, the serial number appears.
The motion is detected on the display, but it is not noted in the report.	Test was stopped before it could finish. Motion was made as the test came to an end.	Count the number of measurements and print the findings. If the result was lower than anticipated, the exam ended early. Repeat the test.
Display shows alternating “INVALID TST DATA” and test status messages	Device is in need of service.	Get in touch with Sun Nuclear Support. See Making Contact with Sun Nuclear Support

Software error message	<p>When launching the Continuous Radon Monitor program or obtaining data from the Radon monitor, the following error messages appear:</p> <p>Error 1 in the Humidity Sensor The humidity and pressure sensors are out of range.</p> <ul style="list-style-type: none"> • Error SPI Port • Memory Error • Dead Channel • High Voltage Out of Range interboard communication fault; • Test Interval Alpha Count Overflow; • Test Hourly Alpha Count overflow. 	Get in touch with Sun Nuclear Support. See Making Contact with Sun Nuclear Support
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3.4 Measurement of Radon/ Preparation

The continuous radon monitor (Radon Sentinel) was used in this investigation to measure radon concentration and annual effective dose in Amabere Ga Nyinamwiru and Semwama Hill cave. The continuous radon monitor was placed in the dry area inside the caves and on an elevated place so as to be able to record the radon in air. Before switching it on, the memory was erased since it records up to two sets of reading in a selected time interval. The continuous radon monitor was used to record readings of radon gas, for 30 minutes interval for 9 hour duration for a number of days at:- Gate of cave position, middle cave position and end of wall cave position. This was done for each of the positions of the cave; morning period (7:00-10:00), mid-morning period (10:00-1:00) and afternoon period (1:00- 4:00). The captured data of radon concentration was entered into Table 3.2. The equipment was timed for 12 hours since its setup cannot time for only 9 hours, then the time (hours) of preference were considered for this study.

Table 3. 2:Radon concentration at different positions of the cave.

Time Interval	Concentration at different Positions of the cave			
	Amabere Cave 1	Amabere Cave 2	Amabere Cave 3	Semwama Cave
7am - 10 am	Cave 1	Cave 2	Cave 3	Semwama 1
10 am -1 pm	Cave 1	Cave 2	Cave 3	Semwama 2
2 pm - 4 pm	Cave 1	Cave3	Cave 3	Semwama 3

3.4 Estimation of Annual Effective Dose

In the UNSCEAR report from 2000, a value of 9.0 nSvh per Bq/m³ was used as the conversion factor (effective dose received by adults per unit radon activity per unit of air volume), and 0.4 as the equilibrium factor of radon indoors and the indoor occupancy factor is represented by the average indoor occupancy time per person (7000 ha⁻¹). Measurements of radon levels were conducted under the same circumstances in Amabere Ga Nyinamwiru and Semwama Hill cave. The yearly mean effective dosage for indoor air was calculated in accordance with standards specified by a UNSCEAR (Vanmarcke, et al, 2000) research as follows:

$$H = C_{Rn} \times F \times O \times D_{CF} \quad (\text{mSv a}^{-1}) \quad (3.1)$$

Where O is the average indoor occupancy time per person (7000 ha⁻¹), F is the equilibrium factor between radon and its decay products (0.4), CRn is the indoor radon concentration (Bq m⁻³), and DCF is the dose conversion factor for radon exposure 9 nSvh⁻¹(Bq m⁻³)⁻¹.

3.5 Data Analysis

To obtain the radon concentration and annual effective in Amabere Ga Nyinamwiru and Semwama Hill cave, the captured data on the Radon Sentinel equipment was uploaded on the computer, it had an instant reading of radon concentration and then the annual effective was obtained using Equation (3.1).

For each cave, different cave positions and periods of the day will be considered in order to get the mean and standard deviations of radon concentrations. The values obtained were analysed using ANOVA to ascertain if there were variations in the following parameters; variation in concentration of radon with period of the day was significant for each location in the cave, and variation in concentration of radon was significant for each period of the day for each position. ANOVA, ORIGIN software 6.0, and an Excel spread sheet were used to analyze the data gathered for this study. ORIGIN software 6.0 was used to draw spectra graphs for all the caves. The purpose of these measurements was to obtain radon level values in different caves and know the convenient time when tourists and tour guides can access the caves.

CHAPTER FOUR: RESULTS OF THE STUDY

4.1 Introduction

This chapter presents the results of the study obtained from radon concentration measurements done in Amabere Ga Nyinamwiru and Semwama Hill cave to achieve the objectives of the study. The results from the measurements in the caves using continuous radon monitor (Radon Sentinel) are presented. The results include radon activity concentrations in the air and radon exposure doses in the four caves in Amabere Ga Nyinamwiru and Semwama Hill cave.

4.2 Radon Activity Concentration in Amabere Caves

The activity concentration values were obtained from the continuous radon monitor (Radon Sentinel) in Table 4.1 and Figure 4.1. The average values were obtained after computing the raw data in Appendix A. Amabere cave 2, had the highest activity concentration throughout the entire time interval selected for this study thus the dose as seen in Table 4.1, 4.3 and Figure 4.1.

Table 4. 1:Average activity concentrations for Amabere caves.

Time Interval	Activity Conc / Bq/m ³		
	Cave 1	Cave 2	Cave 3
7 am-10 am	18.52	19.90	19.18
10 am-1 pm	13.76	15.96	15.29
2 pm- 4 pm	10.54	17.24	12.68
Av	14.27	17.70	15.72
Stdv	4.01	2.01	3.27

4.2.1 Radon activity concentration in Semwama cave

The averages of raw data in Appendix A were considered as measured by the Radon sentinel to obtain the activity concentration for semwama hill cave in Table 4.2 and Figure 4.2.

Table 4. 2: Average activity concentration for Semwama cave.

Time interval	Activity Conc / Bq/m ³
7 am-10 am	447.3
10 am-1 pm	507.63
2 pm-4 pm	486.74
Av	480.56
Stdev	30.64

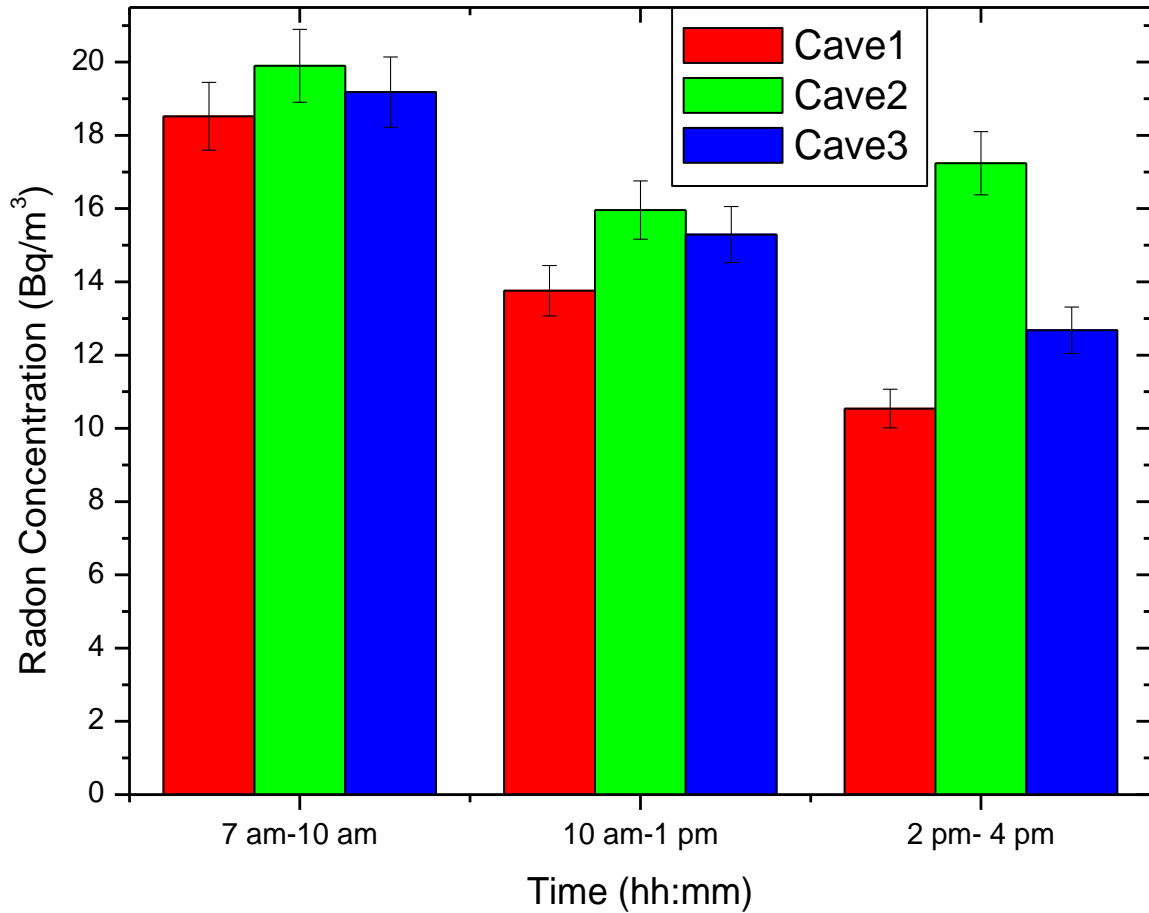


Figure 4. 1: Average radon concentration for Amabere caves at different times of the day.

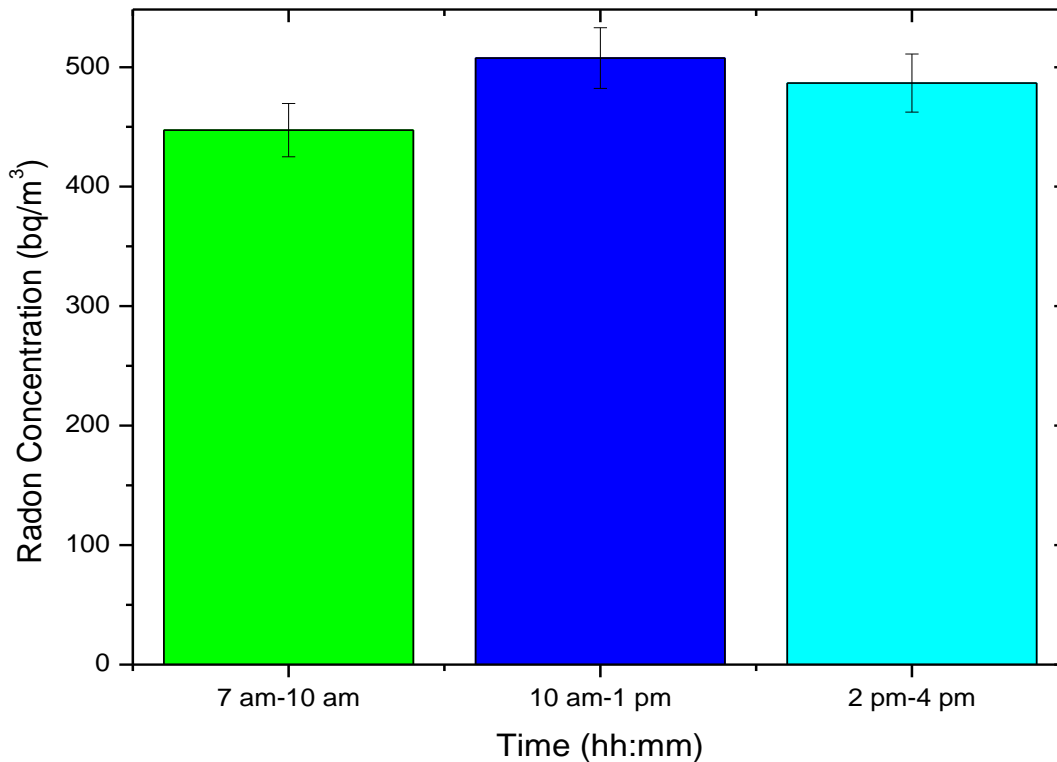


Figure 4. 2:Average radon concentration for Semwama Hill cave at different times of the day.

4.3 The Annual Effective Dose

The average values for radon concentration were used to compute annual effective dose for Amabere Ga Nyinamwiru and Semwama Hill cave.

4.3.1 Annual Effective Dose for Amabere Caves

UNSCEAR values were adopted for this study. The effective dose rate (H) indoors in units of mSv/y, was calculated using the Equation (3.1) in Table 4.3, Table 4.4 and Figure 4.3

Table 4. 3:Annual Effective dose for Amabere caves.

Time Interval	H /mSvyr ⁻¹		
	Cave 1	Cave 2	Cave 3
7 am-10 am	0.47	0.5	0.48
10 am-1 pm	0.35	0.4	0.39
2 pm- 4 pm	0.27	0.43	0.32
Av	0.36	0.44	0.40
Stdv	0.10	0.08	0.08

4.3.2 Annual Effective Dose for Semwama Cave

Table 4. 4:Annual Effective dose for Semwama Hill cave.

Time interval	Activity Conc / Bq/m ³	H / mSvyr ⁻¹
7-10 am	447.3	11.27
10-1 pm	507.63	12.79
2-4 pm	486.74	12.27
Av	480.56	12.11
Stdev	30.64	0.77

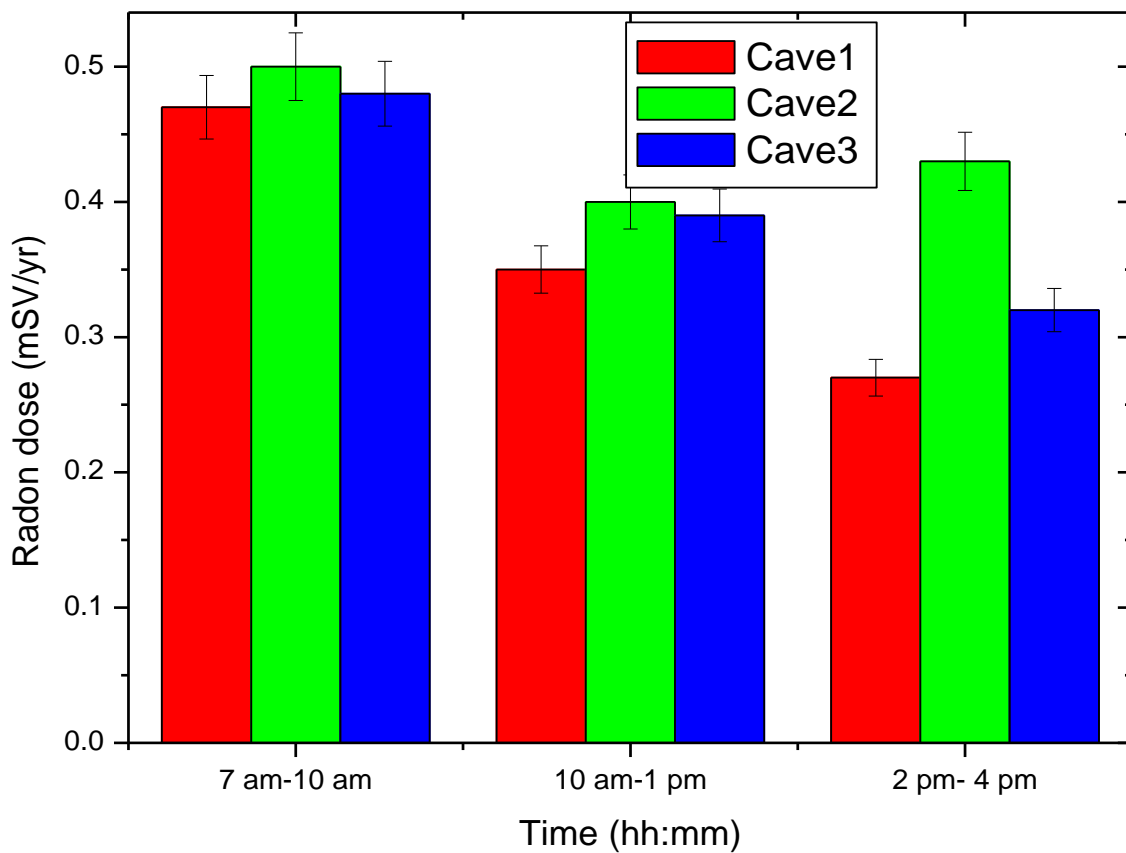


Figure 4. 3:Average radon dose for Amabere caves at different times of the day.

4.4 Comparison of Activity Concentrations and Annual effective Doses

The radon activity concentrations in Amabere Ga Nyinamwiru caves had an average of 14.27 ± 4.01 Bq m⁻³ for cave 1, 17.70 ± 2.01 Bq m⁻³ for cave 2, 15.72 ± 3.27 Bq m⁻³ for cave 3 and 480.56 ± 30.64 Bq m⁻³ for Semwama hill cave in Table 4.4 and Figure 4.3.

The annual effective in Amabere caves and Semwama was compared and was found to have an average value of 0.37mSv/yr for cave 1, 0.46 mSv/yr for cave 2 and 0.41 mSv/yr for cave 3 whereas Semwama had 12.11 mSv/yr in Table 4.5

Table 4. 5:Comparison of average values for Semwama and Amabere caves

Cave	Activity Conc / Bq/m ³	H / mSvyr ⁻¹
Semwama	480.56	12.11
Amabere cave 1	14.72	0.37
Amabere cave 2	18.43	0.46
Amabere cave 3	16.39	0.41
WHO (2009)	100.00	

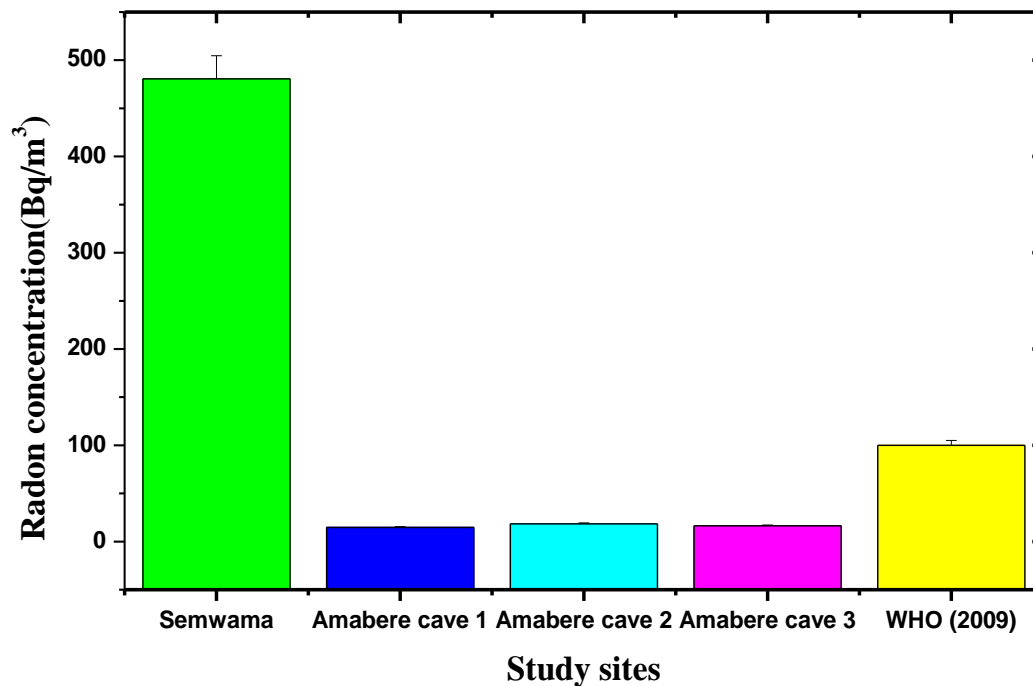


Figure 4.4:Average radon concentration for Semwama Hill cave and Amabere Ga Nyinamwiru cave.

From the graph spectra Figure 4.5, it was observed that the radon concentration and dose were at the peak during morning hours (between 7 am and 10 am) but as time went on, they gradually reduced for Figure A (Amabere cave 1). And again, it was observed that radon concentration

and its dose was at maximum during 9 am and 3 pm for Figure B (Amabere cave 2) and lastly Figure C (Amabere cave 3) showed that Activity concentration and radon dose were at the peak at 9 am and 1 pm hours of the day. It was also observed that increase in Radon concentration increases radon dose and they are not affected by time.

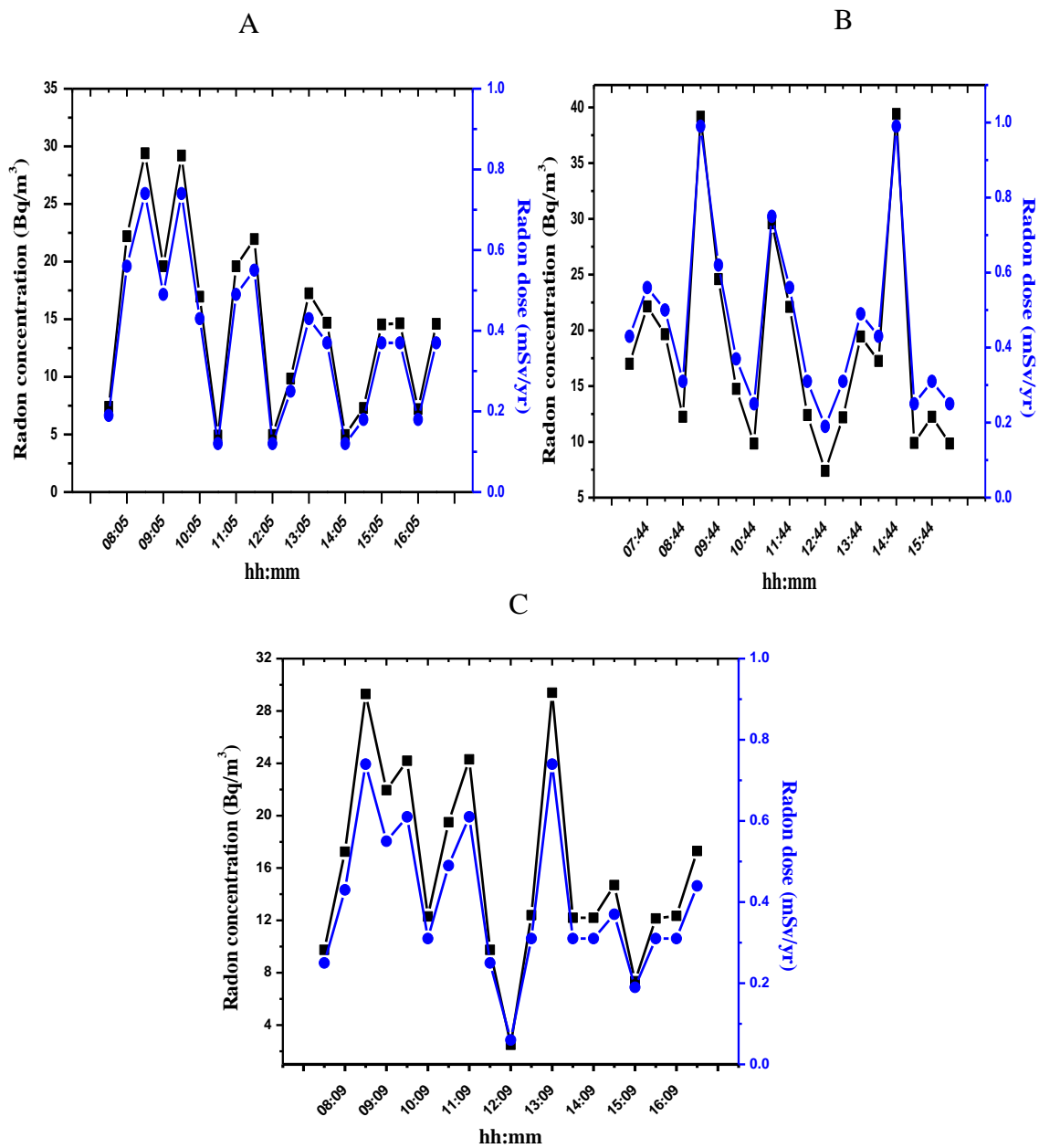


Figure 4. 5: Variation of radon concentration and Radon dose with time (A) Cave 1, (B) Cave 2, (C) Cave 3.

From the graph spectra Figure 4.6 for Semwama cave, it was observed that radon concentration levels and dose were at maximum at 11 am and 1pm hours of the day.

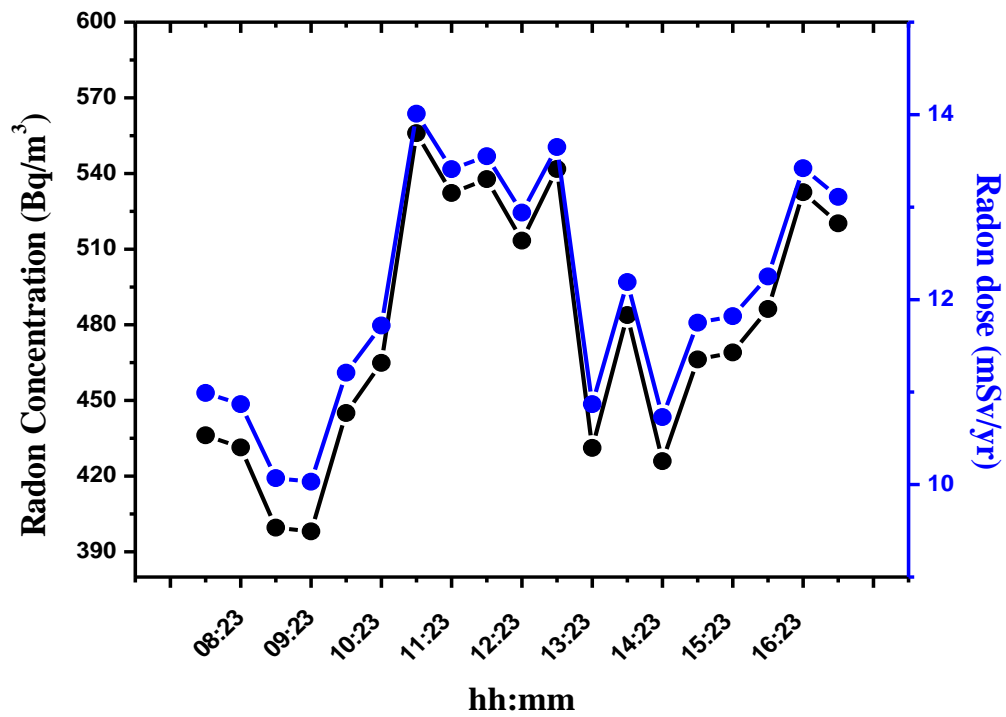


Figure 4. 6: Variation of radon concentration and radon dose with time for Semwama cave.

CHAPTER FIVE: DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussion

This chapter has discussed the results presented in Chapter Four. The findings have also been compared with similar studies done in Uganda and worldwide. The possible conclusion and recommendations have been noted down.

5.1.1 Radon Activity Concentration

The radon concentration levels in Amabere caves for morning period (7:00-10:00), mid-morning period (10:00-1:00) and afternoon period (1:00- 4:00) varied from $14.27 \pm 4.01 \text{ Bqm}^{-3}$ to $17.70 \pm 01 \text{ Bqm}^{-3}$ with mean value of $15.90 \pm 2.76 \text{ Bqm}^{-3}$ (Biira, 2017).

The radon concentration in semwama hill cave for morning period (7:00-10:00), mid-morning period (10:00-1:00) and afternoon period (1:00- 4:00) was found to vary from $447.3 \pm 30.64 \text{ Bqm}^{-3}$ to $507.63 \pm 30.64 \text{ Bqm}^{-3}$ with a mean value of $480.56 \pm 30.64 \text{ Bqm}^{-3}$ (Cuco *et al.*, 2017).

Table 5. 1:Radon concentration on similar studies worldwide.

Radon Concentrations / Bq/m ³					
Country	Study area	Minimum	Maximum	Mean	Reference
Romania	Radon levels in Romanian caves: an occupational exposure survey	53	2866	1857	(Cuco <i>et al.</i> , 2017)
Italy	Study of ²²² Rn continuous monitoring time series and dose assessment in six European caves	3658	6716	4998	(Ambrosino <i>et al.</i> , 2020)
Uganda	Investigation of Radon concentration and annual effective dose in selected caves in Uganda	14.27	507	480	This study

5.1.2 Estimation of Annual Effective Dose

The annual effective dose for Amabere caves varied from $0.36 \pm 0.10 \text{ mSvyr}^{-1}$ to $0.44 \pm 0.08 \text{ mSvyr}^{-1}$ with an average value of $0.40 \pm 0.07 \text{ mSvyr}^{-1}$. The annual effective doses for Semwama hill cave ranged from $11.27 \pm 0.77 \text{ mSvyr}^{-1}$ to $12.27 \pm 77 \text{ mSvyr}^{-1}$ with mean value of $12.11 \pm 0.77 \text{ mSvyr}^{-1}$ (Ambrosino *et al.*, 2020).

Table 5. 2: Similar studies on annual effective doses worldwide.

Country	Study area	Annual effective dose (mSv)	Reference
Italy	Study of ^{222}Rn continuous monitoring time series and dose assessment in six European caves	0.12 - 19.0	(Ambrosino <i>et al.</i> , 2020)
Romania	Radon levels in Romanian caves: an occupational exposure survey	3.9 - 12.8	(Cuco <i>et al.</i> , 2017)
Uganda	Investigation of Radon concentration and annual effective dose in selected caves in Uganda	1.15 - 6.5	This study

Semwama hill cave was found to have higher radon concentration levels than Amabere caves. This could be attributed to poor ventilation that allows radon gas to accumulate in the cave. Amabere caves had the lowest average radon concentration implying a relatively low radiological risk. This could be that the formation of stalactites and stalagmites that allow sufficient air ventilation in these caves.

According to the study's findings, inadequate ventilation caused radon gas concentrations in Semwama Hill cave to exceed the levels recommended by the World Health Organization (WHO), International Commission on Radiological Protection (ICRP), and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) of 200 Bqm^{-3} and 100 Bqm^{-3} , respectively.

5.2 Conclusion

The radon concentration and annual effective doses in selected caves of Semwama and Amabere caves in Kakumiro and forportal districts, western Uganda were determined using a continuous Radon Monitor (Radon Sentinel 1030).

The radon concentration varied from $14.27 \pm 4.01 \text{ Bqm}^{-3}$ to $17.70 \pm 01 \text{ Bqm}^{-3}$ with mean value of $15.90 \pm 2.76 \text{ Bqm}^{-3}$ for Amabere caves and from $447.3 \pm 30.64 \text{ Bqm}^{-3}$ to $507.63 \pm 30.64 \text{ Bqm}^{-3}$ with a mean value of $480.56 \pm 30.64 \text{ Bqm}^{-3}$ for Semwama Hill cave. The annual effective dose for Amabere caves varied from $0.36 \pm 0.10 \text{ mSvy}^{-1}$ to $0.44 \pm 0.08 \text{ mSvy}^{-1}$ with an average value of $0.40 \pm 0.07 \text{ mSvy}^{-1}$. The annual effective doses for Semwama hill cave ranged from $11.27 \pm 0.77 \text{ mSvy}^{-1}$ to $12.27 \pm 77 \text{ mSvy}^{-1}$ with mean value of $12.11 \pm 0.77 \text{ mSvy}^{-1}$.

The Semwama Hill Cave effective dose data show that there is evidence of radon health risk to the general public and workers, as most of the values of yearly effective doses determined are more than 1 mSvy^{-1} as advised by UNSCEAR, ICRP, and WHO. Semwama hill Cave, which has limited ventilation, has higher radon concentrations than Amabere caves.

In conclusion radon concentration levels and effective doses from Semwama hill cave were very high and therefore not safe for inhabitants.

5.3 Recommendations

The findings propose that the following research be done to learn more about radon gas in Uganda.

1. Further studies should be carried out on Semwama hill cave to ascertain the exposure levels to ^{222}Rn Radon gas as compared with a broad baseline measurement.
2. Seasonal variations in the cave's radon content, equilibrium factor, and aerosol state should all be investigated in future studies, along with the tour guides' time spent there.

3. Other methodologies using passive detectors and TLDs (Thermo Luminescent Dosimeter) should be used to compare results.
4. Atomic Energy Council should enforce radiation safety guidelines to protect the inhabitants and visitors of the caves.

REFERENCES

- Aguilera, G. (2011). HPA axis responsiveness to stress: implications for healthy aging. *Experimental gerontology*, 46(2-3), 90-95.
- Al-Azmi, D., Karunakara, N., & Mustapha, A. O. (2013). Teaching about natural background radiation. *Physics Education*, 48(4), 506.

- Al-Zoughool, M., & Krewski, D. (2009). Health effects of radon: a review of the literature. *International journal of radiation biology*, 85(1), 57-69.
- Ambrosino, F., Thinová, L., Briestenský, M., & Sabbarese, C. (2020). Study of ^{222}Rn continuous monitoring time series and dose assessment in six European caves. *Radiation Protection Dosimetry*, 191(2), 233-237.
- Appleton, J. D. (2013). Radon in air and water (pp. 239-277). Springer Netherlands.
- Avwiri, G. O., Ononugbo, C. P., & Nwokeoji, I. E. (2014). Radiation Hazard Indices and Excess Lifetime cancer risk in soil, sediment and water around mini-okoro/oginigba creek, Port Harcourt, Rivers State, Nigeria. *Comprehensive Journal of Environment and Earth Sciences*, 3(1), 38-50.
- Barnes, S. J., & Maier, W. D. (2002). Platinum-group element distributions in the Rustenburg layered suite of the Bushveld Complex, South Africa.
- Bartos, I., & Kowalski, M. (2017). *Multimessenger astronomy*. IOP Publishing.
- Baverstock, K., & Karotki, A. V. (2011). Towards a unifying theory of late stochastic effects of ionizing radiation. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, 718(1-2), 1-9.
- Becker, K. (2003). Health effects of high radon environments in central Europe: another test for the LNT hypothesis?. *Nonlinearity in biology, toxicology, medicine*, 1(1), 15401420390844447.
- Biira, S., Kisolo, A. W., & D'ujanga, F. M. (2014). Concentration levels of radon in mines, industries and dwellings in selected areas of Tororo and Busia districts, Eastern Uganda.

- Butterweck, G., Schuler, C., Vessù, G., Müller, R., W. Marsh, J., Thrift, S., & Birchall, A. (2002). Experimental determination of the absorption rate of unattached radon progeny from respiratory tract to blood. *Radiation protection dosimetry*, 102(4), 343-348.
- Choi, H., & Mazzone, P. (2014). Radon and lung cancer: assessing and mitigating the risk. *Cleve Clin J Med*, 81(9), 567-75.
- Clement, C. H., Stewart, F. A., Akleyev, A. V., Hauer-Jensen, M., Hendry, J. H., Kleiman, N. J., ... & Wallace, W. H. (2012). ICRP publication 118: ICRP Statement on Tissue Reactions and Early and Late Effects of Radiation in Normal Tissues and Organs – Threshold Doses for Tissue Reactions in a Radiation Protection Context. *Annals of the ICRP*, 41(1-2), 1-322.
- Cucoş Dinu, A., Călugăr, M. I., Burghel, B. D., Dumitru, O. A., Cosma, C., & Onac, B. P. (2017). Radon levels in Romanian caves: an occupational exposure survey. *Environmental geochemistry and health*, 39, 1085-1099.
- Cuezva, S., Sanchez-Moral, S., Saiz-Jimenez, C., & Cañaveras, J. C. (2009). Microbial communities and associated mineral fabrics in Altamira Cave, Spain. *International Journal of Speleology*, 38(1), 9.
- De Kruijff, R. M., Wolterbeek, H. T., & Denkova, A. G. (2015). A critical review of alpha radionuclide therapy—how to deal with recoiling daughters?. *Pharmaceuticals*, 8(2), 321-336.
- Faanu, A., Darko, E. O., & Ephraim, J. H. (2011). Determination of natural radioactivity and hazard in soil and rock samples in a mining area in Ghana. *West African Journal of Applied Ecology*, 19(1).

- Gillmore, G. K., Sperrin, M., Phillips, P., & Denman, A. (2000). Radon hazards, geology, and exposure of cave users: A case study and some theoretical perspectives. *Ecotoxicology and Environmental Safety*, 46(3), 279-288.
- Gillmore, G. K., Phillips, P., Denman, A., Sperrin, M., & Pearce, G. (2001). Radon levels in abandoned metalliferous mines, Devon, Southwest England. *Ecotoxicology and Environmental Safety*, 49(3), 281-292.
- Hendry, J. H., Simon, S. L., Wojcik, A., Sohrabi, M., Burkart, W., Cardis, E., ... & Hayata, I. (2009). Human exposure to high natural background radiation: what can it teach us about radiation risks?. *Journal of Radiological Protection*, 29(2A), A29.
- Hosmer, P., Schatz, H., Aprahamian, A., Arndt, O., Clement, R. R. C., Estrade, A., ... & Wöhr, A. (2010). Half-lives and branchings for β -delayed neutron emission for neutron-rich Co–Cu isotopes in the r-process. *Physical Review C*, 82(2), 025806.
- Kappke, J. et al. (2013) ‘Measurements of Radon and Radium Activity in Bottled Mineral Water’, International Nuclear Atlantic Conference - INAC 2013, pp. 7–8.
- Kolapo, A., Kazeem, A. and Caleb, A. (2014) ‘ScienceDirect Determination of natural radioactivity and hazard in soil samples in and around gold mining area in’, *Journal of Radiation Research and Applied Sciences*, 7(3), pp. 249–255. doi: 10.1016/j.jrras.2014.06.001.
- Kozempel, J., Vlk, M., Floriánová, M., Drtinová, B., & Němec, M. (2015). Dissolution of [226 Ra] BaSO₄ as part of a method for recovery of 226 Ra from aged radium sources. *Journal of Radioanalytical and Nuclear Chemistry*, 304, 337-342.

- Kreuzer, M., Fenske, N., Schnelzer, M., & Walsh, L. (2015). Lung cancer risk at low radon exposure rates in German uranium miners. *British journal of cancer*, 113(9), 1367-1369.
- Kumar, A., Kumar, M., Singh, B., & Singh, S. (2003). Natural activities of ^{238}U , ^{232}Th and ^{40}K in some Indian building materials. *Radiation measurements*, 36(1-6), 465-469.
- Kumar, A., Tripathi, R. M., Rout, S., Mishra, M. K., Ravi, P. M., & Ghosh, A. K. (2014). Characterization of groundwater composition in Punjab state with special emphasis on uranium content, speciation and mobility. *Radiochimica Acta*, 102(3), 239-254.
- Laughlin, J. M. (2012) 'An historical overview of radon and its progeny: Applications and health effects', *Radiation Protection Dosimetry*, 152(1-3), pp. 2-8. doi: 10.1093/rpd/ncs189.
- Li, C. I., Pai, J. Y., & Chen, C. H. (2020). Characterization of smoke generated during the use of surgical knife in laparotomy surgeries. *Journal of the Air & Waste Management Association*, 70(3), 324-332.
- Little, M. P., Hoel, D. G., Molitor, J., Boice Jr, J. D., Wakeford, R., & Muirhead, C. R. (2008). New models for evaluation of radiation-induced lifetime cancer risk and its uncertainty employed in the UNSCEAR 2006 report. *Radiation research*, 169(6), 660-676.
- Mancini, S., Vilnitis, M., & Guida, M. (2021). A novel strategy for the assessment of radon risk based on indicators. *International Journal of Environmental Research and Public Health*, 18(15), 8089.
- Marouli, M., Pommé, S., Van Ammel, R., García-Toraño, E., Crespo, T., & Pierre, S. (2017). Direct measurement of alpha emission probabilities in the decay of ^{226}Ra . *Applied Radiation and Isotopes*, 125, 196-202.

- Marrow, B. Townsend, L. W., & Fry (2002). Radiation protection guidance for activities in low-Earth orbit. *Advances in space research*, 30(4), 957-963.
- Marsh, J. W., Harrison, J. D., Laurier, D., Birchall, A., Blanchardon, E., Paquet, F., & Tirmarche, M. (2014). Doses and lung cancer risks from exposure to radon and plutonium. *International Journal of Radiation Biology*, 90(11), 1080-1087.
- Mettler, F. A. (2012). Medical effects and risks of exposure to ionising radiation. *Journal of Radiological Protection*, 32(1), N9.
- Miklyayev, P. S., Petrova, T. B., Marennyy, A. M., Shchitov, D. V., Sidyakin, P. A., Murzabekov, M. A., & Lopatin, M. N. (2020). High seasonal variations of the radon exhalation from soil surface in the fault zones (Baikal and North Caucasus regions). *Journal of Environmental Radioactivity*, 219, 106271.
- Mocktar, F. A., Abdul razab, M. K. A., & Mohamed noor, A. A. (2020). Incorporating kenaf and oil palm nanocellulose in building materials for indoor radon gas emanation reduction. *Radiation protection dosimetry*, 189(1), 69-75.
- Nemangwele, F. (2005). Radon in the Cango Caves (Doctoral dissertation, University of the Western Cape).
- Nikolov, J., Todorovic, N., Pantic, T. P., Forkapic, S., Mrdja, D., Bikit, I., ... & Veskovic, M. (2012). Exposure to radon in the radon spa Niška Banja, Serbia. *Radiation Measurements*, 47(6), 443-450.
- Papp, Z., & Dezső, Z. (2006). Measuring radon progeny and thoron progeny in air by absolute beta counting subsequent to grab sampling. *Radiation measurements*, 41(5), 617-626.

- Perrier, F., Girault, F., & Bouquerel, H. (2018). Effective radium-226 concentration in rocks, soils, plants and bones. *Geological Society, London, Special Publications*, 451(1), 113-129.
- Pisa, F. E., Barbone, F., Betta, A., Bonomi, M., Alessandrini, B., & Bovenzi, M. (2001). Residential radon and risk of lung cancer in an Italian alpine area. *Archives of Environmental Health: An International Journal*, 56(3), 208-215.
- Ramasamy, V., Suresh, G., Meenakshisundaram, V., & Ponnusamy, V. (2011). Horizontal and vertical characterization of radionuclides and minerals in river sediments. *Applied Radiation and Isotopes*, 69(1), 184-195.
- Ramola, R. C., Gusain, G. S., Badoni, M., Prasad, Y., Prasad, G., & Ramachandran, T. V. (2008). ²²⁶Ra, ²³²Th and ⁴⁰K contents in soil samples from Garhwal Himalaya, India, and its radiological implications. *Journal of Radiological Protection*, 28(3), 379.
- Ramola, R. C. (2020) 'Measurements of Radon Concentration in the Soil of Garhwal Region', (January 1998).
- Řeřicha, V., Kulich, M., Řeřicha, R., Shore, D. L., & Sandler, D. P. (2006). Incidence of leukemia, lymphoma, and multiple myeloma in Czech uranium miners: a case-cohort study. *Environmental Health Perspectives*, 114(6), 818-822.
- Ruano-ravina, A. et al. (2014) 'Lung cancer in never-smokers: a case – control study in a radon-prone area (Galicia , Spain)', pp. 994–1001. doi: 10.1183/09031936.00017114.
- Russell, M. J., & MacLean, V. L. (2008). Management issues in a Tasmanian tourist cave: Potential microclimatic impacts of cave modifications. *Journal of environmental management*, 87(3), 474-483.

- Schoonhoven, M. (2012). Occupational Exposure to Radon in a South African Platinum Mine (Doctoral dissertation, North-West University, Potchefstroom Campus).
- Seo, S., Ha, W. H., Kang, J. K., Lee, D., Park, S., Kwon, T. E., & Jin, Y. W. (2019). Health effects of exposure to radon: implications of the radon bed mattress incident in Korea. *Epidemiology and health*, 41.
- Somlai, J., Torma, A., Dombovari, P., Kavasi, N., Kovacs, T., & Nagy, K. (2007). Contribution of ^{222}Rn , ^{226}Ra , ^{234}U and ^{238}U radionuclides to the occupational and patient exposure in Heviz-spas in Hungary. *Journal of Radioanalytical and Nuclear Chemistry*, 272.
- Turner, M. C., Krewski, D., Chen, Y., Pope, C. A., Gapstur, S. M., & Thun, M. J. (2012). Radon and COPD mortality in the American Cancer Society cohort. *European Respiratory Journal*, 39(5), 1113-1119.
- Vanmarcke, H. (2002). UNsCEAR 2000: sources of ionizing radiation. *Annalen van de Belgische vereniging voor stralingsbescherming*, 27(2), 41-65.
- Vilela, D. C., Martin, I. M., Alves, M. A., & Germano, J. S. E. (2019). A low-cost experiment to identify variations in the concentration of environmental radon. *Physics Education*, 54(5), 055001.
- Vogiannis, E. G., & Nikolopoulos, D. (2015). Radon sources and associated risk in terms of exposure and dose. *Frontiers in public health*, 2, 207.
- Watson, R. J., Smethurst, M. A., Ganerød, G. V., Finne, I., & Rudjord, A. L. (2017). The use of mapped geology as a predictor of radon potential in Norway. *Journal of Environmental Radioactivity*, 166, 341-354.

Xie, D., Liao, M., & Kearfott, K. J. (2015). Influence of environmental factors on indoor radon concentration levels in the basement and ground floor of a building—A case study. *Radiation Measurements*, 82, 52-58.

Yoon, J. Y., Lee, J. D., Joo, S. W., & Kang, D. R. (2016). Indoor radon exposure and lung cancer: a review of ecological studies. *Annals of occupational and environmental medicine*, 28(1), 1-9.

APPENDICES

Appendix A: Raw data

Amabere Ga Nyinamwiru cave 1, raw data, mid-point

Date/Time	Bq/m³
12/14/2022 07:44 AM	14.8

12/14/2022 08:14 AM	24.8
12/14/2022 08:44 AM	19.6
12/14/2022 09:14 AM	14.6
12/14/2022 09:44 AM	9.8
12/14/2022 10:14 AM	14.7
12/14/2022 10:44 AM	0
12/14/2022 11:14 AM	29.4
12/14/2022 11:44 AM	19.7
12/14/2022 12:14 PM	4.9
12/14/2022 12:44 PM	14.7
12/14/2022 01:14 PM	19.7
12/14/2022 01:44 PM	19.6
12/14/2022 02:14 PM	4.9
12/14/2022 02:44 PM	9.8
12/14/2022 03:14 PM	14.6
12/14/2022 03:44 PM	24.3
12/14/2022 04:14 PM	9.6
12/14/2022 04:44 PM	14.7

Amabere Ga Nyinamwiru cave 1, raw data, end point

Date/Time	Bq/m³
12/15/2022 07:35 AM	0
12/15/2022 08:05 AM	19.6
12/15/2022 08:35 AM	39.2
12/15/2022 09:05 AM	24.6
12/15/2022 09:35 AM	48.6
12/15/2022 10:05 AM	19.2
12/15/2022 10:35 AM	9.8
12/15/2022 11:05 AM	9.8
12/15/2022 11:35 AM	24.2
12/15/2022 12:05 PM	5
12/15/2022 12:35 PM	5
12/15/2022 01:05 PM	14.8
12/15/2022 01:35 PM	9.8
12/15/2022 02:05 PM	5
12/15/2022 02:35 PM	4.8
12/15/2022 03:05 PM	14.5
12/15/2022 03:35 PM	5
12/15/2022 04:05 PM	4.8
12/15/2022 04:35 PM	14.5

Amabere Ga Nyinamwiru cave 2, raw data, initial point

Date/Time	Bq/m³
12/10/2022 07:14	4.9

12/10/2022 07:44	4.8
12/10/2022 08:14	9.8
12/10/2022 08:44	0
12/10/2022 09:14	14.6
12/10/2022 09:44	9.8
12/10/2022 10:14	0
12/10/2022 10:44	19.7
12/10/2022 11:14	39.3
12/10/2022 11:44	19.7
12/10/2022 12:14	14.8
12/10/2022 12:44	9.9
12/10/2022 13:14	9.7
12/10/2022 13:44	24.4
12/10/2022 14:14	24.5
12/10/2022 14:44	44.2
12/10/2022 15:14	19.8
12/10/2022 15:44	14.6
12/10/2022 16:14	5
12/10/2022 16:44	19.6

Amabere Ga Nyinamwiru cave 2, raw data, mid- point

Date/Time	Bq/m³
12/11/2022 07:57	29.1
12/11/2022 08:27	39.5
12/11/2022 08:57	29.5
12/11/2022 09:27	24.5
12/11/2022 09:57	63.7
12/11/2022 10:27	39.4
12/11/2022 10:57	29.5
12/11/2022 11:27	0
12/11/2022 11:57	19.9
12/11/2022 12:27	24.5
12/11/2022 12:57	10
12/11/2022 13:27	4.9
12/11/2022 13:57	14.7
12/11/2022 14:27	14.5
12/11/2022 14:57	10
12/11/2022 15:27	34.6
12/11/2022 15:57	0
12/11/2022 16:27	9.9
12/11/2022 16:57	14.7

Amabere Ga Nyinamwiru cave 3, raw data, mid- point

Date/Time	Bq/m³
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12/12/2022 07:41	14.6
12/12/2022 08:11	24.8
12/12/2022 08:41	39.3
12/12/2022 09:11	29.2
12/12/2022 09:41	43.6
12/12/2022 10:11	19.6
12/12/2022 10:41	24.3
12/12/2022 11:11	24.4
12/12/2022 11:41	9.8
12/12/2022 12:11	5
12/12/2022 12:41	0
12/12/2022 13:11	29.4
12/12/2022 13:41	5
12/12/2022 14:11	9.7
12/12/2022 14:41	9.7
12/12/2022 15:11	4.8
12/12/2022 15:41	4.9
12/12/2022 16:11	9.9
12/12/2022 16:41	10

Amabere Ga Nyinamwiru cave 3, raw data, end- point

Date/Time	Bq/m³
12/13/2022 07:39 AM	4.9
12/13/2022 08:09 AM	9.7
12/13/2022 08:39 AM	19.3
12/13/2022 09:09 AM	14.7
12/13/2022 09:39 AM	4.8
12/13/2022 10:09 AM	5
12/13/2022 10:39 AM	14.7
12/13/2022 11:09 AM	24.2
12/13/2022 11:39 AM	9.7
12/13/2022 12:09 PM	0
12/13/2022 12:39 PM	24.8
12/13/2022 01:09 PM	29.4
12/13/2022 01:39 PM	19.4
12/13/2022 02:09 PM	14.7
12/13/2022 02:39 PM	19.7
12/13/2022 03:09 PM	9.9
12/13/2022 03:39 PM	19.4
12/13/2022 04:09 PM	14.8
12/13/2022 04:39 PM	24.6

Semwama Hill cave, raw data, mid-point

Date/Time	Bq/m³
12/16/2022 07:53 AM	298.4
12/16/2022 08:23 AM	259.6
12/16/2022 08:53 AM	195.9
12/16/2022 09:23 AM	253.6
12/16/2022 09:53 AM	371.5
12/16/2022 10:23 AM	409.8
12/16/2022 10:53 AM	448.7
12/16/2022 11:23 AM	575.3
12/16/2022 11:53 AM	551.9
12/16/2022 12:23 PM	547.3
12/16/2022 12:53 PM	522.8
12/16/2022 01:23 PM	436.1
12/16/2022 01:53 PM	507.9
12/16/2022 02:23 PM	479.4
12/16/2022 02:53 PM	575.1
12/16/2022 03:23 PM	548.8
12/16/2022 03:53 PM	548.8
12/16/2022 04:23 PM	551.8
12/16/2022 04:53 PM	679.8

Semwama Hill cave, raw data, end-point

Date/Time	Bq/m³
12/17/2022 07:53 AM	574
12/17/2022 08:23 AM	603.2
12/17/2022 08:53 AM	603.2
12/17/2022 09:23 AM	542.6
12/17/2022 09:53 AM	518.5
12/17/2022 10:23 AM	520
12/17/2022 10:53 AM	663.2
12/17/2022 11:23 AM	489.2
12/17/2022 11:53 AM	523.6
12/17/2022 12:23 PM	479.5
12/17/2022 12:53 PM	560.8
12/17/2022 01:23 PM	426.3
12/17/2022 01:53 PM	459.8
12/17/2022 02:23 PM	372.5
12/17/2022 02:53 PM	357.4
12/17/2022 03:23 PM	389.3
12/17/2022 03:53 PM	423.7
12/17/2022 04:23 PM	513.4
12/17/2022 04:53 PM	517.7