

Indoor radon measurements in dwellings and public buildings within the KOSH gold mining region, North West Province

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Declaration

I, **Cynthia Gaabakwe Sethabela (24259357)**, at this moment, declare that the work presented in this mini dissertation is a product of my research. It has not been submitted in part or whole for any degree at another university or higher institution of learning before. The results and data presented in this study are the author's original work, and data analysis was done under the guidance of the supervisors. All other data and information from other sources have been fully referred to and acknowledged.

Dedication

I dedicate this work to my supportive and loving Mother (Galebotse Sethabela), my siblings, and above all to God, Almighty.

Acknowledgments

I would like to extend my sincere gratitude to my supervisor, Dr. Atsile Ocwelwang, for her amazing support, guidance, and encouragement throughout this work. She gave me suggestions, advice, and guidance that made this work possible. I would also like to thank my co-supervisor, Professor Manny Mathuthu, for the guidance, support, and encouragement throughout my studies.

A big thank you to the people of KOSH for letting us into their houses to deploy monitors for trusting us with their homes. I am grateful to the community members and locals, who became our research assistants, for devoting their time to help by showing us around their area. Special thanks to my family, my mother (*Mme Suzan Sethabela*), father, grandmother, and siblings for their love, encouragement, understanding, and support in my academic journey.

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Abstract

South Africa has a rich history of over 100 years of operation of gold mines, which is still ongoing. In many cases, gold mines in South Africa have also been producers of uranium (^{238}U) as a by-product, which ultimately decays into other radionuclides and radon (^{222}Rn). Radon gas can only be detected by detectors that record and give out the activity concentration levels of this radioactive gas in air, soil, water, and building materials. Long-term exposure of human beings to radon and its daughters (^{218}Po and ^{214}Po) have been reported to increase the risk of developing lung cancer. As a result, the International Agency for Research on Cancer (IARC) classified radon and its decay products as carcinogens to human beings. Therefore, studies of indoor radon are of great importance in measuring radon concentration levels in regions with radon sources for exposure and dose assessment.

This study conducted a limited indoor radon survey in North-West Province private residences and public buildings (Schools) in the KOSH (Klerksdorp, Orkney, Stilfontein and Haartebeesfontein) gold mining region. This study aimed to measure the distribution of indoor radon activity and concentration levels in private dwellings and schools and identify the possible factors influencing the levels. Sampling and measurements were conducted for ten months during all four seasons (October 2020 – August 2021) divided into three sets. School measurements were performed during two seasons only, summer and winter, following the passive, long-term (3 months) integrative measurement technique. Over 300 Solid State Nuclear Track Detectors (SSNTDs) were deployed in private dwellings at Klerksdorp, Orkney, Kanana, Stilfontein, and all Khuma. Furthermore, about 100 SSNTDs were deployed in twenty-six schools within the Meepong circuit. Two radon cups were deployed in different rooms in each house and school to obtain the average radon concentration in the building; three radon monitors were deployed in a few homes and schools for an amplified assessment.

A wide distribution of indoor radon levels was observed for measurements conducted in schools and homes in different areas. Schools' results showed a minimum of 18.06 Bq.m^{-3} and a maximum of $154.96 \pm 20.48 \text{ Bq.m}^{-3}$ with the highest concentration of $154.96 \pm 20.48 \text{ Bq.m}^{-3}$ recorded at one of the schools in Khuma township during the summer season. Winter measurements in schools measured a minimum of $83.83 \pm 13.25 \text{ Bq.m}^{-3}$ and a maximum activity concentration of $319.49 \pm 37.02 \text{ Bq.m}^{-3}$. The highest radon concentration of $319.49 \pm 37.02 \text{ Bq.m}^{-3}$ was measured at a school in Khuma that recorded the highest radon concentration of $154.96 \pm 20.48 \text{ Bq.m}^{-3}$ during the summer season. More than 50% of the schools had concentration above 100 Bq.m^{-3} which is the level that the World Health Organization (WHO) has recommended to countries to adopt as a reference level.

The first set of measurements in private dwellings was conducted in six (6) locations within the KOSH region, i.e., Stilfontein, Khuma (Extension 1, 8 & 9), Orkney, and Kanana during spring and summer seasons. A minimum and maximum of $71.69 \pm 12 \text{ Bq.m}^{-3}$ and $97.69 \pm 8.09 \text{ Bq.m}^{-3}$ were recorded in Khuma Extensions 8 and 1, respectively. Radon concentration of $97.69 \pm 8.09 \text{ Bq.m}^{-3}$ from Khuma Extension 1 was significant to $96.28 \pm 14.49 \text{ Bq.m}^{-3}$ from Kanana township which was taken as the maximum measured concentration because, in Khuma Extension 1, detectors were deployed in one dwelling. Therefore, it could not represent the average of the whole area.

The second set of measurements was conducted during the summer/autumn seasons. A minimum concentration level of $45.36 \pm 9.27 \text{ Bq.m}^{-3}$ was measured at Khuma Extension 4, and a maximum of $116.33 \pm 15.56 \text{ Bq.m}^{-3}$ was recorded in Jouberton. However, the measurements were conducted from only one dwelling in Jouberton; therefore, it was not taken as the average of the area. The area with the highest concentration was Khuma Extension 6, with a concentration of $83.63 \pm 13.38 \text{ Bq.m}^{-3}$. The average of all locations during the first and the second sets did not exceed the action level of 100 Bq.m^{-3} recommended by the WHO. Still, it exceeded the World Average Indoor Radon Concentration (WAIRC) of 40 Bq.m^{-3} suggested by the WHO.

The third set of measurements was conducted during winter, and 75% of other data collections were done during different seasons. A minimum indoor radon concentration of $76.36 \pm 12.48 \text{ Bq.m}^{-3}$ was measured from Orkney and a maximum indoor radon concentration of $108.84 \pm 14.53 \text{ Bq.m}^{-3}$ from Khuma Extension 9. As expected, the indoor radon concentration was higher during winter than the spring and summer seasons, i.e., in 80% of the selected dwellings. Only 20%, i.e., three houses, measured slightly higher concentrations in hot and dry seasons than in winter. The highest indoor radon levels in this study were found in Khuma township. First, in a house with an average level of $212.17 \pm 26.24 \text{ Bq.m}^{-3}$ and a school with $319.49 \pm 37.02 \text{ Bq.m}^{-3}$. The home is built near a heap of mine waste rocks, approximately 3 km away. And the school is built on a former mine tailings dam. The study suggests that the waste generated from former and operating gold mine operations in KOSH and the geology of the area could be the primary sources of elevated indoor radon concentration levels.

Keywords: Indoor Radon, Gold/Uranium mine, KOSH, SSNTD, WHO, reference level, Annual Effective dose, Schools, private dwellings

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List of Abbreviations and Symbols

Bq	Becquerel
Bq.m ⁻³	Becquerel per cubic meter
CARST	Centre for Applied Radiation Science and Technology
DMRE	Department of Mineral Resources and Energy
DNA	Deoxyribonucleic acid
IAEA	International Atomic Energy Agency
IARC	International Agency for Research in Cancer
ICRP	International Commission for Radiation Protection
KOSH	Klerksdorp Orkney Stilfontein Haartebeesfontein
NNR	National Nuclear Regulator
NORM	Naturally occurring radioactive materials
NWU	North-West University
SA	South Africa
SSNTD	Solid state nuclear track detector
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization
WAIRC	World average indoor radon concentration
Wits	Witwatersrand
²³⁸ U	Uranium-238
²²² Rn	Radon-222
²²⁶ Ra	Radium-226
λ	Decay constant
μ	Micro
γ	Gamma ray
β	Beta particle
α	Alpha particle
kg.m ⁻³	Kilogram per cubic meter
km	Kilometre

Chapter 1: Background and Problem Statement

1 Background

Radon (^{222}Rn) is a naturally occurring radioactive gas; it is chemically inert, colourless, and odourless with a half-life of 3.8 days (Cothorn and Smith Jr, 2013). This gas emanates from the radioactive decay series of Uranium-238 (^{238}U) by releasing an alpha particle from its parent radionuclide Radium-226 (^{226}Ra). Radon can be found in soil, rocks, and groundwater (Moshupya et al., 2019). This mainly depends on the geology of the area. Sites with a geological formation with high radium and uranium content have a high potential for elevated radon concentrations. Building materials that contain naturally occurring radioactive material (NORM) like uranium, thorium, and potassium have also been noted as potential sources of indoor radon (Wentzel, 2018). Radon gas can seep into buildings by moving from soil and rocks underlying the foundation of buildings by advection and diffusion process. Moreover, buildings without airbricks or adequate ventilation systems and cracks are more at risk of high radon accumulation since radon also accrues in enclosed spaces.

According to the International Atomic Energy Agency (IAEA, 2013), the indoor radon level must not exceed 300 Bq.m^{-3} . The half-life of radon is long enough to exist in the environment; therefore, it can be exhaled immediately after inhalation. However, this is not the case with short-lived alpha particles emitting radon progeny polonium-218 (^{218}Po) and polonium-214 (^{214}Po) (Jobbágy et al., 2017). Long-term exposure to radon and its daughter nuclides has been reported to increase the likelihood of developing lung cancer. Inhalation of alpha particles from these nuclides can cause lung cancer by damaging the deoxyribonucleic acid (DNA) of epithelial cells lining the lungs (Lorenzo-Gonzalez et al., 2020).

The concern about the possible consequences of long-term exposure to high levels of ionizing radiation from radon gas has increased interest in indoor radon measurement studies (Shaikh et al., 2003; Lamonaca et al., 2014). A recent study in Europe showed that increased indoor radon levels correlated with lung cancer (Lorenzo-Gonzalez et al.,

2020). Legislation has been developed in many countries to enforce a decrease in radon levels where indoor radon concentrations exceeded a certain level. For example, in the United States of America, the Environmental Protection Agency (USEPA) recommends an intervention by homes owners when the radon concentration level in their homes is 4 pCi/L (picocuries per litre) or more (i.e., equivalent to 148 Bq.m⁻³) (Lindsay et al., 2008; EPA, 2021). According to the National Nuclear Regulator (NNR) report in 2015, South Africa does not have a regulatory framework for the regulating of indoor radon. However, the reference concentration levels proposed for use are 200 Bq.m⁻³ and 300 Bq.m⁻³ for lower and upper reference limits, respectively (Pule and Speelman, 2015).

We all have a fundamental right to a clean environment and air to breathe. This right is constantly violated; studies indicate that 90% of people breathe polluted air, and 7 million deaths are recorded annually due to air pollution (Dunne et al., 2018). Studies of indoor radon as a pollutant and the adverse effects it causes on human health have been conducted in many countries. Indoor radon studies conducted in South Africa to date are insufficient to quantify the extent of radon challenge in the country or take any mitigation action. Indoor air pollution is equally harmful, if not more, since; people spend almost 80% of their time indoors (Abo-Elmagd, 2008; Ghorani-Azam et al., 2016). Radon was classified as a carcinogen by the International Agency for Research on Cancer in 1988 (ICRP, 2018). Recent studies have shown that radon gas increases lung cancer risk to smokers and non-smokers (IARC and WHO, 2001b; Lorenzo-Gonzalez et al., 2020).

1.1 Problem Statement

South Africa has been mining gold for over 100 years (Casey, 2019), the Witwatersrand basin being the oldest and largest gold and uranium-bearing reef in the world. The study area of this study (KOSH) forms part of the Witwatersrand basin with geology that has relatively high uranium concentrations. In the early years of mining, the radioactivity contamination on the land was very high due to the lack of regulatory control (Pule and Speelman, 2015; Michael I et al., 2019). The legacy of environmental pollution seen in and around the residential areas of KOSH because of the 130 years old gold and uranium mining operations and the geological composition of this region could be compromising the health of the residents of KOSH and exposing them to elevated concentrations of

indoor radon. Radon has proven to be a significant source of ionizing radiation exposure in humans and the second leading cause of lung cancer. The primary source of radon in the KOSH region could be the gold and uranium mining, mine waste (tailings and waste rocks) surrounding the area, and the uranium content in the rocks and soil (Mark, 2015). However, radon levels in KOSH are still not well known, therefore, measurements and monitoring are essential to obtain information on public exposure in homes, workplaces, and other high occupancy buildings. This can ensure that recommendations are made or that further action is taken to reduce the risk of radon exposure to public members.

Currently, South Africa does not have a national indoor radon map and regulatory framework for radon in homes. This implies that radon is not regulated in homes unlike many countries in developed countries where strong regulation is in place. This framework can only be implemented once the indoor radon concentration levels are known and a national database based on scientific data is established.

1.2 Aim of the study

This study aimed to determine the radon concentration in dwellings and workplaces around North West province's KOSH gold mining region. Furthermore, this study created public awareness of the potential health effects of long-term radon gas exposure.

1.3 Objectives of the study

- To deploy solid-state nuclear track detectors (SSNTDs) in dwellings to measure indoor radon concentration levels in selected residential areas in KOSH (passive measurement technique).
- To deploy SSNTDs in schools and public buildings to measure indoor radon concentration levels in selected private and public dwellings in KOSH (passive measurement technique).
- To determine the correlation between the measured indoor radon levels and the geological formation of KOSH.
- To determine the correlation between indoor radon levels and long-term gold and uranium mining activities and resulting mine waste near residential areas in KOSH.
- To calculate the annual effective dose from obtained indoor radon measurements.

1.4 Dissertation outline

This dissertation consists of five chapters. Chapter one introduces the study and problem statement; it presents the background on indoor radon, outlines the challenges encountered due to indoor radon, the aim and objectives of the study. The second chapter widely reviews existing literature on indoor radon. This includes the history of radon, sources of radon, techniques used to measure radon concentration, and previous studies of indoor radon conducted globally.

Chapter three explains the overall methodology of the study; this comprises the description of the study area, instruments and techniques used and a description of the procedure followed for the actual measurement of the radon concentration. This chapter also describes the analysis of the obtained data and the method used to calculate the effective dose of indoor radon.

Chapter four presents the results with tables and figures developed from this study and the discussion of results. Lastly, Chapter five summarises research findings and outlines recommendations derived from the findings and observations made from this research.

Chapter 2: Literature Review

2 Introduction

Indoor radon measurements and studies have been conducted in many countries due to potential health threats posed by radon gas to human beings. Recommendations, guidelines, legislation framework and radon maps, indoor radon reference levels, legislatures and frameworks on indoor radon have been developed over the years by individual countries depending on the guidance from organizations such as the International Atomic Energy Agency (IAEA) (IAEA, 2019) International Commission for Radiation Protection (ICRP), the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC and WHO, 2001a).

2.1 Gold and Uranium Mining in South Africa and KOSH Region

Gold mining in South Africa has a rich history, with Witwatersrand Basin being the oldest mining region that hosts several gold-bearing reefs (Tucker et al., 2016). The actual mining operations of gold started in 1886, and in most South African gold mines, uranium was also extracted from the ore and produced as a by-product (Lusilao-Makiese et al., 2013; Harmony, 2021). The South African economy has significantly benefitted from the mining industry; even today is still generating a significant part of the economy by keeping the country's position in the global market. Despite this great benefit, the mining processes have resulted in mine waste called mine dumps or mine tailings and waste storage facilities all around the mining areas.

The Witwatersrand gold basin alone has been estimated to have produced approximately 270 mine tailings (Iyaloo et al., 2020). The Witwatersrand basin covers three South African provinces, Gauteng, North West, and the Free State. It covers the east of Johannesburg, where the Rand goldfield is located, the central part of Johannesburg where the Central goldfield last, and the West Rand and West Wits goldfields in the western part of Johannesburg. Its extent to Klerksdorp goldfield is 40 km south-west of the east-west wits goldfields in the North West province. Lastly, it goes to the Free State town called Welkom, south of Klerksdorp goldfield (Andraos et al., 2019).

The explosion of gold mining companies in the KOSH region started after gold was discovered at a local farm in the late 1880s. After years of exploration and prospecting, the Klerksdorp Goldfields became home to some of the world's leading gold mining operations and producers and the world's deepest mine ranging from 3.16 km to 3.84 km (Ashanti, 2012). For decades, these gold mining activities also led to uranium production as a by-product. One of the operations of the Anglo Ashanti is the Vaal River operations which consist of: Great Noligwa, Kopanang, and Moab Khotsong which are the three Vaal river underground mine operations under the AngloGold Ashanti Company (Pienaar et al., 2017). These operation is one of the greatest uranium producers in South Africa (Ashanti, 2012). The three underground mines are situated approximately 180 km from Johannesburg in the neighbourhood of Orkney and Klerksdorp, near the Vaal river on the border of North West and Free State provinces (Harmony, 2021).

The study focuses on the mine dwellings near the KOSH mining area, which has several operating shaft systems, mining tailings, and rock dumps that have been accumulated from the beginning of the operation of the mine. Kopanang and Great Noligwa are neighbours, with Kopanang situated on the west side of Great Noligwa. The main product at Kopanang mine is gold, and uranium oxide is a by-product from a single shaft system of 2,600m depth. Moab Khotsong is the newest mine that started operating in November 2003 (Ashanti, 2012).

2.2 Radioactivity

When a large unstable atom become stable, they emit energy particles called radiation. During the decay, the original atom is converted into a new atom. This results in a new element forming from the original element called an isotope (Radvanyi and Villain, 2017). This spontaneous process of change in the nucleus of an unstable atom that results in the emission of radiation energy is called radioactivity. Furthermore, the atom undergoes a decay process. A stable nucleus does not spontaneously decay and emit any radioactivity.

In contrast, an unstable nucleus exhibits radioactivity, whereby the nucleus disintegrates or decay and release radiation energy (L'Annunziata, 2012). Each type of unstable nucleus has its characteristics, i.e., rate of decay which ranges from a few seconds to billions of years, (and the element's half-life). An atom's nucleus determines radioactivity; the nucleus of an element is said to be radioactive when the nucleus is unstable.

Radioactivity was discovered in a series of events; in 1896. Antoine-Henri Becquerel discovered that uranium minerals emitted penetrating radiation that produced images on photographic plates. The plates were covered with paper to prevent them from developing in the presence of light; however, radiation could penetrate the paper and develop the plate (Radvanyi and Villain, 2017). A few years later, Marie Curie discovered that thorium minerals emit radiation. She showed that the intensity of radiation depends on the concentration of the radioactive element in the mineral and not on the nature of the compound (Guerra et al., 2012). After examining uranium minerals, Marie Curie discovered two other radioactive elements; she named them polonium and radium.

Marie Curie, Becquerel, and Rutherford realized that radium forms other elements as it decays. This is how it is known and observed that radiation emission results when an element changes from one element to a different one. This led to the discovery and understanding of the three most common types of radioactive emissions known as alpha (α), beta (β), and gamma (γ) particles. The SI unit for radioactivity is Becquerel (Bq), defined as one disintegration per second (Mann et al., 2016; Radvanyi and Villain, 2017).

Uranium (^{238}U), Thorium (^{222}Th), and Potassium (^{40}K) are naturally occurring unstable radionuclides that are present in rocks, soil, and underground water at different concentrations (Mohammed et al., 2018). Due to them being unstable, they undergo decay series, forming daughter radionuclides through various decay modes, which are; emission of electromagnetic radiation (gamma and X- rays) and particle radiation (alpha and beta particles (Kónya and Nagy, 2018)).

Universal laws govern radioactive decay series, and each radionuclide has its unique decay constant represented by the Greek letter lambda (λ) the probability per unit time ($\lambda.S^{-1}$). The activity (A) of a sample of decaying nuclei (N) is proportional to its decay constant and N of nuclei. The activity (A) of a sample is the decay rate of that sample. It is the product of the number of atoms present in the sample and the decay constant. The decay rate is measured by the number of disintegrations per second (Nagy, 2010).

$$A = \lambda N \quad \text{Eq. 2.1}$$

For a sample of (N) nuclei, the total number of decaying nuclei during a particular time interval (dt) is given by the following equation for the change in the number of nuclei of a duration (dN/dt). The negative sign indicates the decreasing function or a decay.

$$dN = -\lambda N dt \quad \text{Eq. 2.2.}$$

The above differential equation can be solved to give the radioactive decay law presented in the equation below (Lilley, 2013):

$$N(t) = N_0 e^{-\lambda t} \quad \text{Eq. 2.3}$$

The expression above is used to calculate how the number of atoms present will change over time (t)

$N(t)$ is the number of atoms present at time t

N_0 is the number of nuclei at initial time $t = 0$

(t) is the time

λ is the decay constant

The decay constant (λ) is related to the half-life of a sample, which is the time required for the activity to decrease/ decay to one-half of its original value. If A equals one half-life of initial activity (A_0), then A/A_0 equals one half. This is used in an expression to calculate half-life (Lilley, 2013).

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

Eq. 2.4.

2.3 Radon (^{222}Rn) In the Uranium (^{238}U) Decay Series

Uranium is a naturally present element in soil and rocks. Radon is an inert radioactive gas. Friedrich Ernst Don acknowledged it first in the 1900s; he referred to this gas as “radium emanation” (Marshall and Marshall, 2009; Kang et al., 2019). Radon exists in many isotopes; three commonly known are radon (^{222}Rn), thoron (^{220}Rn), and actinon (^{219}Rn). Radon (^{222}Rn), commonly referred to as “radon”, is the only gaseous nuclide produced in the uranium – 238 decay series (Figure 2.1), which ends with stable Lead - 206 (^{206}Pb). Thoron is produced in the thorium (^{232}Th) decay series, where the final product is stable lead (^{208}Pb). Actinon is a product in the natural decay series of uranium (^{235}U), where the final product is a stable ^{207}Pb (Kheder, 2019).

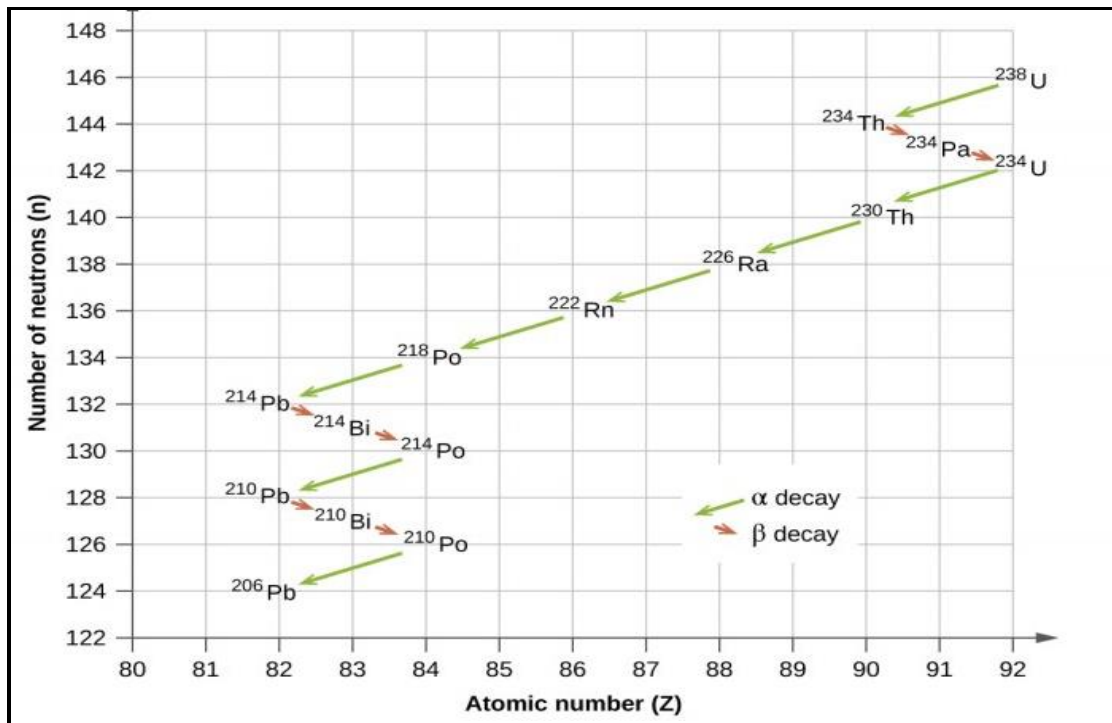


Figure 2.1. Radioactive decay series of Uranium-238 (Flowers, 2018).

2.4 Radon Decay

Radon is the only radionuclide in gaseous form within the uranium-238 decay series. This allows it to penetrate and escape the rock and soil matrix. Its gaseous form properties enable it to move through the pore spaces in soil and the fractures of the rock. Radon decays with a half-life of 3.8 days to a series of daughter radionuclides called progenies. Just like radon, the progenies are also alpha emitters. These alpha emissions from the progenies deliver the most radon dose exposure (Lavarnway, 2006; Appleton, 2013).

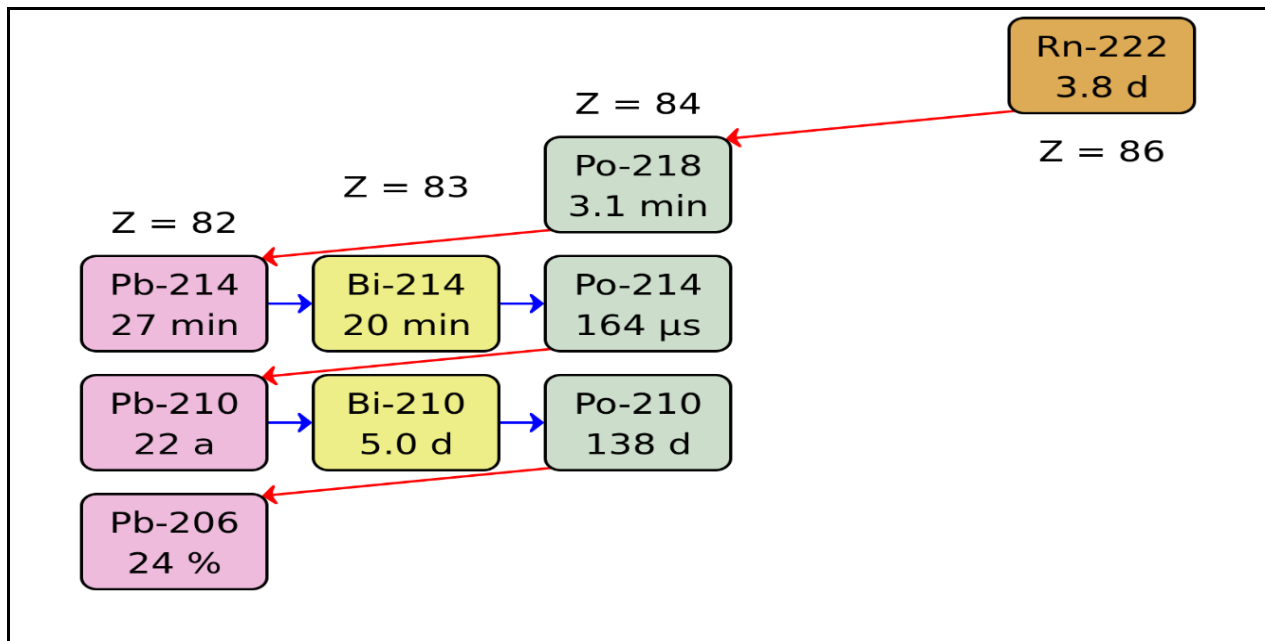


Figure 2.2. Decay of radon-222 and its progenies (Raquel, 2018; Kuiper, 2008).

Radon decays to its short-lived progenies by alpha decay mode emitting ionizing alpha particles; radon progenies also emit ionizing alpha particles when they decay further to a stable isotope of lead-210. The kinetic energy of alpha particles emitted by radon and its progenies (^{218}Po and ^{214}Po) ranges between 4.98 and 5.59 MeV (Hofmann et al., 2004; Zorri et al., 2017). Radon disperses faster when it reaches the open air, generally with an average outdoor air radon concentration of approximately 10 Bq.m^3 ; however, it is as low as 1 Bq.m^3 in other areas and above 100 Bq.m^3 in some regions (Syuryavin et al., 2018). Radon in enclosed spaces or environments such as buildings, caves, and underground mine shafts does not disperse quickly as in outdoor environments. Therefore, radon in

closed environments is found at a higher concentration level than in the outdoors. The worldwide average indoor radon is 40 Bq.m³. Some countries have an average of less than 10 Bq.m³; others are higher than 100 Bq.m³ (WHO, 2000; WHO, 2010).

2.5 Chemical and Physical Properties of Radon

Radon is an inert radioactive gas; it is an odourless, colourless, tasteless gas; it is a non-flammable gas. In a solid-state, radon has a density of 9.96 kg.m⁻³ with boiling and melting points of -61.8°C and -71°C, respectively. ²²²Rn has the longest half-life compared to thoron and actinon with half-lives of 55.8 seconds and 3.96 seconds, respectively. The three isotopes of radon decay by alpha decay mode and emit alpha particles with different energies are used to characterize them (Cothorn and Smith, 2013; Keith et al., 2013).

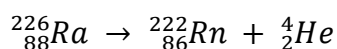
2.6 Three Main Types of Radioactive Decay Modes and Particles

Radioactive decay is a naturally occurring process whereby elements emit energy in ionizing radiation. The radioactive decay occurs in unstable nuclei called radionuclides, whereby a “parent radionuclide” spontaneously disintegrates to release ionizing radiation energy in the form of particles (i.e., alpha, beta, or gamma). A different nucleus called a “daughter nuclide” with less energy is formed. The unstable atom continues to decay and produce daughter nuclides until it reaches a stable state which is not radioactive (Mark, 2015). Some unstable atoms reach stability in one decay step, others undergo many decay steps before they get a stable atom, and this type of decay is called “radioactive decay series”. Atoms decay in many different modes; alpha, beta, and gamma decay; the decay rate differs depending on the nuclei's half-life, which is the time required for the atom to decay to half of its initial radioactivity (Steinberg, 2021).

Alpha Decay

Alpha decay is a nuclear reaction process that results in an emission of an alpha particle (Isaifan, 2018). Alpha particle is essentially a helium nucleus and consists of two protons and two neutrons held together. Most radionuclides with an atomic number of 83 and more are alpha emitters; they release an alpha particle during their decay process

(Radvanyi and Villain, 2017). The emitted alpha particles usually have energies ranging from 4 MeV to 10 MeV, the half-life of the radionuclides that emit alphas is between 10^{10} years to microseconds. Radionuclides that emit low-energy alpha particles have a longer half-life than those that emit high-energy alpha particles. The positively charged protons causes ionization in various substances such as gas, liquid, and solid states; this occurs by forming ion pairs. The ion-pairs form due to Coulomb attraction between an alpha particle passing through and the atomic electrons (WHO, 2009b; WHO, 2016). In an alpha decay process, the parent radionuclide loses two neutrons and two protons. For example, radium undergoes alpha decay to produce radon (Gilbert et al., 2018).

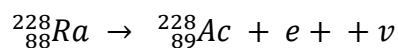
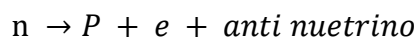


In his experiment that led to discovering the radioactive phenomenon, Antoine Henri Becquerel used positively charged photographic plates to test charges of particles (alpha, beta, and gamma) (Schuck et al., 2016). Alpha particles are deflected away from the electric and magnetic fields, proving that alpha particle is positively charged. Alpha particles are effortlessly shielded compared to beta and gamma; they can be shielded by a layer of human skin or even a sheet of paper. They are harmless to the external human body, but they pose a severe health hazard to the internal human body if inhaled or ingested (Schuck et al., 2016).

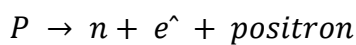
When alpha particles interact with sensitive cells in body parts such as the liver, bones, and lungs, this can lead to cancer. Alpha particles are heavier than both gamma and beta particles; hence they do not move quickly in space. They have high linear energy transfer (Radvanyi and Villain, 2017) and their energy deposits in short distances; this is how they induce cancer because they have a greater chance of breaking the double strand of a DNA molecule (Robertson et al., 2013). Once the double strand is damaged, it will undergo a self-repair process in which the nucleotide's bases mismatch, resulting in the malfunction of cells and rapid cell growth (Forkapic et al., 2017).

2.6.1 Beta Decay

Beta decay is a process whereby a beta particle is emitted from the nucleus during radionuclide decay. The beta particle is a high-energy electron or a positron. The emitted particle can be positively (β^+) charged or negatively (β^-) charged with the same mass. Beta minus decay occurs when a neutron is turned into a proton by the nuclear force; this results in an electron called Beta minus particle and an anti-neutrino ($\bar{\nu}$). During the beta minus decay, the atomic number of the nucleus of the product increases by one. This type of beta decay occurs when there is an excess number of neutrons in a nucleus of an atom. Below is an example of a beta decay whereby a neutron is converted into an electron and a proton (Cothorn and Smith Jr, 2013).



Beta plus decay occurs when a proton (p) is converted to a neutron (n) by the weak nuclear force, and this results in a positron (e^+) which is called beta plus particle and a neutrino. Beta plus decay occurs when there are many protons in a nucleus. It occurs naturally, and the atomic number of the nucleus of the decay product decreases by one (Michael I. Ojovan., 2019).



Beta particles are fast moving electrons that are not appended to atoms. They are light - more than 7,000 times lighter than an alpha particle. The beta particles travel more distance through strong (solid) material than alpha particles. For instance, a high-energy beta particle will travel a large portion through plastic before using all its energy. Like alpha particles, beta particles lose energy in every interaction within the matter and no longer create ions once all their energy is spent. Well-being concerns about beta particles emerge mostly while beta-emitting materials are ingested or breathed in (Michael I et al., 2019).

2.6.2 Gamma Decay

Gamma emission involves the release of high-energy electromagnetic radiation or gamma photons from an excited nucleus of an atom. Gamma beams are electromagnetic, like x-ray beams, and can go totally through the human body. Gamma beams radiated from outside of the body may bring about ionization, and possible well-being impacts, in any organ in the body. However, once a gamma beam loses all its energy, it can no longer cause harm. High energy gamma beams will lose most of their energy in a couple of feet of soil, three feet of cement, or six inches of lead (Michael I et al., 2019; Radvanyi and Villain, 2017).

2.6.3 Radon in Soil

2.6.3.1 Radon Emanation in Soil

Radiation is a concern to the nuclear society and the environmentalists because radiation levels beyond the background radiation are harmful to vegetation and plant growth (Fahiminia, 2016). Radon atoms are emitted from material by a process called the emanation of radon. However, the mechanism is not the same for soils, rock, and water and is poorly understood. A study has reported that the emanation rate is determined by soil condition, porosity, temperature, moisture content, and atmospheric pressure. Low moisture content decreases radon release by the adsorption effect of the radon atoms on the surfaces of the pores (Fahiminia, 2016). It was found that radon emanation from soil depends not only on uranium-238 and radium-226 concentrations but also on the permeability and mineralogy of the host rock and soil. A study has also suggested that paint also has effects on radon concentration. Paint reduces the concentration of radon on the surface of the bricks, which increases the concentration of radon inside the brick. The radon emanation expands from the areas where the bricks are not painted due to increased radon concentration inside. It has been shown that radon emanation also increases from bricks that are overlaid with plaster and gypsum; this suggests that the internal finish increases the concentration of radon inside the houses.

2.6.3.2 Radon Diffusion in Soil

Diffusion is recognized as the most critical method of radon transportation into and out of the basement modules; it is also shown that it does not depend on the insulating materials and vapour retardant (Elzain, 2021). It has been found that various levels of radon that correlate with a different pressure gradient may be associated with the air current in block walls and soil that break off the diffusion of radon inward. After the entrance of radon in the air or water surrounding the emanating radium-bearing particle, it is then transported through earth mechanical and convective flow, diffusion, the flow of groundwater, and percolating of rainwater (Fatimah et al., 2017). It has been shown that there is not enough evidence to accept the pressure-driven mechanism as the leading radon infiltration mechanism in homes (Mitev et al., 2017).

2.7 Radon Accumulation in Buildings

Studies have been conducted on indoor radon concentrations using short-term and long-term methods to solve indoor radon problems. Many sources influence indoor radon, such as water, soil, natural gas, and building materials (Joyce, 2017). The accumulation of radon in a building depends on the concentration of uranium-238 or radium-226 in the soil, type of building material, and isolation are other factors that contribute to the accumulation of radon (Sandle, 2013).

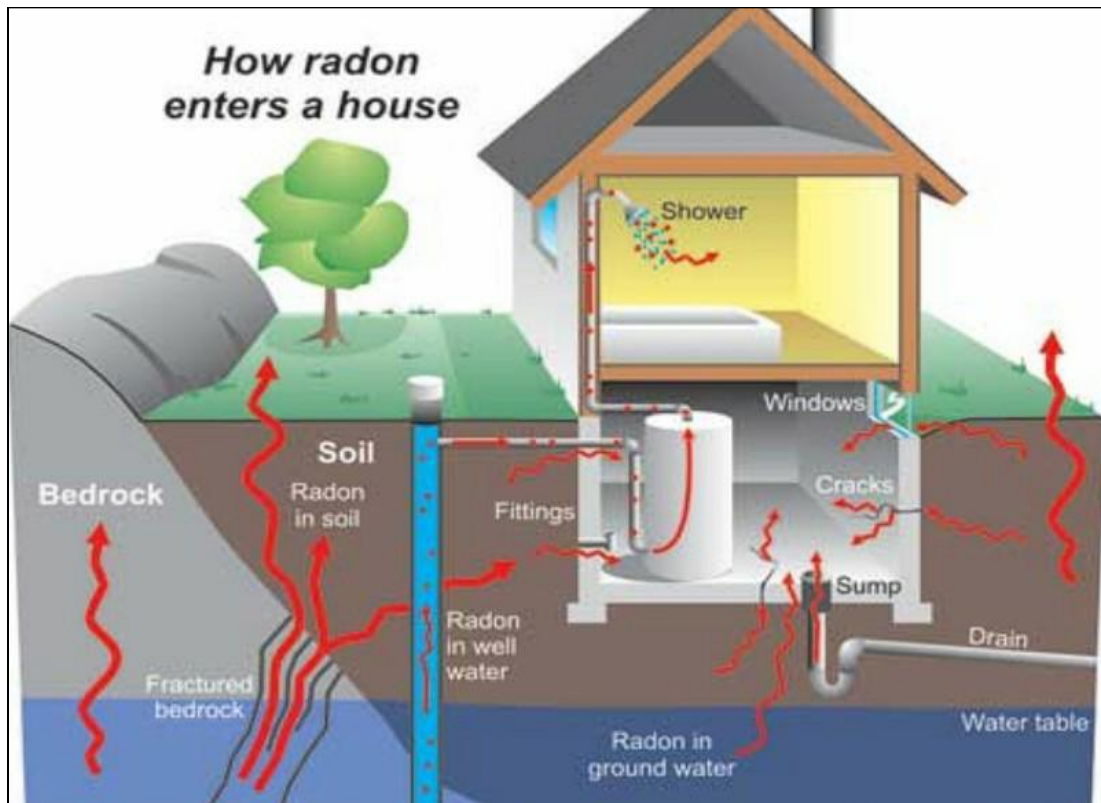


Figure 2.3. Radon Entry into a building (Scott, 2017).

2.8 Sources of Indoor Radon

Radon and its decay products polonium (Po-218), lead (Pb-214), polonium (Po-214) and bismuth (Bi-214) are considered as the primary source of public exposure from the natural radioactivity in dwellings; they contribute approximately 50% of the mean effective dose to the public globally. Radon and thoron (^{220}Rn) are two gaseous isotopes in the air considered primary naturally occurring sources of radiation exposure to the environment (Hadad and Mokhtari, 2015). The highest impact of radon in the environment is poor air quality and water pollution. Areas at increased risk of indoor radon connect with regions with high levels of radon activities in the underground soil, such as mines (Scott, 2017). The most stable isotope of radon (^{222}Rn) in water sources such as raindrops, rivers, underground, lakes, and springs poses an environmental health risk since it is a water contamination problem.

2.8.1 Building Materials

All building materials contain a certain number of radionuclides. Building materials that are composed of soil and rocks may contain natural radionuclides (NORMS) from the decay series of uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) isotopes (Isaifan, 2018). The radioactivity contributed by the nuclides in the building materials contributes to the equivalent dose similar to that of natural background radiation. There is a need for a pre-calibrated technique used to study indoor ^{222}Rn , whether active or passive technique (Cothorn and Smith Jr, 2013).

2.8.2 Radon in Rocks

Granites are ingenious rocks with visible crystalline texture, and they usually consist of field par, quartz, and mica. These rock types typically contain high concentrations of naturally occurring radioactive materials (NORM) (Lamonaca et al., 2014). Studies have shown that granite rocks contain high uranium concentration resulting in a high radon concentration. Therefore, people living in areas rich in granites are more likely to be exposed to radon gas (Dunne et al., 2018). Radon gas is heavier than air. When formed in the earth's layers, it passes through pores in the ground and moves upward by distribution and convection to the surface (Le Roux et al., 2019). This process is called exhalation; the amount depends on the soil's diffusion, air pressure, humidity, and thermal gradient. The primary indoor radon sources that penetrate the dwellings are water, soil via building materials, and basement air. Pores in the foundations of homes, joints, floor cracks, and drains increase the chance of penetration of radon concentration into the house (Bezuidenhout, 2019).

2.9 Anthropogenic Influence on Indoor Radon Levels

Uranium is a naturally occurring trace element in the environment. In South Africa, uranium is mainly brought to the surface through the mining of gold because the two elements are associated with the mined gold-bearing ore reefs of the Witwatersrand Basin. Mining is one of the activities taking place for many decades all over the globe, in SA Witwatersrand basins being the oldest active group of mines. Mining of uranium-

bearing ore such as gold releases high concentrations of different radionuclides from geological underground into the biosphere (surface).

2.10 Health Effects of Exposure to Radon

Mining is one of the big industries that contribute a lot to the economy of the country. The mining industry contributes positively to the country. It is also responsible for human health and environmental pollution by producing high volumes of waste released into the environment (Nissi et al., 2012). It took five decades after radon was discovered before it was associated with lung cancer (Elzain, 2021).

When ^{222}Rn and its daughter products are inhaled, the concentrated ionizing alpha particles emitted by deposited products with short half-life or radon interact with biological lung tissue, resulting in DNA damage. For cancer to occur, there must be a gene mutation and the development of intermediate cells that survived a certain degree of DNA damage, which can highly increase the available cells for cancer development (Kamunda et al., 2017). It has been proven that an alpha particle can induce significant genetic damage to a cell. Inhaled alpha particles have a high chance of causing DNA damage at any level of exposure. According to the World Health Organization (WHO, 2010), it is unlikely to have a threshold concentration that is lower in which radon does not impose a threat of lung cancer (Moshupya et al., 2019).

Tobacco smoke and radon gas are the leading causes of lung cancer in the population. When the two are combined, they are even more toxic, and the chances of lung cancer increases greatly more than a sum of probabilities. People who smoke tobacco and live in houses with a high level of radon have an increased risk of getting lung cancer is ten times greater than that of non-smokers who live in homes with a high level of radon gas (IARC and WHO, 2001b).

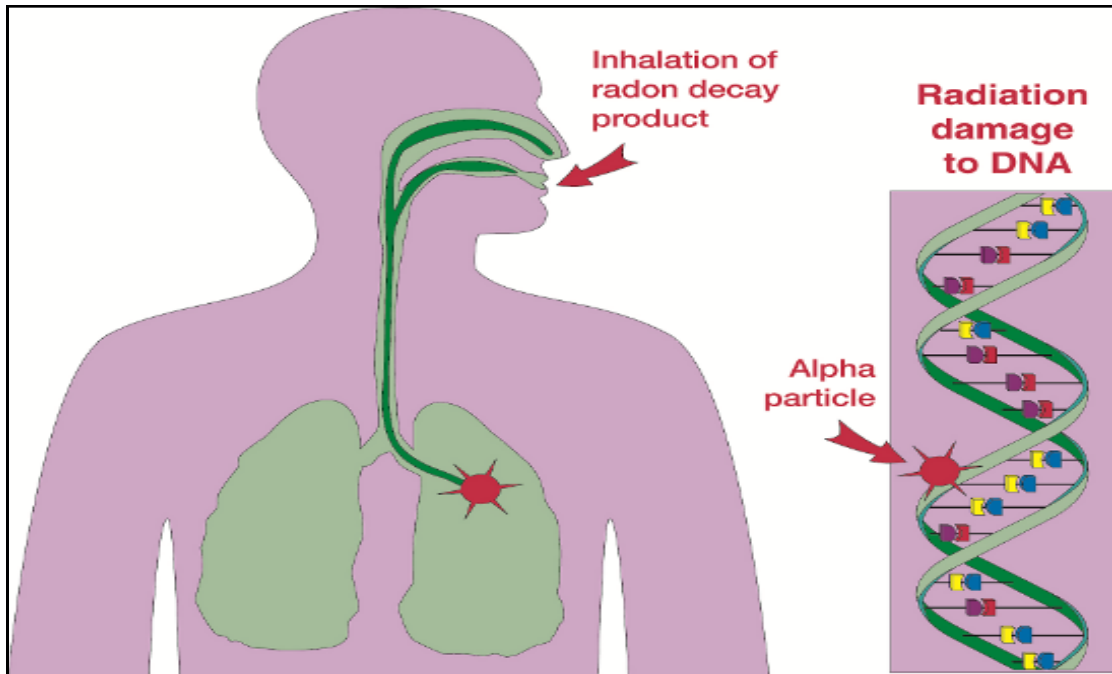


Figure 2.4. How alpha particles (emitted by radon progenies) damage the lung DNA (Interior, 2017).

2.11 Radon Detection and Instruments

There are two types of techniques used to measure radon activity; each method is best depending on the application. It is integrative, passive radon sampling that does not use electrical power, and continuous active radon sampling requires electrical power. The devices used for radon measurement include alpha GUARD monitor, alpha track detectors, and activated charcoal adsorption devices (Sethi et al., 2012).

Active or passive techniques are used for indoor measurements or verification purposes or determining the radon source. Currently, the market offers different instruments used for indoor radon measurements in both developed and developing countries. Radon tests can be conducted over short to long periods. Short-term measurements can vary from minutes, hours to a week, whereas long-term measurements can range from a minimum period of one month to a year. Punctual and continuous radon measurement techniques are short-term active methods, whilst integrated measurement techniques are long-term and passive. Outlined below are four radon measurement devices and techniques used in various independent studies (Hadad et al., 2007; Immèa et al., 2013).

2.11.1 Integrative Passive Radon Detectors

2.11.1.1 Activated Charcoal

Activated charcoal devices are passive detectors with a canister that holds granular-activated carbon, and they do not require power (McMurdy, 2009; Shweikani, 2012). These devices are used to measure indoor radon for 1-7 days. The charcoal absorbs the radon that gets into the canister through a screened opening, the absorbed radon will then decay, and its progenies will be retained. After the set exposure period, the canister is sealed, allowing the radon progeny gamma decay in the charcoal to be collected directly by the HPGe gamma spectrometry of the emissions from lead-214 (^{214}Pb) and bismuth-214 (^{214}Bi). Alternatively, it can be collected by the liquid scintillation counting (LSC) technique. The LSC uses 20 ml liquid scintillation vials that contain about 2-3 g of activated carbon (Miles, 2004).

The device is highly affected by humidity; therefore, it must be calibrated at different humidity levels since the charcoal can get saturated at high humid conditions. However, a diffusion barrier is used to reduce this humidity effect. The device must also be calibrated over the same duration of exposure and the temperature of the area it will be exposed to (Karunakara et al., 2015). The good thing about this method is that, since charcoal allows accumulation and desorption of radon, this method gives a perfect estimation of the average radon concentration over the exposure period if there is a slight change in the radon concentration. Considering the half-life of ^{222}Rn , which is 3.82 days, the device should be returned soon after the exposure period for analysis (Živanović et al., 2020).

2.11.1.2 Electret Ion Chambers EIC)

These passive devices are the electrostatic equivalent of permanent magnets; due to the permanent surface charge, the surface potential may be several kilovolts (kV). It functions as an interoperating detector for measuring the average indoor radon concentration during the measurement period (Zeeb et al., 2009). It contains an electret that functions as a sensor in the ion chamber and an electric field source. A Teflon

electret is placed at the bottom of a conducting plastic chamber called an electret ion chamber (EIC). Radon gas enters the chamber volume by passive diffusion through the inlet; this results in electret losing charge due to the general ionization of the alpha particles from radon gas and the alpha decays of its progenies in the chamber volume (Zeeb et al., 2009; Živanović et al., 2020).

The positively charged electret at the bottom of the chamber collects the negative ions, and the energy released by the positively charged electret in a given time interval is a measure of time-integrated ionization during the interval. A noncontact battery-operated electret reader measures the energy given off by the electret in volts; this value, in alliance with the calibration factor and the duration, is used to obtain the radon concentration. The EICs can be employed for short-term and long-term measurements (Miles, 2004). EICs designed for short-term measurements can measure up to 15 days at a concentration of 50 Bq.m^{-3} , and the long-term detectors are designed to measure from 3 to 12 months at a concentration of 150 Bq.m^{-3} (Karunakara et al., 2015). These devices have proven to be a good measure of radon exposure; however, they have a limited dynamic range. They are sensitive to gamma rays; thus, compensation must be applied. To obtain precise measurements, correction for the elevation must be made to compensate for the variation of atmospheric pressure effects (Kotrappa, 2015).

2.11.1.3 Solid-State Nuclear Track Detectors (SSNTD)

Solid-state nuclear track detectors also referred to as “etched track detectors”, are thin plastic sheets of different materials capable of recording alpha tracks. Due to their integral signal registration and insensitivity to low LET (linear energy transfer), radiations play a vital role in radon passive integrated measurements. Track detectors exist in open and closed types, and sampling is done in passive mode. The open SSNTD type can measure radon and its decay products, while the closed SSNTD type can only measure radon because it has a filter for radon progenies. This detector usually comes in two types, the LR115 (cellulose nitrate) and CR 39 (polyallyl diglycol carbonate), with CR-39 being the most popular detector member. These devices measure the energy of alpha particles emitted by radon and its progenies. The plastic material is etched in NaOH and KOH

solution (ethanol can also be used) to reveal any damages. To obtain representative data from buildings, the exposure period should be as long as possible (WHO, 2009b). Generally, etched track detectors are deployed for a minimum period of a month to a year, and this differs per country.

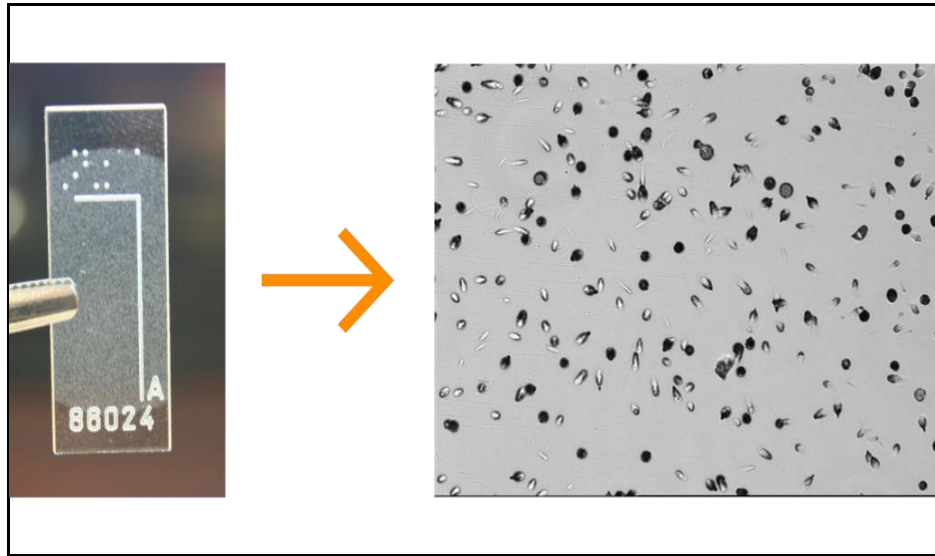


Figure 2.5. Alpha tracks were observed as black holes under an optic microscope (PARC-RGM, 2021).

2.11.2 Continuous Active Radon Detector

2.11.2.1 The alpha GUARD radon detector

AlphaGUARD radon detector is a continuous active radon sampling detector that contains an ionization chamber and uses alpha spectrometry for radon and its progenies detection. ^{220}Rn and ^{222}Rn are common isotopes of radon; their various energies distinguish them from the alpha decays, and this helps to distinguish the two isotopes measured by the AlphaGUARD. (McMurdy, 2009). The AlphaGUARD can be employed ideally for mining environments, radon exhalation, indoor, outdoor, in-water storage, and radon soil-gas radon measurements (PARC-RGM, 2021).

Alpha GUARD professional radon monitor is portable equipment used to measure radon. This device uses the ionization principle for radon measurement in the environment. The

working principle of this device is that when radiation passes through gas-filled space or air (McMurdy, 2009). It is used for continuous and instantaneous measurement of the activity of ^{222}Rn . The measurements of ^{222}Rn in soil, air, and water, can be done using the instrument supplied by the company of the Genitron instrument (Kasar et al., 2020).

2.12 Dose Calculations

In general, there are two types of modes of radiation exposure; external exposure and internal exposure. External exposure is when the radiation source remains external. Internal exposure to radiation is the problematic mode of exposure. This is when a radioactive material enters the body through inhalation, ingestion, absorption through the skin, or a break in the skin (Kadhim, 2020). Insoluble material will be excreted after ingestion; however, inhalation of the radioactive material may be trapped in the lungs and cause damage. Ionizing radiation is energy composed of particles with sufficient energy to eject an electron from an atom or molecule. The energy released is enough to break chemical bonds (Friedberg and Copeland, 2011; Cannan and Pederson, 2016).

The biological effects of radiation dose depend on the energy deposited by radiation to the organ or tissue, the type of radiation, and the mode of radiation exposure. Therefore, linear energy transfer (LET) plays a crucial role in the severity of the radiation damage. LET is defined as the mean energy deposited per unit path length in the absorbing material, usually presented in $\text{keV}/\mu\text{m}$ (Johnson et al., 2015). LET describes how radiation energy penetrates matter or an object. Radiation particles have different LET, which implies that the potential biological effects are different due to other particles and their LET.

Alpha particles are classified as high LET due to their large charge of +2 and relatively large mass of high LET, which causes them to travel slowly and interact strongly with matter; they pass through and produce a dense ionization path. Beta particles that are energetic electrons are classified as low LET radiation. They interact with matter similar to alpha particles; however, due to their smaller charge of +1/-1 and smaller mass, it deposits its energy at a more considerable distance, thus, a lower rate of energy transfer. Gamma radiation is also classified as low LET because ionisations produced by gamma

radiation are due to electrons (Drobny, 2012). Both high and low LET can cause significant damage to the DNA and result in biological effects; however, the effects induced by high LET radiation are more severe than the low LET effects.

The biological effects of ionizing radiation are classified into two; deterministic and stochastic. Deterministic effects occur when a specific part of the body is exposed to a high radiation dose (> 1 Gy) in a short period. These effects induce massive killing of the cells, which can cause eye damage (lens opacities), skin injuries, epilation, and infertility. Stochastic effects are radiation-induced health effects, usually occurring without a threshold dose level. These effects are proportional to the dose, and the perversity is independent of the dose (Lalit Mohan, 2014).

The damage caused by stochastic radiation effects on biological tissue can be classified as either hereditary or somatic. These effects result in damage that lasts for a lifetime, such as cancer induced by radiation, sterility is those that cause genetic effects and cancer (Hamada and Fujimichi, 2014). Damage to tissues and organs depends on the radiation dose received or absorbed, expressed by the SI unit gray (Gy). The potential damage that radiation can cause also depends on the type of radiation and the sensitivity of different organs and tissue. Hereditary effects entail radiation-induced genes and DNA mutation that can affect the birth of abnormal descendants (Grosch, 2012).

The dose is defined as the amount of energy (J) from ionizing radiation deposited in a unit mass (Kg) of material. The SI unit Gray can be used for any type of radiation; it does not describe the biological effects caused by different types of radiation (Sweni et al., 2015).

$$Gy = \frac{1J}{kg} \quad \text{Eq. 2.5}$$

Absorbed dose ($D_{T,R}$) is radiation energy (R) absorbed per unit mass of the specific tissue in the body (T) and measured in (Gy) (Gupta, 2015). Equivalent dose (H_T) to the tissue is defined as the sum of contributions of different types of radiation (R) to the tissue, each multiplied by the radiation weighing factor (W_R) (Mattsson and Söderberg, 2013). The

equivalent dose is measured in Sieverts (Sv); the equation below is used to calculate the Equivalent dose to tissue is:

$$H_T = \sum_R W_R D_{T,R} \quad \text{Eq. 2.6}$$

Effective dose (E) is defined as the sum of equivalent dose (H_T) to a specific organ and tissue exposed, as shown in Table 2.1, each multiplied by the appropriate tissue weighting factor (W_T). Effective dose is used to measure ionizing radiation in terms of the (ICRP, 1991; ICRP, 2007) unit that takes the type of radiation and the sensitivity of the organ or tissue into account. Sievert represents a large unit; therefore, smaller units such as microsievert (μSv) or millisievert (mSv) are used. Furthermore, Sv is also used to express the rate at which the dose is delivered to the tissue or organ. Dose rate takes into account the exposure time. The dose rate is expressed in millisievert per year (mSv/y.) or microsieverts per hour ($\mu\text{Sv/hr}$) (Fisher and Fahey, 2017). The equation below is used to calculate the effective dose:

$$E = \sum_T W_T H_T \quad \text{Eq. 2.7}$$

Table 2.1. Human tissues and their weighing factors (ICRP, 2007; ICRP, 1991).

Tissue	Weighting factor, W_T (ICRP 60)	Weighting factor, W_T (ICRP 103)
Gonads	0.20	0.08
Red bone marrow	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04

Breast	0.05	0.12
Liver	0.05	0.04
Esophagus	0.05	0.04
Bone surfaces	0.01	0.01
Remainder Organs	0.05	0.12

The ICRP defines the annual effective dose as the sum of the tissue-weighted equivalent doses absorbed by a particular organ or tissue in the body (Vaillant and Bataille, 2012). Annual effective dose due to inhalation of radon was estimated using the measured indoor radon concentration. The effective dose presents the dose received by the people in their house. The calculation was performed using the below equation, which UNSCEAR has suggested (UNSCEAR, 2000).

$$E_{Rn} (mSv.y^{-1}) = DCF_{Rn} F_{Rn} A_{Rn} T_{Rn} \times 10^{-6} \quad \text{Eq. 2.8}$$

where:

E_{Rn} is the annual effective dose of inhaled radon;

DCF_{Rn} is the conversion factor of radon through inhalation (which is assumed to be 9 mSv/Bqhm⁻³);

F_{Rn} is the indoor equilibrium factor between radon and its daughters (which is assumed to be 0.4);

A_{Rn} is the activity concentration of radon in Bqm⁻³;

T_{exp} is the exposure time to the measured concentration (assumed to be 7000 hours in a year).

Chapter 3: Methodology

3 Introduction and Overview

Chapter 3 gives a detailed overview of the study area, methods, and procedures that were followed to achieve the aim and objectives of this study. This chapter outlines the geographical location and history of the chosen study area and the supporting background for its selection. Furthermore, Chapter 3 discusses instruments, devices, and all the methodologies used in this study.

3.1 Study Area

This study was conducted in dwellings and public buildings in Klerksdorp goldfields under the Dr. Kenneth Kaunda district municipality, which comprises the Matlosana, JB Marks, and Maquassi Hills local municipalities in the North-West Province, South Africa. The Matlosana local municipality, frequently referred to as the “City of Matlosana” in particular, comprises four gold mining towns, namely Klerksdorp, Orkney, Stilfontein, and Haartebeesfontein (KOSH). As observed in the South African map presented in figure 3.1, KOSH is located along the north-western border of the famous gold-bearing Witwatersrand basin, located approximately 160 km southwest of the Gauteng province’s “city of gold” Johannesburg. This region covers an area of about 2757 km², of which 88.2% consist of urban settlements and only 11.8% rural settlements (Dudumashe, 2020).

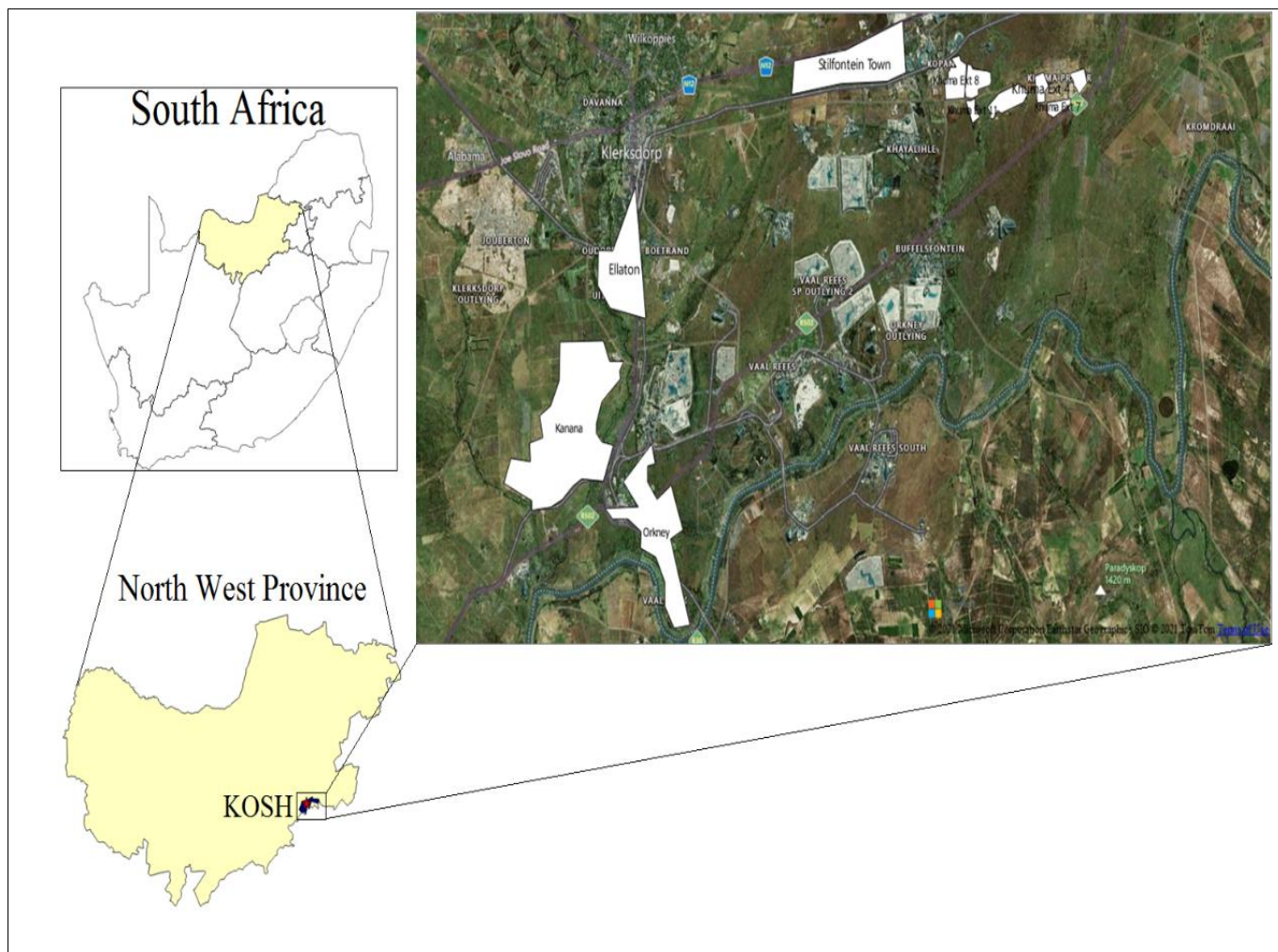


Figure 3.1. KOSH region in the South African Map.

Geology is one of the primary predictors of radon exhalation because uranium is found naturally in the soil and rocks at different concentration levels. This is another reason why uranium and radon concentrations vary from different areas. The geology of South Africa is very complex, with considerable variations in lithology consisting of sedimentary, volcanic, and metamorphic rock units. Figure 3.2 presents the geological layout of the study area and points where measurements were taken. The different rock types shown on the legend of the map contain different quantities of uranium concentration. Uranium concentration in rocks is influenced by factors such as the age and the origin of the rock.

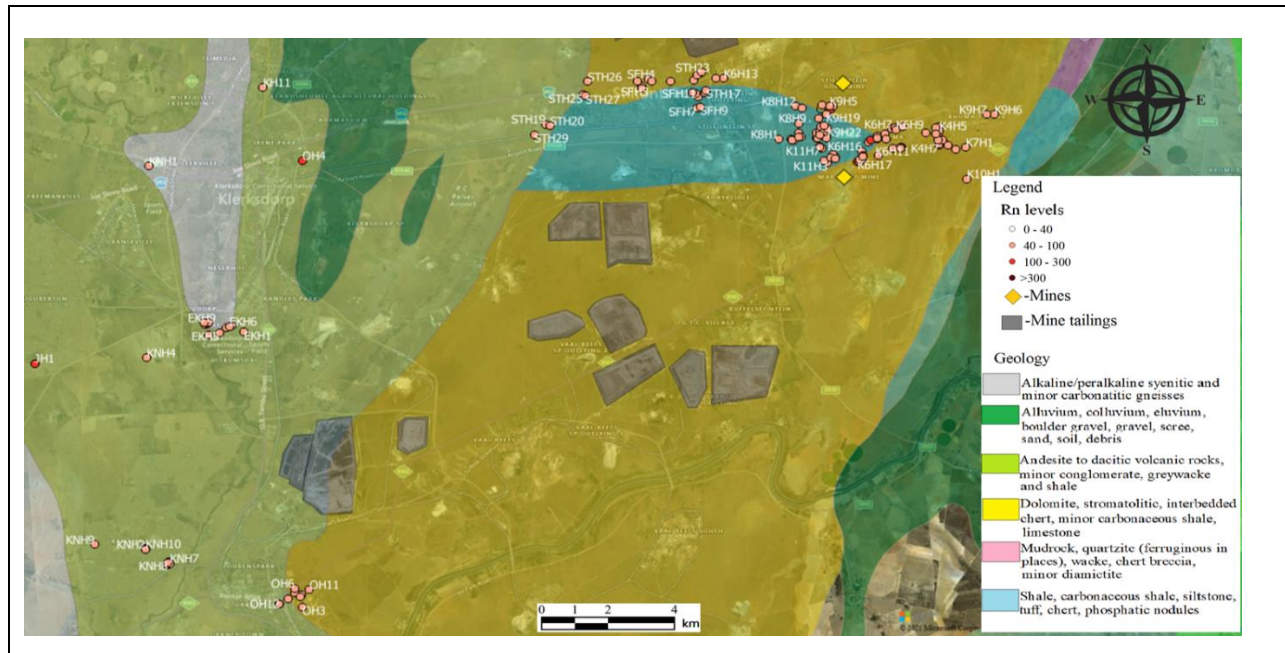


Figure 3.2. Geological layout map of the sampling points for indoor radon measurements for this study.

The rock type of each area is outlined in table 3.1, corresponding to the map in figure 3.2. According to (Bezuidenhout, 2021), sedimentary rocks contain low uranium concentration, excluding phosphate and other sedimentary rocks that originate from a parent rich in uranium. Metamorphic rocks, the “daughter rock”, have the same uranium concentration as the “parent” rock. Stilfontein and Khuma township have the same type of rocks, while Orkney Kanana, Klerksdorp, Ellaton, and Jouberton comprise the same type of rocks.

Table 3.1. Geological characteristics of the study area (rock types) (Bezuidenhout, 2021)

Area	Geology (rock type)
Klerksdorp	Andesite to dacitic volcanic rocks, Minor conglomerate, Greywacke Shale
Ellaton	Andesite to dacitic volcanic rocks, Minor conglomerate, Greywacke, Shale
Jouberton	Andesite to dacitic volcanic rocks, Minor conglomerate,

	Greywacke, Shale
Orkney	Andesite to dacitic volcanic rocks, Minor conglomerate, Greywacke, Shale
Kanana	Andesite to dacitic volcanic rocks, Minor conglomerate, Greywacke, Shale
Stilfontein	Shale, Carbonaceous shale, Siltstone, Tuff, chart, Phosphate nodules, Sandstone, Dolomite, Stromablitic, Limestone and Quartzite
Khuma	Shale, Carbonaceous shale, Siltstone, Tuff, Chart, Phosphate nodules, Sandstone, Dolomite, Stromablitic, Limestone and Quartzite

Like other parts of the Witwatersrand basin, mining activities in the KOSH region have been operational for over a century. Most of the mines in this region are still functional, while some have been liquidated. As the result of the mining activities in this area, most KOSH towns and residential areas are surrounded and engulfed by mine tailings, waste rocks, and environmental waste. The mine waste rock shown in figure 3.3. is located in the residential area in Stilfontein. Some homes and a boarding school in this area are approximately 10 m away from this waste rock. In this phase of the study, data collection was carried out in three of the four towns in KOSH; the Haartebeesfontein was not covered.



Figure 3.3. A picture of one of the mine waste rocks in Stilfontein town, near a residential area.

3.2 Instruments employed in this study

There are two types of techniques that can be used to measure indoor radon levels, the active and passive methods. The continuous active technique and detectors require electricity to work, whereas integrative, passive radon detectors do not. This study followed the long-term integrative detectors and the passive measurement technique. When radon decays into its progenies, alpha particles are emitted, and these detectors are sensitive to alpha particles and able to detect them. The solid-state nuclear track detector (SSNTD), also known as the "radon cup" or "etched track detector," is a passive method for detecting radon.

3.2.1 Solid-state Nuclear Track Detectors (SSNTDs)

The SSNTDs from PARC RGM, were used for long-term radon measurement in dwellings. These are tightly closed black cups with a top hemispheric half, made up of conductive carbon black in modified polypropylene polymer, each with a unique barcode (Figure 3.4(a)). PARC RGM reports that the detector measures approximately 43 mm in

diameter at the flat base (PARC-RGM, 2021). These contain a small solid material with a written code number as the outside cup, as shown in figure 3.2.1 (b). CR-39 is sensitive to alpha particles. A polymer of diethylene glycol bis is also known as allyl carbonate, with a chemical formula of $C_{12}H_{18}O_7$. It is also used for plastic lenses for glasses. Alpha particles from the decay of radon get into the radon cup, penetrate the CR-39 and cause a molecular path of interrupted polymer chains that are invisible. Radon atoms that enter the cup and decay inside the cup will release alpha particles that cause damage to the plastic CR39 if the alpha particle hits it. The damage to the CR39 can be seen under a microscope after etching. The lower limit of detection (LLD) for this technique for a 3-month exposure is $5\text{--}10 \text{ Bq.m}^{-3}$, depending on the size of the scanned detector area (PARC-RGM, 2021).

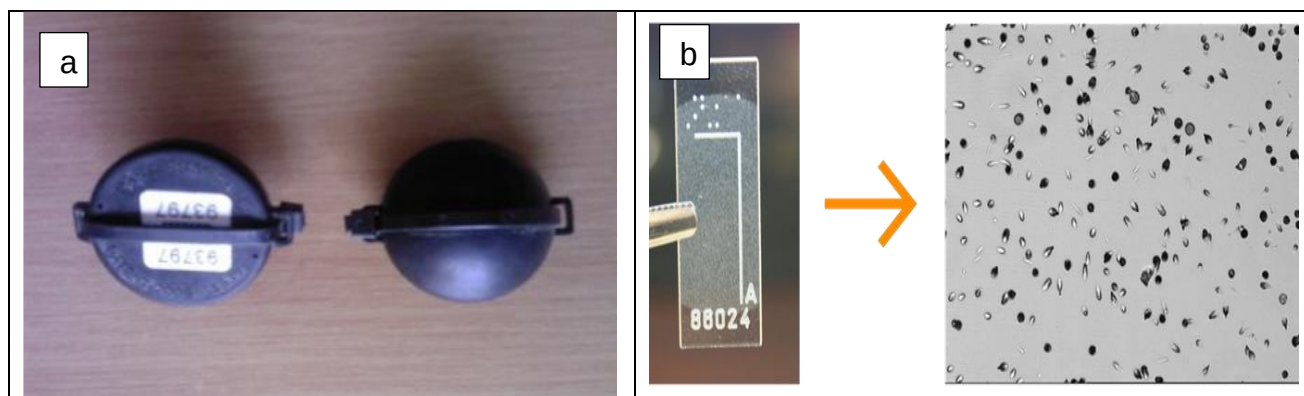


Figure 3.4. (a) PARC RGM solid-state nuclear track detector (SSNTD) and (b) alpha tracks (AT) viewed under the optical microscope (PARC-RGM, 2021).

3.2.2 Generation of maps using GIS

An open-source software called Geographic Information System (QGIS Version 3.22.xBialowieza) was used to generate the maps for this study. A shapefile (shp) layer for coordinates, radon concentration values, and geographic features was incorporated into the software. The information about the houses and schools coordinates and radon concentration levels was imported from excel files (XLS) and then converted to shapefile format in qGIS. On the other hand, the information about geographical features (geology shapefile) was downloaded from inventory information from the council for Geoscience (CGS) website. In the qGIS software, the shapefiles were overlaid over one another in

this order: geology, house and school coordinates, and radon concentration levels. In addition, the open layer plugging the software was used to incorporate google maps. The second part was to include mines and mine tailings within the region. Mines and mine tailings sites were defined from the satellite google maps, and the shapefile for mines and mine tailings were generated. Lastly, the new point composer option in the qGIS was used to output the completed maps as presented in this paper.

3.3 Survey Design and Deployment Strategy

This section discusses how the survey was conducted and where monitors were deployed. It also outlines how dwellings were selected and how consent was obtained from participants.

3.3.1 Questionnaire and Consent Form

This study was conducted voluntarily by the homeowners. Homeowners had to consent to participate in this study by allowing the deployment of detectors. The CARST Radon Team designed the consent form and questionnaire presented in Appendix F, and G. Questionnaires were given and filled in each house and workplace, where the radon monitors were deployed. The sole purpose of the questionnaire was to obtain additional information about the living habits of the home occupants and dwelling type to help in the estimation and justification of the distribution of indoor radon concentration in dwellings. Before deployment of the monitors in homes or buildings, the purpose of the study was explained to the participants. They were asked to sign a consent form as permission to deploy the radon monitors and acknowledge understanding the purpose and conditions of the study.

3.3.2 Survey design

As mentioned, this was a voluntary study conducted by going house to house, giving a brief overview of the radon and this study, then asking for consent to participate in this study by allowing monitors to be deployed in their houses. One of the challenges experienced while conducting this study is that some homeowners did not agree to the

deployment of SSNTDs in their homes. Consent forms were signed before the deployment of monitors (Appendix F) by those who agreed to participate. Long-term quantitative sampling was used for quality assurance purposes, whereby more than one SSNTD was deployed in each house or yard, which ultimately increased the sample size. Two sealed detectors were placed in each dwelling. One monitor was placed in the main living room and TV room and one in the bedroom to obtain radon concentration where people spend most of their time in the house and the average concentration level. Measurements were taken from a variety of different homes with building materials such as homes, i.e., shack, bricks, concrete, wooden floor, ceramic tiles, Plastic tile, concrete floor and concrete floor covered with carpet.

A total of 359 SSNTDs were deployed in 164 houses in the KOSH region, as shown in figure 3.5. In some areas, measurements were taken from only one dwelling because most residents did not want to participate in this study, and some houses were not accessible. In each house, two radon cups were deployed in different rooms. In some cases, one monitor was deployed. Measurements were taken for three months during all four seasons: summer (January-March), spring (October-December), autumn (March-May), and winter (June-August). The first set of measurements was conducted from October 2020 to January 2021 in 54 houses, the second set was conducted from January-April 2021 in 102 places, and the last batch was from May-August 2021 in 30 homes.

The SSNTDs measured indoor radon concentration, and the corresponding standard deviation in $\text{Bq.m}^{-3}.\text{h}^{-1}$ was converted to Bq.m^{-3} by dividing the measured concentration in $\text{Bq.m}^{-3}.\text{h}^{-1}$ with the three months exposure period in hours (2160 hrs). The corresponding annual effective dose that the occupants of each house are exposed to was calculated using equation 2.8. For the final analysis, all indoor radon measurements resulting in the first, second, and third phases (from October 2020 to August 2021) had to be combined into one database to fully evaluate the extent of indoor radon in KOSH.

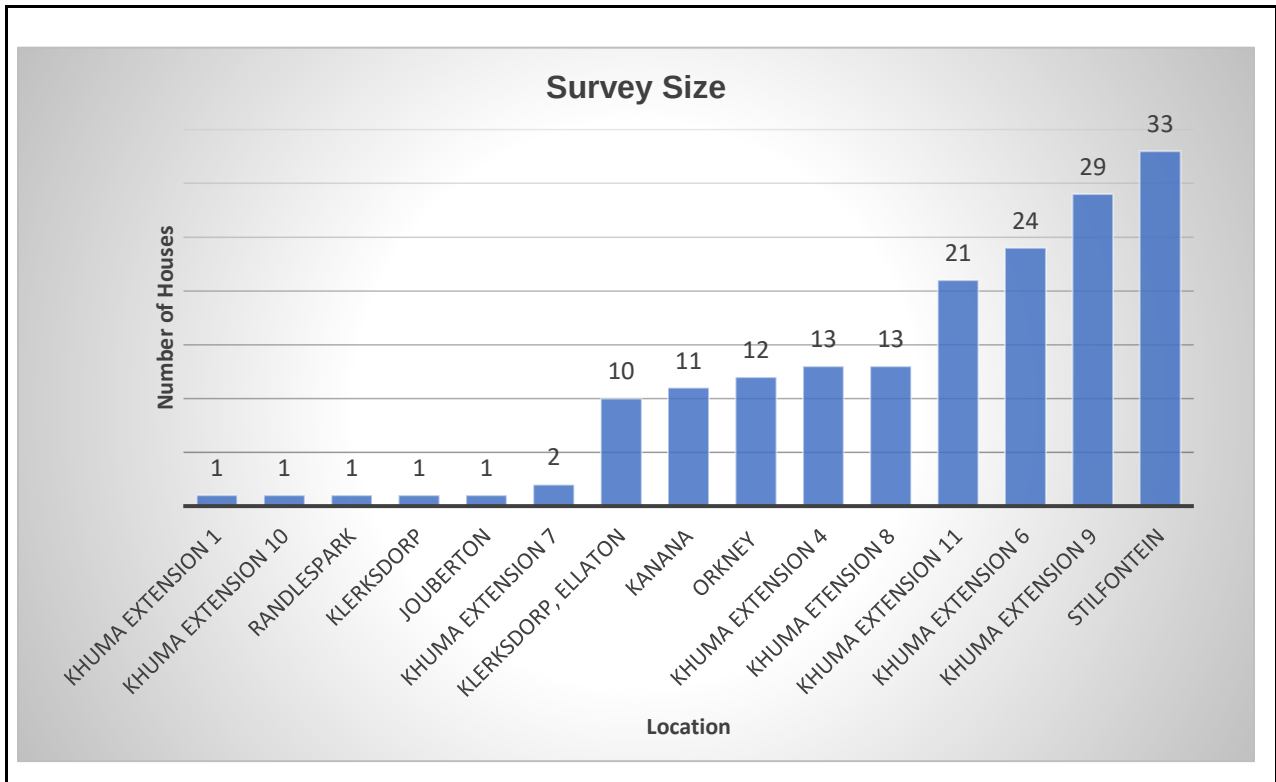


Figure 3.5: Number of selected dwellings for measurements per location.

Figure 3.6 presents survey proportion in each location from all three sets of measurements conducted in this study. More dwellings were covered in Stilfontein with 19%, followed by 17% at Khuma Extension 9, and all Extensions of Khuma Township (in Stilfontein) were covered in different proportions due to the availability of participants. Measurements from Jouberton, Klerksdorp, Randlespark, Khuma Extension 1, and Extension 7 were taken from single dwellings. Therefore, they cannot be used as an average estimate of the whole region but of a single home.

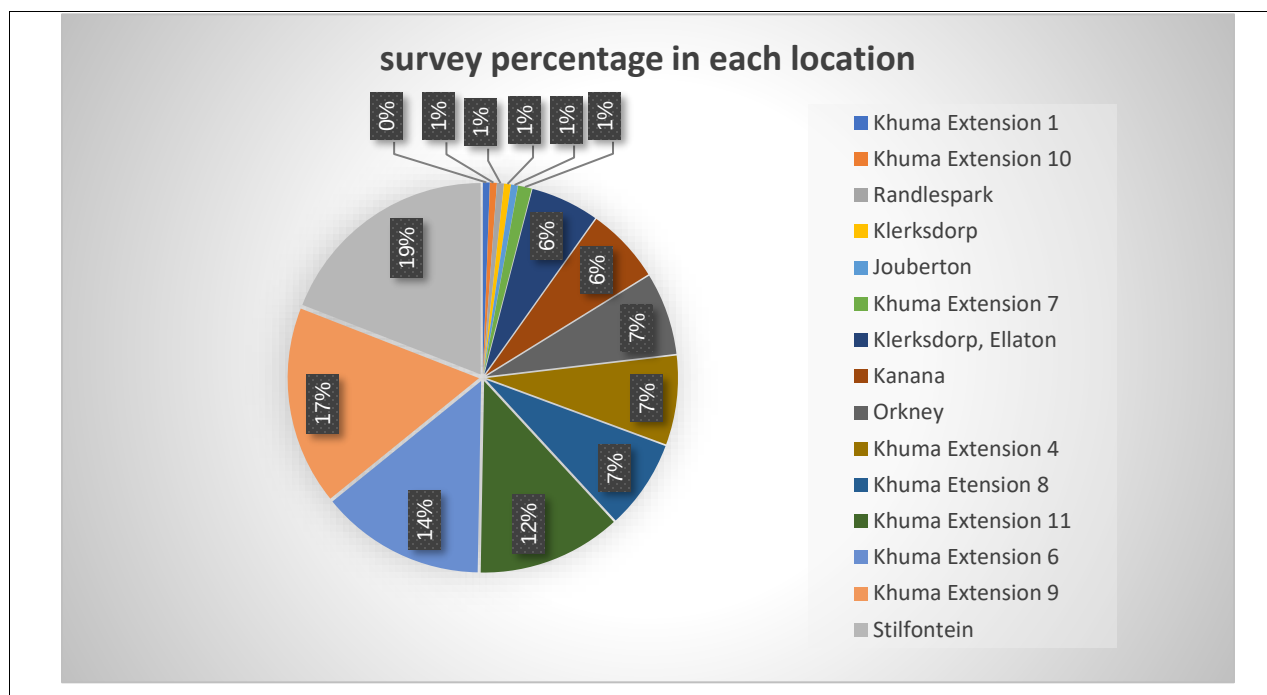


Figure 3.6. Survey size in each selected location in the KOSH region.

3.4 Survey Design and Size for Indoor Radon Measurements in Schools at KOSH

For this study, long-term measurements were conducted for indoor radon concentration levels for three consecutive months in twenty-six (26) private and public schools, both primary and high schools distributed over the KOSH region in the North West province. The study covered two (2) schools in Klerksdorp, four (4) schools in Orkney, seven (7) schools in Stilfontein, including one in the outskirts of the town, and thirteen (13) schools in Khuma township in Stilfontein. A total of fifty-two (52) radon detectors were deployed in 26 schools. Measurements were taken using solid-state nuclear track detectors (SSNTDs), also called radon cups or track etch detectors, during the summer season (December 2020- March 2021) and winter season (May-August 2021).

To obtain presentative results, quantitative and long-term measurements were conducted by deploying more than one detector in each school for three months as recommended by the IAEA (IAEA, 2013). Two radon cups were deployed in different rooms at each school, the principal's office or teacher's staff room, and one classroom; in schools where there is a ground and first floor, detectors were deployed on different floors. To obtain

information about the building, a questionnaire survey was designed to get additional information about the school building, such as how old the building is, floor type, and ventilation.

The detectors were placed 1,5 m above the ground and 1 m away from the wall to obtain representative results. Installation of the detectors was not near the door, windows, and radiators where there is excessive airflow which could affect the true radon concentration of the room. Data were collected during normal school days; therefore, the detectors were deployed in spots that cannot be easily accessible by learners to avoid loss during the measuring period.

3.5 Laboratory Analysis and Etching Process

After a three month exposure period of each set of measurements, the SSNTDs were taken to the PARC RGM laboratories in Pretoria for the chemical etching analysis process. The chemical etching method is used to analyze the SSNTDs; it is a process used to increase the visibility of nuclear tracks on the surface of the CR-39 polymer by enlarging the latent tracks. Concentrated sodium hydroxide (NaOH) solution is used to etch the CR-39 element to make the nuclear tracks visible under the optical microscope. The alpha tracks are observed as black holes when the CR-39 element is illuminated from the back. The counting of the alpha tracks was done by a computerized MIAM and the track analysis (TASL) systems, driving the mechanical stage and the optical microscope. The number of the alpha tracks is directly proportional to the indoor radon concentration (PARC-RGM, 2021).

3.6 Quality Assurance of the Instruments

According to PARC RGM, detectors are sent for calibration at the United Kingdom, Germany, or Italy facilities. In South Africa, the calibration of the detectors is done at the new Calibration Laboratory constructed at the National Metrology Institute of South Africa (NIMSA). Furthermore, participating in the inter-laboratory comparison testing conducted by Public Health England serves as a quality assurance measure (PARC-RGM, 2021).

Chapter 4: Results and Discussion

4 Introduction

Chapter 4 presents results obtained from long-term indoor radon measurements conducted in private dwellings and public buildings in Klerksdorp, Orkney, and Stilfontein in the KOSH region. The chapter is divided into two main sections, sections 4.1 and 4.2. Section 4.1 presents and discusses the results of measurements carried out in homes, and section 4.2 deliberates on findings made from public buildings mainly comprising schools under the Meepong circuit. Results are presented in graphs, tables, and calculations of the annual effective dose due to radon inhalation. Average values are given as mean $\pm$ standard deviation throughout this paper.

4.1 Overview of Indoor Radon measurements in private dwellings

The three tables (table 4.1, 4.2, and 4.3) below present results obtained from the three sets of measurements taken from private homes during all four seasons from October 2020 to August 2021. Indoor radon measurements were taken from 54, 102 and 30 selected houses during the first, second, and third set of data collection, respectively, in Stilfontein, Khuma, Orkney, and Kanana, Klerksdorp, Ellaton, and Randle spark.

Figure 4.1 below depicts an overview of the average radon level distribution in this study, and it also shows that most measurements were conducted in Stilfontein and Khuma township. Compared to other areas surveyed in this study, Stilfontein and Khuma (extensions 1, 4, 6, 7, 8, & 9) are surrounded by closed mine shafts, tailings dams, metal scrap yards, mining water treatment facility, and piled up waste rocks near homes and schools. The map also shows that the highest point of radon concentration was observed in Khuma township; the surrounding mine tailings could highly influence the elevated indoor radon concentration levels as a study on the impact of mine tailings conducted in Krugersdorp area showed higher levels of indoor radon in areas near gold mine tailings (Moshupya et al., 2019)

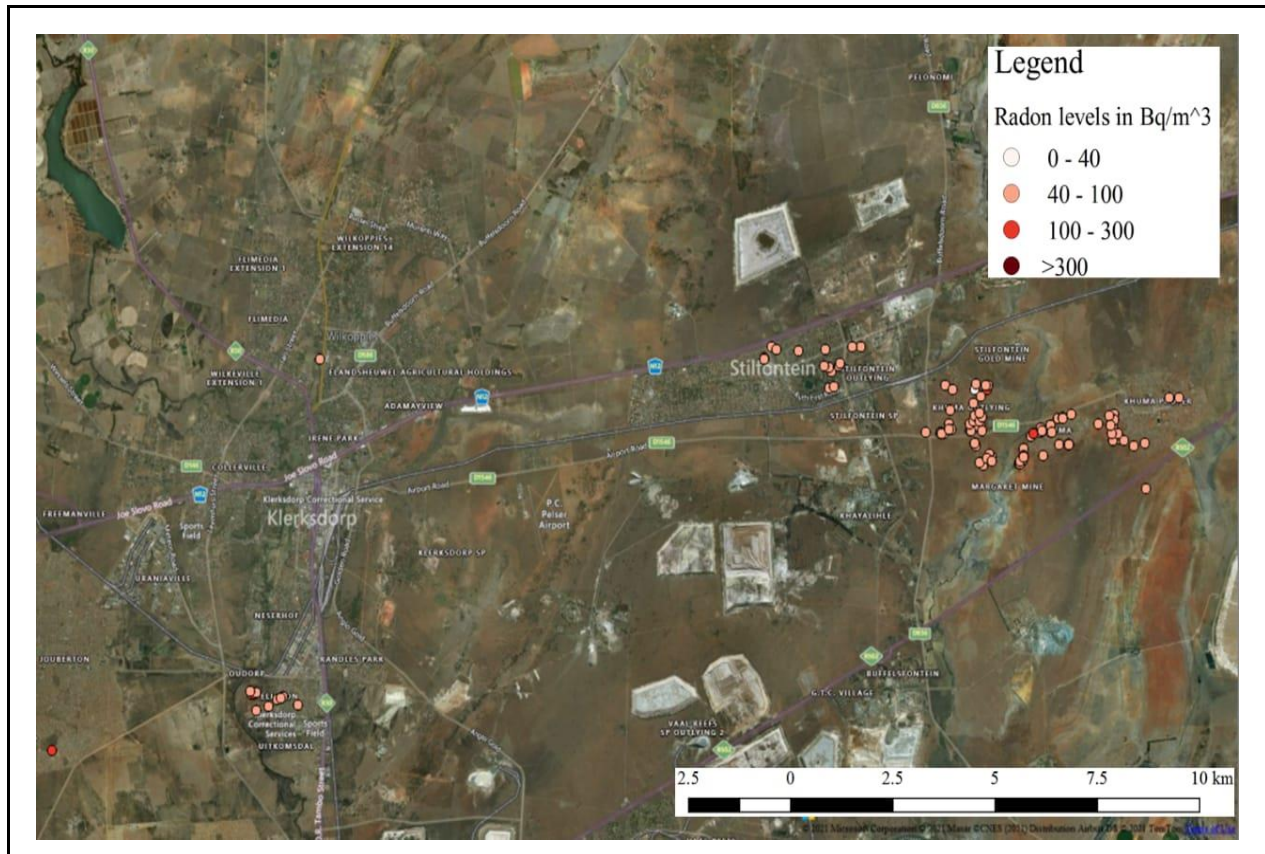


Figure 4.1. Satellite map of the study area and points of indoor radon measurements.

4.1.1 The first set of indoor radon measurements

Average indoor radon concentration levels and the corresponding annual effective dose of the first data set are presented in table 4.1. The first set of measurements was conducted in six (6) locations within the KOSH region, i.e., Stilfontein, Khuma (extension 1, 8 & 9), Orkney, and Kanana. It should be noted that Khuma Extension 1 measurements were taken from one house and, therefore, were not representative of the area. In Khuma Extension 8, SSNTDs were deployed in ten dwellings and measured a minimum of 61.57 Bq.m^{-3} and a maximum of 98.49 Bq.m^{-3} . The mean radon concentration was $71.69 \pm 12 \text{ Bq.m}^{-3}$, which exceeded the WAIRC of 40 Bq.m^{-3} suggested by the WHO (WHO, 2009b; WHO, 2010). However, these levels did not exceed the action level of 100 Bq.m^{-3} .

In Khuma Extension 9, measurements were conducted from seven (7) houses. About 90% of the dwellings recorded radon concentrations from 69.39 to 88.20 Bq.m^{-3} , except

for one home that measured the highest concentration in this study with an average radon level of 212.17 Bq.m⁻³. This dwelling is located at the outer peripheries of the area where there is a mining waste nearby, roughly 3 kilometres away. Proximity to the waste and the daily habits of the occupants such as not opening doors and windows for ventilation could be the possible source for the elevated radon concentration in this dwelling.

The first set of measurements in Orkney was conducted from eight dwellings. There was a range of 63.52 to 73.25 Bq.m⁻³ from seven houses, and only one measured an average that exceeded the action level of 100 Bq.m⁻³. All dwellings measured an average concentration level that was higher than the WAIRC.

Table 4.1 First set indoor radon concentration levels and the corresponding annual effective dose (October- January).

Location	Average indoor [Rn-222] Concentration (Bq.m ⁻³)	Annual effective dose (mSv/y)
Khuma Extension 1	97.69± 8.09	2.46
Khuma Extension 8	71.69±12	1.81
Khuma Extension 9	96.28± 14.49	2.43
Stilfontein	78.78± 17.09	1.99
Orkney	73.89± 12.22	1.86
Kanana	87.81± 13.65	2.22

The first set of measurements in Stilfontein was conducted in seventeen (17) dwellings. The average concentration levels ranged from 65.08 to 94.46 Bq.m⁻³. The small variation in these measurements indicated that the geology of the areas could be the common predictor of indoor radon in these dwellings; also, during spring and autumn, windows and doors are open most of the time, allowing airflow to reduce the accumulated radon. All measurements did not exceed the action level of 100 Bq.m⁻³ but exceeded the WAIRC of 40 Bq.m⁻³.

In Kanana township close to Orkney, measurements were conducted from 11 dwellings. Three houses in this area recorded average radon concentration levels of 123.88, 103.12, and 103.02 Bq.m⁻³, which are above the WHO action level of 100 Bq.m⁻³. The rest

recorded concentration levels between 59.13 Bq.m^{-3} to 96.49 Bq.m^{-3} . Figure 4.2. shows that Khuma extensions 1, 9, and Kanana measured the highest concentration levels (in that order). However, Extension 1 does not represent the whole area; therefore, Khuma Extension 9 has the highest concentration level that could be taken as a good estimate of the indoor radon concentration level of the area. Complete data for the first set of measurements is presented in Appendix A.

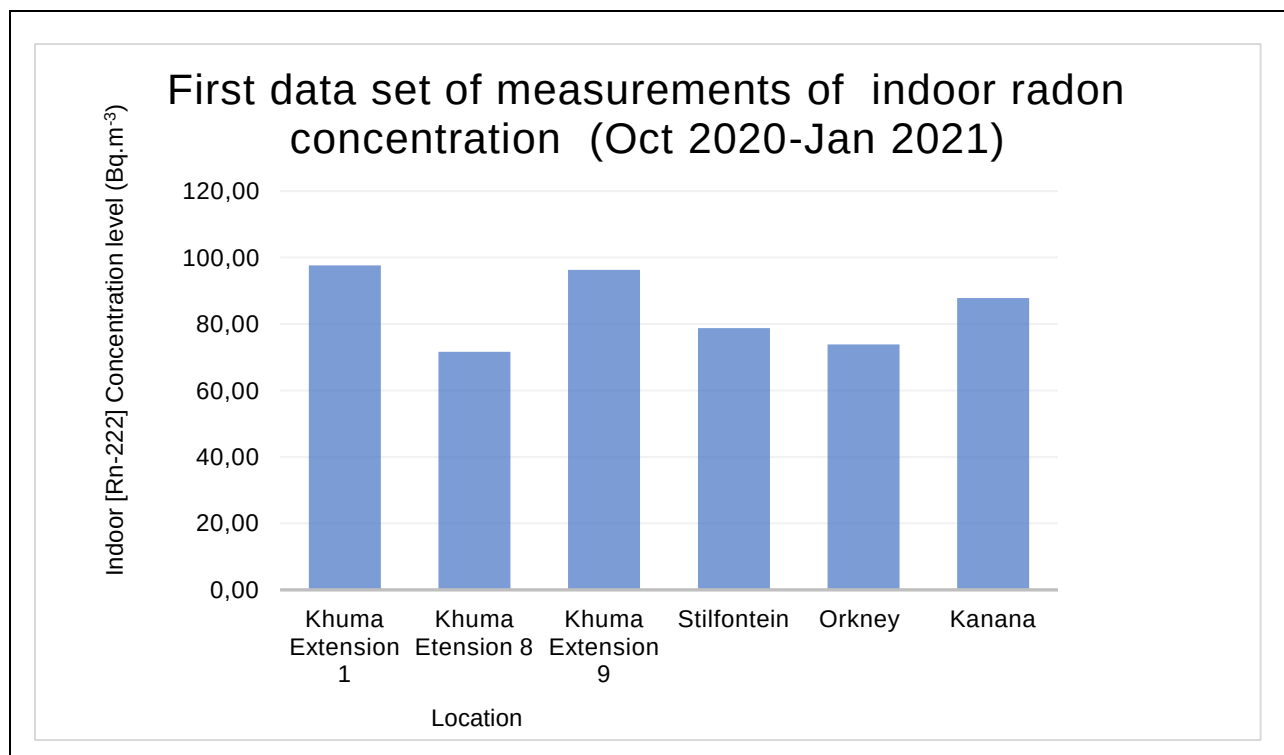


Figure 4.2. First set of indoor radon measurements during the spring and summer seasons (October 2020 – January 2021).

4.1.2 The second set of indoor radon measurements

For the duration of this study, measurements from Jouberton, Khuma Extension 7, 10, and Klerksdorp were collected from a single measurement point (home) in each of these areas. Therefore, the results in table 4.2. are not representative of the entire area. Khuma is a big township divided into sections covered in the second data collection of this study. The results in table 4.2. presents the average radon concentration of each location. Most of the houses selected for this study in Khuma township were RDP (Reconstruction and Development Programme) government houses. They have similarities because they are

built from the same building materials, size, and floor type (concrete, PVC tiles, and carpet). The geological characteristics of Khuma are also similar, as shown in Figure 4.4. however, the radon concentration levels were different due to the factors such as the ventilation of each dwelling. The concentration in this area had a wide variation with no specific trend. The minimum indoor radon concentration of 49.73 Bq.m^{-3} was measured in Extension 4, and the maximum concentration of $85.26 \pm 13.8 \text{ Bq.m}^{-3}$ was measured in Extension 11. These results indicate that the radon levels cannot be attributed to the geology of the area only; other factors that influence the accumulation of radon should be considered.

Table 4.2. Second, set indoor radon measurements during the summer season (January-April 2021).

Location	Average indoor [Rn-222] Concentration (Bq.m^{-3})	Annual effective dose (mSv/y)
Khuma Extension 4	49.74 ± 9.8	1.25
Khuma Extension 6	83.63 ± 13.38	2.11
Khuma Extension 7	49.84 ± 9.74	1.26
Khuma Extension 8	50.65 ± 9.83	1.28
Khuma Extension 9	50.78 ± 9.81	1.28
Khuma Extension 10	81.78 ± 13.08	2.08
Khuma Extension 11	85.26 ± 13.8	1.97
Klerksdorp	85.39 ± 13.51	2.15
Klerksdorp, Ellaton	71.00 ± 11.91	1.79
Stilfontein	83.38 ± 13.19	1.94
Orkney	45.36 ± 9.27	1.14
Jouberton	116.33 ± 15.56	2.93

The average annual effective dose ranged from 1.25 to 1.97 mSv from Khuma extensions 4 and 11. The annual effective doses exceeded one (1) mSv recommended by the ICRP for the public (Harrison and Marsh, 2020). Due to the public's scepticism and unavailability of voluntary participants, few measurements were made in some areas. In Extension 7, data was collected from two dwellings; the average of the two houses was 53.38 Bq.m^{-3} and a corresponding average annual effective dose of 1.35 mSv.

In Extension 8, the concentration ranged between 44 and 57 Bq.m⁻³ with an average of 50.65 Bq.m⁻³, below the action level of 100 Bq.m⁻³. However, they all exceeded the WAIRC. The corresponding annual effective dose of 1.28 mSv was above the 1 mSv recommended by the ICRP for the public.

The average radon concentration in Khuma Extension 9 was close to Extension 8. Data were collected from 18 dwellings at Khuma Extension 9 during the second set of measurements, with seventeen homes having average concentrations ranging from 41.70 to 64.34 Bq.m⁻³ and only one home with an average of 30.96 Bq.m⁻³, the only dwelling with a concentration below the WAIRC of 40 Bq.m⁻³. Results showed that all homes from Khuma Extension 9 had concentration levels below the action level of 100 Bq.m⁻³, recommended by the WHO, and the reference level of 300 Bq.m⁻³ recommended by ICRP and WHO (WHO, 2009a; Harrison and Marsh, 2020)

Khuma Extension 11 measured an average of 85.26 ± 13.8 Bq.m⁻³, which is the area that measured the maximum average concentration in the whole of Khuma Extensions and the second set of measurements. The obtained data shows that 80% of the dwellings at Extension 11 ranged from 81.01 and 98.08 Bq.m⁻³. One home measured a minimum average of 53.24 Bq.m⁻³, and another recorded the highest average concentration of 101 Bq.m⁻³ which was slightly above the action level of 100 Bq.m⁻³. The average radon concentration at extension 11 was below the upper limit of 300 Bq.m⁻³ and lower limits of 100 Bq.m⁻³ recommended by the NNR (Pule and Speelman, 2015).

Figure 4.3 shows a clear distribution of indoor radon levels in different areas. From the figure, it was observed that Jouberton measured the highest. However, since this level does not estimate the radon level of the area, Khuma Extension 6 was the highest measured radon level gave an estimation of the indoor radon level on the area. All measurements from these dwellings exceeded the WAIRC.

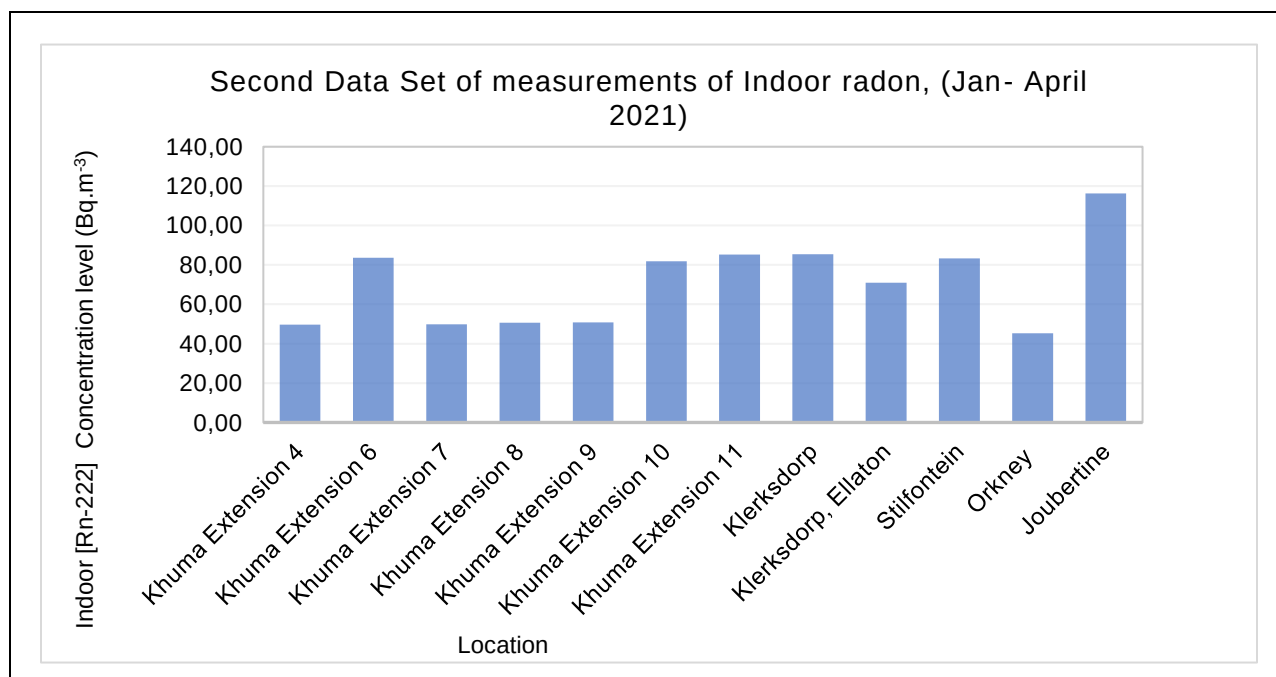


Figure 4.3. Average Indoor radon concentration levels during the summer season (January – April 2021).

Measurements were taken from 10 dwellings at Ellaton, Klerksdorp. Radon concentration ranged from 42.10 Bq.m⁻³ to 103 Bq.m⁻³ with a mean of 71.00 ± 11.91 Bq.m⁻³. Only one house exceeded the action level of 100 Bq.m⁻³. Four houses on the same street were very close to each other, ranging between 91.30 Bq.m⁻³ and 91.83 Bq.m⁻³. These trends showed that the source of indoor radon in this street was the same; also, the lifestyle of the occupants was more likely the same. Most of the houses in this area had cracked walls, which resulted from tremors they experienced due to mining activities in the area. The cracked walls and floors were one of the entry mechanisms of radon into dwellings, suggesting that the cracked walls in this area were an influencing factor.

One measurement was taken from a guesthouse in Klerksdorp. The obtained results were in the same range as Ellaton, with an average of 85.39 Bq.m⁻³ and a corresponding annual effective dose of 2.15 mSv, which exceeds the 1 mSv recommended by ICRP.

The second measurements in Orkney were conducted from only four dwellings, which ranged between 39.98 Bq.m⁻³ and 50.69 Bq.m⁻³. The concentration levels of 42.04 and 39.98 Bq.m⁻³ were measured from the first floor of the same building. The closeness of these results showed a clear suggestion that the source of radon was the same in these two dwellings.

Figure 4.4 below shows the distribution of SSNTDs within the KOSH region during the first and second sets of measurements and the underlying geology of where detectors were deployed. The measurement points presented in this map correspond to the average of each dwelling, as illustrated in Appendix B. The map presented in figure 4.4 showed that Stilfontein and Khuma are closer to former mine shafts, mine tailing dams and waste rocks. Stilfontein and Khuma Extensions 6, 7 and 11 are less than 10 km away from closed shafts of the Buffelsfontein mine. Moreover, Stilfontein residential areas and Khuma Extension 9 are near mine waste rocks.

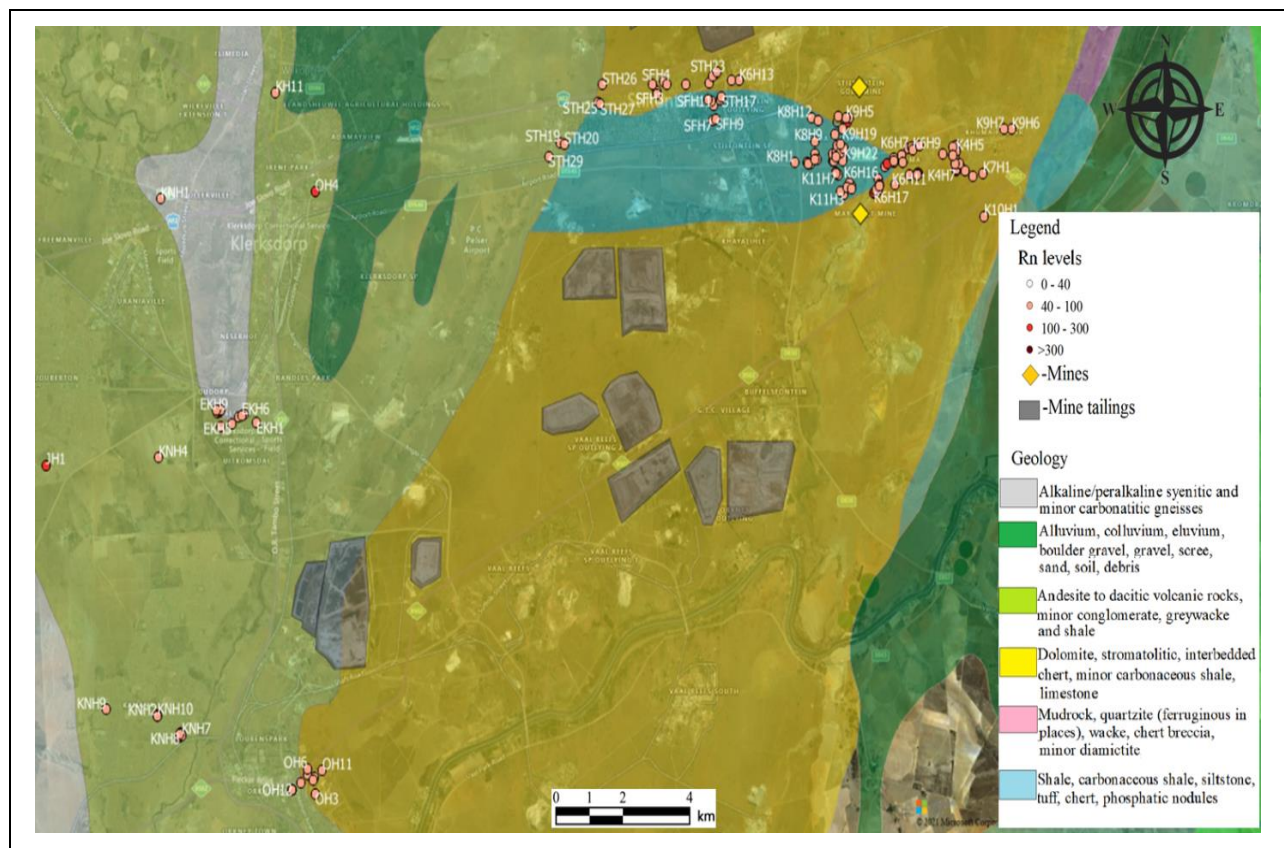


Figure 4.4. The geological layout of first and second data sets measurements points conducted during summer and spring seasons.

4.1.3 The third set of indoor radon concentration measurements during the winter season.

The third set of measurements was conducted during the winter season from June-August 2021. The data collection and sampling were the same as those followed for the spring and summer months. Measurements were collected from twenty-eight (28) houses in seven (7) different locations within the KOSH region. To be noted, measurements in Klerksdorp, Randlespark, and Ellaton were taken from single homes in each area. Therefore, the presented average concentration in table 4.3 did not represent the two areas.

A minimum indoor radon concentration of 76.36 ± 12.48 Bq.m⁻³ with a corresponding annual effective dose of 1.93 mSv/y was measured in Orkney. A maximum indoor radon concentration of 108.84 ± 14.53 Bq.m⁻³ with a corresponding annual effective dose of 2.75 mSv/y was measured at Khuma Extension 9, making it an area with the highest average of indoor radon concentration levels during the winter season, as presented in Table 4.3. All winter measurements exceeded the world average of 40 Bq.m⁻³, and the public's recommended annual dose of 1 mSv. About 50% of the selected areas exceeded the radon concentration level of 100 Bq.m⁻³, the lower limit advised by the NNR (Pule and Speelman, 2015) and recommended by WHO (WHO, 2016). However, they were all below the upper limit of 300 Bq.m⁻³.

Table 4.3. Indoor radon Measurements results during the winter season.

Location	Averaged Indoor Radon Concentration (Bq.m ⁻³)	Annual Effective Dose (mSv/y)
Ext 4	77.41 ± 12.59	1.95
Ext 6	72.99 ± 12.13	1.84
Ext 9	108.84 ± 14.53	2.75
Orkney	76.36 ± 12.48	1.93
Stilfontein	85.97 ± 12.14	2.17

Klerksdorp	104.53±15.36	2.64
Ellaton	104.59±15.37	2.66
Randle spark	180.89±24.54	4.56

Figure 4.5 shows measurements points for the winter season. Winter measurements were conducted from fewer dwellings than in other seasons due to the availability of participants. Figure 4.4 also shows that the geology of the measured points is the same as in the first and second sets, as shown in Appendix C. The elevated indoor radon concentration in Randlespark, Ellaton and Klerksdorp represents one dwelling in each area during the winter measurements. It cannot be taken as an estimated average radon concentration of the whole area. Randlespark and Ellaton are both suburbs of Klerksdorp, with the same geological layout as Klerksdorp as shown in figure 4.5; this explains the elevated radon concentration of $180.89 \pm 23.09 \text{ Bq.m}^{-3}$, $104.53 \pm 14.58 \text{ Bq.m}^{-3}$ and $104.59 \pm 15.37 \text{ Bq.m}^{-3}$ in Randle spark, Klerksdorp, and Ellaton respectively.

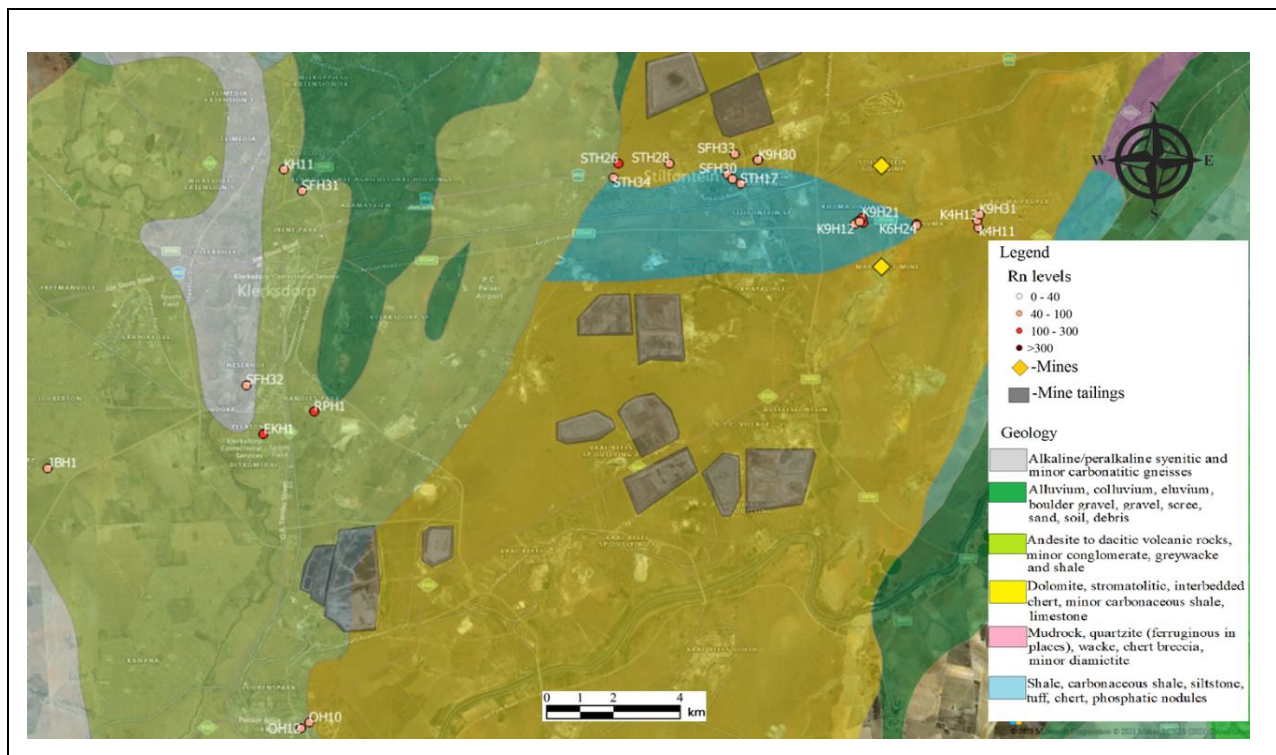


Figure 4.5. The geological layout of winter measurements points.

4.1.4 Factors influencing indoor radon concentration levels

Some factors influence the concentration level of indoor radon, as indicated in the literature. The following characteristics were highlighted:

4.1.4.1 Building type

Some building materials contain a trace number of NORMs (uranium, potassium, and thorium); in this regard, uranium is the source of indoor radon (Wentzel, 2018). In this present study, data were collected from different types of buildings. However, the presence of NORMs in the building material was not studied. Out of 255 selected houses, ten (10) houses were shacks (built with aluminium steel). Radon levels in these dwellings differed from those in brick and concrete homes. Table 4.4 presents the measured radon concentrations from the Shack dwellings in Khuma. the results show no trend and they are not higher or lower than the bricks buildings, they are all within the same range.

Table 4.4. influence of shack dwellings on indoor radon concentration levels.

Location	Indoor Radon Concentration Average (Bq.m ⁻³)	Number of Houses
Khuma Extension 6	70.54 ±12.63	5
Khuma Extension 8	68.09± 11.52	2
Khuma Extension 9	60.54±10.91	2
Khuma Extension 10	81.7±13.03	1

Furthermore, the use of soil from the mines to build houses in Khuma is one of the primary sources of indoor radon in Khuma. This soil is the mine waste, which still contains traces of some elements, including uranium, the primary source of radon. The soil is broken down into smaller sizes, and some of it is used to make bricks sold for building purposes.

Another factor influencing the accumulation of radon in dwellings is the building size or dwelling size. Most homes in Khuma township are generally smaller than those at other study area locations. Radon levels in Tables 4.1. and 4.2 showed that Khuma had higher indoor radon concentrations; this indicates that the size of dwellings in Khuma may have

affected the radon concentration. Homes with bigger space have a higher chance of reducing radon gas by distributing radon and allowing gas to flow out of the building. Smaller spaces accumulate radon quickly, and the flow of radon is not enough to reduce the accrued radon (Noha et al., 2019).

4.1.4.2 Floor-type

Radon moves through the floor from the sub-floor into the building; therefore, different floor types influence the accumulation of radon in a building. Studies such as these (Lindsay et al., 2008; Leuschner et al., 1991) have shown that wooden floors measured higher radon concentrations than other floor types. In this study, 13% of the houses had wooden floors. Table 4.5 presents all measurements from twenty (20) wooden floor houses taken from different locations within KOSH during the Summer and Spring months. Results presented in Table 4.5 are not higher than those from the solid concrete floor, where the maximum concentration was $75.76 \pm 12.44 \text{ Bq.m}^{-3}$, from Stilfontein, and a minimum of $46.33 \pm 9.37 \text{ Bq.m}^{-3}$ from Khuma Extension 4. Therefore, it is clear that wooden floor as the bridge media did have much influence on the accumulation radon dwelling in this study.

In Khuma Extension 6, the maximum indoor radon concentration of $120.84 \pm 17.01 \text{ Bq.m}^{-3}$ was measured from a house with no floor covering; there was just soil. This highest concentration was expected because there was no barrier preventing radon directly from the soil. This agrees with what was indicated in the (Leuschner et al., 1991) study.

Table 4.5. Indoor radon concentration levels in dwellings with wooden floors.

Location	Average Indoor Radon Concentration (Bq.m^{-3})	Number of Houses
Stilfontein	75.76 ± 12.44	12
Ellaton	66.89 ± 11.49	2
Orkney	62.07 ± 10.90	2

Khuma Extension 4	46.33±9.37	2
Khuma Extension 6	83.67±13.46	1
Khuma Extension 9	53.77±11.21	1

4.1.4.3 Geological characteristics

One of the indoor radon entry mechanisms into a building is soil emanation, as shown in Figure 2.3 discussed in Chapter 2. Radon accumulates in the underground spaces and is found at a higher concentration level, which presents a source of indoor radon. Figures 3.2 and 4.4 show the geological layout of KOSH; this gives a clear layout of the rock and soil type in the study area.

Figure 4.6. illustrates the types of South African rocks with uranium content. The results in this figure were obtained from the Council of GeoScience South Africa for a study by J Bezuidenhout (Bezuidenhout, 2021). Table 3.1 presents the types of rocks in the KOSH area, as illustrated in Figure 3.1, which shows the geological layout of the study area. These bits of information indicated that the rocks in Stilfontein and Khuma are similar, with a minimum uranium concentration of 0.1 ppm from the charted rock and a maximum of 23.0 ppm from the carbon rock. Klerksdorp (including Ellaton) Orkney (including Kanana) all have similar rock types, with a minimum uranium concentration of 1.6 ppm from the andesite rock and a maximum of 4.6 ppm from the greywacke shale rock. Stilfontein and Khuma rocks contained higher uranium concentrations as compared to other areas. This agrees with the indoor radon results obtained in this study, which showed high radon levels at Stilfontein and Khuma. This indicates that the uranium content in Stilfontein and Khuma rocks was a source of indoor radon in dwellings.

Rock Types, Groups and Subgroups	Uranium Concentration (ppm)	Rock Types, Groups and Subgroups	Uranium Concentration (ppm)
Amphibolite	3.5	Mafic Volcanic Rocks	4.0
Andesites	1.6	Low-Grade	2.4
Anorthosite	0.2	Metavolcanic and Metasedimentary Rock	
Arenite	2.0	Magnetite	11.2
Basaltic Andesite	1.3	Marine Sediment	1.5
Basalts	0.5	Melanorite	0.1
Biotite	7.9	Melilitite	2.8
Breccia	2.4	Microgranite	3.6
Calc-Silicate Rocks	0.1		
Carbonatite	23.0	Migmatite	0.9
Charnockite	1.8	Monzodiorite	8.1
Chert	0.1	Monzogranite	4.4
Dacite	2.6	Monzonite	8.6
Diamictite	4.0	Quartz-Monzonite	12.8
Diorite	0.8	Mudstone	4.9
Quartz Diorite	6.9	Nephelinite	0.4
Dolerite	0.4	Norite	0.3
Dolomite	2.0	Miscellaneous	3.0
Dunite	0.0	Pegmatite	3.4
Eclogite	3.0	Peridotite	0.0
Enderbite	0.4	Phoscorite	11.2
Felsite	8.4	Phyllite	1.9
Fenite	0.0	Picrite	0.8
Foyaite	33.7	Pyroxenite	0.3
Gabbro	4.2	Quartzite	0.0
Gabbro	4.2	Rhyolite	4.0
Glimmerite	0.4	Sandstone	1.8
Gneiss	1.2	Schist	2.6
Granite-Gneiss	6.0	Shale	4.6
Granite	6.0	Siltstone	5.7
Granodiorite	5.6	Slate	2.7
Biotite-Granodiorite	7.9	Syenite	7.2
Granophyre	3.6	Quartz-Syenite	12.0
Granulite	0.1	Tholeiite	1.4
Gravels	4.0	Tinguaite	22.4
Greywackes	2.0	Tonalite	0.5
Harzburgite	0.1	Trachyandesite	3.1
Hornblendite	4.4	Trachyte	11.6
Hornfels	3.6	Trondhjemite	1.2
Ijolite	3.0	Volcanic Rock	2.2
Jaspilite	4.0	Wacke	4.0
Leucogranite	4.3	Websterite	0.4
Limestone	2.0		

Figure 4.6. Uranium concentration level in different rocks found in South African (Bezuidenhout, 2021).

4.1.5 Comparison of Indoor Radon Concentrations in Different Seasons

4.1.5.1 Summer and Spring measurements

Measurements were consistently carried out in three sets three months apart in four locations. Figure 4.7 shows a comparison of two sets of indoor radon measurements carried out in different seasons. It is observed that the first set of measurements (Oct 2020-Jan 2021) has concentration levels higher than those of the second set (Jan-March 2021) in three locations; it was only in Stilfontein where the second set was slightly higher than the first set, with a difference of 2.84%. Concentration levels of the first set measurements at Khuma were higher than the second set by 21.04 Bq.m⁻³ (17.19%), Extension 9 had a variance of 45.5 Bq.m³ (30.94%), and the variance in Orkney measurements was 28.53 Bq.m⁻³ (23.92%). This trend can be explained by the difference in sample size and the number of dwellings in each set. Even though this study could not look into meteorological parameters (temperature, humidity, and air pressure) in different seasons of each set, the results indicated a possible correlation between radon concentration levels and the different seasons. This strongly supports literature, which stipulated that different season influence the indoor radon concentration levels.

The two sets of measurements were different. The average concentration levels were higher in the first set, with a minimum concentration of 61.72 Bq.m⁻³, which was not even the maximum level in the second set. The minimum concentration level in the second set was 44.56 Bq.m⁻³ with a maximum of 57.33 Bq.m⁻³, which was below the maximum concentration of the first set of measurements. This study did not focus on the influence of meteorological parameters such as temperature, humidity, and air pressure. However, some studies have shown a correlation between indoor radon concentration and these parameters. The change in the climate can then explain the variation in these measurements during the two seasons, also the ventilation since windows and doors are open most of the time.

Comparing data sets one and two of Khuma Extension 9, a decrease in the concentration level was observed. The radon concentration in the first set of measurements for the two extensions was higher than the second set. This trend was also observed in Extension 8

of Khuma. The different meteorological parameters can explain the trend in the two seasons. Studies have shown that radon concentration levels are lower during hot seasons (Maheso, 2021), this is due to high ventilation, doors and windows are open most of the time when it is hot.

The two sets of measurements from Orkney were not in the same range. Concentration levels in this first set were higher than those in the second set. It was observed that the minimum concentration (63 Bq.m^{-3}) in the first set was higher than the maximum concentration (50.69 Bq.m^{-3}) in the second set. The decrease in these measurements could also be explained by the change of climatic parameters in the two seasons.

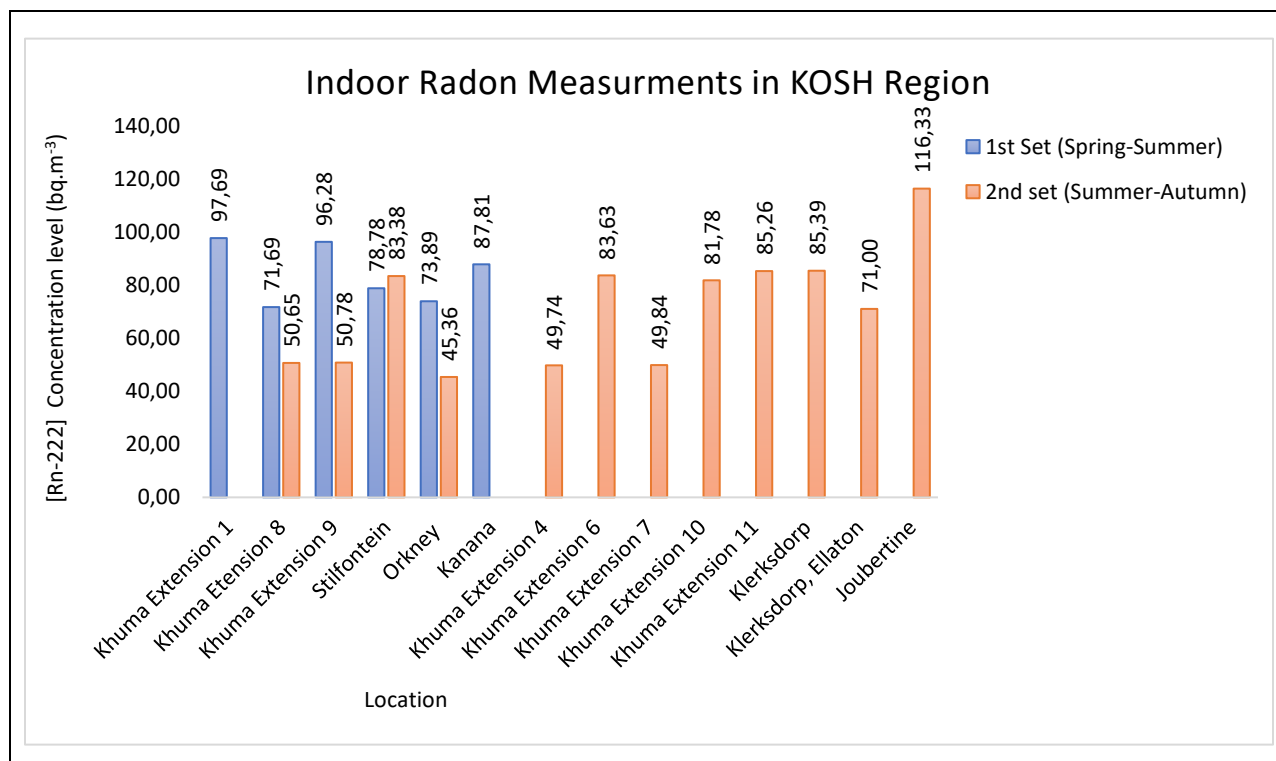


Figure 4.7. Comparison of indoor radon measurements in spring, summer and autumn.

Measurements in Stilfontein, both set one and two, did not vary despite the different seasons during which they were conducted. The consistency in the range of these concentration levels can indicate that the radon in this region was of the same source.

The variation was probably due to lifestyle factors of the occupants, such as ventilation, i.e., closing or opening of windows and doors most of the time.

The minimum measured indoor radon concentration was 38.84 Bq.m³ in Khuma Extension 6; this was the only dwelling that measured a concentration level below the WAIRC of 40 Bq.m⁻³. The minimum average indoor concentration measured in this Extension was 120.84 Bq.m⁻³ with four houses (16%) above 100 Bq.m⁻³. The results show that the average indoor radon concentration in all homes except one exceeded the WAIRC of 40 Bq.m⁻³ and four dwellings exceeded the lower limit of 100 Bq.m⁻³ as suggested by the ICRP and the NNR. However, the average concentration level of each home was well below the upper limit of 300 Bq.m³ recommended by WHO.

4.1.5.2 Spring, summer, autumn and winter measurements

Most winter measurements were taken from the same dwellings as spring and summer, and autumn. Figure 4.8 presents winter/spring and winter and summer measurements taken from the same homes. As expected, the indoor radon concentration was higher during winter than the spring and summer seasons, i.e., in 80% of the selected dwellings. Only 20%, i.e., three homes measured slightly higher concentration in summer and autumn than winter; one in Khuma Extension 6 with a difference of 1.52 Bq.m⁻³ (1.2%) and two dwellings in Stilfontein; i.e., STF#28 with a difference of 7.79 Bq.m⁻³ (4.7%) and STF#25 with a difference of 6.3 Bq.m⁻³ (4.2%). As shown in Figures 4.8 the seasonal variation of indoor radon could be justified by the change in the amount of ventilation adapted during different seasons due to weather changes. In winter, people close doors and windows most of the day to avoid getting cold. This lowers the ventilation in the house, increasing the indoor radon concentration levels.

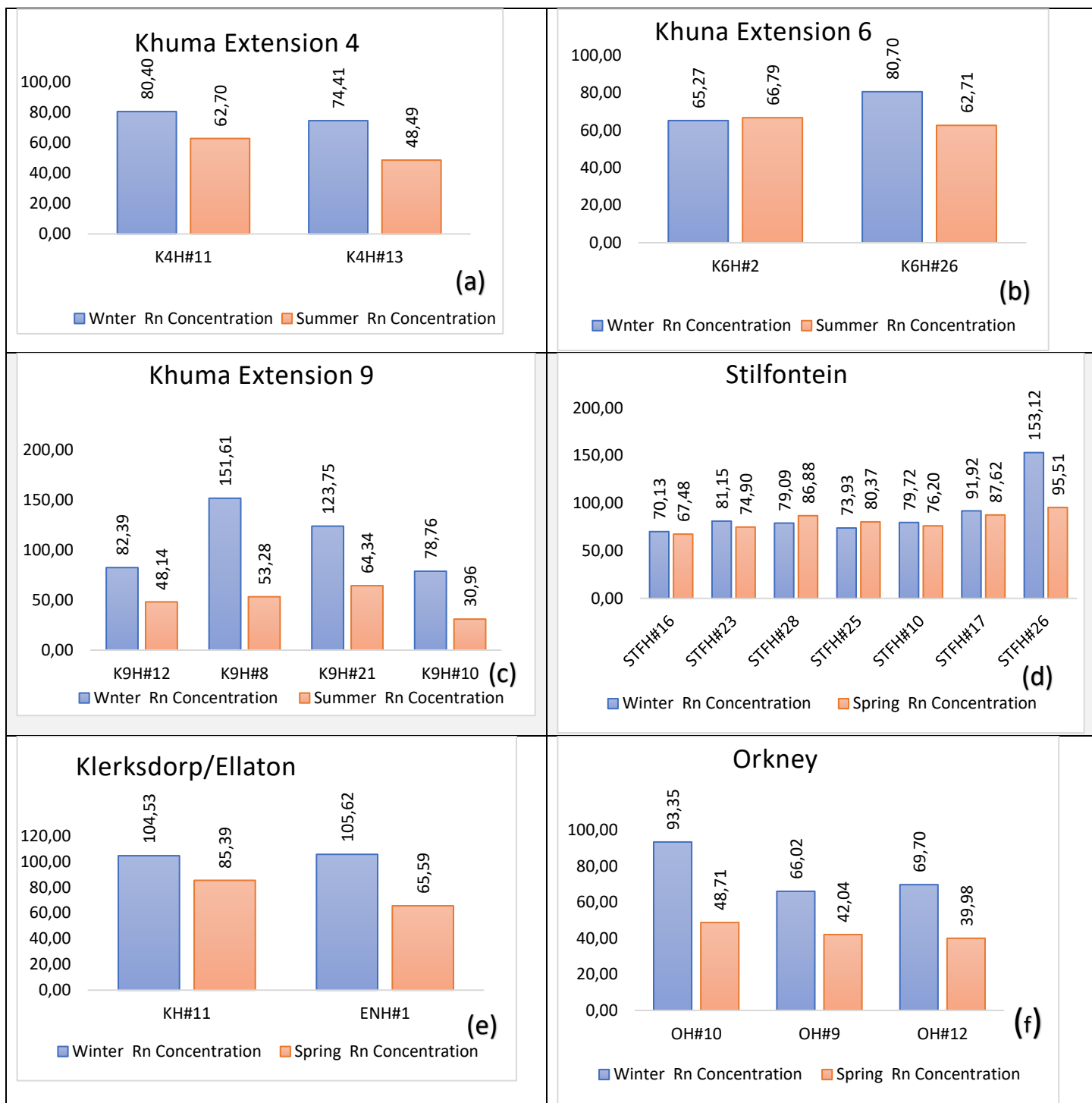


Figure 4.8. Seasonal variation of indoor radon in different private dwellings.

Figure 4.8 present the seasonal average indoor radon concentration of each area. The winter season measured higher concentrations in all areas, however, there is one dwelling at Khuma Extension 6, where radon levels are higher in summer than in winter.

This was not expected; however, it could indicate that dwellings in this area had good ventilation during winter.

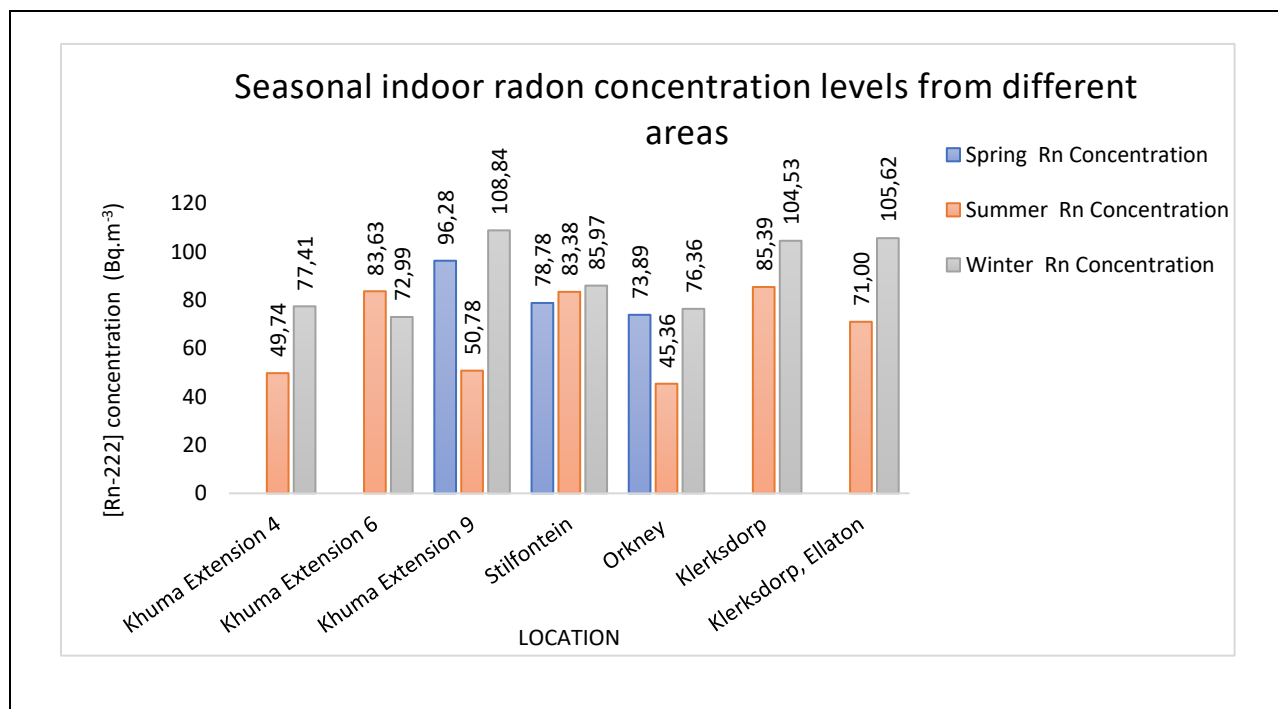


Figure 4.9. Variation of indoor radon concentration levels in three different seasons (spring, summer and autumn, and winter).

4.1.6 Average Indoor Radon Concentration Levels at KOSH Areas

Figure 4.7 presents the indoor radon measurements taken from each area within the KOSH region. The results show that the highest concentration level was 116.33 Bq.m⁻³ from a house at Jouberton Township. However, this did not represent the average concentration of the entire area since measurements were taken in one dwelling in this area. This also applied to other areas, where measurements were from one home, i.e., Khuma Extension 1 (old location), Extension 7, Extension 10, and Klerksdorp town. Kanana township constituted 8% of these results and showed the highest average concentration level of 87 Bq.m⁻³.

4.1.7 Calculated Annual Effective Dose due to Inhalation of Radon

The annual effective dose received due to inhalation of radon by the public in the KOSH region was calculated using equation 2.8. Tables 4.1, 4.2 and 4.3 present each location's average indoor radon concentration and the corresponding annual effective dose. The dose received by the public was directly proportional to the radon concentration, as observed in tables 4.1, 4.2 and 4.3. The highest effective dose of 2.46 mSv during summer and autumn measurements shown in table 4.2 corresponded to the highest radon concentration of $97.69 \pm 8.09 \text{ Bq.m}^{-3}$ in Khuma Extension 1. However, this did not represent the dose received by the public in this area because measurements were taken from only one house. The first data set collected during the summer and autumn months indicated that the population in Khuma Extension 8 received the least effective dose of 1.81 mSv/y, and those in the Khuma Extension 9 population received the maximum dose of 2.43 mSv/y.

From the second data set obtained during the spring months, the minimum effective dose received by the public was 1.14 mSv and a maximum of 2.15 mSv/y from Orkney and Klerksdorp, respectively. The calculated Jouberton dose of 2.93 mSv/y cannot represent the effective dose received by the public in this location because, in this study, data were collected from one house in this location.

The highest annual effective dose received by the public was calculated during the winter season, which ranged between 1.84 and 4.56 mSv; this was expected due to the high radon concentration measured in summer. The levels of effective dose in all selected locations did not exceed 10 mSv/y recommended for the public (UNSCEAR, 2000); however, they were all below the dose of 3-10 mSv, corresponding to the $100\text{-}300 \text{ Bq.m}^{-3}$ as recommended by the ICRP (ICRP, 2018). However, in an area such as KOSH where the ground has high levels of uranium and thorium then the gamma dose that you get may well be around 1.5 mSv per year.

4.1.8 Comparison with previous studies

One of the most extensive radon studies in South Africa, which covered all country provinces, was conducted for three years (from May 1988 to March 1991) by A H Leuschner and the team (Leuschner et al., 1991). One of the areas covered in North West is Stilfontein; the results showed an average radon concentration of 62 Bq.m^{-3} , lower than 81.08 Bq.m^{-3} measured in this study. The maximum concentration of 131 Bq.m^{-3} from that previous study was higher than the measured 104.07 Bq.m^{-3} in this current study.

In this study, the average radon concentration at Ellaton, a suburb of Klerksdorp, is 71 Bq.m^{-3} with a maximum of 103.31 Bq.m^{-3} , and a guesthouse within Klerksdorp measured a concentration level of 85.39 Bq.m^{-3} . The results from the previous study were higher than those obtained in this study. These measurements were carried out using different instruments and detection techniques; the survey size differed, and the time and meteorological parameters differed. All these factors contributed to the variation of the obtained results.

4.2 Indoor Radon Measurements in Schools

Indoor radon measurements were conducted in twenty-six selected schools within the KOSH mining region. A summary of all measurements is presented in Table 4.10, while the distribution of radon is described in Figure 4.10. The selected schools had different floor types, brick types, and classroom sizes. They were all built with bricks; however, the types of bricks were different. Only two schools had a wooden floor, nine schools had plastic tile, ten schools had a ceramic tile, and only four had concrete and carpet.

4.2.1 Indoor Radon Measurements at Schools during the summer season

As observed in table 4.6, radon concentration levels in schools had a lot of variation and showed no specific trend in the obtained results from different locations. This can be due to various factors that influenced the radon concentration levels, such as ventilation systems in different schools, the type of building, the geology of the location, and the underlying soil and rock type. Radon concentration levels were distributed widely and ranged from 18.06 ± 4.63 to $154.96 \pm 20.48 \text{ Bq.m}^{-3}$. In more than half of the measured schools (50%), the radon concentration was above the WHO, and ICRP recommended

level of 100 Bq.m⁻³. All measurements were below the 300 Bq.m⁻³ reference level recommended by the NNR. Eighty-eight percent (88%) of the schools were above the world average indoor radon level of 40 Bq.m⁻³. Only three schools were below the world average. Appendix E shows all measured and calculated results from schools.

Table 4.6. Indoor Radon Concentration levels during summer and winter seasons in schools

	Summer and autumn			Winter	
Location	School Code	Average indoor [Rn-222] Concentration (Bq.m ⁻³)	Annual Effective Dose(mSv)	Average indoor [Rn-222] Concentration (Bq.m ⁻³)	Annual Effective Dose(mSv)
Khuma	SHL #1	88.65±13.74	0.45	162.08 ±21.19	0.82
Khuma	SHL#2	105.43±15.45	0.53	210.86 ±26.11	1.06
Khuma	SHL#3	91.18 ±14.00	0.46	111.81 ±16.10	0.56
Khuma	SHL #4	109.51±15.87	0.55	161.63 ±21.14	0.82
Khuma	SHL#5	125.87±17.53	0.64	178.25 ±22.82	0.90
Khuma	SHL#6	139.09±18.88	0.70	185.56 ±23.56	0.94
Khuma	SHL#7	94.05±14.29	0.47	143.43 ±19.31	0.72
Khuma	SHL#8	106.14±15.53	0.54	187.16 ±23.72	0.94
Khuma	SHL#9	154.96±20.48	0.78	319.49 ±37.02	1.61
Khuma	SHL#10	104.44±15.36	0.53	160.52 ±21.03	0.81
Khuma	SHL#11	108.02±15.72	0.55	160.15 ±21.00	0.81
Khuma	SHL#12	125.37±17.48	0.63		
Stilfontein	SHL#13	85.98±13.48	0.43	142.12 ±19.36	0.72
Stilfontein	SHL#14	105.80±15.50	0.53	143.99 ±19.36	0.73
Stilfontein	SHL#15	90.54 ±13.93	0.46	129.70 ±17.92	0.65
Stilfontein	SHL#16	113.85 ±16.32	0.57	184.29 ±23.43	0.93
Stilfontein	SHL#17	92.60 ±14.14	0.47	89.32 ±13.81	0.45
Stilfontein	SHL#18	103.04 ±16.21	0.52	140.49 ±19.05	0.71
Baffeldorn, Stilfontein	SHL#19	97.03 ±14.60	0.49		
Stilfontein	SHL#20	88.04 ±13.68	0.44	164.42 ±21.43	0.83
Orkney	SHL#21	109.56 ±15.86	0.55		
Orkney	SHL#22	20.83 ±6.48	0.11		
Orkney	SHL#23	23.15 ±6.48	0.12	83.83 ±13.25	0.42
Orkney	SHL#24	18.06 ±4.63	0.09		
Klerksdorp	SHL#25	138.11 ±18.78	0.70	164.13 ±21.40	0.83
Klerksdorp	SHL#26	102.03 ±15.11	0.51	161.85 ±21.17	0.82

The geological layout of the schools is similar to the geology of private homes, as shown in figure 4.10; this is because the schools and homes are in the same area. Radon levels in schools cannot be directly compared to home. However, it is observed that the radon concentration levels have a significant difference; concentration levels at schools are higher than in homes due to factors such as ventilation of the building, schools are closed more often than private homes. Schools open on working hours from 07:00 to 15:00 Monday to Friday; then they are closed for the rest of the day and on weekends. This increases the chances of indoor radon buildup. Studies have shown that low ventilation in schools contributes to the accumulation of radon in schools since they are closed for extended periods (Rosabianca et al., 2010; Mallah, 2013).

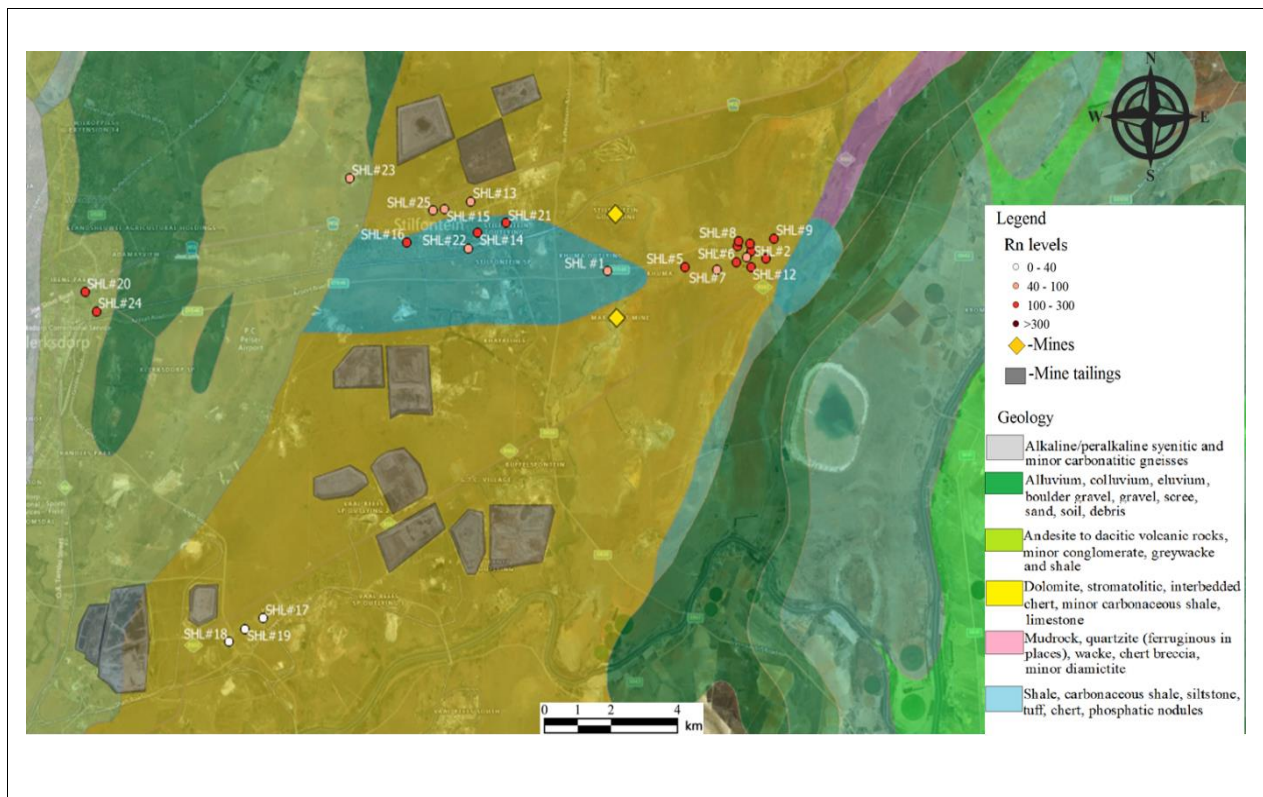


Figure 4.7. The geological layout of measurements in schools during summer and autumn.

4.2.2 Winter Measurements of indoor Radon at Selected Schools

Winter measurements were conducted at 21 schools within the KOSH region. The results in Table 4.6 showed that during winter, 80% of the schools measured concentration

exceeding the lower limit of 100 Bq.m^{-3} , suggested by the NNR and recommended by WHO. Only two schools measured a concentration below 100 Bq.m^{-3} ; one school was in Orkney with a concentration of $83.83 \pm 23.25 \text{ Bq.m}^{-3}$ and another in Stilfontein with a concentration of $89.32 \pm 18.81 \text{ Bq.m}^{-3}$. In winter, the indoor radon concentration ranged from $83.83 \pm 23.25 \text{ Bq.m}^{-3}$ to $319.49 \pm 37.02 \text{ Bq.m}^{-3}$, exceeding the lower and upper limits recommended by WHO and ICRP.

The alarming indoor radon concentration of $319.49 \pm 37.02 \text{ Bq.m}^{-3}$ with a corresponding annual effective dose of 1.61 mSv per year was measured from a school in Khuma Extension 1. Members of the community and school officials have indicated that this school was built on a former mine tailings dump. Therefore, this could be one of the sources of radon in this school. The main factor contributing to the high radon levels in schools during winter is low ventilation. Measurements were taken even during the three weeks of school holidays; during this time, school buildings were closed, doors and windows were close for the whole period of three weeks. During winter, the ventilation decreases since doors and windows are closed most of the time during a class lesson. This increased the accumulation of indoor radon, and there was no ventilation to reduce the accumulated radon.

Figure 4.11 below shows the geological layout of the KOSH region and the location of each school where the indoor measurements were taken during the winter season. One of the factors that influenced the indoor radon concentration was the geology of the area; the underlying soil and rocks were essential to help understand the source of radon. Although the study did not aim to compare radon levels in schools and private homes, the trend between schools and homes due to geology is observed. Similar to the summer results from homes, the highest measured radon concentration was in Khuma, and the lowest measured concentration was in Orkney, as shown in Figures 4.11. This suggested that the geology of an area is the main contributor to the indoor radon concentration.

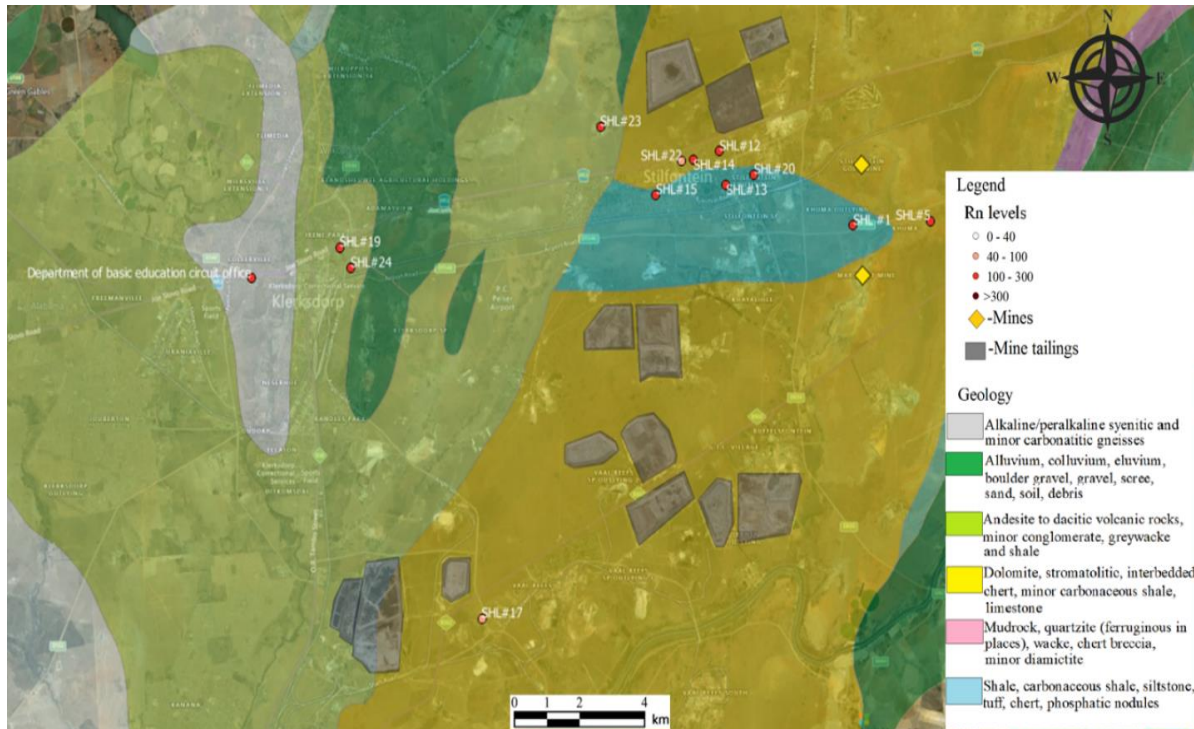


Figure 4.8. Average indoor radon concentration and geological layout of selected schools during the winter season.

Figure 4.12 shows the seasonal fluctuations of indoor radon at schools the trend between indoor radon concentration during summer and winter. Seasonal variations in all selected schools ranged from 1.80 % at a school in Stilfontein to 56.72 % at a school in Orkney. The results show that indoor radon concentration levels during winter are higher than in hot seasons, summer, and spring at schools and private homes. These findings were also observed from a similar SA study by A Maheso (Maheso, 2021) and a survey conducted in Palestine by Mallah (Mallah, 2013). However, from results obtained in private homes as observed in figure 1.10, Khuma Extension 6, the average concentration levels were $83.63 \pm 13.38 \text{ Bq.m}^{-3}$ and $72.99 \pm 12.13 \text{ Bq.m}^{-3}$ in summer and winter, respectively, with a difference of 10.64 Bq.m^{-3} . School SHL#17, located at Stilfontein, measured $92.20 \pm 14.14 \text{ Bq.m}^{-3}$ during summer and $89.32 \pm 13.81 \text{ Bq.m}^{-3}$ during winter, with a difference of 2.88 Bq.m^{-3} . These unexpected findings suggested that the ventilation system in winter was better than in summer.

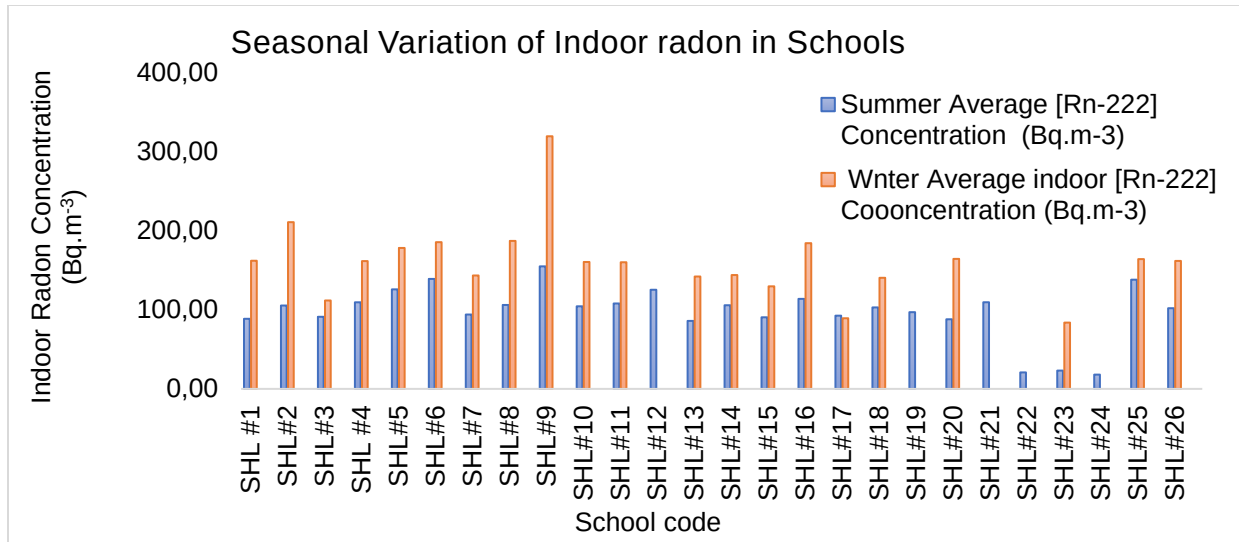


Figure 4.9. Seasonal variation of indoor radon concentration at selected schools

4.2.3 Annual Effective Dose Corresponding to the Measured Radon Concentration at Schools

The annual effective dose due to radon inhalation is calculated using Equation 2.8; however, a different occupancy factor was used for schools because it is different for homes and schools due to the time spent in these areas. The school occupancy factor was calculated to be 0.16. It was estimated as follows:

$$\begin{aligned}
 & \text{Number of hours per week} \times \text{Number of weeks per year} \\
 &= \text{Number of hours spent per year} \\
 & 40 \times 37 = 1480 \\
 & \text{School Occupancy Factor} = \frac{\text{Number of hours spent at school per year}}{\text{Total Number of Hours per Year}} \\
 & \frac{1480}{8760} \\
 & \text{School Occupancy Factor} = 0.16
 \end{aligned}$$

The annual effective dose due to radon exposure at selected schools in KOSH ranged from 0.09 mSv to 0.78 mSv.

Chapter 5: Conclusion and Recommendations

5 Introduction

After the analysis and discussion of the results obtained in this study as presented in Chapter 4 above, Chapter 5 summarises the study findings and observations and gives recommendations.

5.1 Conclusion

This study aimed to establish and document indoor radon levels in homes and public buildings in the KOSH gold and uranium mining region for the sole purpose of determining and preventing possible public exposure to radiation. Long-term indoor radon measurements were carried out in dwellings or private homes and public buildings such as schools and offices by deploying SSNTDs for three months. The fieldwork was conducted over four seasons of the year, spring, summer, autumn, and winter. Data collection began in October 2020 and ended in August 2021.

The average indoor radon concentration in selected areas ranged from $45.36 \pm 9.27 \text{ Bq.m}^{-3}$ to $96.28 \pm 14.49 \text{ Bq.m}^{-3}$. Khuma Extension 9 measured the highest, and Orkney measured the lowest. Table 4.2 showed that the maximum measured radon concentration was $116.33 \pm 15.56 \text{ Bq.m}^{-3}$ for a home in Jouberton township. This did not represent the average of the area but of a single house because measurements were conducted from one house. During winter, Khuma Extension 6 area measured the minimum indoor radon level of $72.99 \pm 12.13 \text{ Bq.m}^{-3}$, and Khuma Extension 9 measured a maximum of $108.84 \pm 14.53 \text{ Bq.m}^{-3}$.

In summer, indoor radon concentration levels at schools ranged from a minimum of $18.06 \pm 4.3 \text{ Bq.m}^{-3}$ at Orkney to a maximum of $154.96 \pm 20.48 \text{ Bq.m}^{-3}$ at Khuma Extension 1. During winter, they measured a minimum concentration of $83.83 \pm 13.25 \text{ Bq.m}^{-3}$ at Orkney and a maximum of $319.49 \pm 37.02 \text{ Bq.m}^{-3}$ at Khuma Extension 1. Seasonal variations in all the schools ranged from 1.80 % at a school in Stilfontein to 56.72 % at a school in Orkney. The results show that indoor radon concentration levels during winter are higher

than in hot seasons, summer, and spring at schools and private homes. These findings were also observed from a similar SA study (Maheso, 2021) and a survey by K Bassam conducted in Palestine (Mallah, 2013). However, the average during summer at Khuma Extension 6 was $83.63 \pm 13.38 \text{ Bq.m}^{-3}$ and $72.99 \pm 12.13 \text{ Bq.m}^{-3}$ in winter, with a difference of 10.64 Bq.m^{-3} . A school SHL#17 located in Stilfontein measured $92.20 \pm 14.14 \text{ Bq.m}^{-3}$ during summer and $89.32 \pm 18.81 \text{ Bq.m}^{-3}$ during winter, with a difference of 2.88 Bq.m^{-3} . These unexpected findings suggested that the ventilation system in winter was better than in summer. From this observation, it can be concluded that, although winter concentrations are normally higher than summer, enough ventilation during winter can reduce the concentration levels of indoor radon.

Results obtained in this study suggest that the waste generated from former and operating gold mine operations and the mine waste in KOSH area could be the main sources of elevated indoor radon concentration levels. The highest indoor radon levels in this study were found at Khuma township. First, in a house with an average level of $212.17 \pm 26.24 \text{ Bq.m}^{-3}$ and a school with $319.49 \pm 37.02 \text{ Bq.m}^{-3}$. The home is located close to mine waste, and the school is built on a former mine waste area. This agrees with a study by Moshupya, where the highest radon levels were found in areas dominated by mine tailings (Moshupya et al., 2019). However, other houses in the same place measured lower concentration levels indicating that geology and underlying rocks are not enough to be used alone to develop an indoor radon strategy survey.

5.2 Recommendations

Radon levels can change daily due to various factors such as the ventilation system of the dwelling, geology, and underlying rocks and soil of the area and building type. For this reason, measuring radon over hours or a few days can result in underestimating the annual average exposure, and such data cannot be used in developing a national radon survey (Kamunda et al., 2017). Therefore, it is not ideal to use short-term measurements as the basis of advice on whether a building has a high radon level or not; hence in this study, long-term measurements were done as recommended by the IAEA (IAEA, 2013). The highest indoor radon concentration of $319.49 \pm 37.02 \text{ Bq.m}^{-3}$ in this study was measured at a school in Khuma Extension 1, and the home survey was not conducted. It

is highly recommended and needed to do home measurements around Khuma Extension1 especially houses near that school that measured above 300 Bq.m⁻³.

Moreover, lung cancer induced by exposure to radon and its progenies is due to long-term exposure; for this reason, long-term measurements are more appropriate to evaluate the cancer risk. Therefore, future indoor radon studies should conduct long-term measurements to obtain qualitative and representative data that would be used for a national radon survey.

Many epidemiological studies have (WHO, 2001) proven that long-term exposure to radon and its daughter products in homes increases the risk of developing lung cancer. However, indoor radon measurements in homes or residential radon concentrations and data on the rate of cancer in geological areas are not suitable for cancer risk assessment. Relevant evidence of lung cancer risk would only come from epidemiological studies using the individual data on indoor radon exposure and health effects (WHO, 2009b). Therefore, epidemiological study on lung cancer risk due to residential exposure to radon needs to be developed for the KOSH region following this study is highly recommended. This might help prevent any potential health risk from radon inhalation over a long period by unaware area residents.

The radon levels in dwellings can be reduced by applying appropriate mitigation and the national radon programmes as advised and recommended by the IAEA and other international regulations and recommendations by the IAEA. The IAEA sets up these programs with the sole purpose of reducing population exposure to indoor radon and its risk (IAEA, 2013). South Africa can benchmark and use the experience of other countries to implement a national indoor radon reduction programme.

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Appendix A: First data set of measurements from private homes during Summer Months (October 2020- January 2021).

*Conversion: measurement period= 90 days × 24 hours= 2160
 $\text{Bq.h.m}^{-3} \div 2160 = \text{Bq.m}^{-3}$

Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	Converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Average Standard Deviation	Annual Effective Dose (mSv)
Orkney town	OH#1	42485	146431.60	25046.94	67.79	11.60	69.05	11.72	1.74
		42573	151853.00	25595.13	70.30	11.85			
	OH#2	42493	159942.70	26445.87	74.05	12.24	71.16	11.94	1.80
		42547	147461.20	25144.57	68.27	11.64			
	OH#3	42502	139455.40	24327.71	64.56	11.26	70.82	11.91	1.79
		42561	166466.90	27110.34	77.07	12.55			
	OH#4	42596	239716.10	34580.31	110.98	16.01	109.56	15.86	2.76
		42647	233604.50	33955.04	108.15	15.72			
Kanana	OH#5	42524	136768.90	24043.96	63.32	11.13	64.04	11.21	1.62
		42539	139871.30	24374.46	64.76	11.28			
	OH#6	42526	149092.50	25340.48	69.02	11.73	73.25	12.18	1.85
		42613	167340.80	27263.09	77.47	12.62			
	OH#7	42544	133257.80	23693.09	61.69	10.97	63.52	11.16	1.60
		42601	141168.50	24496.75	65.36	11.34			
	OH#8	42616	150655.80	25516.23	69.75	11.81	69.71	11.80	1.76
		42648	150482.60	25461.97	69.67	11.79			
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	Converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Average Standard Deviation	Annual Effective Dose (mSv)
Kanana	KNH#1	42468	166026.30	27060.69	76.86	12.53	72.23	12.05	1.82
		42593	146001.00	24998.19	67.59	11.57			
	KNH#2	42474	178622.40	28363.16	82.70	13.13	96.49	14.54	2.43
		42618	238228.20	34441.92	110.29	15.95			
	KNH3	42495	164289.30	26888.51	76.06	12.45	67.34	11.55	1.70
		42543	126628.10	23008.08	58.62	10.65			
	KNH#4	42497	153223.90	25752.39	70.94	11.92	76.85	12.53	1.94
		42569	178753.70	28368.77	82.76	13.13			
	KNH#5	42498	251067.30	35731.17	116.23	16.54	123.88	17.32	3.13
		42609	284103.50	39083.97	131.53	18.09			
Kanana	KNH#6	42515	242084.60	34815.23	112.08	16.12	103.12	15.21	2.60
		42597	203398.60	30884.47	94.17	14.30			
	KNH#7	42552	204733.00	31012.78	94.78	14.36	90.98	13.97	2.30
		42588	188279.90	29343.09	87.17	13.58			
	KNH#8	42556	173972.20	27865.27	80.54	12.90	77.51	12.59	1.96
		42626	160849.80	26525.89	74.47	12.28			
	KNH#9	42568	132758.90	23633.70	61.46	10.94	59.13	10.70	1.49
		42581	122701.70	22609.77	56.81	10.47			

	KNH#10	42614 42633	228477.70 216577.70	33484.35 32235.08	105.78 100.27	15.50 14.92	103.02	15.21	2.60
	KNH#11	42622 42624	200244.30 211515.10	30609.25 31709.00	92.71 97.92	14.17 14.68	95.31	14.43	2.40
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	Converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Average Standard Deviation	Annual Effective Dose (mSv)
Stilfontein town	STFH#1	42540 42452	133238.00 147926.70	23690.12 25212.96	61.68 68.48	10.97 11.67	65.08	11.32	1.64
	STFH#2	37857 37834	143693.90 149024.60	24771.09 25330.51	66.52 68.99	11.47 11.73	67.76	11.60	1.71
	STFH#3	37823 37828	155053.80 188465.30	25938.23 29381.60	71.78 87.25	12.01 13.60	79.52	12.81	2.01
	STFH#4	37826 37833	168063.40 149004.50	27275.87 25327.56	77.81 68.98	12.63 11.73	73.40	12.18	1.85
	STFH#5	37844 37849 37817	148280.90 173170.10 155129.20	25235.89 27812.99 25949.21	68.65 80.17 71.82	11.68 12.88 12.01	73.55	12.28	1.86
	STFH#6	37815 37832	173259.20 226775.10	27812.41 33265.43	80.21 104.99	12.88 15.40	92.60	14.14	2.34
	STFH#7	37842 37864	172725.70 186020.40	27749.71 29110.46	79.97 86.12	12.85 13.48	83.04	13.16	2.10
	STFH#8	37855 37853 37818	134648.90 181418.90 147448.00	23829.33 28646.08 25142.63	62.34 83.99 68.26	11.03 13.26 11.64	71.53	11.98	1.80
	STFH#9	37860	189415.80	29455.96	87.69	13.64	87.69	87.69	2.21
	STFH#10	37845 37839	161267.70 167910.00	26572.42 27253.90	74.66 77.74	12.30 12.62	76.20	12.46	1.92
	STFH#11	37822 37821	176777.40 177268.10	28162.83 28219.32	81.84 82.07	13.04 13.06	81.95	13.05	2.07
	STFH#12	37820 37848	152425.50 168265.50	25664.44 27291.34	70.57 77.90	11.88 12.63	74.23	12.26	1.87
	STFH#13	37835 37846 37856	181738.80 180768.50 178035.80	28678.34 28567.17 28280.17	84.14 83.69 82.42	13.28 13.23 13.09	83.42	13.20	2.10
	STFH#14	37858 37841	196484.60 211597.90	30181.32 31720.33	90.97 97.96	13.97 14.69	94.46	14.33	2.38
	STFH#15	37836 37827	156349.40 188396.00	26060.50 29384.49	72.38 87.22	12.07 13.60	79.80	12.83	2.01
	STFH#16	37825 37829	122701.70 168811.00	22609.77 27355.94	56.81 78.15	10.47 12.66	67.48	11.57	1.70
	STFH#17	37862	189254.40	29433.40	87.62	13.63	87.62	13.63	2.21

Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	Converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Average Standard Deviation	Annual Effective Dose (mSv)
Khuma Ext 8	K8H#1	42457 42629	159801.50 145214.80	26425.44 24911.70	73.98 67.23	12.23 11.53	70.61	11.88	1.78
	K8H#2	42472 42649	144351.70 121621.80	24838.65 22477.34	66.83 56.31	11.50 10.41	61.57	10.95	1.55
	K8H#3	42479 42644	177188.60 117185.80	28208.06 22016.47	82.03 54.25	13.06 10.19	68.14	11.63	1.72
	K8H#4	42528 42585	151911.20 139803.60	25603.63 24379.48	70.33 64.72	11.85 11.29	67.53	11.57	1.70
	K8H#5	42541 42562	139803.10 145646.20	24364.32 24960.59	64.72 67.43	11.28 11.56	66.08	11.42	1.67
	K8H#6	42542 42638	137245.00 156668.40	24099.77 26092.77	63.54 72.53	11.16 12.08	68.04	11.62	1.72
	K8H#7	42640 42594	120170.10 154058.00	22348.08 25821.60	55.63 71.32	10.35 11.95	63.48	11.15	1.60
	K8H#8	42545 42608	200762.90 224729.90	30612.40 33180.13	92.95 104.04	14.17 15.36	98.49	14.77	2.48
	K8H#9	42625 42553	141272.80 236259.80	24512.21 34228.47	65.40 109.38	11.35 15.85	87.39	13.60	2.20
	K8H#10	42628 42623	146236.30 136972.40	25032.83 24074.32	67.70 63.41	11.59 11.15	65.56	11.37	1.65
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	Converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Average Standard Deviation	Annual Effective Dose (mSv)
Khuma Ext 9	K9H#1	37819	458287.00	56668.27	212.17	26.24	212.17	26.24	5.35
	K9H#2	37830 37840	170170.00 159425.30	27487.43 26384.93	78.78 73.81	12.73 12.22	76.30	12.47	1.92
	K9H#3	37837 37863	163078.70 153339.90	26755.34 25769.31	75.50 70.99	12.39 11.93	73.25	12.16	1.85
	K9H#4	37838	190516.10	29572.36	88.20	13.69	88.20	13.69	2.23
	K9H#5	37843 37859	150056.90 149699.00	25414.05 25376.04	69.47 69.31	11.77 11.75	69.39	11.76	1.75
	K9H#6	37854 37861	166509.60 181289.00	27116.47 28627.75	77.09 83.93	12.55 13.25	80.51	12.90	2.03
	K9H#7	42516 42557	159339.30 160849.80	26372.49 26525.89	73.77 74.47	12.21 12.28	74.12	12.24	1.87
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	Converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Average Standard Deviation	Annual Effective Dose (mSv)
Khuma Ext 1 (old Location)	K10H#1	37851	208000.00	31400.00	96.30	1.42	97.69	8.09	2.46
		37831	214000.00	31900.00	99.07	14.77			

**Appendix B: Second data set of measurements from private homes during Spring
Months (January- April 2021).**

Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Khuma Extension 4	K4H#1	57587	127907.40	23127.46	59.22	10.71	10.32	55.42	0.64	1.40
		57589	111495.50	21439.65	51.62	9.93				
	K4H#2	57627	125029.30	22856.32	57.88	10.58	10.04	52.55	0.61	1.33
		57600	102000.00	20500.00	47.22	9.49				
	K4H#3	57596	98725.87	20118.06	45.71	9.31	9.13	43.94	0.51	1.11
		57606	91113.32	19322.41	42.18	8.95				
	K4H#4	57586	111163.10	21405.02	51.46	9.91	9.74	49.85	0.58	1.26
		57590	104173.10	20675.92	48.23	9.57				
	K4H#5	57619	98800.00	20100.00	45.74	9.31	9.15	44.16	0.51	1.11
		57588	91986.97	19407.16	42.59	8.98				
	K4H#6	57602	88437.56	19014.80	40.94	8.80	8.91	41.98	0.49	1.06
		57592	92922.53	19489.12	43.02	9.02				
	K4H#7	57613	89787.01	19177.15	41.57	8.88	9.50	41.57	0.48	1.05
	K4H#8	57620	115360.50	21846.48	53.41	10.11	9.74	49.79	0.58	1.26
		57597	99733.50	20211.70	46.17	9.36				
	K4H#9	57628	100157.00	20261.01	46.37	9.38	9.70	46.37	0.54	1.17
Khuma Extension 6	K4H#10	57616	113298.80	21623.12	52.45	10.01	9.93	51.65	0.60	1.30
		57584	109814.40	21275.23	50.84	9.85				
	J4H#11	57583	160098.60	26468.41	74.12	12.25	11.07	62.70	0.73	1.58
		57603	110779.50	21362.40	51.29	9.89				
	K4H#12	57626	131000.00	23500.00	60.65	10.88	10.63	58.10	0.67	1.47
		57604	120000.00	22400.00	55.56	10.37				
	K4H#13	57594	111066.10	21389.92	51.42	9.90	9.60	48.49	0.56	1.22
		57625	98407.52	20085.51	45.56	9.30				
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Khuma Extension 6	K6H#1	42500	218452.90	32414.32	101.14	15.01	14.83	99.42	0.01	2.51
		42508	211032.80	31654.57	97.70	14.65				
	K6H#2	42584	138085.40	24194.65	63.93	11.20	11.49	66.79	0.77	1.69
		42599	150468.90	25459.96	69.66	11.79				

	K6H#3	42602	165445.60	27004.48	76.60	12.50	12.19	73.54	0.01	1.86
		42639	152253.90	25639.40	70.49	11.87				
	K6H#4	42591	243382.30	34967.22	112.68	16.19	15.37	104.72	1.21	2.64
		42534	208987.20	31452.04	96.75	14.56				
	K4H#5	57599	87758.64	18974.96	40.63	8.78	8.57	38.64	0.45	0.97
		57612	79169.74	18066.83	36.65	8.36				
	K6H#6	42511	180798.70	28571.43	83.70	13.23	13.40	85.36	0.99	2.15
		42631	187957.30	29310.46	87.02	13.57				
	K6H#7	57569	122158.70	22543.10	56.55	10.44	11.07	62.71	0.73	1.58
		57567	148747.50	25289.84	68.86	11.71				
	K6H#8	42558	159469.00	26391.26	73.83	12.22	12.73	78.85	0.91	1.99
		42460	181179.60	28612.32	83.88	13.25				
	K6H#9	42454	154933.00	25920.65	71.73	12.00	12.17	73.37	0.85	1.85
		42637	162015.80	26652.77	75.01	12.34				
	K6HH#10	42643	170000.00	27500.00	78.70	12.73	12.82	79.62	0.92	2.01
		42550	173959.00	27863.40	80.54	12.90				
	K6H#11	42512	165364.80	26992.88	76.56	12.50	13.66	87.88	1.02	2.22
		42450	214289.50	32011.07	99.21	14.82				
	K6H#12	42480	234126.80	34014.36	108.39	15.75	15.25	103.57	1.20	2.61
		42559	213291.10	31886.21	98.75	14.76				
	K6H313	42551	148742.30	25289.08	68.86	11.71	12.74	78.76	0.91	1.99
		42612	191484.60	29732.75	88.65	13.77				
	K6H#14	42481	207510.30	31304.17	96.07	14.49	14.04	91.63	1.06	2.31
		42620	188310.30	29359.89	87.18	13.59				
	K6H#15	42465	163166.40	26767.97	75.54	12.39	12.88	80.33	0.93	2.03
		42531	183869.90	28893.05	85.12	13.38				
	K6H#16	42582	146212.90	25029.38	67.69	11.59	15.34	67.69	0.78	1.71
	K6H#17	42592	305582.20	41256.83	141.47	19.10	17.01	120.84	1.40	3.05
		42484	216438.20	32216.05	100.20	14.91				
	K6H#18	42527	225730.80	33165.12	104.51	15.35	14.94	100.45	1.16	2.53
		42535	208221.50	31390.10	96.40	14.53				
	K6H#19	42499	190617.00	29586.46	83.67	13.70	13.46	83.67	0.97	2.11
		42567	180723.10	28560.76	83.67	13.22				
	K6H#20	42503	168814.90	27369.98	78.16	12.67	13.59	87.20	1.01	2.20
		42469	207892.70	31344.94	96.25	14.51				
	K6H#21	42605	180838.00	28576.97	83.72	13.23	13.65	87.84	1.02	2.22
		42574	198633.70	30398.25	91.96	14.07				
	K6H#22	42520	192358.60	29759.03	89.05	13.78	13.66	89.05	1.03	2.25
	K6H#23	42610	186755.70	29239.08	86.46	13.54	12.82	79.62	0.92	2.01
		42470	157188.60	26154.23	72.77	12.11				
	K6H#24	42489	170503.30	27521.67	78.94	12.74	13.44	85.69	0.99	2.16
		42587	199672.80	30517.97	92.44	14.13				

Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Khuma Extension 7	K7H#1	57608	100023.60	20239.77	46.31	9.37	9.37	46.31	0.54	1.17
	K7H#2	57624	115533.00	21856.34	53.49	10.12	10.11	53.38	0.62	1.35
		57630	115059.40	21799.93	53.27	10.09				
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Khuma Extension 8	K8H#10	57562	119771.10	22303.34	55.45	10.33	10.52	57.33	0.66	1.45
		57538	127904.60	23127.04	59.22	10.71				
	K8H#11	57565	96444.79	19875.80	44.65	9.20	9.20	44.65	0.52	1.13
	K8H#12	57570	103329.20	20608.13	47.84	9.54	9.54	47.84	0.55	1.21
	K8H#13	57547	122664.40	22604.07	56.79	10.46	10.05	52.78	0.61	1.33
		57531	105330.40	20805.33	48.76	9.63				
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Khuma Extension 9	K9H#8	57564	104407.60	20695.23	48.34	9.58	10.09	53.28	0.62	1.34
		57553	125740.50	22905.33	58.21	10.60				
	K9H#9	57561	108446.20	21113.23	50.21	9.77	10.11	53.38	0.62	1.35
		57560	122158.70	22543.10	56.55	10.44				
	K9H#10	57558	46590.09	14609.31	21.57	6.76	7.76	30.96	0.36	0.78
		57535	87147.46	18894.36	40.35	8.75				
	K9H#11	57548	108439.30	21112.14	50.20	9.77	10.05	52.87	0.61	1.33
		57530	119950.20	22314.36	55.53	10.33				
	K9H#12	57534	103984.80	20646.22	48.14	9.56	8.78	48.14	0.56	1.21
	K9H#13	57578	71691.28	17264.51	33.19	7.99	8.88	41.70	0.48	1.05
		57568	108445.80	21113.16	50.21	9.77				
	K9H#14	57576	96708.81	19918.15	44.77	9.22	9.62	44.77	0.52	1.13
	K9H#15	57556	113518.90	21657.26	52.56	10.03	9.94	51.68	0.60	1.30
		57574	109729.80	21262.00	50.80	9.84				
	K9H#16	57532	115992.00	21910.48	53.70	10.14	10.07	53.00	0.61	1.34
		57551	112949.00	21585.80	52.29	9.99				

	K9H#17	42549 57577	151796.80 80474.40	25586.93 18189.51	70.28 37.26	11.85 8.42	10.13	53.77	0.62	1.36
	K9H#18	57566 57543	135694.90 141231.40	23955.13 24506.08	62.82 65.38	11.09 11.35	11.22	64.10	0.74	1.62
	K9H#19	57545 57546	98720.26 90748.23	20117.16 19263.17	45.70 42.01	9.31 8.92	9.12	43.86	0.51	1.11
	K9H#20	57555 57573	98238.89 105514.50	20058.57 20834.35	45.48 48.85	9.29 9.65	9.47	47.17	0.55	1.19
	K9H#21	57557 57536	131608.80 146347.40	23533.69 25049.19	60.93 67.75	10.90 11.60	11.25	64.34	0.74	1.62
	K9H#22	57551 57532	112949.00 115992.00	21585.80 21910.48	52.29 53.70	9.99 10.14	10.07	53.00	0.61	1.34
	K9H#23	57552 57571	152628.20 104392.00	25694.04 20692.77	70.66 48.33	11.90 9.58	10.74	59.50	0.69	1.50
	K9H#24	57563 57544	104439.60 113281.30	20700.28 21620.41	48.35 52.45	9.58 10.01	9.80	50.40	0.58	1.27
	H9H#25	57529 57574	98224.53 109729.80	20056.28 21262.00	45.47 50.80	9.29 9.84	9.56	48.14	0.56	1.21
Khuma Extension 10	K9H#26	42595 42463	172549.20 180738.10	27737.82 28562.89	79.88 83.68	12.84 13.22	13.03	81.78	0.95	2.06
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Khuma Extension 11	K11H1	42491 42646	174531.40 240667.90	27931.59 34675.64	80.80 111.42	12.93 16.05	14.49	96.11	0.01	2.42
	K11H#2	42464 42505	174031.30 186882.80	27873.67 29185.03	80.57 86.52	12.90 13.51	13.21	83.54	0.97	2.11
	K11H#3	42632 42461	179542.00 171835.70	28454.32 27649.43	83.12 79.55	13.17 12.80	12.99	81.34	0.94	2.05
	K11H#4	42607 42482	196593.10 153368.70	30196.38 25773.51	91.02 71.00	13.98 11.93	12.96	81.01	0.94	2.04
	K11H#5	42598 42548	203312.90 177672.00	30872.66 28276.56	94.13 82.26	14.29 13.09	13.69	88.19	1.02	2.22
	K11H#6	42590 42635	164335.50 213333.10	26895.15 31891.94	76.08 98.77	12.45 14.76	13.61	87.42	1.01	2.21

	K11H#7	42475 42566	190444.70 192244.10	29574.84 29743.07	88.17 89.00	13.69 13.77	13.73	88.59	1.02	2.23
	K11H#18	42575 42507	174835.40 164205.80	27961.65 26876.49	80.94 76.02	12.95 12.44	12.69	78.48	0.91	1.98
	K11H#19	42456 42518	225638.90 196829.80	33152.69 30217.06	15.35 91.12	15.35 13.99	14.67	53.24	0.62	1.34
	K11H#20	42494 42453	199529.00 240398.70	30498.06 34650.29	92.37 111.30	14.12 16.04	15.08	101.84	1.18	2.57
	K11H#21	42615 42514	216765.90 206959.00	32272.17 31240.17	100.35 95.81	14.94 14.46	14.70	98.08	1.13	2.47
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Ellaton, Klerksdorp	EKH#1	57537 57559	164305.20 119061.00	26890.79 22210.83	76.07 55.12	12.45 10.28	11.37	65.59	0.76	1.65
	EKH#2	57550 57614	169631.20 109742.40	27423.83 21263.97	78.53 50.81	12.70 9.84	11.27	64.67	0.75	1.63
	EKH#3	57605 57617	107622.20 82809.32	21048.20 18443.05	49.83 38.34	9.74 8.54	9.14	44.08	0.51	1.11
	EKH#4	57610 57618	86800.00 99999.20	18900.00 20235.90	40.19 46.30	8.75 9.37	9.06	43.24	0.50	1.09
	EKH#5	57581 57591	189209.20 109346.00	29427.09 21219.34	87.60 50.62	13.62 9.82	11.72	69.11	0.80	1.74
	EKH#6	57593 57595	80987.41 100877.60	18254.66 20339.43	37.49 46.70	8.45 9.42	8.93	42.10	0.49	1.06
	EKH#7	42467 42455	184752.00 209661.10	28970.30 31521.11	85.53 97.07	13.41 14.59	14.00	91.30	1.06	2.30
	EKH#8	42476 42510	238604.00 207686.50	34470.83 31340.15	110.46 96.15	15.96 14.51	15.23	103.31	1.20	2.61
	EKH#9	42603 42536	224861.70 184725.80	33069.80 28966.62	104.10 85.52	15.31 13.41	14.36	94.81	1.10	2.39
	EKH#10	42555 42532	200437.60 196264.80	30579.42 30150.81	92.80 90.86	14.16 13.96	14.06	91.83	1.06	2.32

Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Stilfontein	STH#18	42586 42533	229681.30 222672.10	33583.92 32847.87	106.33 103.09	15.55 15.21	15.38	104.71	1.21	2.64
	STH#19	42501 42554	195009.90 194457.20	30045.91 29969.03	90.28 90.03	13.91 13.87	13.89	90.15	1.04	2.27
	STH#20	42496 42630	189428.10 170156.60	29457.68 27498.90	87.70 78.78	13.64 12.73	13.18	83.24	0.96	2.10
	STH#21	42462 42583	180000.00 164130.40	28500.00 26879.34	83.33 75.99	13.19 12.44	12.82	79.66	0.92	2.01
	STH#22	42563 42478	142687.00 170851.40	24676.92 27584.76	66.06 79.10	11.42 12.77	12.10	72.58	0.84	1.83
	STH#23	42589 42576	166631.00 156948.00	27133.88 26133.35	77.14 72.66	12.56 12.10	12.33	74.90	0.87	1.89
	STH#24	57540 57554	89645.00 106716.00	19173.20 20940.96	41.50 49.41	8.88 9.69	9.29	45.45	0.53	1.15
	STH#25	42490 42517	181780.80 165408.10	28684.26 26999.10	84.16 76.58	13.28 12.50	12.89	80.37	0.93	2.03 0.00
	STH#26	42570 42636	194098.60 218512.50	29931.41 32422.42	89.86 101.16	13.86 15.01	14.43	95.51	1.10	2.41
	STH#27	42487 42627	227099.20 159075.50	33298.16 26348.23	105.14 73.65	15.42 12.20	13.81	89.39	1.03	2.26
	STH#28	42488 42458	191445.40 183893.20	29656.41 28896.32	88.63 85.14	13.73 13.38	13.55	86.88	1.01	2.19
	STH#29	42604 42483	194202.90 227925.50	29945.92 33387.63	89.91 105.52	13.86 15.46	14.66	97.71	1.13	2.47
Location	Dwelling Code	Monitor ID	Measured [Rn-222] Concentration (Bq.h.m ⁻³)	Standard Deviation	converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Annual Dose (Sv)	Annual Effective Dose (mSv)
Orkney	OH#9	57582	90800.00	19300.00	42.04	8.94	8.94	42.04	0.49	1.06
	OH#10	57598 57609	98807.62 111621.50	20131.11 21459.27	45.74 51.68	9.32 9.93	9.63	48.71	0.56	1.23
	OH#11	57611 57621	117000.00 102000.00	22000.00 20400.00	54.17 47.22	10.19 9.44	9.81	50.69	0.59	1.28
	OH#12	57622	86358.45	18803.93	39.98	8.71	8.71	39.98	0.46	1.01

**Appendix C: Third data set of measurements from Private homes during Winter
Months (May- August 2021).**

Location	Dwelling Code	Monitor ID (PARC RGM)	Measured (Rn-222) Bq h m-3	Standard Deviation	converted (Rn-222) Bq.m3	Converted Standard Deviation	Average (Bq.m3)	Averaged Standard Deviation	Annual Effective Dose (mSv)
Khuma EXT4	k4H#11	K72577	181123.70	28617.28	83.85	13.25	80.40	12.89	2.03
		K72601	166200.90	27085.74	76.94	12.54			
Khuma Ext 4	K4H#13	K72593	150040.70	25426.10	69.46	11.77	74.41	12.28	1.88
		K72560	171421.20	27639.34	79.36	12.80			
Khuma Ext6	K6H#24	K72605	130423.70	23402.16	60.38	10.83	80.70	12.93	2.04
		K72616	218203.00	32445.14	101.02	15.02			
Khuma Ext 6	K6H#2	K72564	139670.00	24359.61	64.66	11.28	65.27	11.34	1.65
		K72529	142315.10	24636.78	65.89	11.41			
Khuma Ext 9	K9H#30	K57020	422255.30	53038.00	195.49	24.55	197.10	24.72	4.97
		K57005	429211.20	53744.52	198.71	24.88			
Khuma Ext9	K9H#31	K72607	176077.50	28089.69	81.52	13.00	82.29	13.09	2.08
		K72612	179401.10	28473.36	83.06	13.18			
Khuma Ext9	K9H#32	K72604	156775.20	26122.33	72.58	12.09	77.13	12.56	1.95
		K72586	176423.70	28138.79	81.68	13.03			
Khuma Ext9	K9H#33	K72540	178501.00	28345.97	82.64	13.12	77.73	12.62	1.96
		K72563	157277.70	26167.16	72.81	12.11			
Khuma Ext9	K9H#12	K72548	174811.70	27971.41	80.93	12.95	82.39	13.12	2.08
		K72538	181108.00	28688.83	83.85	13.28			
Khuma Ext9	K9H#8	K57017	327485.80	43472.51	151.61	20.13	148.73	19.84	3.75
		K57977	315012.30	42216.40	145.84	19.54			
Khuma Ext9	K9H#21	K72585	231211.10	33768.14	107.04	15.63	123.75	17.33	3.12
		K72611	303405.50	41098.17	140.47	19.03			
Khuma Ext9	K9H#10	K72622	165776.10	27051.95	76.75	12.52	78.76	12.73	1.99
		K72559	174475.30	27936.78	80.78	12.93			
Stilfontein	STH#1	K72554	252541.50	35905.94	116.92	16.62	114.52	16.38	2.89
		K72561	242166.40	34836.71	112.11	16.13			
Stilfontein	SFH#16	K72603	158697.10	26307.39	73.47	12.18	70.13	11.84	1.77
		K72618	144267.30	24841.00	66.79	11.50			
Stilfontein	SFH#30	K72613	174686.8	28015.7	80.87	12.97	79.49	12.82	2.00
		K72525	168697.4	27353.15	78.10	12.66			

Stilfontein	SFH#31	K72537 K72570	150706 174464.2	25509.1 27935.19	69.77 80.77	11.81 12.93	75.27	12.37	1.89
Stilfontein	SFH#32	K72543 K72542	163949.7	26867.04	75.90	12.44	75.90	6.22	1.91
Stilfontein	SFH#33	K72557 K72576	179742.5 170829.9	28482.67 27568.3	83.21	13.19 12.7631	81.15	12.97	2.05
Stilfontein	STH#28	K72596 K72589	184761.40 156897.10	28971.61 26140.04	85.54 72.64	13.41 12.10	79.09	12.76	2.00
Stilfontein	STH#34	K72530 K72583	157907.50 161480.40	26244.48 26603.12	73.11 74.76	12.15 12.32	73.93	12.23	1.87
Stilfontein	SFH#10	K72552 K72619	185084.70 159285.70	29063.97 26378.66	85.69 73.74	13.46 12.21	79.72	12.83	2.01
	STH#17	K72606	198556.60	30387.56	91.92	14.07	91.92	14.07	2.32
Stilfontein	STH#26	K72615 K72572	465379.40 196095.40	57427.04 30139.46	215.45 90.78	26.59 13.95	153.12	20.27	3.86
Ellaton	EKH#1	K72558 K72526	223683.60 228135.20	32973.76 33427.01	103.56 105.62	15.27 15.48	104.59	15.37	2.64
Klerksdorp	KH#11	K72566 K72591	192431.00 225781.50	29781.51 33183.11	89.09 104.53	13.79 15.36	96.81	14.58	2.44
Randle spark	RPH#1	K72574 K72569	421691.30 359770.80	53016.13 46745.62	195.23 166.56	24.54 21.64	180.89	23.09	4.56
Jouberton	JBH#1	K72528 K72544	156770.80 192317.10	26121.68 29765.62	72.58 89.04	12.09 13.78	80.81	12.94	2.04
Orkney	OH#10	K72598 K72608	189848.80 213421.60	29504.03 31904.03	87.89 98.81	13.66 14.77	93.35	14.21	2.36
Orkney	OH#9	K72597 K72567	140405.50 144791.00	24438.74 24903.52	65.00 67.03	11.31 11.53	66.02	11.42	1.67
Orkney	OH#12	K72590 K72610	143541.40 157582.50	24748.55 26211.39	66.45 72.95	11.46 12.13	69.70	11.80	1.76

**Appendix D: First data set of measurements from School during Summer Months
(December-March 2021).**

Location	School Code	Monitor ID	Measured [Rn-222] concentration (Bq.h.m ⁻³)	Standard Deviation	Converted [Rn-222] Concentration (Bq.m ⁻³)	Converted Standard Deviation	Average [Rn-222] Concentration (Bq.m ⁻³)	Average Standard Deviation	Annul Dose (Sv)	Annual Effective Dose (mSv)
Khuma	SHL #1	56932	225906.50	33188.89	104.59	15.37	88.65	13.74	1.03	0.45
		56926	157072.60	26151.44	72.72	12.11				
Khuma	SHL#2	56953	275727.20	38259.48	127.65	17.71	105.43	15.45	1.22	0.53
		56927	179739.40	28482.23	83.21	13.19				
Khuma	SHL#3	56958	179739.40	28482.23	83.21	13.19	91.18	14.00	1.05	0.46
		56936	214178.50	31995.92	99.16	14.81				
Khuma	SHL #4	56943	212220.10	31805.5	98.25	14.72	109.51	15.87	1.27	0.55
		56970	260868.60	36744.02	120.77	17.01				
Khuma	SHL#5	56931	246627.70	35290.62	114.18	16.34	125.87	17.53	1.46	0.64
		56956	297123.10	40455.35	137.56	18.73				
Khuma	SHL#6	56971	244612.80	35092.44	113.25	16.25	139.09	18.88	1.61	0.70
		56955	356239.40	46481.29	164.93	21.52				
Khuma	SHL#7	56930	231495.90	33755.07	107.17	15.63	94.05	14.29	1.09	0.47
		56960	174802.50	27983.29	80.93	12.96				
Khuma	SHL#8	56951	243388.00	34967.98	112.68	16.19	106.14	15.53	1.23	0.54
		56961	215148.60	32105.35	99.61	14.86				
Khuma	SHL#9	56954	363906.70	47179.22	168.48	21.84	154.96	20.48	1.79	0.78
		56952	305528.10	41282.9	141.45	19.11				
Khuma	SHL#10	56942	223765.30	32984.84	103.60	15.27	104.44	15.36	1.21	0.53
		56967	227430.20	33353.94	105.29	15.44				
Khuma	SHL#11	56934	223187.80	32917.77	103.33	15.24	108.02	15.72	1.25	0.55
		56948	243470.00	34978.92	112.72	16.19				
Khuma	SHL#12	56968	267886.9	37466.35	124.02	17.35	125.37	17.48	1.45	0.63
		56945	273721.3	38052.82	126.72	17.62				
Stilfontein	SHL#13	56946	192603.50	29793.18	89.17	13.79	85.98	13.48	0.99	0.43
		56962	178822.00	28452.75	82.79	13.17				
Stilfontein	SHL#14	56963	222045.40	32815.54	102.80	15.19	105.80	15.50	1.22	0.53
		56964	234994.40	34141.76	108.79	15.81				
Stilfontein	SHL#15	56939	210469.70	31631.98	97.44	14.64	90.54	13.93	1.05	0.46
		56937	180672.00	28566.41	83.64	13.23				
Stilfontein	SHL#16	56961	215148.60	32105.35	99.61	14.86	113.85	16.32	1.32	0.57
		56966	276699.80	38376.66	128.10	17.77				

Stilfontein	SHL#17	37815 37832	173259.20 226775.10	27812.41 33265.43	80.21 104.99	12.88 15.40	92.60	14.14	1.07	0.47
Stilfontein	SHL#18	56942 56940	223765.30 221349.40	32984.84 32743.64	103.60 102.48	15.27 15.16	103.04	15.21	1.19	0.52
Baffeldorn, Stilfontein	SHL#19	56959 56925	213667.80 205504.50	31980.36 31107.15	98.92 95.14	14.81 14.40	97.03	14.60	1.12	0.49
Stilfontein	SHL#20	56923 56941	190165.80	29548.34	88.04	13.68	88.04	13.68		0.44
Orkney	SHL#21	42596 42647	239716.10 233604.50	34580.31 33955.04	110.98 108.15	16.01 15.72	109.56	15.86	1.27	0.55
Orkney	SHL#22	56992 57018	51000.00 39000.00	14000 14000	23.61 18.06	6.48 6.48	20.83	6.48	0.24	0.11
Orkney	SHL#23	56950 56933	54000.00 46000.00	13000 15000	25.00 21.30	6.02 6.94	23.15	6.48	0.27	0.12
Orkney	SHL#24	56949 56938	27000.00 51000.00	9000 11000	12.50 23.61	4.17 5.09	18.06	4.63	0.21	0.09
Klersdorp	SHL#25	56957 56972	298313.40	40556.4	138.11	18.78 0.00	138.11	18.78	1.60	0.70
Klersdorp	SHL#26	56969 56935	192794.80 247977.20	29819.85 35438.77	89.26 114.80	13.81 16.41	102.03	15.11	1.18	0.51

**Appendix E: Second data set of measurements from Schools during Winter Months
(May-August 2021).**

Location	School Code	Monitor ID (PARC RGM)	Measured (Rn-222) Bq h m-3	Standard Deviation	Converted (Rn-222) Bq.m3	Converted Standard Deviation	Average (Bq.m3)	averaged Standard Deviation	Annual Effective Dose(mSv)
Khuma	SHL #1	K56978	343576.80	45111.59	159.06	20.88	162.08	21.19	0.82
		K56976	356603.30	46427.21	165.09	21.49			
Khuma	SHL#2	K57021	391478.40	49936.82	181.24	23.12	210.86	26.11	1.06
		K56999	519418.80	62842.03	240.47	29.09			
Khuma	SHL#3	K72595	219070.10	32498.27	101.42	15.05	111.81	16.10	0.56
		K72581	263966.70	37074.63	122.21	17.16			
Khuma	SHL #4	K57016	365949.60	47373.22	169.42	21.93	161.63	21.14	0.82
		K57007	332274.80	43956.84	153.83	20.35			
Khuma	SHL#5	K57003	385961.60	49391.54	178.69	22.87	178.25	22.82	0.90
		K56991	384083.70	49210.04	177.82	22.78			
Khuma	SHL#6	K56983	331383.40	43883.63	153.42	20.32	185.56	23.56	0.94
		K56979	470231.40	57886.09	217.70	26.80			
Khuma	SHL#7	K57008	304209.80	41122.93	140.84	19.04	143.43	19.31	0.72
		K57010	311310.90	41852.92	144.13	19.38			
		K57022	313876.90	42121.50	145.31	19.50			
Khuma	SHL#8	K56989	399273.30	50732.71	184.85	23.49	187.16	23.72	0.94
		K56994	409255.40	51728.43	189.47	23.95			
Khuma	SHL#9	K56995	471263.70	57979.81	218.18	26.84	319.49	37.02	1.61
		K57001	908919.80	101945.60	420.80	47.20			
Khuma	SHL#10	K56975	319977.60	42732.05	148.14	19.78	21.03	21.03	0.11
		K57009	373454.00	48134.14	172.90	22.28			
Khuma	SHL#11	K57024	345524.90	45331.70	159.97	20.99	160.15	21.00	0.81
		K56982	346339.60	45387.50	160.34	21.01			
Stilfontein	SHL#12	K57011	321132.80	42829.76	148.67	19.83	142.12	19.17	0.72
		K56996	292823.10	39971.81	135.57	18.51			
Stilfontein	SHL#13	K56993	312833.90	41997.23	144.83	19.44	143.99	19.36	0.73
		K57004	309199.60	41633.48	143.15	19.27			
Stilfontein	SHL#14	K56997	253916.00	36039.83	117.55	16.69	129.70	17.92	0.65
		K57012	306404.50	41353.20	141.85	19.15			
Stilfontein	SHL#15	K56923	460927.50	56942.16	213.39	26.36	184.29	23.43	0.93
		K57006	335194.20	44261.00	155.18	20.49			
Orkney	SHL#17	K72617	176032.50	28083.30	81.50	13.00	83.83	13.25	0.42
		K72592	186125.60	29150.56	86.17	13.50			

Klerksdorp	SHL#19	K57023 K57014	388479.10 320569.20	49644.48 42789.93	179.85 148.41	22.98 19.81	164.13	21.40	0.83
Stilfontein	SHL#20	K56986 K56984	283798.90 323125.30	39247.04 43065.55	131.39 149.60	18.17 19.94	140.49	19.05	0.71
Stilfontein	SHL#22	K72555 K72550	204434.70 181429.80	31015.41 28647.60	94.65 84.00	14.36 13.26	89.32	13.81	0.45
Stilfontein	SHL#23	K56990 K57002	414474.10 295841.20	52263.63 40308.59	191.89 136.96	24.20 18.66	164.42	21.43	0.83
Klerksdorp	SHL#24	K56998 K56981	350050.20 349158.60	45760.46 45694.80	162.06 161.65	21.19 21.16	161.85	21.17	0.82

Appendix F: Questionnaire for household information



Indoor Radon Research Project: Deployment and Household Information Questionnaire

OWNER/RESIDENT DETAILS

Namen and surname:

Contact number:

Physical address:

City:

Province:

DEPLOYMENT INFO

Detector serial number: (*indicated under the detector*)

Start Date: _____

Start Time: _____

Deployed by: _____

End Date: _____

End Time: _____

Retrieved by: _____

SECTION A: DWELLING/HOUSE INFORMATION

Dwelling type:

☐

Shed\Wendy House

☐

Shack

☐

Hut

☐

Concrete\ brick house

☐

Caravan

☐

Other (specify below)



Floor-type:

- ☐ Wood
 - ☐ PVC flooring
 - ☐ Tiles
 - ☐ Mud
 - ☐ Concrete
 - ☐ Carpet
 - ☐ Stone (marble, granite, slate, sandstone, limestone)
 - ☐ Other (specify below)
-
-

How old is the Dwelling\House?

- ☐ 0 – 3years ☐ 3 – 8years ☐ 9 - 20 years ☐ 21- 30 years
- ☐ 31 - 40 years ☐ 41 – 50 years ☐ More than 50 years ☐ Not sure

Residence time in the Dwelling/House



SECTION B: DEPLOYED AREA

Which room did you deployed the detector?

- ☐ Bedroom
- ☐ Living room
- ☐ Other (specify below)

Which level is the room is located in the house:

- ☐ Ground floor
- ☐ First floor
- ☐ Basement
- ☐ The house does not have levels (single storey)
- ☐ Other (specify below)

According to the instructions, the detectors must be deployed 0.5 m away from the wall or open window and 1m above the ground. Did you follow this instruction? Yes ☐ No ☐

If no, please describe how you deployed the detector

Is there a smoker in the house? Yes ☐ No ☐

Appendix G. Consent form for participants

CONSENT FORM TO PARTICIPATE IN A RESEARCH STUDY

PRINCIPAL INVESTIGATOR

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RESEARCHERS/STUDENTS

Name: Dr Atsile Ocwelwang & MSv Cynthia Sethabela

Project Title: Indoor Radon Measurements in Homes and Public Buildings in the KOSH gold mining Region (Khuma & Kanana), North West Province.

INTRODUCTION (*This consent may contain words that you do not understand. Please ask the investigator or the study staff to explain any words or information that you do not clearly understand.*)

You are being asked to participate in a research study that measures radon (^{222}Rn) gas in homes and public buildings using a portable alpha track radon detector. Please find below key facts about radon gas according to the World Health Organization (WHO, 2016):

- Radon is a naturally occurring radioactive gas which may be found in indoor environments such as homes, schools, and workplaces.
- Radon is the most important cause of lung cancer after smoking.
- Radon is estimated to cause between 3–14% of all lung cancers in a country, depending on the national average radon level and smoking prevalence.
- The lower the radon concentration in a home, the lower the risk of lung cancer as there is no known threshold below which radon exposure carries no risk.
- Well-tested, durable and cost-efficient methods exist for preventing radon in new houses and reducing radon in existing dwellings.

You have the right to know what you will be asked to do so that you can decide whether or not to be in the study. Your participation is voluntary.

This research is funded NWU study for academic purposes and public knowledge or information sharing.

WHY IS THIS STUDY BEING DONE?

The purpose of this research is to deploy solid state nuclear track detectors (SSNTDs) in dwellings or homes and schools to measure indoor radon concentration levels in selected residential areas in KOSH (passive measurement technique). To determine the correlation between the measured indoor radon levels and the geological formation of KOSH.

