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# Occupational exposure to radon in a South African platinum mine.

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BSc; BSc Hons.

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# AUTHOR`S CONTRIBUTION

The contribution of each of the role-players in this study is given in the following table:

**Table 1.1: Authors` contributions**

| | |
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| Mr. M Schoonhoven | Responsible for literature searches, statistical analysis, collection of data, design and planning of manuscript, sampling, interpretation of results and writing all of the mini-dissertation. |
| Mr. P.J Laubscher | Supervisor. Supervised the writing of the mini-dissertation, initial planning and design of the mini-dissertation. |
| Mr. M.N Van Aarde | Co-Supervisor. Supervised the initial planning and sampling design. |
| Prof R. Vermeulen | Assistant Supervisor. Supervised the technical and statistical planning of the mini-dissertation. |
| Prof C.J Badenhorst | Supervised the writing of the mini-dissertation, initial planning and design of the mini-dissertation. |
| Mr. W Deysel | Provided technical assistance on site at Bafokeng Rasimone platinum mine |

The following is a statement from the co-authors confirming their individual roles in the study and giving permission that the data may form part of this mini-dissertation.

I declare that I have approved the above-mentioned manuscript, that my role in the study, as indicated above, is representative of my actual contribution and that I hereby give my consent that they may be published as part of the M.Sc. mini-dissertation of Martin Schoonhoven.

| | | |
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| ________________ | ________________ | ________________ |

# LIST OF ABBREVIATIONS

## Elements

| | |
|---|---|
| As-77 | Arsenic-77 |
| Au-198 | Gold-198 |
| Ba-133 | Barium-133 |
| Bi-210 | Bismuth-210 |
| Bi-214 | Bismuth-214 |
| Br-80 | Bromine-80 |
| Br-82 | Bromine-82 |
| C-12 | Carbon-12 |
| Ca-47 | Calcium-47 |
| Cd-109 | Cadmium-109 |
| Ce-144 | Cerium-144 |
| Cf-252 | Californium-252 |
| Co | Cobalt |
| $Co_2$ | Carbon Dioxide |
| Cr | Chromium |
| Cs-134 | Cesium-134 |
| Cs-137 | Cesium-137 |
| Cu | Copper |
| Cu-67 | Copper-67 |
| Fe | Iron |
| Ge-75 | Germanium-75 |
| Ge-77 | Germanium-77 |
| Hf-181 | Hafnium-181 |
| I-128 | Iodine-128 |
| I-131 | Iodine-131 |
| Ir | Iridium |
| La-140 | Lanthanum-140 |
| Mn-56 | Manganese-56 |
| Mo-99 | Molybdenum-99 |
| Nb-92 | Niobium-92 |
| Nb-94 | Niobium-94 |
| Ni | Nickel |
| Ni-65 | Nickel-65 |
| O-19 | Oxygen-19 |
| $O_2$ | Oxygen |
| Os | Osmium |
| P-33 | Phosphorus-33 |
| Pa-234 | Protactinium-234 |
| Pb-206 | Lead-206 |
| Pb-210 | Lead-210 |
| Pb-214 | Lead-214 |
| Pd | Palladium |
| Pm-147 | Promethium-147 |
| Po-210 | Polonium-210 |
| Po-214 | Polonium-214 |
| Po-218 | Polonium-218 |
| Pt | Platinum |
| Ra-226 | Radium-226 |
| Rh | Rhodium |
| Rn-222 | Radon-222 |
| Ru | Ruthenium |
| Sb-124 | Antimony-124 |
| Si-31 | Silicon-31 |
| Sm-151 | Samarium-151 |
| Sm-153 | Samarium-153 |
| Sn | Tin |
| Th-230 | Thorium-230 |
| Th-234 | Thorium-234 |
| Ti | Titanium |
| Tm-170 | Thulium-170 |
| U-234 | Uranium-234 |
| U-238 | Uranium-238 |
| V | Vanadium |
| V-52 | Vanadium-52 |
| ZnS | Zinc Sulfide |

## General

| | |
|---|---|
| amu | Atomic mass unit |
| BRT | Brachytherapy |
| cAMP | Cyclic Adenosine Monophosphate |
| cGMP | Cyclic Guanosine Monophosphate |
| DNA | Deoxyribonucleic Acid |
| EBRT | External Beam Radiation Therapy |
| EGFα | Epidermal Growth Factor Alpha |
| EHF | Extra High Frequency |
| ELF | Extremely Low Frequency |
| HEG | Homogeneous Exposure Group |
| HF | High Frequency |
| LF | Low Frequency |
| MF | Medium Frequency |
| mRNA | Messenger Ribonucleic acid |
| OEL | Occupational Exposure Limit |
| PGM | Platinum Group Metals |
| RDO | Rock Drill Operator |
| RLS | Rustenburg Layered Suite |
| TGFα | Transforming Growth Factor Alpha |
| TGFβ | Transforming Growth Factor Beta |
| TNFα | Tumor Necrosis Factor Alpha |
| UHF | Ultra High Frequency |
| VF | Voice Frequency |
| VLF | Very Low Frequency |

## Units

| | |
|---|---|
| µm | Micrometer |
| Bq | Becquerel |
| eV | Electron Volt |
| Gy | Gray |
| MeV | Milli Electron Volt |
| mm | Millimetre |
| mSv | Millisievert |
| PAEC | Potential Alpha Energy Concentration |
| ppm | Parts per million |
| Sv | Sievert |

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# ABSTRACT

**Background:** The Platinum mining operations in South Africa mining platinum containing ore from areas where variable amounts of uranium are found, leading to the possibility of occupational exposure to the radioactive disintegration products of Uranium-238 and in particular the gas Radon-222. No scientific data is available for occupational exposure to Radon-222 in South African platinum mining operations. **Objective:** To determine the risk of occupational exposure to the radioactive disintegration products of naturally occurring Radon-222 gas in a South African platinum mine. **Design:** Quantitative sampling (personal and static) to establish baseline data on exposure to radioactive disintegration products of naturally occurring Radon-222 gas in a underground South African platinum mine. **Setting:** The Bafokeng Rasimone platinum mine located 30 km North West of Rustenburg in the Bushveld complex in the North West Province of South Africa. **Study subjects:** One hundred and seventy four potentially highest exposed underground employees and one hundred and twelve static underground samples were sampled. **Method:** Personal and area samples were taken on selected employees and in locations using RGM samplers using CR-39 plastic as a detection medium. Employees were selected to sample the highest exposed occupations and static samples were located to sample returning air from levels underneath the sampling point before it is exhausted to the above ground atmosphere. After analysis by an accredited laboratory, the results were converted to exposure following the National Council on Radiation Protection-78 methodology. **Main outcome measures:** Quantify the relative risks of potentially highest exposed employee`s exposure to the radioactive disintegration products of naturally occurring Radon-222 gas in underground working areas in milliSievert per year. **Results:** The mean reference background exposure averaged 0.6168 mSv/a with underground personal exposure averaging 0.6808 mSv/a, and underground static exposure averaging 0.8726 mSv/a. These values are substantially below the 50 mSv/a Occupational Exposure Limit, and only pose a slightly elevated risk for the development of lung cancer above the normal back-ground exposure. Mining Team leaders and rock drill operators were identified as the potentially highest exposed employees due to the close proximity to the working face, large amounts of time spent close to the working face and the lower ventilation volumes at the working face, with Team leaders having the highest exposure of the sampled occupations with a average of 1.16 mSv/a. **Conclusions:** Occupational exposure to radioactive disintegration products of naturally occurring Radon-222 gas in the underground air of a South African platinum mine does not pose a significant risk to the health of employees working in the platinum mine.

Key words*:* Alpha Radiation, Occupational Exposure, Occupational exposure limit, Platinum Mine, Radon-222, RGM, South Africa, Uranium.

# OPSOMMING

**Agtergrond:** Die Platinum mynbedryf in Suid Afrika ontgin platinum bevattende materiaal van areas waar daar variasies in die hoeveelheid uraan binne die natuurlike grondstowwe gevind word en lei tot die moontlikheid van blootstelling aan die radioaktiewe disintegrasie produkte van Uraan-238 en meer spesifiek Radon-222 gas. **Doelstelling:** Om die risiko van blootstelling aan radioaktiewe disintegrasie produkte van Radon-222 gas in `n Suid Afrikaanse platinum myn te bepaal. ***Ontwerp*****:** *Kwantitatiewe monsterneming (beide persoonlik en staties) om `n basislyn te ontwikkel ten opsigte van die blootstelling aan radioaktiewe disintegrasie produkte van Radon-222 gas in `n ondergrondse platinum myn in Suid Afrika.* ***Ligging*****:** *Die Bafokeng Rasimone platinum myn is geleë 30 km noordwes van Rustenburg in die Bosveldkompleks van die Noordwes Provinsie van Suid Afrika.* **Studie proefpersone:** *Honderd vier en sewentig moontlike hoogs blootgestelde ondergrondse werknemers en honderd en twaalf statiese ondergrond monsters is geneem tydens die monsternemings periode.* **Metode:** Persoonlike en area monster is geneem met radon gas monitor monsternemers wat gebruik maak van CR-39 plastiek as `n deteksie medium. Drie beroepe is geïdentifiseer om die potensiële hoogste blootgestelde werknemers te moniteer terwyl statiese monsters so geposisioneer is om blootgestel te word aan lug wat van onderliggende vlakke in die myn af terugbeweeg oppervlak toe. Na analise deur `n geakkrediteerde laboratorium, is die resultate omgeskakel na blootstelling deur van die NCRP-78 metodologie gebruik te maak. **Hoof uitkoms:** Die k*wantifisering van die relatiewe risiko van potentieël hoogs blootgestelde werknemers se blootstelling aan die radioaktiewe disintegrasie produkte van Radon-222 gas in `n ondergrondse areas van die platinum myn in Millisievert per jaar.* **Resultate:** *Die gemiddelde agtergrond blootstelling was 0.6168 mSv/j met ondergrond persoonlike blootstelling wat gemiddeld 0.6808 mSv/j was en gevolg deur ondergrond statiese monsters met `n gemiddelde blootstelling van 0.8726 mSv/j. Hierdie waardes is noemenswaardig minder as die beroeps blootstellings drempel van 50 mSv/j, en hou slegs `n effense verhoogde risiko, bo die agtergrond blootstelling in vir werknemers ten opsigte van die ontwikkeling van longkanker. Span leiers en rotsboor operateurs is geïdentifiseer as die beroepe wat die hoogste potentiële blootstelling het as gevolg van die nabyheid aan die rots area, die groot hoeveelheid tyd wat hulle naby die rots area spandeer en die laer ventilasie volumes teenwoordig in daardie areas. Span leiers het die hoogste blootstelling gehad met `n gemiddeld van 1.16 mSv/j.* **Samevatting:** *Beroeps blootstelling aan radioaktiewe disintegrasie produkte van Radon-222 gas in `n ondergrondse platinum myn in Suid Afrika openbaar nie `n beduidende risiko vir die gesondheid van werknemers nie.*

Kern woorde*:* Alpha Radiasie, Beroepsblootstelling, Beroepsblootstellings limit, Platinum Myn, Radon-222, RGM, Suid Afrika, Uraan.

# CHAPTER 1: INTRODUCTION

## 1.1 INTRODUCTION

Mining is an ancient, multi-disciplinary industry, long recognized as being arduous and liable to injury and disease. [1,4] The industry employs a labor force of several hundred thousand miners, both in South Africa and in the rest of the world. [1,3] Studies of underground miners have consistently shown an increased risk of lung cancer with cumulative exposure to Radon-222 and its decay products. [1] Working with natural raw radioactive materials increases exposure to radiation. [1,4] All rock and soils contain uranium and thorium, which are both radioactive (Uranium isotopes Uranium-238 and Uranium-237, and Thorium isotope, Thorium-232), with uranium concentrations in the Bushveld Complex ranging between 11 and 66 parts per billion. [4,7]

Radon-222 is formed by the decay of Uranium-238 and ultimately Radium-226. [7] Uranium ores contain high concentrations of radioactive elements in relation to other ores with the two main uranium isotopes being Uranium-238 and Uranium-235. [7]

Exposure to radiation in the mining industry varies greatly, depending for instance, on the uranium concentration in the rock, as well as the presence of radon. [7,15] Radon (in this case mainly Radon-222) is a decay product of uranium with radon gas concentrations higher in soil with high concentrations of uranium. [7]

Radon-222 is a radioactive gaseous element usually found in areas with high concentrations of uranium. [6,17] Radon-222 is formed through the decay of Uranium-238 and its daughter elements over thousands of years. [6,17] The decay of Uranium-238 over thousands of years results in situations where there is a mixture of radioactive substances existing in a single environment. [17] Radon-222 is normally found in mines, but Radon-220, formed from the decay of Thorium-232, may sometimes also be found. [6,17] Because of its gaseous nature, Radon-222 concentrations are highly dependent on the amount of ventilating air in which it is dispersed within the underground environment. [6,17]

Radon-222 and its progeny form 54.8% of the effective dose of natural radiation received by the U.S population. [2] Exposure occurs through the inhalation of the radioactive Radon-222 gas and the inhalation of radioactive particles produced by mining and milling. [8] The inhalation of high cumulative levels of Radon-222 and its α-particle emitting decay products has been linked to an increased risk of lung cancer among underground miners. [8] Short lived radon progenies have been established as causative agents of lung cancer. [8] The main carcinogens formed by the decay of Radon-222 are the short-lived progeny Polonium-218 and Polonium-214, both alpha-particle emitting elements. [19]

The decay products of Radon-222 are all solids and are readily deposited on the bronchial airways and inside the alveoli of the lungs during inhalation and exhalation. [12]

The exposure to Radon-222 and Radon-222 progeny only exhibits effects on the lung and bronchial epithelium, because of the weak penetrating power of alpha-particles and the proximity of the Radon-222 gas and progeny with the epithelium cells in the lungs and bronchi, and thus Radon-222 does not affect any other organ or system. [10,17,18] The radiation dose from Radon-222 gas itself is very low in comparison with its decay daughters, as the Radon-222 decay daughters deposit and accumulate on the airway surfaces, increasing the received dose through increased retention time. [17,19]

Bafokeng Rasimone Platinum Mine lies on the Western Limb of the Bushveld Igneous Complex (known as the Bushveld Complex), which hosts approximately 80% of the world's known platinum resources. [1,3] The Bushveld Complex is estimated to have formed approximately 2,060 million years ago and its mafic rock sequence, the Rustenburg Layered Suite (RLS), is the world's largest known mafic igneous layered intrusion containing approximately 90% of the world's known Platinum Group Metals (PGM - Platinum, Palladium, Rhodium, Iridium, Osmium & Ruthenium) reserves. [3,4] In addition to the Platinum Group Metals (PGM's), extensive deposits of Iron, Tin, Chrome, Tin, Vanadium, copper, Nickel and Cobalt also occur. [4] The Bushveld Complex extends approximately 450 km east to west and approximately 250 km north to south. [4] It underlies an area of some 65,000 km², spanning parts of the Limpopo, North West, Gauteng and Mpumalanga Provinces of South Africa. [4]

Occupational exposure to Radon-222 gas in the South African Platinum Mining Industry has never been measured and quantified and no information is available on the possible exposure of underground employees

## 1.2 PROBLEM STATEMENT

The geological composition of the Bushveld complex contains uranium in variable amounts, giving rise to the possibility of occupational exposure to Radon-222 and its decay products in an underground mining environment. No data is available to quantify underground occupational exposure to Radon-222.

## 1.3 RESEARCH OBJECTIVES

- To measure the occupational exposure to Radon-222 in a underground platinum mine in South Africa to establish baseline data for exposure in the South African Platinum mining industry
- To evaluate factors influencing occupational exposure to Radon-222 in a underground platinum mine in South Africa

## 1.4 HYPOTHESIS

The exposure to Radon-222 gas in an underground South African platinum mine is below the occupational exposure limit level of 50 mSv per year.

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# CHAPTER 2: LITERATURE STUDY

## 2.1 OVERVIEW

Atoms are the extremely small particles of which all matter is made. [16] There are 92 naturally occurring elements and scientists have up to now made another 17, bringing the total number of elements known to man to 109. [16] Atoms are the smallest unit of an element that behaves chemically the same way the element does. [16] When any two chemicals react with each other, the reaction takes place between electrons of the individual atoms of the respective chemicals. [11,16] The instability that causes materials to be radioactive and to emit particles and energy also occurs at the atomic level. [11,16]

In the early 20th century, a New Zealand scientist working in England, Ernest Rutherford, and a Danish scientist, Niels Bohr, developed a system that described the structure of an atom as looking very much like the solar system, seen in figure 2.1. [16,24] At the centre of every atom was a nucleus, which is comparable to the sun. Electrons moved around the nucleus in "orbits" similar to the way planets move around the sun. [24]

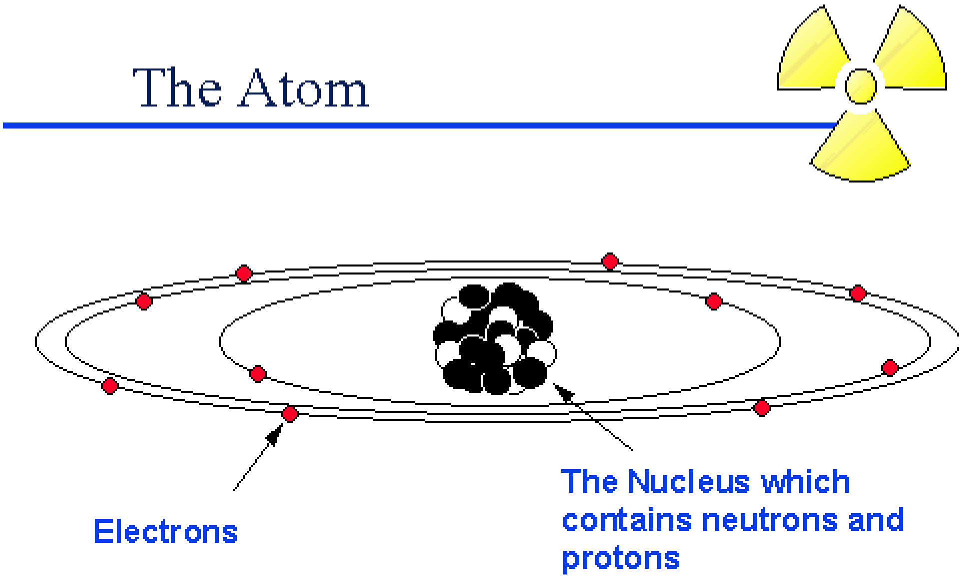

**Figure 2.1**: Atom structure
(http://www.physics.isu.edu/radinf/images/atom.gif)

The nucleus contains protons and neutrons. [24] Neutrons have no electrical charge, and like protons, are about 1800 times as heavy as an electron. [24] Protons are positively charged particles. [24] All atoms of an element (radioactive and non-radioactive) have the same number of protons. [24] The protons and neutrons in the nucleus, and the forces among them, affect an atom's radioactive properties. [25] The particles that orbit the nucleus as a cloud are called electrons. [16] They are negatively charged and balance the positive electrical charge of the protons in the nucleus. [16] The interactions with electrons in the outer orbits affect an atom's chemical properties. [16,24] Opposite electrical charges of the protons and electrons do the work of holding the electrons in orbit around the nucleus. [16] Electrons closer to the nucleus are bound more tightly than the outer electrons because of their distance from the protons in the nucleus. [16] The electrons in the outer orbits are more loosely bound and affect an atom's chemical properties. [16]

The nucleus is held together by the attractive strong nuclear force between protons and neutrons. [24] This force is extremely powerful, but extends only a very short distance, about the diameter of a proton or neutron. [24] There are also electromagnetic forces, which tend to shove the positively-charged protons apart. [24] In contrast to the strong nuclear force, the electric field of a proton falls off slowly over distance extending way beyond the nucleus, binding electrons to it. [16] The balance between the strong nuclear force pulling the nucleus together and the positive charges of the protons pushing it apart is largely responsible for the properties of a particular kind of atom or nuclide. [25]

The delicate balance of forces among nuclear particles keeps the nucleus stable. [25] Any change in the number, the arrangement, or energy of the nucleons can upset this balance and cause the nucleus to become unstable or radioactive. [25] An atom that has an unbalanced ratio of neutrons to protons in the nucleus seeks to become more stable. [24] The unbalanced or unstable atom tries to become more stable by changing the number of neutrons and/or protons in the nucleus. [25] This can happen in several ways:

- Converting neutrons to protons
- Converting protons to neutrons
- Ejecting an alpha particle (two neutrons and two protons) from the nucleus.

Whatever the mechanism, the atom is seeking a stable neutron to proton ratio. [16] In changing the number of protons and neutrons, the nucleus gives off energy in the form of ionizing radiation. [25] The radiation can be in the form of alpha particles (2 protons and 2 neutrons), beta particles (either positive or negative), x-rays, or gamma rays. [25] When there is a change in the number of protons, the atom becomes a different element with different chemical properties. [16] If there is a change in the number of neutrons, the atom is the same element, but becomes a different isotope of that element. [25] All isotopes of one element have the same number of protons but different numbers of neutrons. [24] All isotopes of a certain element also have the same chemical properties but have varying radiological properties such as half-life and type of radiation emitted. [25]

Nuclide is a term used to categorize different forms of atoms very specifically. [16] Each nuclide has a unique set of characteristics [16]

- Number of protons
- Number of neutrons
- Energy state.

If the number of protons, neutrons or the energy state changes, then the atom becomes a different nuclide. [24] Approximately 3,700 nuclides have been identified, with most of them being radionuclides, meaning that they are unstable and undergo radioactive decay. [25] Isotopes are sets of nuclides having the same number of protons, but different number of neutrons, thus having the same atomic number but a different atomic mass. [25] Isotopes that are unstable and undergo radioactive decay are called radioisotopes. [25] A change in the number of neutrons does not affect the charge of the atom. [16] Every known element has isotopic forms (natural or man-made) and heavier elements tend to have more isotopes than lighter elements. [25] A naturally-occurring element has one isotope that is more prevalent than any other. [25] In some cases, the dominant isotope accounts for all, or nearly all, of that specific element found in nature. [25] In other cases, the proportion may be nearly equal among two or more isotopes. [25]

The atomic mass assigned to the element in the periodic table usually represents an average of the masses of its isotopes. [24] The average has been adjusted (weighted) to reflect the relative abundance of the different isotopes found in nature. [24] Sometimes the mass of the most stable (longest-lived) isotope is listed. [24] Therefore, even though the carbon isotope Carbon-12 is the basis for the Atomic Mass Unit, the atomic mass of carbon is usually listed as 12.011, because of its isotopes. [24] Nuclear isomers are two nuclides that have different energy states, but have the same number of protons and the same number of neutrons. [25] As a result, they undergo radioactive decay differently. [25] One of these nuclides is generally less stable and will decay very quickly, although both or neither may be unstable. [25] The nuclear isomer that decays very quickly (has a very short half-life) is sometimes referred to as being metastable. [25] Sometimes the metastable isomer decays to the longer-lived (or more stable) isomer. [25] This type of decay is called isomeric transition. [25] Because both isomers are identical (except for their energies), the existence of a metastable isomer may only be suspected because the energy it gives off is different from the energy given off by the more stable isomer. [25]

Most naturally occurring radioactive materials and many fission products undergo radioactive decay through a series of transformations rather than in a single step. [25] Until the last step, these radionuclides emit energy or particles with each transformation and become another radionuclide. [25] Man-made elements, which are all heavier than uranium and unstable, undergo decay in this way. [25] This decay chain, or decay series, ends in a stable nuclide. [24] Radionuclide decay chains are important in planning for the management of occupational exposure. [19] As radioactive decay progresses, the concentration of the original radionuclides decreases, while the concentration of their decay products increases and then decreases as they undergo transformation. [16]

The importance of understanding decay chains is illustrated by Radon-222 during the decay of Uranium-238. [4,66] Uranium was distributed widely in the earth's crust as it formed. [17] Given the age of the earth, uranium's slowly progressing decay chain now commonly produces Radon-222. [108] Radon-222 is radioactive and has several characteristics that magnify its health effects:

- Radon is a gas. It can seep through soil and cracks in rock into the air. It can seep through foundations into homes (particularly basements), and accumulate into fairly high concentrations. [82]
- Radon decay emits alpha particles, the radiation that presents the greatest hazard to lung tissue. [82]
- Radon's very short half-life (3.8 days) means that it emits alpha particles at a high rate. [82]

Higher than expected levels of lung disease found in uranium miners helped call attention to the effects of Radon-222. [75] The miners worked long hours in enclosed spaces, surrounded by uranium ore and radon that seeped out of the rock. [75] Health workers expected to see health problems in the miners that would reflect direct exposure to radiation. [75] Instead, the predominant health problems were lung cancer and other lung diseases. [65]

Radiation is a form of energy that occurs naturally in the environment and has always been present on earth. [109] Radiation travels through space and air, and exposure to naturally occurring radiation is referred to as background radiation. [109] Background radiation can be explained as the radiation one is constantly exposed to as a result of natural sources. [44] It is similar to background noise, where the ongoing noise in one’s immediate surroundings are taken into account, but does not have a direct influence on one’s activities. [44]

The knowledge or radiation levels and radionuclide distribution in the environment is important for assessing the effects of radiation exposure on workers due to both terrestrial and extra terrestrial sources. [43] Although large amounts of ionizing radiation are artificially produced, the greater proportion of the general public`s exposure is to naturally occurring radiations from radioactive materials in the earth`s crust, radioactive gases in the atmosphere and cosmic radiation from outer space. [66] Terrestrial radiation is due to the radionuclides present in rocks, soils, building materials, water and the atmosphere, with some radionuclides ending up in the food chain or being inhaled, and the ionizing radiation produced artificially by man. [66] The majority of human exposure to ionizing radiation is attributed to naturally occurring radioactive elements in solids and the ground, cosmic rays entering the earth`s atmosphere and internal exposure from radioactive elements ingested with food, water and by breathing. [72]

Exposure to radiation can and must be controlled, since over exposure, depending on the type of radiation, can be hazardous to health, leading to damage or structural and functional changes in various cells involved in genetic storage, immune response, oxygen and carbon dioxide transport and possible leading to cancerous formation. [26,31,62,73] The most common form of thermal radiation known to man is ultraviolet radiation. [31,39] Without it, no life on earth would be sustainable. [39] Too much sunshine, on the other hand, has adverse health effect on all life forms on earth. [39] Sunshine consists of radiation in a range of wavelengths starting at $10^{-1}$ µm, which is in the ultraviolet region, up to $10^{2}$µm, also known as infrared, as indicated in Figure 2.2. [39] Of these, ultraviolet radiation is the most hazardous. [39] Sources of chronic low-dose radiation have become almost omnipresent in our environment as a result of nuclear testing, radiation accidents, and diagnostic-, therapeutic- and occupational exposures. [44]

Exposure to radiation is a great concern in goldmines, due to the high uranium content of the ore, constant employee exposure to radiation, as well as the lack of knowledge concerning the influence of irradiation on the long-term health of employees. [29] This inefficiency will have major financial implications on the mines, as compensation will have to be paid should employees develop pathology as a result of exposure during their employment. [29] Underground exposure to ionizing radiation is higher than surface exposure due to the close proximity of radiation sources coupled with the limited air circulation. [52]

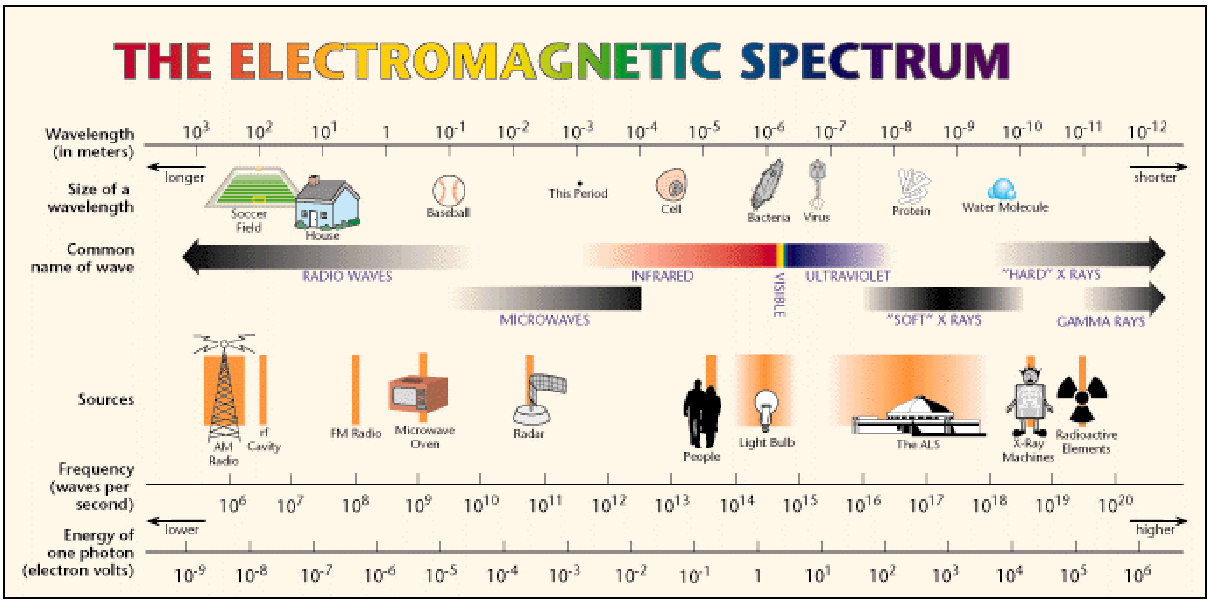

**Figure 2.2** Radiation Spectrums

(http://www.umanitoba.ca/faculties/medicine/radiology/stafflist/staffitems/RADPRO%20Course/spectrum.htm)

Figure 2.2 shows the complete radiation spectrum with thermal radiation as indicated. [58] Visible light can also be found within the thermal radiation region, starting at a wavelength of 0.4 µm and ending at 0.7 µm. [58] it consists of violet, blue, green, yellow and red waves. [58]

## 2.2 RADIATION AND MINING

Mining is an multi-disciplinary industry, long recognized as being arduous and liable to injury and disease. [34,50] The industry employs a labour force of several hundred thousand miners, both in South Africa and in the rest of the world. [34,52] Working with natural raw materials will always increase exposure to radiation. [108] All rock and soils contain uranium and thorium, which are both radioactive (Uranium isotopes, Uranium-238 and Uranium-237, and thorium isotope, Thorium-232), with uranium concentrations in the Bushveld Complex ranging between 11 and 66 parts per billion. [17,45]

Most of these radio-nuclides have extremely long half lives, as can be seen in Table 2.2. These half lives have a great impact on determining exposure time, since the half-life of the nuclide influences the risk to become exposed and develop pathology. [75,82] Exposure to radiation in the mining industry varies greatly, depending for instance, on the uranium concentration in the rock, as well as the presence of radon. [45,75] Radon (in this case mainly Radon-222) is a decay product of uranium with radon gas concentrations higher in soil with high concentrations of uranium. [45]

**Table 2.1** Summary of radiation exposure dosage and effects [53]

| Dose per annum | Effect |
|---|---|
| 0-50 mSv | Typical artificial exposure<br>± 0.005 mSv: Design target for perimeter fences at nuclear electric generating stations.<br>± 0.6 mSv: Most medical exposure doses.<br>± 3-5 mSv: Mining Background exposure (North-America, Australia, Canada).<br>± 20 mSv: Lowest dose that may cause cancer and the highest allowable dose over 5 years consecutively.<br>± 50 mSv: Highest allowable annual dose. |
| >100 mSv | Possibility of cancer |
| >1 Sv | Short term dose: Threshold for immediate radiation sickness |
| >10 Sv | Short term and whole body dose: Immediate illness and subsequent death. |

The above table briefly summarizes the doses of radiation used in certain instances, as well as some presumed pathology as a result of exposure. [53] The maximum allowable annual dose is 50 mSv, but for the continuous exposure the limit of 20 mSv is used, which is referred to as the “threshold” or occupational exposure limit in this study. [77]

**Table 2.2:** Radionuclide half-lives. [89]

| Radio-nuclide | | Half-live |
|---|---|---|
| Antimony-124 | (Sb-124) | 60.2 Days |
| Arsenic-77 | (As-77) | 111 Seconds |
| Barium-133 | (Ba-133) | 10.54 Years |
| Bromine-80 | (Br-80) | 4.4 Hours |
| Bromine-82 | (Br-82) | 35.3 Hours |
| Cadmium-109 | (Cd-109) | 464 Days |
| Calcium-47 | (Ca-47) | 4.53Days |
| Cerium-144 | (Ce-144) | 285 Days |
| Cesium-134 | (Cs-134) | 2.056 Years |
| Cesium-137 | (Cs-137) | 30 Years |
| Copper-67 | (Cu-67) | 2.58 Days |
| Germanium-75 | (Ge-75) | 82 Minutes |
| Germanium-77 | (Ge-77) | 52 Seconds |

| Radio-nuclide | | Half-live |
|---|---|---|
| Gold-198 | (Au-198) | 2.69 Days |
| Hafnium-181 | (Hf-181) | 46 Days |
| Iodine-128 | (I-128) | 25 Minutes |
| Iodine-131 | (I-131) | 8.02 Days |
| Lanthanum-140 | (La-140) | 40.3 Hours |
| Manganese-56 | (Mn-56) | 2.57 Hours |
| Molybdenum-99 | (Mo-99) | 66 Hours |
| Nickel-65 | (Ni-65) | 2.6 Hours |
| Niobium-92 | (Nb-92) | 34.7 Million Years |
| Niobium-94 | (Nb-94) | 20300 Years |
| Oxygen-19 | (O-19) | 26 Seconds |
| Phosphorus-33 | (P-33) | 25.3 Days |
| Promethium-147 | (Pm-147) | 2.62 Years |
| Samarium-151 | (Sm-151) | 90 Years |
| Samarium-153 | (Sm-153) | 46.3 Hours |
| Silicon-31 | (Si-31) | 2.62 Hours |
| Thulium-170 | (Tm-170) | 128 Days |
| Vanadium-52 | (V-52) | 3.67 Minutes |

## 2.3 PROTECTION OF MINE WORKERS AGAINST RADIATION

Protection against radiation aims to lower or limit the possible long-term effects of radiation. [22] There are four ways of protecting people against radiation. [22] The first method entails shielding through various barriers. [22] Lead barriers are most commonly used for this purpose. [22] This control measure is typically applied at nuclear installations and radio-therapy institutions. [22] Limiting the time of exposure to sources of radiation is the second method. [18,22] In the mining industry workers are continually exposed to rock with variable uranium concentrations. Many mine workers work shifts that are longer than eight hours a day due to production pressures, bonuses for overtime worked and a lack of self-discipline. [2,22] Limiting shifts to eight hours a day will have a significant impact on the reduction of exposure levels. [22,26]

The third method entails the distance between the source and the exposed employee. [22,93] This distance can be enlarged to minimize the effect of radiation when the half-life of radon is taken into account. [2,22] Unfortunately this solution is not viable in the mining industry because mine work demands immediate contact with the rock face. The fourth method entails containing the source. [22,93] Containing the source of emission in the mining industry is an impossible task, since the labour required involves direct contact with the rock face. [2] The Fifth method is dilution ventilation. [22,40]

Ventilation plays an important role in pro-actively reducing exposure to radiation by Radon-222 in the mine environment. [2,22] It prevents build-up of radon gas and contaminants through dilution, in areas that are no longer worked in, as well as areas that are actively mined. [2,40] The lower levels of radon gas and contaminants reduce the formation of agglomerated particles that cause internal exposure. [2,96]

Factors that could help to improve the situation are personal hygiene, personal protective equipment and job rotation, depending on the type and source of radiation exposure. [26,28,94] Wearing personal protective equipment (PPE) is impractical in the mine, because the workforce already wears a number of compulsory protective equipment (including hard hats, overalls, gumboots, ear protection, eye protection and sometimes respirators). [26,94] Adding the weight of yet another set of protective equipment, especially the kind of equipment used for radiation exposure, cannot be justified. [41,94] This type of equipment is heavy, expensive and does not allow free movement. [41,94] The physical workload upon these employees, as well as the environment conditions underground, also rules out any possibility of this type of PPE. [94]

## 2.4 RADIATION IN THE ENVIRONMENT

Radiation can be divided into two types on the basis of the formation, namely Natural and man-made. [98] Natural sources of non-ionizing radiation include cosmic radiation, magnetic fields, sunlight and lightning discharges. [98] Man-made sources of non-ionizing include wireless communications, industrial, scientific, medical and household instruments and appliances. Ionizing radiation sources include natural sources such as radioactive elements found in soil, water, air and food items, cosmic radiation, exposure to Radon-222 gas and gamma rays, Man-made sources of ionizing radiation include medical procedures and diagnostic instrumentation, nuclear waste, nuclear weapons, industrial gamma ray use and certain consumer products. [98,103] Ionizing radiation can easily cause damage to matter, and in particular to living tissue, hence the need to control excessive exposure. [103]

## 2.5 TYPES OF RADIATION

Radiation can be divided into 2 groups on the basis of their molecular interaction with matter namely ionizing and non-ionizing radiation. [11] *Non-ionizing* radiation is a term used to describe part of the electromagnetic spectrum that does not induce ionization in living cells and includes two main groups, namely optical radiation and electromagnetic fields. [21,63] Optical radiation includes ultraviolet, infrared and visible light. [21,63] Electromagnetic fields include power frequencies, radio frequencies and microwaves. [21,63] Non-Ionizing radiation consists of a stream of photons, each moving at the speed of light, possessing a certain amount of energy and traveling in a wave-like pattern. [21,63] Radio waves have a long wavelength, low frequency, low energies and behave like waves, with gamma rays as ionizing radiation on the other hand having short wavelengths, high frequencies, high energy and behaving like particles. [21,63] This contrasting behavior is called “wave-particle duality”, and is a function of the photon energy, with low energy photons behaving more like waves, and high energy photons behaving more like particles. [21,63]

### 2.5.1 NON-IONIZING RADIATION

Non-ionizing radiation does not play an active role in the scope of this study, for this reason it will not be discussed in detail and will only be summarized briefly. Non-ionizing radiation includes all forms of electromagnetic radiation. [63] Non-ionizing radiation refers to radiating energy that only has sufficient energy to excite and not to produce charged ions as found in ionizing radiation. [63] The non-ionizing radiation spectrum is divided into two main regions, namely optical radiation and electromagnetic fields. [63] The optical region can be further divided into ultraviolet, visible and infra-red spectrums. [63] The electromagnetic field can be divided roughly into microwave, very high frequency and low frequency radio waves. [63]

Non-ionizing radio wave radiation can be categorized as follows: [32]

ELF - Extremely low frequencies (3-30 Hz)

VF - Voice Frequency (30Hz – 3 kHz)

VLF - Very low frequency (3-30 kHz)

LF - Low frequency (30-300 kHz)

MF - Medium Frequency (300 kHz – 3 MHz)

HF - High Frequency (3-30 MHz)

UHF - Ultra High Frequency (300 MHz – 3 GHz)

EHF - Extra High Frequency (30-300 GHz)

Infrared rays are generally known as radiation heat, and have thermal effects on the environment. [32] All processes involving heat generation are sources of infrared rays, for example the sun, household appliances, telecommunication, airflow control and electrical circuits. [32] There is still considerable scientific debate concerning the possible adverse health effects associated with exposure to extremely low frequency non-ionizing radiation, with some studies hinting towards possible links between exposure and increased incidence of cancer. [21,33]

### 2.5.2 IONIZING RADIATION

Ionizing radiation is a term used to describe any form of radiation that induces ionization in matter. [74] Ionization is the transfer of energy that changes the normal electrical balance within an atom. [74] When a normal (electrically neutral) atom loses one of its orbiting electrons, the atom will become positively charged, forming a positive ion. [74,107] The electron that was stripped from the neutral atom is now a free electron with the ability to attach to another neutral atom to form a negative ion. [74] The negative and positive ions that are produced are known as ion pairs. [74,107] In living tissue, the ionization caused by ionizing radiation interacts with living cells in a manner that affects their normal biological functions and structure. [15] As the ionizing radiation passes through, it interacts with the atoms, transferring some of its energy, which is absorbed and causes the damage to the cells of the living tissue. [15] If the incoming and outgoing energies are almost identical in amount and nature, then there is little transferring of energy to the matter and the dose received will be small. [74,107]

Ionizing radiation can originate from both natural sources and artificial sources, such as accelerators and ortho-voltage machines. [74] In addition, it contributes to the electromagnetic radiation spectrum, in the form of x-rays and gamma-rays (with characteristic short wavelength and high penetration depth capacity). [74] These rays cause ionization in matter and are harmful to both the human body and the environment. [74] Electromagnetic waves have certain characteristics that will differ at different frequencies and wavelengths. [39] These wave characteristics will determine the kind of reactions the wave has with the matter, for example, penetration depth. [39] The energy an electromagnetic wave carries is called a quantum or a photon. [39] Where most atoms are stable, the opposite is true of isotopes. [74] These unstable isotopes are called radio nuclides. [74] Radio nuclides` will spontaneously rearrange into stable nuclei, emitting excess energy during the process. [74]

There are 5 types of ionizing radiation, namely alpha-particles, beta-particles, gamma-radiation, x-radiation and neutron radiation, each with its own hazards and protection measures. [74] The emission of alpha (α), beta (β) and gamma (γ) rays are connected with specific nuclear reactions. [19] The stable nucleus is called the decay product, and the energy emitted during the reaction can contribute to follow up ionization processes. [74] Each radioactive nuclide emits one or more type of radiation and each specific emission has an energy characteristic related to the decaying parent nuclide. [19,74]

### 2.5.2.1 ALPHA-PARTICLES OR RADIATION

Alpha-particles or radiation are formed during the process of disintegration within the nuclei of radioactive atoms. [8] Alpha-particles consist of a cluster of 2 protons and 2 neutrons that are ejected from the nucleus, giving the particle the same structure as a helium atom with a mass number of 4. [8] The ejection of an alpha-particle changes the parent atom by lowering the atomic number by 2 and the atomic mass by 4, e.g. if a atom of Uranium-238 emits a alpha particle, it changes to Thorium-234 as seen in Figure 2.3. [8,54] When the alpha particle is slowed down by material it hits, the alpha particles combine with electrons from the material through which it is traveling, to become helium atoms. [8] The positive charge (+2) of the alpha particles allow them to interact electrically with human tissue and other matter to induce ionization. [8,47] Alpha particles range in energy to over 7 MeV, but because of their large mass and dense ionization along the path they travel through a material, they can travel only short distances (10 cm) in air and are stopped by the outer keratin layers of the skin, a film of water or any other paper-thin material. [8,,47,54] Alpha particles are produced by radioactive elements with high atomic numbers, and alpha emitters are hazardous when taken into the body. [8] Some alpha emitters are chemically similar to calcium, and are absorbed into the bones, where upon disintegration they damage the sensitive bone marrow. [8,29] Other alpha emitters may concentrate in organs such as the kidney, liver, lungs and spleen. [8,29] When alpha-emitting materials are kept outside the body, little damage results because the alpha-particles cannot penetrate the outer keratin layers of the skin. [8,,28,47] Alpha-emitters are considered as only internal radiation hazards, and care is needed to avoid inhalation or ingestion of alpha-particle producing radioactive materials. [8,54]

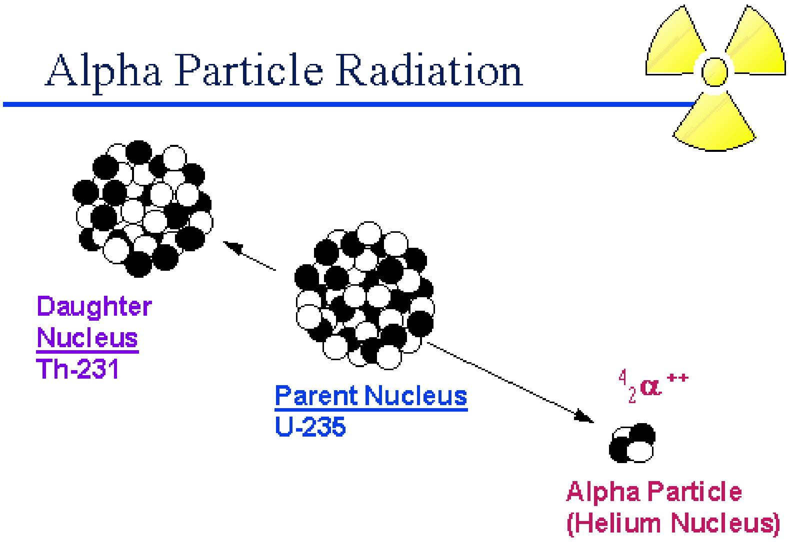

**Fig 2.3:** Alpha particle formation (http://www.umanitoba.ca/faculties/medicine/radiology/stafflist/staffitems/RADPRO%20Course/radiation.htm).

### 2.5.2.2 BETA-PARTICLES OR RADIATION

Beta-particles or radiation is generally negatively electrically charged particles with the same mass as an electron that are ejected from the nuclei of radioactive atoms during disintegration. [9] The ejection of a negative beta-particle during disintegration changes the radioactive atom into an element of a higher atomic number as seen in figure 2.4, when the ejected electron is stripped away from a neutron, turning it into a proton, increasing the atomic number by one. [9,82] Beta-particles have a broad range of energy values ranging from almost zero to the maximum value for a specific radionuclide. [9] The amount of energy of a beta-particle affects its range, with the higher energy beta-particles traveling farther, penetrating deeper, transferring more energy and causing more damage. [9,88] Beta-particles or high-energy electrons are emitted from a wide variety of light and heavy radioactive elements. [9,88] When a beta-particle is slowed down or stopped, secondary bremsstrahlung, a type of x-radiation, may be produced. [90] Aluminum and other light metals are preferred as shielding material for beta-particles because they produce less bremsstrahlung than other types of shielding material. [84]

The ionization caused by beta-particles is reasonably high, but lower than for alpha rays. [107] Beta-particles` penetrating depth is more than alpha rays; up to 3 m in air, and 1-2 cm in water. [107] Beta-particles can penetrate human tissue up to 5 mm. [107] Beta rays can be completely absorbed by thin metal (1-3 mm) or Perspex (10 mm) as shielding material. [84]

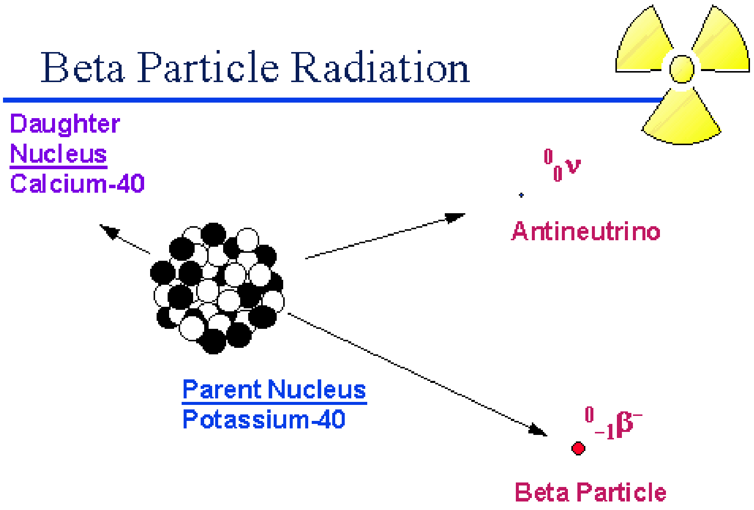

**Fig 2.4:** Beta particle formation (http://www.umanitoba.ca/faculties/medicine/radiology/stafflist/staffitems/RADPRO%20Course/radiation.htm).

### 2.5.2.3 X-RADIATION

X-radiation is commonly known as the electromagnetic radiation produced by an x-ray machine. [43] X-radiation is classified as electromagnetic radiation that originates outside the nucleus. [43] Most x-radiation is produced in specifically designed apparatus such as industrial and medical x-ray sets. [43] In an x-ray machine, the voltage across the electrodes of the vacuum tube accelerates and determines the energy of the electrons forming the x-rays. [43] X-rays may also be produced in any electrical apparatus in which there is a heated cathode emitting electrons and a potential difference of a few thousand volts accelerating the electrons so that they bombard an anode, as with cathode-ray tubes, radio valves, valve rectifiers, electron beam welders, electron microscopes, mass spectrometers and Gyrotrons. [43,74] When high-speed electrons are slowed down by material, they release energy in the form of x-radiation. [10] Because the electrons strike and interact with the material it strikes at various speeds, the x-ray beam has a variety of wavelengths and energies to produce a clear image. [43,74] The wavelength of the x-rays determine the penetrating power, with short wave length x-rays having more penetrating power than long wave length x-rays

### 2.5.2.4 GAMMA-RADIATION

Gamma-radiation is identical to x-radiation except that the electrons originate from within the nucleus of an atom. [10] Gamma-radiation is classified as electromagnetic, and has the ability to ionize molecules within matter. [10,84] Gamma radiation is emitted as an accompaniment to most alpha and beta-particle emissions, with gamma only emissions formed artificially. [10] A gamma-ray emitted by a radionuclide has a fixed energy specific to that radionuclide from which it originated. [10,19] Gamma-rays present a large external radiation hazard because of their ability to penetrate deep into the body. [10,19,86]

Excess energy from the decaying nucleus is emitted with this type of radiation as seen in figure 2.5. [53] It is electromagnetic radiation of very short wavelength, and the energy levels can increase up to 3 x $10^6$ eV. [107] Again there is a decrease in the amount of ionization from beta-rays to gamma-rays. [107] Depending on the energy, gamma rays have extreme penetration depths; accordingly thick concrete or heavy element is needed to absorb the rays. [38] Gamma rays can pass completely through the human body. [38] In mining, the gamma-exposure is mainly an external hazard because of the rock face, stockpiles, localized concentrations and so forth, and is not a risk of major concern in the mining industry. [38]

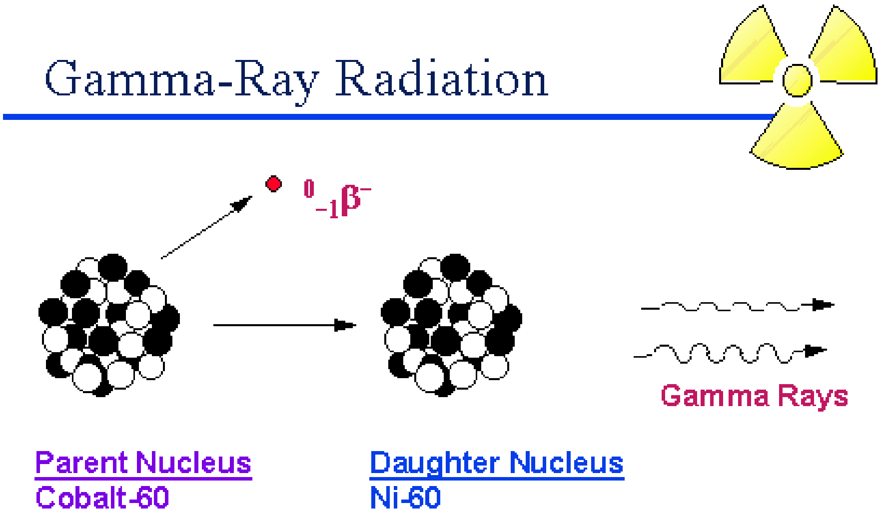

**Fig 2.5:** Gamma particle formation (http://www.umanitoba.ca/faculties/medicine/radiology/stafflist/staffitems/RADPRO%20Course/radiation.htm)

#### 2.5.2.5 NEUTRON RADIATION

Neutron radiation is not commonly encountered, but does pose a health hazard. [59] Neutrons exist within the nuclei of all atoms except hydrogen, and are only released when certain radioactive materials such as Californium-252 and fissionable isotopes (Plutonium-Beryllium, Americium-Beryllium and Americium-Lithium) disintegrate. [68] The energy state of neutrons varies with the method by which they are produced, and the range of neutrons varies with their energy state, high-energy neutrons having more penetrating power. [93]

### 2.5.3 RADIATION CHARACTERISTICS

Of all the types of radiation only alpha and beta-particles are directly ionizing when interacting with the matter, because they carry an electrical charge, the other types of radiation do not poses a electrical charge and do not produce ionization by their interaction with the target material. [20] Ionizing radiation is classified on ground of their origin namely natural and man-made ionizing radiation. [20] Natural ionizing radiation can further be divided into radon exposure, internal radiation sources such as radioactive elements in food, terrestrial sources such as isotopes of uranium and thorium in the earth`s crust and cosmic sources such as radiation from the sun. [55]

Radioactive decay is a random process where a radioactive nucleus is likely to spontaneously break down into other atoms (or daughters) during a period of time. [89,106] All radioactive elements have an element specific time in which the strength (quantity) of the specific radioactive material decreases by one-half, which is known as the element's half-life. [106] The half-life of a radioactive element is not affected by external factors such as temperature, pressure or its chemical state. [53,106] The unique half-life of each radioactive element can vary from billions of years to fractions of seconds. The length of time, steps involved and types of radiation emitted during decay are well-known, and happen randomly, but with certain specific characteristics. [106] The half-life of atoms in a radioactive substance is the time it takes for half of the atoms to decay, or the time it takes for the isotope to give off its radiation and become a different element, which can vary greatly. [106] Radon is a by-product of Uranium-238 decay, contributing to a great deal of one`s natural exposure to radiation. [14,81,87]

The human body can tolerate a certain amount of ionizing radiation without the impairment of its overall functions. [53,81] The human race has continuously been exposed to ionizing radiation from natural sources such as cosmic radiation and radioactive materials inside and around us for millions of years. [53,70] This background radiation is part of the normal everyday environment, with adaptation on a cellular basis to cope with radiation damage. [105] The source and type of radiation has a great impact on the effect of ionizing radiation on a living system. [53]

The focus of this study is mainly on alpha rays, but beta and gamma rays also play an important role in exposure to ionizing radiation. [53] Radon-222 gas enters the lungs and can decay in the time spent in the lungs, with the accompanying alpha emitted causing internal alpha particle exposure of the lung tissue, leading to lung tissue related pathology. [81,87]

### 2.5.4 URANIUM (U) AND RADIATION

Uranium is a naturally occurring radioactive element that is classified as a heavy metal, with an atomic number of 92 and an atomic mass of 238.0289 amu, and primarily radiates alpha particles. [13,14] It is found in small amounts in rock, soil, surface and underground water, air, plants and animals. [13,14] The total amount of uranium on the earth (approximately 2-4 ppm) remains more or less constant as a result of its long half-life. [2] It can, however, be moved around by processes like mining. [2] Uranium mining and milling activities have the potential to remobilize radio nuclides and other pollutants and release them into the environment. [2] When rocks are broken, the uranium can become part of the soil, be carried to rivers and lakes and into the atmosphere. [2] These components have a great contribution to radiation hazards and must, therefore, be further investigated in order to reduce the radiation risks on the change of other non-radiological risks. [13,14] Water and vegetable ingestion are the most important pathways to human health risk in this regards. [13,14] Uranium is usually found in the form of minerals, but can be refined to a very dense, silver-colored metal. Industrial processes which enrich uranium create a by-product called depleted uranium. [13,14] The enriched uranium is far more radio-active than depleted uranium. [13,14]

The external radiation danger of uranium is not great; since the alpha particles generated do not have enough energy to penetrate the human body to an extent that would cause harm. [14,57] Furthermore, most absorbed uranium is excreted in the urine within a few days. [14,57] However, in the occupational environment these uranium particles become airborne and can be inhaled, ingested and the radiation energy produced absorbed by tissue surrounding the particles. [14,50] Inhalation is dangerous because the particles become lodged in the lungs where it becomes an internal hazard, directly affecting the sensitive tissue of the lungs. [14,50]

Uranium and its compounds are extremely toxic substances, with those compounds soluble in bodily fluids being the most toxic. [92] Fortunately, uranium found in South African is low in specific radioactivity. [92] The soluble compounds can be inhaled, systemically absorbed, and be excreted in the urine, or it can remain in the kidneys, which ultimately leads to uranium poisoning. [92,96] A number of projects have been launched to rehabilitate areas that were subject to uranium mining all over the world. [92] In East Germany the WISMUT Corporation started the WISMUT rehabilitation project, which has since become an international reference project for various mining sites. [92]

The decay process of Uranium-238 can be summarized as shown in Figure 2.6. This process will continue until the formation of Lead-206, which is a stable element.

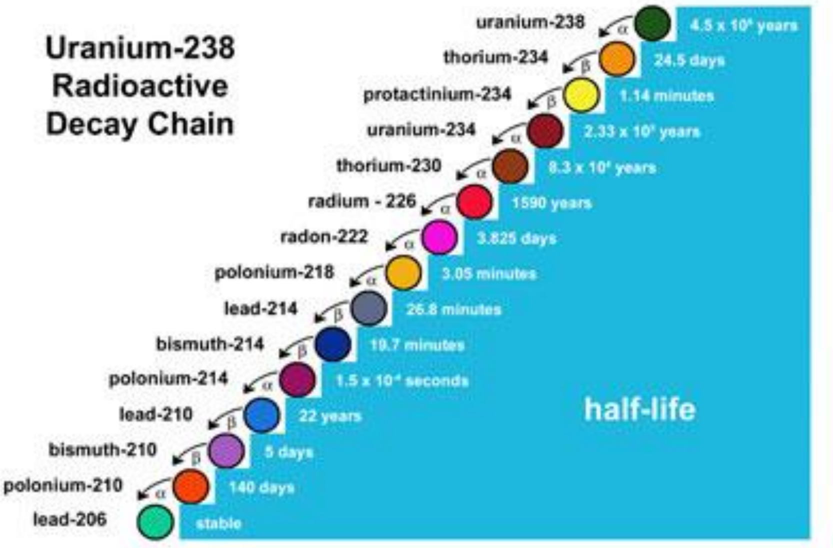

**Fig 2.6:** Uranium-238 decay chain

(http://www.ocrwm.doe.gov/curriculum/unit2/lesson2reading.shtml).

The Uranium-238 atom has 92 protons and 146 neutrons, and a half-life of 4.5 billion years. [53] With decay, it emits an alpha particle, leaving behind Thorium-234 atom. [53] Thorium-234 has a half-life of 24.5 days and emits a beta particle on decay, forming a Protactinium-234 atom. [53] Protactinium-234 has a half-life of 1.14 minutes and emits a beta particle on decay, forming a Uranium-234 atom. [53] Uranium-234 has a half-life of 233 000 years and emits a beta particle and a gamma ray on decay, forming a Thorium-230 atom. [53] Thorium-230 has a half-life of 83 000 years and emits a alpha particle on decay, forming a Radium-222 atom. [53] Radium-222 has a half-life of 1 590 years and emits a alpha particle on decay, forming a Radon-222 atom. [53] Radon-222 has a half-life of 3.825 days and emits a alpha particle on decay, forming a Polonium-218 atom. [53] Polonium-218 has a half-life of 3.05 minutes and emits a alpha particle on decay, forming a Lead-214 atom. [53] Lead-214 has a half-life of 26.8 minutes and emits a beta particle on decay, forming a Bismuth-214 atom. [53] Bismuth-214 has a half-life of 19.7 minutes and emits a beta particle on decay, forming a Polonium-214 atom. [53] Polonium-214 has a half-life of 150 microseconds and emits a beta particle on decay, forming a Lead-210 atom. [53] Lead-210 has a half-life of 22 years and emits a beta particle on decay, forming a Bismuth-210 atom. [53] Bismuth-210 has a half-life of 5 days and emits a beta particle on decay, forming a Polonium-210 atom. [53] Polonium-210 has a half-life of 140 days and emits a alpha particle on decay, forming a Lead-206 atom. Lead-206 is a stable atom and does not undergo further radioactive decay. [53]

## 2.6 PHYSIOLOGICAL EFFECTS OF RADIATION.

### 2.6.1 OVERVIEW

It can be assumed that any radiation dose, whether small or large, poses a health risk. [48,102] Responses to low doses of radiation appear to depend on genetic and environmental factors, the type of cells, the proximity of the cells to one another, the functional state and the demands of the affected organs, and not solely on the dose received. [30,73,102] Survival among cells exposed to a single dose of radiation is higher than cells exposed to continual radiation due to the cumulative effects of radiation exposure on living cells and tissue, depending on the specific tissue`s ability to withstand and repair radiation induced damage. [73,99,102]

Cells in the body generally reproduce and divide in order to repair damaged tissue and bring about growth (proliferation). [3] With cancer, the cells multiply at uncontrollable rates, forming tissue masses that are called tumors. [3] These tumors can either be malignant (cancerous) or benign (non-cancerous). [3] Benign tumors usually stay localized in the area they first appeared and are in general not life threatening. [3] Malignant tumors can spread throughout the body and damage healthy tissue. [3] Lung cancer will generally spread through the whole body until it reaches the lymphatic system. [3] From there it moves toward any organ in the body. [3] Secondary tumors, also called metastic tumors, are formed and primarily found in the brain, liver and bone (including bone marrow). [3]

The lungs, for example, are able to tolerate high doses of exposure, in small quantities, but cannot tolerate low doses in large quantities, while the spinal cord cannot handle a high dose exposure at low quantities. [73,97] Environmental factors play a definite role in the onset of cancer as a result of radiation exposure, which complicates the verification of the outcome (responses and symptoms), because not all contributing factors, including those at cellular level, are known. [73,97]

Smoking, strong sunlight (especially in South Africa), environmental, dietary, health and genetic factors all play a role in the production of various forms of cancer. [2] The body has defense mechanisms in place against the damage done by radiation, since we are being bombarded by background radiation, which constantly affects approximately 10 million cells per minute. [99] On the other hand, radiation is widely used (in a controlled, direct manner) to kill cancerous cells in a tumor, often saving lives, as well as to kill bacteria in food and sterilize medical equipment. [107]

There are scientific studies done that determine the occupational exposure limits (OEL`s) and threshold level of safety. [107] It seems that the lower the dose and the rate (at least 10 mSv/a), the greater the possibility that there will either be a fifty percent beneficial or adverse effects following exposure. [107] It can also be assumed that genetic mutations occur after extensive exposure, affecting future generations. [53] At very high doses, exposure to radiation can cause sickness and death within weeks. [57]

The degree of damage depends on many factors, including the dose, type of radiation, age, health and tissue exposed. [53] Radiation injury can be defined as acute, consequential and late effects of radiation exposure, depending on the latent time between exposure and the first signs of symptoms. [53] Damage to cells due to radiation will have adverse health effects if not given sufficient time to repair. [57] These effects are known as deterministic and stochastic effects. [57,107] Deterministic effects are found when the dose exceeds the threshold, and the cells cannot survive or reproduce. [57] Excessive damage can result in loss of tissue function. [57] When the dose is above the threshold, the harm caused rises steeply with increased dosage. [97] This effect is uncommon under normal mining conditions and usually restricted to accidents at nuclear installations. [97] Stochastic effects are effects that occur on a random basis with its effect being independent of the size of dose. [97] The effect typically has no threshold and is based on probabilities, with the chances of seeing the effect increasing with dose. [97] Cancer formation is a stochastic effect. [97]

Epidemiological studies have shown a correlation between a prolonged exposure to ionizing radiation and definite and measurable increases in the occurrence of cancers, such as lung cancer, and leukaemia (blood cancer). [1,52,53,62,64]

There is insufficient evidence to determine a correlation between uranium exposure and lymphatic- and bone cancer, but the possibility cannot be ruled out. [1] Research also suggests that exposure to radiation in a gold mine does not justify close monitoring, although there have been previous correlations between silica dust, smoking and radiation regarding the risk of lung cancer. [1,52] The prevalence of lung cancer seems to be higher in silicotics than nonsilicotics, regardless of the smoking habits of mine workers who were exposed to low radon levels over extended periods of time. [1,52] The results were inconclusive though, because of the large numbers of variables that play a role in the onset of cancer. [52,64]

Underground Radon-222 exposure comes through the ore or underground water containing uranium or associated decay products. [107] Particles liberated by natural air movement or human activities will become airborne and ready for inhalation, although the radiated particles are not retained in the respiratory system, because these free radon daughters are too small to be deposited in the respiratory tract. [107] These free radon daughters are metallic ions that readily attach themselves to water molecules and atmospheric gasses, forming small particles that attach themselves to larger airborne particulates or dust (with a diameter of 0.3 mm or larger). [107] It is these agglomerated particles that are then inhaled and become lodged in the airways and lungs. [107] The radiation particles are deposited onto the tissue before it can be removed naturally, leading to increased retention time and ultimately radiation exposure. [107] Thus proper ventilation plays a very important role in the prevention of over-exposure to radiation in the mining environment through the removal of airborne particulates to which these radon daughters can attach. [107]

The uranium particles can also be absorbed into the blood through the lungs or gastrointestinal tract, carrying the particles throughout the whole body. [14] Most of the particles are excreted within a few days, but some are retained in the kidneys and bones. [14] Animal studies show a tendency towards kidney diseases after prolonged exposure to large doses of uranium. [14] These diseases are not prevalent in mine workers as a result of uranium exposure, since they are only subject to small amounts of exposure. [14,42]

Low-dose ionizing radiation has become an area of great concern, even though there is not sufficient evidence or data available to substantiate finding and assumptions. [34] Radiation dose-response relationship can be determined with the linear-no-threshold model that has been adopted, but is limited, insufficient and too simplistic for scientific research. [34,47]

The linear no-threshold model is a model of the damage caused by ionizing radiation, and particularly the increased risk of cancer. [47] It assumes that the response is linear and that this linear relationship continues to very small doses. [47] In other words, there is no threshold of exposure below which the responses cease to be linear. [47] A practical example is that if a thousand people are exposed, the model predicts that one thousandth of this dose will produce one extra case in every million people equally exposed, and that one millionth of this dose will produce one extra case in every billion people exposed. [47] This model has been in use for a long period of time. [47]

The effects resulting from exposure can be acute, where symptoms are immediately recognized. [97] This happens mostly in tissue with proliferating cells (cells that are able to multiply themselves) such as the epithelial surface of the skin. [97] The effect is mainly deterministic, because the functional cell damage occurs at the stem-cell compartment and the cells cannot be replaced. [97]

Compensatory proliferation occurs in the skin and gastrointestinal tract, since these cells are more tolerant to irradiation that others. [97] Vital cellular components are damaged as a result of ionization and the free radicals that are produced with radiation exposure, leading to DNA damage, and ultimately, cell death. [48,78,97] Unrepaired chromosome damage also causes cell death. The maintenance of genomic stability depends on the ability of cells to sense and recognize damaged DNA and then to either repair or induce an exit, through apoptosis or cell differentiation. [78,97]

Apoptosis can be defined as programmed cell death, brought on by a genetic process where cells destroy themselves by the fragmentation of nuclear DNA. [76] This is activated by the presence or absence of stimuli and is a normal physiological process of removing unwanted and damaged DNA cells from the body. [104] Uncontrolled cell growth and tumor formation, similar to genetic mutation, might result when this process is blocked. [104]

It is suggested that p53, a tumor suppressor gene that is activated following genotoxic stress, may trigger the onset of DNA-repair leading to the completion of the cell cycle. [97] It may also induce apoptosis or terminal differentiation, leading to exit from the cell cycle. [78,97] It was found that this DNA repair was enhanced at high doses of γ-irradiation and when p53-protein levels were reduced. [78,97] Responses to irradiation include fibroblast responses, which results in excess collagen deposition and fibrosis, activation various cellular signaling pathways involved with the onset of oedema and inflammatory conditions. [97]

Late effects have extended latent periods (as with the onset of cancer) and symptoms appear spontaneously and in a number of ways. [91,97] The tissues involved are tissue with slow turnover, such as subcutaneous, fatty, muscle, brain, kidney and liver tissue, as well as the intestinal wall, resulting in injuries like fibrosis, necrosis, atrophy and vascular damage. [91,97] The responses to these injuries include cytokine production, which leads to adaptive responses in the surrounding tissue and cells (much like wound healing responses). [91,97] Cytokines are a class of immunoregulatory substances (similar to lymphokines) that are secreted by cells of the immune system. [91,97] Consequential effects target mainly the skin, mucosa, urinary and intestinal systems and are the result of chronic injury. [91,97]

### 2.6.2 CELLULAR PATHOLOGY

Radiation therapy, usually conducted with gamma-rays, has advanced technologically in the last couple of years. [30,95] It has only been recently that doses can be administrated and distributed more accurately, ensuring less tissue damage, reduced toxicity levels, increased quality of life and a subsequent increase in the likelihood of tumor control. [30,47] It is not only the targeted cells that respond to radiation, but also the bystander cells, or those cells in close proximity to the targeted cells that is influenced by irradiation. [15,65]

There are a number of limitations to radiation therapy research. [30,47,99] These include methods of analysis, limitations of the cumulative dose-volume histogram that is used, uncertainty concerning normal tissue complication probabilities and unethical as well as unplanned exposure of individuals. [30] Dose-volume applications will remain subjective until these variables are better understood. [30,95] The most studied organs up to date are the lungs, liver and parotid glands. [95,]

An understanding of the possible effects of radio-frequency exposure on the genetic material of cells are important, since damage to DNA can lead to all kinds of pathology in different cell types. [95,99] There is little evidence that exposure is directly mutagenic, although there are some indirect effects on DNA replication/transcription of genes under controlled exposures. [95,99] Accumulation of dense extra cellular matrix (collagen and glycosaminoglycans), or fibrosis, plays a large role in irradiation processes, especially in the submucosa, muscular propria and subserosa of the lung, skin, muscle, liver and gastro-intestinal tract. [99]

Changes in cellular organelles include cellular swelling, mitochondrial swelling, irregular shaping of the cell membrane, degranulation and vesicularisation of the endoplasmic reticulum, enlargement of the Golgi complex, rearrangement of the cytoplasmic actin and cytokine filaments, and protein degradation, increase in the cytoplasmic volume of lysosome-like vacuoles in the enterocytes and increased activity of lysosomal hydrolysis. [15,95]

Irradiated cells have abnormal projections, altering the cells` interaction with one another, as well as normal homeostasis in the cellular environment. [15] Tight junctions in the epithelial and endothelial cells are very important for transport processes in as well as between cells and have a great impact on the pathology of the organs. [15] Gap junctions are junctions that consist of a complete cell-to-cell channel that span two plasma membranes. [15] They result from the association of tow connexons (an extensive family of proteins), contributed separately by each of the two participating cells. [15]

Homeostatic control of normal cell growth pathways is known to be strongly dependent on oxidants. [91] A disruption of the balance between oxidant production and antioxidant defense leads to a state of oxidative stress that can induce several pathological conditions. [91,95] The endogenous targets of oxidants are diverse and include nucleic acids, proteins and lipids. [91,95]

Research done on cyclic AMP (cAMP) and the adenylate cyclase system which is involved in intracellular communication, found that functions of both these systems were altered with irradiation; cAMP concentrations increased, and adenylate cyclase activity via VIP (vasointestinal peptide) stimulation also increased. [15,95] Gap junctions in the cells are selective, and these second messengers (cAMP and cGMP) may be discriminated by or favored when damage is done. Calcium can also influence intracellular homeostasis in the small intestine. [15,95]

#### 2.6.2.1 LUNGS

The lungs are the most frequently exposed and the most radio-sensitive organs in the body. [97] Symptoms of exposure vary from congestion, cough, dyspnoea, fever, pneumonitis to breathing difficulties. [97] Tuberculosis may also result from exposure, but mostly because of the dust particles itself to which radionuclides readily attach. [97]

On a cellular level, the concentration of type II pneumocytes and alveolar macrophages increase, parenchymal cells and surfactant concentrations decrease, and hyaline membranes tend to develop. [79,97] Studies on cancer patients undergoing radiotherapy revealed that those with high plasma concentrations of the cytokines interleukin 1 and/or interleukin 6, before or during therapy, have a higher risk of developing pneumonitis. [79,97] Those with increased transforming growth factor β (TGFβ) have a higher risk of radiation induced lung injury. [79,97] TGFβ is a group of polypeptides that are secreted by a variety of cells, like monocytes, T cells, or blood platelets, and have diverse effects on the division and activity of cells. [79,97] These effects include induced angiogenesis, stimulating fibroblast proliferation, or inhibiting T cell proliferation. [79,97] The rennin-angiotensin system, associated with the development of radiation nephropathy, is also involved in the development of pulmonary injury after radiation exposure. [79,97]

Lung cancer is the most common form of cancer diagnosed in the United States (U.S.) and a major cause of death. [3] Lung cancer accounts for 28% of all cancer related deaths; with cigarette smoking contributing to 87% of all lung cancer deaths to date. [3] Lung cancer, as a result of radon exposure, is the second leading cause of lung cancer in the U.S. [3] Scientists believe that radon induced lung cancer is responsible for 15 000 to 22 000 deaths per year. [3,23]

Researchers first associated radon exposure with the prevalence of lung cancer when it became obvious that a large population of underground mine workers suffered from lung cancer. [3,5,6,12,35,64] Some research disagrees with the theory that uranium exposure contributes to cancer, saying that no human cancer has ever resulted because of uranium, although uranium decay products might contribute after prolonged exposure, and supports the view of other research. [12,14,35,69]

These contradictions necessitate an investigation into the effects of irradiation on workers in the mining environment, stressing the importance of obtaining data, which is why this particular study was conducted. This will allow proactive and progressive intervention in order to minimize any possibility of occupational disease in this regard.

#### 2.6.2.2 RADIATION SICKNESS

A single, high dose of radiation can be lethal. Uranium poisoning has adverse effects on the kidneys and the body's defense mechanisms. [3,107] This is generally as a consequence of accidents at nuclear installations or similar incidents and is not something commonly encountered. [3,107]

### 2.6.3 EXPOSURE LIMITS AND REGULATIONS

Occupational exposure to radiation in the mining industry in South Africa is regulated by two pieces of legislation. There is the Mine Health and Safety Act, 1996 (Act 29 of 1996), as well as the National Nuclear Regulator Act, 1999 (Act 47 of 1999). The International Commission on Radiological Protection (ICRP) has three basic principles, which have become the international standards for radiation protection: justification of practice, optimization of protection and individual dose and risk limits. [56,57] According to the abovementioned laws, the following dose limits have been proposed and implemented: An effective dose of 20mSv/a, over 3 consecutive years and a maximum effective dose of 50 mSv per year.

## 2.7 RADIATION MEASUREMENT

The amount of radioactive material is measured in Becquerel (Bq), which is a measure that enables one to compare the radioactivity of materials with one another. [74] One Becquerel equals one atomic decay per second. [74] The former unit of radioactivity was Curie. [74] The decay of radon results in a decay chain with the short-lived radioactive nuclides Polonium-218, Lead-214, Bismuth-214 and Polonium-214. [74] In general Polonium-214 is not specified. [74] Because of its short half-life, the concentration of Polonium-214 is in practice equal to the concentration of Bismuth-214. [74]

Decay product concentration is often described with a special unit: The potential alpha energy concentration (PAEC).[101] This unit originates from uranium ore mining and quantifies the biological influence of a decay product mixture.[101] It describes the resulting α-energy of all decay products in a distinct volume until their total decay.[101] The common unit is MeV/l .[101]

It is difficult to express different types of exposure in the same unit, because one gray of alpha radiation will have a greater effect than one gray of beta radiation.[74] Therefore, radiation effects are referred to as effective dose, which is a unit called Sievert (Sv).[74] In most cases the dose is expressed in Millisievert (mSv).[74] The effective dose reflects the biological effects, not the specific dose.[74]

### 2.7.1 AVAILABLE METHODS

Radiation cannot be detected through human senses, accordingly a variety of instruments have been developed to measure radiation.

#### 2.7.1.1 PASSIVE SAMPLING METHODS

**Table 2.3:** Passive sampling methods.[101]

| Method | Description |
|---|---|
| Charcoal absorption method | After a sampling period ranging between hours to three days, charcoal and absorbed radon, as well as decay products, are measured with liquid scintillation or gamma-spectroscopy. Various influences like atmospheric pressure, humidity, the type of charcoal used must be taken into account. |
| Nucleus tracing | A synthetic detector foil is placed in a measuring chamber with an inlet filter. Nuclei from radio-active decays inside the chamber cause damage to the foil. By corroding procedures this damage results in tiny, visible holes, where the number of holes is proportional to the radon concentrations. |
| Lucas-method | Radon decays cause scintillation effects in a chamber with activated (ZnS) walls. These scintillations are counted by use of a photo-multiplier. |

The above Table 2.3 shows a summary of the passive sampling methods. These methods do not need any power supply during sampling and a high number of equipment can be used at minimal costs.

#### 2.7.1.2 ACTIVE SAMPLING METHODS

**Table 2.4:** Active sampling methods. [101]

| Method | Description |
|---|---|
| Double filter method | Air is pumped through a measuring chamber, with a specific volume of air passing through an inlet filter. New decay products generated in the chamber are sampled and measured on an outlet filter. |
| Diffusion chamber method (nucleus trace method) | In this method an electronic detector and additional concentration systems are used. Decay products deposit on the walls and the detector. An electrical field between the detector and chamber is often used for higher deposition and measurement efficiency. |
| Ionization chamber method | Charge pulses from decays in a ray sensible volume are counted. At high radon levels a direct current can be measured instead of single pulses. |
| Filter method | Air is passed through a filter while decay products deposit on it. A detector measures the radioactivity on the filter. Various methods exist with different designs, flow rates, detectors, sampling and measuring intervals and calculation algorhythms. The use of filter ribbons and automatic transport systems allow long-term operations. |

These methods generally use pumps and electronic detectors for automatic operation. The double filter method, diffusion chamber or pulse ionization chamber methods are the preferred methods to detect and analyze irradiation from radon gas, as can be seen from Table 2.4.

#### 2.7.1.3 AREA SAMPLING / MONITORING

##### 2.7.1.3.1 GRS-2000 MultiSpec gamma-ray spectrometer

This instrument can be used for a variety of tasks for surface and borehole surveying. [46] It is a compact waterproof probe, equipped with a scintillator and sophisticated analysis applications. [46] It was designed for geophysical and environmental surveying, geological prospecting, industrial monitoring of radioactivity and laboratory analysis. [46] Both single and profile measurements can be taken and results are displayed in a graph on downloading. [46] One of the disadvantages is that it only measures gamma-rays. Accordingly it will not be effective in mines where alpha-rays are the main concern. [46]

#### 2.7.1.3.2 PGR portable scintillation meter

The PGR meter is accurate, sensitive and reliable. [36] It has the same disadvantages as the GRS-2000 MultiSpec gamma-ray spectrometer, namely that it only measures gamma-rays and it is relatively expensive. [36] It can be used many different spectrums, including mining and geology. [46] It is fairly easy to use and data can be downloaded onto a computer. [46] The fact that it can function in very rugged and robust conditions is a major advantage. [46]

#### 2.7.1.3.3 GRM-260

The GRM-260 is designed for field assays of rocks and for dose rate measurements. [46] Unfortunately its application is also limited to measuring gamma-rays. [46] It can be operated from a computer and is easy to operate in the field. [46] The GRM is quite expensive. [46]

#### 2.7.1.3.4 Electra

The Electra is a digital, microprocessor based rate meter and is compatible with most survey probes. Readings are displayed numerically and as bar graphs. It is robust, sturdy, balanced and easy and comfortable to use over long periods of time.

#### 2.7.1.3.5 Tracerlab IRG probe

This instrument is an AC-line/battery operating Radon gas monitor. [101] It is a self contained portable system based on air diffusion and system control by integrated display. [101]

### 2.7.1.4 PERSONAL SAMPLING

The impracticality of area sampling makes it necessary to use personal sampling methods to monitor radiation in mining. Most areas sampling instruments are expensive and produce a representative reading of doses in specific areas. The instruments are either stationary, subject to blasting fumes an do not represent the whole area, or must be carried around by a designated person, which influences exposure time and reliability. These instruments are, however, effective when spot readings are required for planning purposes.

#### 2.7.1.4.1 LCD-BWLM-PLUS

This is an AC-line/battery operation radon monitor, which is a self contained light weight portable system with a removable sampler. [101] It is compatible with most computers. [101]

#### 2.7.1.4.2 BWLM-PLUS

This is an AC-line/battery operating radon-monitor. [101] It is self contained, portable, simple to operate and can also be used to determine the Radon / Thoron free fractions. [101]

#### 2.7.1.4.3 RGM/ARDM-PLUS

This is the type of instrument that is in use in South African mines. [51] It is a radon-thoron-daughter monitor with a fixed filter. [51] This self contained system has a CR-39 plastic disk contained in a protection cap for installation under rough conditions. [51]

RGM Badges are used because it is the most cost effective method available. [51] The large numbers of employees required to be monitored on a regular basis makes this the best option. [51] The size of the badge makes it logistically flexible and it has the added advantage of not influencing the mine worker's performance. [51,100] It is also the best source of area monitoring, as radon gas concentrations fluctuate over time. [51,100] These instruments accompany the workers everywhere in the workplace. [51] A representative reading of the radon gas concentration for that workplace over a given period of time is acquired in effect. [51] Carbon infused RGMs are available that limit the impact of electrostatically charged particles that could negatively affect sampling results. [51]

## 2.8 RADON-222 (Rn-222)

Radon-222 is a radioactive gaseous element usually found in areas with high concentrations of uranium. [40,83] Radon-222 is formed through the decay of Uranium-238 and its daughter elements over thousands of years. [40,83] The decay of Uranium-238 over thousands of years results in situations where there is a mixture of radioactive substances existing in a single environment. [83] Radon-222 is normally found in mines, but Radon-220, formed from the decay of Thorium-232, may sometimes also be found. [40,83] Because of its gaseous nature, Radon-222 concentrations are highly dependent on the amount of ventilating air in which it is dispersed within the underground environment. [40,83]

**Table 2.5**: Characteristics of Radon-222. [4]

| | |
|---|---|
| Molecular formula: | Rn |
| Cas no: | 10043-92-2 |
| EINECS no: | 233-146-0 |
| Appearance: | Colorless Gas |
| Melting point: | -71 $^{o}$C |
| Boiling point: | -62 $^{o}$C |
| Density: | 4.4 g.cm$^{-3}$ |
| Radiochemical: | Unstable |
| Chemical: | Unreactive |

Radon-222 is formed by the decay of Uranium-238 and ultimately Radium-226. [50] Uranium ores contain high concentrations of radioactive elements in relation to other ores with the two main uranium isotopes being Uranium-238 and Uranium-235. [50]

Radon-222 and its progeny form 54.8% of the effective dose of natural radiation received by the U.S population. [3] Exposure occurs through the inhalation of the radioactive Radon-222 gas and the inhalation of radioactive particles produced by mining and milling. [50] The inhalation of high cumulative levels of Radon-222 and its α-particle emitting decay products has been linked to an increased risk of lung cancer among underground miners. [50] Short lived radon progenies have been established as causative agents of lung cancer. [50] The main carcinogens formed by the decay of Radon-222 are the short-lived progeny Polonium-218 and Polonium-214, both alpha-particle emitting elements. [23] The decay products of Radon-222 are all solids and are readily deposited on the bronchial airways and inside the alveoli of the lungs during inhalation and exhalation. [66]

The bronchial epithelium lining of the airways is very thin (40 µm) and the alpha-particles that are emitted are able to reach the cells implicated in lung cancer induction, and transfer significant amounts of energy to these cells [60,61,67]

When Radon-222 gas decays to Polonium-218, 8 to 15% of the total amount of Polonium-218 formed during the decay of Radon-222 does not attach to aerosol particles. [83] These ultrafine, unattached Polonium-218 particles are deposited with 100% efficiency on the upper bronchial airways. [83] Within the underground mine environment, the unattached fraction of Polonium-218 particles is usually between 4 and 5% because of the high aerosol concentration in the circulating air, with the rest of the formed Polonium-218 particles attached to the ambient aerosol particles. [83] The major characteristic affecting the deposition of aerosols in the respiratory system is the aerosol size, with particles 5 µm or larger being deposited in the nasopharyngeal region, particles between 2 and 5 µm mainly being deposited in the tracheobronchiolar regions of the lungs and particles 1 µm and smaller penetrating to the alveoli of the lungs. [60,61]

The exposure to Radon-222 and Radon-222 progeny only exhibits effects on the lung and bronchial epithelium, because of the weak penetrating power of alpha-particles and the proximity of the Radon-222 gas and progeny with the epithelium cells in the lungs and bronchi, and thus Radon-222 does not affect any other organ or system. [60,83,96] The radiation dose from Radon-222 gas itself is very low in comparison with its decay daughters, as the Radon-222 decay daughters deposit and accumulate on the airway surfaces, increasing the received dose through increased retention time. [83,108]

## 2.9 BAFOKENG RASIMONE PLATINUM MINE (BRPM)

BRPM operations lie on the Western Limb of the Bushveld Igneous Complex (known as the Bushveld Complex), which hosts approximately 80% of the world’s known platinum resources. [7] The Bushveld Complex is estimated to have formed approximately 2,060 million years ago and its mafic rock sequence, the Rustenburg Layered Suite (RLS), is the world’s largest known mafic igneous layered intrusion containing approximately 90% of the world's known Platinum Group Metals (PGM - Pt, Pd, Rh, Ir, Os & Ru) reserves. [17] In addition to the Platinum Group Metals (PGM’s), extensive deposits of Fe, Ti, Ch, Sn, V, Cu, Ni and Co also occur. [17] The Bushveld Complex extends approximately 450 km east to west and approximately 250 km north to south. [17] It underlies an area of some 65,000 km², spanning parts of the Limpopo, North West, Gauteng and Mpumalanga Provinces of South Africa. [17] The Bafokeng Rasimone Platinum Mine (BRPM) is located on the Western Limb of the Bushveld

Complex, approximately 30km north west of Rustenburg in the North West Province of South Africa. [7] BRPM comprises the Boschkoppie and Styldrift mining right areas, along with a portion of the Frischgewaagd prospecting right area. [7]

The RLS is subdivided geographically into five discrete compartments termed "limbs", three of which are being exploited for PGM's. [17] These are the Western, Eastern and Northern Limbs. [17] Figure 2.7 shows the extent of the RLS and the location of BRPM in a regional context. [17] The RLS comprises rock types ranging from dunite and pyroxenite through norite, gabbro and anorthosite to magnetite- and apatite-rich diorite, subdivided in terms of a mineralogically based, zonal stratigraphy into five principal zones. [17] From bottom to top these are the Marginal, Lower, Critical, Main and Upper Zones. However, the PGM bearing reefs are typically only 0.3 m to 15 m thick, although much greater thicknesses are recorded in the Platreef of the Northern Limb. [17] In the Eastern and Western Limbs, the Critical Zone contains the two principal PGM-bearing reefs: the Merensky Reef and the Upper Group 2 (UG2) chromitite. [17] In the Northern Limb, the Platreef is thought to be the local equivalent of the Critical Zone and Merensky Reef. [17]

The Pilanesberg Complex, the remnant of an alkaline volcanic plug which intruded into the Bushveld Complex about 1,250 million years ago, splits the Western Limb into two lobes (northwestern and southwestern) while the Eastern Limb is split into two lobes (northeastern and southeastern) at the Steelpoort Fault. [17] BRPM is located immediately south of the Pilanesberg Complex on the Western Limb. BRPM property is underlain by rocks of the Lower, Critical and Main Zones of the RLS, apart from a very small portion of the northern boundary area where rocks of the Pilanesberg Complex occur. [7] Due to the gently undulating nature of the topography, little surface outcrop is visible and the mine property is mostly covered by the clay-rich, black cotton soils which are typical of the area. [7] Two primary economic favorable stratigraphic horizons of the Western Bushveld Complex namely the Merensky Reef and the UG2 Reef are being exploited on the Boschkoppie 104JQ Farm, on which BRPM`s North and South shafts are located. [7,17]

Both the North and South Shafts of BRPM use a reef plane return air strategy for the ventilation of all underground areas. A reef plane return air strategy comprises the introduction of air at various points underground, from where the air moves through the working areas, stopes, haulages and walkways upwards towards the level above it, and finally from level one into a upcast shaft that is exhausted into at the surface, as seen in figure 2.8. Both Shafts have three types of activities taking place in underground areas, namely production, expansion and non-production. [7]

**Fig 2.7:** Location of BRPM (Anon, 2010)

The Boschkoppie Mine and Styldrift mining complex is located between Anglo Platinum's Rustenburg Section operations to the southeast and its Union Section to the north. [7] The operations are up-dip (immediate northwest) of Impala Platinum, with the Western Bushveld Joint Venture (WBJV) on the northeastern boundary, and Wesizwe's Platinum Limited's Frisch Ledig Project to the east and northeast of the Styldrift Project. [7] Current mining operations — at North Shaft and South Shaft — are situated within the farm boundary of Boschkoppie 104 JQ, with development taking place at Styldrift. [7] The villages of Rasimone, Mafenya, Robega and Chaneng are in close proximity. [7]

Bafokeng Rasimone Platinum mine (BRPM) consists currently of 2 working shafts, namely North Shaft and South Shaft. [7] Both Shafts function individually but are connected to each other and other mines in the area with rescue passages. [7] Both shafts use a reef plane return ventilation technique where air is inserted to the various levels through piping from the main shaft and the air flows upwards through the various haulages, cross cuts and return airways to the up cast shaft, from where the air is extracted to the atmosphere, as seen in figure 2.8. Air thus flows from lower levels to the upper levels and is extracted at the upper levels to the atmosphere. [7]

Both shafts have independent lamp rooms where employees` lamps are stored and charged when not in use. [7] Lamps can only be stored in the lamp rooms when they are not underground. [7] Both shafts have electronic access control to the shafts that automatically records the time employees enter and exit the shaft. [7] These enter and exit times can then be used to calculate the time the employee spent underground. [7]

## 2.10 EXPERIMENTAL PROCEDURE

### 2.10.1 INTRODUCTION

Underground radiation gas monitoring is conducted to determine present exposure levels of the workforce to ensure that exposure levels comply with the requirements of the National Nuclear Regulator and to continuously monitor and assess risks as required by the aforementioned Council in mines where radioactive gasses pose a health risk underground. Monitoring is done in accordance with the Radiation Protection Procedure guidelines for radiation gas monitoring in terms of the National Nuclear Safety Act (Act 47 of 1996), as well as the Mine Health and Safety Act (Act 29 of 1996).

For the purpose of this study and discussions with specialists in the South African Gold Mining industry, it was decided that a two pronged approach was to be used to determine the presence of Radon-222 in a South African Platinum mine.

### 2.10.2 INSTRUMENTATION

Carbon infused Radon Gas Monitors supplied by PARC RGM were used during this study. The reason behind the use of the Carbon infused RGM`s is this reduces the possibility of background interference from magnetically charged surfaces, thus giving a more accurate reflection of the occupational exposure to Radon-222.

### 2.10.3 SAMPLING

The following methodology was followed with regards to the area sampling. Strategic sampling points were identified where the largest volume of reasonable stable airflow from lower levels would be found during the running time of the study that would give a representative exposure to possible Radon-222 in the underground air. These specific areas were identified and sampled because the airflow design of the mine is designed to collect moving air from working areas and moved through ventilation passages and shafts up to the surface. The sampling points identified would allow sampling of the level below the sampling point’s air before it was moved up towards the surface and exhausted into the atmosphere. The following areas were identified and sampled:

**Table 2.6:** Sampling information – Area sampling locations six samples per location

| Identification | Description | Reason for sampling |
|---|---|---|
| **North shaft** | | |
| L01S34 | North Shaft, level 1, South, cross cut 34 | Identified strategic point, allows sampling of air from L01 to L03 South production areas. |
| L01N32 | North Shaft, level 1, North, cross cut 32 | Identified strategic point, allows sampling of air from L01 to L03 North production areas. |
| L03S29 | North Shaft, level 3, South, cross cut 29 | Identified strategic point, allows sampling of air from L03 to L05 South production areas. |
| L03N22 | North Shaft, level 3, North, cross cut 22 | Identified strategic point, allows sampling of air from L03 to L05 North production areas. |
| L05S03 | North Shaft, level 5, South, cross cut 03 | Identified strategic point, allows sampling of air from L05 to L07 South production areas. |
| L05N03 | North Shaft, level 5, North, cross cut 03 | Identified strategic point, allows sampling of air from L05 to L07 North production areas. |
| L06N01 | North Shaft, level 6, North, cross cut 01 | Identified strategic point, allows sampling of all air from expansion areas. |
| L09S01 | North Shaft, level 9, South, cross cut 01 | Identified possible problem area, expansion area with limited air flow. |
| **South Shaft** | | |
| L01S40 | South Shaft, level 1, South, cross cut 40 | Identified strategic point, allows sampling of air from L01 to L03 South production areas. |
| LO1N44 | South Shaft, level 1, North, cross cut 44 | Identified strategic point, allows sampling of air from L01 to L03 North production areas. |
| L03S40 | South Shaft, level 3, South, cross cut 40 | Identified strategic point, allows sampling of air from L03 to L05 South production areas. |
| L03N40 | South Shaft, level 3, North, cross cut 40 | Identified strategic point, allows sampling of air from L03 to L05 North production areas. |
| L05S28 | South Shaft, level 5, South, cross cut 28 | Identified strategic point, allows sampling of air from L05 to L07 South production areas. |
| L05N28 | South Shaft, level 5, North, cross cut 28 | Identified strategic point, allows sampling of air from L05 to L07 North production areas. |
| L06S01 | South Shaft, level 6, South, cross cut 01 | Identified strategic point, allows sampling of all air from expansion areas. |
| L07N01 | South Shaft, level 7, North, cross cut 01 | Identified possible problem area, expansion area with limited air flow. |

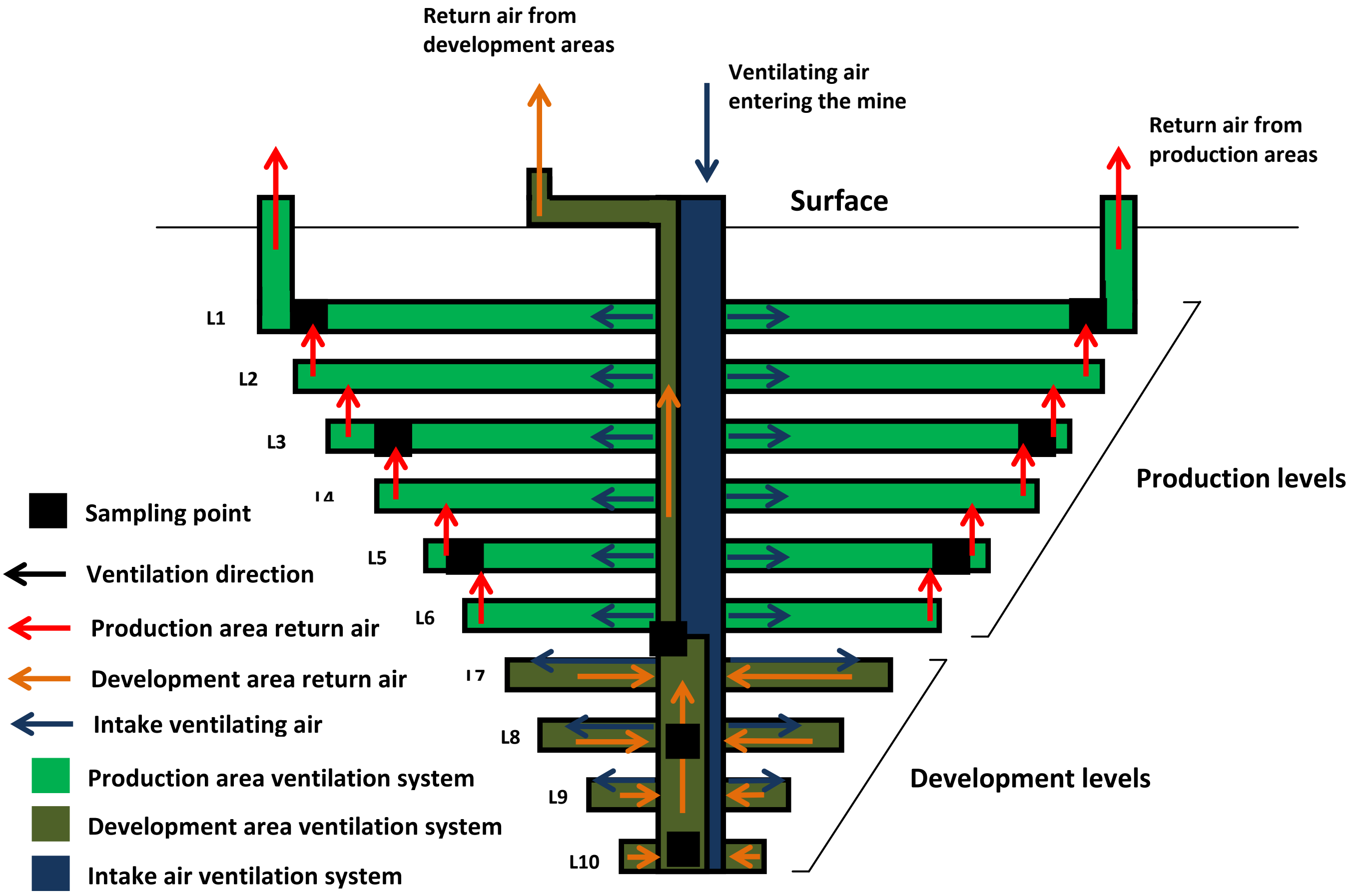

**Fig 2.8**: Shaft layout, return airways and area sampling

The personal sampling methodology was developed after discussions with Radiation Protection Officers from Anglo Gold Ashanti. South African Gold Mines are required by law to implement radiation protection programmes for all underground employees. Data from these gold mines show that the Rock Drill Operators (RDO`s) and team leaders have the highest exposure to Radon-222 because of the proximity to the rock face, the amount of time they spend near the rock face and the lower levels of ventilation in their working areas. Underground safety officers were included to serve as a roaming Homogenous exposure group (HEG) and to help with employee participation in the project through increased knowledge transfer between safety officers and employees selected for participation.

The workforce in an underground mine consists of many occupations performing different tasks. This study concentrated on employees involved in production that work in close proximity to the ore in the production areas (stopes and cross cuts). Three groups of employees were selected because of their relation to the type of work they do namely, Shift leaders, who spend a large amount of time in the stopes, Rock drill operators (RDO`s), who spend most of their time in close proximity to the rock face, and safety officers, who spend large amounts of time in close proximity to the rock face and stopes.

Employees were randomly selected, based on the availability of the employee for the full duration of the study period and the need to sample selected occupations, by their supervisors for participation in this study. Employees worked for the total duration of the study in the identified areas and where not moved to different levels or occupations during the course of the study. The selection of employees was depended on the production activity and employees per level. Safety representatives did not stay in one particular area, and rotated between different levels. They are classified as roaming. The following numbers of employees were selected and sampled during the study:

Table 2.7: Sampling information – Personal samples taken

| **Level** | **Team Leader** | **Rock Drill Operator** | **Safety Rep** | **Level** | **Team Leader** | **Rock Drill Operator** | **Safety Rep** |
|---|---|---|---|---|---|---|---|
| **North Shaft** | | | | **South Shaft** | | | |
| Level 1 & 2 | 5 | 5 | 20 | Level 1 & 2 | 11 | 10 | 15 |
| Level 3 | 1 | 5 | | Level 3 | 2 | 5 | |
| Level 4 | 3 | 5 | | Level 4 | 4 | 6 | |
| Level 5 | 2 | 5 | | Level 5 | 5 | 5 | |
| Level 6 | 4 | 7 | | Level 6 | 4 | 7 | |
| Level 7 | 3 | 5 | | Level 7, 8 & | 1 | 8 | |
| Level 8 | 3 | 4 | | | | | |
| Level 9 & 10 | 7 | 7 | | | | | |

24 personal RGM`s and 9 area monitoring RGM`s were lost during the study and 7 RGM`s were spoiled because of various factors including tampering and damage to the RGM plastic casing. All RGM`s were transported and kept in Radon-222 impermeable plastic buckets. All RGM`s were transported to the PARC RGM laboratory in Vereeniging, South Africa, for analysis on the 24th of December 2008. Analysis of the RGM`s took place under the control and supervision of Dr Hein Strauss at PARC RGM. Exposure rate to radon progeny while working is evaluated in accordance with the NCRP-78 methodology. Assuming a 2,040 hour work year, or 170 work hours per month, the following equation is used to calculate the radon progeny exposure dose rates.

***Dose rate (pSv hr*** $^{-1}$) =[***CF x Rn x Q x WF x C] / WY***

where: CF = Conversion Factor (Gy yil [Bq m"1-l), Rn = Radon Concentration (Bqm$^{-3}$), Q = Quality Factor, 20 (Sv Rad-'),WF = Weighting Factor, 0.12, c = Unit Conversion, IO$^{6}$ (pSv SV'), WY = Work Year, 2040 (hrs yr$^{-1}$)

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# Guidelines for Authors – Annals of Occupational Hygiene

1. **Originality.**

   Only work that has not been published elsewhere, and is original should be submitted. If the findings have already been published, in part, or were part of a series of closely-related articles it should be stated in the submitted manuscript and a copy should also be included.

2. **Authorship.**

   The corresponding author should be identified in the submission. Full postal addresses should be included for all co-authors. A letter consenting to publication should be signed by all authors of a submission and sent to the Editorial Office.

3. **Ethics.**

   On request, authors must produce original data for inspection by the editor. Studies that were conducted on human subjects, other than measurements in the course of their normal work activities, have to get approval from a competent ethics committee using the standards of the Helsinki Declaration of the World Medical Association. The Ethics committee used must also be named in the paper.

4. **Conflict of interest.**

   Unless it is clear from the authors` affiliations, the source of financial support must be mentioned in the Acknowledgements. Other possible conflicts of interest should also be declared to the Editor.

5. **Language.**

   Manuscripts must be in English and written in a way that is understandable and clear to all. British or American styles and spelling can be used, but it should be used consistently while words and phrases that might not be clear in other parts of the world should be avoided.

6. **Brevity and supplementary material.**

   Regarding the length of the paper, it depends on the subject, but should be as brief as possible and consistent in clarity. The number of words, excluding the abstract, references, tables and figures, must be stated as a message to the Editor at the time of submission. If the length of the paper is more than 5000 words, a statement must be included justifying the extra length.

7. **Structure.**

   Papers should generally follow the format of: Introduction, Methods, Results, Discussion and Conclusions. The abstract should include argument and findings and can be arranged under the headings: Objectives, Methods, Results, and Conclusions. Keywords should be given after the list of authors.

8. **Survey design.**

   Sampling surveys should be planned using modern statistical principles so that the quality of the data is good enough to justify the inferences and conclusions drawn.

9. **Units and symbols.**

   SI units should be used and their equivalent in other systems can be given as well

10. **Figures.**

    Figures, Photographs, diagrams and charts should be about the same size as will be reproduced in, and the font size should be at least 6 point using standard Adobe set of fonts. Fine hairlines should be avoided and clear hatching patterns should be used in preference to solid grey shadings.

11. **Tables.**

    Numbering of tables should be consecutively and given a suitable caption, and each table typed on a separate page. Footnotes to tables should be typed below the table and should be referred to by superscript lowercase letters.

12. **References.**

    References in the text should be in the form Jones (1995), or Jones and Brown (1995), or Jones *et al.* (1995) if there are more than two authors. References at the end of the paper should be listed alphabetically by name of first author, using the Vancouver Style of abbreviation and punctuation. ISBNs should be given for books and other publications where appropriate.

# Occupational Exposure to Radon-222 in a South African Platinum Mine

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### *3.1 ABSTRACT:*

**Background:** The Platinum mining operations in South Africa mining platinum containing ore from areas where variable amounts of uranium are found, leading to the possibility of occupational exposure to the radioactive disintegration products of Uranium-238 and in particular the gas Radon-222. No scientific data is available for occupational exposure to Radon-222 in South African platinum mining operations. **Objective:** To determine the risk of occupational exposure to the radioactive disintegration products of naturally occurring Radon-222 gas in a South African platinum mine. **Design:** Quantitative sampling (personal and static) to establish baseline data on exposure to radioactive disintegration products of naturally occurring Radon-222 gas in a underground South African platinum mine. **Setting:** The Bafokeng Rasimone platinum mine located 30 km North West of Rustenburg in the Bushveld complex in the North West Province of South Africa. **Study subjects:** One hundred and seventy four potentially highest exposed underground employees and one hundred and twelve static underground samples were sampled. **Method:** Personal and area samples were taken on selected employees and in locations using RGM samplers using CR-39 plastic as a detection medium. Employees were selected to sample the highest exposed occupations and static samples were located to sample returning air from levels underneath the sampling point before it is exhausted to the above ground atmosphere. After analysis by an accredited laboratory, the results were converted to exposure following the National Council on Radiation Protection-78 methodology. **Main outcome measures:** Quantify the relative risks of potentially highest exposed employee`s exposure to the radioactive disintegration products of naturally occurring Radon-222 gas in underground working areas in milliSievert per year. **Results:** The mean reference background exposure averaged 0.6168 mSv/a with underground personal exposure averaging 0.6808 mSv/a, and underground static exposure averaging 0.8726 mSv/a. These values are substantially below the 50 mSv/a Occupational Exposure Limit, and only pose a slightly elevated risk for the development of lung cancer above the normal back-ground exposure. Mining Team leaders and rock drill operators were identified as the potentially highest exposed employees due to the close proximity to the working face, large amounts of time spent close to the working face and the lower ventilation volumes at the working face, with Team leaders having the highest exposure of the sampled occupations with a average of 1.16 mSv/a. **Conclusions:** Occupational exposure to radioactive disintegration products of naturally occurring Radon-222 gas in the underground air of a South African platinum mine does not pose a significant risk to the health of employees working in the platinum mine.

Key words*:* Alpha Radiation, Occupational Exposure, Occupational exposure limit, Platinum Mine, Radon-222, RGM, South Africa, Uranium.

## 3.2 INTRODUCTION

Mining is an ancient, multi-disciplinary industry, long recognized as being arduous and liable to injury and disease. [3] The industry employs a labor force of several hundred thousand miners, both in South Africa and in the rest of the world. [7] Studies of underground miners have consistently shown an increased risk of lung cancer with cumulative exposure to Radon-222 and its decay products. [2,18] Working with natural raw radioactive materials increases exposure to radiation. [6,7] All rock and soils contain uranium and thorium, which are both radioactive (Uranium isotopes Uranium-238 and Uranium-237, and Thorium isotope, Thorium-232), with uranium concentrations in the Bushveld Complex ranging between 11 and 66 parts per billion. [5,6]

Most of these radio-nuclides have extremely long half lives ranging from seconds to millions of years. These half lives have a great impact on determining exposure time, since the half-life of the nuclide influences the risk to become exposed and develop pathology. [15] Exposure to radiation in the mining industry varies greatly, depending for instance, on the uranium concentration in the rock, as well as the presence of radon. [5] Radon (in this case Radon-222) is a decay product of uranium with radon gas concentrations higher in soil with high concentrations of uranium. [13]

Radon-222 is a colourless, odourless, radioactive noble gas usually found in areas with high concentrations of uranium. [4] Radon-222 is formed through the decay of Uranium-238 and its daughter elements over thousands of years. [4] The decay of Uranium-238 over thousands of years results in situations where there is a mixture of radioactive substances existing in a single environment. [16] Radon-222 is normally found in mines, but Rn-220, formed from the decay of Thorium-232, may sometimes also be found. [4] Because of its gaseous nature, Radon-222 concentrations are highly dependent on the amount of ventilating air in which it is dispersed within the underground environment. [16]

Radon-222 is formed by the decay of Uranium-238 and ultimately Radium-226. Uranium ores contain high concentrations of radioactive elements in relation to other ores with the two main isotopes being Uranium-238 and Uranium-235. [6,17] Radon-222 and its progeny form 54.8% of the effective dose of natural radiation received by the U.S population. [9] Exposure occurs through the inhalation of the radioactive Radon-222 gas and the inhalation of radioactive particles produced by mining and milling. [10] The inhalation of high cumulative levels of Radon-222 and its α-particle emitting decay products have been linked to an increased risk of lung cancer among underground miners. [10] Short lived radon progenies have been established as causative agents of lung cancer. [12]

The main carcinogens formed by the decay of Radon-222 are the short-lived progeny Polonium-218 and Polonium-214, both alpha-particle emitting elements. [10] The decay products of Radon-222 are all solids and are readily deposited on the bronchial airways and inside the alveoli of the lungs during inhalation and exhalation. The bronchial epithelium lining of the airways is very thin (40 µm) and the alpha-particles that are emitted are able to reach the cells implicated in lung cancer induction, and transfer significant amounts of energy to these cells. [8,9,11]

When Radon-222 gas decays to Polonium-218, 8 to 15% of the total amount of Polonium-218 formed during the decay of Radon-222 does not attach to aerosol particles. [6] These ultrafine, unattached Polonium-218 particles are deposited with 100% efficiency on the upper bronchial airways. [9] Within the underground mine environment, the unattached fraction of Polonium-218 particles is usually between 4 and 5% because of the high aerosol concentration in the circulating air, with the rest of the formed Polonium-218 particles attached to the ambient aerosol particles. [16] The major characteristic affecting the deposition of aerosols in the respiratory system is the aerosol size, with particles 5 µm or larger being deposited in the nasopharyngeal region, particles between 2 and 5 µm mainly being deposited in the tracheobronchiolar regions of the lungs and particles 1 µm and smaller penetrating to the alveoli of the lungs [8,9]

The exposure to Radon-222 and Radon-222 progeny only exhibits effects on the lung- and bronchial epithelium, because of the weak penetrating power of alpha-particles and the proximity of the Radon-222 gas and progeny with the epithelium cells in the lungs and bronchi, and thus Radon-222 does not affect any other organ or system. [8,17] The radiation dose from Radon-222 gas itself is very low in comparison with its decay daughters, as the daughters deposit and accumulate on the airway surfaces, increasing the received dose through increased retention time. [17,18]

Bafokeng Rasimone Platinum Mine lies on the Western Limb of the Bushveld Igneous Complex (known as the Bushveld Complex), which hosts approximately 80% of the world’s known platinum resources. [1,2] The Bushveld Complex is estimated to have formed approximately 2,060 million years ago and its mafic rock sequence, the Rustenburg Layered Suite (RLS), is the world’s largest known mafic igneous layered intrusion containing approximately 90% of the world's known Platinum Group Metals (PGM - Platinum, Palladium, Rhodium, Iridium, Osmium & Ruthenium) reserves. [2,5] In addition to the Platinum Group Metals (PGM’s), extensive deposits of Iron, Tin, Chrome, Tin, Vanadium, copper, Nickel and Cobalt also occur. [2] The Bushveld Complex extends approximately 450 km east to west and approximately 250 km north to south. [2] It underlies an area of some 65,000 km², spanning parts of the Limpopo, North West, Gauteng and Mpumalanga Provinces of South Africa. [2]

## 3.3 AIM

To determine the risk of occupational exposure to the radioactive disintegration products of naturally occurring Radon-222 gas in a South African platinum mine.

## 3.4 METHOD

A two pronged approach was to be used to determine the presence of Radon-222 in a South African Platinum mine, utilizing strategic area sampling of air accumulation points and personal sampling of potentially highest exposed employees. The mine identified for the study was Bafokeng Rasimone Platinum Mine (BRPM) situated 30 km north of the town of Rustenburg in the North West Province of South Africa, mining the Bushveld Complex. Carbon infused Radon Gas Monitors (RGMs) from PARC RGM were used to minimize possible interference from electrostatically charged particles present in the underground environment.

### 3.4.1 STRATEGIC AREA SAMPLING

The following methodology was followed with regards to the area sampling. Strategic areas were identified where the largest volume of reasonable stable airflow would be found during the running time of the study that would give a representative exposure to possible Radon-222 in the underground air. These specific areas were identified and sampled by placing RGMs in the underground environment away from any electrostatically charged surface and cables because the airflow design of the mine is designed to collect moving air form working areas and moved through ventilation passages and shafts up to the surface. The sampling points identified allowed sampling of the levels below the sampling point's air before it was moved up towards the surface and exhausted into the atmosphere.

Locations were named according to the location of the area, with the first 3 digits (L01S34) indicating the level within the mine, namely level 1, the last 3 digits identified the direction, North or South and the exact location of the sampling area, namely cross cut number 34. Sampling started on 3 November 2008 and ended on 22 December 2008.

### 3.4.2 PERSONAL SAMPLING OF POTENTIALLY HIGHEST EXPOSED EMPLOYEES

The personal sampling methodology was developed to include the highest exposed occupations considering the average time spent underground and the occupations, proximity to the rock face. South African Gold Mines are required by law to implement radiation protection programmes for all underground employees. Data from these gold mines showed that the Rock Drill Operators (RDO`s) and team leaders have the highest exposure to Radon-222 because of the proximity to the rock face, the amount of time they spend near the rock face and the lower levels of ventilation in immediate area close to the rock face. Underground safety officers were included to serve as a roaming homogonous exposure group and to help with employee participation in the project through increased knowledge transfer between safety officers and employees selected for participation.

Employees within the selected occupations were randomly selected based on the availability of the employee for the full duration of the study. Safety representatives were classified as roaming employees, giving an indication of possible exposure to employees not working in designated areas and tasks. Instrumentation was attached to the selected employees cap lamps the evening before the selected start date of the study, by cable tying the RGM to the electrical cord connecting the cap lamp to the battery pack at a distance so that the RGM would be located just below the back of the hard hat. Individually chosen employees were paraded following the issuing of the instruments and were individually briefed by their safety representatives before being allowed to collect their cap lamps with attached RGMs and proceeding underground. Sampling started on day shift on 2 November 2008 and ended on 22 December 2008.

### 3.4.3 DATA AND STATISTICAL ANALYSIS

Instrumentation (RGM`s) was transported to a accredited laboratory for analysis. Personal exposure and static sample data was kept separate throughout the analysis of the data. Statistical analysis was done by using Statistica 8 (Statsoft Inc.) and Microsoft Excel (Microsoft Corporation). Statistical analysis included basic statistics (mean, standard deviation, minimum and maximum values), as well as P-test. P-tests were performed between reference values paired with, personal exposures per level and area exposures per level. All differences were considered as statistically significant at a level of $P > 0.8$.

Exposure rate to radon progeny while working is evaluated in accordance with the NCRP-78 methodology. Assuming a 2,040 hour work year, or 170 work hours per month, the following equation is used to calculate the radon progeny exposure dose rates. [14]

***Dose rate (pSv hr*** $^{-1}$) = [***CF x Rn x Q x WF x C] / WY***

where: CF = Conversion Factor (Gy yil [Bq m"1-l), Rn = Radon Concentration **(**Bqm$^{-3}$), Q = Quality Factor, 20 (Sv Rad-'),WF = Weighting Factor, 0.12, c = Unit Conversion, IO$^{6}$ (pSv SV'), WY = Work Year, 2040 (hrs yr$^{-l}$)

## 3.5 RESULTS AND DISCUSSION

The average exposure for North Shaft was 0.7362 mSv/a and for South Shaft was 0.6254 mSv/a, and a combined value for both lamp room reference groups of 0.6169 mSv/a, representing a natural exposure to Radon-222 that equates to 1.23% of the OEL of 50 mSv/a. The lamp room reference samples represent natural exposure to Radon-222 for above ground exposure.

The following figures are a summary of the data retrieved and analyzed during this study.

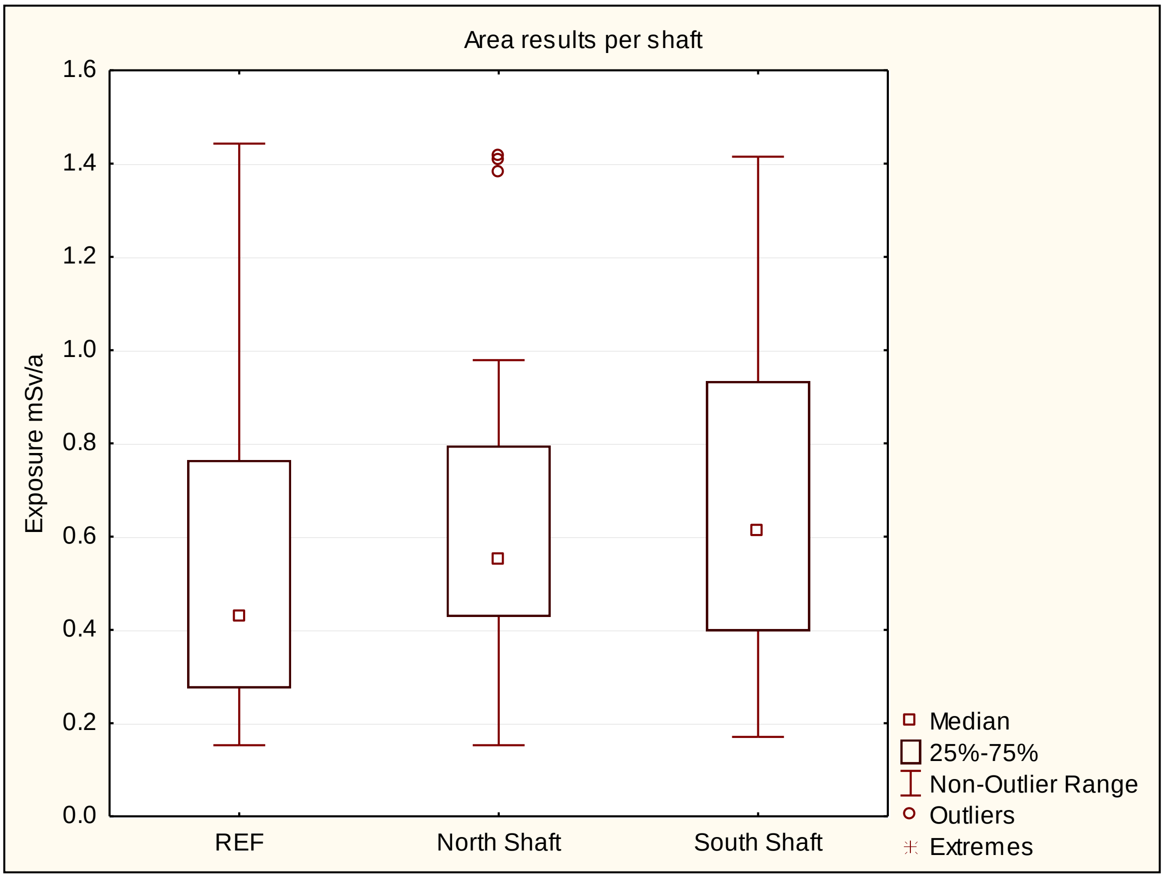

**Fig 3.1: Area sampling results for each shaft (mSv/a)**

From Figure 3.1 it is clear that the area monitoring results for both shafts showed a difference between the underground areas monitored and the associated lamp room references than the personal exposure results. The mean North Shaft underground area monitoring results were 0.6234 mSv/a and the mean South Shaft underground area monitoring results were 0.7280 mSv/a. This shows higher exposure than the mean lamp room reference was 0.5358 mSv/a. Area monitoring produced higher exposure values due to the increased underground exposure time

**Table 3.1: Basic statistical interpretation for area sampling results (mSv/a)**

| | Reference (lamp room) | North Shaft | South shaft |
|---|---|---|---|
| **N** | 13 | 51 | 39 |
| **Mean** | 0.5358 | 0.6234 | 0.7280 |
| **Median** | 0.4281 | 0.5504 | 0.6115 |
| **Std Dev** | 0.3351 | 0.2949 | 0.4109 |
| **Min** | 0.1528 | 0.1528 | 0.1704 |
| **Max** | 1.4430 | 1.1415 | 1.4148 |
| **25th Percentile** | 0.2750 | 0.4281 | 0.3975 |
| **75th Percentile** | 0.7644 | 0.7950 | 0.9335 |

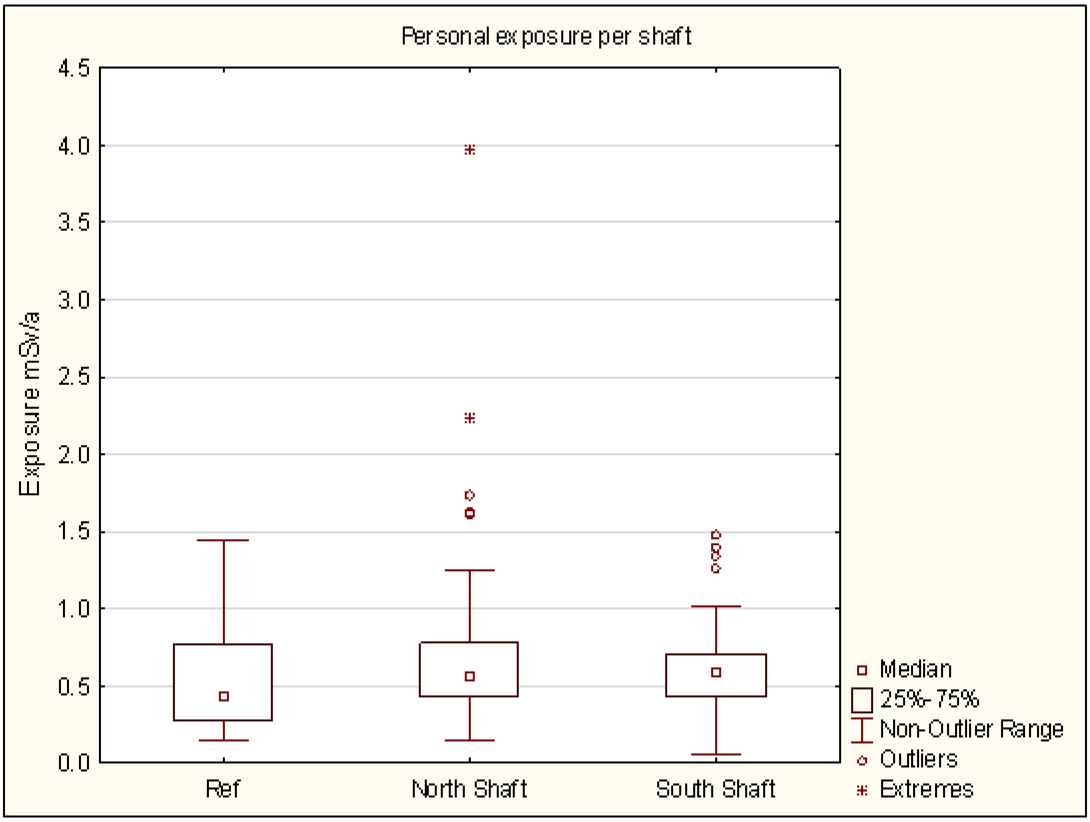

**Fig 3.2: Personal Exposure for each shaft (mSv/a)**

From Figure 3.2 it is clear that the personal exposure results for both shafts showed a close correlation to the reference exposure values. The mean exposure for all sampled employees at North Shaft was 0.6997 mSv/a and the mean exposure for all sampled employees at South Shaft was 0.6023 mSv/a. The mean lamp room reference was 0.5358 mSv/a.

**Table 3.2: Basic statistical interpretation for personal sampling results (mSv/a)**

| | Reference (lamp room) | North Shaft | South shaft |
|---|---|---|---|
| **N** | 13 | 86 | 80 |
| **Mean** | 0.5358 | 0.6997 | 0.6023 |
| **Median** | 0.4281 | 0.5504 | 0.5824 |
| **Std Dev** | 0.3351 | 0.5011 | 0.2822 |
| **Min** | 0.1528 | 0.1528 | 0.0552 |
| **Max** | 1.4430 | 3.9750 | 1.4720 |
| **25th Percentile** | 0.2750 | 0.4281 | 0.4291 |
| **75th Percentile** | 0.7644 | 0.7787 | 0.7055 |

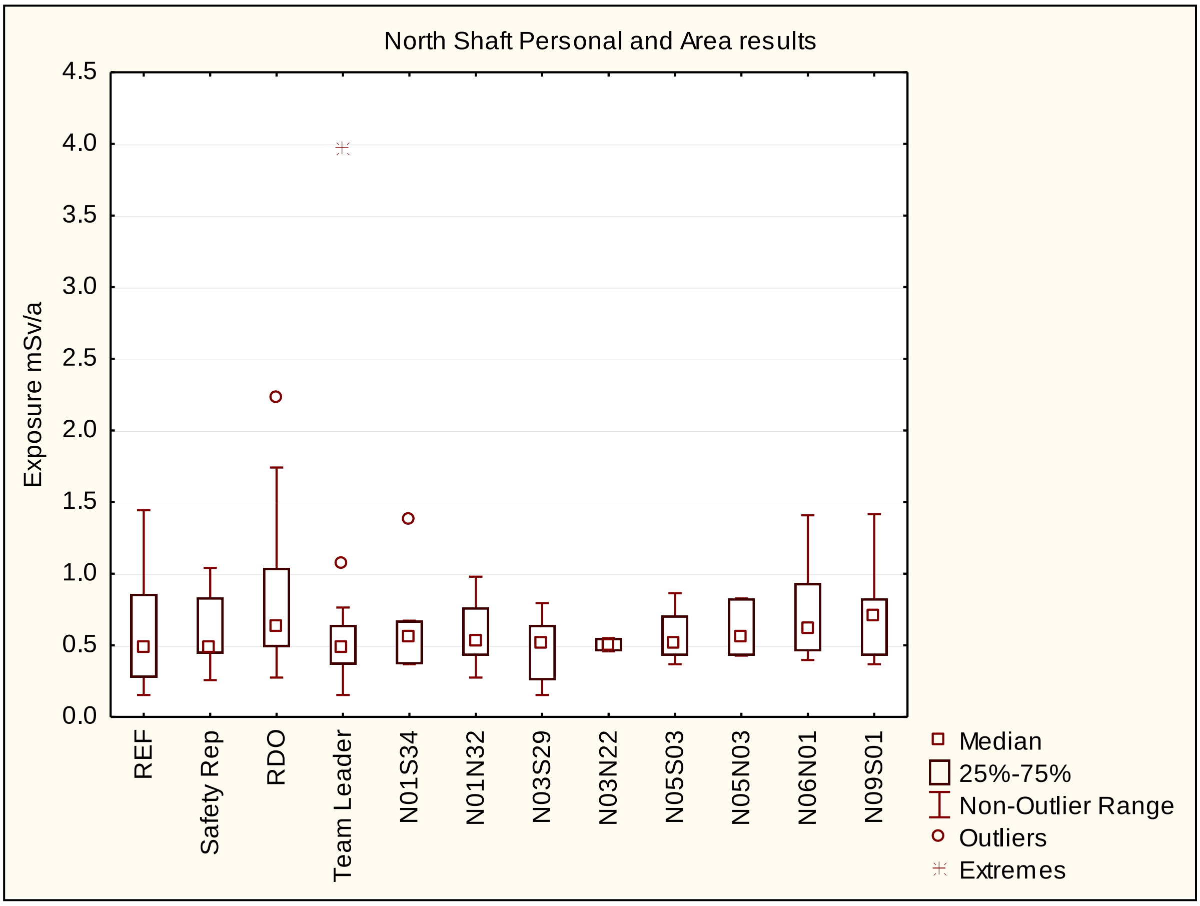

**Fig 3.3: North Shaft Area and personal sampling results (mSv/a)**

From Figure 3.3 it can be seen that the Team Leaders on the North Shaft had the largest mean exposure at 1.6450 mSv/a, followed by the Rock Drill Operators (RDO) with an mean exposure of 0.9936 mSv/a, followed by the Safety Representatives with the lowest mean exposure at 0.5884 mSv/a. The area monitoring results followed no definitive trend with N09S01 having the largest mean exposure at 1.2840 mSv/a, followed by N06N01 with 0.9629 mSv/a, followed by N01S34 with 0.8869 mSv/a, followed by N05S03 with 0.8403 mSv/a, followed by N01N32 with 0.8014 mSv/a, followed by N03S29 with 0.6667 mSv/a, followed by N05N03 with 0.6156 mSv/a, followed by N03N22 with the lowest mean exposure of 0.5167 mSv/a.

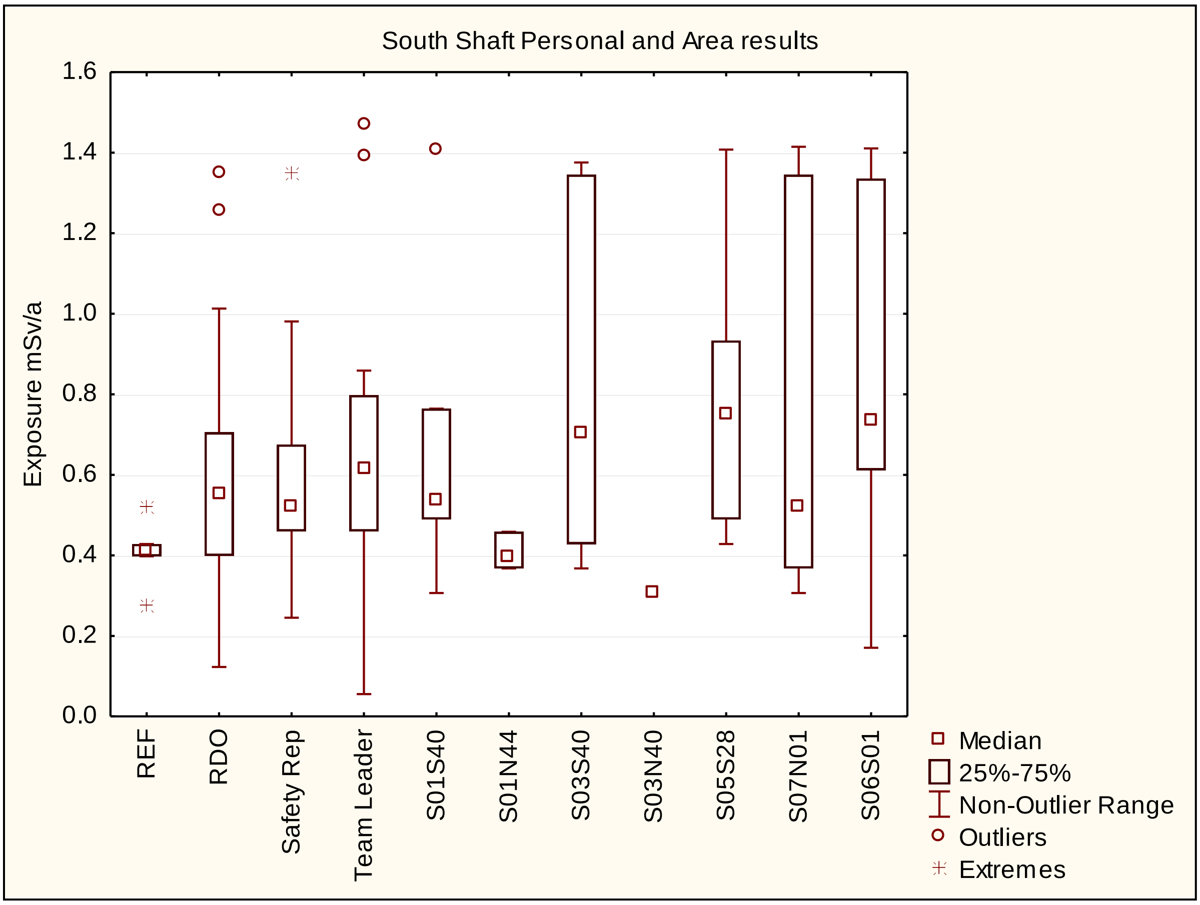

**Fig 3.4: South Shaft Area and personal sampling results (mSv/a)**

From Figure 3.4 it can be seen that the Team Leaders on South Shaft had the largest mean exposure at 0.6812 mSv/a, followed by the Safety Representative with a mean exposure of 0.6133 mSv/a, followed by the Rock Drill Operators with the lowest mean exposure at 0.5817 mSv/a. The area monitoring results followed no definitive trend with S06S01 having the largest mean exposure at 1.1900 mSv/a, followed by S0S40 with 1.0340 mSv/a, followed by S05S28 with 0.9828 mSv/a, followed by S01S40 with 0.9479 mSv/a, followed by S03S40 with 0.9048 mSv/a, followed by S01N44 with 0.8826 mSv/a, followed by S07N01 with 0.7830 mSv/a, followed by S03N40 with the lowest mean exposure of 0.6618 mSv/a.

Personal sampling results indicate exposure below 0.7500 mSv/a and area sampling indicates exposure below 0.9005 mSv/a. North and South Shaft personal sampling results for all occupations differ with 0.1001 mSv. This difference can be attributed to different levels of production activities between the two shafts, variations in ore and waste rock composition, differences in ventilation volumes and the amounts of airborne particles present in the circulating air.

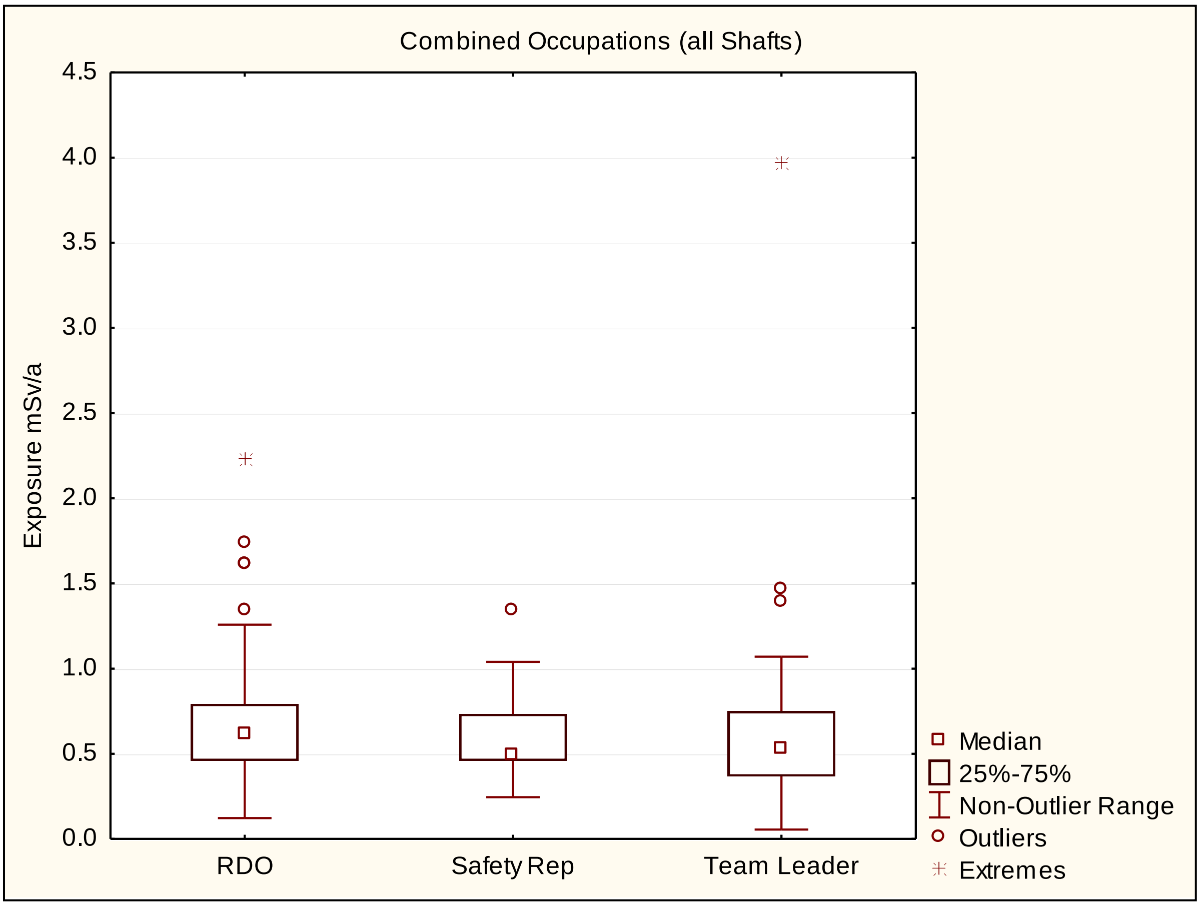

**Fig 3.5: Exposure results per occupation sampled (mSv/a)**

From Figure 3.5 it can be seen that the HEG with the highest exposure is the Rock Drill Operators with a mean exposure of 0.7877 mSv/a, followed by Team leaders with a mean exposure of 0.6564 mSv/a, and lastly the Safety Representatives with a mean exposure of 0.5984 mSv/a. This high exposure relative to the other HEGs can be explained by the close proximity and large amounts of time spent close to the working rock face. Radon-222 emanates in small quantities through the rock face into the underground atmosphere, with disturbing of and physical work on the rock face speeding up the emanation process. Large amounts of time are spent within 2 meters of the rock face where ventilation is low while work is being performed by Rock drill operators. The mean dose of 0.7877 mSv/a equates to less than 1.58% of the OEL limit of 50 mSv/a.

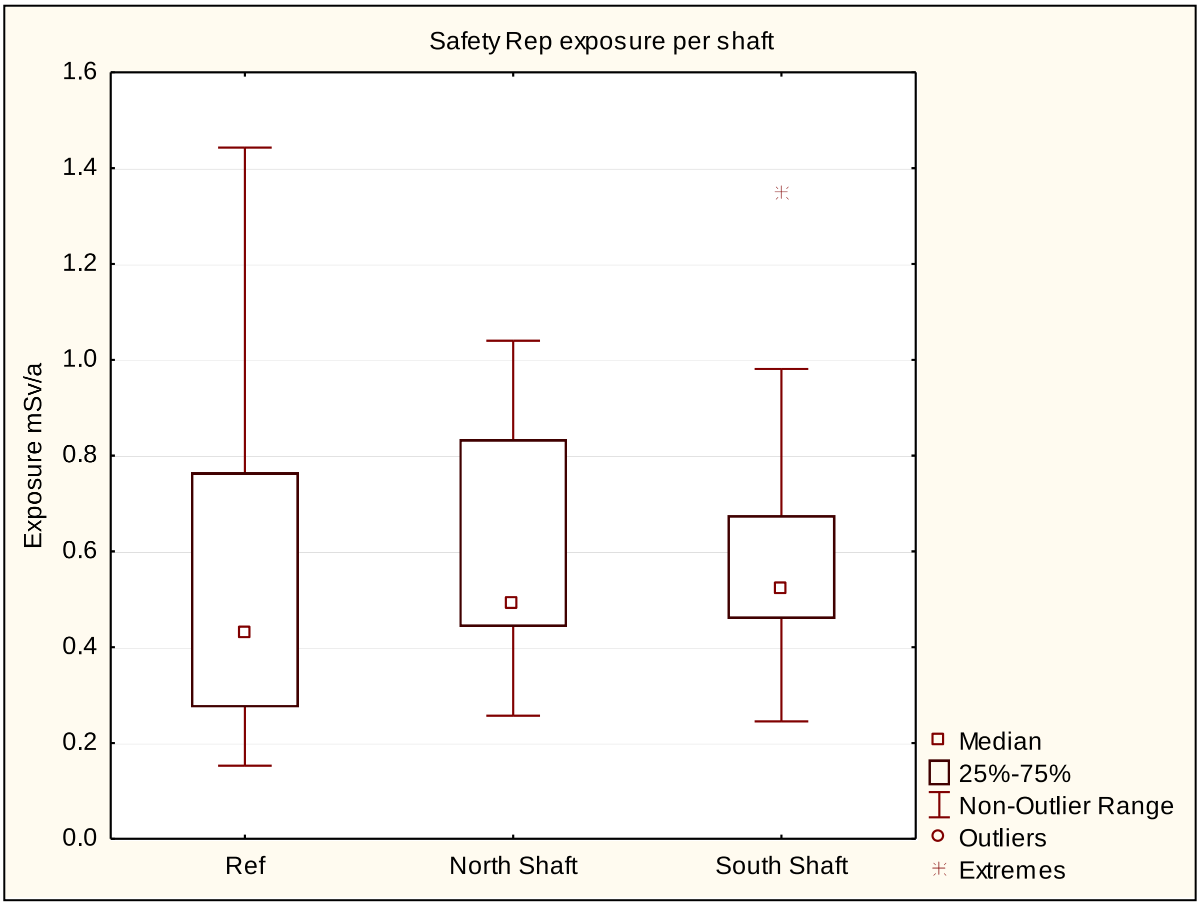

**Fig 3.6: Safety Representative exposure results (mSv/a)**

From Figure 3.6 it can be seen that mean exposure for Safety Representatives as a HEG on both shafts is 0.5984 mSv/a, with Safety Representatives working at North Shaft having a mean exposure of 0.5884 mSv/a and South Shaft having a mean exposure of 0.6133 mSv/a. The mean exposure of Safety Representatives (0.5984 mSv/a) is below the mean reference exposure of 0.6168 mSv/a as measured in the lamp rooms of both North and South Shafts. The mean exposure for Safety Representatives on North Shaft (0.5884 mSv/a) is lower than the mean reference exposure for North Shaft of 0.6943 mSv/a. The mean exposure for Safety Representatives on South Shaft of 0.6133 mSv/a is higher than the mean reference exposure for South Shaft of 0.5393 mSv/a. Possible explanations for this is the variable nature of the Safety representatives role in the mine, with large amounts of time being spent doing safety related tasks and travelling between working areas.

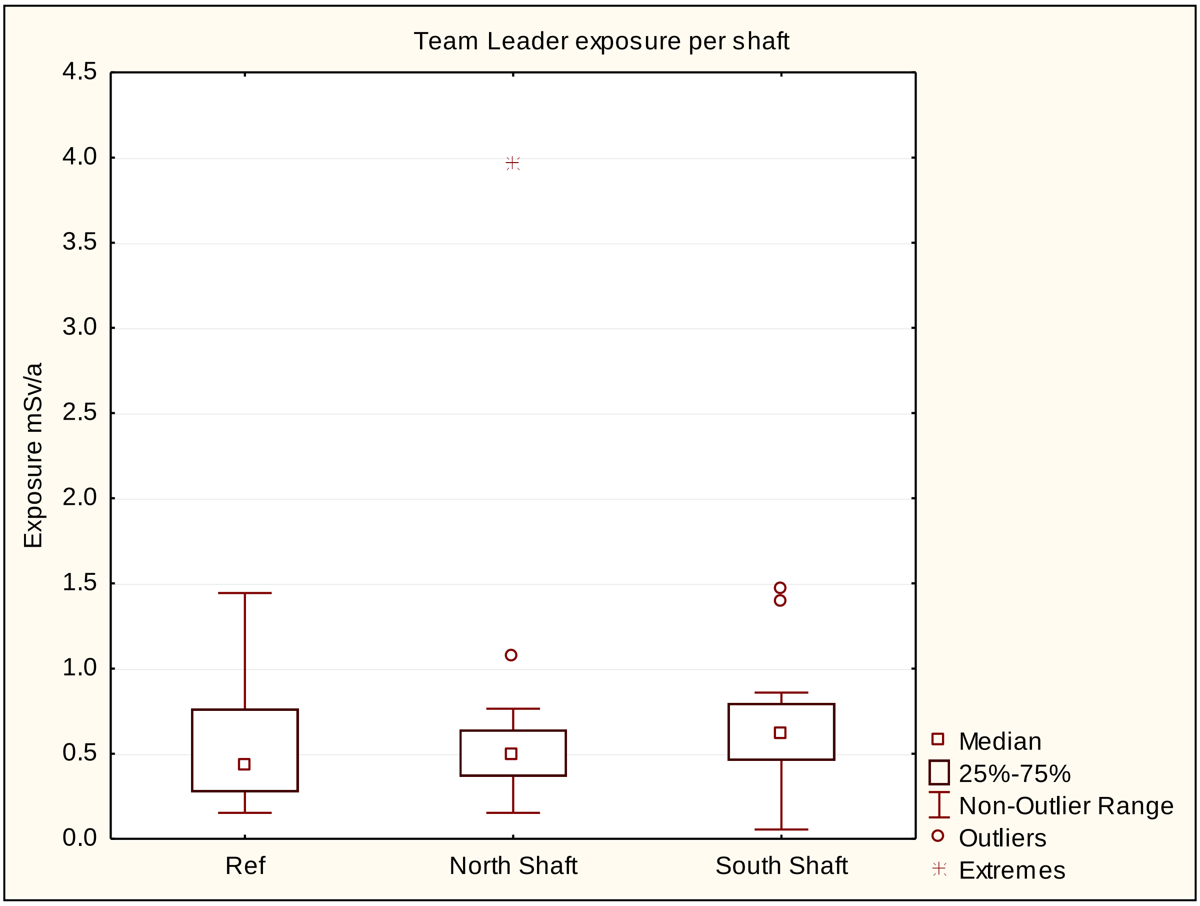

**Fig3.7: Team Leaders exposures results (mSv/a)**

From Figure 3.7 it can be seen that the mean exposure for Team Leaders as a HEG on both shafts is 0.6564 mSv/a, with Team Leaders working at North Shaft having a mean exposure of 1.6540 mSv/a and South Shaft having a mean exposure of 0.6812 mSv/a. The mean exposure of Team Leaders of 0.6564 mSv/a is above the mean reference exposure of 0.6168 mSv/a as measured in the lamp rooms of both North and South shafts. The mean exposure for Team Leaders on North Shaft of 1.6540 mSv/a is significantly higher than the mean reference exposure for North Shaft of 0.6943 mSv/a. The mean exposure for Team Leaders on South Shaft of 0.6812 mSv/a is higher than the mean reference exposure for South Shaft of 0.5393 mSv/a.

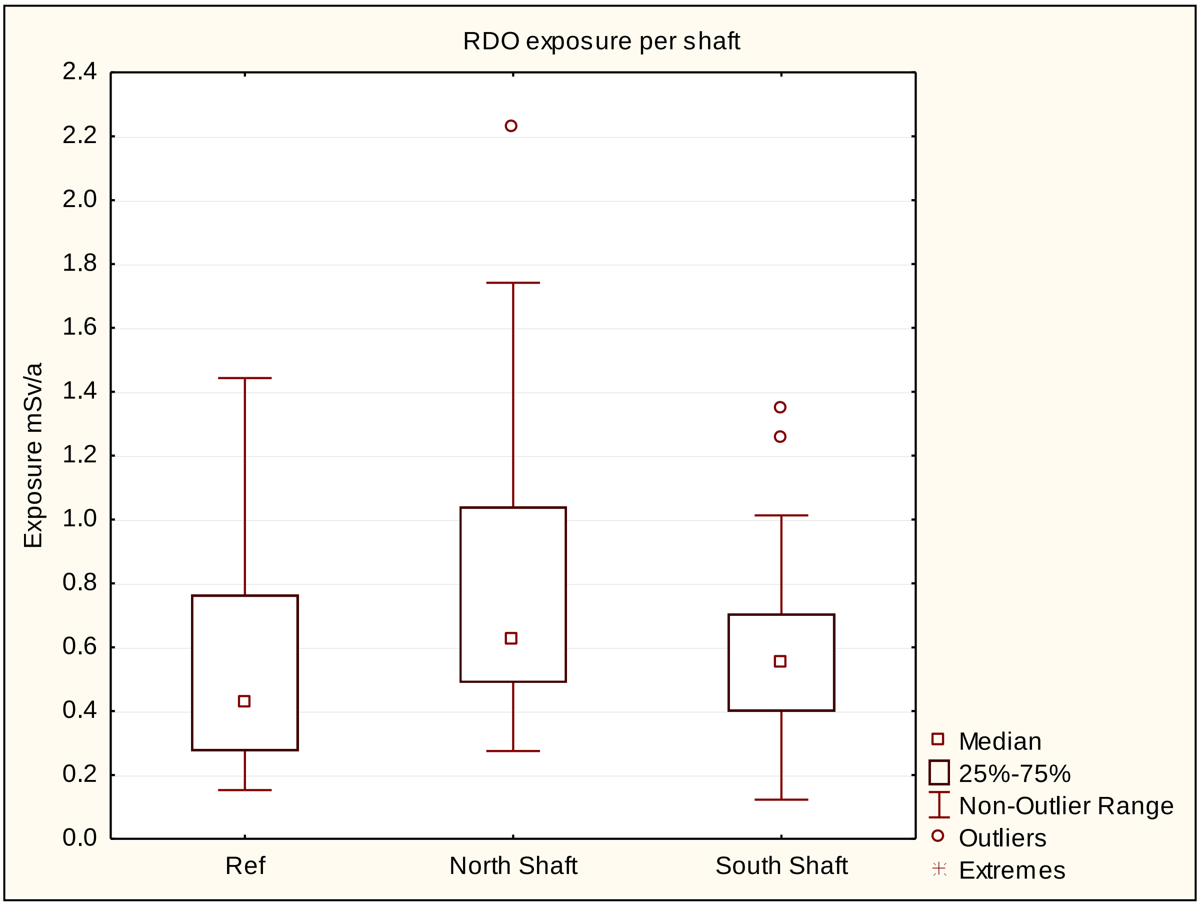

**Fig3.8: Rock Drill Operators exposures results (mSv/a)**

From Figure 3.8 it can be seen that the mean exposure for Rock Drill Operators as a HEG on both shafts is 0.7877 mSv/a, with Rock Drill Operators working at North Shaft having a mean exposure of 0.9936 mSv/a and South Shaft having a mean exposure of 0.5817 mSv/a. The mean exposure of Rock Drill Operators (0.7877 mSv/a) is above the mean reference exposure (0.6168 mSv/a) as measured in the lamp rooms of both North and South shafts. The mean exposure for Rock Drill Operators on North Shaft (0.9936 mSv/a) is significantly higher than the mean reference exposure for North Shaft (0.6943 mSv/a). The mean exposure for Rock Drill Operators on South Shaft (0.5817 mSv/a) is higher than the mean reference exposure for South Shaft (0.5393 mSv/a).

Personal exposure samples were influenced by a number of factors including the amount of Radon-222 being introduced into the underground atmosphere (Volume of Radon-222 being produced through natural decay and diffusion through the rock and man-made activities), the average air flow in the area being worked, time spent underground and the type of activities being performed. The only large difference in air flow existed between normal production areas and development areas. Areas being developed receive large volumes of air from the surface area to extract pollutants being produced by expansion activities.

Practical significant differences (d>0.8) were detected between the reference exposure values and the exposure values for personal exposure at North Shaft, level 2, level 6, level 7, level 8 and at South shaft, Level 5. Activities varied in these levels between production and expansion activities. Practical significant differences (d>0.8) were detected between the reference exposure values and the exposure values for area samples at North Shaft, Level 9 and South Shaft, Level 7, both Levels focusing on expansion activities.

The time spent underground varied from employee to employee, where employees who have finished their tasks for the day being able to leave their underground working areas. True working time is thus not normally the full 8hour shift and even working shifts as long as 12 hours. The OEL for ionizing radiation is calculated over a full year, thus including exposure above ground and exposure below ground. Actual time spent underground (average 265.8 hours during the duration of the study) and working in designated areas should be taken into account in any future studies to exclude any possible interference through worker habits and working culture within the workforce if direct reading instrumentation is used.

Two distinct types of activities were sampled in this study: Production and expansion. Expansion activities include decline sinking, tram-way blasting, installation of ventilation piping, fans and various underground systems and removal of waste rock to surface to produce underground areas used for access to the reef. The aim of these activities is to open up new areas for mining. Production activities centered on rock face drilling, blasting and the removal of reef to surface with the aim of producing ore for processing and platinum production.

The main reason for the low exposure to Radon-222 is the low Uranium composition of the ore and waste rock being mined. With the fluid and variable nature of the geography of the Bushveld complex, potential exists for platinum mines with potentially higher underground exposure to Radon-222 due to variations in Uranium content in the ore being mined in platinum mines, but the general composition of the ore bodies does not contain large amounts of Uranium and the subsequent Uranium-238. An evaluation of the uranium content of an individual mine`s ore and waste rock will give a early indication to the potential Radon-222 exposure.

## 3.6 CONCLUSIONS AND RECOMMENDATIONS

South African platinum mines in the Bushveld complex do not appear to have exposure to Radon-222 gas warranting continual monitoring and control measures, but slight variations in individual ore body compositions may lead to slightly elevated or lower exposures in relation to the mine sampled in this study.

With exposure to all sampled employees in this study well below the OEL, exposure to Radon-222 at an underground platinum mine does not pose a health threat.

The following recommendations are made regarding underground exposure to Radon-222 gas in South African Platinum Mines:

- A broad based baseline measurement of exposure to Radon-222 gas to be done at South African Platinum Mines to evaluate individual mine`s exposure levels to Radon-222 gas.
- Uranium content of ore and waste rock bodies to be evaluated to determine areas of potentially high exposure to Radon-222.
- Employees with impaired lung function to be excluded from areas were Radon-222 exposure is excessive (above 5mSv/a) if applicable, because of their increased risk for the development of lung cancer.
- Employees with a history of smoking to be frequently screened for lung function impairment and possible cancerous growths to identify possible cancerous growths early by means of chest x-rays.
- Control of airborne platinum mine dust to be increased in platinum mines with high uranium content in their ore and waste rock bodies, to minimize the airborne particles to which charged decay products can attach.

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# CHAPTER 4: CONCLUDING CHAPTER

## 4.1 CONCLUSIONS

Bafokeng Rasimone platinum mine (BRPM) in the Bushveld complex does not have exposure to Radon-222 gas warranting continual monitoring and control measures, but slight variations in individual ore body compositions may lead to slightly elevated or decreased exposures in relation to the ore and waste rock being mined with regards to uranium content. The large size and complexity of the Bushveld complex does not allow for the generalization of one set of results to all mines in the Bushveld complex, although the general uranium content is low, some areas of high uranium concentration may be present and need to be individually evaluated.

## 4.2 RECOMMENDATIONS

The following recommendations can be made regarding underground exposure to Radon-222 gas in South African Platinum Mines:

- A baseline measurement of exposure to Radon-222 gas to be done at South African Platinum Mines to evaluate individual mine`s exposure levels to Radon-222 gas.
- Uranium content of ore and waste rock bodies to be evaluated to determine areas of potentially high exposure to Radon-222.
- Mines with elevated levels of Radon-222 to be zoned to indicate areas with high levels of Radon-222 gas.
- High risk occupations to be sampled and employees withdrawn to lower exposure areas when results indicate exposure close to the permissible Occupational exposure limit.
- Employees with a family history of lung cancer to be excluded from areas where Radon-222 exposure is excessive (above 5mSv/a) if practicable due to possible genetic factors making them more susceptible to the development of lung cancer.
- Employees with a history of smoking to be screened at higher frequencies for cancerous growths identify possible cancerous growths early by means of chest x-rays.
- Control of airborne platinum mine dust to be increased in platinum mines with high uranium content in their ore and waste rock bodies, to minimize the airborne particles to which charged decay products can attach.