

Radiometric risk assessment of naturally occurring radioactive materials in the proposed radioactive waste storage area of Pilikwe, Botswana

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Declaration

I solemnly declare that this thesis is my own work. It is being submitted for the fulfilment of the requirements for the degree Doctor of Philosophy (PhD) in Science with Radiation Science at Centre for Applied Radiation Science and Technology (CARST) under the Faculty of Natural and Agricultural Sciences of the North-West University, Mafikeng campus.

This thesis was never submitted in whole or in part anywhere else for any sort of award. In parts of this submission where other sources of information have been used, such sources have been cited in this work and acknowledged under references. Supervised by Prof. Manny Mathuthu and Dr. Chamunorwa Oscar Kureba.



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Tshegofatso Solomon

22/02/2021

.....
Date

Dedication

I dedicate this work to my parents for raising me up. I also devote this research work to my wife and children for their love, support, encouragement, and positive attitude towards me.

Acknowledgement

Special thanks go to my supervisors Prof. Manny Mathuthu and Dr. Chamunorwa Oscar Kureba for their support and guidance on this thesis. It was because of their humility, humbleness and patience that this work was a success. I would also like to thank the Centre for Applied Radiation Science and Technology (CARST) management for giving me the opportunity to be their student.

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Abstract

Determination of natural occurring radioactive material concentrations followed by the radiological risk assessment were conducted for the radioactive waste storage facility to be constructed at Pilikwe village of Central district in Botswana. Sixty soil and two borehole water samples were collected representing the area of construction site and its surroundings. The radioactivity measurements were performed by determining gamma-ray energies with high resolution provided by a high-purity germanium (HPGe) detector, inductively coupled plasma mass spectrometer (ICP-MS), in a low background configuration at the Centre for Applied Radiation Science and Technology laboratories, North-West University and alpha spectroscopy was used to identify and quantify radionuclides at the Radiation Protection Inspectorate.

The high resolution purity germanium detector attained activity concentration results for the soil samples showed that the maximum value for ^{226}Ra was found to be 36.31 Bq/kg, with a minimum value of 6.66 Bq/kg and an average value of 15.86 Bq/kg; maximum value of ^{238}U was found to be 53.47 Bq/kg, with a minimum value of 7.75 Bq/kg and an average value of 25.55 Bq/kg; a maximum value of ^{234}Th was found to be 46.78 Bq/kg, with a minimum value of 11.58 Bq/kg and an average value of 24.98 Bq/kg and the maximum value for ^{40}K was found to be 468.60 Bq/kg, with a minimum value of 59.15 Bq/kg and an average value of 201.30 Bq/kg for the Pilikwe area before any construction work of the radioactive waste storage facility had been conducted.

The average estimated absorbed dose rate (D) for soil samples was found to be 35.29 ± 2.26 nGy/h, which was lower than the worldwide absorbed dose rate of 57.00 nGy/h for soil. The average estimated annual effective dose equivalent (AEDE) from the soil samples was also found to be 43.28 ± 2.77 $\mu\text{Sv/y}$, which was lower than the recommended worldwide value of 70.00 $\mu\text{Sv/y}$ for soils. The radium equivalent activity (R_{aeq}) for soil was 76.78 ± 5.06 Bq/kg. The external hazard index (H_{ext}) for soil was 0.21 ± 0.01 . The mean R_{aeq} values for soil, were all below the worldwide accepted value of 370.00 Bq/kg. The average H_{ext} value for soil, was found to be below the worldwide recommended value of 1.00. All the hazard indices showed that the samples from the Pilikwe village area and its surrounding had acceptable indices with no hazard. Thus, a radioactive storage facility should be built in the identified location provided there will be proper management and safeguarding the leaching of the stored radioactive waste into the soil, as well as having measures in place for monitoring and inspecting the NORMs activity concentrations of the area on specified time frames.

There has been little development regarding analysis of polonium in environmental samples since 1960 as radiochemical analysis of polonium is quite straight forward due to easy of source preparation through auto deposition onto metal surfaces. Thus, in this study the determination of polonium-210 concentrations on the soil and water samples was given more emphasis for the radiological impact

assessment. The average activity concentrations were very low, for the soil samples analysed and for water samples there was no activity concentrations recorded as it was below the instrument detection limit. The reference material: BOT 7003 soil test sample's determined average activity concentration level was 3.27 ± 1.40 Bq/kg for ^{210}Po from a control area. The average activity concentration for all the 60 soil samples on preparation date was 3.10 ± 1.60 Bq/kg. The soil samples were collected from a depth of about 30 cm from the study area. The ^{210}Po measured/ ^{209}Po reference (tracer) ratios for soils from the study area of Pilikwe varied considerably, ranging between 0.17 and 5.98 with an average value of 0.85. This was constantly in agreement with the established view that ^{210}Po measured/ ^{209}Po reference ratios from soils samples could be anticipated to reflect equilibrium for these isotopes (i.e., be near to 1.00) and that ingrowth of ^{210}Po is from ^{210}Pb in the soil as the main source having some excess ^{210}Po decayed away in a relatively short period following deposition.

The ICP-MS attained average elementary concentration results for the soil samples for selected heavy metals were: As (0.02); Pb (0.29); Cr (0.20); Cu (0.03); Zn (0.02); Co (0.47); Th (0.05) and U (0.13) in mg.kg^{-1} , while for Cd, it was below the instrument detection limit. This average elemental concentrations of all selected nuclides in the soil samples were lower than the permissible limits. The heavy metal concentrations in water (mg. L^{-1}) were: Cu (0.03); Zn (0.09) and Ni (0.27) while for As, Pb, Hg, Cd, Cr and Co were below the instrument detection limit. The results showed that the average concentrations of the selected nuclides in soil and water were lower than the WHO permissible limit for all selected nuclides, indicating that it is safe to reside in the study area.

The total excess cancer risk CNRS (i, p, t) for initially existent radionuclides (i) and pathways (p) and fraction of total risk at time (t) years for water dependent pathways and water independent pathways (inhalation excludes radon) analysis obtained from the average activity concentrations of the three radiometrical techniques used. Thus, demonstrated that the total cancer fraction and risk were very low and negligible to have the potential to cause any harm with respect from the initial (0 year) to the final (1000 years) year of interest from the study. Therefore, the cancer risk results from both the water dependent and independent pathways showed that the risk decreased with time from the initial year. The values were less than 1, which indicated that there was no health risk associated with NORMs to the residents of the study area.

Keywords: NORMs, Radiometric risk assessment, Total excess cancer risk, Residual radioactivity

LIST OF ABBREVIATION

ADI	-	Average daily intake
AEDE	-	Annual effective dose equivalent
ALARA	-	As low as reasonably achievable
ASTM	-	The American Standard for Testing and Materials
BSS	-	Basic safety standards
CNRS	-	Total excess cancer risk
CRM	-	Certified reference material
DCF	-	Dose conversion factor
DPCs	-	Dual-purpose canisters
DWC	-	Double-walled canisters
GDMS	-	Glow discharge mass spectrometry
GPS	-	Geographical positioning system
H_{ex}	-	External hazard index
H_{in}	-	Internal hazard index
HLW	-	High-level radioactive waste
HPGe	-	High purity germanium
HQ	-	Hazard quotient
H_T	-	Equivalent dose
IAEA	-	International Atomic Energy Agency
ICP-MS	-	Inductively coupled plasma-mass spectrometry
ICRP	-	International Commission for Radiological Protection
ILW	-	Intermediate-level radioactive waste
L_c	-	Critical level
L_D	-	Detection limit
LLW	-	Low-level radioactive waste
MDA	-	Minimum detection activity
MPCs	-	Multi-purpose canisters
NIST	-	National Institute of Standards and Technology
NORMs	-	Naturally occurring radioactive materials
PLKV	-	Pilikwe village
PLKVB	-	Pilikwe village borehole
ppb	-	Parts per billion
ptt	-	Parts per trillion
QINT	-	Amount of intake quantities

R _{aeq}	-	Radium equivalent
RCAP	-	Recoil contamination avoidance package
RESRAD	-	Residual radioactivity
RPI	-	Radiation Protection Inspectorate
RWSA	-	Radioactive waste storage area
RWSAB	-	Radioactive waste storage area boundary
SIMS	-	Secondary ion mass spectrometry
SRM	-	Standard reference material
TRU	-	Transuranic
UNSCEAR	-	United Nations Scientific Committee on the Effects of Atomic Radiation
USAEPA	-	United States of America Environmental Protection Agency
WIPP	-	Waste isolation pilot plant

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CHAPTER 1: INTRODUCTION AND PROBLEM STATEMENT

1.1 General background

Radiological risk assessment can be defined as a way of identifying potential hazards associated with radioactive materials whilst analyzing the possible effects that can arise if an exposure were to occur accidentally (Prlic et al. 2017). It can also be defined as an evaluation process of potential impacts as a result of interruption of Natural occurring radioactive materials (NORMs) in the environment with time sensitivity or critical material processes that can end up being a health problem to its ecosystem (Batlle et al. 2016). Radiological risk assessment can be achieved by the use of detectors and monitors of radiation to identify the nuclides and their radioactivity in a place of interest (Oughton 2012).

Radiological risk assessment and environmental analysis are key in explaining techniques employed to estimate people exposure risk in relation to radioactive materials from nuclear facilities and act of terrorism into the environment (Picone et al. 2010). This helps in tracking the pathways of radioactive materials in the environment to their destination with keen interest on the risk posed to the people. Many radiological risk cases do exist that need to be put into consideration, and in each radiological risk case, possibility of popping up a different scenario is based on timing, magnitude and location of the radioactive material (Sen 2011). For instance, if there is flood in an area where radioactive materials are mined or stored, the biome stand to be disturbed as risk of radioactive material encroaching the food chain and the water cycle increases significantly (Picone et al. 2010).

Radioactivity naturally exists and thus the environment consists of radiation sources occurring naturally. Humans benefit from numerous radiation and radioactive substances applications such as in power generation, medicine, industry and agriculture (IAEA 2013). The radiation workers, public and the environment are exposed to the radiation risk, therefore assessment and control is necessary. Radioactive materials shall be subjected to standards of safety regarding taking care of substances from activities as medicine, nuclear power plants, production and transport of radioactive material (IAEA 2016).

In order to ensure that people and the environment are protected from harmful ionizing radiation the International Atomic Energy Agency (IAEA) established fundamental safety principles, requirements and measures from its safety standards to control exposures of people to radiation and its release on the environment (Efstathiou et al. (2012). The IAEA mandate being to monitor events that can results in mismanagement of nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and thus strategize on ways to prevent consequences of such events for incase they were to be mismanaged and end up on the wrong intended application (IAEA 2016). All facilities and activities that deals with nuclear and radiological materials giving rise to radiation risks must adhere to the safety standard. This may include nuclear power plants, radiation and radioactive

sources, transport of radioactive material and management of radioactive waste. The aim of the safety and security measures is to protect human life, health and the environment. These measures are designed and implemented in any combined way so that security measures does not compromise safety, as well safety measures does not compromise security (IAEA 2016).

Many aspects of life are at risk from radiation exposure, the first and foremost of them being human lives, which should be the first to consider of any risk assessment on radiation exposure. High-risk activities which result in severe injuries need proper monitoring, thus appropriate emergency plans should be put in place. Physical properties such as buildings and machinery are also at risk due to radiation exposure (IAEA 2013). Environmental impact assessment is of high consideration, thus paying attention to the impact an incident could have on its community as well as putting attention to circumstances that would cause people to have doubt in an organization and products or services (Efstathiou et al. 2012).

When conducting a radiological risk assessment, more emphasis is on the vulnerabilities, and weaknesses that can make people's lives and the environment susceptible to risk over radiation exposure wave. These vulnerabilities can mainly be due to construction of buildings and protection security systems (Kabadayi 2012). These may lead to more radiation exposure effects during an incident. Minimization of impacts from radioactive materials risk is achievable by investing in mitigation strategies, thus ensuring that having a mitigation strategy for radiation exposure is a priority in the Pilikwe radioactive waste storage surrounding area. Risks that can be associated with radioactive waste storage facility may be based on activities, such as natural occurring activity risks; (hurricanes, tropical cyclones, earthquake, tsunami, landslide, and volcanoes). Human activity risks may include; transportation accidents, structural failure, mechanical breakdown, intentional acts, labor strike, demonstrations, civil disturbance, bomb threat, robbery and terrorism (Benedik 2012).

NORMs exposure cases usually get less attention when making estimations to ionizing radiation exposure scenarios. Therefore, this creates additional need to conduct more researches regarding the input data for the models used for providing accurate predictions of radionuclide transmission mechanisms in a radiological risk assessment (Kabadayi 2012). The suitability of available radiometric characterization mathematical models is tested, and necessary improvements determined and implemented. More studies on NORMs related topics should be of high priority in Botswana and the entire world community. Therefore, this study will act as a point of reference in the future regarding studies of NORMs, and the results obtained are of great prominence as it is the first of its kind in the study area.

Although radionuclides are present all over the surface of the earth, they are classified in for groups based on their beginning; primordial, cosmogonic , natural decay series daughters and anthropogenic radionuclides (Dinh 2011). Primordial radionuclides existed with earth as it was formed, this is evident from very long half-lives which are comparable to years of the earth, such as ^{238}U ($T_{1/2} = 4.468 \times 10^9$ years), ^{232}Th ($T_{1/2} = 1.405 \times 10^{10}$ years) and ^{40}K ($T_{1/2} = 1.248 \times 10^9$ years) (Al Shamsi 2014). Whereas Cosmogonic radionuclides are formed due to the earth's atmosphere and surface interacting with cosmic radiation. Frequently acknowledged and used cosmogonic radionuclides examples are ^{10}Be and ^{14}C . Natural decaying radionuclides series are the cause to nonstop decaying of radioactive primordial isotopes such as ^{235}U , ^{238}U and ^{232}Th . The decay progressions comprises nuclear transformation allied with discharge of assorted subatomic particle forms (Al Shamsi 2014). The daughter decay nuclides prompt 80% or more effective radiation dose to the environment thus making it a major radiation risk contributor. Radionuclides such as ^{131}I and ^{137}Cs decay product $^{137\text{m}}\text{Ba}$ are short-lived thus presented to the environment via human actions such as testing of nuclear weapons, nuclear power plants accidental release, nuclear fuel reprocessing, industrial and medical uses. Radionuclides resulting from latter are termed anthropogenic radionuclides. The rest of the three radionuclides origins are natural occurring (Dinh 2011).

1.2 Biological effects of radiation

Human body comprises of organ systems such as the skeletal, digestive and urinary etc. these system structures are in consensus with their functions (Mashaba et al. 2017). The organ system is made up of various tissues such as tendons and muscles. Every tissue contains precise cells that perform specific functions. Normal functioning cells can be damaged if they are being exposed to ionizing radiation. The damage occurs when radiation strikes critical areas like the DNA of the cell, inhibiting the cell from dividing due to the breakdown of DNA molecules. (Martin 2013).

Exposures to ionizing radiation can be categorized into chronic and acute exposures. Chronic exposure being the one that occurs over a long period of time (months or years). This happens when a low radiation dose is delivered slowly over a long time, hence giving cells a high chance of recovering. The main source of this radiation exposure is from NORMs and it occurs to the public. Whereas acute exposure occurs over a short period of time (within minutes, hours or several days at most) making it difficult for the cells to recover due to relatively fast damage due to high radiation doses within a short time and mostly occurs due to radiation accident circumstances. (Saad et al. 2014).

When the cells are not able to repair themselves, permanent effects of radiation damage can be realized as biological changes in tissues and organs. These alterations may be stated as medical symptoms, which are classified into deterministic or stochastic effects (Mashaba et al. 2017).

1.2.1 Deterministic Effects (Non-stochastic)

Deterministic effects exist when there is a threshold below which no detrimental effects are noticed, and the percentage response, known as severity, depends on the dose. The effect increases with increasing radiation dose. The deterministic effects occur only if the radiation dose is substantial (e.g., in an accident). Below the threshold level there is no effect observed, and it is difficult to predict what the risk is to an individual and whether there will be an effect if the radiation dose exceeds a threshold level. This type of effect is also called threshold effect because of the minimum radiation dose that has to be exceeded before any sign of effect to the individual (Mittal 2016).

An example of a deterministic effect is cataract, which is an opacification of the lens of the eye. The exposure to a low radiation dose level of the lens of the eye for patients treated with X-rays (ionizing radiation) is estimated at about 2 Gy. Exposure to ionizing radiation above the threshold dose level (2 Gy) may cause severe damage or can even lead to blindness (Martin 2013).

Another example of this effect is erythema (skin reddening). Below the threshold radiation dose, exposure to a low level of ionizing radiation dose cannot cause skin reddening. But if the radiation dose is increased above the threshold radiation dose level the skin will redden. And if the dose is further increased, severe burn, blistering, or ulceration may occur. Death may occur if high levels of ionizing radiation are exposed to the whole body, which may damage the body organs and eventually stop them from functioning (US.EPA 2018).

1.2.2 Stochastic Effects

Stochastic effect occurs without a threshold level of the dose of radiation exposure effects, and the severity of the damage is self-determining with respect to the quantity of the dose causing it (IAEA 2014a). Contrary to deterministic effects, the amount of radiation exposure does not change the severity (risk of cancer) but it does alter the chance of getting cancer. For the purpose of radiation protection, it is assumed that the probability of stochastic effect increases linearly as the dose increases and that there is no threshold dose. If there is no threshold dose, then it is considered that even small doses of radiation might cause an effect. According to the linear, zero-threshold model; every increment in radiation, no matter how small, carries with it a corresponding increased probability of the stochastic effect (IAEA 2012).

1.3 Problem Statement

Both anthropogenic and natural radionuclides in the environment might enter human body through ingestion and inhalation, thus it is very crucial to conduct NORMs studies regarding environment compartment (atmosphere, hydrosphere, lithosphere and biosphere) in the worldwide and perform human health risk hazard assessment. Many investigations concerning NORMs, considerations has

been focused on the isotopes of uranium, thorium, radon and radium for the reason that they are utmost regularly found in the environment (Benedik 2012).

Naturally occurring polonium (^{210}Po), ($T_{1/2} = 138.4$ days) and lead (^{210}Pb), ($T_{1/2} = 22.3$ years) radionuclide pair continues to be broadly used in radiological risk assessment for the past several decades examining dissolved marine ecosystem particles. Both nuclides are members of the ^{238}U decay series, ^{210}Po coming from the decay of ^{210}Pb via ^{210}Bi ($T_{1/2} = 5.0$ days). In seawater, both ^{210}Pb and ^{210}Po are the reactive particles, nevertheless ^{210}Po also accumulates inside organic tissues (Rigaud 2013). These two radionuclides specific activity difference is frequently employed in the water column quantitatively to assess export fluxes of material particulate sinking properties, such as organic carbon with depth from the ocean surface to the bottom. Since the fundamental measurement techniques for sample preparation and processing, it is of notable improvement regarding the use of exchange resins. There is evident success in research conducted with these methods in the separation of Po and Pb, thus during processing ^{210}Pb can be lost. This loss of ^{210}Pb at the moment it is not clear on calculations ensuing accountability for the assessment of the loss. This loss in most of the laboratories in the world is considered to be minor thus rendering it irrelevant and being ignored, whereas where it is taken into consideration more extensive procedures and process for its correction are being applied (Benedik 2012).

When calculating radionuclide ingrowth, decay, and recovery during sample processing and error treatment laboratories have different methods of doing that, and this is based on a range of assumptions. Thus, the accuracy and precision of ^{210}Po and ^{210}Pb measurements for radiological risk assessment result have always raised some questions from previous studies by other researchers. Therefore, there is still a gap that need to be closed regarding this method. Assessment of the Precision and accuracy procedures for ^{210}Po and ^{210}Pb measurement, are conducted during inter-laboratory comparison exercise on calibrations for seawater particulate samples (Rigaud 2013).

One of the most poisonous radionuclides known to human beings is ^{210}Po , thus still it is found within their surroundings. There are very low concentrations of ^{210}Po in the environment and it is transmitted into the human body through the food chain, such as eating seafood. Due to its low levels in the environment, it is harmless to human health, except in smokers, who have higher levels. However, if more amounts of ^{210}Po enters the human body is very lethal within days or weeks, therefore because of this toxicity there is need for radiological risk assessment of polonium in the environment (Sen 2011).

Likewise, gross beta and alpha activities measurements have been of great use mostly as baseline studies for the environmental radioactivity risk assessment. Uranium isotopes attracts a lot of attention worldwide, due to their operational use in nuclear power plants (Al-Aasm et al. 2013). The

reason being that ^{235}U is key in nuclear power plants energy generation, and the need for its enrichment from natural uranium (Al Shamsi 2014). Uranium, thorium and their decay products leach from rocks thus creating possibility for their transference into the water systems as weathered rock particles in the soil, sediments and dust. Thus, these radionuclides end up in the food chain causing environmental hazard when exceeding statutory set radiation limits (Al-Aasm et al. 2013). Since radioactivity and radionuclides risk and their distribution within Pilikwe region has not been investigated before, this work considers some aspects of radiological risk assessment due to NORMs in more elaborate and informative details.

Radiometric risk assessment due to NORMs in the proposed radioactive waste storage area of Pilikwe, Botswana is a new subject to deal with as there is no referencing data for radiometric characterization of radiological risk assessment associated with radioactive waste storage facilities regarding the study area. This is a challenge to Pilikwe residents and the whole of the country to determine the activity concentrations of NORMs as a forward step to the effects of radioactivity exposure due to waste storage operations in the defined region, since that will now count as additional source of doses to the surrounding. The use of gamma, alpha and inductively coupled plasma mass (ICP-M) spectrometry's for radiometric determination of NORMs radioactivity risks and levels play an important role by providing research data that helps in distinguishing between the importance of having a radioactive waste storage facility and radiological risks associated with it. Therefore, carrying out this research will enable the community of this area and the country of Botswana to understand risks that they can face.

As there is little information in the literature regarding radiometric risk assessment due to NORMs in the proposed radioactive waste storage area of Pilikwe, Botswana. Thus, radiological risk assessment of NORMs in the study area poses a great challenge. Therefore, radiometric risk assessment of NORMs using techniques such as gamma, alpha and inductively coupled plasma mass spectrometry's proves to be significant due to the presence of heterogeneities in the radiation field caused by variations in the radiochemical composition within the surrounding area of the proposed storage facility locality.

Upon completion of the study, this will enable the community of this area and the Policy makers in the country of Botswana to know the radioactivity levels of NORMs and the risks they posed to them and their habitat before construction of a storage. The study will be of great value also for post research that will be conducted after the completion of the radioactive waste storage based on different time interval prior to its operation, in order to detect if there is any change in the NORMs radioactivity levels in the storage site area and its surrounding.

In this research of radiometric risk assessment of NORMs from the soil and water samples from Pilikwe, their radioactivity concentration was determined and compared among the three techniques used, being gamma, alpha and ICP-M spectrometry techniques. Based on available research there is no published research of radiometric risk assessment due to NORMs in the proposed radioactive waste storage area of Pilikwe, Botswana. Hence, there was a scientific gap that needed to be investigated. Thus, found it imperative and interesting to undertake this study on the radiometric risk assessment due to NORMs in the proposed radioactive waste storage area of Pilikwe, Botswana.

Therefore, it is envisioned that this research would shed light on the geological events that affected or caused the alterations to the underground geochemistry of Pilikwe and provide a baseline information to other scholars in the future who will conduct a similar research.

1.4 Research Aim and Objectives

1.4.1 Aim

The aim of this research was to assess the radiological risk due to NORMs in the proposed radioactive waste storage area of Pilikwe, Central Botswana, using radiometric techniques.

1.4.2 Objectives

In order to investigate the aim of this research, the following objectives were identified:

- To evaluate the activity concentrations of NORMs in the proposed waste storage facility site using gamma and alpha spectroscopy techniques.
- To determine the elemental concentrations of NORMs in the proposed waste storage facility site using ICP-MS total quantitative and isotopic ratio techniques.
- To apply RESRAD (Residual Radioactivity) software to produce a conceptual model for the radiological risk assessment for Pilikwe proposed waste storage facility.
- To investigate the effectiveness of mathematical models used to estimate the radiological risks assessment through various parts of the NORMs industries that account the uncertainties related to data input parameters.
- To provide reference data for future risk assessments in order to improve decision-making and policy formulation.

CHAPTER 2: LITERATURE REVIEW

2.1 Background of naturally occurring radioactive materials

Due to human activities on the earth, NORMs radionuclide concentrations become higher than the usually undisturbed present in the earth crust (Turhan 2011). The radiation workers and the public risk to radiation exposure increases as they work with these materials or store them (Ajmal et al. 2014). The radiation workers and the public can be exposed to this radiation in two pathways being gamma radiation emitted from the radionuclides external exposure and the alpha and beta particles internal exposure of the respiratory tract due to the inhalation of the radioactive inert gas radon and the inhalation and/or ingestion of dust particles (Turhan 2010).

For the last decade or so, the assessment of the radiological impact on radiation workers and members of the public has gained interest across the globe regarding the large amounts of NORMs production and the potential radiological hazards, leading to more extensive studies to explain measurement of the activity concentrations of the radionuclides in NORMs (Dhawal et al. 2013). Knowledge of the soil radionuclides activity concentration is very crucial in evaluation radiation exposure to human. The availability of radionuclides in the soil leads to external and internal irradiation of plants and animals through the food chain or inhalation of stemmed radionuclides. Natural radioactivity comprises of terrestrial long lived radioisotopes found in all environments being ^{40}K , ^{238}U and ^{232}Th , their content and individual isotopes ratio are altered by natural process as well as human activities (Simion 2017)

In most laboratories methods used for radiometric and mass spectrometric include gamma spectrometry for fast screening of sediment samples for radionuclides and alpha spectrometry used for determination of the activity of radionuclides isotopes (Dhawal et al. 2013). Long lived radionuclides are determined by mass spectrometric which is also used to confirm radionuclide concentrations to assure quality and control purposes. Glow discharge mass spectrometry (GDMS) has been used to measure ^{237}Np at reference laboratory to determine the level of radioactivity in the environment thus providing scientific and technical guide to the policy of the general directorate transport and energy (radiation protection unit) of the European Commission. These reference laboratory activities are very crucial with respect to the OSPAR (Oslo-Paris, convention) strategy implementation regarding the requirements on environmental radioactivity surveillance and its framework on the management of radioactive substances for the protection of marine environment of the North-East Atlantic (Ozmen et al. 2014).

The high resolution inductively coupled plasma mass spectrometry (HR-ICP-MS) was designed to be world class master piece instrument for the determination of radionuclides isotopes which the alpha-spectrometry is not capable to individually determine, whereas the secondary ion mass

spectrometry (SIMS) is special designed for the characterization of the hot particles distinguished in the samples by means of autoradiography (Ozmen et al. 2014).

2.2 Naturally occurring radioactivity

The earth crust is believed to be approximately populated with 340 naturally occurring nuclides and about 70 are radionuclides. Naturally occurring radionuclides decay into daughters which are radioactive leading to radioactive decay chains. All nuclides in a lineage constitute a decay chain or series (Isinkaye et al. 2015). Radioactive decay chains in nature occurs in four ways being, uranium, thorium, actinium, and neptunium. From all this radioactive series, only uranium and thorium series are the only once contributing to population exposure noticeably. Uranium-238 is the longest-lived member of the uranium series and constitutes about 99.27% of natural uranium with half-life of 4.47×10^9 years. Its concentration in common rock is about 4.7 ppm and decays through alpha particle emission (Montes et al. 2012). Thorium series is headed by ^{232}Th with half-life of 1.41×10^{10} years having a concentration ranges from 1.6–20 ppm in common rocks and decays by alpha particle emission. There are other radionuclides in nature that exist as singly occurring and from these only ^{40}K notable contributes to population exposure (Isinkaye et al. 2015)

Continuous exposure of humans to radiation comes from different sources such as soil, which also act as a radionuclides transport that moves them into the biological systems. The anthropogenic radiological environment contamination can be successively acquired from the soil (Doyi et al. 2017). Man-made activities affect the soil radioactivity thus the radiological risk assessment of the soil is crucial to understand the behaviour the ecosystem radioactivity. This is because of the impact it has on the absorbed dose due to inhalation, ingestion and external irradiation. Studies on soil radioactivity in the past have mainly focused on radiation protection, creating baseline data for future radiological impact assessments and estimation of radioactivity variations caused by nuclear, industrial, and other human activities in the environment (Badhan et al. 2017).

It has been discovered and proved that naturally radioactivity comes due to primordial radionuclides, such as ^{40}K , ^{238}U series and ^{232}Th series with their daughter nuclides, that are found in traces at all levels of ground formations (Manigandan 2014). Soil radioactivity doses widely varies and thus levels of gamma radiation are affected tremendously, which in most cases is used to assess the rate of terrestrial gamma dose. The main human's exposure to radiation is due to the naturally occurring one, thus leading to studies on radiation levels, natural radiation sources dose rates and health effects. More studies on distribution of radionuclides in the environment will lead to an improved understanding of radiation risk thus becoming of great importance as a reference for setting standards and regulatory control actions on radiation protection establishment (Doyi et al. 2017).

Studies have shown that human exposure to NORMs occurs on diverse stages subject to the expected radioactive elements existing in each area, therefore the need for investigations on environmental natural radiation and radioactivity to conduct soil background checks and detect environmental radioactivity in surrounding areas and within radioactive material facilities or places affected by other human activities such as mining. These radioactivity levels can be used to calculate public dose rates and radioactive pollution and envisage deviations in environmental radioactivity instigated by nuclear fortunes, engineering events, and other human actions (Alzubaidi et al. 2016). NORMs mainly are from the earthly layers (soil or rocks) and water bodies (ocean, sea, or lakes) thus making it easy to enter the food chain causing contamination (Yigitoglu et al. 2018).

The physical conformation of the individually detached lithological area and the thorium, uranium, and potassium contents in rocks from which soils initiate is related to specific terrestrial environment radiation levels. Due to physical and chemical properties of soil, it is categorized into several types. Studies conducted worldwide continue to reveal that ^{238}U with its progenies in soils and rocks, and ^{232}Th from monazite sands are the primary causes of extreme natural background radiation (Yigitoglu et al. 2018). There is a lot of research interest on the field of radiation and radioactivity with respect to the natural environment because of human population exposure increase to natural radioactivity proportional to the levels of natural radioactive elements present in each part of the world (Tabar et al. 2017).

The phosphogypsum usage in building materials and agriculture for fertilization results in radionuclides in phosphate rocks entering the environment through different mechanisms. This include fallout from the atmosphere on the vegetation, which is the prime source of contamination due to radiation. Absorbing and maintaining fission products strongly by soil particles and becoming like natural occurring radionuclides, which are extensively spread at diverse depths of the soil. Therefore, radiological risk assessment acquaintance on radionuclide circulation in soils is very crucial in controlling of health risks to the surrounding area of the radioactive storage area and its population (Shohda et al. 2018).

2.3 Radiological risk assessment impact in the environment

The soil and groundwater have natural uranium, thorium, radium and radon due to contact with aquifer rocks, uranium tailings, radioactive storage, absorption from soils and fertilizer leaching (Al Shamsi 2014). Radionuclides once entered the groundwater, moves into the environment through drinking, domestic, farming and industrial uses etc. Through direct or indirect pathways radionuclides are able to pass into the human body. Direct pathway occurs by means of groundwater for drinking and eating vegetables contaminated with radionuclides fallout, whereas indirect pathway involves the consumption of products watered with contaminated water or livestock nourished by contaminated

feedstuff. Nevertheless, the indirect feeding is known to be non-risky to wellbeing of humans and animals in all-purpose due to small amount of acquired dosage (Murad et al. 2014).

The radon gas released easily get inhaled by humans from water and waste storage facilities. The radioactivity emitted from radon isotopes is in the form of α radiation of which its penetrating ability is very low and thus not able to penetrate the skin outer layers. The human health main major risk of concern is the consumption of radionuclides through ingestion and inhalation. There are other risks to health as a result of radionuclide during construction leading to aggregation in kidneys and bones therefore ending up causing cancer (Makoti et al. 2012). Although uranium radioactivity is very weak it has the potential to cause harm to the kidneys, since it's a heavy metal and thus posing risk due to long term accumulation. When the human body is exposed to high levels of radium, the immune system gets weakened leading to possibilities of diseases such as, anaemia, cataracts and teeth frailty. Exposure to high radium radiation at workplace can cause these health risks. The lung cancer risk is associated with inhalation of uranium, radium dust and radon gas resulting from water and waste storage facilities of radioactive materials (Zorer et al. 2013).

The standard international unit for measuring dose is sieverts (Sv) or millisieverts (mSv), where 1 Sv = 1 Joule/kg. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has estimated the individual annual average dose to be about 3.0 mSv/year. The NORMS contributing 80% of the annual dose, medical diagnosis being 19.6% and other anthropogenic sources at 0.4% of the annual dose (UNSCEAR 2012). Cancer risk increases at the exposure to radiation doses of more than 100 mSv thus an increase in the formation of cancerous cells. Exposures below 100 mSv of radiation doses have omissible risk for the formation of cancerous cells and very difficult to identify (Bromet 2014).

There are various ways of reducing or limiting radionuclides radiation exposure either by using simple or complicated techniques, this is in most cases determined by radionuclide decay mode. The high penetrating ability gamma emitting radionuclide are mainly stopped by very dense materials such as thick concrete or lead blocks respectively. Beta emitters are termed as having medium penetrating ability and can be stopped by a piece of cloth or thin layer of wood. Alpha emitters have very low penetrating ability and considered to be safe if irradiated from external source and are not able to penetrate the skin thus can be stopped by a piece of paper (Santawamaitre 2012)

Human exposure to radionuclides cases of dinking groundwater has led to development of new techniques and the mandate being to safeguard against any type of exposure, these techniques work by chemical altering the radionuclides thus making them insoluble and eliminating at the same time. Another technique is used to lower the concentrations of uranium from groundwater by a way of injecting certain bacteria which are able to reduce hexavalent state uranium to a tetravalent state,

which is insoluble (Veeramani 2011). A regulated special cleaning up method is required to alleviate the high levels of radionuclides that poses danger to habitat. Periodically monitoring of contaminated areas with radionuclides should be given proper attention with samples being collected with documented date and time. Risk severity must be shared with the affected community in an understandable clear audible language to the public (WHO 2011).

2.4 Storage of radioactive waste

When storing radioactive waste suitable conditions for its management must be put in place for easy inspections, monitoring, retrieving and preserving. For each storage timeframe there should be accountability and transparency policy in place for the extent possible as well indicating the passive safety features that must be considered. When dealing with a long term storage, to ensure that containment of the waste does not degrade specific measures must be in place (IAEA 2012). The science of radioactive waste management refers to storage as a temporary facility where radioactive waste is placed and having proper segregation and monitoring tools in place. Storage should be a step of management of radioactive waste prior to disposal and be used in facilitating the subsequent steps, thus being an intermediary between and within the waste management steps. This should be a way of providing sufficient time for radionuclides to decay before they can be cleared and authorised for discharge, it can also act as a quarantine for waste generated in emergency situations awaiting final disposal management decision (IAEA 2014b). There are different options of storing radioactive waste, for example, disposal to the near surface and deep geological.

2.4.1 Interim waste storage and transport

There are interim facilities for storing radioactive waste either on the surface or sub-surface, which are specially designed and presently being used by various countries in ensuring that hazardous radioactive waste is precisely managed before being disposed on long-term basis. For storage of intermediate level radioactive waste (ILW) and high-level radioactive waste (HLW) as well as used nuclear fuel from reactors, interim storage facilities are the preferred ones for the management of this types of waste (US DOE 2014).

2.4.1.1 Storage ponds

Nuclear reactors have storage ponds, and there are those in centralised facilities with a depth of 7-12 metres thus allowing the gathered nuclear fuel materials to be roofed down by water for some metres. These used nuclear fuel materials are about 4m long. The different gathered racks of the used nuclear fuel materials are made of metals with neutron absorbers fused on them. The purpose of covering this material with water is to act as shielding and at the same time cooling the fuel. The ponds are gigantically made up of thick concrete reinforced with steel. With regard to ponds made at reactor

plants their design is that it should be able to store all the used fuel for the concerned reactors life span, but also the design can cater for removal of cooled fuel for reprocessing or to transfer into a dry storage (World Nuclear Association 2016).

2.4.1.2 Dry storage

The United States of America nuclear power plants have been using dry storage since 1986 up to date with one-third of its spent fuel found in this type of storage containers. Stored spent fuel that has been in ponds cooling for a period of at least five years, then it is moved into dry storage containers or domes, where the concrete shielding must be having adequate circulation of air within the storage. The process of transferring from wet ponds to dry casks storage within the site of the power plant requires a specialised container that is well shielded designed for spent nuclear fuel transfer purpose specifically and being less strong than ones used in transporting outside the nuclear plant site. This special designed containers may have an internal sealed canister which is transferable between different types containers with easy (Jamrožík et al. 2011).

2.4.1.3 Multi-purpose canisters

The sealed multi-purpose canisters (MPCs), which are also referred to as dual purpose canisters (DPCs), have the capacity to house up to 89 spent fuel logs with inert gas. This type in most cases specifically designed for transporting, storing and ultimately for disposal of spent nuclear fuel. MPCs are strongly designed and well-built containers inside packs of metal for transport and concrete for storage. The design of each MPC, is constituted of 13 mm stainless steel soldered and having a very secure lid within an internal fuel basket that keeps the spent nuclear fuel piles detached. This type is built to be able to withstand the heat load of up to 45 kW. The standard external proportions of the MPCs are subjected to their physiognomies regarding the number of used nuclear fuel logs to be loaded. Double walled canisters (DWC), are embedded with helium between the layers and once loaded with the spent nuclear material for storage it is of no importance for it to be remanded again (Juenger 2015).

2.4.1.4 Transport casks

Meticulously shielded containers with steel or lead are used for the shipment of nuclear fuel waste and these containers weigh up to 110 tonnes when empty. They are able to enclose the highly radioactive waste safely for transportation and has the capacity to take load from 6 to 24 tonnes of spent fuel (US DOE 2014).

2.4.2 Near surface disposal

According to the IAEA near surface disposal can be defined as whereby radioactive waste is being disposed within or without barriers designed for that purpose (IAEA 2016).

2.4.2.1 Near surface disposal facilities at ground level

As the name suggest these facilities are designed so that they can be on the surface and below the ground surface with depth of few metres thick from protective covering. Waste containers are sited on the constructed arches and once they are fully packed, they are being backfilled, covered and capped using an impermeable membrane and topsoil. These facilities must have good drainage system as well as good gas expelling system. It is commonly known that majority (about 90% by volume) of radioactive waste classified as low level (LLW) as soon as it is packaged for a longer-term management is preferably dumped on land-based disposal facility. These includes all types of waste resulting from nuclear technological activities, and this makes this type of waste disposal to be of acceptable standard and being used all over the world (Cooper 2018).

2.4.2.2 Near-surface disposal facilities in caverns below ground level

Ground level disposal by near surface method is contrary to below ground level disposal in a way that excavations conducted from the surface are shallow and requires underground diggings of caves. Thus, making the facility to a depth deep down the earth surface with tens of metres and can only be accessed through a drift. The term shallow land disposal was used in the olden days and have since been replaced by near surface disposal, and it is notable that the term shallow land disposal is still being used sometimes when referring to near surface disposal. Long term climate change such as glaciation do affect this option of facility and during their design this has to be accounted for and put into considerations to avoid any future mishap for the future generation safety as well as the environment. This type of facility are in most parts of the world used for disposal of LLW and short-lived ILW with half-lives of up to 30 years as they have been found to be the most appropriate and suitable ones for this kind of waste (World Nuclear Association 2016).

2.4.2.3 Deep geological disposal

The disposal of radioactive waste in deep geological idea was established about long timescales as some waste remained radioactive ensuing in formations of underground stable geological repositories. Natural barriers such as rocks and clay as well as engineered ones provides isolation, ensuring that there are no burdens passed on to future generations regarding maintenance of the facilities. This option is also sometimes called multi barrier, since the barrier is strategically developed either by the packaging of waste, repository engineering and the surrounding geology thus all preventing the radionuclides from reaching humans and the environment. The chemical

mobilisation of radioactive waste underground is minimal since the deep groundwater is devoid of oxygen.

Most countries are more into the idea of deep geological disposal for the management of their radioactive waste, this includes countries such as Argentina, Australia, Belgium, Canada, Czech Republic, Finland, France, Japan, the Netherlands, Republic of Korea, Russia, Spain, Sweden, Switzerland, United Kingdom and United States of America. Thus, there are more literature available regarding the deep geological disposal concepts (Leonad 2010). Only the USA has a licensed waste isolation pilot plant (WIPP) which is well purpose-built deep geological repository. Spent fuel disposal ideas in countries such as Finland, Sweden, France, and the USA are in a more advanced stages, although in the USA there are some delays which are mainly political. Canada and United Kingdom are the two countries that has fully supported the idea of deep geological disposal and have commenced on selection of sites for construction of this facilities (Steliga 2014).

Intermediate-level radioactive waste (ILW), having long-lived radioisotopes in most cases are better placed under deep geological repository awaiting their final disposal. With regard to defence related transuranic (TRU) waste, it is treated similarly to ILW by the USA, thus disposed of into the waste isolation pilot plant (WIPP) which is a deep geological repository found in New Mexico. Disposal of short-lived radioisotopes of the ILW type by many country's is by means of near-surface disposal facilities, (Stępień 2014). Table 2.1 outlines the commonly accepted disposal options in the world. To consider an option for disposal, there are prerequisites that must be satisfied, such as suitability of an options dependence on the waste form, volume, and waste radioactivity (Stryczek et al. 2014).

For the waste of high-level radioactivity (HLW), a preferred way for its disposal management is that of deep geological, and in most cases, attention is on where and how the facility should be constructed. In order to undertake disposal of HLW in a secure and safe manner, firstly it must be stored to allow radioactivity decay and heat cooling for safer handling. Storing of spent fuel is usually in most cases in dry casks or ponds, this can be at the site of the reactor or at a temporary storage waiting final disposal. There are many options that have been investigated and others still under investigation that are aimed at providing publicly safe and acceptable way, as well as environmentally friendly final disposal of HLW radioactive waste solutions (Stryczek et al. 2015). Recycling and reprocessing of uranium and plutonium is also an option for spent fuel that is not for final disposal. Separated HLW liquid that arises through the reprocessing and recycling processes are encapsulated in ceramics and glass temporally waiting final disposal (Tanatwy et al. 2012).

Table 2.1: Disposal options that are commonly accepted (Stryczek et al. 2015).

Disposal options	Waste types acceptable	Examples and countries were implemented or investigated
Near-surface disposal	LLW and short-lived ILW	<ul style="list-style-type: none"> • Disposal is at ground level, or in caverns below ground level (at depths of few meters) • Implemented for LLW in countries, such as Czech Republic, Finland, France, Japan, Netherlands, Spain, Sweden, UK, and USA. • Implemented in Finland and Sweden for LLW and short-lived ILW.
Deep geological	Long-lived ILW and HLW	<ul style="list-style-type: none"> • Disposable at depths between 250 m and 1000 m for mined repositories, and 2000 m to 5000 m for boreholes • Deep geological disposal has been investigated by many countries that have developed official policies. • Implemented in the USA for defence-related transuranic waste at WIPP. • Site selection process for geological repository commenced in the UK and Canada.

2.4.2.4 Long-term above ground storage

From long time back storage of radioactive waste over the ground has always been regarded as a priority for disposal but lately it is used as a temporary measure for storage. This resonated from past research conducted by the French for HLW based on the framework of the 1991 law on research into radioactive waste management (Act No 91-1381 of 30 December 1991, which is normally termed as the 'Bataille Act' named after its proposer), with respect that it should not be the disposal stage. Surface storage of waste for extended long time for up to some hundreds of years on controlled areas have been considered by many countries as an option for long-term waste management option (Grabowska 2016). Facilities above the ground level that have been designed for long term storage, their design should be that they are not prone to backfilling and not be sealed permanently. This is considered for the future continuous monitoring of the facility and for purposes of easy retrieval with less expenses. Above the ground long-term storage proposals can be broadly categorised into two; being conventional stores which are preferred for interim storage, and lasts for 200 years and beyond before replacement and repackaging of waste can be done (Tanatwy et al. 2012).

Permanent stores which have the ability to stay intact for thousands of years, and it is commonly known as Monolith stores or Mausoleums. This category of store is based on the guardianship principle, which takes into considerations the future generations responsibilities for continuous monitoring and supervision of the waste without being a burden to their wellbeing and the environment. In both store categories it is mandatory that the relevant information be transferred to the future generation, thus safeguarding stability for the future and ensuring that monitoring and

supervision will be done on an on-going bases process. Meanwhile there is no country in the world that have plans for utilisation of long-term above ground storage (i.e., more than some hundred years). There are some still ongoing research by France regarding long-term interim storage, and considerations that it should not be above the ground level (Leonad 2010).

Table 2.2: Other ideas tried in the past regarding long-term radioactive waste storage (USDOE 2014).

Ideas	Examples
Above ground Long-term storage	This type of storage has been considered by France, Netherlands, Switzerland, UK, and USA, and it have not been used anywhere.
Outer space disposal (considered for storing highly concentrated waste)	This option was considered by USA and got abandoned because of high cost and potential risks from launch failure.
Rock-melting (proposed for wastes that are heat-generating)	This was studied by Russia, UK, and USA, and have never been used anywhere.
Subduction zones disposal	Studies were carried out by USA and never adopted for use anywhere as it was rejected on international agreements.
Disposal at sea	This option has been used by some countries such as Belgium, France, Germany, Italy, Japan, Netherlands, Russia, South Korea, Switzerland, UK, and USA, and it is not being allowed by the international agreements.
Disposal at sub-seabed	It has been considered by Sweden and UK and has never been put into practice anywhere as it was rejected by international agreements.
Ice sheets disposal (proposed for heat generating waste)	It was proposed by USA and was not accepted by the Antarctic Treaty signatory countries.
Well deep injection (liquid wastes form)	Have been proposed and approved by Russia for use regarding LLW and ILW. USA stopped it in consideration for disposal on deep geological of wastes in solid form.

2.5 Types of decay

Experiments by Ernest Rutherford's regarding radiation interacting with electric and magnetic field respectfully, resulted in him discovering that α particles were massive and positively charged; β particles were less massive and charged negatively, and that γ rays were electromagnetic waves with no charge. The α particles are found to be the helium nuclei that is highly energized, β particles

comprised of electrons that are highly energized electrons, and γ radiation being composed of electromagnetic radiation of high energy. The type of radiation produced during radioactive decay is used for its classification. Table 2.3 summarizes the type, nuclear equation, representation, and mass or atomic number changes (OpenStax 2016).

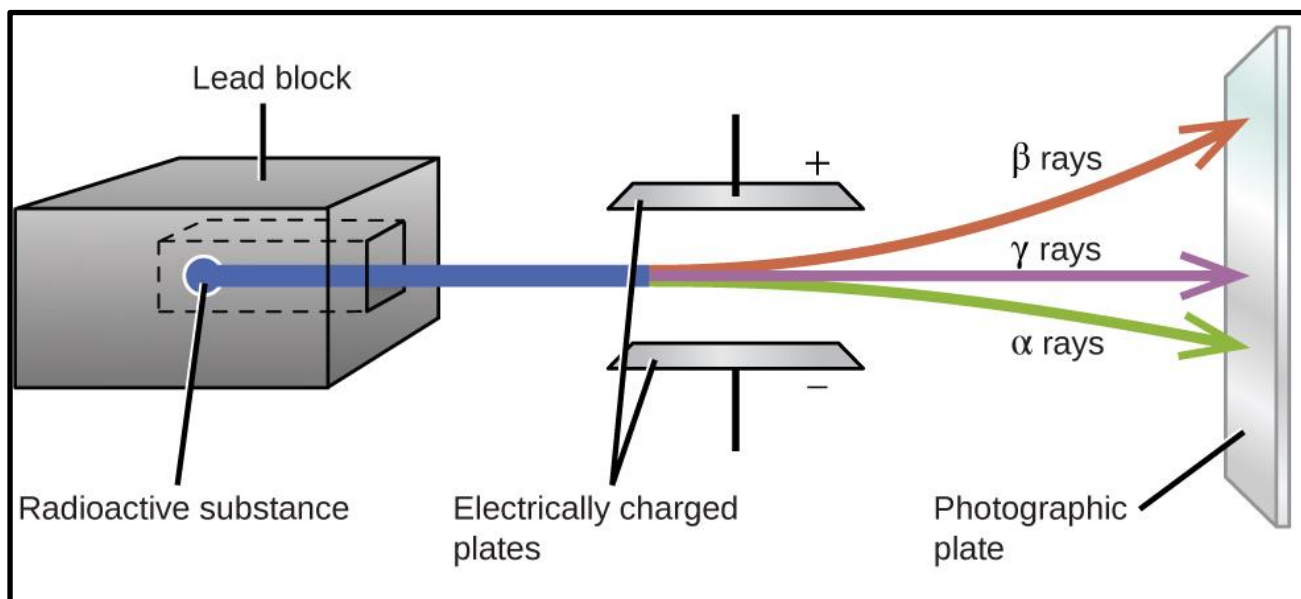
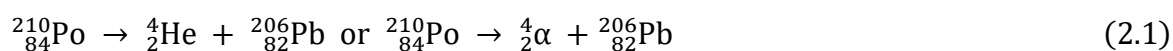


Figure 2.1: Experiments by Ernest Rutherford's of interacting radiation with magnetic or electric field (Flowers et al. 2019).

In Figure 2.1 the plate charged negative attracts alpha particles and they deflect in rather small amount, showing that they carry a positive charge and fairly massive. The positive plate attracts the beta particles which deflect at large relative amount, indicating that they are light and carry a negative charge and the gamma rays are being not affected by the electric nor the magnetic field, thus have no charge (Flowers et al. 2019).

2.5.1 Alpha (α) decay

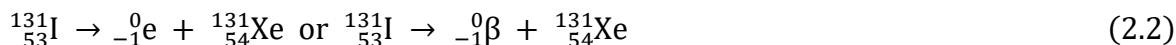
Alpha decay is when an α particle is being emitted from a nucleus. An example of α decay is Polonium-210 (Langley 2019):



The loss of an α particle result in a daughter nuclide of both atomic and mass number, four units smaller and two units smaller than the parent nuclide respectively. This means that the n:p ratio of daughter nuclide to the parent nuclide is large (OpenStax 2019).

2.5.2 Beta (β) decay

When a nucleus emits an electron is referred to as β decay. An example of β decay is Iodine-131 (Robinson 2019).



When a proton is converted into a neutron and a β particle, it is termed as the beta decay. It occurs mainly in nuclides having a large n:p ratio. The atomic nucleus emits an electron (beta particle) instead of the orbiting one and this type of nuclei is above stability band. The loss of an electron in this process does not alter nuclide mass number, but rather increase the protons and decrease neutrons number differentially. This subsequently result in a decreased n:p ratio, with the daughter nuclide being in close proximity to stability band compared to the parent nuclide (OpenStax 2019).

2.5.3 Gamma emission (γ emission)

When a nuclide is formed during excitation state and then decays to its ground state is called gamma emission process. This process involves the release of a γ ray which is a highly energized electromagnetic radiation quantum. The scientific symbolization of a nucleus in an excited state is by an asterisk (*). Gamma radiation is very crucial in the medical field for the treatment of cancer using radiation sources such as cobalt-60 (Langley 2019).



Gamma rays emission results with no alterations in the mass number or atomic number unless the γ emission is in accomplice of other radiation decay modes (Robinson 2019).

2.5.4 Positron emission (β^+ decay)

When a nucleus emits a positron, it is called β^+ decay. Oxygen-15 is an example of nuclide decaying by emitting a positron (OpenStax 2016).



Low nuclides n:p ratio is a testifies the emission of a positron. These takes place for nuclides below stability band; thus, a proton is converted into a neutron and a positron emitted. When these occurs there is an increase in n:p ratio increases, therefore resulting in the daughter nuclide being nearer to the stability band more than the parent nuclide was before positron emission (Flowers et al. 2019).



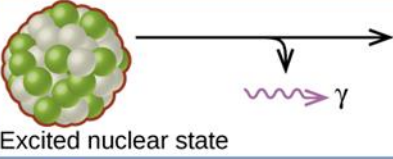

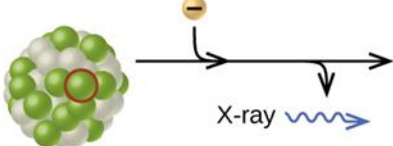
2.5.5 Electron capture

Electron capture is when an atom nucleus captures one of the inner electrons. Potassium-40 is an example of a nuclide that decays by electron capture (Flowers et al. 2019).



The process of electron capture takes place when an electron from the inner shell and a proton combines and being converted into a neutron. The forfeiture of the electron in the inner shell creates a gap that is should be filled with an electron from the outer shell. Energy is being released in the form of x-rays when an electron moves from the outer into the inner shell. Positron emission is comparable to electron capture in the sense that they both occur to the proton-rich nuclei that are below the stability band and causing the same effect to nucleus, such as a decrease in atomic number by one with no change in mass number (Robinson 2019). At the end there is an increased ratio of n:p and the daughter nuclides are closer to the stability band than their parent nuclides were. Therefore, making it very difficult to distinguish which process has occurred, either electron capture or positron emission. Kinetic factors determines the choice, based on principle of the activation energy, as the reaction process that requires less activation energy is considered to have taken place as its likelihood to have occurred is high (OpenStax 2019).

Table 2.3: Decay type table summarizing the type, nuclear equation, representation, and mass or atomic numbers changes (OpenStax 2019).

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	${}_{Z}^AX \rightarrow {}_{2}^4\text{He} + {}_{Z-2}^{A-4}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	${}_{Z}^AX \rightarrow {}_{-1}^0\text{e} + {}_{Z+1}^AY$		A: unchanged Z: increase by 1
Gamma decay	${}_{Z}^AX \rightarrow {}_{0}^0\gamma + {}_{Z}^AY$		A: unchanged Z: unchanged
Positron emission	${}_{Z}^AX \rightarrow {}_{+1}^0\text{e} + {}_{Z-1}^AY$		A: unchanged Z: decrease by 1
Electron capture	${}_{Z}^AX + {}_{-1}^0\text{e} \rightarrow {}_{Z-1}^AY$		A: unchanged Z: decrease by 1

2.6 Radioactive half-lives

Radioactive nuclides have different distinctive half-life's ($t_{1/2}$), this is the period needed for half an atom to decay in a given sample. Isotope's half-life is very crucial in determination of the timeframes an isotope in a sample will last or should be stored until all the harmful ones have all decayed to a safer low radiation level considered to be not dangerous (Almayahi et al. 2012).

Cobalt-60 isotope when decaying it discharges gamma rays, the ^{60}Co nuclei decay to half in every 5.27 years. If a radioactive nuclide decays, its radiation strength is directly proportional to the rate of decay of the substance and the amount of the radioactive nuclide material as illustrated in Figure 2.2 (Alzubaidi et al. 2016).

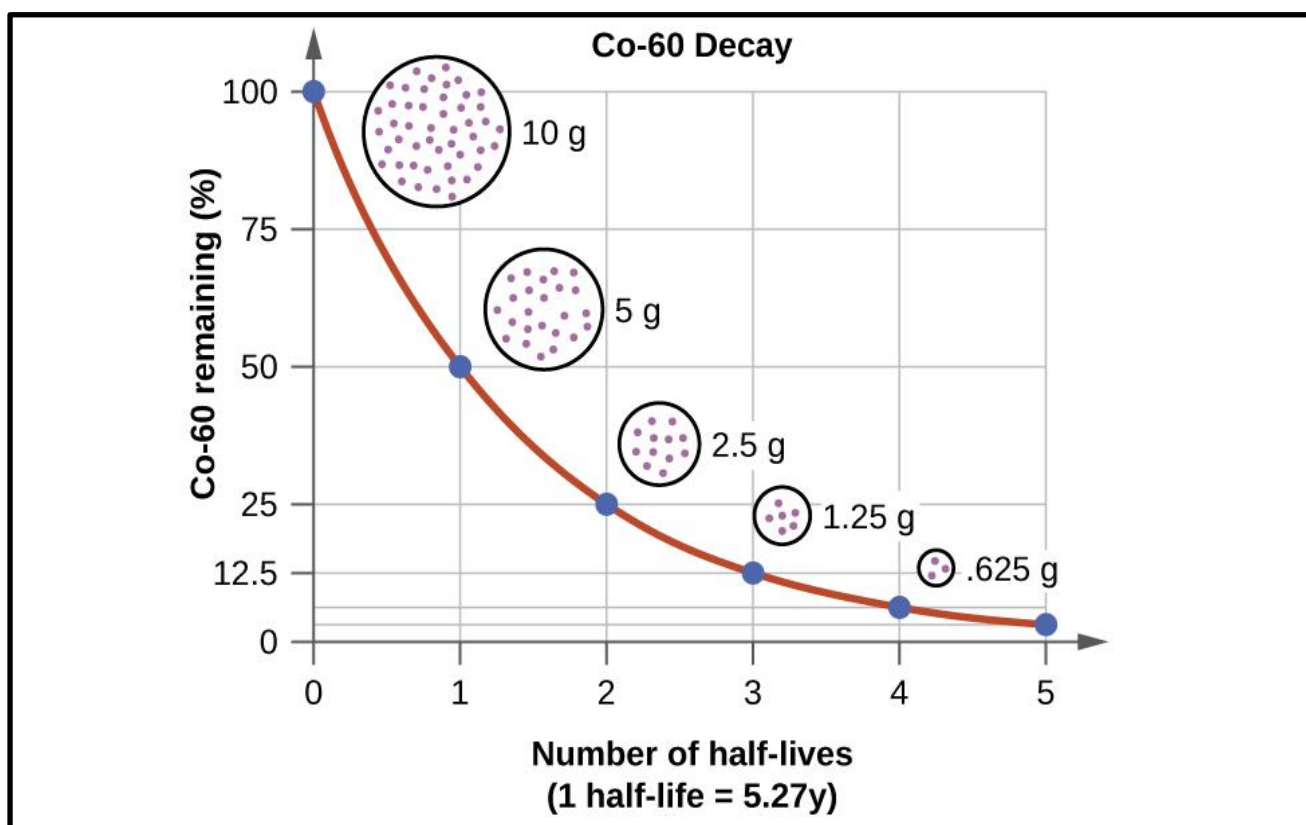


Figure 2.2: Decay of cobalt-60 with half-life of 5.27 years (Alzubaidi et al. 2016).

When ^{60}Co decays 50% remains after 5.27 years (one half-life), 25% remains after 10.54 years (two half-lives), 12.5% remains after 15.81 years (three half-lives), and so on. Nuclear decay follows first-order kinetics; thus, making it possible to use mathematical relationships for first-order chemical reactions. This is possible by generally substituting the number of nuclei, N , for the concentration. When the nuclear rate of decay is per second, it is considered as the radioactivity of the samples (Ahmad et al. 2015). The radioactive decay rate is:

Decay rate = λN ; with λ = the decay constant for the particular radioisotope, which can also be expressed by the decay constant in terms of the half-life, $t_{1/2}$:

$$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}} = \frac{0.693}{t_{\frac{1}{2}}} \quad \text{or} \quad t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \quad (2.6)$$

The first-order equations relating amount, N , and time are:

$$N_t = N_0 e^{-kt} \quad \text{or} \quad t = -\frac{1}{\lambda} \ln \left(\frac{N_t}{N_0} \right) \quad (2.7)$$

where N_0 is the initial number of nuclei or moles of the isotope, and N_t is the number of nuclei/moles remaining at time t .

2.7 Radioactive decay series

Heavy elements radioactive isotopes that occur naturally are classified into series of sequential disintegrations or decays, with the constituent isotopes of each series forming a radioactive decay series (Issa 2013). There are four known radioactive decay series being uranium series, actinide series, thorium series and neptunium series. The neptunium series is no longer considered applicable on earth due to its constituent isotope's short half-lives. The radioactive decay series takes the parent nuclides traits and are categorized based on it, as having long half-life. The daughters take a sequential order of decay leading to stable end nuclide and found on the stability band. All three series have lead as the end stable product (Huy et al. 2012).

2.7.1 Uranium series

The $4n+2$ chain of U-238 is called the "uranium series" or "radium series". The naturally occurring uranium-238 starts the series and followed by astatine, bismuth, lead, polonium, protactinium, radium, radon, thallium, and thorium as shown in Figure 2.3. All these isotopes are found transiently in the series for any natural sample comprising uranium. It can be found in metal, compound, or mineral samples and the series still terminating with lead-206 (Mehra 2011).

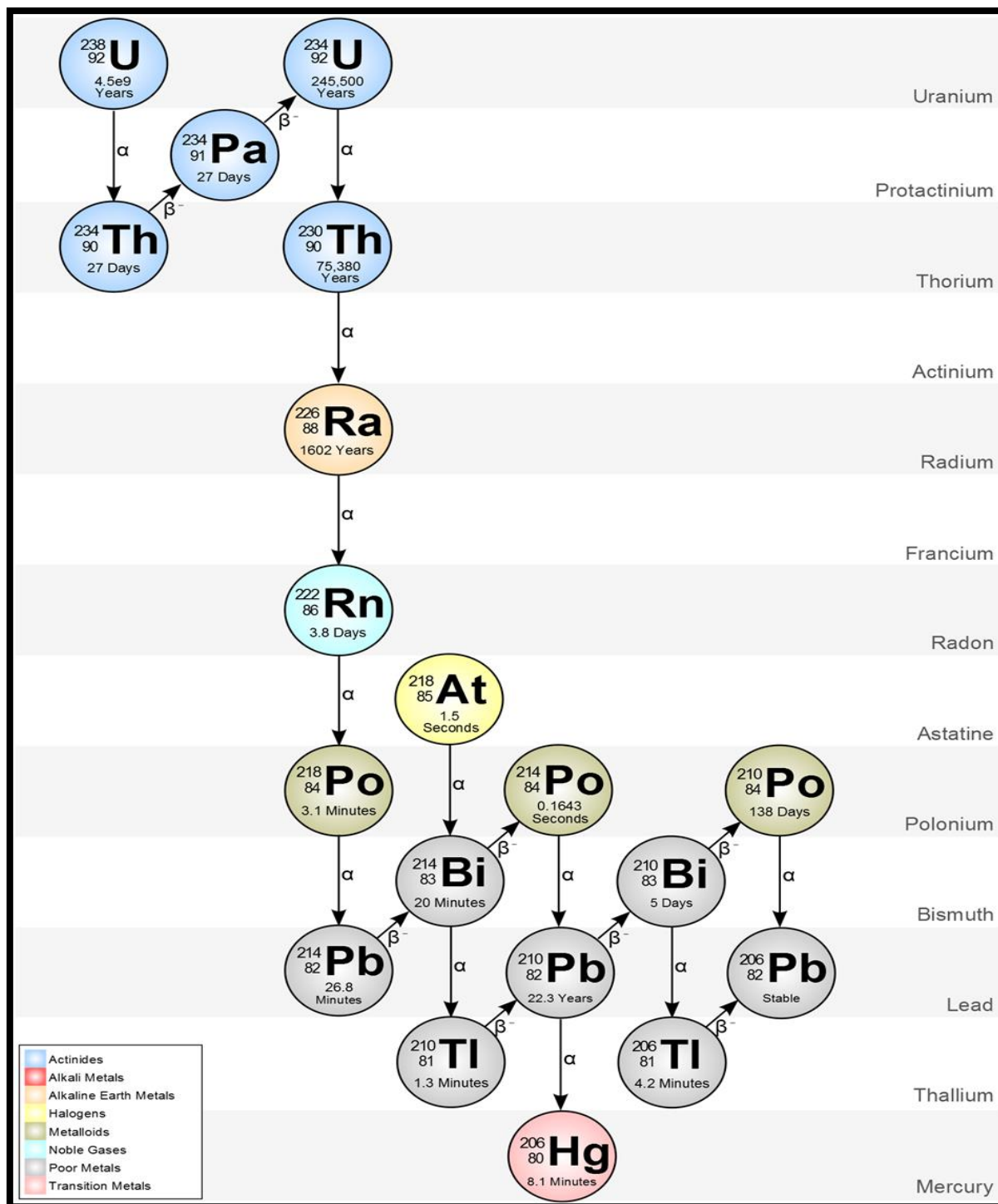


Figure 2.3: Decay series of uranium-238 comprising of 14 separate steps before it produces the stable lead-206. The series have eight α decays and six β decays (Mehra 2011).

2.7.2 Thorium series

The $4n$ chain of Th-232 in Figure 2.4 is frequently termed the "thorium series". Beginning with naturally occurring thorium-232, it includes the following elements: actinium, bismuth, lead, polonium, radium, radon and thallium. All are present, at least transiently, in any natural thorium-containing sample, whether metal, compound, or mineral. The series terminates with lead-208 (Zubair et al. 2013).

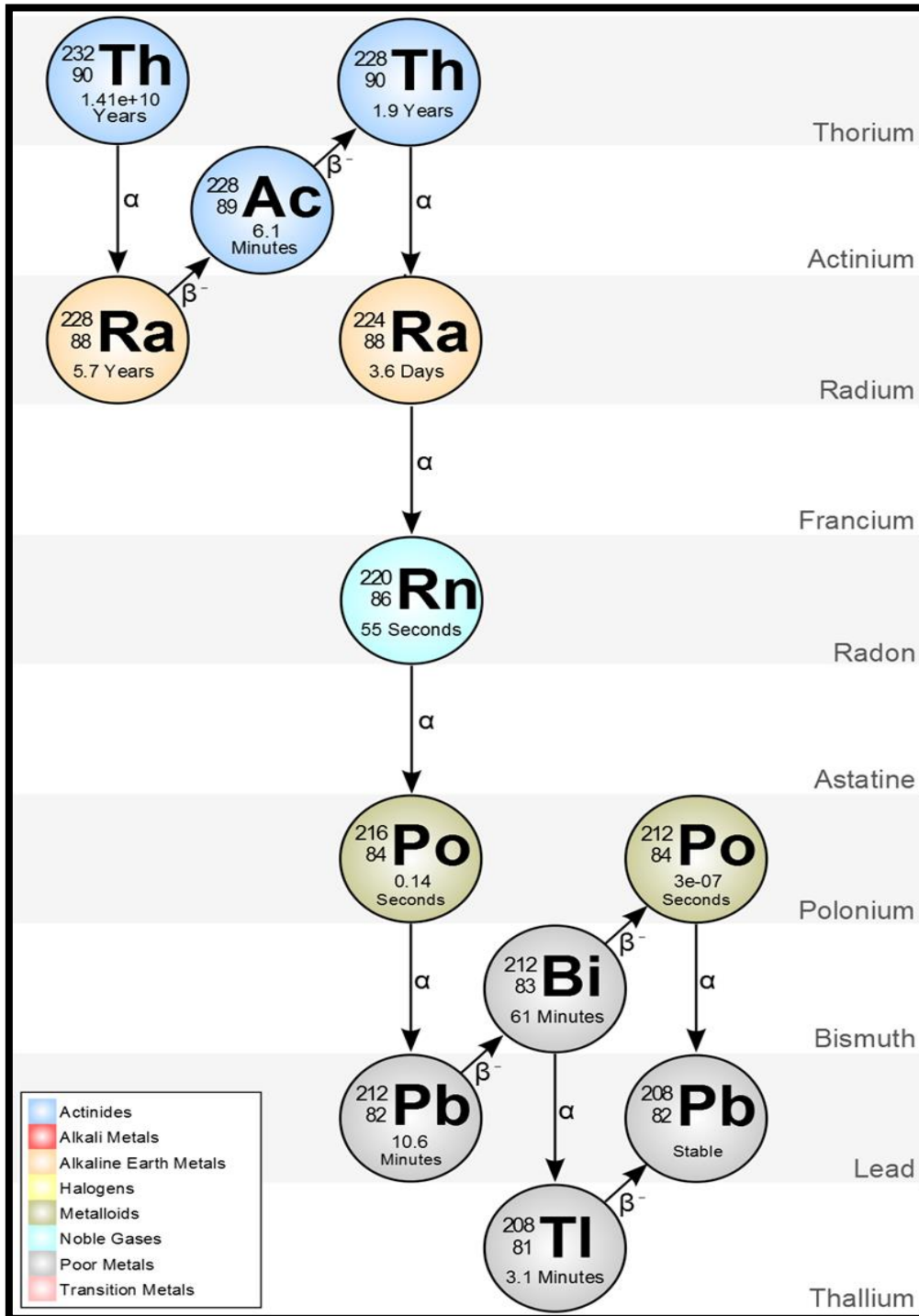


Figure 2.4: Thorium-232 undergoes a radioactive decay series consisting of 12 separate steps before producing stable lead-208. This series consists of seven α decays and five β decays (Zubair et al. 2013).

2.7.3 Actinium series

The $4n+3$ chain of uranium-235 is commonly known as the actinium series shown in Figure 2.5. The naturally occurring uranium-235 isotope is the one that begins this decay series. In this decay series the following elements: actinium, astatine, bismuth, francium, lead, polonium, protactinium, radium, radon, thallium, and thorium are all present at least transiently, in any sample containing uranium-235, whether metal, compound, ore, or mineral. This series terminates with the stable isotope lead-207 (EL-Kameesy et al. 2016).

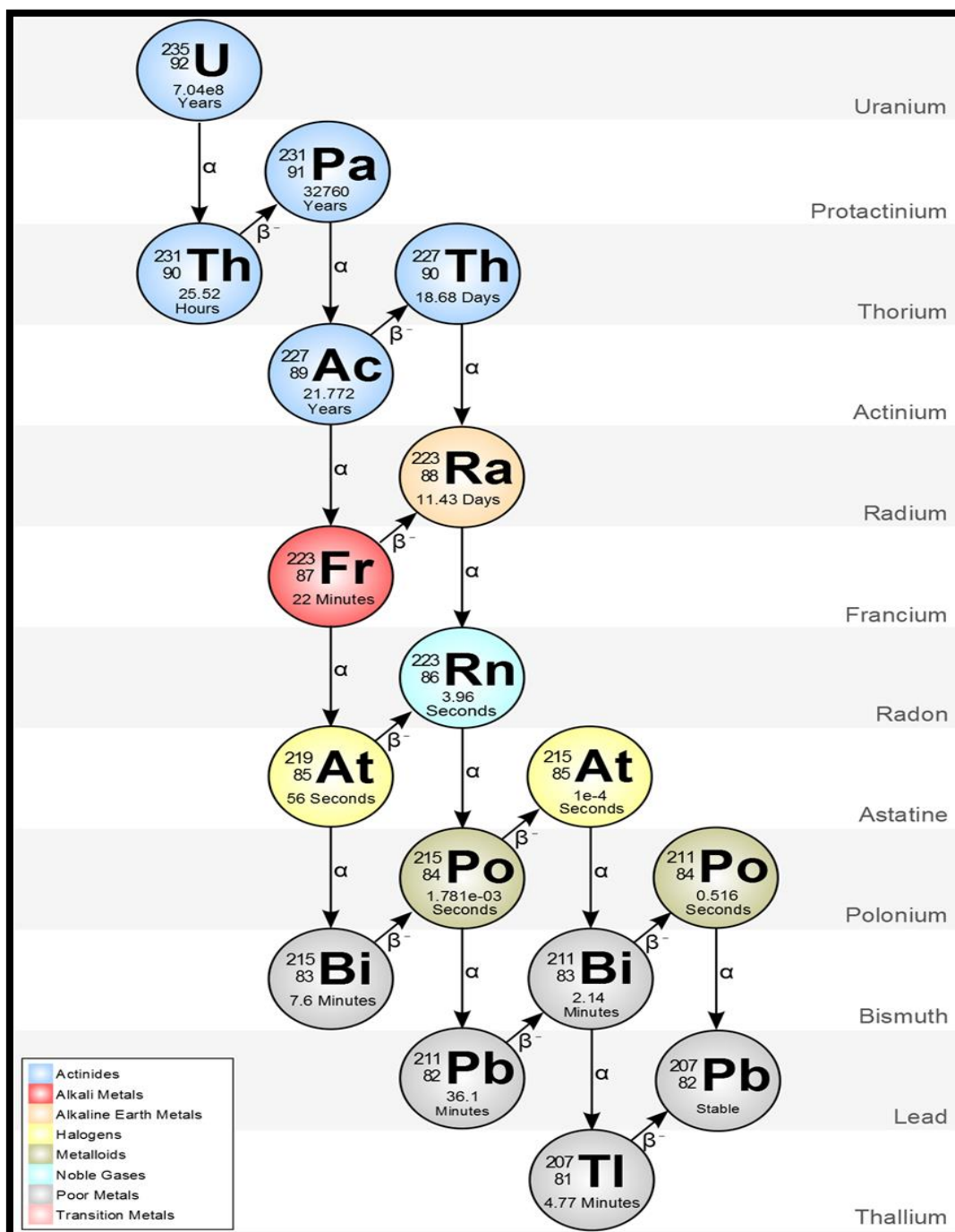


Figure 2.5: The actinium series (uranium-235) undergoes a radioactive decay series consisting of 17 separate steps before producing stable lead-207. This series consists of twelve α decays and nine β decays (EL-Kameesy et al. 2016).

2.8 Human health and environment protection

There are international established standards for radiation protection such as the IAEA basic safety standard (BSS). It is mandatory that any person exposed to radiation be protected, these persons include radiation workers from radioactive waste storages and the public, this is done to optimise the radioactive waste by considering dose constraints and ensuring that international set dose limit standards are adhered to (IAEA 2012). Management for storage of radioactive waste must guarantee safety for human health and the environment at present and the future to come, as well that future generations will not be put under any burdens of the present situations. From the design of the radioactive waste storage to the operation stage it should be a mandatory requirement that protection of workers, the public and the environment follows the requirements and principles of the IAEA-BSS. This should be done to ensure radiation doses to workers and the public are kept as low as reasonable achievable (ALARA) and does not exceed the international set limits as a result of radioactive waste storage (IAEA 2014b).

The significances of any likelihood for a mistake or accident to occur should be counteracted with protective actions measures that have been laid out to optimize the severity of radiation danger as per the requirement of the BSS. Any outflows from the storage facilities into the environment must be taken care of with regard to the guidelines provided by the safety standard and the facility specific conditions that have been approved by a regulatory body. Adequate control measures must be active in ensuring that exposure of workers to radiation is minimal and there be an effective individual and workplace monitoring that should be referenced to verify the amount of radiation dose exposure. During the process of generation of waste to its storage and its final disposal, it is important to foster and maintain a safety culture that encourages an inquisitive and learning attitude to protection and safety and discouraging complacency (IAEA 2012).

CHAPTER 3: METHODOLOGY

The chapter describes the methods and techniques employed in the research, explanation of area mapping, equipment that was used, sampling procedures and sample preparation. The chapter starts by focusing on the international standard certified reference materials as they are used for the validation of the methods used and the results obtained.

Radiometric techniques are found to be a complete set of measurements required to detect, intervene, categorize and characterize radioactivity of NORMs. The investigation makes use of the concentrations, abundance and activity of a given radionuclide isotope. Radiometric risk assessment of NORMs is important for setting up of nuclear facilities reference material and policy formulation for decision making by political leaders and researchers.

In this study samples of water and soil were sampled from around Pilikwe. The soil samples were collected using a hand corer at depth of ± 30 cm after removing the topsoil with a spade to get rid of organic matter. Soil samples were collected at 500 m apart for the specified area for the construction of the facility and the rest of the samples were collected on the boundary of the construction area of the proposed radioactive storage facility 3km apart. The water samples were collected from two boreholes in the study area, of which they are the sources of drinking water for the humans and their livestock. Both the soil and water samples were analyzed to identify and quantify radionuclides present in each sample and the activity concentrations.

3.1 Reference materials

Certified reference materials (CRMs) from national and international organizations, served as critical standards in this research work, such as the National Institute of Standards and Technology (NIST), Standard Reference Material (SRM) and International Atomic Energy Agency (IAEA). This was vital for instrument calibration and method validation to ensure the integrity of critical radiometric risk assessment of NORMs results obtained (Morgenstern et al. 2018). The United States of America spearheaded a multi-agency program for identifying and prioritizing the development of radio-analytical certified reference materials for field and laboratory nuclear measurement that meets the emerging needs of the nuclear industry and are available to both the United States and international community (Inn 2013).

3.1.1 Measurement of reference materials

The accuracy and appropriateness of radiometric technique system and its validation by quality assurance control checks was verified by NORMs concentrations values being comparable to the

certified reference materials values (Tomarchio 2011). There are three reference materials that are within 95% confidence level and have been certified in a powder state matrix and its concentrations being $4940 \pm 30 \text{ Bq kg}^{-1}$ for ^{238}U , $3250 \pm 90 \text{ Bq kg}^{-1}$ for ^{232}Th and $14000 \pm 400 \text{ Bq kg}^{-1}$ for ^{40}K in secular equilibrium. The sample containers were filled with the reference materials, dried at 60°C temperature, sealed and stored for 30 days so that radioactive equilibrium could be established for the ^{226}Ra decay series before analysing.

Table 3.1 is a report of reference material activities certificated by IAEA acquired from principal gamma lines that are used in estimation of the isotopes of uranium series, thorium series and for potassium, calculated using equation 3.1.

$$A \text{ (Bq/kg)} = \frac{R}{\varepsilon I_\gamma m} C_{SA} C_G C_{CS}^* \quad (3.1)$$

Where, A is the activity, R is the measured count rate (corrected background), ε is the absolute efficiency, I_γ is the gamma line intensity, m is the mass of the sample, C_{SA} is the correction factors for self-absorption, C_G is the geometrical correction factor and C_{CS}^* is the coincidence summing correction factor (calculated using the same approach as described above for the specific decay chains of the uranium and thorium). The overall relative discrepancy of the results is less than 5% and are within the certified central value and the reported uncertainty,

Table 3.1: The IAEA certified reference material activities (Xhixha et al. 2012).

Parent Isotope	Daughter Isotope	<i>E</i> (keV)	C_{CS}^*	C_{SA}	Activity (Bq kg^{-1})	Certified Reference Material Activity (Bq kg^{-1})
^{238}U	^{234m}Pa	1001.0	1.000	1.24	4875 ± 48	4940±30
	^{214}Bi	609.3	1.190	1.32	4872 ± 4	
	^{214}Pb	351.9	1.002	1.42	4772 ± 3	
^{232}Th	^{228}Ac	922.2	1.024	1.24	3092 ± 4	3250±90
	^{212}Pb	238.6	0.990	1.48	3246 ± 2	
	^{212}Bi	727.3	1.056	1.27	3389 ± 9	
^{208}Tl	583.2	1.298	1.31	3342 ± 4		
^{40}K		1460.8		1.21	14274 ± 71	14000±400

The activity concentrations (in Bq kg^{-1}) that have been calculated for the main energetic lines used for ^{238}U and ^{232}Th decay chains, as well as for ^{40}K are presented in table 3.1; together with their respective statistical uncertainties (Abo-Elmagd et al. 2010).

3.2 The study area

Kgosi Tshekedi Khama of Bangwato is believed to be the one who founded Pilikwe village which is a rural place in the Central District of Botswana. The current chief of this village is Kgosi Gasebalwe Seretse and the native's commonly known name for this village is Rametsana. Pilikwe village is located 10 km east from the Martin's Drift Tswapong highway and 32 km north-eastern from Radisele and is on its Northside is surrounded by a hill, its geographical coordinates are 22° 47' 0" South, 27° 14' 0" East shown in Figure 3.1.



Figure 3.1: Google maps picture of Botswana, showing the location of Pilikwe.

3.2.1 Sampling

Samples were collected at the site where the radioactive waste storage facility is proposed to be built in Pilikwe, and within the surrounding area of the village making a boundary. Sampling consisted of 60 soil and 2 borehole water samples. Figure 3.3 shows google maps picture of Pilikwe showing the GPS locations of the samples collected from the study area.

3.2.1.1 Soil sample collection

Soil samples within the area of the storage facility were collected ± 100 metres apart, while those in the village were collected 500 metres apart. Soil samples on the boundary were collected about 3 kilometres apart. All the soil samples were randomly collected systematically marking a boundary.

The samples were collected by first removing the topsoil using a spade and then drilling the soil from a depth of ± 30 cm using a hand corer as shown in Figure 3.2. The topsoil was removed in order to take away the organic matter. The geographical location coordinates of samples are in appendix: D.



Figure 3.2: Soil sample collection and data recording.

3.2.1.2 Water sample collection

Water samples were specifically collected from the two borehole that are found in Pilikwe, as these boreholes are there as the source of water for dinking and farming by the residents of the study area. The water samples were manually pumped from the boreholes into 2 litres bottles for each sample. Borehole water samples collected location are shown in Figure 3.3 marked by a green symbol.

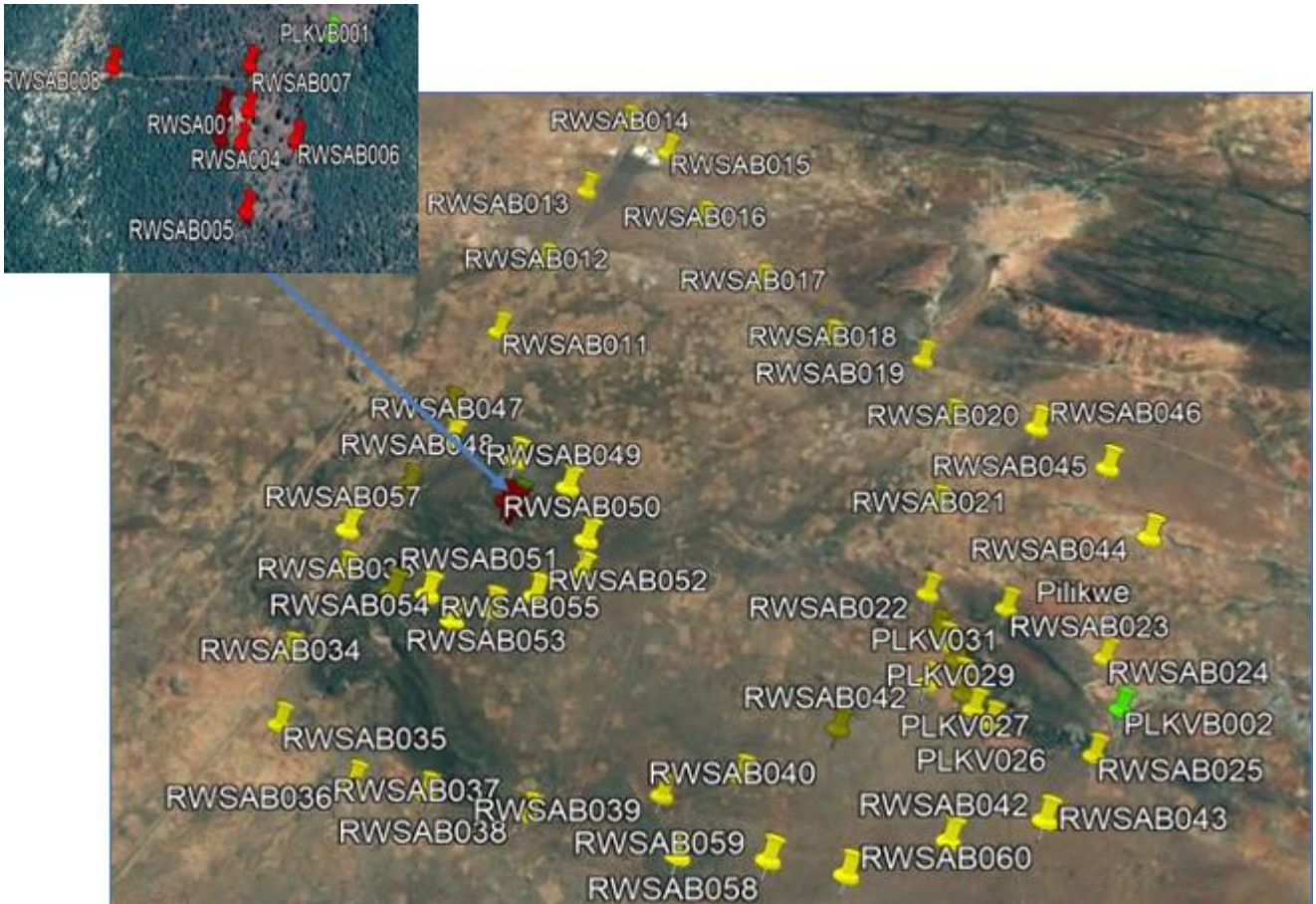


Figure 3.3: Google maps picture of Pilikwe showing the GPS locations of the samples collection area.

3.2.2 Sample preparation

Sample preparation was a very important part in this research, as it is considered one of the major contributors of errors if not done in an acceptable manner, thus leading to wrong results with misleading conclusions and recommendations. In this research attention was paid to every sample to avoid cross-contamination and radionuclide losses. Soil samples were first spread out on plastic sheets and allowed to dry up for 2-3 days at Centre for Applied Radiation Science and Technology laboratory (CARST). Soil samples were crushed into small grain sizes using mortar and pestle and then sieved through a 2 mm sieve to obtain a homogenous sample matrix based on an IAEA 1989 procedure for gamma spectrometry soil sample preparation.

The samples, were then packed, sealed, and weighed in 500 ml plastic Marinelli beakers, then stored for 30 days to reach equilibrium. Sealing ensured establishment of secular equilibrium among the progenies of ^{238}U and ^{232}Th series by ensuring that there is no radon gas leakage due to the decay of ^{226}Ra . The samples were then run using high purity germanium detector of high-resolution. A small quantity of 1g of each sample was also packaged in pairs of clean plastic bottles for elemental analysis using ICP-MS and the alpha spectrometry.

The water samples from the 2 boreholes collected in Pilikwe village were also prepared by sealing them into Marinelli beakers for 30 days to establish secular equilibrium in readiness for gamma analysis. Water samples were also stored in clean containers and preserved at room temperature in readiness for elemental analysis using ICP-MS and alpha spectrometry techniques.

3.3 Radiometric analytical techniques

Measurements of activity concentrations in soil and water was done using the following methods: high resolution gamma spectrometry using a broad high energy germanium (HPGe) detector, inductively coupled plasma-mass spectrometry (ICP-MS), alpha spectrometry was used for polonium analysis of the samples.

3.3.1 Gamma spectrometry

The gamma spectrometry was used to acquire data from the samples by identification and quantification of gamma-emitting radionuclides present in a given sample. The high-resolution gamma spectrometry system available at the North-West University (NWU), Mafikeng campus under the Centre for Applied Radiation Science and Technology (CARST), was used in this study. It is a well-type high-purity germanium (HPGe) detector resolution (FWHM) (Canberra, United States of America) at 122 keV (^{57}Co) is 0.85 keV and at 1332.5 keV (^{60}Co) is 1.86 keV and relative efficiency for energy 1.33 MeV relative to (NaI) Tl was 36%, (Dlamini et al. 2016). It consists of a detector crystal made of high-purity germanium which is cooled by a liquid nitrogen, preamplifier, cooling system, electronics unit, and a computer for displaying, saving, and analysing gamma spectra. The gamma counting system consists of a Canberra model 2022 amplifier and a Canberra model 8075 analogue-to-digital converter as shown in figure 3.4. In the laboratory about 600 g of each sample was from Marinelli plastic containers.

To collect a gamma spectrum, samples under investigation were placed one after another in front of the detector in a configuration specific to the detector orientation and sample type parameters. Gamma radiation emitted from the sample goes into the detector and produces electronic signals that are automatically counted and sorted into discrete channels according to their energy by the electronics and Gamma Acquisition software (Genie 2000 ver. 3.3). The measured spectra were then evaluated using Gamma Analysis software. The measurement time was set to 12 hours. For most radiological technique scenarios and sample types, the counting time required to collect spectra for a detailed radiological risk assessment analysis in the laboratory is on the order of hours to a day (Apostol 2016).

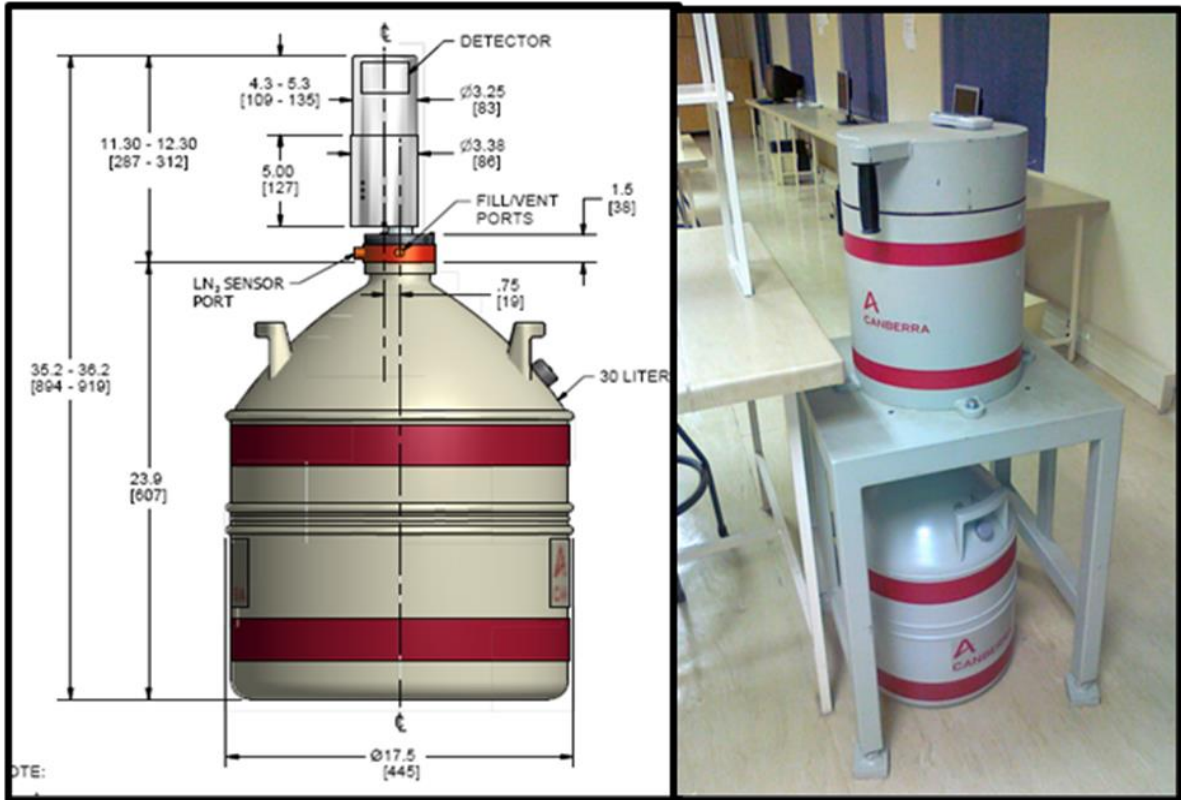


Figure 3.4: The high-resolution gamma spectrometry at CARST.

3.3.1.1 Calibration

Calibration was done using IAEA certified reference material (IAEA-RGU-1, RGTh-1) with known number of radioactive elements for the Canberra HPGe well type Detector (Model 747) in order to acquire the nuclides, present in the sample. Figures 3.5 and 3.6 shows the calibration energy and efficiency graphs of the instrument used for running and analyzing the samples.

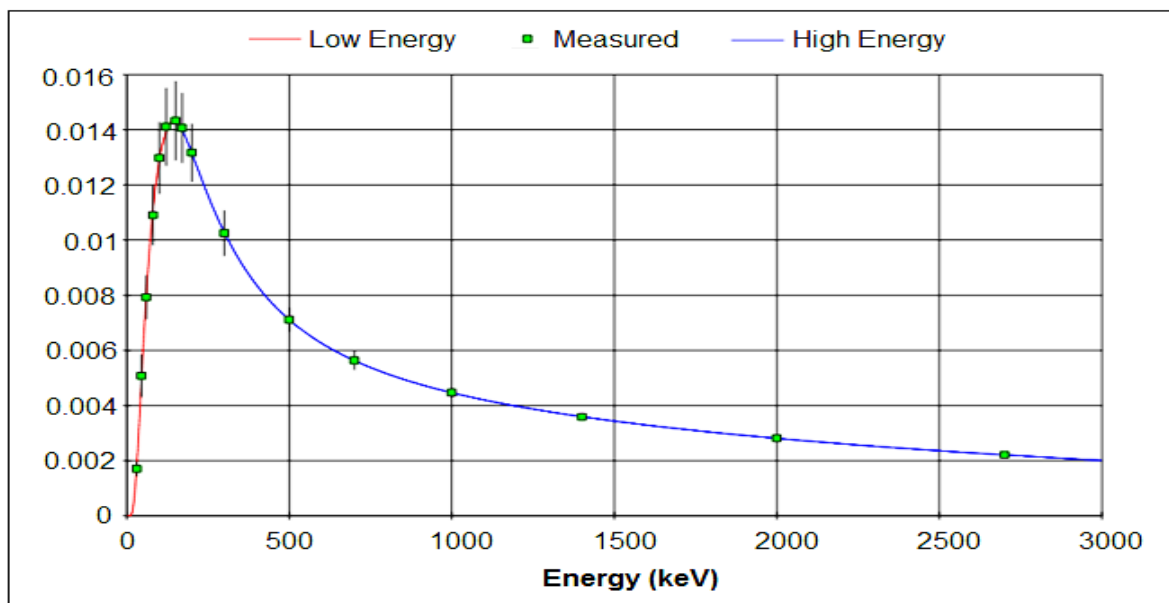


Figure 3.5: Efficiency calibration curve for the HPGe well detector.

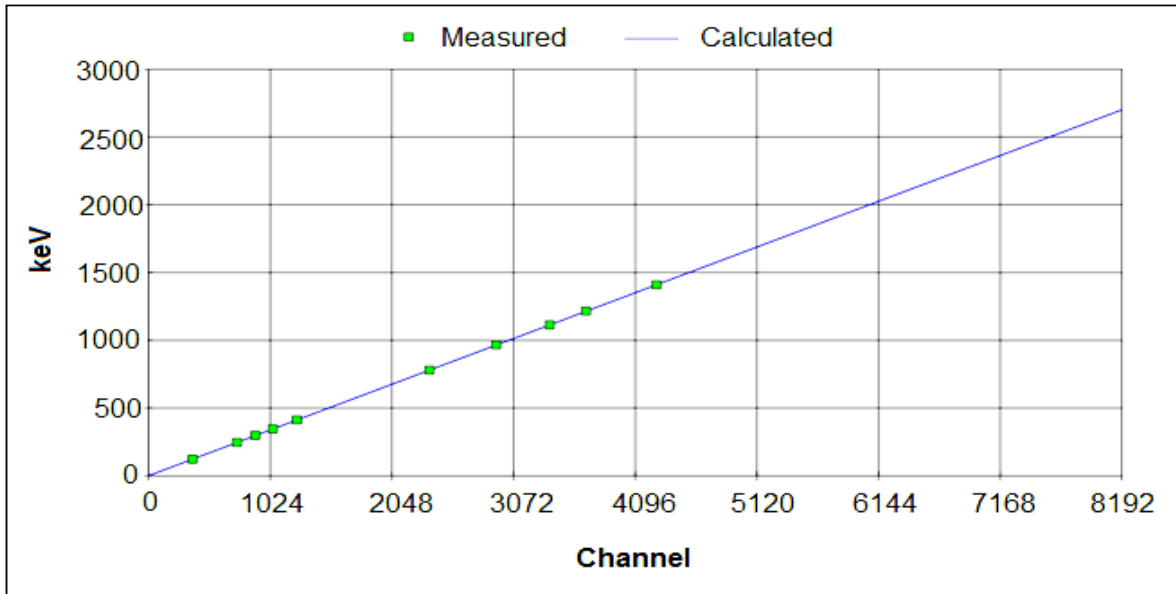


Figure 3.6: Energy calibration curve.

3.3.1.2 Detection limit and minimum detectable activity (MDA)

Detection proficiencies to counting and analysing of radioactivity varies with respect to the used techniques and analytical instrument (Canbazoglu 2013). During counting of low-level radioactivity, the detection limit (L_D) of the system should be firstly determined. The detection limit refers to the significant net counts detectable above the critical level (L_C) when an opportunity for actual activity is existent.

Currie in 1968, established the decision level or critical-level and detection limit concepts. Therefore, defining the critical level (L_C) as a decision level above which the net counts present some detected activity with a certain degree of confidence. When the critical level is more than the net count, the sample activity is undetectable, whereas if the net count exceeds critical level it can be assumed that some real and/or excess activity is existent (El-Taher 2014). Then L_C can be expressed as:

$$L_C = 2.36\sigma_{N_B} \quad (3.2)$$

Where, σ_{N_B} is the standard deviation of the blank sample number of counts, the decision level is generally not important for the activity measurement and thus the detection limit (L_D) is introduced, and can be represented mathematically by Equation 3.3 (El-Taher 2014).

$$L_D = 2.706 + 4.653\sigma_{N_B} \quad (3.3)$$

The minimum detection activity (MDA) can be described as a performance criterion in γ -ray spectrometry (Currie 1968). The MDA depends on the values of the L_D and the efficiency of a counting system. The MDA can be calculated using Equation 3.4.

$$MDA = \frac{L_D}{\varepsilon_f P_\gamma T} \quad (3.4)$$

Where, ε_f is the absolute efficiency, P_γ is a γ -emission probability and T is the time of measurement in seconds.

The lowest radioactivity quantity that can be measured at specific conditions is known as the minimum detectable activity (MDA) (Faanu 2011). The Detection limit is the minimum number of counts that should be measured from a sample in order to ensure a 95% probability for the true net counts to reach the critical level (Santawamaitre 2012). Minimum detectable activities (MDA) are shown in Table 3.2, and were estimated for ^{238}U , ^{232}Th and ^{40}K and acquired a 95% confidence level.

Table 3.2: Minimum detectable activities for ^{238}U , ^{232}Th and ^{40}K .

Nuclide	MDA (Bq/kg)
^{238}U	0.13
^{232}Th	0.13
^{40}K	0.12

3.3.1.3 Determination of activity concentrations

The activity concentrations of ^{238}U , ^{232}Th and ^{40}K in samples was calculated using Equation 3.5 (Darko 2010).

$$A = \frac{N}{\varepsilon_f P_\gamma t_S m K} \quad (3.5)$$

Where, $N = (N_S - N_B)$ is the corrected net counts of the equivalent full-energy peak, N_S and N_B are the counts in the spectrum of the sample and the background spectrum obtained from counting an empty Marinelli beaker, ε_f is the counting efficiency at the photo peak energy under consideration, P_γ

is the likelihood of the γ -ray emission equivalent to the peak energy, t_s is the sample counting time in seconds, m is the sample mass in kg, K is the decay correction factor.

3.3.1.4 Activity uncertainty

The individual sample activity uncertainty was calculated using Equation 3.6 and 3.7 (Ajmal et al. 2014).

$$\sigma_c = c \cdot \sqrt{\left(\frac{\sigma_R}{100}\right)^2 + \left(\frac{\sigma_S}{S}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2 + \left(\frac{\sigma_{\varepsilon'}}{\varepsilon'}\right)^2 + \left(\frac{\sigma_K}{K}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2} \quad (3.6)$$

Where, c is the calculated activity, σ_R is relative uncertainty in the calibration due to uncertainty of activity of the reference source, S is the net peak area and σ_S its uncertainty, M is the sample mass and σ_M its uncertainty, ε' is the attenuation corrected efficiency and $\sigma_{\varepsilon'}$ its uncertainty defined by equation 3.7, K is the decay correction factor and σ_K its uncertainty, and y is the branching ratio and σ_y its uncertainty,

$$\sigma_{\varepsilon'} = \varepsilon' \sqrt{\left(\frac{\sigma_{\varepsilon}}{\varepsilon}\right)^2 + (\rho t \cdot \sigma_{\mu(E)})^2 + (\mu(E) \cdot \sigma_{\rho t})^2} \quad (3.7)$$

Where, ε is the non-attenuation detection efficiency at the peak in question and σ_{ε} its uncertainty, ρt is the average sample mass per unit area and $\sigma_{\rho t}$ its uncertainty, and $\mu(E)$ is the mass attenuation in units of cm^2/g at γ -energy (E) and $\sigma_{\mu(E)}$ its uncertainty.

3.3.1.5 Interference of peaks

Most serious interferences seen in HPGe γ -spectrometry are probably spectral overlaps, which are mostly caused by other NORM-nuclides peaks that are very close in γ -energy values. An example of such peaks is the interference of ^{235}U at the γ -energy of 185.7 keV and ^{226}Ra at the γ -energy of 186.2 keV. The branching ratios of ^{235}U and ^{226}Ra are 57.2% and 3.59% respectively. If secular equilibrium exists between the parent nuclide and its daughters, the activity of the parent can be obtained through daughter nuclides that have more appropriate γ -transitions, for example

^{226}Ra and its progenies ^{214}Pb and ^{214}Bi following an in-growth period of at least 30 days after the samples were sealed (Marin et al. 2013).

The contribution of ^{226}Ra through its γ -ray at the energy of 186.2keV at the branching ratio of 3.59% is calculated by employing the spectral mathematical interference correction equations using the least spectrally disturbed peak (reference peak) at 295.2keV from the decay of ^{214}Pb . The net peak area or

net counts of ^{226}Ra at the line 186.2 keV can be extracted using Equation 3.8 taking into consideration γ -ray intensities I_γ and peak detection efficiencies ε_p of the reference peak: (Tabar et al. 2017)

$$N_p[186.2\text{keV}, ^{226}\text{R}] = \frac{[I_\gamma \varepsilon_p F_{\text{COI}} F_s]_{186.1\text{keV}}}{[I_\gamma \varepsilon_p F_{\text{COI}} F_s]_{295.2\text{keV, Ref}}} \times N_p[295.2\text{keV}, ^{214}\text{Pb}]_{\text{Ref}} \quad (3.8)$$

Where, N_p is the net counts, I_γ is γ -ray emission probability, ε_p is the full-energy peak efficiency. F_{COI} and F_s are the correction factors of the true coincidence summing peak and self-absorption. The true coincidence summing peak and self-absorption effects were considered to be negligible in this study.

3.3.1.6 Evaluation

The activity concentration of ^{238}U and ^{232}Th were determined by measuring the counts of γ -ray energies of daughter nuclides if secular equilibrium exist in the decay chain. The ^{232}Th activity concentration was calculated as the weighted mean value of ^{228}Ra and ^{228}Th concentration. ^{228}Ra was measured as ^{228}Ac using the 209.30, 270.20, 911.10 and 969.00 keV γ -rays while ^{228}Th was measured through ^{212}Pb using the 238.60 keV γ -ray line, ^{212}Bi using the 727.30 keV γ -ray, and ^{208}Tl using the 583.20 keV γ -ray corrected for the branching ratio of 0.36. The ^{238}U content was determined from the corrected ^{235}U concentration assuming a natural $^{238}\text{U}/^{235}\text{U}$ activity ratio of 20.70. The ^{235}U content was based on the spectral interference of ^{226}Ra at of 186.20 keV and ^{235}U at 185.70 keV as given in Equation 3.8. ^{40}K was determined directly from its γ -ray energy at 1460.80 keV. Table 3.3 shows the γ -ray energies used in the determination of the activity concentrations.

Table 3.3: Gamma-ray energies and their associated intensities used in the determination of activity concentrations.

Radionuclide	Daughter nuclides considered	Gamma lines (keV)
^{238}U	^{234}Th	63.280
		92.600
	^{234}mPa	1001.000
^{226}Ra	^{214}Pb	295.224
		351.932
	^{214}Bi	609.312
		1120.287
		1764.494
^{232}Th	^{228}Ac	338.320
		911.200
	^{212}Pb	238.632
^{40}K	^{40}K	1460.810

3.3.2 Alpha spectrometry

Alpha spectroscopy in Figure 3.7 was used for the identification and quantifying of radionuclides emitting alpha particle during the decay process. The generation of energy spectra was acquired by the Canberra alpha analyst system spectrometry model: 7200 – 08, using Apex-Alpha; Alpha spectrometry software suite 1.1. The process of quantifying and identifying radionuclides that emit alpha particles is of very important use in site environmental characterization and radiation protection. This makes alpha spectroscopy an important tool and technique of analysis and providing guiding information in waste management, decommissioning and decontamination. A complete system of alpha spectroscopy will have:

- high resolution, low background, and detection efficiency charged particle detector
- Vacuum Chamber that enables alpha particles to reach the detector since they are attenuated easily by air.
- Recoil contamination avoidance package (RCAP) to safeguard the detectors from contamination of daughter nuclides that may leave the sample material.
- Signal detector electronics for processing and storing the energy data.
- Analyzing software that controls the electronics, analyze spectra, establish quality control processes, and integrate data with laboratory data management system.

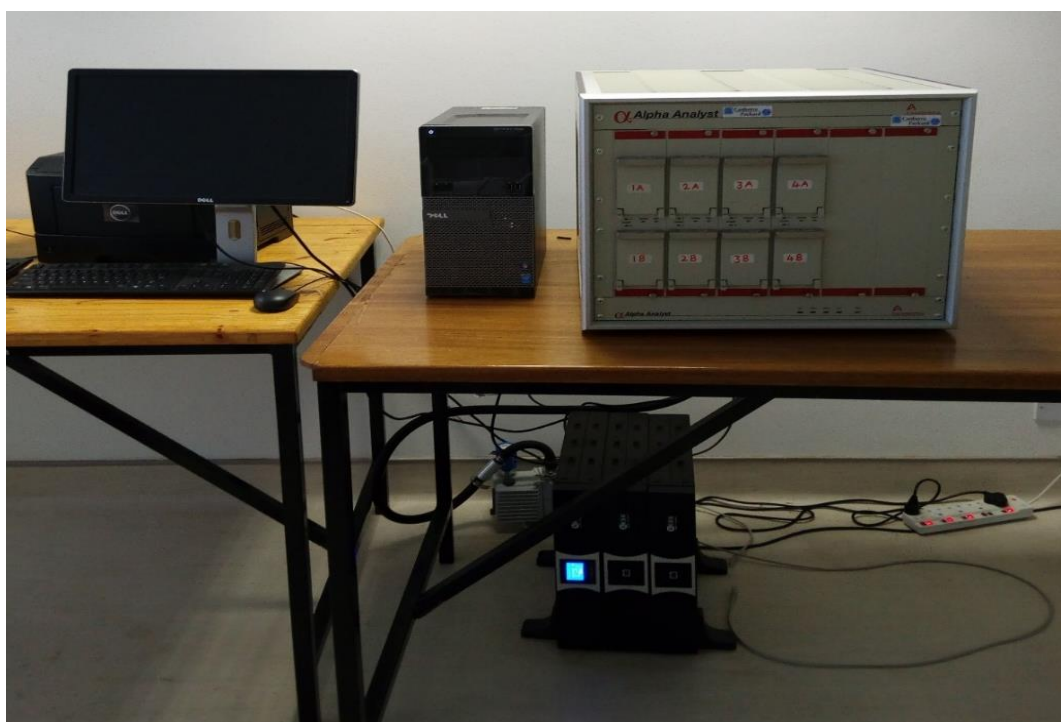


Figure 3.7: Alpha spectroscopy used to identify and quantify radionuclides at RPI.

The samples were firstly prepared and digested using the Milestone ETHOS EASY microwave digester specified in Table 3.4, after completion of the digestion process samples were loaded into the Canberra alpha analyst system spectrometry model: 7200 – 08, for sample run using Apex-Alpha;

Alpha spectrometry software suite 1.1. The following steps were taken for sample digestion: samples were weighed to approximately 0.200 g, 8 ml of nitric acid (HNO₃) added with 1g \approx 0.188 Bq of polonium tracer, the samples were then digested.

After digestion there was qualitative transfer from the digester vessels to 210 ml beakers with addition of 5 ml HNO₃, then evaporation to dryness, added 3ml hydrogen peroxide (H₂O₂) to oxidise organic matter and evaporating the solution to dryness with the step repeated twice. 5 ml of hydrochloric acid (HCL) was added and evaporating the solution to dryness with the step repeated twice. 1ml of HCL was added and make up volume to 100 ml with deionized water, added ascorbic acid gradually until the yellow colour of Iron (Fe) ions disappears. We then placed a magnetic stirring bar into the reaction vessels, set the temperature to 85°C and speed 300 rpm in the stirring hotplate. After we immersed the silver disc into the reaction mixture and covered with parafilm plastic, there was deposition with stirring and heating for 8 hours.

Table 3.4: Milestone ETHOS EASY microwave digestion specification.

MILESTONE ETHOS EASY MICROWAVE DIGESTION			
General Information			
Unit Model	ETHOS EASY	Unit serial number	18063270
Terminal Model	T480	Terminal serial number	18061833
Line voltage	230 V	Line frequency	50 HZ
Fuse	16 AT, 0.5 AT	High voltage capacitors	2x0.95 μ F
Main Supply			
Input current at rated supply voltage (result obtained at 230 V)	25% =0 50%=0 75%=0 100%=14.5 A		
Electrical safety test			
Dielectric strength test on basic insulation (Standards IEC/EN 61010-1)			V
Continuity test of protective earth (Standards IEC/EN 61010-1)			34 m Ω

To measure the ²¹⁰Po (half-life = 138.376d), ²⁰⁹Po tracer, activity: 0.188 \pm 0.004 Bq/g, K=2 Ref date: 18 April 2018 was spiked into the vessel using the standard technique (the silver disc technique) whereby two grams of soil samples were taken in duplicate samples having been spiked with 1g \approx 0.188 Bq of ²⁰⁹Po as a yield tracer during digestion of the samples.

Alpha counting of ²⁰⁹Po and ²¹⁰Po were conducted using Canberra alpha analyst system spectrometry for sample run using Apex-Alpha; Alpha spectrometry software suite 1.1, with the background counts taken into consideration. The ²¹⁰Po activity was corrected for recovery by comparison with measured activity of the ²⁰⁹Po yield tracer and for radioactive decay since the time of sampling (Al-Masri 2010).

The ^{209}Po activity was determined using internal standard technique. The MDA of the method used was 0.40 Bq kg^{-1} . The determination of the MDA was done by analysing 10 replicates of the reference material: BOT7003 Sample 03 Soil with a known activity of ^{210}Pb (about 5 to 7 times of MDA). The standard deviation (STD) of the ten replicates was calculated using Equation 3.9 (Al-Masri 2010).

$$\text{MDA} = 3\text{STD} \quad (3.9)$$

3.3.3 Inductively coupled plasma mass spectrometer

The inductively coupled plasma mass spectrometry (ICP-MS) as its name suggest works by synergistic combination of an inductively coupled plasma with a quadrupole mass spectrometer. It uses argon inductively coupled plasma to generate singly charged ions efficiently from the elemental species in the sample. These ions then go into a quadrupole mass spectrometer which functions as a monochromator in an ICP emission system. The mass spectrometer rather separates the ions introduced from the ICP according to their mass-to-charge ratio instead of separating light according to its wavelength.

The ions of mass/charge selected goes into the detector and the number of ions present quantified. The ICP-MS technique is useful in determining low-concentrations (range: ppb = parts per billion = $\mu\text{g/l}$) and ultra-low-concentrations of elements (range: ppt = parts per trillion = ng/l). The ICP-MS technique has been increasingly used during the last years in nuclear forensics analysis to perform isotope ratio measurements (Marin 2013). The advantages of the ICP-MS technique are ease operation, low detection limits, good precision and accuracy, and its high degree of sensitivity multi-elemental analysis (Woodhead et al. 2014).

In this study, the NexION 2000C ICP-MS was used for the analysis of the soil samples collected from the study area. The double focusing magnetic sector inductively coupled plasma mass spectrometer (ICP-MS) is shown in Figure 3.8 and its optimization operating parameters in Table 3.5. The samples were analysed for isotopic composition of different NORMs for radiometric risk assessment.



Figure 3.8: The NexION 2000C inductively coupled plasma - mass-spectrometry at CARST.

Both the water and soil samples for this study were run with the Perkin Elmer, NexION 2000C, ICP-MS, manufactured in the United States of America. The instrument has a quadrupole ion deflector which directs the ion beam to the dual mode detector. The isotope-ratio accuracy of this instrument is defined for the isotope ratio of $^{107}\text{Ag}/^{109}\text{Ag}$ internal standard using a 25 $\mu\text{g}/\text{L}$ solution. This is attained by single-point peak hopping with a relative standard deviation (RSD) ($= 100 \times \text{SD}/\text{AVERAGE}$, ((0)) of $< 0.2\%$ RSD.

Table 3.5: NexION 2000C ICP-MS optimized operating parameters.

Parameter	Value
Nebulizer	Glass concentric
Cones (Sampler, Skimmer, super-skimmer)	nickel
Spray Chamber	glass cyclonic
Sample Uptake Rate	300 $\mu\text{L}/\text{min}$
Plasma gas flow	18.0 L/min
Auxiliary gas flow	1.2 L/min
Nebulizer Gas Flow	0.98 L/min (Optimized for 2% CeO/Ce)
RF Power	1600W
Cell Gas	Argon
Detector Type	Dual mode
Sweeps/Reading	200
Readings/Replicate	10
Replicates per sample	2
Mode / Universal Cell Technology™	Isotope Ratio/Collision mode
Internal Standard	$^{107}\text{Ag}/^{109}\text{Ag}$ using a 25 $\mu\text{g}/\text{L}$ solution
Total integration time	3.4s

Samples were run using auto sampler with the ICP-MS Instrument controlled by Syngistix Software that acquires the data. The instrument was run for total quant analysis, to identify the elemental concentrations in the samples (Vilta 2016).

3.3.3.1 Interference reduction

It has been established that in the absence of two non-radiogenic isotopes in the element (e.g., Pb) or two more isotope ratio, the internal standard normalization method becomes obsolete for mass correction (Horn et al. 2016). Thus, pseudo-internal standard normalization can be used to determine the mass fractionation normalization for one element by directly applying this normalization to another element of like or closer mass in the periodic table (Lin et al. 2016). In addition, it has been argued that UV radiation causes the photo-oxidation of Tl^+ to Tl^{+3} , which then exhibits a different chemical behavior than its single ionic state in the presence of Pb, resulting in higher values of Pb/Tl and $^{205}Tl/^{203}Tl$ ratios. On the other hand, UV oxidation of Ag is known to significantly enhance Ag^+ release (Mittelman 2015), and thus samples can be handled even in the open laboratory

Possible sources of interferences in the ICP-MS sample analysis, emanates from molecular ions such as oxides, hydrides, hydroxides, nitrides (Verni 2017). The Perkin Elmer NexION 2000C desolating nebulizer is efficient in dropping the effects of interferences from the molecular ions. The instrument's quadrupole ion deflector focuses on only selected isotopes in the ion beam to the dual mode detector and other ions interfering pass through to the waste thus minimizing interference (Bosnak 2014). Th NexION 2000C proficiencies together with its universal cell technology™, qualifies momentous decrease in most or all the molecular ions in the sample (Lin et al. 2016).

3.3.3.2 Trace element analysis calibration

Quality assurance checks were conducted using blanks, calibration standard check, duplicates, and certified reference material. During trace elements analysis, the instrument uses a dual detector calibration solution as the atomic spectrometric standard. The used calibration standard for total quantitative method has 10 mg/L of Al, Ba, Ce, Co, Cu, In, Li, Mg, Mn, Ni, Pb, Tb, U and Zn. A blank and a standard check was run at every ten samples for every measurement. The targeted NORM were of the uranium series, thorium, actinium and potassium-40 (Kamunda 2016) .

3.4 Radiological health risk assessment due to NORMs

Naturally occurring radioactive materials of uranium, thorium series and potassium-40 are present everywhere in the earth crust. These radionuclides concentrations dependent of the soil and rock compositions. All NORMs produce radiation doses to every human being, and these nuclides contains small amounts of natural uranium and thorium and their radioactive daughters (Ali 2017).

Mining is the main cause of NORMs in Botswana. Most of the mining areas are still to be assessed for radiological risk posed NORMs as they contribute to the main radiation exposure to workers and the public. Regarding radioactive storage this will be the first of its kind in Botswana thus this research is a fundamental baseline for radiological risk assessment. When proper measures are not put in place during the construction of the radioactive waste storage facility the radionuclides might be transferred by different means to the surrounding environment. Various radioactive wastes are produced in the medical and mining. Sludge, drilling mud, and pipe scales are examples of materials that can contain elevated levels. An understanding of the radiation hazards and protection principles within the radioactive waste storage facility would result in an efficient and increasingly safer operation and making it easy for concentrations of NORM and radiological risk indices to be investigated and monitored (Al-Talib 2015).

Radiological assessment means estimating the dose and risk to humans from radioactive materials in the environment (Sam 2010). The concentrations can be converted to dose and risk by making assumptions about exposure to people using the activity of NORMs and the radiation dose as the main basic quantities in the assessment of radiation risk levels. Activity of a radioactive material is defined as the number of nuclear disintegrations per unit time (with unit of Becquerel (Bq)). One Becquerel is one disintegration per second. The term radiation dose can serve several terms, such as; absorbed dose, equivalent dose or effective dose (Grupen 2010).

The dose or risk to an individual is influenced by a number of exposure factors, such as time, location, transport of radionuclides through the environment, and the traits of the individual like physiological parameters (e.g., breathing rate), type of dietary consumption of various foods, living habits, use of local resources like agricultural resources, and so forth (Kahraman et al. 2015).

In radiological assessment, a definite set of these characteristics is referred to as an exposure scenario. The radiological assessment target may be of real individuals or representative individuals. Real individuals are those who are or were exposed. Their characteristics should be defined as closely as possible to those that exist. Representative, or hypothetical, individuals are not characterized by specific persons but have characteristics similar to individuals in the area who are or were exposed in the past or who may be exposed in the future (Khan 2013).

3.5 Estimation of hazard indices

There are different kinds of hazard indices that are being used to show the radiation level and its radiological effect conferring to level values indorsed by IAEA, ICRP and UNSCEAR and other agencies. The following hazard indices were applied in these research work (Lehto 2017).

3.5.1 Gamma absorbed dose rate

The outdoor air-absorbed dose rates due to terrestrial gamma rays at 1m above the ground level was calculated from ^{226}Ra , ^{232}Th , and ^{40}K radioactivity concentration values in soil samples assuming that the total dose from environmental background radionuclides, such as ^{137}CS , ^{90}Sr and the ^{235}U decay series to be negligible and was ignored as their contributions were insignificant (Likuku et al. 2017). Therefore, the gamma dose rate (D) in the outdoor air at 1 m above the ground level was calculated using Equation 3.10.

$$D(\text{nGy/h}) = 0.462C_{\text{Ra}} + 0.621C_{\text{Th}} + 0.041C_{\text{K}} \quad (3.10)$$

3.5.2 Exposure

Exposure is the measure of radiation level exposure to humans from radioactive materials. For gamma and X-rays it is the amount of ionization they produce in air. Exposure can also be defined as the quotient of ΔQ by Δm , whereby ΔQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons liberated by photons in air of mass Δm are completely stopped in air (ICRU 2011).

$$\text{Exposure} = \frac{\Delta Q}{\Delta m} \quad (3.11)$$

The radiation exposure is measured in roentgen (R), which was first presented at the radiological congress in Stockholm by the year 1928. Initially before the Stockholm congress it was defined as the amount of gamma or exposure radiation that produces in air 1 esu of electrical charge of either sign in 1 cm³ or 0.001293 g of air at standard temperature and pressure (Liu 2013). Since 1 esu is equivalent to 3.34×10^{-10} coulomb (C), the S.I unit of radiation exposure can now be defined as

$$1\text{R} = \frac{1\text{esu}}{\text{cm}^3} = \frac{3.34 \times 10^{-10}\text{C}}{0.001293\text{g} \times 10^{-3}\text{kg.g}^{-1}} = 2.58 \times 10^{-4}\text{C.kg}^{-1} \quad (3.12)$$

From the perspective of radiological protection, radiation exposure can mainly be in two categories which are based on the location of the radiation regarding the human body, thus it can either be inside or outside (Liu 2013).

3.5.2.1 Internal exposure

Inhalation and ingestion are the pathways for internal exposure by the intake of radionuclides (Sultana 2017). Inhalation radiation doses come from radionuclides in the air or as part of dust particles whereas ingestion radiation doses arise from food consumption and drinking of water that is contaminated with radionuclides. The ingestion of radionuclides is determined by the consumption rates of food or water and the radionuclide concentrations. Due to the background radiation levels in soil, the climate and the agricultural conditions there is a significant variation in concentrations of

radionuclides in food. There is a chance that majority of primordial radionuclides such as ^{238}U , ^{232}Th , and ^{40}K find their ways into foodstuffs and drinks (Naveed 2014).

3.5.2.2 External exposure

Radioactivity present in the soil and any other material from the surrounding are the main causes of external exposure. Information on external exposure dose rate measurements are directly acquired from the soil and the surrounding materials or by evaluating the measurements of radionuclide concentrations in the soil (UNSCEAR 2012).

3.5.3 Absorbed dose

There are numerous radiometric and dosimetric techniques highly specialised for radiation measurement and assessment purposes. Since being exposed to radiation didn't account for biological implication caused, absorbed dose was introduced by the International Commission for Radiological Protection (ICRP) to cater for the energy imparted by ionising radiation to any kind of material (Umar et al. 2012). The absorbed dose is very fundamental in radiological protection for calculating radiation dose and it is measured in joule per kilogram, which is referred to as gray (Gy) and 1 Gy is equal to 1 joule per kilogram. The relationship between absorbed dose and the risk of biological effects is defined by the weighted dose quantities recommended by ICRP for the several types and energies of radiation incident or emitted from within the body and for selected tissues and organs (UNSCEAR 2016). Table 3.6 shows a list of radiation weighting factors for various types of ionizing radiation.

Table 3.6: Weighing factor (W_R) for different radiations (Umar et al. 2012).

Type of Radiation	Energy range	Weighting factor (W_R)
Photons (X, γ -rays, β)	All energies	1
Neutrons	< 10 keV	5
	10 - 100 keV	10
	100 keV – 2 MeV	20
	2 – 20 MeV	10
	> 20 MeV	5
Protons and charged ions	< 20 MeV	2
α -particles, fission fragments, heavy nuclei		20

3.5.4 Equivalent dose

It has long been approved that the absorbed dose that can cause a biological effect differs for each radiation type. The term linear energy transfer (LET) is used to characterize the distribution of ionizing events along the path of impinging radiation (Jeje 2014). The high energy transfers radiation has more potential to damaging the biological system per unit dose compared to a low LET radiation. Since the high-LET radiations can cause more damage per unit absorbed dose, the International

Commission for Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and the International Commission on Radiation Units and Measurements (ICRU) introduced the concept of equivalent dose for radiation-protection purposes. The equivalent dose, symbolized by the letter H_T , can be defined as the product of the absorbed dose $D_{T,R}$ and a dimensionless quality factor Q_R , absorbed over a tissue or organ (T), which depends on the LET (Al-Kinani et al. 2015) and is given by Equation 3.13.

$$H_T = \sum_R W_R \cdot D_{T,R} \quad (3.13)$$

Where, H_T is the equivalent dose absorbed by tissue T, $D_{T,R}$ is the absorbed dose in tissue T by radiation type R and W_R is the radiation weighting factor defined by regulation.

Whereby H_T is expressed in Sievert (Sv), when the absorbed dose is expressed in gray (Gy), thus one Sievert is also equal to one joule per kilogram. An older unit of the H_T is the rem (radiation equivalent man) with the absorbed dose expressed in units of rad, and 1 Sv equals to 100 rem (Badhan et al. 2017).

3.5.5 Effective dose

The biological risk effect to radiation is determined by the sensitivity of tissues or organs (T) that have been exposed to radiation. The difference of radiation sensitivity of each organ is taken into consideration in the input of the H_T in all tissues and organs involved. Based on this, ICRP introduced the effective dose, to indicate the combination of different doses to several different tissues or organs. Effective dose (E) is the summation of tissue equivalent doses (H_T), each multiplied by the appropriate tissue weighting factor (W_T) of a specific tissue type and its SI unit is the Sievert (Sv). The values assigned to weighing factors are given in Table 3.7 according to ICRP to indicate the combination of different doses to several different tissues as in Equation 3.14 (ICRP 2012).

$$E = \sum_T w_T \cdot H_T \quad (3.14)$$

Considering equations 3.13 and 3.14, effective dose (E) can be presented as:

$$E = \sum_T w_T \sum_R W_R \cdot D_{T,R} \quad (3.15)$$

Table 3.7: Tissue weighting factor (W_T) for different body tissues (ICRP 2012).

Type of Tissue	Weighting factor (W_T)	Sum of W_T values
Gonads	0.20	0.20
Bone-marrow (red), colon, lung, stomach	0.18	0.48
Bladder, breast, liver, liver, oesophagus, thyroid	0.05	0.25
Skin, bone surface	0.01	0.02
Remainder	0.05	0.05
Whole body total	-	1.00

3.5.6 Dose assessment

For assessment and characterisation of radiological hazard regarding exposure to radiation from NORMs contributing to rise in both internal and external human radiation doses, can be determined in terms of many parameters. A direct connection between radioactivity concentrations of NORMs and human exposure is known as the absorbed dose rate in the air at 1 metre above the ground level. The activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K ($\text{Bq}\cdot\text{kg}^{-1}$) representing the main external sources of natural radiation to the human body are used to calculate the absorbed dose rate (UNSCEAR 2016).

3.5.6.1 Dose rate

The absorbed dose rate D , outdoors due to terrestrial γ -rays at 1 meter above the ground surface can be calculated from the mean activity concentration of ^{226}Ra , ^{232}Th and ^{40}K in the soil as shown by Equation 3.16 (Chiroma et al. 2014).

$$D = \sum_x A_x \cdot C_x \quad (3.16)$$

Where, A_x is the mean specific activity of ^{226}Ra , ^{232}Th or ^{40}K in Bq/kg , while C_x is the corresponding dose conversion factor (DCF) in nGy/h (Cinelli et al. 2017) and given as 0.462, 0.604 and 0.0417 respectively. The Equation 3.16 can be re-written as Equation 3.10.

3.5.6.2 Radium equivalent activity

The radium equivalent (Ra_{eq}) is used to assess hazards associated with materials containing ^{226}Ra , ^{232}Th and ^{40}K nuclides. The values were calculated on the assumption that 370 Bq/kg of ^{226}Ra or 259 Bq/kg of ^{232}Th or 4810 Bq/kg of ^{40}K produce the same γ dose rate (Ademola et al. 2015) and can be given as:

$$Ra_{eq} = A_{Ra} + (A_{Th} \times 1.43) + (A_K \times 0.077) \quad (3.17)$$

where, A_{Ra} , A_{Th} , and A_K are the specific activities in $Bq\ kg^{-1}$ of ^{226}Ra , ^{232}Th and ^{40}K , respectively for Equation 3.17. The published permissible maximum value for Ra_{eq} is 370 Bq/kg (Asaduzzaman et al. 2015) and corresponds to an effective dose of 1 mSv for the public.

3.5.6.3 External hazard index

The external hazard index (H_{ex}) is used to evaluate the hazard of natural γ radiation (Hushari et al. 2015) and its purpose is to limit the radiation dose to the permissible dose equivalent limit of 1 mSv/y. To determine this index Equation 3.18 is used.

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} < 1 \quad (3.18)$$

Where, A_{Ra} , A_{Th} , and A_K are the specific activities in $Bq.kg^{-1}$ of ^{226}Ra , ^{232}Th and ^{40}K , respectively. The value of H_{ex} must be less than unit to keep the radiation hazard insignificant. The criterion considered by the model is that the maximum value of the external hazard due to γ -rays corresponds to a maximum Ra_{eq} activity of 370 Bq/kg for materials containing ^{226}Ra , ^{232}Th and ^{40}K nuclides (Taqi et al. 2016).

3.5.6.4 Annual effective dose equivalent (AEDE)

The annual effective dose equivalent (*AEDE*), in mSv/y, is the dose received by an adult given an average worldwide outdoor occupancy factor of about 20% and is derived from the absorbed dose rate in air (Equation 3.19) using a conversion factor of 0.7 Sv/Gy. The *AEDE* is given by Equation 3.20 (Kamunda et al. 2016a).

$$AEDE = D \left(\frac{10^9 Gy}{h} \right) \times 24 \frac{h}{day} \times 365 \frac{day}{y} \times \frac{10^{-6} mGy}{10^9 Gy} \times 0.7 \frac{Sv}{Gy} \times 0.2 \quad (3.19)$$

$$AEDE = D \times 1.23 \times 10^{-3} mSvy^{-1} \quad (3.20)$$

The world average *AEDE* from outdoor terrestrial γ -radiation is 460 μ Sv/y (UNSCEAR 2012). In the case of the food samples, the average annual effective doses (E_{av}) were estimated from the activity concentrations of each individual NORM nuclide (^{238}U , ^{232}Th and ^{40}K) and applying the yearly food consumption rate for the adult members of the community and the dose conversion factors of 4.50×10^{-8} , 2.30×10^{-7} and 5.90×10^{-9} Sv/Bq for ^{238}U , ^{232}Th and ^{40}K (Durowoju et al. 2018) using equation 3.21. In Botswana, the average consumed weight in grams per meal is approximately 260 g of vegetables, 100 g of fish, and 200 g of beef liver once a day. Therefore, based on this information and the non-availability of well-accepted consumption rates of these foodstuffs, an annual consumption

rate of 100 kg/y was assumed for all vegetables, 35 kg/y for fish and 70 kg/y for beef liver. The average effective dose can be calculated using Equation 3.21.

$$E_{ave} = I_p \times D_i \times A_i \quad (3.21)$$

Where, I_p is the consumption rate from intake of NORMs in foodstuff, D_i is the ingestion dose conversion factor and A_i is the activity concentration of the NORMs in the food sample.

The annual α/β committed effective dose (AED) associated with radiation exposure through ingestion of water was estimated to assess the health risk to adult members of the public. The expression for the AED is provided in Equation 3.22 (Mangset et al. 2014).

$$AED_{(\alpha/\beta)} = A_{(\alpha/\beta)} \times W \times DC \quad (3.22)$$

Where, AED (α/β) is the gross annual α / β committed effective dose due to the consumption, of water, $A_{(\alpha/\beta)}$ is the gross α / β activity (Bq/l) concentration in the water, W is the consumption rate of water, set at 730 l/year for adults (World Health Organization 2008), and DC is the ingestion dose coefficient of 4.50×10^{-8} Sv/Bq for adults (WHO 2011).

CHAPTER 4: RESULTS AND DATA ANALYSIS

The aim of this research was to assess the radiological risk due to NORMs in the area proposed to build a radioactive waste storage facility in Pilikwe, central Botswana, using radiometric techniques. Both soil and water samples used in this study were prepared and stored prior to measurement. This chapter describes the results obtained from each technique, organized in the following manner:

- Gamma spectrometry
- ICP-MS
- Alpha spectrometry

4.1 Activity concentrations of NORMs in the proposed waste storage facility site using gamma spectrometry

4.1.1 Background spectrum

There is significant provision of shielding for the detector, thus the effect of the background radiation which is continuously produced by the cosmic radiation and gamma-ray sources in the vicinity of the detector are reduced significantly compared to an unshielded detector (Kshetri 2012). The radioactive contaminants of the detector assembly and its shielding are the main sources of the background radiation level within the detector. It is clear that most gamma-ray energy peaks shown in the spectrum originate from the decays of primordial radionuclides, which are the ^{238}U and ^{232}Th decay chains and ^{40}K ; these are contained in both the detector material and the wider environment. These radionuclides exist at trace levels in the materials used for the manufacture of the detector and its shielding. For example, aluminium, which is the structural material of the detector endcap and other part within the detector housing, contains some uranium and thorium daughter nuclides and ^{40}K . The printed circuit boards in the germanium detector preamplifier (which is mounted with the detector) can contain significant concentrations of primordial radionuclides relative to other materials of detector assembly (Luca et al. 2012).

4.1.2 NORMs activity concentrations, absorbed dose rates and annual effective dose equivalent

The ^{238}U , ^{232}Th chains and ^{40}K activity concentrations in all the soil samples from the study area was acquired and are presented in Figures 4.1A and 4.1B. For detailed information, see Appendix A (Tables A.1 – A.4).

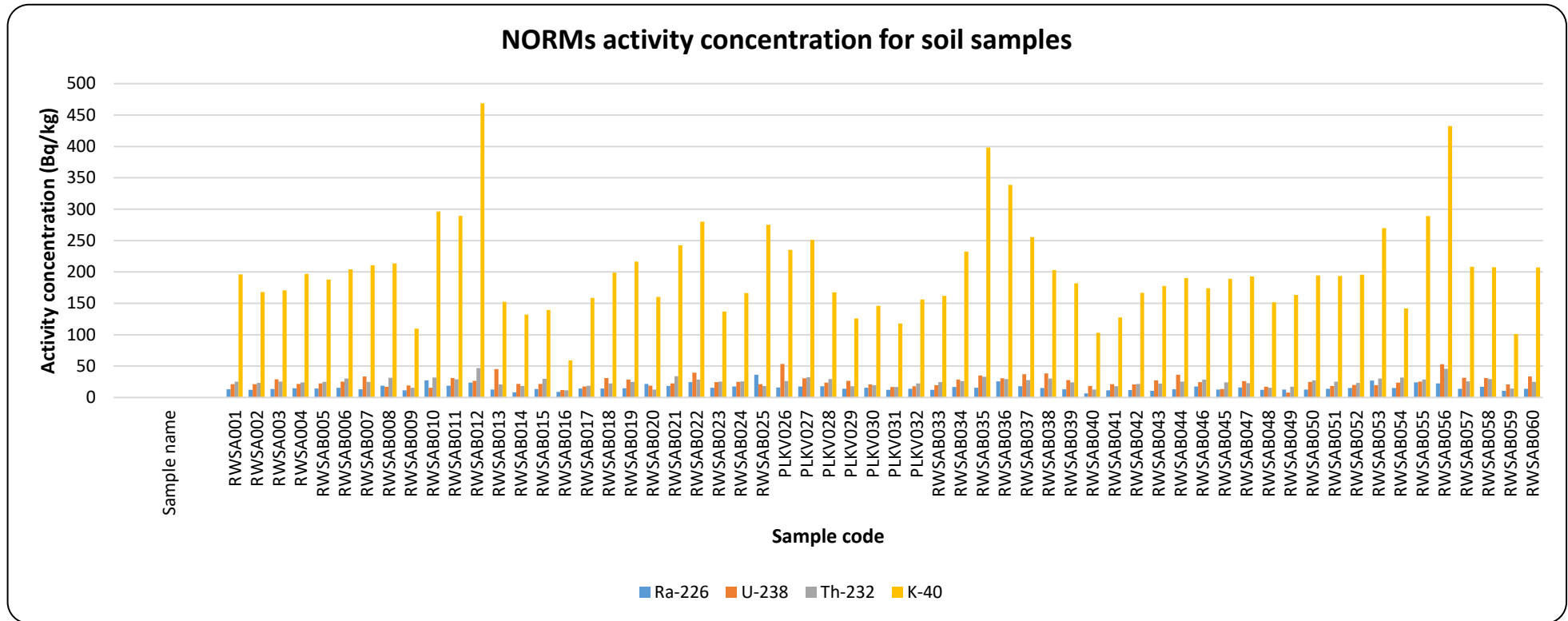


Figure 4.1A: The ^{238}U , ^{232}Th chains and ^{40}K activity concentrations in all the soil samples from the study area.

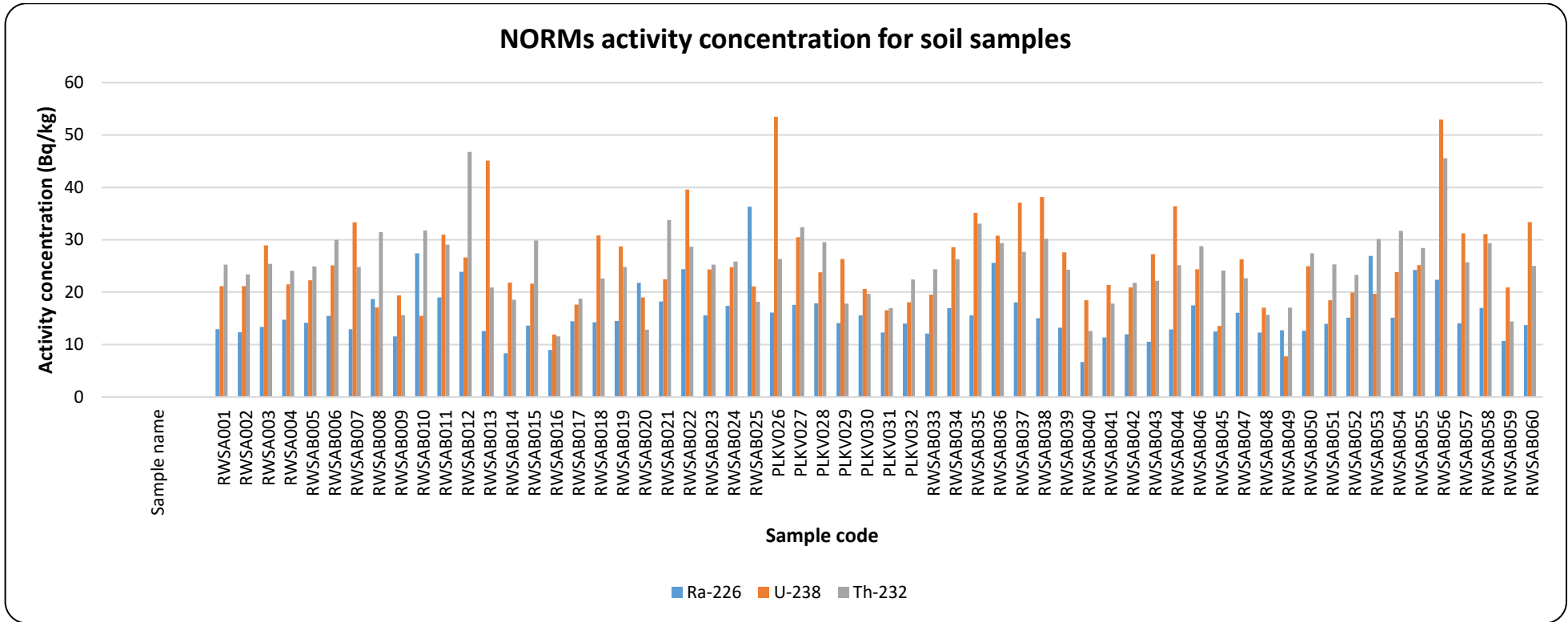


Figure 4.1B: The ^{238}U , ^{226}Ra and ^{232}Th activity concentrations in all the soil samples from the study area retrieved from Figure 4.1A omitting ^{40}K .

4.1.3 Comparison of activity concentrations of ^{238}U , ^{232}Th and ^{40}K in soils from the study area with other countries

The activity concentrations of ^{238}U , ^{232}Th and ^{40}K results from the study area were compared to the published data from other countries and world-wide average values as shown in Table 4.1. The activity concentrations of the soil from the study area were found to be below the worldwide acceptable standard values as per the UNSCEAR publication of September 14, 2017.

Table 4.1: Comparison of natural radioactivity (^{238}U , ^{232}Th and ^{40}K) levels of soil samples from study area and other countries (Thabayneh 2012).

Country	Activity concentration of soil samples (Bq/kg)					
	^{238}U		^{232}Th		^{40}K	
	Range	Average	Range	Average	Range	Average
Present study Botswana	7.75 - 53.47	25.55	11.58 - 46.78	24.98	59.15 - 468.60	201.30
China	2 - 440	32	1 - 360	41	9 - 1800	440
Egypt	5 - 64	17	2 - 96	18	29 - 650	320
India	7 - 81	29	14 - 160	64	38 - 760	400
Iran	8 - 55	28	5 - 42	22	250 - 980	640
Japan	6 - 98	33	2 - 88	28	15 - 990	310
Luxembourg	6 - 52	35	7 - 70	50	80 - 1800	620
Malaysia	38 - 94	67	63 - 110	82	170 - 430	310
Nigeria	9 - 18	14	1 - 38	19	712 - 1098	896
Poland	5 - 120	26	4 - 77	21	110 - 970	410
Romania	8 - 60	32	11 - 75	38	250 - 1100	490
Spain	6 - 250	32	2 - 210	33	25 - 1650	470
USA	8 - 160	40	4 - 130	35	100 - 700	370
Worldwide average (UNSCEAR 2017)	17 - 60	35	11 - 64	30	140 - 850	400

4.1.4 Absorbed dose rate, annual effective dose equivalent, radium equivalent activity and external hazard index for all soil samples from the study area

Estimation of radiation dose and biological effects to humans due to ionising radiation is a fundamental objective for measurements of environmental radioactivity from soil samples. Radiometric risk assessment can be conducted by considering several parameters such as absorbed dose rate (D), annual effective dose equivalent (AEDE), radium equivalent activity ($R_{a_{eq}}$) and external hazard index (H_{ext}). Table 4.2 shows the above-mentioned parameters linked to natural radionuclides for soil samples considered in this study. These parameters help to estimate the gamma radiation hazards on human subjects linked to the use of the soil samples as building material by calculating the values of the four quantities for all samples (Nguelem et al. 2016). The actual estimated values of these radiological parameters are in APPENDIX A, Table A5.

Table 4.2: Pilikwe soil samples absorbed dose rate, annual effective dose equivalent, radium equivalent activity and external hazard index.

	D (nGy/h)	AEDE (μSv/y)	$R_{a_{eq}}$ (Bq/kg)	H_{ext}
Min	14.957 \pm 0.777	18.344 \pm 0.953	33.011 \pm 1.682	0.0891 \pm 0.005
Max.	70.020 \pm 4.454	85.872 \pm 5.463	151.411 \pm 10.545	0.410 \pm 0.285
Average	34.066 \pm 1.606	41.778 \pm 1.969	74.158 \pm 3.487	0.200 \pm 0.009
Recommended limit	-	-	< 370	< 1
Worldwide average	57	70	-	-
Range	18 - 93	-		-

From the study area, the estimated absorbed dose rates (D) for soil samples ranged from 14.957 \pm 0.777 to 70.020 \pm 4.454 nGy/h, with an average of 34.066 \pm 1.606 nGy/h. These values were lower than the worldwide absorbed dose rate of 57 nGy/h. The estimated AEDE for soil samples ranged from 18.344 \pm 0.953 μ Sv/y to 85.872 \pm 5.463 μ Sv/y with an average of 41.778 \pm 1.969 μ Sv/y. These values of AEDE were below the worldwide value of 70 μ Sv/y. The $R_{a_{eq}}$ ranged from 33.011 \pm 1.682 Bq/kg to 151.411 \pm 10.545 Bq/kg, with an average of 74.158 \pm 3.487Bq/kg. These values were less than the worldwide recommended limit value of 370 Bq/kg. The H_{ext} ranged from 0.089 \pm 0.005 to 0.410 \pm 0.285, with an average of 0.200 \pm 0.009. These average H_{ext} values were within the worldwide recommended limit value of less than 1

4.2 Elemental concentrations of NORMs in the proposed waste storage facility site using ICP-MS

A TotalQuant analysis was performed on the solutions of the 60 soil and 2 borehole water samples collected at the proposed radioactive waste storage area of Pilikwe, and within the surrounding area of the village, in order to determine elements, present at measurable concentrations, the elemental concentration ranges for the nuclides of interest, interfering molecular ions and the masses at which no elements are present (masses where internal standards could be defined). Having gathered total TotalQuant information helps in determination of potential interferences, sample dilutions and thus an internal standard TotalQuant can also be used to help determine unusual results from a sample that is analyzed in the quantitative mode. During TotalQuant method the more usable data from the mass spectrum, the more accurate the results will be (PerkinElmer 2009).

To acquire the concentration information about the sample, the intensity results was compared to a response curve that is stored on the ICP-MS computer system. This response curve is in (counts/second)/PPM for every element. The response curve unit works well after updating the response by adding standards used to the calibration page. When the Response Curve is updated, all the elements are adjusted with the points in the calibration window (PerkinElmer 2009). The results obtained by this technique are presented in Figures 4.2, Table 4., Table 4.4, Table 4.5, Table 4.6 and Table 4.7.

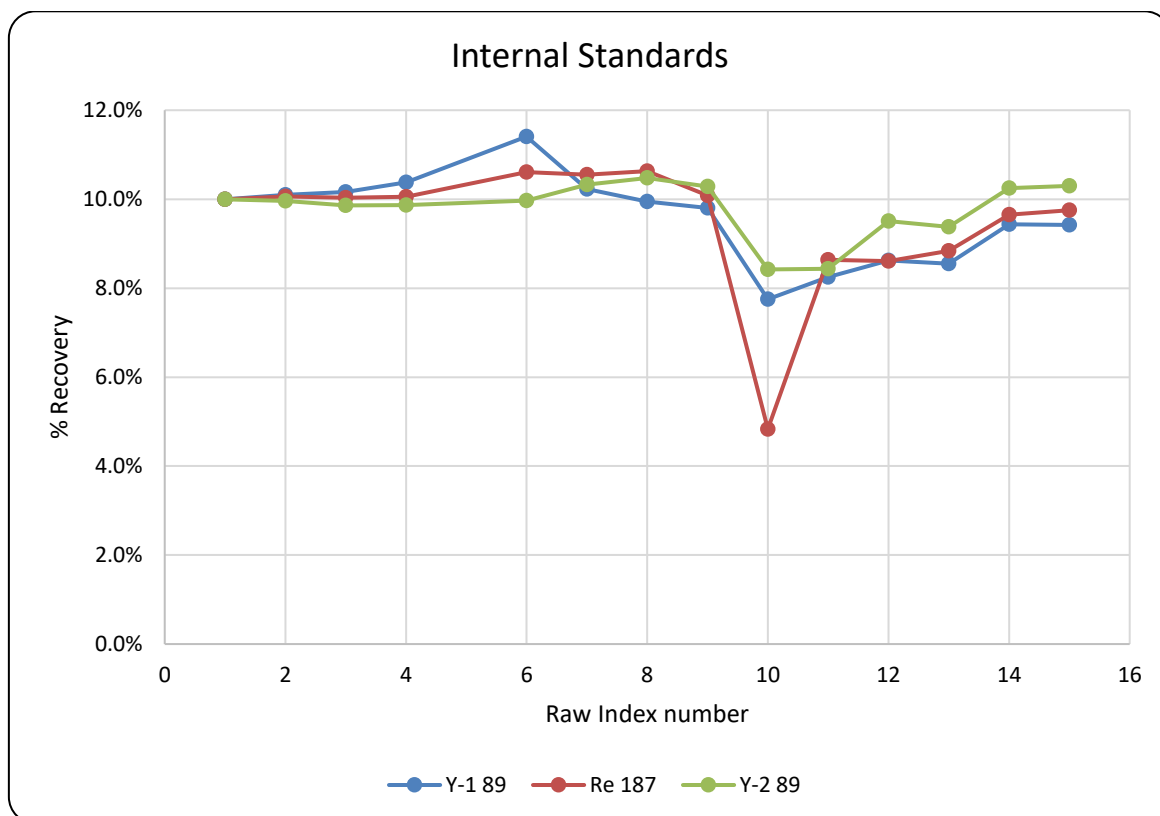


Figure 4.2: Internal standard used during the analysis of the samples.

4.2.1 Elementary concentrations in water samples

The concentrations ($\mu\text{g/L}$) of different elements in water samples are presented in Table 4.3 and their percentage ratios in Table 4.4. These results were compared with those of international guidelines for permissible limits of heavy metals in drinking water. The average elemental concentrations of the heavy metals in the water samples were lower than the WHO permissible limit for all selected heavy metals indicating safe water drinking for the residents of Pilikwe as indicated in Table 4.3. The elementary concentrations from the boreholes water are extremely very low with some exceptions of some high concentrations of Mg and Ni elements.

Table 4.3: Factored concentrations of water samples.

Sample Id	Al ($\mu\text{g/L}$)	Li7 ($\mu\text{g/L}$)	Mg ($\mu\text{g/L}$)	Mn ($\mu\text{g/L}$)	Co ($\mu\text{g/L}$)	Ni ($\mu\text{g/L}$)	Cu ($\mu\text{g/L}$)	Zn ($\mu\text{g/L}$)	Y-1 89 (IS)	Ba ($\mu\text{g/L}$)	Ce ($\mu\text{g/L}$)	Tb ($\mu\text{g/L}$)	Pb ($\mu\text{g/L}$)	Th ($\mu\text{g/L}$)	U ($\mu\text{g/L}$)	Re 187 (IS)	Ni 60 Helium KED ($\mu\text{g/L}$)	Y-2 89 (IS) Helium KED
Calibration blank									100.0%							100.0%		100.0%
std 1 at 5 ppb	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	101.0%	5.00	5.00	5.00	5.00	5.00	5.00	100%	5.00	99.6%
std 2 at 10 ppb	9.87	9.94	9.91	9.97	9.93	9.95	9.92	9.79	101.6%	9.99	9.99	9.97	9.94	9.84	9.98	100%	9.98	98.6%
std 3 at 20 ppb	19.22	19.71	19.42	19.71	19.75	19.72	19.63	19.74	103.8%	19.81	19.94	19.97	19.92	20.03	19.89	100%	19.94	98.7%
PLKVB 001	57.43	35.02	16014.83	10.15	0.21	277.13	35.46	87.70	98.1%	51.48	1.45	0.02	1.31	0.02	4.63	100%	274.41	99%
PLKVB 002	54.10	33.53		9.70	0.21	261.86	36.04	85.91	85.5%	49.61	1.44	0.02	1.23	0.01	4.54	88.4%	271.42	93.8%
Calibration blank check	0.01	0.02	4.95	0.01	0.00	0.03	1.89	0.01	94.3%	0.01	0.00	0.00	0.00	0.00	0.01	96.5%	0.03	99.8%
std 10ppb check	11.81	10.14	15.68	10.74	10.48	10.25	11.47	10.46	94.2%	10.17	10.26	10.24	10.45	10.02	10.41	97.5%	10.56	99.8%

Table 4.4: Concentrations RSDs of water samples.

Sample Id	Al	Li	Mg	Mn	Co	Ni	Cu 63	Zn	Y-1 89 (IS)	Ba	Ce	Tb	Pb	Th	U	Re 187 (IS)	Ni 60 Helium KED	Y-2 89 (IS)
Calibration blank									1.3%							2.3%		1.5%
std 1 at 5 ppb	2.4%	1.8%	1.5%	1.1%	1.3%	2.0%	1.9%	2.5%	1.1%	1.1%	1.0%	0.7%	1.1%	1.1%	2.4%	1.0%	1.2%	1.2%
std 2 at 10 ppb	2.3%	2.8%	2.0%	2.6%	1.2%	3.4%	3.1%	2.0%	2.8%	3.2%	0.8%	2.0%	2.2%	1.5%	0.4%	1.9%	0.6%	0.8%
std 3 at 20 ppb	3.1%	2.5%	3.2%	0.8%	2.8%	5.2%	2.5%	2.4%	1.9%	2.7%	2.1%	1.1%	1.1%	1.3%	1.1%	0.3%	0.7%	0.8%
PLKVB 001	3.8%	2.6%	1.4%	1.8%	1.6%	1.8%	1.1%	2.4%	1.2%	1.2%	1.6%	5.2%	1.2%	8.3%	2.1%	1.1%	0.2%	1.0%
PLKVB 001	1.3%	1.7%		1.8%	1.5%	2.3%	1.9%	1.1%	0.8%	1.6%	2.2%	4.6%	1.7%	6.8%	1.1%	1.1%	1.6%	0.6%
Calibration blank check	22.3%	15.0%	5.4%	13.6%	359.8%	20.4%	8.3%	10.9%	0.9%	5.4%	53.7%	28.5%	94.7%	33.7%	15.4%	1.8%	3.3%	1.0%
std 10ppb check	1.3%	3.3%	11.3%	2.3%	0.7%	2.7%	0.8%	3.7%	1.0%	1.7%	0.4%	0.6%	2.3%	1.7%	1.1%	0.9%	1.5%	0.7%

Table 4.5: Acceptable limits of heavy metals in drinking water (WHO 2011).

Country / Organization	Heavy metals concentration limit (mg/L)								
	As	Pb	Hg	Cd	Cr	Cu	Zn	Co	Ni
USEPA	0.010	0.015	0.002	0.005	0.100	1.300	0.500	0.100	n/a
WHO	0.010	0.010	0.006	0.003	0.050	2.000	n/a	n/a	0.070
South Africa	0.010	0.010	0.001	0.003	n/a	1.000	n/a	n/a	n/a
Current study	0.000	0.001	0.00	0.00	0.00	0.029	0.087	0.0002	0.027

4.2.2 Elementary concentrations in soil samples

The soil sample concentrations of the elements were found to be lower than the maximum acceptable worldwide limit when the heavy metals in the study area results were compared with those of other countries presented in Table 4.6. The average concentrations of these heavy metals suggest that the soil of this area is not polluted with heavy metals and its NORMs concentrations are very low as expected thus making it a suitable place for construction of a radioactive waste storage facility.

Table 4.6: Acceptable maximum concentration limit of heavy metals in soil (mg/kg) for different countries (Kamunda et al. 2016b).

Country	Acceptable maximum concentration limit of selected heavy metals in soil (mg/kg) for different countries								
	As	Pb	Cd	Cr	Cu	Zn	Co	Th	U
Germany	50	70	1	60	40	150	-	-	-
Poland	-	100	3	100	100	300	50	5.19	2.08
Australia	20	300	3	50	100	200	-	1.3	2.2
Taiwan	60	300	5	250	200	600	-	10.8	2.4
Bulgaria	10	26	0.4	65	345	88	20	7.41	3.2
Canada	20	200	3	250	150	500	-	11.9	4.1
China	30	80	0.5	200	100	250	-	15.2	-
Tanzania	1	200	1	100	200	150	-	-	-
South Africa	5.8	20	7.5	6.5	16	240	300	7.77	2.29
World average	30	140	2.8	120	139	275	125	11.08	2.67
FAO/WHO Guidelines	20	100	3	100	100	300	50	-	1.4

The average concentrations and radiotoxicity of selected nuclides from the soil samples of the study area are presented in Table 4.7. Detailed results and additional nuclides of all samples for this study are presented in APPENDIX B, Table B.1.

Table 4.7: Minimum, maximum, and average concentrations (mg/kg) of selected heavy metals in soil samples from the study area.

Location (Pilikwe Botswana)	Minimum, maximum, and average concentrations of selected heavy metals in soil samples (mg/kg)								
	As	Pb	Cd	Cr	Cu	Zn	Co	Th	U
Minimum	0.0007	0.0062	0.000	0.000	0.007	0.009	0.010	0.004	0.000
Maximum	0.072	0.840	0.0002	0.319	0.066	0.071	1.334	0.294	0.973
Average	0.018	0.286	0.00003	0.195	0.027	0.018	0.460	0.050	0.126

The results for the average elemental concentrations on Table 4.7 were compared with those of international guidelines for permissible limits of selected heavy elements concentrations in the soil on Table 4.6. The average elemental concentrations of all selected heavy metals in the soil samples were lower than the permissible limits. The results showed that the average concentrations of the selected heavy metals in soil were lower than the WHO permissible limit, indicating that it's safe to reside and for the construction of the radioactive waste storage facility in the study area.

4.3 Activity concentrations of NORMs in the proposed waste storage facility site using alpha spectroscopy

For alpha spectrometry the polonium determination method was applied on running both the soil and water samples respectively, the determination of polonium concentrations in the samples was crucial as ^{210}Po is a naturally occurring alpha emitter and exists in the environment as a result of the ^{210}Pb decay within the ^{238}U decay chain. Polonium has 25 known radioactive isotopes with mass numbers of 192 to 218, of which only the 208, 209 and 210 isotopes have half-lives longer than 1 day. Of these three, it is ^{210}Po which is of most interest from an environmental impact viewpoint, thus the results are reported as follows. There is very little information known about the soil chemistry of polonium but it is expected to be adsorbed onto soil particles, such as mineral colloids (Sethy et al. 2015). The ^{210}Po is considered to be in equilibrium with ^{210}Pb , suggesting that the ^{210}Pb in the soil is the main source of ^{210}Po irreversibly adsorbed on clay and organic colloids in the soil. The activity concentration levels of ^{210}Po in various soils that have been reported are in the range of 20 to 40 Bq.kg⁻¹ respectively (Lozano et. al 2010).

4.3.1 Determination of Polonium 210 in the soil samples

Samples were run concurrently with a tracer and a reference material i.e., Reference material: BOT7003 sample 03 soil, and polonium 209 tracer, activity: 0.188 ± 0.004 Bq/g, K=2 and ref date: 18 April 2018.

Table 4.8: The average activity concentration of ^{210}Po in the soil samples.

	Gross Activity (Bq)	Net Activity (Bq)	Total Activity (Bq/kg)	Total Activity on preparation date (Bq/kg)
Min	0.0000± 0.0000	0.0001 ± 0.0000	0.4975± 0.0106	0.4976± 0.0106
Max	0.0070± 0.0001	0.0069± 0.0046	27.5161± 1.844	27.5231± 1.844
Average	0.0010± 0.0004	0.0007± 0.0004	3.10 ± 1.60	3.10 ± 1.60
Tracer Average	0.0010±0.0004	0.0008 ±0.0004	0.0188±0.0004	0.0188±0.0004

The average activity concentrations for soil samples from the study area in Table 4.8 are way below the available reported and accepted activity concentration levels of ^{210}Po in various soils that have been reported ranging from 20 to 40 Bq/kg. A full detailed analysis of all the samples analysed can be found in Appendix C Table C.1.

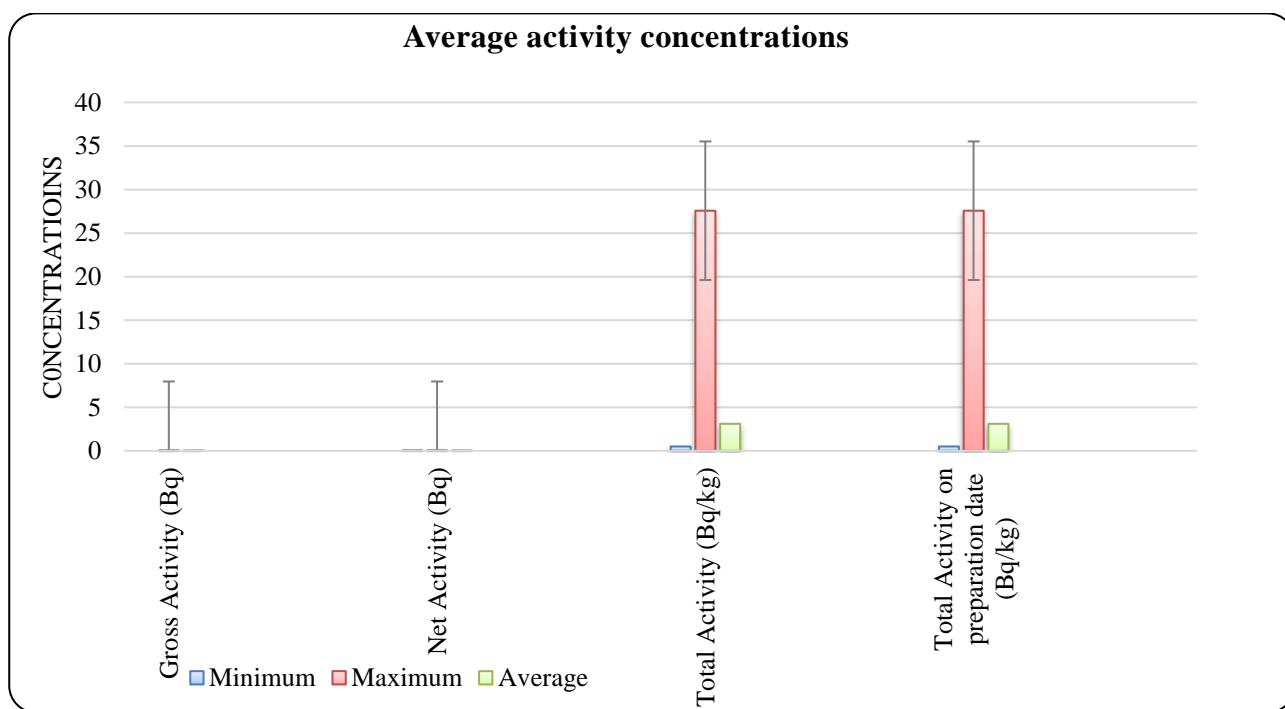


Figure 4.3: The average activity concentration of ^{210}Po in the soil samples.

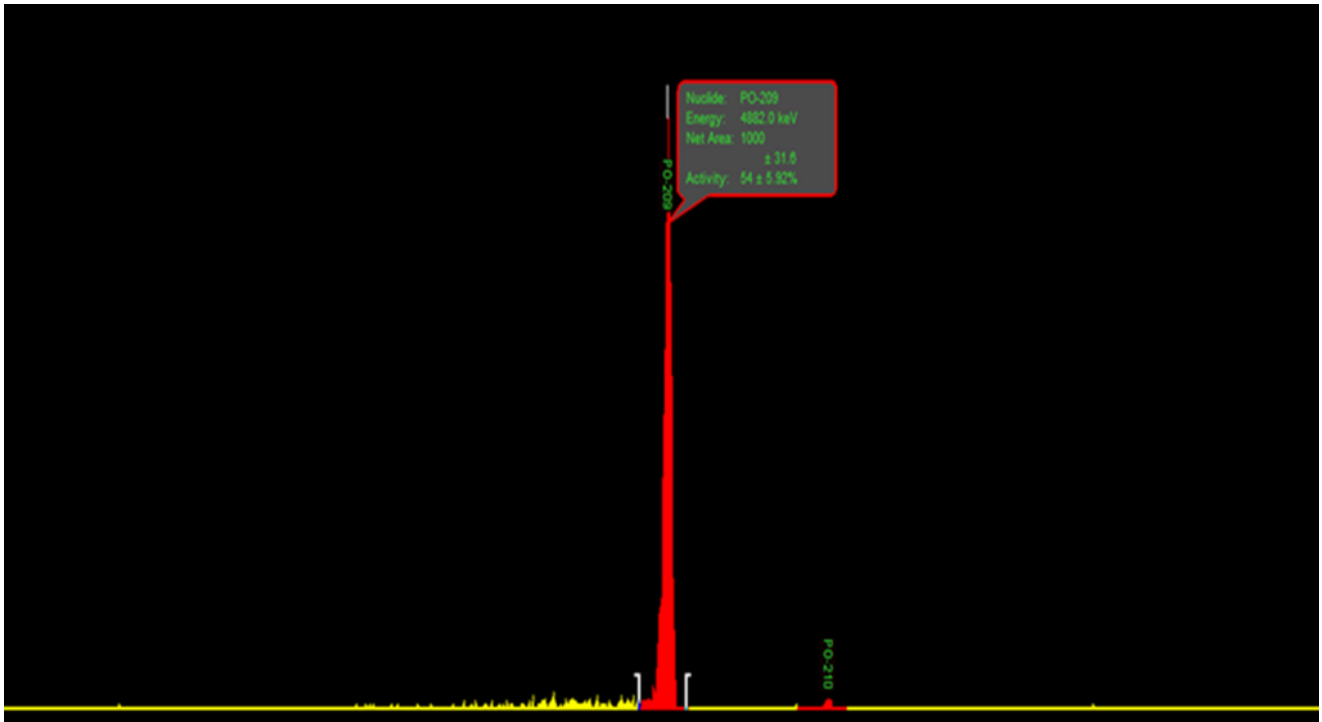


Figure 4.4: Screenshot picture of sample RWSAB018 analyzed by alpha spectrometry using Apex-Alpha; Alpha spectrometry software suite.

4.3.2 Calculation of ^{210}Po activity concentration

After obtaining the count rates of the tracer (^{209}Po) and ^{210}Po peaks as in Figure 4.4, the tailing allowed for the contributions due to detector background are subtracted with procedure blank. The ratio of the net count rates in the two peaks was used to calculate the activity concentration of ^{210}Po of the samples on the date of chemical separation of Polonium, considering the activity concentration of the tracer solution, the masses of the sample and the tracer solution used, the decay of ^{210}Po between separation and counting, the decay of the tracer between its calibration date and counting, and the alpha emission probabilities in the measured areas in the α -spectrum. The detection efficiency of the counting system was required for the determination of ^{210}Po recovery in the chemical process. (Casacuberta et al. 2012).

Lastly the concentration of ^{210}Po in the samples were calculated backward to their date of collection, considering the decay of the original ^{210}Po and ingrowth from its progenitors ^{226}Ra , ^{210}Pb , and ^{210}Bi . This was done being mindful of Pb and Bi which are the major contributors to ingrowth over delayed period of time between sampling and separation. Therefore, to minimize the necessary correction, the delay time between sample collection and the separation for ^{210}Po measurement was kept as short as possible. This was very vital for these soil and water samples as their activity concentration for ^{210}Po was expected to be lower than those of its progenitors and the tracer since the ingrowth and decay calculations are dependent on the procedure followed (Abdulrahman 2011).

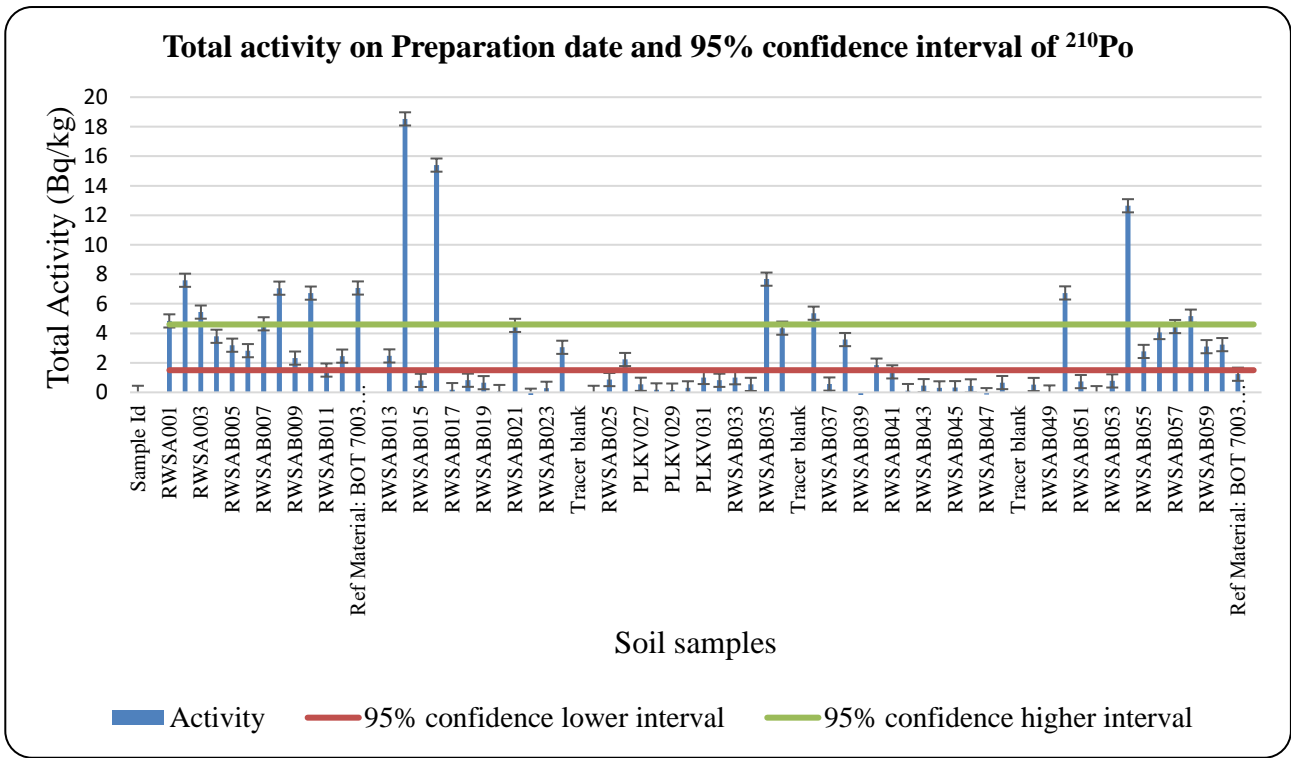


Figure 4.5: The total activity concentration of ²¹⁰Po at a confidence interval of 95%.

The average activity of ²¹⁰Po was 1.5 Bq/kg and 4.6 Bq/kg for the lower and higher interval of 95% confidence level, thus Figure 4.5 shows the total activity concentration on preparation date of the samples with respect to the confidence level. The activity concentrations on preparation date are within acceptable range of 0 to 20 Bq/kg (Lannuzel et al. 2011).

The minimum, maximum and average recovery of ²¹⁰Po from the samples using ²⁰⁹Po tracer was 65%, 104% and 86%. This testifying that the ²¹⁰Po in the samples was recovered satisfactory. Figure 4.6 shows the recovery bar graph for the ²¹⁰Po in the soil samples.

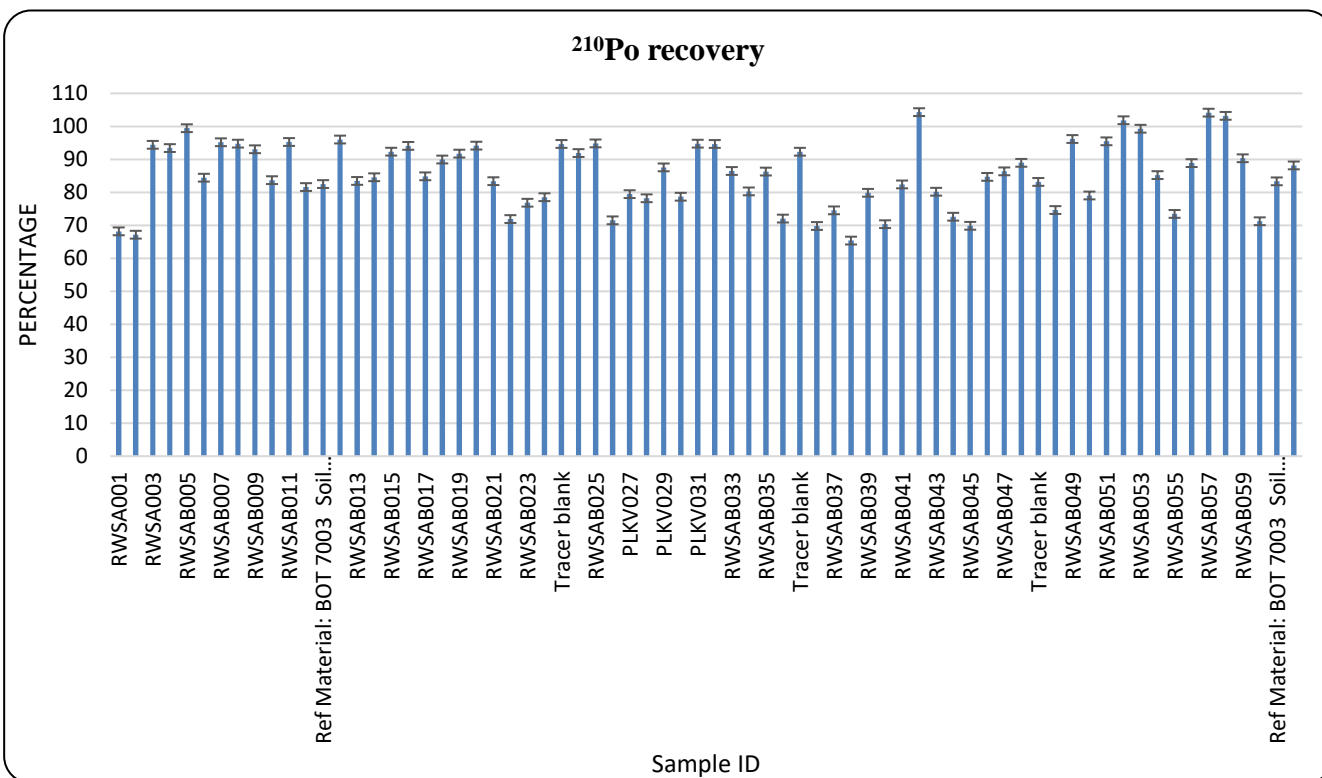


Figure 4.6: Percentage recovery of ²¹⁰Po from the soil samples using ²⁰⁹Po tracer.

For most of the soil samples as in Figure 4.5, the activity concentration at the date of preparation was below the theoretical lower interval level, this was expected due to the ingrowth of ²¹⁰Pb (from the date of sampling to the preparation time for analysis). This means that when the calculated value of ²¹⁰Po that should have been present was subtracted from the total ²¹⁰Po measured on the date of analysis, the value was below the detection limit. For these scenarios nothing could be inferred about the initial activities of ²¹⁰Po present in the soil samples. Another illustration is on the spectra on figure 4.4, as it can be observed that the peak for the ²¹⁰Po is very small compared to the peak of the ²⁰⁹Po tracer (Bowie et. al 2010). Where the derivation of ²¹⁰Po activity concentrations was possible on the samples, the activity concentrations for some soil's samples were above the theoretical higher interval level as shown in Figure 4.5 and thus still, they are relatively below the accepted natural environments although direct comparison is difficult since activity concentrations are often quoted for different depths of surface soil. This is in reference to Bunzl and Kracke (Bunzl et al. 1984) measured activity concentrations in the range of 11-28 Bq/kg for ²¹⁰Po in soil samples from a heathland in Western Germany. The soil samples consisted of the upper 15 cm of soil (Gjelsvik 2012).

The reference material: BOT 7003 soil test sample determined average activity concentration level was 3.273 ± 1.4 Bq/kg for ²¹⁰Po from a control area. The average activity concentration for all the 60 soil samples on preparation date was 3.10 ± 1.60 Bq/kg. The soil samples were from about 30 cm depth from the study area. Thus, with the depth of soil samples accounted for, the activity concentrations measured in the present study are proportionate with the data reported in the above-mentioned studies. The ²¹⁰Po measured/ ²⁰⁹Po reference (tracer) ratios for soils from the study area of

Pilikwe varied considerably ranging between 0.17 and 5.98 with an average value of 0.85 as shown in Figure 4.7. This was consistently in agreement with the established view that ^{210}Po measured/ ^{209}Po reference ratios from soils samples could be anticipated to reflect equilibrium for these isotopes (be near to 1) and that ingrowth of ^{210}Po is from ^{210}Pb in the soil as the main source having some excess ^{210}Po decayed away in a relatively short period following deposition.

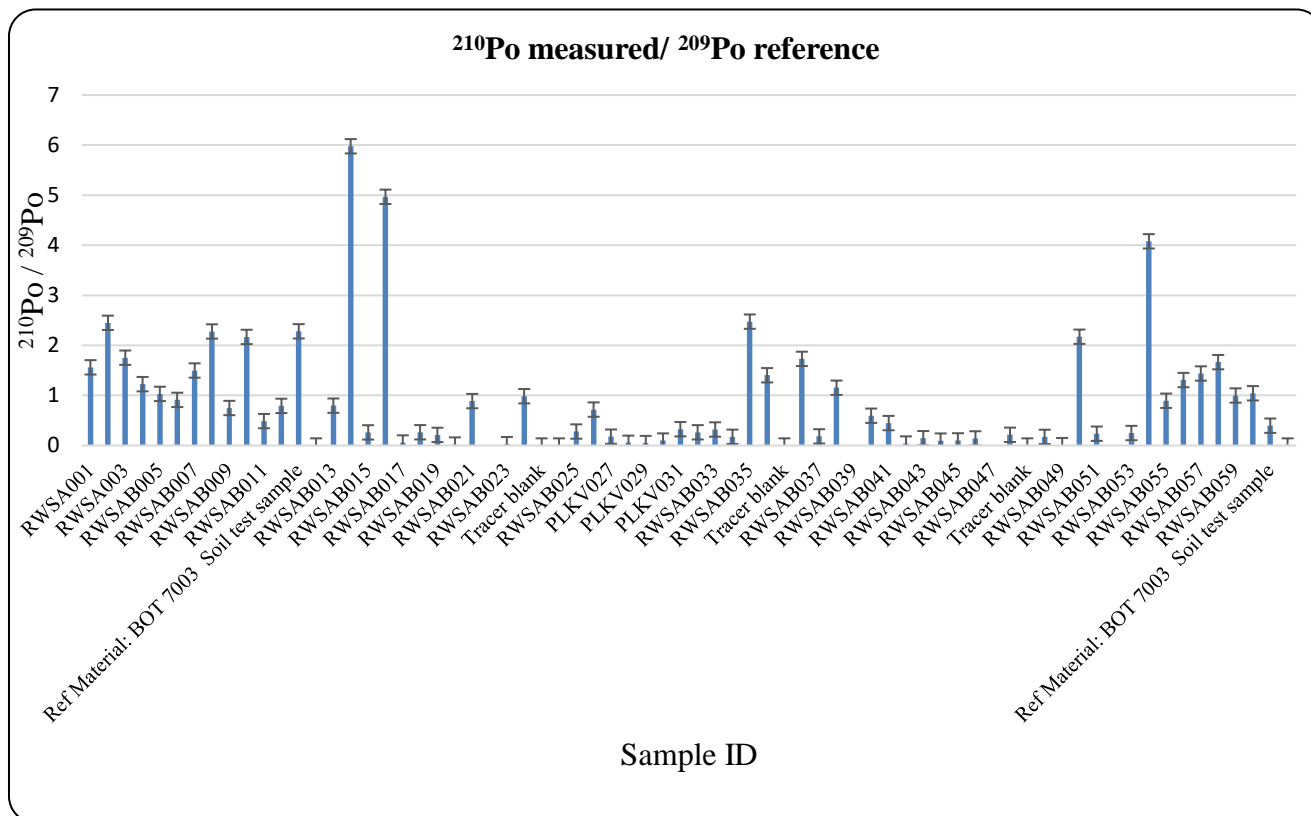


Figure 4.7: The ^{210}Po measured/ ^{209}Po reference (tracer) ratios for soils from the study area.

4.4 RESRAD (RESidual RADioactivity) radiological risk assessment

The RESidual RADioactivity (RESRAD) model and computer code is a software that was developed as a multifunctional tool to assist in developing cleanup criteria and assessing the dose or risk associated with residual radioactive material. In this study RESRAD was used to: compute potential annual doses or lifetime risks to workers or members of the public resulting from exposures to residual radioactive material and compute concentrations of radionuclides in various media (air, surface water, and groundwater) resulting from residual activity in soil.

4.4.1 Radionuclide's intake and cancer risk

The radiometric risk assessment of naturally occurring radioactive materials in the proposed radioactive waste storage area of Pilikwe, Botswana using RESRAD software was determined by inputting the average activity concentrations of the gamma, alpha and inductively coupled plasma spectrometry's radionuclides results into the RESRAD software for simulation. The RESRAD was

utilised to generate the quantity of intake QINT (i,p,t) of specific radionuclides (i) and pathways (p); Excess cancer risks CNRS (i,p,t) of specific radionuclides (i) and pathways (p) and fraction of total risk at time (t) in years and the total excess cancer risk CNRS(i,p,t) of the originally existent radionuclides (i) and pathways (p) and fraction of total risk at time (t). The amount of radionuclides intake, excess cancer risk and the total cancer risk was analysed for a period of 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years.

4.4.1.1 Radionuclides intake from gamma spectrometry obtained activity concentrations

The amount of radionuclides intake was of the average activity concentrations obtained by the use of the gamma spectrometry for the period of 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years. The intake rates were calculated by the RESRAD code and generated after each execution. They were listed by radionuclide and pathway corresponding to specific times. Intake rates for inhalation and ingestion pathways were calculated first for all of the principal radionuclides and then multiplied by the risk coefficients to estimate cancer risks. The inhalation and soil ingestion pathways intake rates (Bq/yr. or pCi/yr.) were calculated using the following equation:

$$(\text{Intake})_{j,p}(t) = \sum_{i=1}^M (\text{ETF}_{j,p}(t) \times \text{SF}_{ij}(t) \times S_i(0) \times \text{BRF}_{i,jb_n}) \quad (4.1)$$

whereby; $(\text{Intake})_{j,p}(t)$ = intake rate of radionuclide j at time t (Bq/yr. or pCi/yr.)

M = the number of initially existent radionuclides,

$\text{ETF}_{j,p}(t)$ = environmental transport factor for radionuclide j at time t (g/yr.),

p = primary index of pathway,

$\text{SF}_{ij}(t)$ = source factor,

i, j = index of radionuclide (i for the initially existent radionuclide and j for the radionuclides in the decay chain of radionuclide i),

$S_i(0)$ = initial soil concentration of radionuclide i at time 0, and

BRF_{ij} = a branching factor that is the fraction of the total decay of radionuclide i that results in the ingrowth of radionuclide j (RESRAD 2001).

The acquired radionuclide intake results from the RESRAD software using equation 4.1 are presented in APPENDIX E, Table E.1 to Table E.16 in more details. Figure 4.8 shows intake quantities of specific radionuclides and pathways as Bq/yr. for different years interval.

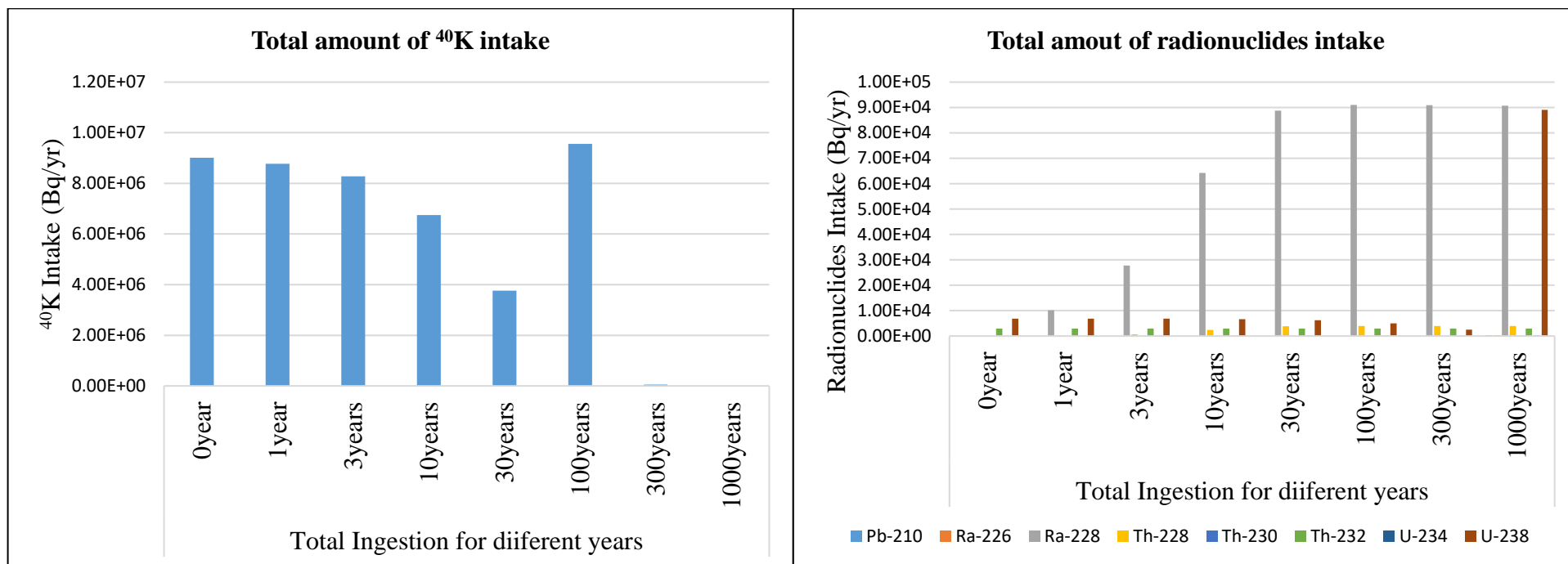


Figure 4.8: Intake quantities of specific radionuclides and pathways as Bq/yr. for different years interval.

The amount of the radionuclides of interest from the gamma spectrometry results varies from the initial to the last years (0 to 1000) of the RESRAD result analysis, for the ^{40}K there is a decrease in the amount of intake from the initial amount until 30 years, then an increase after 100 years more than the initial amount and decrease at 300 years and at 100 years there is no more intake of ^{40}K radionuclide from the samples for both the pathways (water independent pathways (inhalation without radon) and water dependent pathways). For ^{228}Ra there is a steady increase in its uptake from the initial amount up to 30 years and from there it remains constant until 100 years. The amount of ^{238}U total ingestion shows a decrease in its intake up to 300 years and an increase after 1000 years, as for the other radionuclides such as ^{230}Th , ^{232}Th , ^{210}Pb and ^{226}Ra there total ingestion rate remained relatively low from the initial year (0 year) to the final year (1000 years) of analysis.

4.4.1.2 Total excess cancer risk for activity concentration obtained using gamma spectrometry

The total excess cancer risk CNRS (i, p, t) for initially existent radionuclides (i) and pathways (p) and fraction of total risk at 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years respectively, based on the average activity concentrations obtained by the use of the gamma spectrometry for the water independent pathways (inhalation excludes radon) and water dependent pathways. The water pathway factors being components of the environmental transport factors for the water dependent ingestion pathways. Water-dependent ingestion pathway is divided into two segments: (1) a water pathway segment that extends from the contaminated zone to a point where transport through the food chain begins (a well or surface water body) and (2) a food chain pathway segment that extends from the point of entry of a radionuclide from water into the food chain to a point of human exposure (RESRAD 2001).

In this study, the transport through the water pathway segment was characterized by a water/soil concentration ratio, which is defined as the ratio of the concentration of the principal radionuclide (either parent or progeny) in water used for drinking, irrigation, or livestock water to the initial parent radionuclide concentration in the contaminated zone (RESRAD 2001). Transport through the food chain pathway segment is characterized by a water exposure factor, which is defined as the ratio of the quantity of a radionuclide ingested annually to the concentration in water used for drinking, irrigation, or livestock water (RESRAD 2001). The environmental transport factor for the water-dependent ingestion pathway is expressed as a product of a water exposure factor and a water/soil concentration ratio:

$$\text{ETF}_{ij, pqr}(t) = \text{WEF}_{ij, pqr}(t) \times \text{WSR}_{ij, r}(t) \quad (4.2)$$

whereby;

$ETF_{ij,pqr}(t) = E_{ij,pqr}(t)/S_i(0)$ is environmental transport factor at time t for the j th principal radionuclide transported through the pqr th ingestion pathway (g/yr.). $E_{ij,pqr}(t)$ is the rate of ingestion (Bq/yr. or pCi/yr.) at time t of the j th principal radionuclide transported through the pqr th pathway from the contaminated zone to a point of human exposure, and $S_i(0)$ is the initial concentration (Bq/g or pCi/g) of the i th principal radionuclide in the contaminated zone (RESRAD 2001);

ij = subscript index of a variable whose quantity is assigned to the principal radionuclide j as the result of the decay of the principal radionuclide i , which initially exists in the contaminated zone (RESRAD 2001).

p, q, r = pathway indices. The indices p and q identify the food chain segment of the pathway and the index r identifies the water pathway segment, that is, the segment from the contaminated zone to well water ($r = 1$) or surface water ($r = 2$) (RESRAD 2001).

$WEF_{ij,pqr}(t) = E_{ij,pqr}(t)/W_{ij,r}(t)$ = water exposure factor at time t for the j th principal radionuclide transported through the pqr th pathway from the point of water use to the point of exposure (L/yr). $E_{ij,pqr}(t)$ is the rate of ingestion (Bq/yr or pCi/yr) at time t of the j th principal radionuclide transported through the pqr th pathway, and $W_{ij,r}(t)$ is the concentration in water (Bq/L or pCi/L) at time t of the j th principal radionuclide transported through the r th water pathway segment at the point of entry into the pq th food chain (RESRAD 2001).

$WSR_{ij,r}(t) = W_{ij,r}(t)/S_i(0)$ = water/soil concentration ratio at time t for the r th water pathway segment (g/L). $W_{ij,r}(t)$ is the concentration in water (Bq/L or pCi/L) at time t of the j th principal radionuclide transported through the r th water pathway segment at the point of entry into a food chain pathway segment, and $S_i(0)$ is the average concentration (Bq/g or pCi/g) at time 0 of the i th principal radionuclide in the contaminated zone (RESRAD 2001). The RESRAD obtained results analysis for the total cancer risk are presented in APPENDIX F, Table F.1 to Table F.16.

The total excess cancer risk CNRS (i, p, t) for initially existent radionuclides (i) and pathways (p) and fraction of total risk at time (t) years for water dependent pathways and water independent pathways (inhalation excludes radon) from APPENDIX F, Table F.1 to Table F.16 shows that the total cancer fraction and risk are very low. The cancer risk remains constant from the initial year up to 30 years and from there slightly decreases at 100 years and then remains constant again up to 1000 years as evidenced by Figure 4.9A and Figure 4.10A.

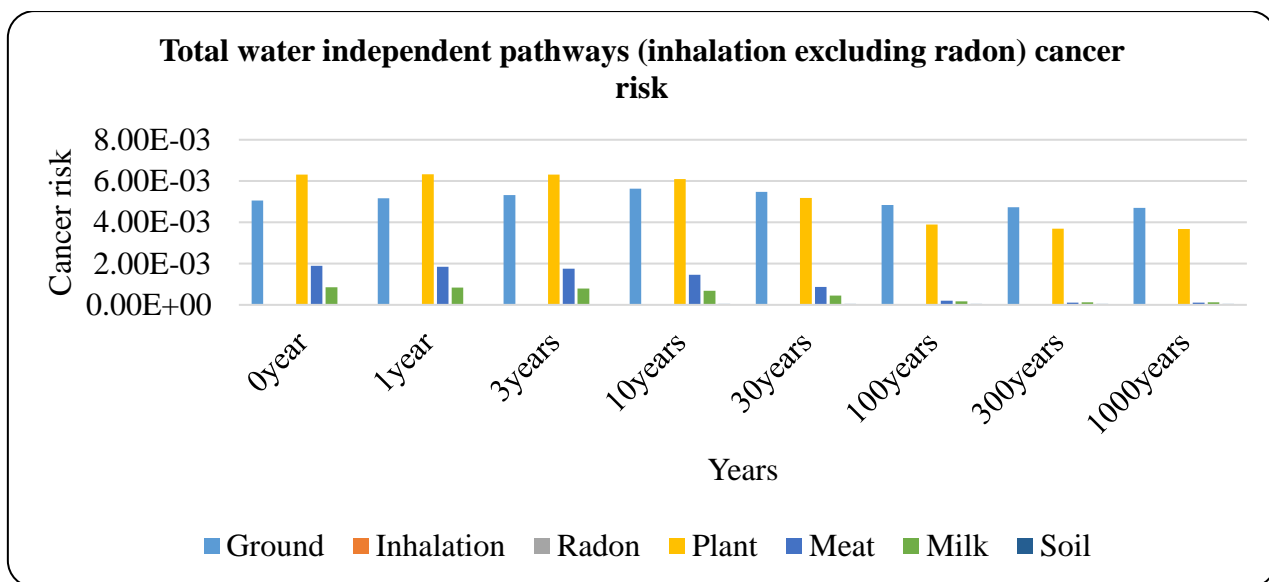


Figure 4.9A: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways of total risk at time (t) years for water independent pathways (inhalation excludes radon).

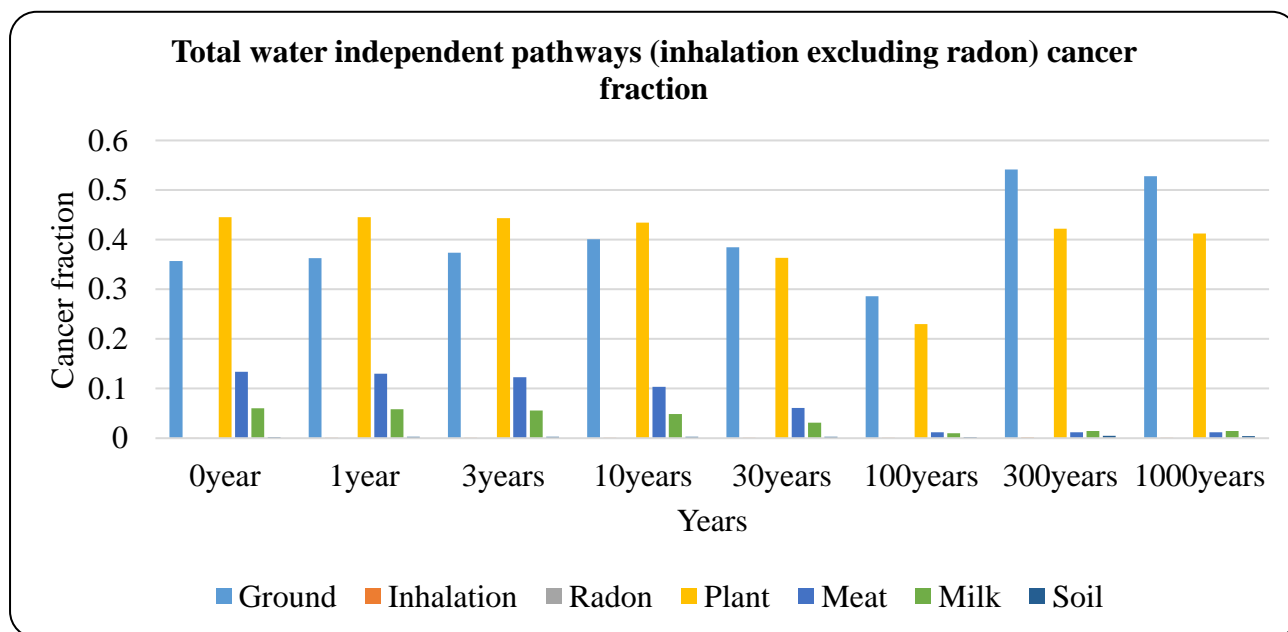


Figure 4.9B: The total cancer fraction for originally existent radionuclides and pathways at time (t) years for water independent pathways.

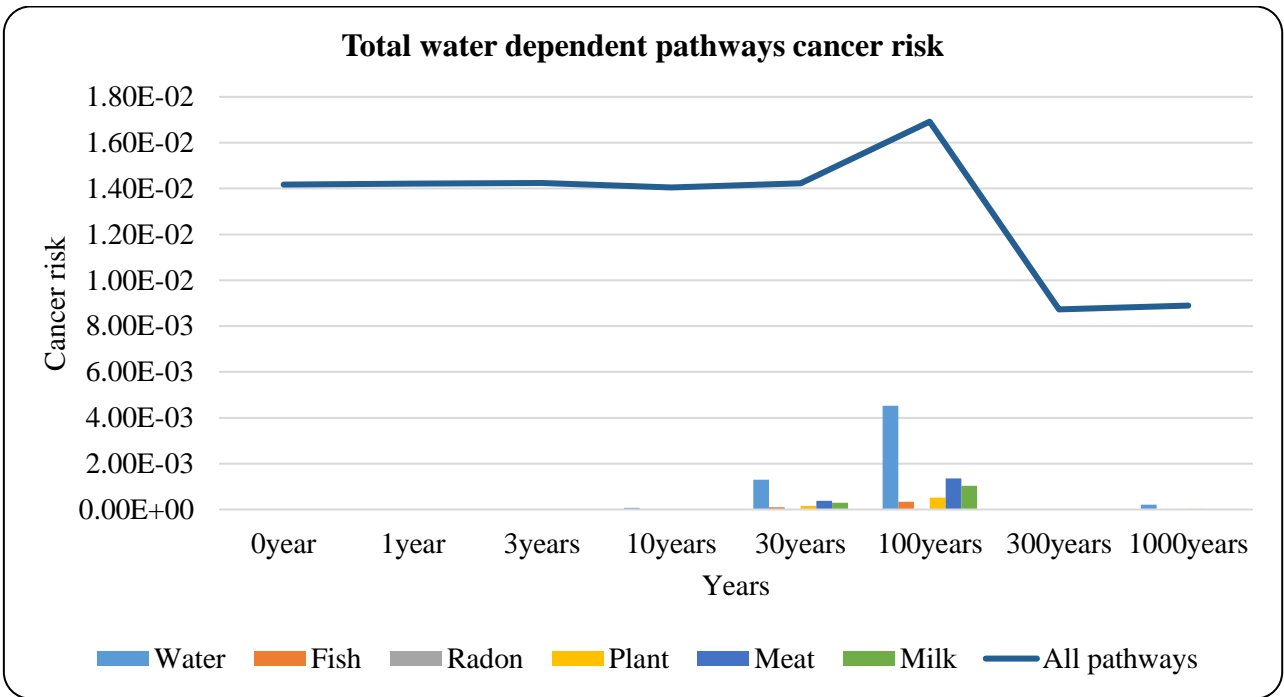


Figure 4.10A: Activity total excess cancer risk from originally existent radionuclides and pathways at time (t) years for water dependent pathways (inhalation excludes radon).

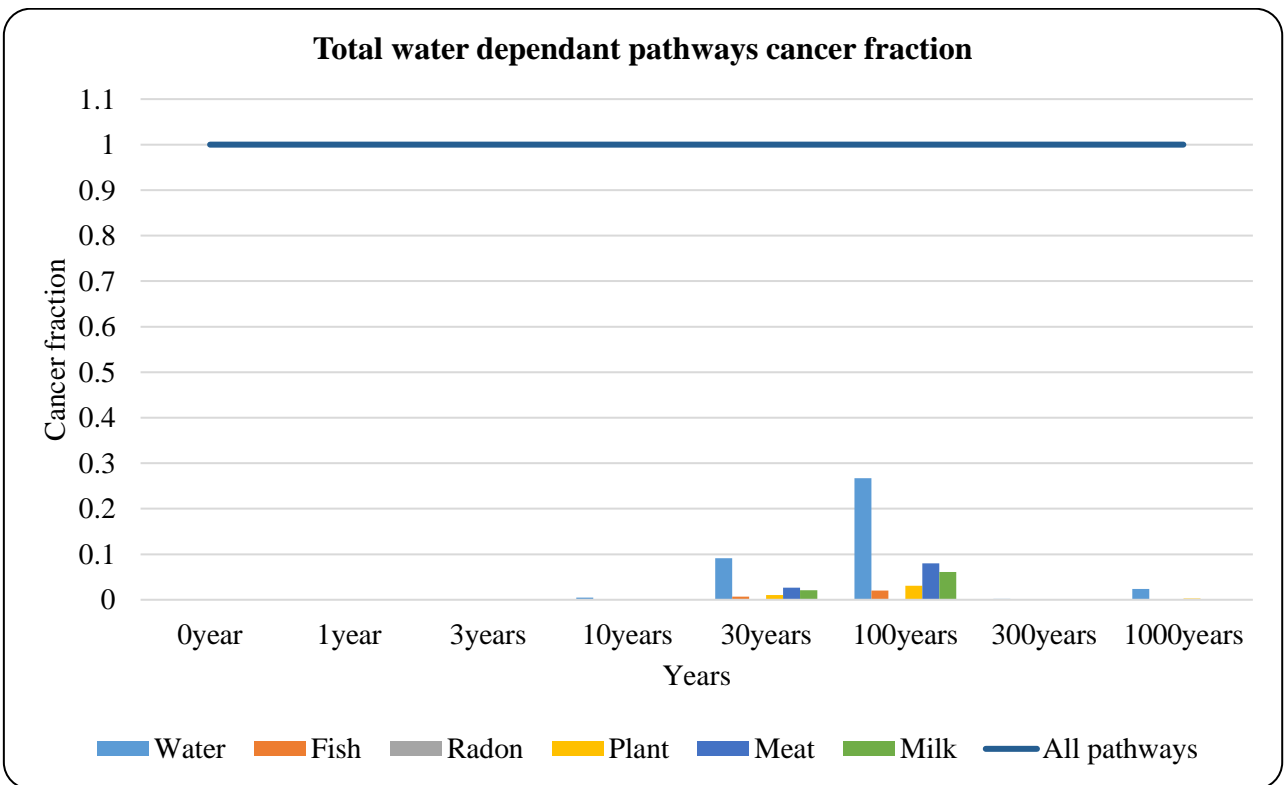


Figure 4.10B: The total cancer fraction from originally existent radionuclides and pathways at time (t) years for water dependent pathways (inhalation excludes radon).

4.4.1.3 Radionuclides intake from ICP-Ms obtained activity concentrations

The amount of radionuclides intake based on the average activity concentrations obtained by the use of the inductively coupled plasma mass spectrometry for the period of 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years. The intake rates were calculated by the RESRAD code and generated after each execution. They were listed by radionuclide and pathway corresponding to specific times as shown in Figure 4.11 and Figure 4.12. Intake rates for inhalation and ingestion pathways were calculated first for all of the principal radionuclides and then multiplied by the risk coefficients to estimate cancer risks. The inhalation and soil ingestion pathways intake rates (Bq/yr. or pCi/yr.) were calculated using Equation 4.1 and the analysis is shown in APPENDIX G, Table G.1 to Table G.16.

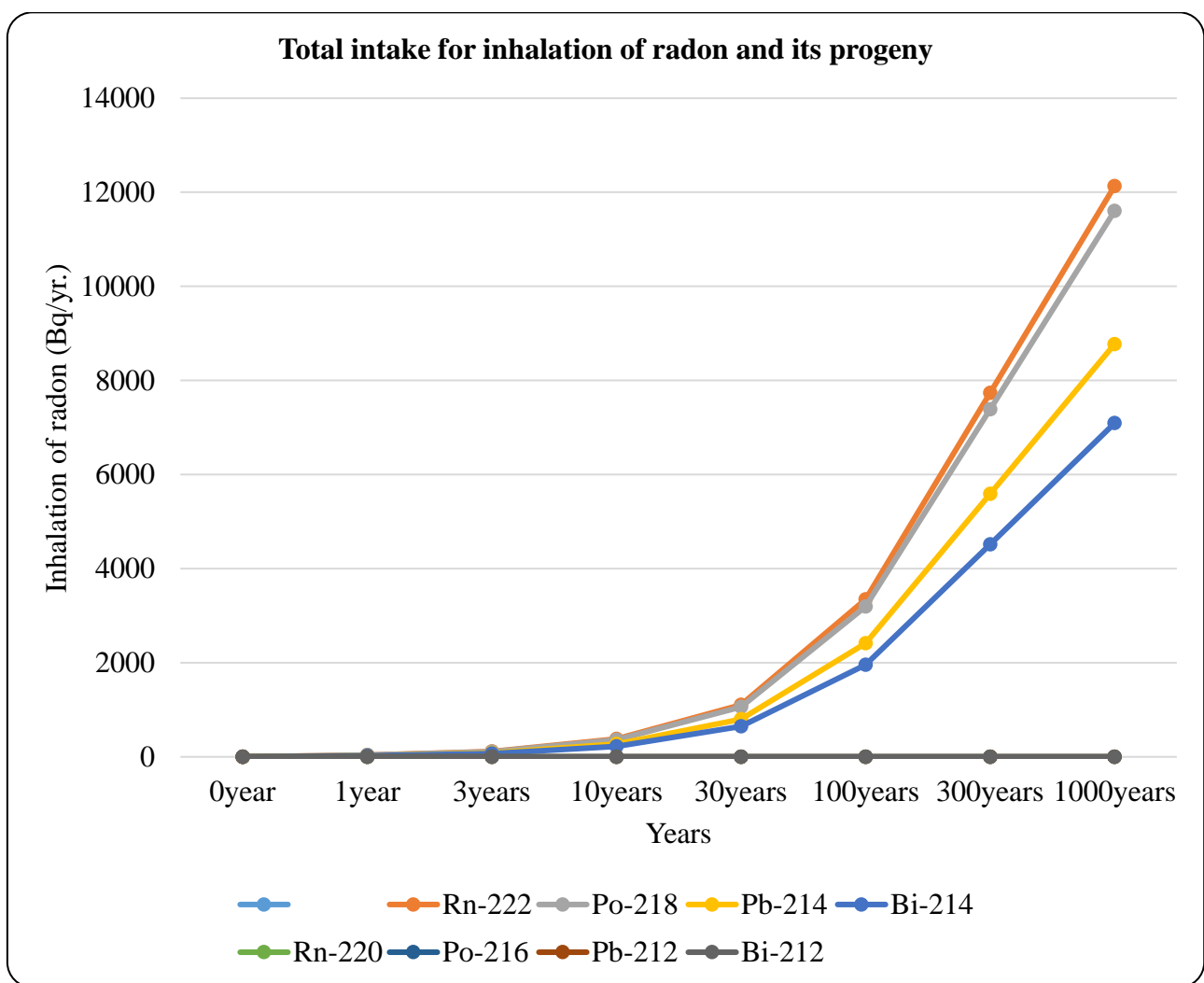


Figure 4.11: Amount of intake quantities for inhalation of radon and its decay products as Bq/yr. at (t) in years.

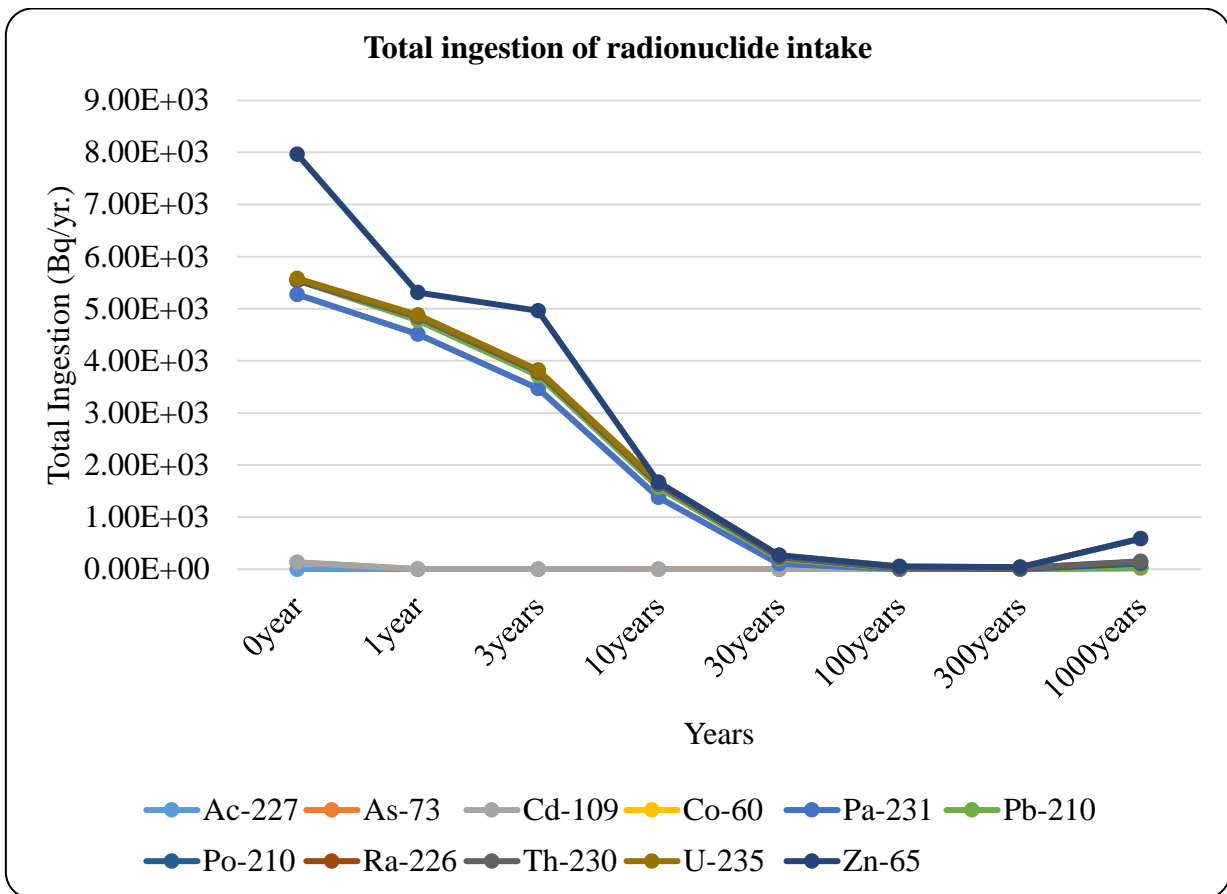


Figure 4.12: Amount of intake quantities for specific radionuclides and pathways as Bq/yr. at t in years for both water independent pathways (inhalation without radon) and water dependent pathways.

4.4.1.4 Total excess cancer risk for activity concentration obtained using ICP-MS

The total excess cancer risk CNRS (i, p, t) for initially existent radionuclides (i) and pathways (p) and fraction of total risk at 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years, based on the average activity concentrations obtained by the use of the inductively coupled plasma mass spectrometry for the water independent pathways (inhalation excludes radon) and water dependent pathways.

The total excess cancer risk CNRS (i, p, t) for initially existent radionuclides (i) and pathways (p) and fraction of total risk at time (t) years for water dependent pathways and water independent pathways (inhalation excludes radon) from APPENDIX G, Table G.1 to table G.16 show that the total cancer fraction and risk are very low. The total excess cancer risk decreases from the initial year up to 100 years and from there slightly increases up to 1000 years as shown in Figure 4.14B, whereas for radon gas and its daughters the cancer risk is very low and constant up to 3 years and after 10 years there is a slightly increase up to 1000 years shown in Figure 4.13, even though there is an increase in cancer risk due to radon and its progenies as years pass by the risk is still very low and negligible to have the potential to cause any harm.

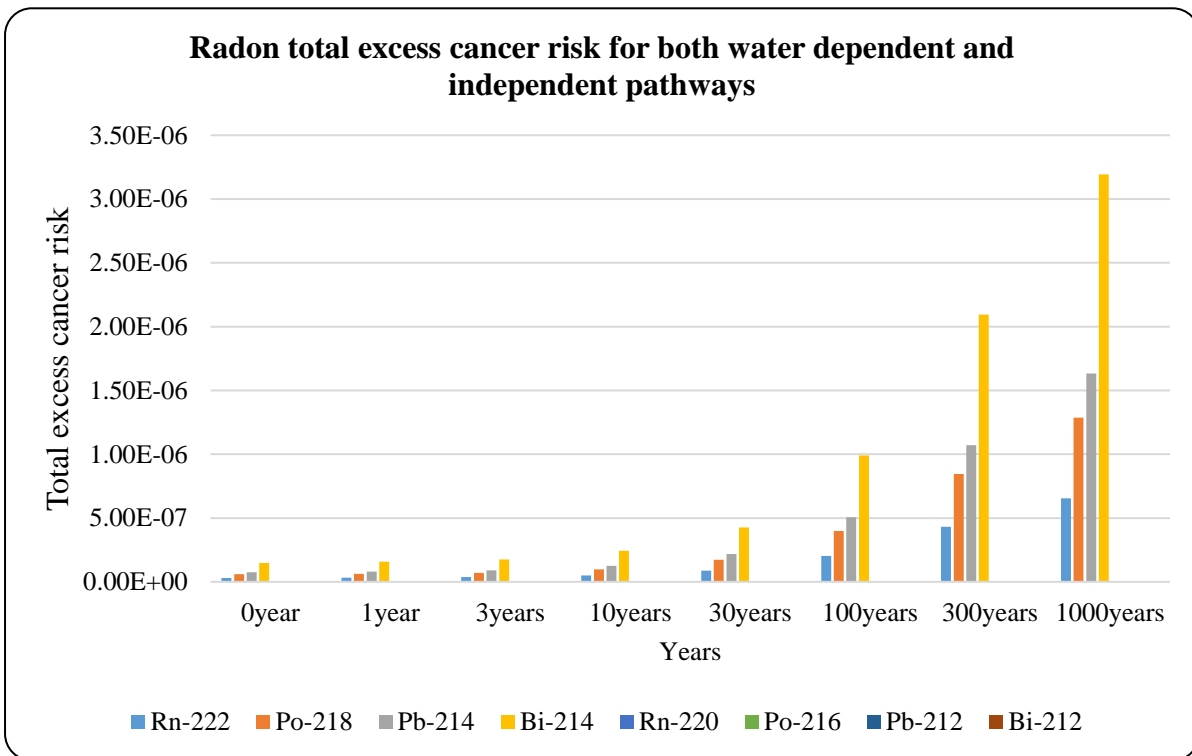


Figure 4.13: Activity concentrations total excess cancer risks for inhalation of radon and its decay products at different years.

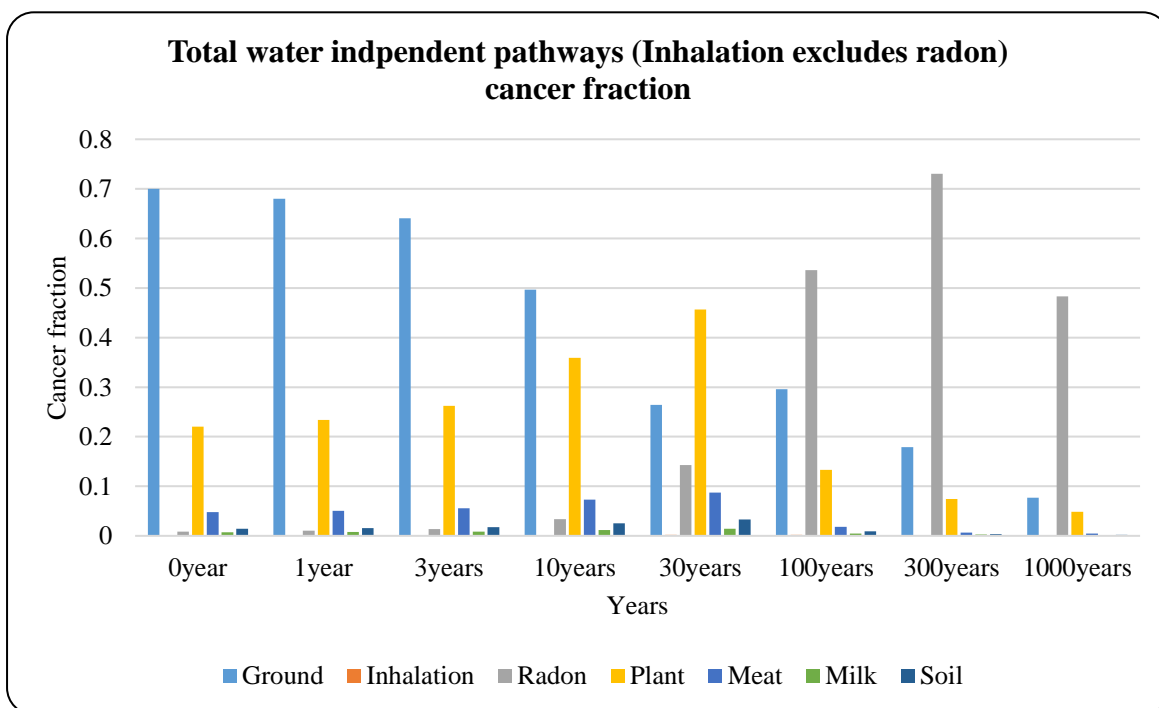


Figure 4.14A: Total cancer fraction for originally existent radionuclides and pathways at time (t) in years for water independent pathways.

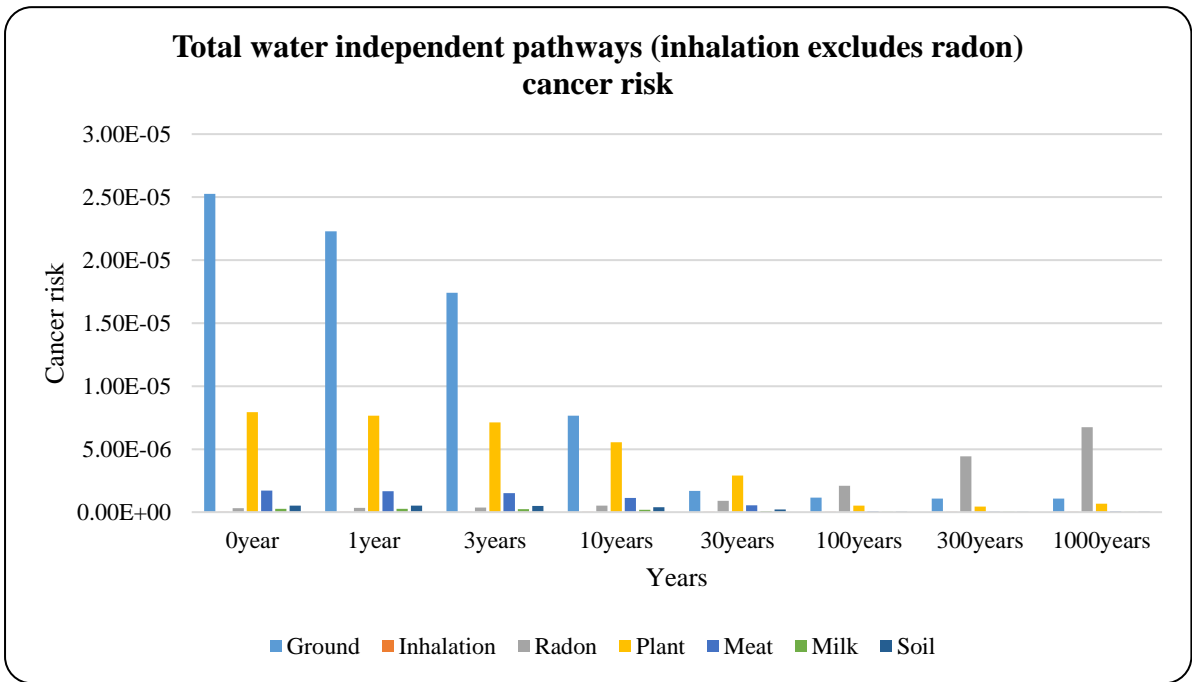


Figure 4.14B: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways at time (t) in years for water independent pathways.

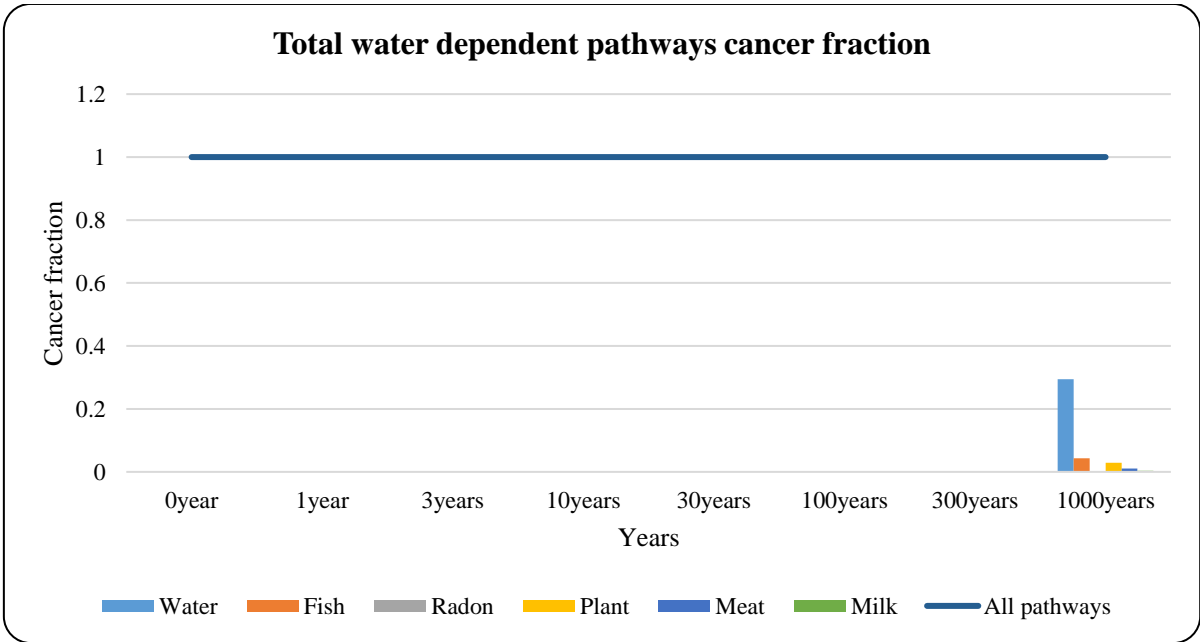


Figure 4.15A: Total cancer fraction for originally existent radionuclides and pathways at time (t) in years for water dependent pathways (inhalation excludes radon).

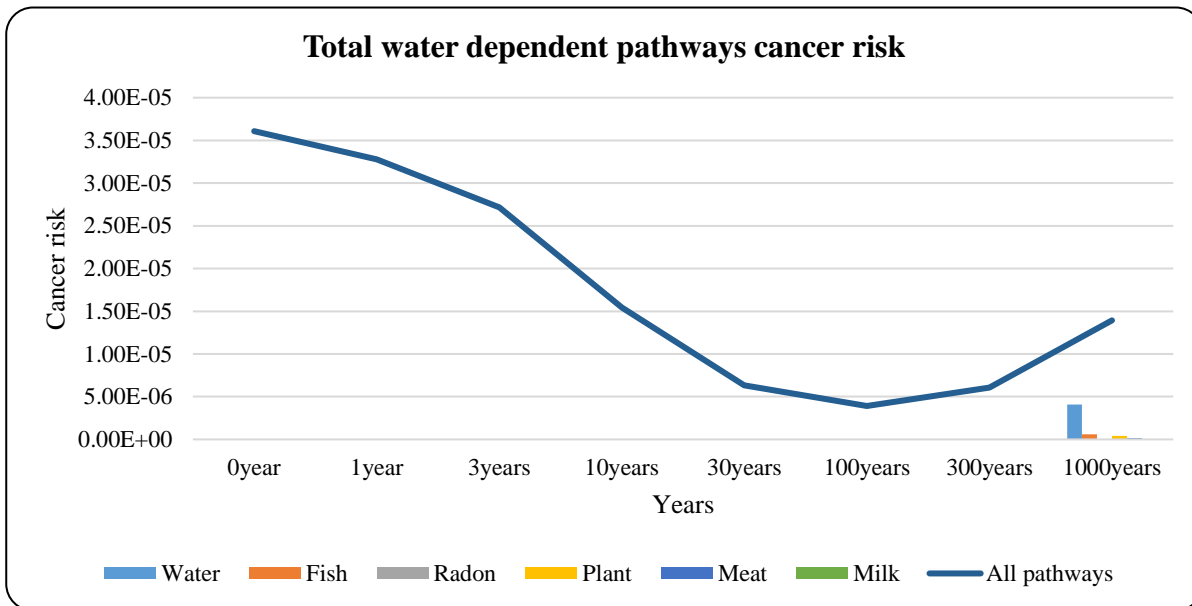


Figure 4.15B: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways at time (t) in years for water dependent pathways (inhalation excludes radon).

The total water dependent pathways cancer fraction Figure 4.15A shows that for all the pathways the fraction remains at one from the 0 year up to 1000 years, with water, fish, radon, plant, meat and milk pathways cancer fraction being below 0.1 from the 0 year up to 1000 years, with an exemption of water at the 1000 years. For the cancer risk shown in Figure 4.15B all pathways cancer risk decreases with time from 3.60E-05 to 4.00E-06 at 100 years and then increases to 1.40E-05 at 1000 years, whereas for water, fish, radon, plant, meat and milk pathways cancer risk is below 4.1E-06 for all the years (0 year to 1000 years) thus the cancer risk from the consumption of the NORMs can be of negligible impact.

4.4.1.5 Radionuclides intake from alpha spectrometry obtained activity concentrations

The amount of radionuclides intake based on the average activity concentrations obtained by the use of the Canberra alpha analyst system spectrometry using Apex-Alpha; alpha spectrometry software suite 1.1 for the period of 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years. The intake rates were calculated by the RESRAD code and generated after each execution. They were listed by radionuclide and pathway corresponding to specific times. Intake rates for inhalation and ingestion pathways were calculated first for all of the principal radionuclides and then multiplied by the risk coefficients to estimate cancer risks. The inhalation and soil ingestion pathways intake rates (Bq/yr. or pCi/yr.) were calculated using Equation 4.1 and the analysis are presented on Figure 4.16 and APPENDIX I Table I.1 to Table I.8.

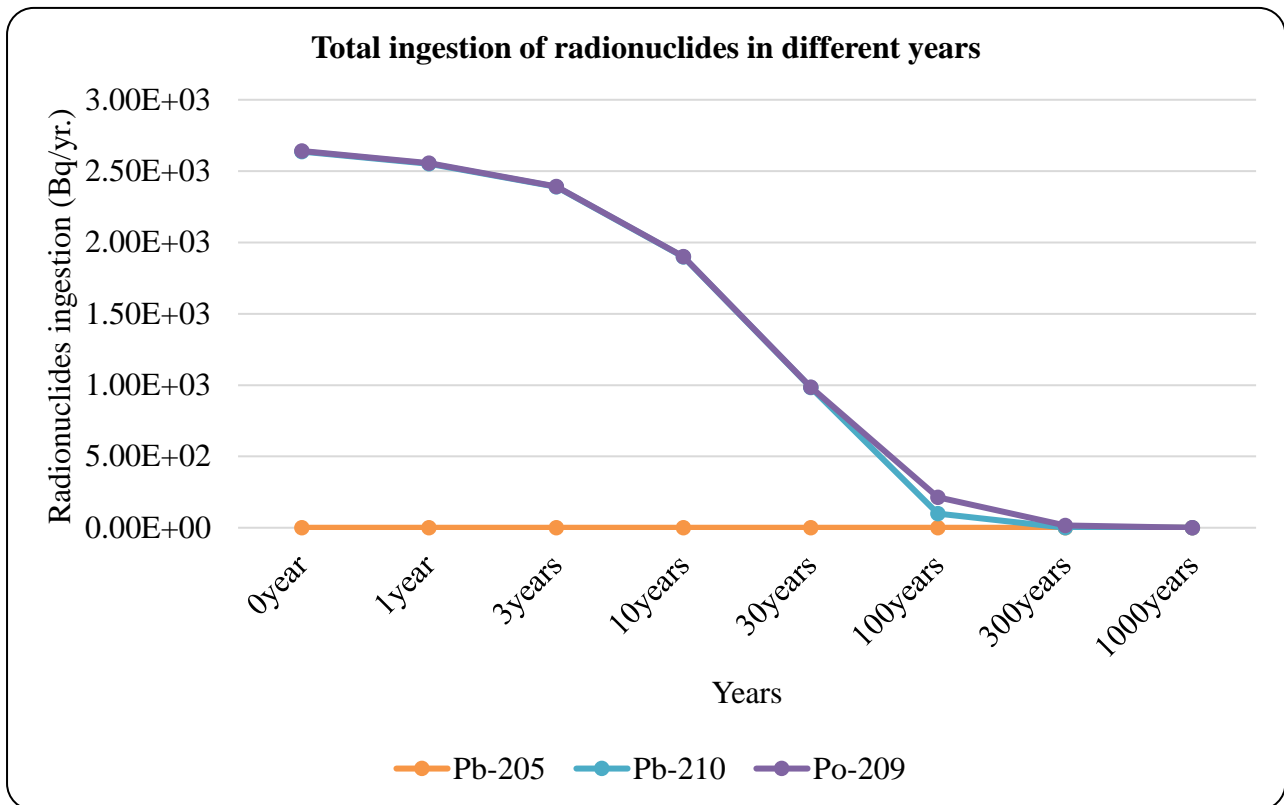


Figure 4.16: Total amount of intake quantities for specific radionuclides and pathways as Bq/yr. at time (t) in different years.

The amount of radionuclides intake quantities in Figure 4.16 shows that the intake decreases with time as years increases from the initial amount of 2637 Bq/yr. for Pb-210 and 4.083 Bq/yr. for Po-209 and remains constant at zero for Pb-205. The total ingestion of radionuclides for the alpha spectrometry results are relatively very low for all the pathways thus considered to be cancer risk free.

4.4.1.6 Total excess cancer risk for activity concentration obtained using alpha spectrometry

The total excess cancer risk CNRS (i, p, t) for initially existent radionuclides (i) and pathways (p) and fraction of total risk at 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years, based on the average activity concentrations obtained by the use of the Canberra alpha analyst system spectrometry using Apex-Alpha; alpha spectrometry software suite 1.1 for the water independent pathways (inhalation excludes radon) and water dependent pathways.

The total excess cancer risk CNRS (i, p, t) for initially existent radionuclides (i) and pathways (p) and fraction of total risk at time (t) years for water dependent pathways and water independent pathways (inhalation excludes radon) from APPENDIX J, table J.1 to table J.16 shows that the total cancer fraction and risk are very low and negligible to have the potential to cause any harm with respect from the initial (0 year) to the final (1000 years) year of interest from the study.

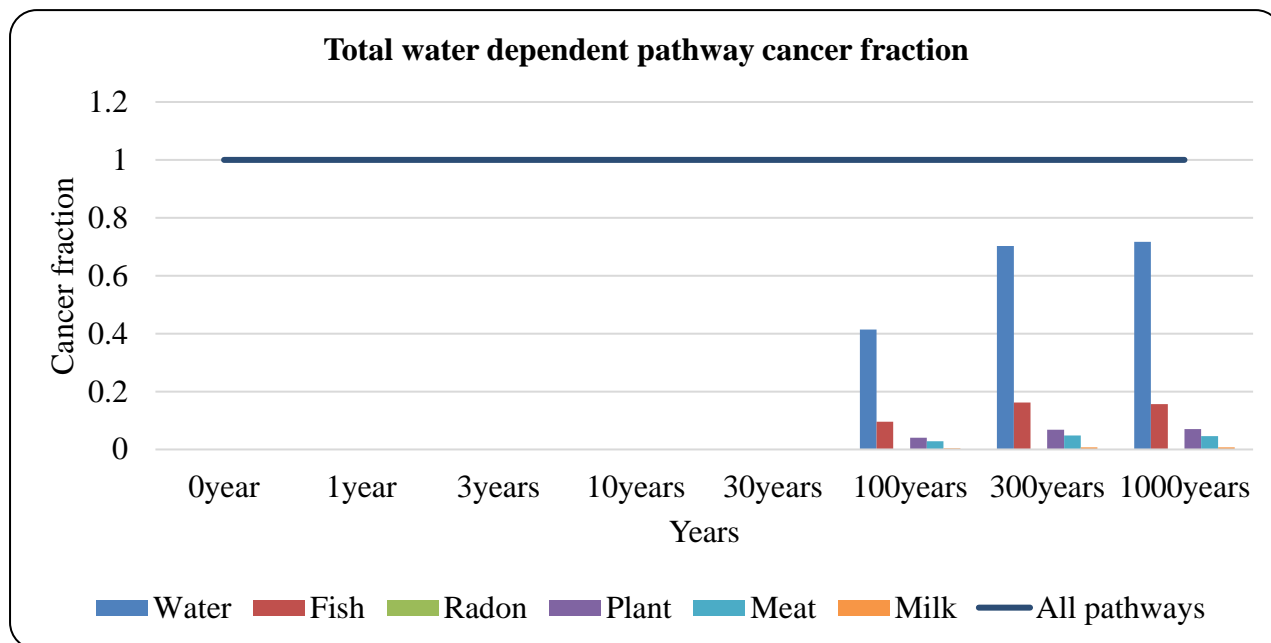


Figure 4.17A: Total cancer fraction for originally existent radionuclides and pathways at time (t) in years for water dependent pathways (inhalation excludes radon).

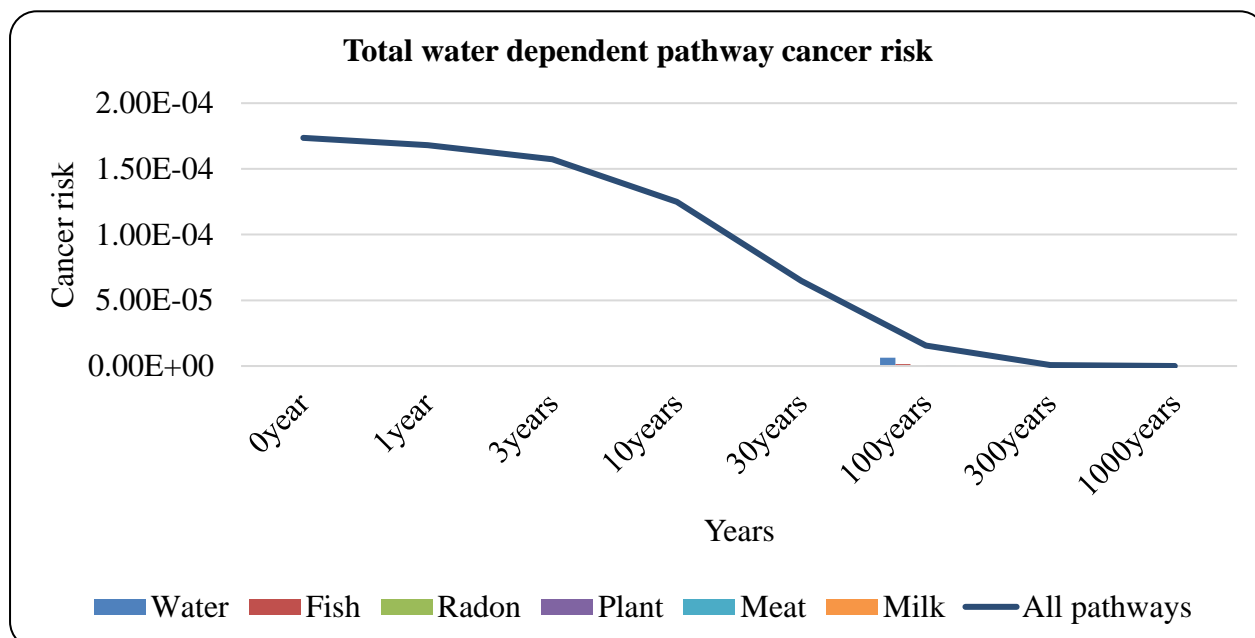


Figure 4.17B: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways at time (t) in years for water dependent pathways (inhalation excludes radon).

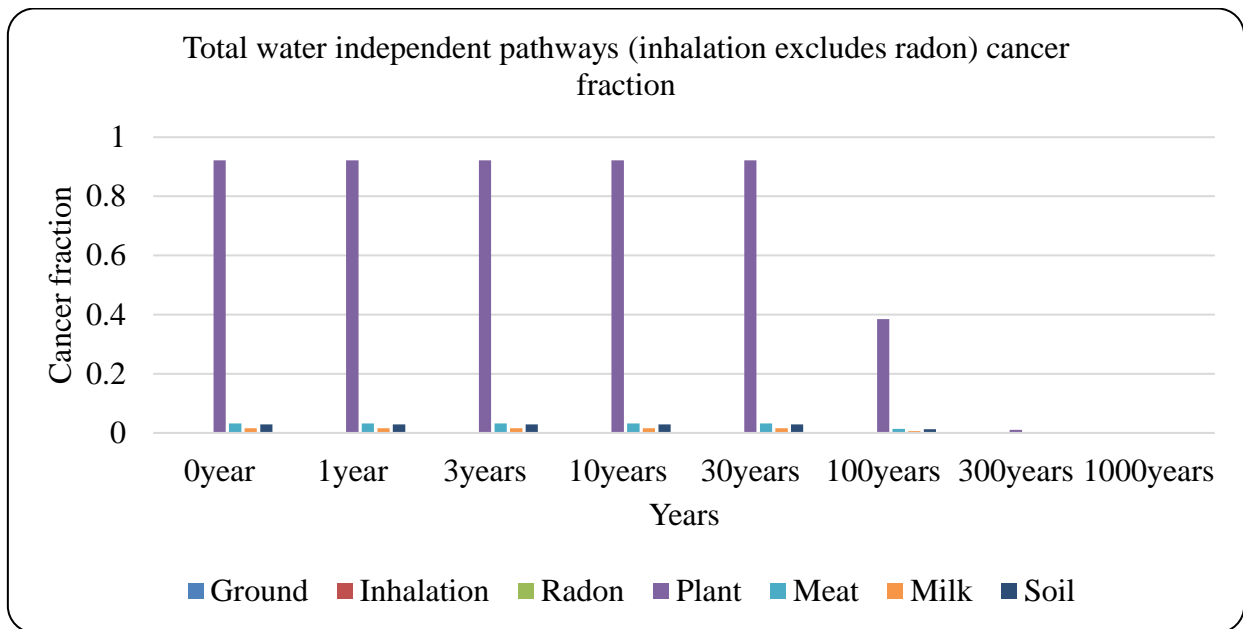


Figure 4.18A: Total cancer fraction for originally existent radionuclides and pathways at time (t) in years for water independent pathways.

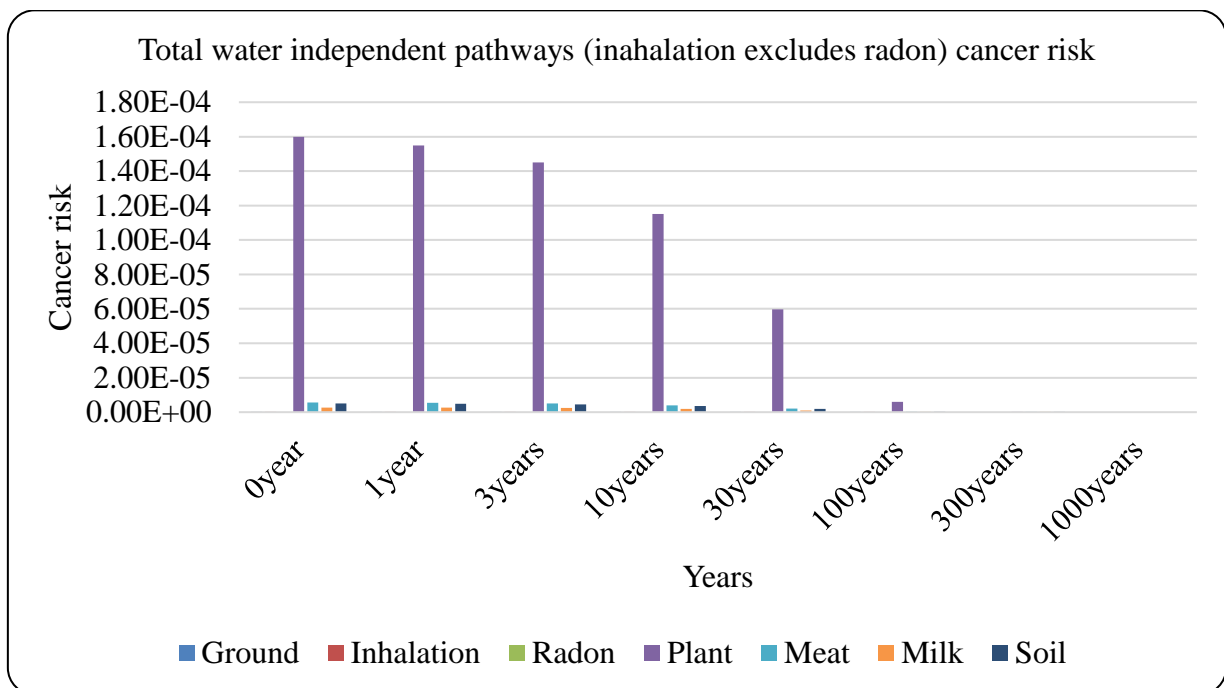


Figure 4.18B: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways at time (t) in years for water independent pathways.

The cancer risk results from both the water dependent and independent pathways show that the risk decreases with time from the initial year (0 year) as shown in Figures 4.17B and 4.18B, whereas cancer fraction remains constant or decrease with time from the initial to 1000 years as in Figures 4.17A and 4.18A. The values are less than 1, which indicate that there is no health risk to the residents of the study area.

CHAPTER 5: DISCUSSIONS

The results obtained from the study area using three radiometric technique (high-resolution gamma-ray spectrometry, inductively coupled plasma mass spectrometer and alpha spectroscopy) to determine the activity concentrations of NORMs in the soil and water samples were analyzed, compared and assessed for radiological risk posed for the proposed construction of a radioactive waste storage facility to the environment and residents of Pilikwe, central Botswana as a baseline study before the construction of the storage facility commences.

Concentration levels of ^{238}U , ^{232}Th chains and ^{40}K were determined from two different boreholes drinking water samples collected and 60 soil samples within the proposed area for construction of the storage facility and at various locations in Pilikwe village surrounding the proposed storage facility site to evaluate annual effective dose due to the ingestion of the drinking water samples. The high-resolution gamma-ray spectrometry's attained activity concentration results for the soil samples showed that the maximum value for ^{226}Ra was 36.31 Bq/kg, minimum value was 6.66 Bq/kg and an average value of 15.85 Bq/kg; maximum value for ^{238}U was 53.47 Bq/kg, minimum value was 7.75 Bq/kg and an average value of 25.55 Bq/kg; maximum value for ^{234}Th was 46.78 Bq/kg, minimum value was 11.58 Bq/kg and an average value of 24.98 Bq/kg and the max value for ^{40}K was 468.60 Bq/kg, minimum value was 59.15 Bq/kg and an average value of 201.30 Bq/kg for the study area before any construction work of the radioactive waste storage facility was conducted. The activity concentrations of ^{226}Ra , ^{238}U , ^{232}Th chains and ^{40}K natural radionuclides in the drinking water samples were lower than the minimum detectable activity limit of the instrument and were not reported for this technique in this study.

The average estimated absorbed dose rate (D) for soil samples was 35.29 ± 2.26 nGy/h, which was lower than the worldwide absorbed dose rate of 57.00 nGy/h for soil. The average estimated annual effective dose equivalent (AEDE) from soil samples was 43.28 ± 2.77 $\mu\text{Sv/y}$, which was lower than the recommended worldwide value of 70.00 $\mu\text{Sv/y}$ for soils. The radium equivalent activity (Ra_{eq}) for soil was 76.78 ± 5.05 Bq/kg. The external hazard index (H_{ext}) for soil was 0.21 ± 0.01 . The mean Ra_{eq} values for soil, were all below the worldwide accepted value of 370.00 Bq/kg. The average H_{ext} value for soil, was found to be below the worldwide recommended value of one. All the hazard indices show that the samples from Pilikwe village area and surrounding have acceptable indices with no hazard. Thus, a radioactive storage facility can be built in the identified location provided there is proper management and safeguarding the leaching of the stored radioactive waste into the soil, as well as having measures in place for monitoring and inspecting the NORM concentrations activities of the area on specified time frames.

The elemental concentrations of NORM in the proposed waste storage facility site and its surrounding were determined by the use ICP-MS total quantitative run of the borehole water and soil samples respectfully. The results obtained for elemental concentrations of NORM in the samples were lower than the WHO permissible limit for all selected nuclides indicating safe water drinking for the residents of Pilikwe as indicated in Table 4.3, and also for the soil samples elemental concentrations of the nuclides were found to be lower than the maximum acceptable worldwide limit when the nuclides in the study area results were compared with those of other countries as shown in Table 4.5. The average concentrations of these nuclides suggest that the soil of this area is not polluted with heavy metals and its NORMs concentrations are very low as expected thus making it a suitable place for construction of a radioactive waste storage facility.

Extensive studies carried out over the years using alpha spectrometry provided alternative choices to this research for radiochemical analysis and determination of polonium in the water and soil samples. Polonium is considered to be poisonous thus if inhaled and deposited in the lung tissues will contribute to an increase in the internal radiation dose and in the number of lung cancer incidences observed among the resident of the area for the proposed radioactive waste storage. The concentration levels result for ^{210}Po obtained in this study indicated that the activity concentrations of ^{210}Po ranged from 0.50 ± 0.01 Bq/kg to 27.52 ± 1.84 Bq/kg and with an average of 3.10 ± 1.60 Bq/kg. The activity concentration levels of ^{210}Po in the proposed radioactive storage facility site and the village of Pilikwe was found to be below the available reported and accepted activity concentration levels of ^{210}Po in various soils that have been reported ranging from 20 to 40 Bq/kg (Sethy et al. 2015). The polonium was non-uniformly distributed within the samples thus the data obtained was indicating that it was generally from the dry or wet deposition of the radioactive fall-out into the soil.

The radiological risk assessment by the RESidual RADioactivity (RESRAD) model and computer code software for the analysis and modelling of cancer risk to the community residing in the study area was conducted by assessing the radionuclides activity concentrations results from all the three techniques. The cancer risk for people living in the study area, as a result of NORMs in soil and water, was evaluated using the average concentrations of nuclides found in the samples to calculate the average intakes from 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years for determination of cancer risk associated with the ingestion of the radionuclides. From all the three techniques used in this study, the results obtained were very much lower than the acceptable worldwide value of one as shown in Figures 4.9A, 4.10A, 4.13, 4.14B, 4.15B, 4.17B and 4.18B. These cancer risk results show that the NORMs concentrations in the Pilikwe area are safe for the community when ingested for a period from 0 year up to 1000 years without causing any health problems. However, this baseline NORMS activity concentrations need to be maintained by the radioactive waste storage operators.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of the study findings

The aim of this study was to assess the radiological risk due to NORMs in the proposed radioactive waste storage area of Pilikwe, central Botswana, using radiometrical techniques. The findings from this study showed that the aim of the study was fulfilled as rigorous measurements of NORMs activity concentrations was conducted using three radiological techniques (high-resolution gamma-ray spectrometry, inductively coupled plasma mass spectrometer and Alpha spectroscopy) and the radiological risk assessment estimation performed using the RESidual RADioactivity (RESRAD) model and computer code software. The analysis of radionuclide contents and the determination of their activity concentration obtained from the three radiometric techniques were compared and found to be significantly in comparable range.

The first objective of this research was to evaluate the activity concentrations of NORMs in the proposed waste storage facility site using gamma and alpha/beta spectroscopy techniques. The findings of NORMs activity concentrations were found to be of acceptable values as they are lower than the worldwide acceptable limits. Since there are no radioactivity projects or mining going on in the Pilikwe region, thus the natural radioactivity is undisturbed and stable. The second objective was to determine the elemental concentrations of NORMs in the proposed waste storage facility site using ICP-MS total quantitative and isotopic ratio techniques, the obtained results were below the recommended worldwide limits by WHO as on Tables 4.5, 4.6 and 4.7.

The third objective was to apply RESidual RADioactivity (RESRAD) model and computer code software to produce a conceptual model for the radiological risk assessment for Pilikwe proposed waste storage facility of which it was a success as it was utilized to estimate the cancer risk for residents and other public members in the vicinity of the proposed radioactive waste storage. Figures 4.9A, 4.10A, 4.13, 4.14B, 4.15B, 4.17B and 4.18B. presents cancer risks for all the pathways summed over a duration of 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years. In the case of natural radionuclides ^{238}U , ^{232}Th and ^{40}K , the total excess cancer risk (from RESRAD code) for all pathways was found to be 1.42E-02, 1.42E-02, 1.42E-02, 1.41E-02, 1.42E-02, 1.69E-02, 8.73E-03 and 8.90E-03 for the 0-year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years respectfully. This total excess cancer risk values were lower than the recommended WHO limit value of 1, which shows that the NORM concentrations in Pilikwe are non- carcinogenic (USEPA 1989).

The RESidual RADioactivity (RESRAD) model and computer code software was found to be a very effective mathematical models used to estimate the radiological risks assessment through various parts of the NORM industries that account the uncertainties related to data input parameters as it was applied for the analysis of data acquired from three different techniques that were used in this study and a comparable extrapolation of total excess cancer risk model was determined for the 0 year, 1 year, 3 years, 10 years, 30 years, 100 years, 300 years and 1000 years thus satisfying the fourth objective of these study which was to determine the effectiveness of mathematical models used to estimate the radiological risks assessment through various parts of the NORMs industries that account the uncertainties related to data input parameters.

Through firmness to addressing the current scientific gaps regarding radiological risk assessment in the surrounding area of the proposed waste storage facility and impact the study will have in the community, which was the fifth objective of the study it can be boldly concluded that the existed gap regarding radiological risk assessment for Pilikwe environment is a thing of the past with data from this study being published in accredited international journals and also presented at international conferences. The final objective of these study was to provide reference data for future risk assessments in order to improve decision-making and policy formulation, based on the acquired data and rigorous analysis done, this study data can be used as a baseline for future investigations and providing the government of Botswana an overview of the levels of radioactivity concentrations of NORMS and their non-carcinogenic and carcinogenic properties, thus an informed decision could be made regarding the construction of a radioactive waste storage facility in Pilikwe.

6.2 Conclusion and recommendations

Determination of NORMs concentrations followed by the radiological risk assessment were conducted and then characterized based on the activities of the identified nuclides for the different stages of the radioactive waste storage facility to be constructed at Pilikwe village, central district Botswana. Sixty soil and two borehole water samples were collected representing the area of construction site and its surrounding. The radioactivity measurement was performed by means of high-resolution gamma-ray spectrometry in a low background configuration at the Centre for applied radiation science and technology laboratories, North-West University. The high-resolution gamma-ray spectrometry attained activity concentration results for the soil samples showed that the maximum value for ^{226}Ra was 36.31 Bq/kg, minimum value was 6.66 Bq/kg and an average value of 15.85 Bq/kg; maximum value for ^{238}U was 53.47 Bq/kg, minimum value was 7.75 Bq/kg and an average value of 25.55 Bq/kg; maximum value for ^{234}Th was 46.78 Bq/kg, minimum value was 11.58 Bq/kg and an average value of 24.98 Bq/kg and the maximum value for ^{40}K was 468.60 Bq/kg, minimum value was 59.15 Bq/kg and an average value of 201.30 Bq/kg for the Pilikwe area before any

construction work of the radioactive waste storage facility was conducted. All the hazard indices showed that the samples from Pilikwe village area and its surrounding have acceptable indices with no hazard.

The average elemental concentrations of the heavy metals in the water samples were lower than the WHO permissible limit for all selected heavy metals indicating safe water drinking for the residents of Pilikwe as indicated in Table 4.3. The elementary concentrations from the boreholes water are extremely very low with some exceptions of some high concentrations of Mg and Ni. The soil sample concentrations of the elements were found to be lower than the maximum acceptable worldwide limit when the heavy metals in the study area results were compared with those of other countries as shown in Table 4.5. The average concentrations of these heavy metals suggest that the soil of this area is not polluted with heavy metals and its NORMs concentrations are very low.

The average activity concentration of ^{210}Po in the soil samples from the study area in Table 4.8 are way below the available reported and accepted activity concentration levels of ^{210}Po in various soils that have been reported ranging from 20 to 40 Bq/kg. The average activity of ^{210}Po was 1.50 Bq/kg and 4.60 Bq/kg for the lower and higher interval of 95% confidence level, as in Figure 4.5 which shows the total activity concentration on preparation date of the samples with respect to the confidence level. The activity concentrations on preparation date were within acceptable range of 0 to 20 Bq/kg. The minimum, maximum and average recovery of ^{210}Po from the samples using ^{209}Po tracer was 65%, 104% and 86% respectfully. This testifies that the ^{210}Po in the samples was recovered satisfactory.

The total excess cancer risk CNRS (i, p, t) for initially existent radionuclides (i) and pathways (p) and fraction of total risk at time (t) years for water dependent pathways and water independent pathways (inhalation excludes radon) analysis demonstrated that the total cancer fraction and risk were very low and negligible. Thus, had no potential to cause any harm from the initial (0 year) to the final (1000 years) year of interest from the study. Therefore, the cancer risks result from both the water dependent and independent pathways show that the risk decreased with time from the initial year (0 year) as revealed in Figures 4.9A, 4.10A, 4.13, 4.14B, 4.15B, 4.17B and 4.18B. The values were less than 1, which indicated that there was no health risk associated with NORMs to the residents of the study area.

Thus, a recommendation was made that a radioactive waste storage facility could be built in the identified location provided there will be proper management and safeguarding the leaching of the stored waste into the soil. As well as having measures in place for monitoring and inspecting the NORMs radioactivity concentrations of the area on specified time frames for assuring that there are no nonconformities.

It was also recommended that further research be conducted to include samples of field crops, pasture, livestock analysis and all other foodstuff since they are a potential ingestion exposure pathway to man. More water samples should be collected to give a more comprehensive representation of water from the study area. Future studies should consider physical and chemical environmental factors such as pH, temperature, electrical conductivity, chemical composition that can affect the mobility of radionuclides as this would result in more inclusive results.

Based on the extensive results analysis obtained from this study it was concluded that the general recommendation be for a continuous monitoring of the study area to allow future evaluations for potential changes if a radioactive waste storage facility was built in Pilikwe and in full operation.

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APPENDICES

APPENDIX A: DETAILS OF ACTIVITY CONCENTRATIONS OF SOIL SAMPLES FROM THE PROPOSED RADIOACTIVE WASTE STORAGE AREA OF PILIKWE.

Table A.1: NORMs activity concentrations of soil samples for ²³⁸U series.

Sample name	²³⁸ U			Weighted mean
	²³⁴ Th	²³⁴ Th	^{234m} Pa	
	63.28keV	92.6keV	1001keV	
RWSA001	26.60±9.68	20.27±3.84	ND	21.13±3.57
RWSA002	15.46±8.47	31.76±3.91	ND	21.13±3.55
RWSA003	19.84±8.02	21.80±3.43	ND	28.90±3.15
RWSA004	18.86±8.93	23.63±5.62	ND	21.50±4.76
RWSAB005	18.75±8.95	26.14±3.60	ND	22.28±3.34
RWSAB006	19.11±8.98	34.16±3.87	99.73±23.66	25.11±3.51
RWSAB007	21.14±9.13	16.37±3.79	ND	33.30±3.50
RWSAB008	15.62±2.03	35.95±4.26	ND	17.07±1.83
RWSAB009	10.79±6.59	17.08±3.88	ND	19.39±3.34
RWSAB010	9.99±6.12	42.11±4.69	129.20±42.65	15.46±3.71
RWSAB011	22.92±7.39	27.87±4.33	ND	30.99±3.74
RWSAB012	23.02±7.04	57.69±5.31	ND	26.61±4.24
RWSAB013	16.33±7.01	23.69±4.09	ND	45.11±3.54
RWSAB014	18.12±6.97	20.91±3.55	40.15±12.00	21.82±3.06
RWSAB015	24.55±7.87	33.81±3.85	ND	21.62±3.46
RWSAB016	31.13±11.93	10.25±3.49	ND	11.90±3.35
RWSAB017	11.33±5.72	21.09±4.23	ND	17.63±3.40
RWSAB018	22.17±9.30	32.10±3.87	163.10±91.45	30.84±3.57
RWSAB019	16.49±6.11	34.06±4.05	ND	28.70±3.37
RWSAB020	22.78±8.76	18.25±3.83	ND	18.98±3.51
RWSAB021	15.35±6.36	24.47±3.98	74.66±31.95	22.49±3.35
RWSAB022	46.26±14.91	39.08±4.14	ND	39.60±3.99
RWSAB023	24.35±11.50	24.34±3.42	ND	24.34±3.28
RWSAB024	19.37±4.10	29.40±4.00	57.00±31.91	24.77±2.85
RWSAB025	42.72±15.52	19.68±3.99	ND	21.11±3.86
PLKV026	29.73±10.64	54.59±2.31	ND	53.47±2.26
PLKV027	43.77±15.57	29.68±3.84	ND	30.49±3.73
PLKV028	15.64±5.01	28.95±4.00	ND	23.77±3.12
PLKV029	57.19±11.31	24.68±3.65	44.78±24.11	26.33±3.54
PLKV030	19.57±5.04	21.19±3.74	ND	20.62±3.00
PLKV031	16.37±4.91	16.63±3.48	ND	16.54±2.84
PLKV032	33.29±1.34	16.78±3.57	ND	18.05±3.43
RWSAB033	25.61±2.18	19.41±3.58	ND	19.55±3.53
RWSAB034	23.25±1.02	28.39±3.51	58.30±22.04	28.60±3.30
RWSAB035	20.88±9.54	37.23±3.66	ND	35.13±3.42
RWSAB036	25.82±2.07	29.64±3.92	104.80±29.43	30.80±3.83
RWSAB037	45.37±14.43	36.58±3.64	ND	37.10±3.53
RWSAB038	25.68±2.10	38.90±3.58	30.83±14.99	38.18±3.44
RWSAB039	27.40±1.92	27.53±3.24	30.27±17.23	27.61±3.09

RWSAB040	18.00±3.19	18.59±1.90	ND	18.44±1.63
RWSAB041	17.98±11.40	21.01±3.22	36.30±15.42	21.39±3.04
RWSAB042	12.52±3.97	26.51±3.25	ND	20.89±2.52
RWSAB043	37.61±13.54	26.70±3.22	ND	27.28±3.13
RWSAB044	25.62±22.10	36.63±3.29	ND	36.39±3.25
RWSAB046	12.68±4.10	32.61±3.61	38.37±14.76	24.37±2.66
RWSAB045	7.51±2.03	28.29±3.16	ND	13.58±1.71
RWSAB047	9.35±4.65	35.31±3.40	ND	26.28±2.74
RWSAB048	10.45±3.60	21.36±3.39	50.08±15.88	17.02±2.44
RWSAB049	6.60±3.54	9.19±3.94	ND	7.75±2.63
RWSAB050	12.42±3.97	33.28±3.44	45.19±14.71	24.97±2.56
RWSAB051	9.15±6.12	21.13±3.26	ND	18.48±2.88
RWSAB052	13.50±3.79	24.85±3.45	27.51±14.70	19.93±2.51
RWSAB053	7.17±3.06	38.96±3.81	ND	19.67±2.39
RWSAB054	8.52±4.21	35.39±3.66	ND	23.83±2.76
RWSAB055	8.55±4.11	39.63±3.83	ND	25.18±2.80
RWSAB056	54.35±22.75	52.88±4.37	ND	52.93±4.29
RWSAB057	41.98±19.94	30.94±3.52	30.58±16.24	31.24±3.39
RWSAB058	44.84±22.47	30.76±3.49	ND	31.09±3.44
RWSAB059	79.54±23.73	19.77±3.27	ND	20.88±3.24
RWSAB060	68.40±22.28	32.98±3.43	26.42±13.96	33.39±3.29

ND: Not Detectable

Table A.2: NORMs activity concentrations of soil samples for ^{232}Th series and ^{40}K .

Activity concentration (Bq/kg)						
Sample name	^{232}Th			Weighted mean	^{40}K	Weighted mean
	^{228}Ac	^{228}Ac	^{212}Pb			
	338.320keV	911.204keV	238.632keV		1460.81keV	
RWSA001	27.85±2.41	24.81±1.38	25.07±0.99	25.27±0.76	196.10±6.19	196.10±6.19
RWSA002	20.42±2.62	23.77±1.51	23.60±0.87	23.40±0.73	167.80±6.05	167.80±6.05
RWSA003	20.29±2.26	25.10±0.83	26.63±0.93	25.39±0.60	170.70±5.75	170.70±5.75
RWSA004	23.99±2.53	29.20±1.34	22.63±0.71	24.08±0.61	196.70±6.11	196.70±6.11
RWSAB005	23.09±2.20	24.45±1.40	25.50±1.00	24.90±0.74	188.10±5.77	188.10±5.77
RWSAB006	27.72±1.06	30.56±1.50	31.99±1.06	29.99±0.67	204.10±6.39	204.10±6.39
RWSAB007	23.59±1.97	23.90±1.52	25.49±0.99	24.80±0.77	210.80±6.16	210.80±6.16
RWSAB008	28.30±2.39	30.97±1.48	32.66±1.22	31.48±0.88	213.60±6.74	213.60±6.74
RWSAB009	15.06±2.39	18.05±1.21	15.30±0.43	15.60±0.40	109.50±5.19	109.50±5.19
RWSAB010	32.37±3.22	36.13±1.86	31.30±0.60	31.78±0.56	296.30±8.04	296.30±8.04
RWSAB011	25.40±2.91	29.53±1.66	29.48±1.24	29.07±0.94	289.30±7.75	289.30±7.75
RWSAB012	44.91±4.18	24.81±2.62	48.13±1.61	46.78±1.30	468.60±10.80	468.60±10.80
RWSAB013	18.63±2.45	21.26±1.48	21.18±1.10	20.91±0.83	152.50±6.29	152.50±6.29
RWSAB014	17.82±1.72	18.45±1.49	18.80±0.88	18.56±0.69	132.10±5.15	132.10±5.15
RWSAB015	28.78±1.99	27.86±1.63	31.10±1.10	29.86±0.83	139.30±5.67	139.30±5.67
RWSAB016	19.09±1.93	12.68±1.23	11.54±0.38	11.58±0.35	59.15±4.62	59.15±4.62
RWSAB017	20.82±2.81	21.30±1.40	18.42±0.48	18.73±0.45	158.50±6.61	158.50±6.61
RWSAB018	21.49±2.68	21.20±1.55	23.39±0.98	22.59±0.79	198.80±6.37	198.80±6.37
RWSAB019	14.72±2.32	24.62±1.63	25.50±0.98	24.83±0.79	216.40±6.33	216.40±6.33
RWSAB020	27.85±0.88	14.84±0.67	11.70±0.40	12.83±0.32	160.40±5.72	160.40±5.72
RWSAB021	27.16±2.94	33.21±1.04	35.47±1.17	33.75±0.75	242.60±6.84	242.60±6.84
RWSAB022	29.52±1.17	30.72±1.84	28.32±0.54	28.68±0.47	279.90±7.35	279.90±7.35

RWSAB023	22.67±2.13	24.52±0.81	26.78±0.94	25.27±0.59	136.90±5.14	136.90±5.14
RWSAB024	26.70±2.27	29.55±0.97	24.82±0.50	25.86±0.44	166.20±5.76	166.20±5.76
RWSAB025	20.98±2.09	18.57±1.63	18.00±0.47	18.17±0.44	275.30±7.67	275.30±7.67
PLKV026	23.32±2.07	24.73±1.44	27.87±1.04	26.31±0.78	235.00±6.12	235.00±6.12
PLKV027	27.81±2.24	32.72±1.63	33.32±1.08	32.39±0.84	250.90±6.70	250.90±6.70
PLKV028	26.81±2.78	29.65±1.67	29.95±1.11	29.55±0.88	167.50±6.17	167.50±6.17
PLKV029	19.63±1.63	20.67±1.25	17.35±0.43	17.81±0.39	125.90±5.01	125.90±5.01
PLKV030	16.07±2.50	21.97±1.40	19.56±0.45	19.68±0.42	145.80±5.50	145.80±5.50
PLKV031	15.26±1.98	19.05±1.23	16.85±0.27	16.92±0.26	117.70±5.08	117.70±5.08
PLKV032	21.66±0.93	21.63±1.14	23.68±0.93	22.42±0.57	156.10±5.50	156.10±5.50
RWSAB033	20.53±1.64	26.82±1.32	24.41±0.92	24.38±0.69	162.00±5.51	162.00±5.51
RWSAB034	24.58±2.13	26.38±0.97	26.65±1.04	26.29±0.77	232.50±6.34	232.50±6.34
RWSAB035	30.65±2.36	32.55±1.00	34.16±1.08	33.06±0.70	398.20±7.91	398.20±7.91
RWSAB036	29.06±2.19	32.76±1.66	29.05±0.52	29.36±0.48	338.90±7.55	338.90±7.55
RWSAB037	24.71±1.35	27.33±1.13	28.55±0.67	27.69±0.53	255.50±6.32	255.50±6.32
RWSAB038	26.02±1.52	29.25±1.09	31.50±0.71	30.19±0.56	203.10±5.65	203.10±5.65
RWSAB039	20.83±1.30	25.12±0.82	24.56±0.60	24.28±0.45	181.70±5.10	181.70±5.10
RWSAB040	12.88±0.79	11.58±0.43	13.14±0.33	12.60±0.25	103.30±2.88	103.30±2.88
RWSAB041	16.62±1.31	17.73±0.81	18.11±0.60	17.81±0.45	127.80±4.61	127.80±4.61
RWSAB042	22.12±1.42	21.12±0.87	22.02±0.58	21.78±0.46	166.90±5.01	166.90±5.01
RWSAB043	20.49±1.23	22.44±0.91	22.45±0.57	22.19±0.45	177.90±5.08	177.90±5.08
RWSAB044	22.41±1.24	24.79±1.33	25.94±0.63	25.15±0.52	190.30±5.24	196.70±5.24
RWSAB046	24.16±1.51	28.46±0.90	30.04±0.73	28.76±0.53	174.20±5.36	174.20±5.36
RWSAB045	22.12±1.18	23.83±0.96	24.80±0.62	24.12±0.48	189.0±5.12	189.00±5.12
RWSAB047	22.71±1.37	26.96±1.05	21.95±0.43	22.66±0.38	192.80±5.31	192.80±5.31
RWSAB048	15.89±1.26	17.59±0.89	15.27±0.39	15.66±0.34	151.50±4.97	151.50±4.97
RWSAB049	17.98±1.04	20.35±0.73	15.30±0.50	17.05±0.38	163.30±5.05	163.30±5.05
RWSAB050	20.60±1.26	28.00±1.11	29.20±0.69	27.38±0.53	194.60±5.46	194.60±5.46

RWSAB051	23.28±1.49	24.42±0.98	26.09±0.65	25.31±0.51	193.80±5.36	193.80±5.36
RWSAB052	20.22±1.51	21.28±0.94	24.87±0.65	23.31±0.51	195.80±5.50	195.80±5.50
RWSAB053	29.93±1.67	33.14±1.21	29.65±0.51	30.17±0.46	269.80±6.65	269.80±6.65
RWSAB054	29.36±1.71	30.14±1.10	32.87±0.74	31.71±0.58	141.70±5.07	141.70±5.07
RWSAB055	27.88±1.59	32.69±1.23	27.77±0.51	28.43±0.45	288.80±6.87	288.80±6.87
RWSAB056	38.04±2.00	44.95±2.06	47.34±0.93	45.57±0.78	432.60±8.98	432.60±8.98
RWSAB057	20.95±1.46	25.52±1.04	26.63±0.63	25.68±0.51	208.10±5.69	208.10±5.69
RWSAB058	24.25±1.43	29.92±1.15	30.33±0.68	29.37±0.54	207.60±5.64	207.60±5.64
RWSAB059	14.84±1.10	16.72±0.89	13.93±0.37	14.38±0.32	101.00±4.36	101.00±4.36
RWSAB060	24.03±1.45	25.58±1.04	24.97±0.64	25.00±0.51	207.00±5.59	207.00±5.59

Table A.3: NORMs activity concentrations of soil samples for ²²⁶Ra.

Activity concentration (Bq/kg)						
Sample name	Ra-226					Weighted mean
	²¹⁴ Pb	²¹⁴ Pb	²¹⁴ Bi	²¹⁴ Bi	²¹⁴ Bi	
	295.224keV	351.932keV	609.312keV	1120.287keV	1764.494keV	
RWSA001	12.70±0.56	12.04±0.81	13.39±0.77	14.56±0.98	11.53±2.10	12.94±0.36
RWSA002	12.64±0.56	12.04±0.87	11.68±0.73	12.92±0.97	13.09±2.00	12.35±0.36
RWSA003	12.36±0.53	13.23±0.69	13.29±0.71	17.06±0.93	11.77±1.81	13.35±0.33
RWSA004	14.21±0.60	14.36±0.81	15.91±0.85	14.88±0.97	16.16±1.81	14.76±0.38
RWSAB005	13.35±0.55	14.19±0.64	14.47±0.73	14.73±0.93	15.31±0.92	14.16±0.32
RWSAB006	16.42±0.60	15.31±0.69	14.74±0.75	14.76±1.00	14.49±2.10	15.48±0.36
RWSAB007	13.16±0.55	13.36±0.78	12.91±0.69	12.23±0.94	10.43±1.91	12.92±0.35
RWSAB008	19.56±0.69	18.11±1.04	18.06±0.88	17.46±1.13	20.64±1.73	18.72±0.43
RWSAB009	10.91±0.54	11.95±0.74	11.68±0.61	12.16±0.94	12.90±1.73	11.56±0.33
RWSAB010	26.72±0.84	29.62±1.14	26.73±1.07	25.69±1.44	30.48±2.26	27.39±0.52
RWSAB011	19.53±0.69	18.69±0.92	18.02±0.79	18.37±1.20	22.71±1.81	18.98±0.41
RWSAB012	23.47±0.86	23.72±1.13	24.19±1.10	24.06±2.85	26.27±2.65	23.86±0.56
RWSAB013	12.88±0.59	11.66±0.72	13.19±0.83	12.33±1.01	14.12±2.03	12.59±0.37
RWSAB014	11.75±0.52	6.90±0.25	11.49±0.78	11.22±0.85	12.68±1.49	8.33±0.21
RWSAB015	12.90±0.57	13.15±0.79	14.62±0.74	14.49±0.94	13.59±1.86	13.60±0.35
RWSAB016	8.94±0.47	8.42±0.66	8.51±0.69	10.39±0.79	9.52±1.44	8.99±0.30
RWSAB017	13.43±0.62	15.24±0.92	13.95±0.94	16.65±1.06	15.49±1.82	14.45±0.41
RWSAB018	14.390±0.59	14.77±0.81	13.18±0.89	14.25±1.04	14.19±2.05	14.23±0.38
RWSAB019	13.95±0.61	14.66±0.82	14.50±0.83	15.75±1.05	15.17±2.37	14.51±0.39
RWSAB020	20.57±0.67	22.98±0.80	21.04±0.78	24.23±1.20	23.41±2.12	21.78±0.40
RWSAB021	17.63±0.64	18.99±0.88	17.29±0.96	20.64±1.12	16.42±2.08	18.23±0.41
RWSAB022	23.28±0.73	25.89±0.99	25.38±0.94	22.50±1.26	26.29±1.84	24.38±0.45

RWSAB023	15.38±0.56	15.63±0.67	13.98±0.81	17.98±0.93	16.45±1.73	15.59±0.35
RWSAB024	17.21±0.65	17.45±0.81	17.65±0.89	16.91±1.11	19.15±2.08	17.39±0.40
RWSAB025	37.15±0.86	36.11±1.08	35.52±0.94	36.41±1.46	35.69±2.44	36.31±0.50
PLKV026	15.58±0.61	16.20±0.78	16.24±0.81	16.66±1.02	17.35±1.82	16.09±0.36
PLKV027	17.25±0.63	18.78±0.91	16.65±0.70	18.13±0.68	17.94±1.59	17.58±0.35
PLKV028	17.42±0.66	18.31±0.89	16.53±0.97	19.59±1.11	19.90±1.96	17.88±0.42
PLKV029	14.10±0.56	13.94±0.84	13.94±0.63	13.19±0.94	17.18±1.40	14.09±0.34
PLKV030	16.32±0.58	15.88±0.76	13.91±0.78	15.43±0.97	16.23±1.71	15.59±0.36
PLKV031	12.72±0.52	11.12±0.67	11.35±0.73	13.60±0.90	14.05±1.28	12.28±0.32
PLKV032	15.39±0.56	13.00±0.78	12.87±0.80	12.83±0.97	14.82±1.73	14.01±0.36
RWSAB033	11.60±0.53	11.51±0.83	12.69±0.68	13.54±0.93	11.01±1.84	12.10±0.34
RWSAB034	16.74±0.60	16.81±0.82	16.35±0.72	20.60±1.86	19.04±1.66	16.93±0.38
RWSAB035	14.73±0.58	16.58±0.76	15.51±0.82	16.14±1.01	16.40±1.68	15.58±0.37
RWSAB036	23.98±0.73	26.69±0.96	26.66±0.96	24.77±1.29	28.90±1.72	25.58±0.45
RWSAB037	16.61±0.58	19.48±0.59	17.60±0.59	18.84±1.02	19.99±1.57	18.06±0.32
RWSAB038	14.18±0.54	15.48±0.54	15.05±0.52	16.97±0.96	14.05±1.16	15.04±0.28
RWSAB039	12.89±0.49	13.54±0.50	12.89±0.48	12.99±0.82	15.68±1.16	13.23±0.26
RWSAB040	6.19±0.25	6.61±0.24	6.66±0.25	7.63±0.46	7.79±0.58	6.66±0.13
RWSAB041	11.18±0.46	11.27±0.44	10.54±0.48	12.13±0.78	15.50±1.02	11.38±0.24
RWSAB042	11.71±0.47	12.39±0.50	11.72±0.47	11.53±0.78	12.76±1.07	11.93±0.25
RWSAB043	10.60±0.45	10.67±0.44	10.2±0.43	10.80±0.77	10.61±1.07	10.53±0.24
RWSAB044	12.53±0.49	12.63±0.48	13.06±0.47	13.76±0.85	13.72±1.05	12.89±0.26
RWSAB046	17.37±0.58	18.07±0.59	17.07±0.59	16.78±0.98	18.63±1.33	17.49±0.31
RWSAB045	12.89±0.48	12.71±0.44	11.57±0.44	12.56±0.80	14.60±1.06	12.50±0.24
RWSAB047	14.99±0.54	16.13±0.53	16.51±0.53	16.63±0.92	18.00±1.16	16.08±0.28
RWSAB048	12.67±0.49	12.40±0.49	10.99±0.48	13.56±0.87	14.56±1.10	12.28±0.26
RWSAB049	12.57±0.50	13.24±0.49	12.24±0.49	13.23±0.85	12.87±1.13	12.75±0.26
RWSAB050	11.72±0.50	13.60±0.53	12.65±0.50	12.71±0.84	13.06±1.16	12.65±0.27

RWSAB051	13.51±0.50	14.63±0.53	13.98±0.52	12.54±0.85	15.49±1.08	13.96±0.27
RWSAB052	14.82±0.53	15.35±0.53	15.02±0.50	15.40±0.90	15.88±1.22	15.14±0.28
RWSAB053	26.29±0.71	28.28±0.71	25.86±0.66	28.11±1.23	27.40±1.44	26.93±0.37
RWSAB054	15.39±0.56	14.89±0.50	14.93±0.57	14.60±0.90	16.98±1.28	15.11±0.29
RWSAB055	23.28±0.68	24.33±0.65	24.69±0.67	24.50±1.19	25.53±1.55	24.22±0.36
RWSAB056	22.29±0.72	22.44±0.92	22.59±0.72	21.88±1.25	22.62±1.55	22.39±0.41
RWSAB057	13.12±0.53	14.48±0.52	14.87±0.51	12.91±0.89	14.53±1.17	14.07±0.28
RWSAB058	17.28±0.56	16.85±0.52	16.61±.54	16.37±0.94	19.00±1.23	16.97±0.29
RWSAB059	10.54±0.46	10.31±0.44	11.16±0.46	9.50±0.74	13.11±0.99	10.68±0.24
RWSAB060	13.81±0.52	13.77±0.47	13.03±0.47	14.48±0.89	16.15±1.14	13.74±0.26

Table A.4: NORMs activity concentrations of soil samples for ²¹⁰Pb.

Activity Concentration (Bq/kg)				
Sample name	²¹⁰ Pb	Weighted mean	²¹² Bi	²⁰⁸ Tl
	46.54keV			
RWSA001	ND	ND	19.36±2.80	6.49±0.34
RWSA002	50.93±21.94	50.93±21.94	22.89±4.02	6.82±0.29
RWSA003	30.98±15.62	30.98±15.62	25.78±3.62	6.78±0.29
RWSA004	ND	ND	18.03±1.75	7.68±0.33
RWSAB005	ND	ND	26.05±3.56	6.93±0.30
RWSAB006	ND	ND	37.2±4.06	8.93±0.32
RWSAB007	28.19±14.66	28.19±14.66	12.46±1.39	6.66±0.32
RWSAB008	39.69±20.68	39.69±20.68	34.76±3.7519	9.07±0.35
RWSAB009	48.57±18.52	48.57±18.52	12.24±2.99	5.03±0.27
RWSAB010	ND	ND	42.88±4.80	10.50±0.42
RWSAB011	ND	ND	36.54±4.70	7.99±0.35
RWSAB012	61.62±28.58	61.62±28.58	42.33±5.02	12.68±0.50
RWSAB013	58.94±20.86	58.94±20.86	12.43±3.40	5.92±0.34
RWSAB014	ND	ND	6.81±1.47	5.26±0.28
RWSAB015	61.89±21.54	61.89±21.54	29.16±4.07	8.24±0.35
RWSAB016	35.79±16.43	35.79±16.43	34.38±2.51	3.92±0.24
RWSAB017	ND	ND	12.85±1.39	5.24±0.34
RWSAB018	65.18±17.75	65.18±17.75	25.41±3.23	6.11±0.30
RWSAB019	ND	ND	9.672±1.52	6.48±0.34
RWSAB020	ND	ND	17.3±3.19	3.28±0.33
RWSAB021	49.78±19.81	49.78±19.81	31.59±3.73	8.80±0.35
RWSAB022	ND	ND	18.05±2.34	9.84±0.37
RWSAB023	ND	ND	16.27±2.36	6.54±0.31
RWSAB024	45.05±7.41	45.05±7.41	21.04±4.35	8.32±0.32
RWSAB025	ND	ND	24.44±3.44	5.23±0.33
PLKV026	38.11±18.82	38.11±18.82	17.9±1.50	8.47±0.29
PLKV027	ND	ND	29.11±4.73	9.43±0.34
PLKV028	ND	ND	19.13±1.66	7.98±0.37
PLKV029	31.93±16.40	31.93±16.40	22.22±3.69	5.56±0.26
PLKV030	ND	ND	18.87±3.466	6.01±0.33
PLKV031	28.57±13.50	28.57±13.50	18.35±1.78	4.66±0.28
PLKV032	ND	ND	22.85±3.15	6.69±0.30
RWSAB033	ND	ND	17.88±2.37	7.02±0.29
RWSAB034	33.20±11.58	33.29±11.58	19.1±1.64	7.90±0.31
RWSAB035	ND	ND	32.13±3.85	8.91±0.32
RWSAB036	71.32±18.74	71.32±18.74	48.64±3.92	9.66±0.34
RWSAB037	ND	ND	31.91±1.53	7.94±0.27

RWSAB038	ND	ND	23.43±2.89	8.38±0.27
RWSAB039	ND	ND	23.21±2.37	7.03±0.24
RWSAB040	46.53±42.58	46.53±42.58	7.79±0.81	4.02±0.28
RWSAB041	ND	ND	19.15±2.04	5.14±0.23
RWSAB042	15.52±8.32	15.52±8.32	19.19±2.61	6.01±0.23
RWSAB043	20.99±9.14	20.99±9.14	20.32±2.11	5.91±0.23
RWSAB044	19.92±7.34	19.92±7.34	23.96±2.28	7.79±0.25
RWSAB046	ND	ND	34.31±2.98	7.76±0.26
RWSAB045	ND	ND	27.22±2.54	6.65±0.23
RWSAB047	39.57±9.81	39.57±9.814	16.55±1.66	7.36±0.25
RWSAB048	30.56±10.09	30.56±10.09	15.70±1.40	4.74±0.24
RWSAB049	17.80±10.09	17.8±10.09	7.76±0.74	5.51±0.24
RWSAB050	ND	ND	28.63±2.48	7.59±0.28
RWSAB051	ND	ND	23.17±2.23	7.39±0.25
RWSAB052	ND	ND	18.95±2.12	6.08±0.24
RWSAB053	28.30±13.40	28.30±13.40	11.37±1.23	9.44±0.29
RWSAB054	ND	ND	29.92±2.63	8.45±0.28
RWSAB055	41.10±13.44	41.10±13.44	29.94±2.47	9.00±0.28
RWSAB056	39.78±12.66	39.78±12.66	46.98±3.35	12.32±0.34
RWSAB057	ND	ND	21.77±2.59	7.35±0.26
RWSAB058	27.31±8.68	27.31±8.68	32.41±2.74	8.54±0.26
RWSAB059	21.67±8.26	21.67±8.26	17.00±1.84	4.54±0.22
RWSAB060	ND	ND	28.14±2.27	7.07±0.25

ND: Not Detectable

Table A.5: Absorbed dose rate (D), annual effective dose equivalent (AEDE), radium equivalent activity (R_{aeq}) and external hazard index (H_{ext}) for all soil samples from the study area.

Sample No.	D (nGy/h)	AEDE (μSv/y)	R _{aeq} (Bq/kg)	H _{ext}
RWSA001	33.20±1.73	40.72±2.12	72.37±3.76	0.20±0.01
RWSA002	30.89±1.71	37.88±2.10	67.51±3.72	0.18±0.01
RWSA003	35.81±1.52	43.92±1.86	78.36±3.30	0.21±0.01
RWSA004	32.68±2.24	40.07±2.75	71.07±4.86	0.19±0.01
RWSAB005	33.18±44.54	40.69±54.63	72.37±1.05	0.20±0.01
RWSAB006	38.23±1.69	46.88±2.08	83.71±3.67	0.23±0.01
RWSAB007	39.16±1.70	48.02±2.09	85.00±3.70	0.23±0.01
RWSAB008	35.81±1.04	43.91±1.27	78.53±2.28	0.21±0.01
RWSAB009	22.94±1.58	28.14±1.93	50.12±3.41	0.14±0.01
RWSAB010	38.69±1.78	47.45±2.18	83.72±3.84	0.23±0.01
RWSAB011	43.94±1.85	53.89±2.26	94.84±4.01	0.26±0.01
RWSAB012	60.09±2.16	73.69±2.65	129.59±4.70	0.35±0.01
RWSAB013	39.83±1.73	48.85±2.12	86.76±3.76	0.23±0.01
RWSAB014	26.80±1.49	32.87±1.83	58.53±3.24	0.16±0.01
RWSAB015	33.83±1.69	41.49±2.071	75.05±3.68	0.20±0.01
RWSAB016	14.96±1.57	18.34±1.93	33.01±3.41	0.10±0.01
RWSAB017	26.07±1.62	31.97±1.98	56.62±3.50	0.15±0.01
RWSAB018	36.18±1.74	44.37±2.13	78.45±3.77	0.21±0.01
RWSAB019	37.28±1.65	45.72±2.02	80.86±3.59	0.22±0.01
RWSAB020	23.21±1.65	28.46±2.03	49.68±3.57	0.13±0.01
RWSAB021	40.89±1.64	50.15±2.01	89.43±3.56	0.24±0.01
RWSAB022	47.28±1.89	57.99±2.32	102.15±4.09	0.28±0.01
RWSAB023	32.22±1.57	39.51±1.92	71.02±3.41	0.19±0.01
RWSAB024	33.99±1.36	41.69±1.67	74.55±2.95	0.20±0.01

RWSAB025	32.21±1.83	39.50±2.25	68.29±3.96	0.18±0.01
PLKV026	50.39±1.17	61.80±1.44	109.19±2.56	0.29±0.01
PLKV027	44.11±1.82	54.10±2.23	96.13±3.95	0.26±0.01
PLKV028	35.82±1.56	43.93±1.91	78.93±3.40	0.21±0.01
PLKV029	28.17±1.67	34.55±2.04	61.49±3.61	0.17±0.01
PLKV030	27.49±1.43	33.71±1.75	59.98±3.09	0.16±0.01
PLKV031	22.77±1.34	27.92±1.64	49.80±2.89	0.13±0.01
PLKV032	28.39±1.64	34.82±2.01	62.13±3.55	0.17±0.01
RWSAB033	30.51±1.70	37.42±2.09	66.89±3.69	0.18±0.01
RWSAB034	38.79±1.62	47.57±1.98	84.10±3.51	0.23±0.01
RWSAB035	52.81±1.67	64.76±2.04	113.08±3.61	0.31±0.01
RWSAB036	46.10±1.82	56.53±2.23	98.88±3.93	0.27±0.01
RWSAB037	44.52±1.68	54.60±2.06	96.38±3.64	0.26±0.01
RWSAB038	44.34±1.64	54.38±2.01	96.99±3.56	0.26±0.01
RWSAB039	35.00±1.47	42.92±1.80	76.32±3.18	0.21±0.01
RWSAB040	20.44±0.78	25.06±0.95	44.41±1.68	0.12±0.00
RWSAB041	25.97±1.44	31.85±1.77	56.70±3.12	0.15±0.01
RWSAB042	29.77±1.21	36.51±1.49	64.89±2.63	0.18±0.01
RWSAB043	33.43±1.49	40.99±1.82	72.71±3.22	0.20±0.01
RWSAB044	40.21±1.55	49.31±1.90	87.50±3.36	0.24±0.01
RWSAB046	35.89±1.29	44.02±1.58	78.91±2.80	0.21±0.01
RWSAB045	28.72±0.87	35.22±1.06	62.62±1.88	0.17±0.01
RWSAB047	33.87±1.31	41.54±1.60	73.54±2.83	0.20±0.01
RWSAB048	23.64±1.16	28.99±1.43	51.08±2.52	0.14±0.01
RWSAB049	20.69±1.26	25.37±1.54	44.71±2.72	0.12±0.01
RWSAB050	36.19±1.25	44.39±1.53	79.11±2.70	0.21±0.01
RWSAB051	31.90±1.38	39.13±1.70	69.59±3.00	0.19±0.01

RWSAB052	31.45±1.22	38.58±1.50	68.35±2.65	0.18±0.01
RWSAB053	38.56±1.179	47.23±1.43	83.58±2.53	0.23±0.01
RWSAB054	36.07±1.34	44.24±1.64	80.09±2.91	0.22±0.01
RWSAB055	40.85±1.35	50.10±1.66	88.07±2.92	0.24±0.01
RWSAB056	70.02±2.07	85.87±2.54	151.41±4.49	0.41±0.01
RWSAB057	38.62±1.61	47.37±1.98	83.99±3.49	0.23±0.01
RWSAB058	40.76±1.64	49.99±2.01	89.07±3.56	0.24±0.01
RWSAB059	22.55±1.52	27.65±1.86	49.23±3.28	0.13±0.01
RWSAB060	39.158±1.57	48.02±1.92	85.08±3.40	0.23±0.01
MIN	14.96±0.78	18.34±0.95	33.01±1.68	0.09±0.01
MAX	70.02±4.45	85.87±5.46	151.41±10.55	0.41±0.03
MEAN	34.07±1.61	41.78±1.97	74.16±3.49	0.20±0.01

APPENDIX B: ELEMENTARY CONCENTRATIONS OF SOIL SAMPLES FROM THE PROPOSED RADIOACTIVE WASTE STORAGE AREA OF PILIKWE.

Table B.1: Elementary concentrations.

Sample Code	Radionuclide's activity concentrations (ppb)														
	Li	Be	B	C	N	F	Ne	Na	Mg	Al	Si	P	S	Cl	Ar
STD ppb check	6.14	6.28	0.00	0.00	0.00	0.00	0.00	0.00	5.81	5.78	0.00	0.00	0.00	0.00	0.00
BLANK	0.05	0.00	0.00	0.00	20000000.00	0.00	0.00	195.20	12.78	23.98	19.49	199.84	261.85	744487.00	0.00
RWSA001	597.99	0.25	65.35	0.00	0.00	0.00	39941.00	0.00	0.00	0.00	0.00	560.80	14580.00	0.00	0.00
RWSA002	477.97	0.18	63.99	0.00	0.00	0.00	35052.00	0.00	0.00	0.00	0.00	421.78	14514.00	0.00	0.00
RWSA003	492.71	0.17	62.42	0.00	0.00	0.00	32128.00	0.00	0.00	0.00	0.00	341.93	13392.00	0.00	0.00
RWSA004	680.42	0.23	63.72	0.00	0.00	0.00	45301.00	0.00	0.00	0.00	0.00	344.41	846.36	0.00	0.00
RWSAB005	331.75	0.12	41.60	0.00	0.00	0.00	28894.00	0.00	0.00	0.00	0.00	223.51	1700.30	0.00	0.00
RWSAB006	725.59	0.26	63.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	504.48	14335.00	0.00	0.00
RWSAB007	874.44	0.29	65.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	521.75	14717.00	0.00	0.00
RWSAB008	1789.80	0.56	74.25	0.00	0.00	0.00	0.00	0.00	0.00		0.00	766.48	19939.00	0.00	0.00
RWSAB009	678.99	0.24	69.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	791.22	16484.00	0.00	0.00
RWSAB010	2189.30	0.62	68.70	0.00	0.00	0.00	0.00	0.00	0.00		0.00	700.70	16638.00	0.00	0.00
RWSAB011	2366.60	0.59	68.22	0.00	0.00	0.00	0.00	0.00	0.00		0.00	825.94	16647.00	0.00	0.00
RWSAB012	2598.90	1.18	72.93	0.00	0.00	0.00	0.00	0.00	0.00		0.00	810.13	18973.00	0.00	0.00
RWSAB013	949.22	0.28	63.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	348.42	16203.00	0.00	0.00
RWSAB014	1071.20	0.36	64.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	528.43	15225.00	0.00	0.00
RWSAB015	1578.60	0.49	69.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	614.93	15479.00	0.00	0.00
RWSAB016	301.85	0.08	47.44	0.00	0.00	0.00	24904.00	0.00	0.00	0.00	0.00	206.69	6365.40	0.00	0.00
RWSAB017	697.93	0.15	46.48	0.00	0.00	0.00	40546.00	0.00	0.00	0.00	0.00	220.50	4889.70	0.00	0.00
RWSAB018	656.95	0.17	45.71	0.00	0.00	0.00	31616.00	0.00	0.00	0.00	0.00	228.06	4862.50	0.00	0.00
RWSAB019	404.07	0.12	45.84	0.00	0.00	0.00	28760.00	0.00	0.00	0.00	0.00	186.56	5726.70	0.00	0.00
RWSAB020	361.79	0.09	44.34	0.00	0.00	0.00	35766.00	0.00	0.00	0.00	0.00	158.09	4288.00	0.00	0.00
RWSAB021	1126.50	0.42	40.21	0.00	0.00	0.00	38034.00	0.00	0.00	0.00	0.00	839.20	3819.90	0.00	0.00

RWSAB022	1425.10	0.45	55.97	0.00	0.00	0.00	61221.00	0.00	0.00		0.00	1074.20	10472.00	0.00	0.00
RWSAB023	269.35	0.17	49.57	0.00	0.00	0.00	25030.00	0.00	0.00	0.00	0.00	906.95	7178.10	0.00	0.00
RWSAB024	444.69	0.19	48.10	0.00	0.00	0.00	27332.00	0.00	0.00	0.00	0.00	824.96	6144.00	0.00	0.00
RWSAB025	703.44	0.27	50.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	917.15	9569.70	0.00	0.00
PLKV026	550.69	0.23	47.32	0.00	0.00	0.00	23543.00	0.00	0.00	0.00	0.00	844.14	6908.40	0.00	0.00
PLKV027	739.93	0.29	49.61	0.00	0.00	0.00	32019.00	0.00	0.00	0.00	0.00	851.03	6463.10	0.00	0.00
PLKV028	42.93	2.24	7.53	0.00	10000000.00	0.00	0.00	364.46	2135.00	79402.00	9494.30	324.02	990.02	651107.00	0.00
PLKV029	10.72	1.06	0.00	0.00	0.00	0.00	0.00	99.67	601.27	13429.00	1702.50	231.86	0.00	0.00	0.00
PLKV030	68.23	3.61	16.49	0.00	9000000.00	0.00	0.00	290.68	5593.10		10103.00	410.07	619.91	662711.00	0.00
PLKV031	53.99	2.62	9.45	0.00	10000000.00	0.00	0.00	250.42	3527.10	85302.00	8436.40	392.30	770.35	635433.00	0.00
PLKV032	6.59	0.83	0.00	0.00	0.00	0.00	0.00	102.40	716.52	9590.20	2178.10	238.61	0.00	0.00	0.00
RWSAB033	38.56	1.59	0.00	0.00	10000000.00	0.00	0.00	170.94	1590.70	56726.00	7840.90	284.07	79.28	637440.00	0.00
RWSAB034	15.34	1.48	4.58	0.00	9000000.00	0.00	0.00	216.88	1644.80	46086.00	7080.00	294.44	233.62	607698.00	0.00
RWSAB035	535.00	0.19	50.90	0.00	0.00	0.00	35875.00	0.00	0.00	0.00	0.00	249.14	8112.10	0.00	0.00
RWSAB036	474.23	0.17	45.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	236.83	7845.90	0.00	0.00
RWSAB037	821.47	0.25	59.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	544.60	26553.00	0.00	0.00
RWSAB038	970.55	0.32	139.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	752.84	20177.00	0.00	0.00
RWSAB039	619.14	0.17	139.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	395.73	17148.00	0.00	0.00
RWSAB040	2280.80	0.82	64.86	0.00	0.00	0.00	0.00	0.00	0.00		0.00	1151.50	27017.00		0.00
RWSAB041	876.29	0.30	180.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	564.62	16178.00	0.00	0.00
RWSAB042	981.83	0.32	55.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	470.01	17407.00	0.00	0.00
RWSAB043	762.20	0.24	53.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	363.29	16966.00	0.00	0.00
RWSAB044	787.86	0.25	178.77	0.00	0.00	0.00	54895.00	0.00	0.00	0.00	0.00	361.39	15480.00	0.00	0.00
RWSAB045	683.36	0.20	174.27	0.00	0.00	0.00	55810.00	0.00	0.00	0.00	0.00	392.94	14078.00	0.00	0.00
RWSAB046	1660.60	0.40	55.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	419.90	17722.00	0.00	0.00
RWSAB047	871.59	0.30	174.87	0.00	0.00	0.00	49946.00	0.00	0.00	0.00	0.00	382.22	13834.00	0.00	0.00
RWSAB048	1110.30	0.26	178.33	0.00	0.00	0.00	66489.00	0.00	0.00	0.00	0.00	264.68	14220.00	0.00	0.00
RWSAB049	1108.10	0.26	171.31	0.00	0.00	0.00	57810.00	0.00	0.00	0.00	0.00	247.30	13269.00	0.00	0.00
RWSAB050	2044.20	0.56	54.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	648.67	15763.00	0.00	0.00

RWSAB051	1117.80	0.25	139.83	0.00	0.00	0.00	67817.00	0.00	0.00	0.00	0.00	251.95	16726.00	0.00	0.00
RWSAB052	953.86	0.21	163.01	0.00	0.00	0.00	52576.00	0.00	0.00	0.00	0.00	214.68	12098.00	0.00	0.00
RWSAB053	2235.70	0.69	168.64	0.00	0.00	0.00	0.00	0.00	0.00		0.00	653.58	14009.00	0.00	0.00
RWSAB054	1363.90	0.42	157.08	0.00	0.00	0.00	58961.00	0.00	0.00	0.00	0.00	429.49	12577.00	0.00	0.00
RWSAB055	1866.00	0.50	163.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	549.48	14355.00	0.00	0.00
RWSAB056	2698.60	1.32	135.05	0.00	0.00	0.00	0.00	0.00	0.00		0.00	808.44	18139.00	0.00	0.00
RWSAB057	944.30	0.31	170.78	0.00	0.00	0.00	14697.00	0.00	0.00	0.00	0.00	459.86	14916.00	0.00	0.00
RWSAB058	1904.60	0.63	50.41	0.00	0.00	0.00	0.00	0.00	0.00		0.00	695.37	27153.00	0.00	0.00
RWSAB059	665.45	0.20	136.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	550.90	19028.00	0.00	0.00
RWSAB060	617.63	0.20	124.56	0.00	0.00	0.00	53660.00	0.00	0.00	0.00	0.00	285.00	7433.40	0.00	0.00
BLANK01	29.93	0.00	46.18	0.00	0.00	0.00	18512.00	0.00	0.00	63.15	0.00	611.91	7666.00	0.00	0.00
BLANK02	41.08	0.00	63.24	0.00	0.00	0.00	26147.00	0.00	0.00	110.41	0.00	87.37	15125.00	0.00	0.00
BLANK03	31.16	0.00	50.51	0.00	0.00	0.00	19419.00	0.00	0.00	61.84	0.00	63.70	8384.00	0.00	0.00
CAL BLANK	1.26	0.00	1.21	2.05	368.07	23867.00	3889.00	13.63	2.31	0.81	0.84	3.58	2989.70	243.83	5000000.00
CAL BLANK01	1.05	0.00	0.91	2.01	361.50	23867.00	3326.00	12.12	2.19	1.62	0.84	3.51	2763.20	243.83	5000000.00
RINSE CHECK	150.72	0.00	91.89	0.00	0.00	0.00	0.00	0.00	0.00	14.22	0.00	17.99	3173.00	0.00	0.00
std ms-3 at 8 ppb	8.00	8.00	8.58	0.00	0.00	0.00	66187.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
std ms-3 at 8 ppb_01	8.00	8.00	8.24	0.00	0.00	0.00	64733.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B.1: Elementary concentrations (continued).

Sample Code	Radionuclide's activity concentrations (ppb)															
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se
STD ppb check	1.06	0.00	0.00	0.00	5.84	5.43	5.96	0.00	5.79	5.39	5.47	5.74	6.67	0.00	7.32	6.05
BLANK	34.25	0.00	0.00	0.70	23.29	0.00	0.75	0.00	0.01	0.00	0.00	0.50	0.00	0.01	14.93	0.00
RWSA001	0.00	257.48	0.15	59.69	7697.10	221.82	80.00	0.00	563.31	35.09	23.99	14.95	333.59	0.02	7.86	0.24
RWSA002	0.00	217.82	0.14	58.33	7724.30	222.98	80.00	0.00	457.29	31.07	19.79	13.80	290.03	0.02	8.34	0.10
RWSA003	0.00	195.67	0.12	40.15	6964.70	227.46	80.00	0.00	482.27	150.16	16.73	13.35	256.36	0.02	7.97	0.07
RWSA004	0.00	266.37	0.15	32.18	7189.30	211.39	80.00	0.00	754.21	177.84	19.34	13.94	309.71	0.03	8.31	0.24
RWSAB005	0.00	205.66	0.09	8.91	2445.10	123.06	80.00	0.00	446.62	110.91	12.55	10.49	158.80	0.01	0.75	0.09
RWSAB006	0.00	74.45	0.16	42.11	7153.30	240.15	80.00	0.00	729.68	187.43	23.93	15.01	312.27	0.03	8.15	0.11
RWSAB007	0.00	177.59	0.20	52.15	8663.90	238.33	80.00	0.00	637.42	155.91	43.50	16.00	393.75	0.03	8.46	0.10
RWSAB008	0.00	0.00	0.29	61.42	3012.10	285.00	80.00	0.00	1228.60	92.16	48.29	21.20	629.82	0.04	12.62	0.17
RWSAB009	0.00	0.00	0.14	29.21	7913.80	193.00	80.00	0.00	595.08	168.76	16.38	13.84	247.86	0.02	10.19	0.08
RWSAB010	0.00	0.00	0.34	67.33	2683.80	107.87	80.00	0.00	1003.10	90.40	42.40	18.57	645.79	0.04	10.32	0.16
RWSAB011	0.00	0.00	0.28	48.35	2801.60	84.70	80.00	0.00	841.64	91.56	40.03	22.64	638.43	0.04	10.13	0.16
RWSAB012	0.00	0.00	0.56	57.87	80.00	97.00	80.00	0.00	1334.00	0.00	60.46	33.82	1057.90	0.06	11.90	0.24
RWSAB013	0.00	210.54	0.16	37.80	7108.30	295.90	80.00	0.00	415.52	198.63	18.46	12.58	344.80	0.03	8.37	0.08
RWSAB014	0.00	203.34	0.22	59.15	8611.70	221.95	80.00	0.00	718.38	61.39	34.84	14.45	435.43	0.03	8.30	0.10
RWSAB015	0.00	65.18	0.26	34.87	9776.00	287.32	80.00	0.00	589.63	222.73	35.32	16.17	538.48	0.03	9.13	0.14
RWSAB016	0.00	162.66	0.08	19.01	3046.80	144.15	6969.40	0.00	162.84	83.71	6.92	9.48	190.56	0.01	2.38	0.05
RWSAB017	0.00	270.61	0.10	16.98	3667.90	199.84	80.00	0.00	279.62	133.28	10.61	14.69	222.03	0.01	1.77	0.04
RWSAB018	0.00	202.47	0.09	22.13	4263.60	88.52	80.00	0.00	286.39	158.00	11.45	12.39	211.66	0.02	1.72	0.04
RWSAB019	0.00	190.22	0.08	4.89	3377.30	158.42	80.00	0.00	237.71	115.76	9.07	9.89	128.39	0.01	1.75	0.02
RWSAB020	0.00	237.47	0.06	13.86	2465.00	97.52	2058.80	0.00	161.80	87.58	7.67	10.04	134.70	0.01	1.16	0.01
RWSAB021	0.00	244.71	0.25	37.63	10654.00	197.35	80.00	0.00	512.27	45.84	22.40	10.97	17.06	0.00	0.67	0.18
RWSAB022	0.00	82.08	0.43	78.89	19583.00	88.85	80.00	0.00	889.34	78.56	54.56	12.45	24.37	0.00	4.06	0.18
RWSAB023	0.00	152.94	0.17	54.52	8814.10	229.36	80.00	0.00	468.89	25.87	14.21	8.52	8.98	0.00	2.57	0.10
RWSAB024	0.00	172.36	0.17	56.52	8503.40	174.38	80.00	0.00	397.84	27.16	17.86	9.32	8.37	0.00	2.54	0.09

RWSAB025	0.00	0.00	0.24	80.73	10057.00	248.33	80.00	0.00	485.33	46.06	20.77	11.25	11.57	0.00	3.98	0.10
PLKV026	0.00	150.55	0.18	66.44	8291.30	194.50	80.00	0.00	393.52	27.59	20.47	9.40	10.93	0.00	2.57	0.12
PLKV027	0.00	204.59	0.20	66.23	9091.80	162.03	80.00	0.00	465.73	211.74	22.68	9.82	14.06	0.00	2.62	0.11
PLKV028	6837.70	968.35	5.26	617.89	151.45	195.74	690.80	55461.00	23.68	29.50	39.94	46.04	33.03	1.19	20.51	0.35
PLKV029	1676.90	457.03	2.51	16.02	55.09	96.99	300.86	26981.00	10.05	6.95	14.00	14.69	9.34	0.10	2.49	0.00
PLKV030	9959.40	7384.50	6.35	843.40	191.57	257.68	1507.40	78346.00	43.08	38.83	65.50	67.63	41.23	1.99	21.32	0.52
PLKV031	8887.80	2585.30	5.67	771.66	192.35	319.42	1073.30	74269.00	34.53	32.78	61.71	70.62	32.74	1.82	19.88	0.24
PLKV032	1189.10	502.33	1.55	21.76	46.33	78.12	423.94	20847.00	10.39	6.77	15.39	13.73	5.97	0.10	1.93	0.00
RWSAB033	4088.80	1084.80	3.72	490.06	108.41	182.90	576.52	41444.00	15.62	30.41	25.73	28.98	21.21	1.10	16.71	0.00
RWSAB034	6056.10	965.37	2.82	451.47	90.99	179.95	575.34	36884.00	21.25	20.53	15.82	24.65	17.56	1.21	14.84	0.00
RWSAB035	0.00	243.45	0.14	30.57	7368.70	236.22	80.00	0.00	335.80	33.25	21.77	9.06	8.82	0.00	1.88	0.10
RWSAB036	0.00	0.00	0.11	33.09	7001.50	204.81	80.00	0.00	280.84	26.89	16.38	8.66	9.21	0.00	1.07	0.09
RWSAB037	0.00	243.71	0.19	47.68	80.00	230.52	80.00	0.00	410.88	26.35	24.02	16.26	8.02	0.01	47.39	0.13
RWSAB038	0.00	263.84	0.24	1.69	80.00	243.51	80.00	0.00	508.13	34.09	29.87	17.67	11.01	0.00	37.92	0.19
RWSAB039	0.00	221.61	0.14	35.22	80.00	196.84	80.00	0.00	294.91	19.81	19.47	15.25	6.15	0.00	36.09	0.10
RWSAB040	0.00	75.13	0.50	1.69	80.00	0.00	80.00	0.00	1066.00	68.37	58.68	21.04	23.73	0.01	71.74	0.37
RWSAB041	0.00	235.51	0.22	1.69	80.00	242.05	80.00	0.00	442.43	31.98	28.42	18.15	10.92	0.00	34.12	0.16
RWSAB042	0.00	226.11	0.22	42.65	80.00	253.98	80.00	0.00	542.36	31.43	27.23	17.03	10.76	0.00	37.16	0.18
RWSAB043	0.00	212.53	0.17	119.97	80.00	251.97	80.00	0.00	421.17	24.39	22.78	16.25	7.95	0.00	37.60	0.16
RWSAB044	0.00	219.69	0.20	45.63	80.00	187.19	80.00	0.00	431.41	25.82	23.10	16.48	8.43	0.00	33.03	0.14
RWSAB045	0.00	220.86	0.17	49.41	80.00	196.35	80.00	0.00	373.76	24.56	23.30	15.68	7.94	0.00	30.57	0.12
RWSAB046	0.00	73.19	0.23	81.98	80.00	294.66	80.00	0.00	356.72	37.38	21.66	16.60	11.99	0.00	36.09	0.14
RWSAB047	0.00	200.16	0.20	127.84	80.00	84.82	80.00	0.00	364.58	160.37	25.19	15.14	9.33	0.00	31.83	0.12
RWSAB048	0.00	262.26	0.17	87.93	80.00	252.00	80.00	0.00	238.37	136.99	17.18	15.25	7.48	0.00	31.71	0.11
RWSAB049	0.00	236.35	0.17	74.54	80.00	280.36	80.00	0.00	254.08	150.50	19.17	20.39	7.13	0.00	30.43	0.11
RWSAB050	0.00	180.87	0.26	117.02	80.00	291.00	80.00	0.00	477.84	42.74	33.70	19.34	13.81	0.00	33.73	0.15
RWSAB051	0.00	257.98	0.15	75.59	80.00	220.60	80.00	0.00	217.15	124.65	16.83	15.59	7.37	0.00	33.26	0.08
RWSAB052	0.00	216.46	0.14	74.87	6169.40	232.11	3173.60	0.00	211.73	128.97	15.88	15.30	6.14	0.00	22.09	0.10
RWSAB053	0.00	78.45	0.37	48.21	7799.50	298.84	80.00	0.00	694.12	57.64	40.43	19.66	17.25	0.00	24.25	0.23

RWSAB054	0.00	246.79	0.26	35.88	7024.60	229.25	80.00	0.00	316.38	147.38	27.83	15.99	13.00	0.00	22.23	0.15
RWSAB055	0.00	83.70	0.36	129.57	80.00	83.53	80.00	0.00	701.56	65.58	47.35	17.60	17.69	0.00	24.77	0.15
RWSAB056	0.00	0.00	0.58	34.38	80.00	78.34	80.00	0.00	881.65	0.00	53.19	28.19	30.12	0.00	30.11	0.22
RWSAB057	0.00	265.73	0.21	47.27	80.00	194.47	80.00	0.00	537.57	29.37	22.96	16.62	9.65	0.00	28.63	0.13
RWSAB058	0.00	0.00	0.30	1.69	80.00	247.37	80.00	0.00	839.00	57.71	41.76	19.46	15.31	0.00	44.04	0.14
RWSAB059	0.00	280.53	0.14	75.28	80.00	134.30	80.00	0.00	329.89	101.90	16.05	14.84	4.85	0.00	31.28	0.07
RWSAB060	0.00	232.64	0.19	99.88	15091.00	153.78	80.00	0.00	361.91	123.28	17.68	14.29	6.52	0.01	10.93	0.10
BLANK01	0.00	115.78	0.01	0.22	1980.10	5.39	73.97	13.82	2.35	1.35	2.37	6.67	0.08	0.00	2.34	0.03
BLANK02	0.00	146.40	0.01	1.03	9937.80	31.29	75.12	17.82	5.81	7.29	3.30	6.94	0.09	0.00	8.55	0.03
BLANK03	0.00	128.24	0.01	0.91	3239.90	21.90	74.29	9.99	4.64	6.60	3.15	6.54	0.02	0.00	2.49	0.03
CAL BLANK	38.10	2.73	0.00	0.01	11.91	0.86	2.35	2.68	0.20	0.34	0.12	0.25	0.01	0.00	0.01	0.01
CAL BLANK01	38.55	2.08	0.00	0.01	9.82	0.70	3.30	2.99	0.21	0.11	0.10	0.18	0.09	0.00	0.01	0.01
RINSE CHECK	0.00	0.00	0.05	0.58	216.19	10.22	45.85	3.03	2.86	7.85	5.56	20.85	0.05	0.00	0.02	0.09
std ms-3 at 8 ppb	0.00	0.00	0.00	0.01	8.00	0.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	0.00	8.00	8.00
std ms-3 at 8 ppb_01	0.00	8.00	0.00	0.00	8.00	0.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	0.00	8.00	8.00

Table B.1: Elementary concentrations (continued).

Sample Code	Radionuclide's activity concentrations (ppb)															
	Br	Kr	Rb	Sr	Y	Zr	Nb	Mo	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb
STD ppb check	0.00	0.00	6.41	6.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.16	5.66	7.35	0.00	0.00
BLANK	0.00	0.00	0.11	0.39	0.01	1.60	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	39.00	0.07
RWSA001	5.89	0.00	1687.80	17078.00	275.54	296.64	6.00	8.65	0.00	0.21	3.65	13.96	0.16	56.27	156.59	7.64
RWSA002	5.89	0.00	1661.90	12382.00	195.15	244.11	5.43	9.78	0.07	0.19	3.21	3.08	0.01	3.48	144.05	6.11
RWSA003	5.32	0.00	1621.20	11515.00	196.70	197.48	4.36	8.71	0.09	0.19	3.42	1.89	0.01	1.81	128.56	7.49
RWSA004	5.11	0.00	2036.80	18149.00	283.91	220.64	4.29	8.47	0.00	0.31	4.96	1.86	0.02	1.97	147.34	10.74
RWSAB005	3.71	0.00	1125.50	15744.00	200.48	101.25	1.07	5.35	0.01	0.14	1.43	0.52	0.00	0.00	79.89	3.18
RWSAB006	5.32	0.00	2040.60	20445.00	350.57	230.24	4.36	9.09	0.04	0.20	3.70	1.08	0.02	1.04	155.51	9.33
RWSAB007	4.74	0.00	2000.60	22782.00	408.59	382.96	4.13	8.51	0.00	0.21	4.12	0.98	0.01	2.07	180.16	9.85
RWSAB008	6.90	0.00	4343.40	80.00	581.45	375.30	4.14	7.21	0.02	0.26	6.37	2.40	0.05	3.82	222.04	8.66
RWSAB009	4.73	0.00	2103.40	39060.00	238.17	231.16	2.49	7.23	0.00	0.22	4.34	0.43	0.01	0.14	130.39	7.58
RWSAB010	4.96	0.00	4175.50	48273.00	658.64	483.02	3.95	17.54	0.09	0.21	13.85	1.49	0.04	4.51	258.46	10.18
RWSAB011	3.95	0.00	3958.80	60891.00	499.47	358.37	4.51	14.55	0.05	0.22	5.60	1.02	0.05	5.13	311.50	18.11
RWSAB012	4.38	0.00	1805.50	31743.00	833.29	605.50	4.03	10.14	0.03	0.25	7.89	2.49	0.08	12.60	495.36	16.24
RWSAB013	3.47	0.00	2063.50	13831.00	237.67	338.33	3.36	7.69	0.00	0.17	3.54	0.18	0.01	1.78	216.73	6.96
RWSAB014	3.97	0.00	2251.00	19804.00	424.32	494.79	4.38	10.57	0.00	0.19	3.96	0.59	0.01	3.16	271.68	4.10
RWSAB015	3.88	0.00	3058.10	55497.00	450.90	505.30	2.72	7.62	0.03	0.21	11.61	1.37	0.04	5.10	331.39	16.12
RWSAB016	2.91	0.00	956.18	10881.00	121.80	172.43	1.80	5.96	0.03	0.20	2.99	0.46	0.00	0.00	245.14	5.22
RWSAB017	2.51	0.00	1442.80	18472.00	180.69	386.72	1.48	4.74	0.03	0.18	2.84	0.11	0.00	0.22	262.74	4.31
RWSAB018	2.32	0.00	1505.80	21139.00	134.03	353.06	1.89	8.04	0.05	0.18	2.81	3.83	0.00	0.04	248.82	4.35
RWSAB019	1.91	0.00	1243.70	24768.00	116.07	150.89	0.69	4.27	0.00	0.17	3.38	0.00	0.00	0.00	219.90	2.59
RWSAB020	1.77	0.00	1063.30	24833.00	123.26	124.96	1.26	4.99	0.02	0.18	3.38	0.00	0.00	0.00	202.78	3.63
RWSAB021	3.58	0.00	3008.00	16696.00	141.56	89.07	0.00	0.71	0.02	0.02	1.20	9.16	0.19	48.20	508.49	3.25
RWSAB022	5.43	0.00	5653.90	10775.00	227.07	186.40	0.05	1.57	0.02	0.04	1.18	6.15	0.08	12.47	1791.34	5.48
RWSAB023	4.99	0.00	2260.40	9545.50	91.78	97.74	0.35	2.87	0.03	0.02	0.76	2.06	0.03	4.00	1630.16	5.57

RWSAB024	5.29	0.00	1682.60	6094.60	100.41	105.04	0.43	2.40	0.01	0.01	0.48	1.92	0.02	3.11	1592.85	5.52
RWSAB025	6.24	0.00	2718.40	16218.00	113.85	131.07	0.39	0.87	0.02	0.02	1.45	1.99	0.06	4.01	1718.70	5.09
PLKV026	5.57	0.00	1810.90	4593.10	122.31	110.12	0.19	4.20	0.01	0.01	0.60	1.20	0.00	3.04	1602.76	3.63
PLKV027	5.81	0.00	2685.70	6046.10	120.34	143.11	0.13	3.14	0.01	0.02	0.70	1.35	0.00	2.97	1629.85	2.22
PLKV028	7.27	0.00	112.50	18.97	21.96	25.12	0.34	2.22	0.00	0.00	0.07	0.08	0.00	0.00	36.95	0.13
PLKV029	0.00	0.00	33.11	6.56	13.40	0.54	0.01	0.23	0.00	0.00	0.01	0.00	0.00	0.00	0.13	0.00
PLKV030	0.00	0.00	162.47	42.80	38.53	41.74	0.48	2.13	0.00	0.00	0.11	0.10	0.00	0.00	40.25	0.30
PLKV031	0.00	0.00	130.58	25.88	30.17	38.26	0.49	2.38	0.00	0.00	0.09	0.07	0.00	0.00	39.82	0.39
PLKV032	0.00	0.00	21.08	7.62	9.38	1.05	0.02	0.23	0.00	0.00	0.01	0.00	0.00	0.00	1.37	0.01
RWSAB033	0.00	0.00	75.35	15.12	16.97	24.08	0.43	1.35	0.00	0.00	0.05	0.00	0.00	0.00	36.90	0.45
RWSAB034	0.00	0.00	89.66	16.95	10.98	25.45	0.62	1.47	0.00	0.00	0.05	0.00	0.00	0.00	35.71	0.16
RWSAB035	5.42	0.00	1589.80	4480.80	91.97	61.70	0.77	3.70	0.03	0.13	2.00	0.75	0.02	2.67	271.42	7.59
RWSAB036	4.96	0.00	1285.50	19733.00	75.33	75.98	0.82	2.74	0.00	0.14	3.03	0.64	0.01	2.27	236.78	5.37
RWSAB037	9.67	0.00	1096.60	6780.40	61.05	129.18	10.41	2.83	0.02	0.05	1.26	1.86	0.02	2.75	151.75	19.81
RWSAB038	9.61	0.00	1534.30	8392.90	106.08	228.27	18.52	4.19	0.03	0.05	1.18	2.33	0.03	3.75	184.85	13.57
RWSAB039	8.72	0.00	845.46	6148.30	50.79	115.40	10.32	4.21	0.03	0.05	0.92	1.84	0.02	2.02	138.44	38.60
RWSAB040	14.46	0.00	3427.20	12166.00	231.12	478.88	30.25	19.15	0.05	0.12	8.46	4.53	0.06	7.30	367.91	21.02
RWSAB041	9.38	0.00	1678.40	7142.40	93.12	153.41	12.88	9.99	0.03	0.06	1.17	2.57	0.03	3.57	177.88	42.70
RWSAB042	9.60	0.00	1837.40	7098.90	94.40	141.04	11.20	11.96	0.03	0.04	1.19	2.66	0.03	3.18	175.78	189.67
RWSAB043	9.45	0.00	1396.60	6246.10	68.88	108.53	9.16	14.31	0.02	0.06	1.09	2.20	0.02	2.31	151.79	15.46
RWSAB044	9.49	0.00	1524.10	6438.80	78.87	141.58	12.88	3.01	0.03	0.06	0.97	1.78	0.02	2.49	172.47	22.15
RWSAB045	8.67	0.00	1257.40	6372.90	63.46	135.30	11.72	2.97	0.02	0.05	0.89	1.51	0.02	2.48	165.51	13.47
RWSAB046	9.15	0.00	1921.70	12074.00	104.93	153.04	10.30	3.14	0.03	0.06	1.52	1.45	0.03	3.59	198.41	13.28
RWSAB047	8.88	0.00	1391.40	6479.60	90.00	132.21	14.52	6.23	0.01	0.06	1.03	1.74	0.02	2.64	180.48	17.03
RWSAB048	8.76	0.00	1260.40	9080.30	61.67	106.42	9.48	1.22	0.02	0.05	1.26	1.21	0.03	2.47	154.75	11.37
RWSAB049	7.90	0.00	1396.70	9992.10	47.69	105.77	7.85	44.70	0.02	0.05	1.23	1.27	0.02	1.83	162.16	11.94
RWSAB050	8.53	0.00	2498.50	17555.00	127.84	131.19	11.25	8.06	0.03	0.06	1.92	1.71	0.05	4.01	325.95	24.36
RWSAB051	8.73	0.00	1208.00	9240.90	58.24	90.93	7.57	1.00	0.02	0.05	1.16	1.14	0.02	2.29	149.32	11.16
RWSAB052	6.87	0.00	1202.00	9177.50	43.85	84.85	7.55	3.97	0.00	0.04	1.13	1.15	0.02	1.81	125.89	22.63

RWSAB053	7.64	0.00	3245.00	17359.00	219.54	204.50	13.73	6.18	0.03	0.06	1.87	13.86	0.05	4.98	229.88	32.98
RWSAB054	6.93	0.00	1949.80	16327.00	110.89	187.40	14.03	2.17	0.04	0.06	1.49	2.06	0.04	4.38	217.85	41.62
RWSAB055	7.26	0.00	4096.90	10733.00	157.89	157.59	12.53	4.77	0.03	0.05	1.40	2.23	0.05	4.76	218.05	57.62
RWSAB056	7.99	0.00	5450.40	10603.00	264.14	219.43	16.84	2.94	0.07	0.08	2.83	3.09	0.07	9.97	403.36	18.81
RWSAB057	7.53	0.00	1818.20	8531.30	110.79	150.28	12.06	3.17	0.02	0.06	1.27	1.70	0.01	3.14	172.60	13.69
RWSAB058	8.92	0.00	3051.00	11345.00	166.91	200.17	11.26	2.10	0.00	0.08	2.74	2.44	0.05	4.28	187.90	20.16
RWSAB059	7.13	0.00	1146.50	11424.00	52.17	90.46	6.34	1.95	0.02	0.05	1.38	1.36	0.02	1.34	120.04	14.93
RWSAB060	4.78	0.00	1112.30	7641.80	73.47	74.77	5.59	2.37	0.02	0.05	0.82	1.26	0.02	2.05	126.81	11.57
BLANK01	5.31	0.00	51.82	1573.10	0.24	41.14	0.00	0.05	0.00	0.00	0.07	0.25	0.01	0.00	1577.88	1.58
BLANK02	6.14	0.00	59.69	1828.80	0.00	12.82	0.10	0.61	0.00	0.13	2.27	0.31	0.01	0.94	129.17	4.16
BLANK03	5.25	0.00	53.95	1780.10	0.00	6.47	0.09	0.66	0.00	0.12	2.12	0.20	0.00	0.38	172.16	5.67
CAL BLANK	0.91	0.00	0.88	49.40	0.00	0.09	0.01	0.05	0.00	0.00	0.01	0.06	0.00	0.24	3.23	2.04
CAL BLANK01	0.51	0.00	0.96	112.29	0.03	0.34	0.01	0.07	0.00	0.00	0.01	0.01	0.00	0.02	2.71	1.71
RINSE CHECK	18.19	0.00	26.35	11121.00	0.00	6.68	0.07	0.00	0.00	0.08	0.41	1.41	0.01	2.99	27.73	33.93
std ms-3 at 8 ppb	0.80	0.00	8.00	8.00	0.03	0.00	0.00	0.00	0.03	0.03	0.25	8.00	8.00	8.00	0.15	0.31
std ms-3 at 8 ppb_01	0.86	0.00	8.00	8.00	0.00	0.00	0.00	0.00	0.00	0.02	0.20	8.00	8.00	8.00	0.00	0.48

Table B.1: Elementary concentrations (continued).

Sample Code	Radionuclide's activity concentrations (ppb)												
	Te	I	Xe	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb
STD ppb check	0.00	0.00	0.00	5.83	6.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BLANK	0.00	0.00	0.00	0.07	0.48	0.02	0.07	0.00	0.27	0.00	0.12	0.00	0.00
RWSA001	0.00	1872.29	117.66	191.29	42401.40	1766.01	2182.92	179.36	551.95	80.44	17.03	74.03	10.94
RWSA002	0.00	1886.97	107.16	164.50	31571.24	1712.77	1797.58	163.39	486.16	66.35	13.74	56.98	8.29
RWSA003	0.00	1788.36	160.38	150.90	29196.85	1518.32	1562.77	150.23	464.32	65.54	13.85	56.56	8.20
RWSA004	7.45	2008.90	221.61	186.15	9666.46	2273.46	2478.02	230.57	703.24	98.91	19.43	83.95	12.21
RWSAB005	0.24	1270.56	0.00	90.33	30624.62	1606.51	1622.28	154.46	469.44	66.39	13.44	60.26	8.27
RWSAB006	1.62	2084.89	136.89	188.84	16081.48	2561.48	2548.23	248.10	756.40	105.97	22.53	93.79	13.23
RWSAB007	1.21	2647.48	111.35	175.65	14728.98	2301.75	2355.03	244.98	795.03	116.58	25.12	106.56	15.58
RWSAB008	2.10	5607.92	100.15	394.27	0.00	4459.90	1193.03	428.13	1278.48	174.62	37.28	155.74	22.76
RWSAB009	1.42	2141.23	121.16	197.89	0.00	2189.61	2353.77	207.21	608.32	82.03	15.90	69.58	9.81
RWSAB010	1.60	3560.36	89.20	417.37	0.00	4673.29	1172.10	466.48	1391.16	188.68	40.83	169.65	25.22
RWSAB011	2.72	4639.39	121.86	493.23	0.00	4400.50	1255.72	413.17	1198.23	161.87	30.66	137.03	20.21
RWSAB012	2.62	2575.33	56.10	745.61	0.00	1804.88	43.45	703.99	2090.91	286.34	56.10	239.93	35.37
RWSAB013	0.00	2183.99	74.24	235.53	36609.24	2069.76	2086.33	190.19	555.38	76.59	16.11	65.65	9.66
RWSAB014	1.43	2321.24	80.79	269.61	15725.09	2670.24	2988.12	275.69	863.39	127.90	27.21	111.69	16.46
RWSAB015	2.25	3979.32	112.20	416.79	0.00	3805.66	1076.71	372.43	1100.72	156.24	30.33	129.18	18.80
RWSAB016	0.52	1208.37	11.22	96.99	24490.74	1431.19	1556.98	140.29	420.93	57.53	10.23	46.69	6.10
RWSAB017	0.67	1413.50	0.00	114.62	42555.88	1240.50	1396.98	120.91	375.14	54.70	11.35	49.54	7.43
RWSAB018	0.77	2045.73	0.00	122.48	31008.62	949.68	1043.56	89.15	271.69	36.70	7.83	33.31	4.86
RWSAB019	0.31	1722.36	0.00	91.33	34249.82	957.94	1169.57	95.23	284.49	39.93	6.86	33.54	4.88
RWSAB020	0.19	2005.67	0.00	82.85	27309.66	1486.79	1574.22	133.96	389.99	49.57	7.14	40.91	5.77
RWSAB021	0.22	728.97	0.00	325.23	80.00	2580.68	2927.75	246.88	742.84	98.33	18.95	86.43	12.74
RWSAB022	1.22	4010.69	52.01	541.39	80.00	3257.66	928.94	321.73	957.91	136.11	24.76	126.98	19.00
RWSAB023	1.31	1790.98	56.04	152.49	16467.55	2023.28	2148.29	187.46	555.38	76.33	14.44	61.31	8.63

RWSAB024	1.27	2311.31	0.00	131.15	11704.06	1921.77	2062.62	181.18	544.29	76.02	13.75	67.82	9.41
RWSAB025	0.90	4209.15	162.61	183.85	15962.00	1899.90	2141.57	182.22	540.13	74.97	15.01	64.51	9.60
PLKV026	0.00	2374.54	91.58	140.21	34419.92	2356.75	2443.35	225.95	675.10	92.50	16.03	80.12	11.44
PLKV027	1.05	3657.37	51.94	198.12	43085.72	2332.01	2527.80	216.32	645.19	85.16	16.56	75.08	10.46
PLKV028	0.00	12.47	0.00	4.77	110.11	50.63	92.94	12.18	46.80	8.70	1.71	8.53	1.27
PLKV029	0.00	0.00	0.00	0.69	64.91	22.97	39.89	5.88	22.71	4.48	1.01	4.33	0.67
PLKV030	0.00	16.28	0.00	5.80	289.10	78.12	152.73	19.01	74.61	14.20	2.88	14.07	2.14
PLKV031	0.01	0.00	0.00	5.63	176.93	66.35	125.18	15.61	60.52	11.23	2.03	11.48	1.76
PLKV032	0.00	0.00	0.00	0.45	52.75	17.01	31.33	4.15	16.17	3.15	0.77	2.99	0.46
RWSAB033	0.00	0.00	0.00	3.35	103.70	37.73	70.49	9.07	33.99	6.44	1.21	6.39	0.96
RWSAB034	0.00	0.00	0.00	4.54	113.47	29.69	52.20	7.05	26.54	4.66	1.02	4.30	0.63
RWSAB035	0.70	1616.57	0.00	125.72	29834.62	2091.75	2342.27	206.58	614.58	81.26	11.76	65.24	9.00
RWSAB036	0.03	1730.97	0.00	91.74	36002.10	1708.86	1884.69	155.33	456.04	58.51	10.45	48.98	6.97
RWSAB037	1.45	1648.13	0.00	97.72	27698.00	1671.39	1883.04	161.93	475.12	63.08	9.09	49.48	6.25
RWSAB038	0.00	1947.29	29.56	138.85	39266.57	3044.51	877.46	308.35	894.32	126.09	14.00	89.68	11.95
RWSAB039	0.00	1612.46	25.29	77.58	24703.56	1133.30	1240.51	112.49	328.79	44.98	7.24	35.36	5.09
RWSAB040	2.77	2383.48	0.00	304.42	80.00	4049.75	1079.54	415.24	1225.30	171.71	30.26	137.71	19.06
RWSAB041	0.00	2076.82	85.43	163.15	37094.86	2348.25	2408.91	231.63	670.40	89.86	14.20	70.27	9.14
RWSAB042	0.00	2124.49	79.96	159.96	36097.30	1731.96	1755.34	171.05	508.22	69.56	14.38	55.24	8.05
RWSAB043	0.00	1953.75	80.48	121.32	27944.25	1298.89	1360.00	132.28	385.12	53.95	10.16	42.01	6.05
RWSAB044	0.00	2041.23	101.15	130.92	31785.91	1334.81	1364.25	132.72	390.79	54.82	11.08	44.48	6.65
RWSAB045	0.00	1761.16	112.77	117.96	30272.55	1044.25	1151.49	105.35	312.57	45.24	9.41	37.06	5.40
RWSAB046	1.68	2523.06	7.52	145.49	13538.72	2480.53	2827.52	244.44	709.17	93.93	14.64	70.84	10.25
RWSAB047	0.00	2159.38	28.47	108.68	30407.46	1825.22	1847.46	172.44	506.62	67.83	13.17	53.58	7.35
RWSAB048	0.00	2040.60	0.00	95.05	36911.29	1098.67	1253.12	108.34	321.78	44.21	8.89	35.08	5.15
RWSAB049	0.00	2980.66	40.32	110.24	30857.42	915.03	1004.10	86.84	254.72	34.49	6.80	26.97	3.91
RWSAB050	2.81	3309.27	0.00	270.36	80.00	2419.23	2711.81	230.89	663.52	89.46	16.66	70.16	10.33
RWSAB051	0.00	2014.77	0.00	91.57	35962.06	1161.59	1336.51	112.76	332.91	43.28	8.68	33.99	4.97
RWSAB052	0.00	2719.12	29.02	99.57	28538.66	869.06	967.67	84.09	244.12	33.74	6.11	25.98	3.81

RWSAB053	2.48	3537.17	0.00	298.22	80.00	3355.09	848.95	332.37	997.48	139.71	29.13	116.60	17.29
RWSAB054	3.36	3412.90	47.16	224.14	16491.39	2083.39	2332.99	199.60	573.54	79.18	15.55	64.53	9.74
RWSAB055	2.08	3992.73	27.92	413.70	16566.58	3014.31	2082.40	294.19	877.43	125.67	21.10	103.65	15.36
RWSAB056	2.27	2541.41	58.78	502.43	80.00	5204.82	41.18	517.26	1525.71	205.65	39.04	161.01	23.44
RWSAB057	1.31	2166.23	11.62	156.73	12953.77	2291.96	2469.53	218.37	627.14	84.42	14.94	66.82	9.66
RWSAB058	1.55	4304.79	0.00	241.74	80.00	2781.74	2954.97	263.18	784.53	107.87	22.36	89.47	13.00
RWSAB059	0.00	1867.96	0.00	100.82	41004.35	952.71	1033.47	90.38	260.61	35.93	7.44	29.17	4.29
RWSAB060	0.94	2079.77	0.00	94.96	33184.78	1487.48	1524.98	145.78	422.52	56.87	10.99	45.72	6.47
BLANK01	0.00	1184.33	53.31	0.61	2432.00	2.32	2.76	0.22	0.68	0.07	0.03	0.06	0.01
BLANK02	0.00	1056.01	91.43	0.73	2804.95	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
BLANK03	0.00	932.47	19.64	0.40	2790.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CAL BLANK	0.03	158.81	93.13	0.24	60.44	0.02	0.09	0.00	0.06	0.00	0.00	0.00	0.00
CAL BLANK01	0.00	111.34	86.45	0.05	51.79	0.26	0.31	0.02	0.11	0.01	0.00	0.01	0.00
RINSE CHECK	0.05	2966.64	77.91	2.99	14138.40	0.00	0.00	0.00	0.95	0.00	0.06	0.00	0.01
std ms-3 at 8 ppb	0.09	224.10	0.00	8.00	0.00	0.17	0.12	0.01	0.02	0.07	0.08	0.00	0.00
std ms-3 at 8 ppb_01	0.04	213.70	0.00	8.00	8.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00

Table B.1: Elementary concentrations (continued).

Sample Code	Radionuclide's activity concentrations (ppb)									
	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re
STD ppb check	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BLANK	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
RWSA001	64.33	11.43	29.57	3.99	25.00	3.89	20.79	0.06	1.34	0.03
RWSA002	47.26	8.35	21.21	3.03	19.08	2.94	17.71	0.06	0.98	0.04
RWSA003	46.78	8.23	21.31	2.97	18.80	3.02	13.60	0.03	1.46	0.02
RWSA004	68.14	11.78	30.61	4.19	27.31	4.43	16.39	0.24	1.98	0.34
RWSAB005	48.01	8.28	20.67	2.86	18.55	2.85	6.03	0.04	0.26	0.02
RWSAB006	77.87	13.62	35.56	4.84	31.16	4.90	15.99	0.06	1.81	0.02
RWSAB007	91.93	16.46	41.68	5.79	35.94	5.59	25.39	0.07	1.53	0.02
RWSAB008	128.75	23.11	59.08	8.26	51.60	8.05	26.61	0.10	1.46	0.03
RWSAB009	55.24	9.67	24.75	3.47	22.26	3.51	15.50	0.05	1.53	0.02
RWSAB010	148.42	26.45	68.39	9.62	61.44	9.80	34.43	0.13	1.28	0.02
RWSAB011	115.60	20.24	53.74	7.36	46.54	7.20	26.06	0.10	2.10	0.03
RWSAB012	202.75	34.84	89.49	12.38	79.47	12.32	44.84	0.16	1.42	0.03
RWSAB013	54.75	9.69	25.19	3.53	22.43	3.48	22.85	0.04	1.05	0.02
RWSAB014	97.68	17.14	44.65	6.14	38.12	5.93	31.41	0.07	1.00	0.02
RWSAB015	106.50	18.74	46.83	6.52	41.04	6.23	31.81	0.08	1.21	0.02
RWSAB016	31.29	5.19	12.94	1.85	11.54	1.72	11.50	0.03	0.16	0.02
RWSAB017	41.92	7.39	18.95	2.81	18.48	2.95	21.83	0.02	0.50	0.02
RWSAB018	29.90	5.45	14.78	2.16	14.54	2.29	19.46	0.03	0.42	0.02
RWSAB019	27.98	4.79	12.16	1.72	11.28	1.77	7.88	0.02	0.31	0.01
RWSAB020	30.96	5.19	12.84	1.76	11.05	1.76	8.43	0.02	0.19	0.02
RWSAB021	76.42	13.68	35.94	5.06	32.42	5.16	13.17	0.06	0.08	0.05
RWSAB022	114.85	20.99	55.21	8.09	52.74	8.28	23.89	0.09	0.14	0.06
RWSAB023	48.72	8.42	21.48	3.03	19.00	2.97	11.98	0.04	0.40	0.05

RWSAB024	53.27	9.21	24.53	3.41	21.76	3.45	13.50	0.04	0.06	0.03
RWSAB025	56.97	10.59	28.10	4.12	26.47	4.15	17.77	0.04	0.03	0.04
PLKV026	64.91	11.12	28.64	3.98	25.04	3.91	14.92	0.05	0.12	0.02
PLKV027	61.48	10.76	27.73	3.91	24.36	3.83	17.79	0.05	0.08	0.04
PLKV028	7.09	1.22	3.16	0.45	2.82	0.41	1.25	0.00	0.00	0.00
PLKV029	4.11	0.77	2.13	0.30	1.94	0.29	0.02	0.00	0.00	0.00
PLKV030	12.23	2.22	5.65	0.79	4.98	0.73	1.86	0.01	0.00	0.00
PLKV031	9.73	1.72	4.52	0.64	3.98	0.58	1.87	0.01	0.00	0.00
PLKV032	2.81	0.53	1.43	0.21	1.28	0.20	0.04	0.00	0.00	0.00
RWSAB033	5.51	0.98	2.55	0.35	2.16	0.32	1.17	0.00	0.00	0.00
RWSAB034	3.45	0.60	1.59	0.22	1.34	0.20	1.16	0.01	0.00	0.00
RWSAB035	49.76	8.37	22.00	3.10	18.86	3.11	9.01	0.04	0.48	0.03
RWSAB036	39.55	6.83	18.12	2.68	16.78	2.65	11.05	0.03	0.22	0.08
RWSAB037	30.42	5.42	13.80	1.87	11.91	1.88	13.80	0.21	2.53	0.03
RWSAB038	59.42	9.42	23.01	3.31	19.85	3.00	25.44	0.07	3.95	0.03
RWSAB039	27.27	4.50	11.09	1.58	9.72	1.58	13.02	0.25	3.16	0.03
RWSAB040	102.27	17.90	45.97	6.40	39.67	5.96	44.58	0.29	8.55	0.05
RWSAB041	47.68	8.28	20.67	2.83	18.11	2.74	18.76	0.16	3.92	0.03
RWSAB042	47.35	8.17	21.42	3.00	19.06	3.04	16.26	0.13	4.11	0.02
RWSAB043	34.39	5.93	15.08	2.18	13.75	2.06	12.39	0.07	3.36	0.02
RWSAB044	38.41	6.85	18.02	2.61	16.63	2.59	15.83	0.11	4.03	0.02
RWSAB045	31.66	5.58	14.46	2.09	12.96	2.02	16.01	0.22	2.86	0.03
RWSAB046	55.88	9.13	22.53	3.11	19.23	3.01	17.05	0.29	4.07	0.03
RWSAB047	41.86	7.53	19.12	2.88	17.90	2.79	14.21	0.05	7.14	0.03
RWSAB048	29.98	5.47	13.65	1.97	12.32	2.00	12.29	0.11	4.10	0.02
RWSAB049	23.17	4.09	10.62	1.54	9.98	1.61	11.63	0.09	6.05	0.05
RWSAB050	60.82	10.90	28.13	3.92	24.54	3.85	15.83	0.05	6.48	0.03
RWSAB051	28.83	5.12	13.44	1.94	11.68	1.75	10.49	0.11	3.31	0.03
RWSAB052	22.20	3.96	9.94	1.47	9.22	1.51	9.97	0.22	4.01	0.02

RWSAB053	103.18	18.55	47.79	7.05	43.18	6.92	25.44	0.08	6.14	0.03
RWSAB054	54.91	9.75	25.04	3.44	21.68	3.43	21.11	0.05	6.12	0.02
RWSAB055	84.71	14.08	35.08	4.72	31.15	4.86	18.02	0.07	8.82	0.03
RWSAB056	128.90	22.63	59.33	8.30	53.15	8.11	25.40	0.13	9.61	0.03
RWSAB057	54.03	9.51	23.90	3.17	21.11	3.31	15.98	0.19	3.54	0.02
RWSAB058	74.88	13.48	35.41	4.89	31.27	4.92	22.10	0.06	3.43	0.02
RWSAB059	24.05	4.27	10.93	1.66	10.59	1.58	9.04	0.17	3.91	0.01
RWSAB060	36.84	6.24	16.16	2.40	14.63	2.38	8.43	0.03	1.18	0.01
BLANK01	0.02	0.01	0.03	0.00	0.02	0.01	4.24	0.01	0.96	0.03
BLANK02	0.00	0.00	0.00	0.00	0.00	0.00	1.95	0.00	0.46	0.01
BLANK03	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.66	0.01
CAL BLANK	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00
CAL BLANK01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00
RINSE CHECK	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.00	0.48	0.04
std ms-3 at 8 ppb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
std ms-3 at 8 ppb_01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B.1: Elementary concentrations (continued).

Sample Code	Radionuclide's activity concentrations (ppb)									
	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Th	U
STD ppb check	0.00	0.00	0.00	0.00	0.00	5.66	5.15	0.00	0.00	5.44
BLANK	0.02	0.00	0.00	0.00	0.01	0.00	0.14	0.00	0.16	0.00
RWSA001	0.01	0.04	1.29	0.28	1.01	23.13	406.35	238.92	108.96	302.59
RWSA002	0.00	0.04	1.45	0.72	1.07	11.70	344.01	11.04	106.10	108.15
RWSA003	0.00	0.04	1.48	0.08	0.68	9.64	336.38	6.03	86.56	45.88
RWSA004	0.57	0.51	2.68	1.58	6.85	12.52	394.86	6.18	109.90	31.96
RWSAB005	0.00	0.00	1.04	0.13	0.52	6.68	363.31	1.80	117.45	61.27
RWSAB006	0.00	0.02	1.39	0.19	1.25	10.81	383.68	5.57	119.47	63.39
RWSAB007	0.00	0.05	1.55	0.29	0.84	9.74	329.34	3.29	94.34	108.52
RWSAB008	0.01	0.06	1.45	0.45	1.20	23.65	649.74	6.46	173.61	399.75
RWSAB009	0.00	0.04	1.30	0.17	0.80	9.86	307.76	1.87	96.65	0.00
RWSAB010	0.00	0.12	1.66	0.31	1.43	24.06	583.68	9.07	214.13	972.45
RWSAB011	0.00	0.08	1.60	0.35	1.61	25.43	681.45	12.97	188.06	144.19
RWSAB012	0.00	0.11	1.61	0.32	1.44	42.12	840.17	18.48	293.73	445.16
RWSAB013	0.00	0.05	1.47	0.21	0.53	13.40	337.75	4.31	89.12	0.00
RWSAB014	0.01	0.05	1.53	0.31	0.93	13.55	331.67	4.23	107.49	73.82
RWSAB015	0.00	0.09	1.57	0.23	1.85	19.51	714.37	15.19	174.89	659.36
RWSAB016	0.00	0.02	1.26	0.08	0.49	6.36	193.44	0.00	66.35	656.86
RWSAB017	0.00	0.05	1.20	0.12	0.57	7.04	254.70	1.56	70.74	127.80
RWSAB018	0.00	0.02	1.17	0.13	0.65	8.07	219.33	2.51	59.32	68.24
RWSAB019	0.00	0.00	0.97	0.05	0.75	4.06	184.24	0.80	62.42	599.02
RWSAB020	0.00	0.01	1.05	0.21	0.36	3.94	176.36	0.00	92.79	293.99
RWSAB021	0.00	0.03	0.07	0.29	0.26	28.71	418.33	8.97	16.09	50.27
RWSAB022	0.00	0.08	0.24	0.60	1.25	32.79	468.89	2.77	19.36	121.24
RWSAB023	0.00	0.03	0.06	0.38	0.52	13.51	243.15	0.62	10.45	68.85
RWSAB024	0.00	0.03	0.10	0.28	1.40	10.64	311.07	0.46	10.30	41.31

RWSAB025	0.00	0.03	0.05	0.56	0.88	12.00	350.77	0.52	10.72	51.63
PLKV026	0.00	0.05	0.04	0.21	0.00	11.17	304.56	0.34	16.18	74.13
PLKV027	0.00	0.03	0.08	0.13	0.96	14.03	266.00	0.31	14.23	308.68
PLKV028	0.01	0.00	0.00	0.00	0.04	0.45	22.47	0.00	39.39	3.20
PLKV029	0.00	0.00	0.00	0.00	0.02	0.15	12.94	0.00	6.09	1.53
PLKV030	0.01	0.00	0.01	0.00	0.06	0.62	31.78	0.00	37.72	3.30
PLKV031	0.00	0.00	0.01	0.00	0.04	0.56	21.28	0.00	40.75	4.12
PLKV032	0.00	0.00	0.00	0.01	0.03	0.09	6.19	0.00	4.88	0.32
RWSAB033	0.01	0.00	0.01	0.00	0.03	0.32	12.67	0.00	25.80	0.64
RWSAB034	0.01	0.00	0.00	0.00	0.03	0.37	10.19	0.00	17.07	0.21
RWSAB035	0.00	0.03	0.98	0.05	0.57	8.89	254.03	0.27	17.46	96.55
RWSAB036	0.00	0.04	0.95	0.06	0.57	7.47	256.60	0.22	11.11	88.81
RWSAB037	0.00	0.03	0.37	0.04	0.45	3.09	201.48	0.29	8.03	42.92
RWSAB038	0.00	0.02	0.40	0.04	0.73	5.13	253.39	0.23	18.66	84.61
RWSAB039	0.00	0.02	0.29	0.04	0.97	3.54	161.48	0.16	5.91	46.28
RWSAB040	0.00	0.08	0.74	0.17	2.12	11.51	495.20	0.46	19.22	174.45
RWSAB041	0.00	0.01	0.39	0.03	1.28	7.15	304.56	0.22	13.12	81.25
RWSAB042	0.00	0.02	0.37	0.09	1.41	7.11	340.73	0.23	8.16	46.01
RWSAB043	0.00	0.02	0.35	0.00	1.26	5.43	252.94	0.16	7.25	53.19
RWSAB044	0.00	0.03	0.33	0.00	0.45	6.09	196.72	0.18	6.62	43.60
RWSAB045	0.00	0.01	0.32	0.00	0.73	5.63	182.76	0.13	6.11	31.48
RWSAB046	0.00	0.02	0.36	0.00	0.87	6.78	231.94	0.21	11.29	79.21
RWSAB047	0.00	0.02	0.29	0.05	0.67	5.97	224.79	0.16	9.16	60.56
RWSAB048	0.00	0.03	0.29	0.06	0.35	4.80	168.43	0.14	5.27	73.65
RWSAB049	0.00	0.02	0.39	0.02	0.50	5.43	157.81	0.18	4.92	40.23
RWSAB050	0.00	0.04	0.37	0.03	0.84	9.53	322.12	0.33	11.40	77.07
RWSAB051	0.00	0.01	0.26	0.00	0.73	5.31	156.10	0.13	4.90	43.45
RWSAB052	0.00	0.02	0.25	0.00	0.51	5.36	142.92	0.13	4.83	29.93
RWSAB053	0.00	0.05	0.29	0.00	0.96	11.56	356.12	0.34	17.38	182.69

RWSAB054	0.00	0.02	0.35	0.04	1.40	9.22	307.45	0.43	10.33	38.80
RWSAB055	0.00	0.05	0.35	0.12	0.96	13.20	280.32	0.36	13.85	92.51
RWSAB056	0.00	0.06	0.46	0.15	1.31	17.80	469.28	0.56	20.61	81.19
RWSAB057	0.00	0.04	0.37	0.07	0.78	9.52	267.31	0.18	9.85	44.22
RWSAB058	0.00	0.03	0.35	0.06	1.02	10.91	330.29	0.20	10.16	19.20
RWSAB059	0.00	0.01	0.28	0.00	0.69	5.93	126.40	0.09	3.91	25.50
RWSAB060	0.00	0.02	0.23	0.00	0.70	6.92	198.42	0.13	11.65	16.35
BLANK01	0.00	0.00	0.00	0.04	0.59	0.11	5.67	0.03	0.06	0.00
BLANK02	0.00	0.00	0.97	0.06	0.13	0.23	5.16	0.17	0.00	0.00
BLANK03	0.00	0.00	1.05	0.03	0.31	0.09	4.57	0.01	0.00	0.00
CAL BLANK	0.00	0.00	0.01	0.01	0.02	0.17	0.41	0.02	0.00	9.35
CAL BLANK01	0.00	0.00	0.01	0.01	0.01	0.03	0.24	0.08	0.05	13.24
RINSE CHECK	0.00	0.00	0.56	0.05	0.00	2.08	26.01	0.46	0.00	164.30
std ms-3 at 8 ppb	0.00	0.00	0.00	0.01	0.11	8.00	8.00	8.00	0.00	8.00
std ms-3 at 8 ppb_01	0.00	0.00	0.00	0.00	0.12	8.00	8.00	8.00	0.00	8.00

APPENDIX C: POLONIUM-210 DETERMINATION AND ACTIVITY CONCENTRATIONS SPREADSHEET OF SOIL SAMPLES FROM THE PROPOSED RADIOACTIVE WASTE STORAGE AREA OF PILIKWE.

Table C.1: Soil samples from the proposed radioactive waste storage area of Pilikwe results analysis for ²¹⁰Po.

Sample ID	Depth (cm)	Sample mass (g)	²⁰⁹ Po added (g)	Tracer solution 18/04/2018 (Bq/g)	²⁰⁹ Po corrected activity (Bq)	Date of sample preparation	Date of sample deposition	Date of analysis	Quantification time (s)	Detector	²⁰⁹ Po (quantified counts)	²¹⁰ Po (quantified counts)
RWSA001	30.00	0.2688	0.0984±0.0007	0.188±0.004	0.0184±0.0004	16-04-19	18-04-19	25-04-19	75934.1	2A	179	16
RWSA002	30.00	0.2225	0.1090±0.0007	0.188±0.004	0.0204±0.0004	16-04-19	18-04-19	25-04-19	86400.1	2A	222	22
RWSA003	30.00	0.1018	0.0992±0.0007	0.188±0.004	0.0185±0.0004	16-04-19	18-04-19	25-04-19	77480.8	2B	249	10
RWSA004	30.00	0.2088	0.0975±0.0007	0.188±0.004	0.0182±0.0004	16-04-19	18-04-19	25-04-19	53707.8	2B	168	9
RWSAB005	30.00	0.2835	0.1046±0.0007	0.188±0.004	0.0195±0.0004	16-04-19	18-04-19	25-04-19	45174	2A	164	10
RWSAB006	30.00	0.2216	0.1016±0.0007	0.188±0.004	0.0190±0.0004	16-04-19	18-04-19	25-04-19	71699.9	3A	204	8
RWSAB007	30.00	0.2456	0.1062±0.0007	0.188±0.004	0.0198±0.0004	16-04-19	18-04-19	25-04-19	47741.7	3A	160	10
RWSAB008	30.00	0.2125	0.1065±0.0007	0.188±0.004	0.0199±0.0004	16-04-19	18-04-19	25-04-19	38095.7	2B	132	11
RWSAB009	30.00	0.2338	0.1050±0.0007	0.188±0.004	0.0196±0.0004	16-04-19	18-04-19	25-04-19	56283	3B	190	7
RWSAB010	30.00	0.2240	0.1038±0.0007	0.188±0.004	0.0194±0.0004	16-04-19	18-04-19	25-04-19	43209.7	3B	130	11
RWSAB011	30.00	0.2196	0.0995±0.0007	0.188±0.004	0.0186±0.0004	16-04-19	18-04-19	25-04-19	54051	4A	177	5
RWSAB012	30.00	0.2933	0.1029±0.0007	0.188±0.004	0.0192±0.0004	16-04-19	18-04-19	25-04-19	43748.1	4A	127	6
Ref Material: BOT 7003 Soil test sample	30.00	0.2408	0.1002±0.0007	0.188±0.004	0.0187±0.0004	16-04-19	18-04-19	25-04-19	43144.4	4B	125	12
Tracer blank	30.00		0.1026±0.0007	0.188±0.004	0.0192±0.0004	16-04-19	18-04-19	25-04-19	43150	4B	148	9
RWSAB013	30.00	0.2360	0.0643±0.0007	0.188±0.004	0.0120±0.0004	19-04-19	23-04-19	30-04-19	67292.8	3A	120	7
RWSAB014	30.00	0.2283	0.1160±0.0007	0.188±0.004	0.0217±0.0004	19-04-19	23-04-19	30-04-19	61971.4	3B	210	41
RWSAB015	30.00	0.2035	0.1073±0.0007	0.188±0.004	0.0200±0.0004	19-04-19	23-04-19	30-04-19	31844.9	4A	109	2
RWSAB016	30.00	0.2318	0.0982±0.0007	0.188±0.004	0.0183±0.0004	19-04-19	23-04-19	30-04-19	53044.5	4B	171	33

RWSAB017	30.00	0.2663	0.0947±0.0007	0.188±0.004	0.0177±0.0004	19-04-19	23-04-19	30-04-19	46530	2A	131	3
RWSAB018	30.00	0.2121	0.1059±0.0007	0.188±0.004	0.0198±0.0004	19-04-19	23-04-19	30-04-19	47704.7	2B	156	3
RWSAB019	30.00	0.2928	0.0997±0.0007	0.188±0.004	0.0186±0.0004	19-04-19	23-04-19	30-04-19	75139.9	3A	228	4
RWSAB020	30.00	0.2585	0.1093±0.0007	0.188±0.004	0.0204±0.0004	19-04-19	23-04-19	30-04-19	52096.8	3B	185	2
RWSAB021	30.00	0.2930	0.1157±0.0007	0.188±0.004	0.0216±0.0004	19-04-19	23-04-19	30-04-19	85130.2	2B	182	13
RWSAB022	30.00	0.2043	0.1154±0.0007	0.188±0.004	0.0215±0.0004	19-04-19	23-04-19	30-04-19	86400	2A	211	4
RWSAB023	30.00	0.2649	0.1145±0.0007	0.188±0.004	0.0214±0.0004	19-04-19	23-04-19	30-04-19	86400	2B	201	3
Ref Material: BOT 7003 Soil test sample	30.00	0.2239	0.1078±0.0007	0.188±0.004	0.0201±0.0004	19-04-19	23-04-19	30-04-19	86400	4A	253	11
Tracer blank	30.00		0.0991±0.0007	0.188±0.004	0.0185±0.0004	19-04-19	23-04-19	30-04-19	37583.9	4B	123	5
RWSAB024	30.00	0.2141	0.1056±0.0007	0.188±0.004	0.0197±0.0004	19-04-19	23-04-19	30-04-19	86400	3A	278	2
RWSAB025	30.00	0.2798	0.1005±0.0007	0.188±0.004	0.0188±0.0004	23-04-19	26-04-19	03-05-19	64797.1	2B	212	5
PLKV026	30.00	0.2743	0.1048±0.0007	0.188±0.004	0.0196±0.0004	23-04-19	26-04-19	03-05-19	86400.1	3A	215	8
PLKV027	30.00	0.2660	0.1005±0.0007	0.188±0.004	0.0188±0.0004	23-04-19	26-04-19	03-05-19	76202.4	3B	211	4
PLKV028	30.00	0.2657	0.1055±0.0007	0.188±0.004	0.0197±0.0004	23-04-19	26-04-19	03-05-19	78528.2	4A	224	3
PLKV029	30.00	0.2299	0.1015±0.0007	0.188±0.004	0.0189±0.0004	23-04-19	26-04-19	03-05-19	76027.3	4B	236	3
PLKV030	30.00	0.2433	0.0977±0.0007	0.188±0.004	0.0182±0.0004	23-04-19	26-04-19	03-05-19	70465.9	2B	186	3
PLKV031	30.00	0.2301	0.0983±0.0007	0.188±0.004	0.0184±0.0004	23-04-19	26-04-19	03-05-19	65062.9	3A	201	4
PLKV032	30.00	0.2802	0.1006±0.0007	0.188±0.004	0.0188±0.0004	23-04-19	26-04-19	03-05-19	67463.1	3B	222	5
RWSAB033	30.00	0.2495	0.1028±0.0007	0.188±0.004	0.0192±0.0004	23-04-19	26-04-19	03-05-19	69315.4	4A	213	5
RWSAB034	30.00	0.2336	0.1023±0.0007	0.188±0.004	0.0191±0.0004	23-04-19	26-04-19	03-05-19	79999.3	3A	218	3
RWSAB035	30.00	0.2284	0.1070±0.0007	0.188±0.004	0.0200±0.0004	23-04-19	26-04-19	03-05-19	40085.4	3B	128	12
Ref Material: BOT 7003 Soil test sample	30.00	0.2367	0.1007±0.0007	0.188±0.004	0.0188±0.0004	23-04-19	26-04-19	03-05-19	86400	4A	217	14
Tracer blank	30.00		0.0996±0.0007	0.188±0.004	0.0186±0.0004	23-04-19	26-04-19	03-05-19	33668	4B	108	8
RWSAB036	30.00	0.2667	0.0984±0.0007	0.188±0.004	0.0184±0.0004	23-04-19	26-04-19	03-05-19	57971.8	4A	138	12
RWSAB037	30.00	0.2018	0.1005±0.0007	0.188±0.004	0.0188±0.0004	29-04-19	01-05-19	08-05-19	86400	2A	227	6
RWSAB038	30.00	0.2088	0.1048±0.0007	0.188±0.004	0.0196±0.0004	29-04-19	01-05-19	08-05-19	86400	2A	208	12
RWSAB039	30.00	0.2835	0.1005±0.0007	0.188±0.004	0.0188±0.0004	29-04-19	01-05-19	08-05-19	86400	2B	238	1

RWSAB040	30.00	0.2216	0.1055±0.0007	0.188±0.004	0.0197±0.0004	29-04-19	01-05-19	08-05-19	86400	2B	220	7
RWSAB041	30.00	0.2456	0.1015±0.0007	0.188±0.004	0.0189±0.0004	29-04-19	01-05-19	08-05-19	37583.9	2A	110	4
RWSAB042	30.00	0.2125	0.0977±0.0007	0.188±0.004	0.0182±0.0004	29-04-19	01-05-19	08-05-19	64797.1	3A	219	2
RWSAB043	30.00	0.2338	0.0983±0.0007	0.188±0.004	0.0184±0.0004	29-04-19	01-05-19	08-05-19	86400.1	3A	226	3
RWSAB044	30.00	0.2240	0.1006±0.0007	0.188±0.004	0.0188±0.0004	29-04-19	01-05-19	08-05-19	76202.4	2B	191	3
RWSAB045	30.00	0.2196	0.1028±0.0007	0.188±0.004	0.019±0.00042	29-04-19	01-05-19	08-05-19	78528.2	3B	196	3
RWSAB046	30.00	0.2933	0.1023±0.0007	0.188±0.004	0.0191±0.0004	29-04-19	01-05-19	08-05-19	76027.3	3B	228	4
RWSAB047	30.00	0.2408	0.1070±0.0007	0.188±0.004	0.0200±0.0004	29-04-19	01-05-19	08-05-19	70465.9	4A	225	2
Ref Material: BOT 7003 Soil test sample	30.00	0.2408	0.1007±0.0007	0.188±0.004	0.0188±0.0004	29-04-19	01-05-19	08-05-19	67463.1	4B	211	4
Tracer blank	30.00		0.0996±0.0007	0.188±0.004	0.0186±0.0004	29-04-19	01-05-19	08-05-19	69315.4	4B	201	9
RWSAB048	30.00	0.2125	0.1084±0.0007	0.188±0.004	0.0202±0.0004	06-05-19	08-05-19	15-05-19	65062.9	4A	182	3
RWSAB049	30.00	0.2035	0.1090±0.0007	0.188±0.004	0.0203±0.0004	06-05-19	08-05-19	15-05-19	79999.3	3A	278	2
RWSAB050	30.00	0.2318	0.0992±0.0007	0.188±0.004	0.0185±0.0004	06-05-19	08-05-19	15-05-19	56283	3B	153	14
RWSAB051	30.00	0.2663	0.0975±0.0007	0.188±0.004	0.0182±0.0004	06-05-19	08-05-19	15-05-19	43209.7	4A	139	3
RWSAB052	30.00	0.2121	0.1046±0.0007	0.188±0.004	0.0195±0.0004	06-05-19	08-05-19	15-05-19	54051	4B	200	2
RWSAB053	30.00	0.2239	0.1016±0.0007	0.188±0.004	0.0190±0.0004	06-05-19	08-05-19	15-05-19	43748.1	2A	154	4
RWSAB054	30.00	0.2125	0.1062±0.0007	0.188±0.004	0.019±0.00048	06-05-19	08-05-19	15-05-19	43144.4	2B	134	19
RWSAB055	30.00	0.2798	0.1065±0.0007	0.188±0.004	0.0199±0.0004	06-05-19	08-05-19	15-05-19	43150	3A	112	5
RWSAB056	30.00	0.2743	0.1050±0.0007	0.188±0.004	0.0196±0.0004	06-05-19	08-05-19	15-05-19	67292.8	3B	217	14
RWSAB057	30.00	0.2660	0.1038±0.0007	0.188±0.004	0.0194±0.0004	06-05-19	08-05-19	15-05-19	61971.4	2B	230	16
RWSAB058	30.00	0.2657	0.1047±0.0007	0.188±0.004	0.0195±0.0004	06-05-19	08-05-19	15-05-19	31844.9	2A	120	10
RWSAB059	30.00	0.2367	0.1029±0.0007	0.188±0.004	0.0192±0.0004	06-05-19	08-05-19	15-05-19	86400	4B	280	13
RWSAB060	30.00	0.2657	0.1032±0.0007	0.188±0.004	0.0193±0.0004	06-05-19	08-05-19	15-05-19	86400	2B	218	12
Ref Material: BOT 7003 Soil test sample	30.00	0.2408	0.1001±0.0007	0.188±0.004	0.0187±0.0004	06-05-19	08-05-19	15-05-19	78528.2	3B	227	6
Tracer blank	30.00		0.1028±0.0007	0.188±0.004	0.0192±0.0004	06-05-19	08-05-19	15-05-19	76027.3	4A	238	11

Table C.2: Soil samples from the proposed radioactive waste storage area of Pilikwe results analysis for ²¹⁰Po (continued).

Sample ID	²⁰⁹Po net (cpm)	Background ²⁰⁹Po (cpm)	²¹⁰Po net (cpm)	Background ²¹⁰Po (cpm)	Recovery (%)
RWSA001	0.139±0.011	0.0028±0.0014	0.011±0.003	0.0021±0.0012	68
RWSA002	0.151 ±0.010	0.0028±0.0014	0.013±0.003	0.0021±0.0012	67
RWSA003	0.193±0.012	0.0000±0.0000	0.007±0.003	0.0007±0.0007	94
RWSA004	0.188±0.014	0.0000±0.0000	0.009±0.003	0.0007±0.0007	93
RWSAB005	0.215±0.017	0.0028±0.0014	0.011±0.004	0.0021±0.0012	99
RWSAB006	0.170±0.012	0.0007±0.0007	0.007±0.002	0.0000±0.0000	84
RWSAB007	0.200±0.016	0.0007±0.0007	0.013±0.004	0.0000±0.0000	95
RWSAB008	0.208±0.018	0.0000±0.0000	0.017±0.005	0.0007±0.0007	95
RWSAB009	0.199±0.015	0.0035±0.0016	0.007±0.003	0.0007±0.0007	93
RWSAB010	0.177±0.016	0.0035±0.0016	0.015±0.005	0.0007±0.0007	84
RWSAB011	0.195±0.015	0.0014±0.0010	0.005±0.003	0.0007±0.0007	95
RWSAB012	0.173±0.015	0.0014±0.0010	0.008±0.003	0.0007±0.0007	82
Ref Material: BOT 7003 Soil test sample	0.168±0.016	0.0063±0.0021	0.016±0.005	0.0007±0.0007	83
Tracer blank	0.200 ±0.017	0.0063±0.0021	0.012±0.004	0.0007±0.0007	96
RWSAB013	0.106±0.010	0.0007±0.0007	0.006±0.002	0.0000±0.0000	83
RWSAB014	0.200±0.014	0.0035±0.0016	0.039±0.006	0.0007±0.0007	85
RWSAB015	0.204±0.020	0.0014±0.0010	0.003±0.003	0.0007±0.0007	92
RWSAB016	0.187±0.015	0.0063±0.0021	0.037±0.007	0.0007±0.0007	94
RWSAB017	0.166±0.015	0.0028±0.0014	0.002±0.003	0.0021±0.0012	85
RWSAB018	0.196±0.016	0.0000±0.0000	0.003±0.002	0.0007±0.0007	90

RWSAB019	0.181±0.012	0.0007±0.0007	0.003±0.002	0.0000±0.0000	92
RWSAB020	0.210±0.016	0.0035±0.0016	0.002±0.002	0.0007±0.0007	94
RWSAB021	0.128±0.010	0.0000±0.0000	0.008±0.003	0.0007±0.0007	54
RWSAB022	0.144±0.010	0.0028±0.0014	0.001±0.002	0.0021±0.0012	60
RWSAB023	0.140±0.010	0.0000±0.0000	0.001±0.001	0.0007±0.0007	59
Ref Material: BOT 7003 Soil test sample	0.174±0.011	0.0014±0.0010	0.007±0.002	0.0007±0.0007	79
Tracer blank	0.190±0.018	0.0063±0.0021	0.007±0.004	0.0007±0.0007	95
RWSAB024	0.192±0.012	0.0007±0.0007	0.001±0.001	0.0000±0.0000	92
RWSAB025	0.196±0.013	0.0000±0.0000	0.004±0.002	0.0007±0.0007	95
PLKV026	0.149±0.010	0.0007±0.0007	0.006±0.002	0.0000±0.0000	72
PLKV027	0.163±0.012	0.0035±0.0016	0.002±0.002	0.0007±0.0007	79
PLKV028	0.170±0.011	0.0014±0.0010	0.002±0.001	0.0007±0.0007	78
PLKV029	0.180±0.012	0.0063±0.0021	0.002±0.002	0.0007±0.0007	88
PLKV030	0.158±0.012	0.0000±0.0000	0.002±0.002	0.0007±0.0007	79
PLKV031	0.185±0.013	0.0007±0.0007	0.004±0.002	0.0000±0.0000	95
PLKV032	0.194±0.013	0.0035±0.0016	0.004±0.002	0.0007±0.0007	95
RWSAB033	0.183±0.013	0.0014±0.0010	0.004±0.002	0.0007±0.0007	86
RWSAB034	0.163±0.011	0.0007±0.0007	0.002±0.001	0.0000±0.0000	80
RWSAB035	0.188±0.017	0.0035±0.0016	0.017±0.005	0.0007±0.0007	86
Ref Material: BOT 7003 Soil test sample	0.149±0.010	0.0014±0.0010	0.009±0.003	0.0007±0.0007	72
Tracer blank	0.186±0.019	0.0063±0.0021	0.014±0.005	0.0007±0.0007	92
RWSAB036	0.141±0.012	0.0014±0.0010	0.012±0.004	0.0007±0.0007	70
RWSAB037	0.155±0.011	0.0028±0.0014	0.002±0.002	0.0021±0.0012	75
RWSAB038	0.142±0.010	0.0028±0.0014	0.006±0.003	0.0021±0.0012	65
RWSAB039	0.165±0.011	0.0000±0.0000	0.000±0.001	0.0007±0.0007	80
RWSAB040	0.153±0.010	0.0000±0.0000	0.004±0.002	0.0007±0.0007	70
RWSAB041	0.173±0.017	0.0028±0.0014	0.004±0.003	0.0021±0.0012	82

RWSAB042	0.202±0.014	0.0007±0.0007	0.002±0.001	0.0000±0.0000	104
RWSAB043	0.156±0.010	0.0007±0.0007	0.002±0.001	0.0000±0.0000	80
RWSAB044	0.150±0.011	0.0000±0.0000	0.002±0.002	0.0007±0.0007	73
RWSAB045	0.146±0.011	0.0035±0.0016	0.002±0.001	0.0007±0.0007	70
RWSAB046	0.176±0.012	0.0035±0.0016	0.002±0.002	0.0007±0.0007	85
RWSAB047	0.190±0.013	0.0014±0.0010	0.001±0.001	0.0007±0.0007	86
Ref Material: BOT 7003 Soil test sample	0.181±0.013	0.0063±0.0021	0.003±0.002	0.0007±0.0007	89
Tracer blank	0.168±0.012	0.0063±0.0021	0.007±0.003	0.0007±0.0007	83
RWSAB048	0.166±0.012	0.0014±0.0010	0.002±0.002	0.0007±0.0007	75
RWSAB049	0.208±0.013	0.0007±0.0007	0.002±0.001	0.0000±0.0000	96
RWSAB050	0.160±0.013	0.0035±0.0016	0.014±0.004	0.0007±0.0007	79
RWSAB051	0.192±0.016	0.0014±0.0010	0.003±0.003	0.0007±0.0007	95
RWSAB052	0.216±0.016	0.0063±0.0021	0.002±0.002	0.0007±0.0007	102
RWSAB053	0.208±0.017	0.0028±0.0014	0.003±0.003	0.0021±0.0012	99
RWSAB054	0.186±0.016	0.0000±0.0000	0.026±0.006	0.0007±0.0007	85
RWSAB055	0.155±0.015	0.0007±0.0007	0.007±0.003	0.0000±0.0000	73
RWSAB056	0.190±0.013	0.0035±0.0016	0.012±0.003	0.0007±0.0007	89
RWSAB057	0.223±0.015	0.0000±0.0000	0.015±0.004	0.0007±0.0007	104
RWSAB058	0.223±0.021	0.0028±0.0014	0.017±0.006	0.0021±0.0012	103
RWSAB059	0.188±0.012	0.0063±0.0021	0.008±0.003	0.0007±0.0007	90
RWSAB060	0.151±0.010	0.0000±0.0000	0.008±0.003	0.0007±0.0007	71
Ref Material: BOT 7003 Soil test sample	0.170±0.012	0.0035±0.0016	0.004±0.002	0.0007±0.0007	83
Tracer blank	0.186±0.012	0.0014±0.0010	0.008±0.003	0.0007±0.0007	88

Table C.3: Soil samples from the proposed radioactive waste storage area of Pilikwe results analysis for ^{210}Po .

^{210}Po					Preparation date	Reference Activity	95% Confidence Interval	Measured / Reference	Z Score
Sample ID	Gross Activity (Bq)	Net Activity (Bq)	Total Activity (Bq/kg)	Total Activity on preparation date (Bq/kg)		on preparation date	^{210}Pb (Bq/kg)		
RWSA001	0.0014±0.0005	0.0013±0.0005	4.8±1.8	4.8±1.8	16-04-2019	3.1	1.5	1.56	1.0
RWSA002	0.0018±0.0005	0.0017±0.0005	7.6±2.3	7.6±2.3	16-04-2019	3.1	1.5	2.45	2.0
RWSA003	0.0007±0.0003	0.0006±0.0003	5.4±2.7	5.4±2.7	16-04-2019	3.1	1.5	1.75	0.9
RWSA004	0.0009±0.0004	0.0008±0.0004	3.8±1.8	3.8±1.8	16-04-2019	3.1	1.5	1.23	0.4
RWSAB005	0.0011±0.0004	0.0009±0.0004	3.2±1.5	3.2±1.5	16-04-2019	3.1	1.5	1.03	0.1
RWSAB006	0.0008±0.0003	0.0006±0.0003	2.8±1.3	2.8±1.3	16-04-2019	3.1	1.5	0.91	0.2
RWSAB007	0.0013±0.0004	0.0011±0.0004	4.6±1.8	4.6±1.8	16-04-2019	3.1	1.5	1.50	0.9
RWSAB008	0.0016±0.0005	0.0015±0.0006	7.1±2.6	7.1±2.6	16-04-2019	3.1	1.5	2.28	1.5
RWSAB009	0.0007±0.0003	0.0005±0.0003	2.3±1.4	2.3±1.4	16-04-2019	3.1	1.5	0.75	0.6
RWSAB010	0.0017±0.0005	0.0015±0.0006	6.7±2.5	6.7±2.5	16-04-2019	3.1	1.5	2.17	1.4
RWSAB011	0.0005±0.0003	0.0003±0.0003	1.5±1.3	1.5±1.3	16-04-2019	3.1	1.5	0.49	1.3
RWSAB012	0.0009±0.0004	0.0007±0.0004	2.5±1.4	2.5±1.4	16-04-2019	3.1	1.5	0.79	0.5
Ref Material: BOT 7003 Soil test sample	0.0018±0.0006	0.0017±0.0006	7.1±2.5	7.1±2.5	16-04-2019	3.1	1.5	2.28	1.6
Tracer blank	0.0012±0.0004	0.0010±0.0004			16-04-2019	3.1	1.5	0.00	
RWSAB013	0.0007±0.0003	0.0006±0.0003	2.5±1.3	2.5±1.3	19-04-2019	3.1	1.5	0.80	0.5
RWSAB014	0.0044±0.0008	0.0042±0.0008	18.5±3.4	18.5±3.4	19-04-2019	3.1	1.5	5.98	4.5
RWSAB015	0.0003±0.0003	0.0002±0.0003	0.8±1.5	0.8±1.5	19-04-2019	3.1	1.5	0.26	1.5

RWSAB016	0.0037±0.0007	0.0036±0.0007	15.4±3.2	15.4±3.2	19-04-2019	3.1	1.5	4.97	3.9
RWSAB017	0.0002±0.0003	0.0000±0.0003	0.2±1.1	0.2±1.1	19-04-2019	3.1	1.5	0.06	2.6
RWSAB018	0.0003±0.0002	0.0002±0.0003	0.8±1.2	0.8±1.2	19-04-2019	3.1	1.5	0.26	1.8
RWSAB019	0.0003±0.0002	0.0002±0.0002	0.7±0.7	0.7±0.7	19-04-2019	3.1	1.5	0.21	3.6
RWSAB020	0.0002±0.0002	0.0000±0.0002	0.1±0.8	0.1±0.8	19-04-2019	3.1	1.5	0.02	3.8
RWSAB021	0.0015±0.0005	0.0013±0.0005	4.5±1.7	4.5±1.7	19-04-2019	3.1	1.5	1.46	0.9
RWSAB022	0.0001±0.0003	0.0000±0.0003	0.2±1.5	0.2±1.5	19-04-2019	3.1	1.5	-0.06	2.2
RWSAB023	0.0002±0.0002	0.0001±0.0002	0.3±0.9	0.3±0.9	19-04-2019	3.1	1.5	0.09	3.1
Ref Material: BOT 7003 Soil test sample	0.0008±0.0003	0.0007±0.0003	3.1±1.4	3.1±1.4	19-04-2019	3.1	1.5	0.98	0.0
Tracer blank	0.0007±0.0004	0.0006±0.0004			19-04-2019	3.1	1.5	0.00	
RWSAB024	0.0001±0.0001	0.0000±0.0001	0.0±0.0	0.0±0.0	19-04-2019	3.1	1.5	0.00	4.5
RWSAB025	0.0004±0.0002	0.0002±0.0002	0.9±0.9	0.9±0.9	23-04-2019	3.1	1.5	0.28	2.6
PLKV026	0.0008±0.0003	0.0006±0.0003	2.2±1.1	2.2±1.1	23-04-2019	3.1	1.5	0.72	0.8
PLKV027	0.0003±0.0002	0.0001±0.0002	0.5±0.9	0.5±0.9	23-04-2019	3.1	1.5	0.18	2.9
PLKV028	0.0002±0.0002	0.0000±0.0002	0.2±0.8	0.2±0.8	23-04-2019	3.1	1.5	0.05	3.7
PLKV029	0.0002±0.0002	0.0000±0.0002	0.2±0.9	0.2±0.9	23-04-2019	3.1	1.5	0.05	3.4
PLKV030	0.0002±0.0002	0.0001±0.0002	0.3±0.9	0.3±0.9	23-04-2019	3.1	1.5	0.10	3.1
PLKV031	0.0004±0.0002	0.0002±0.0002	1.0±0.9	1.0±1.0	23-04-2019	3.1	1.5	0.33	2.2
PLKV032	0.0004±0.0002	0.0002±0.0002	0.8±0.8	0.8±0.8	23-04-2019	3.1	1.5	0.26	2.7
RWSAB033	0.0004±0.0002	0.0002±0.0002	1.0±1.0	1.0±1.0	23-04-2019	3.1	1.5	0.32	2.1
RWSAB034	0.0003±0.0002	0.0001±0.0002	0.5±0.8	0.5±0.8	23-04-2019	3.1	1.5	0.17	3.1
RWSAB035	0.0019±0.0006	0.0018±0.0006	7.7±2.7	7.7±2.7	23-04-2019	3.1	1.5	2.47	1.7
Ref Material: BOT 7003 Soil test sample	0.0012±0.0004	0.0010±0.0004	4.3±1.6	4.4±1.6	23-04-2019	3.1	1.5	1.40	0.8
Tracer blank	0.0014±0.0005	0.0013±0.0006			23-04-2019	3.1	1.5	0.00	
RWSAB036	0.0016±0.0005	0.0014±0.0005	5.4±2.0	5.4±2.0	23-04-2019	3.1	1.5	1.73	1.2
RWSAB037	0.0003±0.0003	0.0001±0.0003	0.6±1.4	0.6±1.4	29-04-2019	3.1	1.5	0.18	1.8
RWSAB038	0.0009±0.0004	0.0007±0.0004	3.6±1.9	3.6±1.9	29-04-2019	3.1	1.5	1.15	0.2

RWSAB039	0.0000±0.0001	0.0001±0.0002	0.5±0.5	0.5±0.5	29-04-2019	3.1	1.5	-0.17	6.6
RWSAB040	0.0006±0.0003	0.0004±0.0003	1.8±1.3	1.8±1.3	29-04-2019	3.1	1.5	0.59	1.0
RWSAB041	0.0005±0.0004	0.0003±0.0004	1.4±1.6	1.4±1.6	29-04-2019	3.1	1.5	0.45	1.0
RWSAB042	0.0002±0.0001	0.0000±0.0002	0.1±0.8	0.1±0.8	29-04-2019	3.1	1.5	0.04	3.9
RWSAB043	0.0003±0.0001	0.0001±0.0002	0.5±0.8	0.5±0.8	29-04-2019	3.1	1.5	0.15	3.4
RWSAB044	0.0002±0.0002	0.0001±0.0002	0.3±1.0	0.3±1.0	29-04-2019	3.1	1.5	0.10	2.8
RWSAB045	0.0002±0.0002	0.0001±0.0002	0.3±1.0	0.3±1.0	29-04-2019	3.1	1.5	0.10	2.7
RWSAB046	0.0003±0.0002	0.0001±0.0002	0.4±0.8	0.4±0.8	29-04-2019	3.1	1.5	0.14	3.5
RWSAB047	0.0001±0.0002	0.0000±0.0002	0.2±0.8	0.2±0.8	29-04-2019	3.1	1.5	-0.05	4.3
Ref Material: BOT 7003 Soil test sample	0.0003±0.0002	0.0002±0.0002	0.7±1.0	0.7±1.0	29-04-2019	3.1	1.5	0.21	2.5
Tracer blank	0.0008±0.0003	0.0007±0.0003			29-04-2019	3.1	1.5	0.00	
RWSAB048	0.0003±0.0002	0.0001±0.0002	0.5±1.1	0.5±1.1	06-05-2019	3.1	1.5	0.17	2.2
RWSAB049	0.0002±0.0001	0.0000±0.0002	0.0±0.7	0.0±0.7	06-05-2019	3.1	1.5	0.01	4.2
RWSAB050	0.0017±0.0005	0.0016±0.0005	6.7±2.2	6.7±2.2	06-05-2019	3.1	1.5	2.17	1.6
RWSAB051	0.0003±0.0002	0.0002±0.0003	0.7±1.0	0.7±1.0	06-05-2019	3.1	1.5	0.24	2.3
RWSAB052	0.0001±0.0002	0.0000±0.0002	0.0±0.9	0.0±0.9	06-05-2019	3.1	1.5	-0.01	3.4
RWSAB053	0.0003±0.0003	0.0002±0.0003	0.8±1.3	0.8±1.3	06-05-2019	3.1	1.5	0.25	1.7
RWSAB054	0.0028±0.0007	0.0027±0.0007	12.6±3.4	12.6±3.4	06-05-2019	3.1	1.5	4.08	2.8
RWSAB055	0.0009±0.0004	0.0008±0.0004	2.8±1.6	2.8±1.6	06-05-2019	3.1	1.5	0.89	0.2
RWSAB056	0.0013±0.0004	0.0011±0.0004	4.1±1.4	4.1±1.4	06-05-2019	3.1	1.5	1.31	0.7
RWSAB057	0.0013±0.0004	0.0012±0.0004	4.5±1.4	4.5±1.4	06-05-2019	3.1	1.5	1.44	0.9
RWSAB058	0.0015±0.0006	0.0014±0.0006	5.2±2.2	5.2±2.2	06-05-2019	3.1	1.5	1.67	0.9
RWSAB059	0.0009±0.0003	0.0007±0.0003	3.1±1.3	3.1±1.3	06-05-2019	3.1	1.5	1.00	0.0
RWSAB060	0.0010±0.0003	0.0009±0.0004	3.2±1.3	3.2±1.3	06-05-2019	3.1	1.5	1.04	0.1
Ref Material: BOT 7003 Soil test sample	0.0004±0.0002	0.0003±0.0003	1.2±1.0	1.2±1.0	06-05-2019	3.1	1.5	0.40	1.8
Tracer blank	0.0009±0.0003	0.0007±0.0003			06-05-2019	3.1	1.5	0.00	

APPENDIX D: STUDY AREA SAMPLING GPS COORDINATES.

Table D.1: Pilikwe soil samples coordinates.

Sample	Sample Coordinates	
	Latitude	Longitude
RWSA001	-22.752998	27.068579
RWSA002	-22.752979	27.068176
RWSA003	-22.753334	27.068152
RWSA004	-22.753388	27.068487
RWSAB005	-22.754167	27.06861
RWSAB006	-22.753354	27.069361
RWSAB007	-22.752447	27.068577
RWSAB008	-22.752461	27.066316
RWSAB009	-22.747610	27.037954
RWSAB010	-22.723825	27.048501
RWSAB011	-22.699275	27.061458
RWSAB012	-22.676022	27.074082
RWSAB013	-22.651096	27.086462
RWSAB014	-22.626575	27.098849
RWSAB015	-22.637183	27.111689
RWSAB016	-22.661495	27.122619
RWSAB017	-22.683419	27.140462
RWSAB018	-22.702106	27.160898
RWSAB019	-22.708702	27.188232
RWSAB020	-22.727397	27.195232
RWSAB021	-22.753831	27.189675
RWSAB022	-22.779419	27.185348
RWSAB023	-22.783623	27.206868
RWSAB024	-22.797321	27.232761
RWSAB025	-22.823362	27.227115
PLKV026	-22.814822	27.199887
PLKV027	-22.811208	27.195778
PLKV028	-22.807190	27.193405
PLKV029	-22.803085	27.192320
PLKV030	-22.797997	27.191916
PLKV031	-22.793300	27.188715
PLKV032	-22.789976	27.186836
RWSAB033	-22.773026	27.021909
RWSAB034	-22.795921	27.008770
RWSAB035	-22.814867	27.008151
RWSAB036	-22.830176	27.029544
RWSAB037	-22.833163	27.048970
RWSAB038	-22.838387	27.076313
RWSAB039	-22.833581	27.111579
RWSAB040	-22.828852	27.132565
RWSAB041	-22.816262	27.158825
RWSAB042	-22.505638	27.112540
RWSAB043	-22.472061	27.162688
RWSAB044	-22.462570	27.144597
RWSAB045	-22.444856	27.141178
RWSAB046	-22.444440	27.132430
RWSAB047	-22.441807	27.249950
RWSAB048	-22.443932	27.357750
RWSAB049	-22.459490	27.453440

RWSAB050	-22.465330	27.514000
RWSAB051	-22.464106	27.591400
RWSAB052	-22.473380	27.424320
RWSAB053	-22.471677	27.340700
RWSAB054	-22.472793	27.331300
RWSAB055	-22.471110	27.236500
RWSAB056	-22.465886	27.213600
RWSAB057	-22.455405	27.110530
RWSAB058	-22.519920	27.647990
RWSAB059	-22.511327	27.812630
RWSAB060	-22.512664	27.925190

Table D.2: Pilikwe borehole water for drinking coordinates.

Sample	Sample Coordinates	
	Latitude	Longitude
PLKVB001	-22.752081	27.069900
PLKVB002	-22.811189	27.235555

APPENDIX E: INTAKE QUANTITIES OF SPECIFIC RADIONUCLIDES AND PATHWAYS, GAMMA SPECTROMETRY.

Table E.1: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 0 year.

Radon pathways	Radionuclides							
	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table E.2: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 0 year.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
⁴⁰ K	1.29E+01	5.25E+06	2.65E+06	1.10E+06	5.51E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.01E+06
²¹⁰ Pb	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²²⁶ Ra	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²²⁸ Ra	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²²⁸ Th	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²³⁰ Th	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²³² Th	1.60E+00	2.18E+03	4.47E+01	3.19E+00	6.84E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.91E+03
²³⁴ U	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²³⁸ U	1.64E+00	5.56E+03	1.83E+02	4.50E+02	6.99E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.89E+03
Total for all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table E.3: Intake quantities and for radon inhalation and its products as Bq/yr. at t = 1 year.

Radionuclides								
Radon pathways	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table E.4: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 1 year.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
⁴⁰ K	1.25E+01	5.11E+06	2.59E+06	1.07E+06	5.35E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.78E+06
²¹⁰ Pb	2.37E-17	4.44E-13	1.87E-14	8.29E-15	1.02E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.81E-13
²²⁶ Ra	3.06E-15	1.50E-10	2.96E-12	4.37E-12	1.31E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.59E-10
²²⁸ Ra	1.81E-01	9.50E+03	2.41E+02	3.15E+02	7.76E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E+04
²²⁸ Th	2.98E-02	1.59E+02	6.32E+00	4.25E-01	1.28E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.78E+02
²³⁰ Th	2.12E-11	3.18E-08	8.05E-10	7.53E-11	9.06E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.18E-08
²³² Th	1.60E+00	2.18E+03	4.47E+01	3.19E+00	6.84E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.91E+03
²³⁴ U	4.60E-06	1.57E-02	5.16E-04	1.27E-03	1.97E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E-02
²³⁸ U	1.63E+00	5.54E+03	1.83E+02	4.48E+02	6.97E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.87E+03
Total for all ingestion pathways i.e. water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table E.5: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 3 years.

Radionuclides								
Radon pathways	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table E.6: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 3 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
⁴⁰ K	1.18E+01	4.82E+06	2.44E+06	1.01E+06	5.05E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.28E+06
²¹⁰ Pb	1.89E-15	2.93E-11	1.21E-12	5.36E-13	8.08E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.18E-11
²²⁶ Ra	8.22E-14	4.32E-09	1.11E-10	1.44E-10	3.52E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.61E-09
²²⁸ Ra	4.84E-01	2.59E+04	7.20E+02	9.01E+02	2.07E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.78E+04
²²⁸ Th	1.98E-01	5.93E+02	2.20E+01	1.45E+00	8.49E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.02E+02
²³⁰ Th	1.90E-10	2.67E-07	5.96E-09	4.77E-10	8.12E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.55E-07
²³² Th	1.60E+00	2.18E+03	4.47E+01	3.19E+00	6.84E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.91E+03
²³⁴ U	1.37E-05	4.66E-02	1.54E-03	3.77E-03	5.87E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.78E-02
²³⁸ U	1.62E+00	5.51E+03	1.82E+02	4.45E+02	6.93E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.83E+03
Total of all ingestion pathways i.e. water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table E.7: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 10 years.

Radionuclides								
Radon pathways	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table E.8: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 10 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
⁴⁰ K	9.62E+00	3.93E+06	1.99E+06	8.26E+05	4.12E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.75E+06
²¹⁰ Pb	2.20E-13	3.13E-09	1.16E-10	5.42E-11	9.42E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E-09
²²⁶ Ra	2.99E-12	1.61E-07	4.53E-09	5.64E-09	1.28E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.73E-07
²²⁸ Ra	1.11E+00	6.00E+04	1.71E+03	2.12E+03	4.74E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.43E+04
²²⁸ Th	8.95E-01	1.97E+03	6.43E+01	4.25E+00	3.83E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.42E+03
²³⁰ Th	2.08E-09	2.86E-06	6.02E-08	4.47E-09	8.88E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.81E-06
²³² Th	1.60E+00	2.18E+03	4.47E+01	3.19E+00	6.84E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.91E+03
²³⁴ U	4.47E-05	1.52E-01	5.01E-03	1.23E-02	1.91E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.88E-01
²³⁸ U	1.58E+00	5.38E+03	1.78E+02	4.35E+02	6.77E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.67E+03
Total of all ingestion pathways i.e. water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table E.9: Intake quantities for radon inhalation and its products as Bq/yr. at t = 30 years.

Radionuclides								
Radon pathways	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table E.10: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 30 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
⁴⁰ K	5.37E+00	2.19E+06	1.11E+06	4.61E+05	2.30E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.77E+06
²¹⁰ Pb	1.52E-11	2.10E-07	7.44E-09	3.56E-09	6.50E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.28E-07
²²⁶ Ra	7.71E-11	4.18E-06	1.20E-07	1.48E-07	3.30E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.48E-06
²²⁸ Ra	1.53E+00	8.28E+04	2.38E+03	2.93E+03	6.54E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.87E+04
²²⁸ Th	1.51E+00	3.09E+03	9.67E+01	6.43E+00	6.45E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.83E+03
²³⁰ Th	1.79E-08	2.44E-05	5.06E-07	3.66E-08	7.65E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.26E-05
²³² Th	1.60E+00	2.18E+03	4.47E+01	3.19E+00	6.84E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.91E+03
²³⁴ U	1.25E-04	4.26E-01	1.41E-02	3.45E-02	5.36E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.29E-01
²³⁸ U	1.48E+00	5.03E+03	1.66E+02	4.07E+02	6.33E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.24E+03
Total of all ingestion pathways i.e. water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table E.11: Intake quantities for radon inhalation and its products as Bq/yr. at t = 100 years.

Radionuclides								
Radon pathways	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table E.12: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 100 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
⁴⁰ K	6.97E-01	2.85E+05	1.44E+05	5.98E+04	2.98E+02	5.98E+06	3.27E+05	4.95E+05	1.29E+06	9.84E+05	9.56E+06
²¹⁰ Pb	1.14E-09	1.56E-05	5.42E-07	2.62E-07	4.88E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.69E-05
²²⁶ Ra	2.42E-09	1.32E-04	3.83E-06	4.69E-06	1.04E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.41E-04
²²⁸ Ra	1.57E+00	8.49E+04	2.44E+03	3.01E+03	6.70E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.10E+04
²²⁸ Th	1.57E+00	3.19E+03	9.98E+01	6.63E+00	6.70E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.97E+03
²³⁰ Th	1.71E-07	2.32E-04	4.79E-06	3.43E-07	7.30E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.11E-04
²³² Th	1.60E+00	2.18E+03	4.47E+01	3.19E+00	6.84E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.91E+03
²³⁴ U	3.31E-04	1.13E+00	3.72E-02	9.11E-02	1.42E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.40E+00
²³⁸ U	1.17E+00	3.99E+03	1.32E+02	3.23E+02	5.02E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.95E+03
Total of all ingestion pathways i.e. water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table E.13: Intake quantities for radon inhalation and its products as Bq/yr. at t = 300 years.

Radionuclides								
Radon pathways	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table E.14: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 300 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
⁴⁰ K	2.04E-03	8.33E+02	4.22E+02	1.75E+02	8.73E-01	3.40E+04	1.86E+03	2.82E+03	7.36E+03	5.61E+03	5.31E+04
²¹⁰ Pb	3.11E-08	4.25E-04	1.47E-05	7.11E-06	1.33E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.60E-04
²²⁶ Ra	4.14E-08	2.25E-03	6.56E-05	8.04E-05	1.77E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.42E-03
²²⁸ Ra	1.57E+00	8.48E+04	2.44E+03	3.00E+03	6.70E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.09E+04
²²⁸ Th	1.57E+00	3.19E+03	9.97E+01	6.63E+00	6.70E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.97E+03
²³⁰ Th	1.01E-06	1.38E-03	2.83E-05	2.02E-06	4.32E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.84E-03
²³² Th	1.60E+00	2.17E+03	4.47E+01	3.19E+00	6.83E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.91E+03
²³⁴ U	5.12E-04	1.74E+00	5.74E-02	1.41E-01	2.19E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.16E+00
²³⁸ U	6.04E-01	2.05E+03	6.78E+01	1.66E+02	2.58E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.55E+03
Total of all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table E.15: Intake quantities for radon inhalation and its products as Bq/yr. at t = 1000 years.

Radionuclides								
Radon pathways	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table E.16: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 1000 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
⁴⁰ K	2.77E-12	1.13E-06	5.73E-07	2.38E-07	1.18E-09	3.37E-05	1.85E-06	2.80E-06	7.30E-06	5.56E-06	5.32E-05
²¹⁰ Pb	3.28E-07	4.48E-03	1.54E-04	7.49E-05	1.41E-04	4.26E-02	7.15E-04	3.29E-03	3.67E-04	2.97E-04	5.21E-02
²²⁶ Ra	3.58E-07	1.95E-02	5.68E-04	6.95E-04	1.53E-04	6.70E-02	3.26E-04	5.21E-03	7.19E-04	1.56E-03	9.57E-02
²²⁸ Ra	1.56E+00	8.47E+04	2.43E+03	3.00E+03	6.69E+02	2.10E-26	1.02E-28	1.63E-27	2.21E-28	4.90E-28	9.08E+04
²²⁸ Th	1.56E+00	3.18E+03	9.95E+01	6.61E+00	6.69E+02	4.55E-29	0.00E+00	1.96E-29	5.10E-30	0.00E+00	3.96E+03
²³⁰ Th	3.23E-06	4.39E-03	9.03E-05	6.44E-06	1.38E-03	5.75E-04	5.57E-06	4.87E-05	1.23E-06	1.60E-07	6.50E-03
²³² Th	1.59E+00	2.17E+03	4.46E+01	3.18E+00	6.82E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.90E+03
²³⁴ U	1.67E-04	5.67E-01	1.87E-02	4.59E-02	7.14E-02	2.29E+02	2.42E-01	1.76E+01	8.32E-01	3.21E+00	2.51E+02
²³⁸ U	5.92E-02	2.01E+02	6.64E+00	1.63E+01	2.53E+01	8.10E+04	8.58E+01	6.23E+03	2.95E+02	1.14E+03	8.90E+04
Total of all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

APPENDIX F: ACTIVITY CONCENTRATIONS TOTAL EXCESS CANCER RISK FOR ORIGINALLY EXISTENT RADIONUCLIDES AND PATHWAYS AND FRACTION OF TOTAL RISK, GAMMA SPECTROMETRY.

Table F.1: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 0 year; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	1.82E-03	0.1281	5.72E-08	0	0.00E+00	0	3.59E-03	0.2535	1.82E-03	0.1284	7.56E-04	0.0533	3.77E-06	0.0003
²³² Th	3.20E-03	0.2256	7.99E-06	0.0006	0.00E+00	0	2.71E-03	0.1909	7.74E-05	0.0055	9.44E-05	0.0067	2.94E-05	0.0021
²³⁸ U	4.92E-05	0.0035	1.11E-06	0.0001	0.00E+00	0	1.91E-05	0.0013	6.31E-07	0	1.55E-06	0.0001	2.41E-06	0.0002
Total	5.06E-03	0.3572	9.15E-06	0.0006	0.00E+00	0	6.32E-03	0.4457	1.90E-03	0.1339	8.51E-04	0.0601	3.55E-05	0.0025

Table F.2: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 0 year; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	7.99E-03	0.5636
²³² Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.11E-03	0.4312
²³⁸ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	7.40E-05	0.0052
Total	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.42E-02	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table F.3: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1 year; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	1.76E-03	0.1241	5.55E-08	0	0.00E+00	0	3.49E-03	0.2456	1.77E-03	0.1244	7.34E-04	0.0516	3.66E-06	0.0003
²³² Th	3.35E-03	0.2354	8.27E-06	0.0006	0.00E+00	0	2.82E-03	0.1982	8.06E-05	0.0057	9.83E-05	0.0069	3.05E-05	0.0021
²³⁸ U	4.90E-05	0.0034	1.10E-06	0.0001	0.00E+00	0	1.91E-05	0.0013	6.29E-07	0	1.54E-06	0.0001	2.40E-06	0.0002
Total	5.16E-03	0.3629	9.42E-06	0.0007	0.00E+00	0	6.33E-03	0.4451	1.85E-03	0.1301	8.34E-04	0.0587	3.66E-05	0.0026

Table F.4: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1 year; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	7.76E-03	0.5459
²³² Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.38E-03	0.4489
²³⁸ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	7.38E-05	0.0052
Total	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.42E-02	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table F.5: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 3 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	1.66E-03	0.1168	5.24E-08	0	0.00E+00	0	3.29E-03	0.2312	1.67E-03	0.1171	6.92E-04	0.0486	3.45E-06	0.0002
²³² Th	3.61E-03	0.2536	8.78E-06	0.0006	0.00E+00	0	3.01E-03	0.211	8.61E-05	0.006	1.05E-04	0.0074	3.25E-05	0.0023
²³⁸ U	4.87E-05	0.0034	1.09E-06	0.0001	0.00E+00	0	1.89E-05	0.0013	6.25E-07	0	1.53E-06	0.0001	2.38E-06	0.0002
Total	5.33E-03	0.3738	9.93E-06	0.0007	0.00E+00	0	6.32E-03	0.4435	1.76E-03	0.1232	7.99E-04	0.0561	3.83E-05	0.0027

Table F.6: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 3 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	7.32E-03	0.5139
²³² Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.85E-03	0.481
²³⁸ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	7.33E-05	0.0051
Total	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.42E-02	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table F.7: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 10 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	1.36E-03	0.0965	4.27E-08	0	0.00E+00	0	2.69E-03	0.1911	1.36E-03	0.0968	5.65E-04	0.0402	2.81E-06	0.0002
²³² Th	4.23E-03	0.3011	9.98E-06	0.0007	0.00E+00	0	3.40E-03	0.2418	9.75E-05	0.0069	1.19E-04	0.0084	3.67E-05	0.0026
²³⁸ U	4.76E-05	0.0034	1.07E-06	0.0001	0.00E+00	0	1.85E-05	0.0013	6.11E-07	0	1.50E-06	0.0001	2.33E-06	0.0002
Total	5.63E-03	0.401	1.11E-05	0.0008	0.00E+00	0	6.10E-03	0.4342	1.46E-03	0.1038	6.85E-04	0.0487	4.19E-05	0.003

Table F.8: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 10 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	7.09E-05	0.005	5.34E-06	0.0004	0.00E+00	0	8.05E-06	0.0006	2.00E-05	0.0014	1.59E-05	0.0011	6.09E-03	0.4334
²³² Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	7.89E-03	0.5615
²³⁸ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	7.16E-05	0.0051
Total	7.09E-05	0.005	5.34E-06	0.0004	0.00E+00	0	8.05E-06	0.0006	2.00E-05	0.0014	1.59E-05	0.0011	1.41E-02	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table F.9: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 30 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	7.57E-04	0.0532	2.38E-08	0	0.00E+00	0	1.50E-03	0.1053	7.59E-04	0.0533	3.15E-04	0.0221	1.57E-06	0.0001
²³² Th	4.67E-03	0.3282	1.08E-05	0.0008	0.00E+00	0	3.66E-03	0.2571	1.05E-04	0.0074	1.28E-04	0.009	3.97E-05	0.0028
²³⁸ U	4.45E-05	0.0031	1.00E-06	0.0001	0.00E+00	0	1.73E-05	0.0012	5.72E-07	0	1.40E-06	0.0001	2.18E-06	0.0002
Total	5.47E-03	0.3845	1.19E-05	0.0008	0.00E+00	0	5.17E-03	0.3636	8.65E-04	0.0608	4.44E-04	0.0312	4.34E-05	0.0031

Table F.10: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 30 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	1.30E-03	0.0911	9.81E-05	0.0069	0.00E+00	0	1.49E-04	0.0104	3.83E-04	0.0269	2.94E-04	0.0207	5.55E-03	0.3901
²³² Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	8.61E-03	0.6052
²³⁸ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.70E-05	0.0047
Total	1.30E-03	0.0911	9.81E-05	0.0069	0.00E+00	0	1.49E-04	0.0104	3.83E-04	0.0269	2.94E-04	0.0207	1.42E-02	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table F.11: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 100 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	9.82E-05	0.0058	3.09E-09	0	0.00E+00	0	1.95E-04	0.0115	9.85E-05	0.0058	4.09E-05	0.0024	2.04E-07	0
²³² Th	4.71E-03	0.2783	1.09E-05	0.0006	0.00E+00	0	3.68E-03	0.2175	1.06E-04	0.0063	1.29E-04	0.0076	3.99E-05	0.0024
²³⁸ U	3.53E-05	0.0021	7.93E-07	0	0.00E+00	0	1.37E-05	0.0008	4.53E-07	0	1.11E-06	0.0001	1.73E-06	0.0001
Total	4.84E-03	0.2862	1.17E-05	0.0007	0.00E+00	0	3.89E-03	0.2298	2.05E-04	0.0121	1.71E-04	0.0101	4.19E-05	0.0025

Table F.12: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 100 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	4.52E-03	0.2671	3.43E-04	0.0202	0.00E+00	0	5.19E-04	0.0307	1.35E-03	0.0798	1.03E-03	0.0609	8.20E-03	0.4842
²³² Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	8.68E-03	0.5127
²³⁸ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	5.31E-05	0.0031
Total	4.52E-03	0.2671	3.43E-04	0.0202	0.00E+00	0	5.19E-04	0.0307	1.35E-03	0.0798	1.03E-03	0.0609	1.69E-02	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table F.13: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 300 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	2.88E-07	0	9.06E-12	0	0.00E+00	0	5.69E-07	0.0001	2.88E-07	0	1.20E-07	0	5.96E-10	0
²³² Th	4.71E-03	0.5392	1.09E-05	0.0013	0.00E+00	0	3.68E-03	0.4215	1.06E-04	0.0121	1.29E-04	0.0147	3.99E-05	0.0046
²³⁸ U	1.82E-05	0.0021	4.09E-07	0	0.00E+00	0	7.07E-06	0.0008	2.33E-07	0	5.72E-07	0.0001	8.90E-07	0.0001
Total	4.73E-03	0.5413	1.13E-05	0.0013	0.00E+00	0	3.69E-03	0.4224	1.06E-04	0.0122	1.29E-04	0.0148	4.08E-05	0.0047

Table F.14: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 300 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	1.67E-05	0.0019	1.27E-06	0.0001	0.00E+00	0	1.92E-06	0.0002	5.01E-06	0.0006	3.82E-06	0.0004	3.00E-05	0.0034
²³² Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	8.67E-03	0.9934
²³⁸ U	2.42E-07	0	3.52E-10	0	0.00E+00	0	2.54E-08	0	1.13E-09	0	4.59E-09	0	2.76E-05	0.0032
Total	1.70E-05	0.0019	1.27E-06	0.0001	0.00E+00	0	1.95E-06	0.0002	5.01E-06	0.0006	3.82E-06	0.0004	8.73E-03	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table F.15: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1000 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	3.90E-16	0	1.23E-20	0	0.00E+00	0	7.73E-16	0	3.91E-16	0	1.62E-16	0	8.09E-19	0
²³² Th	4.70E-03	0.5279	1.09E-05	0.0012	0.00E+00	0	3.67E-03	0.4127	1.06E-04	0.0119	1.28E-04	0.0144	3.98E-05	0.0045
²³⁸ U	1.78E-06	0.0002	4.01E-08	0	0.00E+00	0	6.95E-07	0.0001	2.29E-08	0	5.62E-08	0	8.73E-08	0
Total	4.70E-03	0.5281	1.09E-05	0.0012	0.00E+00	0	3.67E-03	0.4128	1.06E-04	0.0119	1.29E-04	0.0144	3.99E-05	0.0045

Table F.16: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1000 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁴⁰ K	1.65E-14	0	1.25E-15	0	0.00E+00	0	1.90E-15	0	4.95E-15	0	3.77E-15	0	3.01E-14	0
²³² Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	8.66E-03	0.9726
²³⁸ U	2.13E-04	0.024	3.13E-07	0	0.00E+00	0	2.27E-05	0.0026	1.07E-06	0.0001	4.15E-06	0.0005	2.44E-04	0.0274
Total	2.13E-04	0.024	3.13E-07	0	0.00E+00	0	2.27E-05	0.0026	1.07E-06	0.0001	4.15E-06	0.0005	8.90E-03	1

Excess cancer risk entails contribution from decay daughter radionuclides.

APPENDIX G: INTAKE QUANTITIES OF SPECIFIC RADIONUCLIDES AND PATHWAYS, ICP-MS.

Table G.1: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 0 year.

Radionuclides								
Radon pathway	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table G.2: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 0 year.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion	
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk		
²²⁷ Ac	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
⁷³ As	1.15E-03	1.25E+02	5.05E+00	4.06E-01	4.93E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.31E+02
¹⁰⁹ Cd	1.92E-06	7.83E-01	7.90E-03	2.35E-02	8.21E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.15E-01
⁶⁰ Co	2.94E-02	3.20E+03	1.72E+03	2.07E+02	1.26E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.14E+03
²³¹ Pa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²¹⁰ Pb	1.83E-02	2.49E+02	8.51E+00	4.15E+00	7.83E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.69E+02
²¹⁰ Po	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²²⁶ Ra	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²³⁰ Th	3.20E-03	4.36E+00	8.95E-02	6.39E-03	1.37E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.82E+00
²³⁵ U	8.06E-03	2.74E+01	9.05E-01	2.22E+00	3.45E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.40E+01
⁶⁵ Zn	1.15E-03	6.26E+02	1.57E+03	1.86E+02	4.93E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.38E+03
Total for all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.												

Table G.3: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 1 year.

Radionuclides								
Radon pathways	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
	Water independent	3.85E+01	3.67E+01	2.78E+01	2.24E+01	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	3.85E+01	3.67E+01	2.78E+01	2.24E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table G.4: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 1 year

Radio-nuclide	Water independent pathways (inhalation without radon)					Water dependent pathways					
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	Ingestion
²²⁷ Ac	2.67E-09	1.10E-05	7.87E-07	2.79E-08	1.14E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.29E-05
⁷³ As	4.92E-05	5.35E+00	2.16E-01	1.73E-02	2.10E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.61E+00
¹⁰⁹ Cd	5.09E-07	2.13E-01	2.40E-03	6.84E-03	2.18E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.23E-01
⁶⁰ Co	2.58E-02	2.81E+03	1.51E+03	1.82E+02	1.10E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.51E+03
²³¹ Pa	1.70E-07	2.25E-03	4.42E-04	7.37E-07	7.27E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.77E-03
²¹⁰ Pb	1.77E-02	2.41E+02	8.23E+00	4.01E+00	7.58E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.61E+02
²¹⁰ Po	1.50E-02	3.40E+01	2.43E+01	2.47E+00	6.40E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.71E+01
²²⁶ Ra	1.38E-06	7.27E-02	1.85E-03	2.42E-03	5.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.75E-02
²³⁰ Th	3.20E-03	4.36E+00	8.95E-02	6.39E-03	1.37E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.82E+00
²³⁵ U	8.04E-03	2.73E+01	9.02E-01	2.21E+00	3.44E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E+01
⁶⁵ Zn	1.87E-04	1.05E+02	2.93E+02	3.34E+01	8.01E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.31E+02
Total for all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table G.5: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 3 years.

Radionuclides								
Radon pathway	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	1.15E+02	1.10E+02	8.30E+01	6.71E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.15E+02	1.10E+02	8.30E+01	6.71E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table G.6: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 3 years.

Radio-nuclide	Water independent pathways (inhalation without radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²²⁷ Ac	2.33E-08	8.51E-05	2.63E-06	2.25E-07	9.98E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.80E-05
⁷³ As	8.95E-08	9.74E-03	3.93E-04	3.15E-05	3.83E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E-02
¹⁰⁹ Cd	3.58E-08	1.50E-02	1.69E-04	4.81E-04	1.53E-05	3.26E+00	9.16E-02	2.67E-01	1.34E-02	7.55E-02	3.72E+00
⁶⁰ Co	1.98E-02	2.16E+03	1.16E+03	1.40E+02	8.48E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.47E+03
²³¹ Pa	5.07E-07	6.83E-03	1.42E-03	2.01E-06	2.17E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.47E-03
²¹⁰ Pb	1.66E-02	2.26E+02	7.71E+00	3.76E+00	7.09E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.44E+02
²¹⁰ Po	1.67E-02	3.54E+01	2.64E+01	2.67E+00	7.13E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.17E+01
²²⁶ Ra	4.14E-06	2.23E-01	6.23E-03	7.77E-03	1.77E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.38E-01
²³⁰ Th	3.20E-03	4.36E+00	8.95E-02	6.39E-03	1.37E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.82E+00
²³⁵ U	7.98E-03	2.72E+01	8.96E-01	2.20E+00	3.42E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.37E+01
⁶⁵ Zn	4.95E-06	2.77E+00	7.75E+00	8.82E-01	2.12E-03	4.51E+02	6.34E+01	3.78E+01	4.67E+02	1.05E+02	1.14E+03
Total for all ingestion pathways i.e. water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table G.7: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 10 years.

Radionuclides								
Radon pathway	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	3.80E+02	3.62E+02	2.74E+02	2.22E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	3.80E+02	3.62E+02	2.74E+02	2.22E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table G.8: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 10 years.

Radio-nuclide	Water independent pathways (inhalation without radon)					Water dependent pathways					Total ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²²⁷ Ac	2.33E-07	8.12E-04	9.82E-06	2.18E-06	9.98E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.24E-04
⁷³ As	2.30E-17	2.51E-12	1.01E-13	8.12E-15	9.86E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.63E-12
¹⁰⁹ Cd	3.29E-12	1.38E-06	1.55E-08	4.42E-08	1.41E-09	2.31E-03	6.60E-05	1.95E-04	1.11E-05	5.65E-05	2.64E-03
⁶⁰ Co	7.89E-03	8.58E+02	4.61E+02	5.56E+01	3.38E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.38E+03
²³¹ Pa	1.65E-06	2.24E-02	4.75E-03	6.32E-06	7.06E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.78E-02
²¹⁰ Pb	1.32E-02	1.79E+02	6.13E+00	2.98E+00	5.64E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E+02
²¹⁰ Po	1.33E-02	2.82E+01	2.11E+01	2.13E+00	5.69E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.71E+01
²²⁶ Ra	1.37E-05	7.41E-01	2.13E-02	2.63E-02	5.85E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.94E-01
²³⁰ Th	3.20E-03	4.36E+00	8.95E-02	6.39E-03	1.37E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.82E+00
²³⁵ U	7.80E-03	2.65E+01	8.75E-01	2.15E+00	3.34E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.29E+01
⁶⁵ Zn	1.49E-11	8.33E-06	2.33E-05	2.65E-06	6.37E-09	1.05E-02	1.50E-03	9.02E-04	1.26E-02	2.56E-03	2.81E-02
Total for all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table G.9: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 30 years.

Radionuclides								
Radon pathway	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	1.11E+03	1.06E+03	7.99E+02	6.46E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.11E+03	1.06E+03	7.99E+02	6.46E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table G.10: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 30 years.

Radio-nuclide	Water independent pathways (inhalation without radon)					Water dependent pathways					Total ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²²⁷ Ac	1.58E-06	5.43E-03	3.38E-05	1.46E-05	6.77E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.16E-03
⁷³ As	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
¹⁰⁹ Cd	9.65E-24	4.05E-18	4.55E-20	1.30E-19	4.13E-21	6.73E-15	1.93E-16	5.68E-16	3.24E-17	1.65E-16	7.69E-15
⁶⁰ Co	5.67E-04	6.17E+01	3.32E+01	3.99E+00	2.43E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.91E+01
²³¹ Pa	4.63E-06	6.29E-02	1.34E-02	1.76E-05	1.98E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.83E-02
²¹⁰ Pb	6.84E-03	9.30E+01	3.18E+00	1.55E+00	2.93E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E+02
²¹⁰ Po	6.90E-03	1.46E+01	1.09E+01	1.11E+00	2.95E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.96E+01
²²⁶ Ra	3.99E-05	2.17E+00	6.29E-02	7.72E-02	1.71E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.32E+00
²³⁰ Th	3.20E-03	4.35E+00	8.95E-02	6.38E-03	1.37E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.82E+00
²³⁵ U	7.30E-03	2.48E+01	8.19E-01	2.01E+00	3.12E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.08E+01
⁶⁵ Zn	2.49E-27	1.39E-21	3.90E-21	4.44E-22	1.07E-24	1.74E-18	2.49E-19	1.50E-19	2.10E-18	4.26E-19	4.67E-18
Total for all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table G.11: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 100 years.

Radionuclides								
Radon pathway	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	3.35E+03	3.20E+03	2.42E+03	1.95E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	3.35E+03	3.20E+03	2.42E+03	1.95E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table G.12: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 100 years.

Radio-nuclide	Water independent pathways (inhalation without radon)					Water dependent pathways					Total ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²²⁷ Ac	7.78E-06	2.66E-02	1.13E-04	7.17E-05	3.33E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.01E-02
⁷³ As	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
¹⁰⁹ Cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
⁶⁰ Co	5.64E-08	6.13E-03	3.30E-03	3.97E-04	2.41E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.85E-03
²³¹ Pa	1.22E-05	1.66E-01	3.55E-02	4.62E-05	5.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.07E-01
²¹⁰ Pb	7.66E-04	1.04E+01	3.57E-01	1.74E-01	3.28E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.13E+01
²¹⁰ Po	7.71E-04	1.64E+00	1.22E+00	1.24E-01	3.30E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.32E+00
²²⁶ Ra	1.21E-04	6.57E+00	1.91E-01	2.34E-01	5.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.04E+00
²³⁰ Th	3.20E-03	4.35E+00	8.94E-02	6.38E-03	1.37E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.81E+00
²³⁵ U	5.79E-03	1.97E+01	6.49E-01	1.59E+00	2.48E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.44E+01
⁶⁵ Zn	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total for all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table G.13: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 300 years.

Radionuclides								
Radon pathway	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	7.73E+03	7.39E+03	5.59E+03	4.52E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	7.73E+03	7.39E+03	5.59E+03	4.52E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table G.14: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 300 years.

Water independent pathways (inhalation without radon)						Water dependent pathways					Total ingestion
Radio-nuclide	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²²⁷ Ac	1.49E-05	5.07E-02	1.94E-04	1.37E-04	6.35E-03	4.79E-01	4.60E-03	3.68E-02	1.02E-04	2.24E-04	5.78E-01
⁷³ As	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
¹⁰⁹ Cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
⁶⁰ Co	2.07E-19	2.25E-14	1.21E-14	1.46E-15	8.84E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.61E-14
²³¹ Pa	1.89E-05	2.56E-01	5.48E-02	7.12E-05	8.06E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.19E-01
²¹⁰ Pb	2.49E-04	3.39E+00	1.17E-01	5.67E-02	1.06E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.67E+00
²¹⁰ Po	2.46E-04	5.26E-01	3.91E-01	3.96E-02	1.05E-01	6.41E-24	1.13E-24	4.65E-25	2.55E-25	4.62E-26	1.06E+00
²²⁶ Ra	2.81E-04	1.53E+01	4.45E-01	5.44E-01	1.20E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E+01
²³⁰ Th	3.19E-03	4.34E+00	8.92E-02	6.36E-03	1.36E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.80E+00
²³⁵ U	2.98E-03	1.01E+01	3.34E-01	8.20E-01	1.27E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.26E+01
⁶⁵ Zn	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total for all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

Table G.15: Intake quantities for radon inhalation and its decay products as Bq/yr. at t = 1000 years.

Radionuclides								
Radon pathway	²²² Rn	²¹⁸ Po	²¹⁴ Pb	²¹⁴ Bi	²²⁰ Rn	²¹⁶ Po	²¹² Pb	²¹² Bi
Water independent	1.21E+04	1.15E+04	8.73E+03	7.06E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water dependent	5.80E+01	5.60E+01	4.23E+01	3.42E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.21E+04	1.16E+04	8.77E+03	7.09E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table G.16: Intake quantities of specific radionuclides and pathways as Bq/yr. at t = 1000 years.

Radio-nuclide	Water independent pathways (inhalation without radon)					Water dependent pathways					Total ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²²⁷ Ac	5.15E-06	1.76E-02	6.50E-05	4.74E-05	2.20E-03	2.02E+01	1.94E-01	1.55E+00	5.09E-03	9.45E-03	2.20E+01
⁷³ As	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
¹⁰⁹ Cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
⁶⁰ Co	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²³¹ Pa	6.11E-06	8.31E-02	1.78E-02	2.31E-05	2.61E-03	8.37E+00	1.26E-02	6.45E-01	4.48E-01	9.81E-04	9.58E+00
²¹⁰ Pb	4.34E-04	5.93E+00	2.04E-01	9.91E-02	1.86E-01	4.82E+00	8.08E-02	3.72E-01	4.14E-02	3.39E-02	1.18E+01
²¹⁰ Po	4.31E-04	9.20E-01	6.85E-01	6.93E-02	1.84E-01	4.87E+01	8.59E+00	3.58E+00	2.06E+00	3.59E-01	6.51E+01
²²⁶ Ra	4.60E-04	2.50E+01	7.29E-01	8.93E-01	1.97E-01	7.04E+00	3.42E-02	5.47E-01	7.54E-02	1.65E-01	3.47E+01
²³⁰ Th	3.16E-03	4.30E+00	8.85E-02	6.31E-03	1.35E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.75E+00
²³⁵ U	2.92E-04	9.92E-01	3.27E-02	8.03E-02	1.25E-01	4.00E+02	4.23E-01	3.07E+01	1.46E+00	5.62E+00	4.39E+02
⁶⁵ Zn	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total for all ingestion pathways i.e., water independent; plant, meat, milk, soil and water dependent; water, fish, plant, meat, milk pathways.											

APPENDIX H: ACTIVITY CONCENTRATIONS TOTAL EXCESS CANCER RISK FOR ORIGINALLY EXISTENT RADIONUCLIDES AND PATHWAYS AND FRACTION OF TOTAL RISK, ICP-MS.

Table H.1: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 0 year; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	1.96E-11	0	1.82E-15	0	0.00E+00	0	9.09E-11	0	3.66E-12	0	2.94E-13	0	3.57E-13	0
¹⁰⁹ Cd	1.18E-13	0	3.17E-17	0	0.00E+00	0	4.04E-12	0	4.43E-14	0	1.27E-13	0	4.14E-15	0
⁶⁰ Co	2.40E-05	0.6649	2.21E-11	0	0.00E+00	0	5.32E-07	0.0147	2.86E-07	0.0079	3.45E-08	0.001	2.09E-09	0.0001
²¹⁰ Pb	1.36E-08	0.0004	1.07E-08	0.0003	0.00E+00	0	7.29E-06	0.2021	1.42E-06	0.0393	2.18E-07	0.006	5.07E-07	0.0141
²³⁰ Th	4.56E-08	0.0013	3.29E-09	0.0001	3.13E-07	0.0087	3.57E-08	0.001	1.41E-09	0	7.19E-10	0	5.24E-09	0.0001
²³⁵ U	1.19E-06	0.0329	5.77E-09	0.0002	0.00E+00	0	7.67E-08	0.0021	2.57E-09	0.0001	6.18E-09	0.0002	9.62E-09	0.0003
⁶⁵ Zn	1.57E-08	0.0004	4.79E-15	0	0.00E+00	0	5.39E-09	0.0001	1.46E-08	0.0004	1.68E-09	0	4.16E-12	0
Total	2.53E-05	0.6999	1.97E-08	0.0005	3.13E-07	0.0087	7.94E-06	0.2201	1.72E-06	0.0477	2.61E-07	0.0072	5.24E-07	0.0145

Table H.2: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 0 year; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.15E-10	0
¹⁰⁹ Cd	5.37E-11	0	2.02E-12	0	0.00E+00	0	5.85E-12	0	2.87E-13	0	1.65E-12	0	6.78E-11	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	2.48E-05	0.6886
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	9.46E-06	0.2621
²³⁰ Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	4.05E-07	0.0112
²³⁵ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.29E-06	0.0357
⁶⁵ Zn	1.71E-08	0.0005	3.13E-09	0.0001	0.00E+00	0	1.85E-09	0.0001	2.11E-08	0.0006	5.05E-09	0.0001	8.55E-08	0.0024
Total	1.71E-08	0.0005	3.13E-09	0.0001	0.00E+00	0	1.85E-09	0.0001	2.11E-08	0.0006	5.05E-09	0.0001	3.61E-05	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table H.3: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1 year; water independent pathways (inhalation excludes radon).

Water Independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	8.37E-13	0	7.78E-17	0	0.00E+00	0	3.88E-12	0	1.56E-13	0	1.26E-14	0	1.52E-14	0
¹⁰⁹ Cd	3.12E-14	0	8.39E-18	0	0.00E+00	0	1.08E-12	0	1.21E-14	0	3.45E-14	0	1.10E-15	0
⁶⁰ Co	2.10E-05	0.6418	1.93E-11	0	0.00E+00	0	4.66E-07	0.0142	2.51E-07	0.0077	3.02E-08	0.0009	1.84E-09	0.0001
²¹⁰ Pb	1.31E-08	0.0004	1.04E-08	0.0003	0.00E+00	0	7.09E-06	0.2162	1.40E-06	0.0427	2.14E-07	0.0065	4.99E-07	0.0152
²³⁰ Th	4.85E-08	0.0015	3.29E-09	0.0001	3.33E-07	0.0102	3.71E-08	0.0011	1.50E-09	0	7.68E-10	0	5.27E-09	0.0002
²³⁵ U	1.18E-06	0.0361	5.75E-09	0.0002	0.00E+00	0	7.64E-08	0.0023	2.56E-09	0.0001	6.16E-09	0.0002	9.59E-09	0.0003
⁶⁵ Zn	2.55E-09	0.0001	7.78E-16	0	0.00E+00	0	8.84E-10	0	2.47E-09	0.0001	2.81E-10	0	6.76E-13	0
Total	2.23E-05	0.6799	1.95E-08	0.0006	3.33E-07	0.0102	7.67E-06	0.234	1.66E-06	0.0506	2.51E-07	0.0077	5.15E-07	0.0157

Table H.4: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1 year; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	4.90E-12	0
¹⁰⁹ Cd	5.38E-11	0	2.02E-12	0	0.00E+00	0	5.85E-12	0	2.87E-13	0	1.65E-12	0	6.47E-11	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	2.18E-05	0.6647
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	9.22E-06	0.2814
²³⁰ Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	4.30E-07	0.0131
²³⁵ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.28E-06	0.0392
⁶⁵ Zn	1.72E-08	0.0005	3.13E-09	0.0001	0.00E+00	0	1.85E-09	0.0001	2.10E-08	0.0006	5.06E-09	0.0002	5.44E-08	0.0017
Total	1.72E-08	0.0005	3.14E-09	0.0001	0.00E+00	0	1.85E-09	0.0001	2.10E-08	0.0006	5.06E-09	0.0002	3.28E-05	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table H.5: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 3 years; water independent pathways (inhalation excludes radon).

Water Independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	1.52E-15	0	1.42E-19	0	0.00E+00	0	7.06E-15	0	2.85E-16	0	2.29E-17	0	2.77E-17	0
¹⁰⁹ Cd	2.19E-15	0	5.90E-19	0	0.00E+00	0	7.56E-14	0	8.51E-16	0	2.43E-15	0	7.72E-17	0
⁶⁰ Co	1.62E-05	0.5952	1.49E-11	0	0.00E+00	0	3.59E-07	0.0132	1.93E-07	0.0071	2.32E-08	0.0009	1.41E-09	0.0001
²¹⁰ Pb	1.23E-08	0.0005	9.79E-09	0.0004	0.00E+00	0	6.64E-06	0.2445	1.32E-06	0.0484	2.00E-07	0.0074	4.68E-07	0.0173
²³⁰ Th	5.44E-08	0.002	3.30E-09	0.0001	3.74E-07	0.0138	4.00E-08	0.0015	1.69E-09	0.0001	8.67E-10	0	5.33E-09	0.0002
²³⁵ U	1.18E-06	0.0433	5.71E-09	0.0002	0.00E+00	0	7.59E-08	0.0028	2.55E-09	0.0001	6.12E-09	0.0002	9.53E-09	0.0004
⁶⁵ Zn	6.74E-11	0	2.06E-17	0	0.00E+00	0	2.34E-11	0	6.53E-11	0	7.44E-12	0	1.79E-14	0
Total	1.74E-05	0.6409	1.88E-08	0.0007	3.74E-07	0.0138	7.11E-06	0.262	1.51E-06	0.0557	2.31E-07	0.0085	4.85E-07	0.0178

Table H.6: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 3 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	8.92E-15	0
¹⁰⁹ Cd	2.91E-11	0	1.10E-12	0	0.00E+00	0	3.22E-12	0	1.68E-13	0	9.18E-13	0	3.46E-11	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.67E-05	0.6164
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	8.64E-06	0.3184
²³⁰ Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	4.80E-07	0.0177
²³⁵ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.28E-06	0.0469
⁶⁵ Zn	5.56E-09	0.0002	1.03E-09	0	0.00E+00	0	6.16E-10	0	7.79E-09	0.0003	1.72E-09	0.0001	1.69E-08	0.0006
Total	5.59E-09	0.0002	1.03E-09	0	0.00E+00	0	6.20E-10	0	7.79E-09	0.0003	1.72E-09	0.0001	2.72E-05	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table H.7: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 10 years; water independent pathways (inhalation excludes radon).

Water Independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	3.93E-25	0	3.61E-29	0	0.00E+00	0	1.82E-24	0	7.33E-26	0	5.88E-27	0	7.14E-27	0
¹⁰⁹ Cd	2.02E-19	0	5.43E-23	0	0.00E+00	0	6.96E-18	0	7.82E-20	0	2.23E-19	0	7.10E-21	0
⁶⁰ Co	6.43E-06	0.4169	5.91E-12	0	0.00E+00	0	1.43E-07	0.0092	7.67E-08	0.005	9.24E-09	0.0006	5.61E-10	0
²¹⁰ Pb	9.75E-09	0.0006	7.78E-09	0.0005	0.00E+00	0	5.27E-06	0.3419	1.04E-06	0.0677	1.59E-07	0.0103	3.72E-07	0.0241
²³⁰ Th	7.46E-08	0.0048	3.31E-09	0.0002	5.15E-07	0.0334	5.04E-08	0.0033	2.44E-09	0.0002	1.22E-09	0.0001	5.58E-09	0.0004
²³⁵ U	1.15E-06	0.0744	5.59E-09	0.0004	0.00E+00	0	7.43E-08	0.0048	2.52E-09	0.0002	5.98E-09	0.0004	9.32E-09	0.0006
⁶⁵ Zn	2.03E-16	0	6.19E-23	0	0.00E+00	0	7.03E-17	0	1.97E-16	0	2.24E-17	0	5.38E-20	0
Total	7.66E-06	0.4968	1.67E-08	0.0011	5.15E-07	0.0334	5.54E-06	0.3592	1.13E-06	0.073	1.76E-07	0.0114	3.88E-07	0.0251

Table H.8: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 10 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	2.30E-24	0
¹⁰⁹ Cd	8.68E-15	0	3.33E-16	0	0.00E+00	0	9.81E-16	0	5.61E-17	0	2.85E-16	0	1.03E-14	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.66E-06	0.4317
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.87E-06	0.4452
²³⁰ Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.53E-07	0.0423
²³⁵ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.25E-06	0.0808
⁶⁵ Zn	6.69E-14	0	1.26E-14	0	0.00E+00	0	7.60E-15	0	1.06E-13	0	2.16E-14	0	2.16E-13	0
Total	7.55E-14	0	1.29E-14	0	0.00E+00	0	8.59E-15	0	1.07E-13	0	2.19E-14	0	1.54E-05	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table H.9: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 30 years; water independent pathways (inhalation excludes radon).

Water Independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
¹⁰⁹ Cd	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.97E-29	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
⁶⁰ Co	4.62E-07	0.0729	4.25E-13	0	0.00E+00	0	1.03E-08	0.0016	5.51E-09	0.0009	6.64E-10	0.0001	4.03E-11	0
²¹⁰ Pb	5.05E-09	0.0008	4.03E-09	0.0006	0.00E+00	0	2.73E-06	0.4312	5.41E-07	0.0854	8.25E-08	0.013	1.93E-07	0.0304
²³⁰ Th	1.30E-07	0.0206	3.34E-09	0.0005	9.03E-07	0.1426	8.18E-08	0.0129	5.07E-09	0.0008	2.29E-09	0.0004	6.46E-09	0.001
²³⁵ U	1.08E-06	0.1697	5.25E-09	0.0008	0.00E+00	0	7.00E-08	0.011	2.41E-09	0.0004	5.59E-09	0.0009	8.74E-09	0.0014
⁶⁵ Zn	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Total	1.67E-06	0.264	1.26E-08	0.002	9.03E-07	0.1426	2.89E-06	0.4568	5.54E-07	0.0875	9.10E-08	0.0144	2.08E-07	0.0328

Table H.10: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 30 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
¹⁰⁹ Cd	2.53E-26	0	9.70E-28	0	0.00E+00	0	2.86E-27	0	1.61E-28	0	8.29E-28	0	3.02E-26	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	4.78E-07	0.0755
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	3.56E-06	0.5615
²³⁰ Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.13E-06	0.1787
²³⁵ U	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.17E-06	0.1842
⁶⁵ Zn	1.06E-29	0	1.55E-30	0	0.00E+00	0	6.25E-31	0	1.64E-29	0	2.45E-30	0	3.16E-29	0
Total	2.53E-26	0	9.72E-28	0	0.00E+00	0	2.86E-27	0	1.78E-28	0	8.31E-28	0	6.34E-06	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table H.11: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 100 years; water independent pathways (inhalation excludes radon).

Water Independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
¹⁰⁹ Cd	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
⁶⁰ Co	4.59E-11	0	4.22E-17	0	0.00E+00	0	1.02E-12	0	5.48E-13	0	6.60E-14	0	4.01E-15	0
²¹⁰ Pb	5.06E-10	0.0001	4.03E-10	0.0001	0.00E+00	0	2.73E-07	0.0698	5.41E-08	0.0138	8.25E-09	0.0021	1.93E-08	0.0049
²³⁰ Th	3.02E-07	0.0773	3.47E-09	0.0009	2.10E-06	0.5362	1.92E-07	0.049	1.58E-08	0.004	5.96E-09	0.0015	1.01E-08	0.0026
²³⁵ U	8.55E-07	0.2186	4.22E-09	0.0011	0.00E+00	0	5.66E-08	0.0145	2.07E-09	0.0005	4.44E-09	0.0011	7.01E-09	0.0018
⁶⁵ Zn	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Total	1.16E-06	0.296	8.09E-09	0.0021	2.10E-06	0.5362	5.22E-07	0.1333	7.20E-08	0.0184	1.87E-08	0.0048	3.64E-08	0.0093

Table H.12: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 100 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
¹⁰⁹ Cd	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	4.76E-11	0
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	3.56E-07	0.0909
²³⁰ Th	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	2.63E-06	0.6715
²³⁵ U	3.89E-15	0	4.95E-17	0	0.00E+00	0	3.92E-16	0	9.86E-19	0	2.35E-18	0	9.30E-07	0.2376
⁶⁵ Zn	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Total	3.89E-15	0	4.95E-17	0	0.00E+00	0	3.92E-16	0	9.86E-19	0	2.35E-18	0	3.91E-06	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table H.13: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 300 years; water independent pathways (inhalation excludes radon).

Water Independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
¹⁰⁹ Cd	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
⁶⁰ Co	1.68E-22	0	1.50E-28	0	0.00E+00	0	3.73E-24	0	2.01E-24	0	2.42E-25	0	1.47E-26	0
²¹⁰ Pb	7.04E-13	0	5.61E-13	0	0.00E+00	0	3.80E-10	0.0001	7.53E-11	0	1.15E-11	0	2.68E-11	0
²³⁰ Th	6.42E-07	0.1057	3.74E-09	0.0006	4.44E-06	0.7307	4.20E-07	0.0691	3.90E-08	0.0064	1.35E-08	0.0022	1.80E-08	0.003
²³⁵ U	4.45E-07	0.0733	2.27E-09	0.0004	0.00E+00	0	3.10E-08	0.0051	1.31E-09	0.0002	2.29E-09	0.0004	3.73E-09	0.0006
⁶⁵ Zn	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Total	1.09E-06	0.179	6.01E-09	0.001	4.44E-06	0.7307	4.51E-07	0.0743	4.04E-08	0.0066	1.58E-08	0.0026	2.18E-08	0.0036

Table H.14: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 300 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
¹⁰⁹ Cd	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.74E-22	0
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	4.95E-10	0.0001
²³⁰ Th	1.73E-28	0	3.57E-29	0	0.00E+00	0	1.28E-29	0	2.30E-30	0	0.00E+00	0	5.58E-06	0.9178
²³⁵ U	1.17E-08	0.0019	1.39E-10	0	0.00E+00	0	1.20E-09	0.0002	8.63E-12	0	2.50E-11	0	4.99E-07	0.0821
⁶⁵ Zn	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Total	1.17E-08	0.0019	1.39E-10	0	0.00E+00	0	1.20E-09	0.0002	8.63E-12	0	2.50E-11	0	6.08E-06	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table H.15: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1000 years; water independent pathways (inhalation excludes radon).

Water Independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
¹⁰⁹ Cd	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
²¹⁰ Pb	7.08E-23	0	5.64E-23	0	0.00E+00	0	3.83E-20	0	7.58E-21	0	1.16E-21	0	2.70E-21	0
²³⁰ Th	1.02E-06	0.0734	4.02E-09	0.0003	6.73E-06	0.4831	6.77E-07	0.0486	6.53E-08	0.0047	2.21E-08	0.0016	2.70E-08	0.0019
²³⁵ U	4.53E-08	0.0032	2.54E-10	0	0.00E+00	0	3.64E-09	0.0003	2.09E-10	0	2.25E-10	0	4.07E-10	0
⁶⁵ Zn	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Total	1.07E-06	0.0767	4.28E-09	0.0003	6.73E-06	0.4831	6.81E-07	0.0488	6.55E-08	0.0047	2.23E-08	0.0016	2.74E-08	0.002

Table H.16: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1000years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
⁷³ As	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
¹⁰⁹ Cd	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
⁶⁰ Co	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
²¹⁰ Pb	1.94E-18	0	4.15E-19	0	0.00E+00	0	1.82E-19	0	1.00E-19	0	1.81E-20	0	2.70E-18	0
²³⁰ Th	2.89E-06	0.2074	6.02E-07	0.0431	3.39E-08	0.0024	2.72E-07	0.0195	1.46E-07	0.0105	2.89E-08	0.0021	1.25E-05	0.8986
²³⁵ U	1.21E-06	0.0867	5.20E-09	0.0004	0.00E+00	0	1.26E-07	0.009	7.47E-09	0.0005	1.67E-08	0.0012	1.41E-06	0.1014
⁶⁵ Zn	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Total	4.10E-06	0.2941	6.07E-07	0.0435	3.39E-08	0.0024	3.98E-07	0.0285	1.53E-07	0.011	4.56E-08	0.0033	1.39E-05	1

Excess cancer risk entails contribution from decay daughter radionuclides.

APPENDIX I: INTAKE QUANTITIES OF SPECIFIC RADIONUCLIDES AND PATHWAYS, ALPHA SPECTROMETRY.

Table I.1: Intake quantities for specific radionuclides and pathways as Bq/yr. at t = 0 year.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion	
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk		
²⁰⁵ Pb	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²¹⁰ Pb	1.79E-01	2.44E+03	8.33E+01	4.06E+01	7.67E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.64E+03
²⁰⁹ Po	1.23E-03	1.67E+00	1.72E+00	1.67E-01	5.26E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.08E+00

Table I.2: Intake quantities for specific radionuclides and pathways as Bq/yr. at t = 1 year.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion	
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk		
²⁰⁵ Pb	5.47E-11	7.21E-07	2.66E-08	1.17E-08	2.34E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.82E-07
²¹⁰ Pb	1.73E-01	2.36E+03	8.06E+01	3.93E+01	7.42E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.55E+03
²⁰⁹ Po	1.20E-03	1.64E+00	1.68E+00	1.63E-01	5.14E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.99E+00

Table I.3: Intake quantities for specific radionuclides and pathways as Bq/yr. at t = 3 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²⁰⁵ Pb	1.60E-10	2.16E-06	7.56E-08	3.56E-08	6.85E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.34E-06
²¹⁰ Pb	1.62E-01	2.21E+03	7.55E+01	3.68E+01	6.95E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.39E+03
²⁰⁹ Po	1.15E-03	1.56E+00	1.61E+00	1.56E-01	4.90E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.81E+00

Table I.4: Intake quantities for specific radionuclides and pathways as Bq/yr. at t = 10 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²⁰⁵ Pb	4.90E-10	6.65E-06	2.29E-07	1.11E-07	2.10E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.20E-06
²¹⁰ Pb	1.29E-01	1.75E+03	6.00E+01	2.92E+01	5.52E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.90E+03
²⁰⁹ Po	9.75E-04	1.33E+00	1.37E+00	1.32E-01	4.17E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.24E+00

Table I.5: Intake quantities for specific radionuclides and pathways as Bq/yr. at t = 30 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²⁰⁵ Pb	1.17E-09	1.58E-05	5.43E-07	2.64E-07	4.99E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.72E-05
²¹⁰ Pb	6.68E-02	9.08E+02	3.11E+01	1.51E+01	2.86E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.83E+02
²⁰⁹ Po	6.14E-04	8.37E-01	8.60E-01	8.34E-02	2.63E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E+00

Table I.6: Intake quantities for specific radionuclides and pathways as Bq/yr. at t = 100 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²⁰⁵ Pb	1.93E-09	2.63E-05	8.98E-07	4.37E-07	8.26E-07	1.02E-05	1.84E-07	7.92E-07	1.01E-07	7.28E-08	3.97E-05
²¹⁰ Pb	6.69E-03	9.09E+01	3.11E+00	1.51E+00	2.86E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.84E+01
²⁰⁹ Po	1.22E-04	1.66E-01	1.71E-01	1.65E-02	5.21E-02	8.72E+01	1.59E+01	6.70E+00	4.66E+00	6.94E-01	1.16E+02

Table I.7: Intake quantities for specific radionuclides and pathways as Bq/yr. at t = 300 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²⁰⁵ Pb	1.57E-09	2.13E-05	7.28E-07	3.55E-07	6.70E-07	8.88E-05	1.49E-06	6.85E-06	7.63E-07	6.25E-07	1.22E-04
²¹⁰ Pb	9.30E-06	1.27E-01	4.33E-03	2.11E-03	3.98E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.37E-01
²⁰⁹ Po	1.20E-06	1.63E-03	1.68E-03	1.63E-04	5.12E-04	1.16E+01	2.10E+00	8.89E-01	6.20E-01	9.22E-02	1.53E+01

Table I.8: Intake quantities for specific radionuclides and pathways as Bq/yr. at t = 1000 years.

Radio-nuclide	Water independent pathways (inhalation without Radon)					Water dependent pathways					Total Ingestion
	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk	
²⁰⁵ Pb	4.90E-10	6.66E-06	2.28E-07	1.11E-07	2.09E-07	1.34E-04	2.25E-06	1.03E-05	1.15E-06	9.42E-07	1.56E-04
²¹⁰ Pb	9.36E-16	1.27E-11	4.35E-13	2.12E-13	4.00E-13	5.00E-11	8.39E-13	3.86E-12	4.29E-13	3.52E-13	6.93E-11
²⁰⁹ Po	1.13E-13	1.53E-10	1.58E-10	1.53E-11	4.82E-11	8.18E-07	1.49E-07	6.29E-08	4.39E-08	6.52E-09	1.08E-06

APPENDIX J: ACTIVITY CONCENTRATIONS TOTAL EXCESS CANCER RISK FOR ORIGINALLY EXISTENT RADIONUCLIDES AND PATHWAYS AND FRACTION OF TOTAL RISK, ALPHA SPECTROMETRY.

Table J.1: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 0 year; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	1.33E-07	0.0008	1.05E-07	0.0006	0.00E+00	0	1.60E-04	0.9213	5.47E-06	0.0315	2.66E-06	0.0153	5.03E-06	0.029
²⁰⁹ Po	6.24E-09	0	7.50E-10	0	0.00E+00	0	1.01E-07	0.0006	1.04E-07	0.0006	1.01E-08	0.0001	3.17E-08	0.0002
Total	1.39E-07	0.0008	1.06E-07	0.0006	0.00E+00	0	1.60E-04	0.9219	5.57E-06	0.0321	2.67E-06	0.0154	5.06E-06	0.0292

Table J.2: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 0 year; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.73E-04	0.9985
²⁰⁹ Po	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	2.54E-07	0.0015
Total	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.74E-04	1
Excess cancer risk entails contribution from decay daughter radionuclides.														

Table J.3: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1 year; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	1.28E-07	0.0008	1.02E-07	0.0006	0.00E+00	0	1.55E-04	0.9213	5.29E-06	0.0315	2.58E-06	0.0153	4.87E-06	0.029
²⁰⁹ Po	6.10E-09	0	7.32E-10	0	0.00E+00	0	9.87E-08	0.0006	1.02E-07	0.0006	9.84E-09	0.0001	3.10E-08	0.0002
Total	1.35E-07	0.0008	1.03E-07	0.0006	0.00E+00	0	1.55E-04	0.9219	5.39E-06	0.0321	2.59E-06	0.0154	4.90E-06	0.0292

Table J.4: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1 year; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.68E-04	0.9985
²⁰⁹ Po	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	2.48E-07	0.0015
Total	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.68E-04	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table J.5: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 3 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	1.20E-07	0.0008	9.54E-08	0.0006	0.00E+00	0	1.45E-04	0.9213	4.95E-06	0.0315	2.41E-06	0.0153	4.56E-06	0.029
²⁰⁹ Po	5.83E-09	0	6.99E-10	0	0.00E+00	0	9.42E-08	0.0006	9.69E-08	0.0006	9.39E-09	0.0001	2.96E-08	0.0002
Total	1.26E-07	0.0008	9.61E-08	0.0006	0.00E+00	0	1.45E-04	0.9219	5.05E-06	0.0321	2.42E-06	0.0154	4.59E-06	0.0292

Table J.6: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 3 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.57E-04	0.9985
²⁰⁹ Po	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	2.37E-07	0.0015
Total	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.57E-04	1
Excess cancer risk entails contribution from decay daughter radionuclides.														

Table J.7: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 10 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	9.55E-08	0.0008	7.58E-08	0.0006	0.00E+00	0	1.15E-04	0.9212	3.94E-06	0.0315	1.92E-06	0.0153	3.62E-06	0.029
²⁰⁹ Po	4.96E-09	0	5.95E-10	0	0.00E+00	0	8.02E-08	0.0006	8.24E-08	0.0007	7.99E-09	0.0001	2.52E-08	0.0002
Total	1.00E-07	0.0008	7.64E-08	0.0006	0.00E+00	0	1.15E-04	0.9218	4.02E-06	0.0322	1.93E-06	0.0154	3.65E-06	0.0292

Table J.8: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 10 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.25E-04	0.9984
²⁰⁹ Po	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	2.01E-07	0.0016
Total	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.25E-04	1
Excess cancer risk entails contribution from decay daughter radionuclides.														

Table J.9: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 30 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	4.95E-08	0.0008	3.93E-08	0.0006	0.00E+00	0	5.96E-05	0.9209	2.04E-06	0.0315	9.93E-07	0.0153	1.88E-06	0.029
²⁰⁹ Po	3.12E-09	0	3.75E-10	0	0.00E+00	0	5.05E-08	0.0008	5.19E-08	0.0008	5.03E-09	0.0001	1.59E-08	0.0002
Total	5.26E-08	0.0008	3.97E-08	0.0006	0.00E+00	0	5.97E-05	0.9217	2.09E-06	0.0323	9.98E-07	0.0154	1.89E-06	0.0292

Table J.10: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 30 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.46E-05	0.998
²⁰⁹ Po	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.27E-07	0.002
Total	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.48E-05	1

Excess cancer risk entails contribution from decay daughter radionuclides.

Table J.11: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 100 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	4.95E-09	0.0003	3.93E-09	0.0003	0.00E+00	0	5.97E-06	0.3838	2.04E-07	0.0131	9.94E-08	0.0064	1.88E-07	0.0121
²⁰⁹ Po	6.19E-10	0	7.43E-11	0	0.00E+00	0	1.00E-08	0.0006	1.03E-08	0.0007	9.98E-10	0.0001	3.14E-09	0.0002
Total	5.57E-09	0.0004	4.00E-09	0.0003	0.00E+00	0	5.98E-06	0.3845	2.14E-07	0.0138	1.00E-07	0.0065	1.91E-07	0.0123

Table J.12: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 100 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	6.47E-06	0.416
²⁰⁹ Po	6.44E-06	0.4144	1.48E-06	0.0954	0.00E+00	0	6.27E-07	0.0404	4.36E-07	0.0281	6.50E-08	0.0042	9.08E-06	0.584
Total	6.44E-06	0.4144	1.48E-06	0.0954	0.00E+00	0	6.27E-07	0.0404	4.36E-07	0.0281	6.50E-08	0.0042	1.55E-05	1
Excess cancer risk entails contribution from decay daughter radionuclides.														

Table J.13: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 300 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	6.89E-12	0	5.47E-12	0	0.00E+00	0	8.30E-09	0.0106	2.84E-10	0.0004	1.38E-10	0.0002	2.61E-10	0.0003
²⁰⁹ Po	6.08E-12	0	7.30E-13	0	0.00E+00	0	9.84E-11	0.0001	1.01E-10	0.0001	9.81E-12	0	3.09E-11	0
Total	1.30E-11	0	6.20E-12	0	0.00E+00	0	8.40E-09	0.0108	3.85E-10	0.0005	1.48E-10	0.0002	2.92E-10	0.0004

Table J.14: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 300 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	9.00E-09	0.0115
²⁰⁹ Po	5.48E-07	0.7028	1.26E-07	0.1619	0.00E+00	0	5.35E-08	0.0685	3.73E-08	0.0478	5.54E-09	0.0071	7.71E-07	0.9885
Total	5.48E-07	0.7028	1.26E-07	0.1619	0.00E+00	0	5.35E-08	0.0685	3.73E-08	0.0478	5.54E-09	0.0071	7.80E-07	1
Excess cancer risk entails contribution from decay daughter radionuclides.														

Table J.15: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1000 years; water independent pathways (inhalation excludes radon).

Water independent pathways (inhalation excludes radon)														
Radio-nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	6.93E-22	0	5.50E-22	0	0.00E+00	0	8.35E-19	0	2.86E-20	0	1.39E-20	0	2.63E-20	0
²⁰⁹ Po	9.78E-19	0	1.01E-19	0	0.00E+00	0	1.66E-16	0.0029	1.49E-17	0.0003	3.53E-18	0.0001	7.83E-18	0.0001
Total	9.78E-19	0	1.02E-19	0	0.00E+00	0	1.67E-16	0.0029	1.49E-17	0.0003	3.54E-18	0.0001	7.85E-18	0.0001

Table J.16: Activity concentrations total excess cancer risk for originally existent radionuclides and pathways and fraction of total risk at t = 1000 years; water dependent pathways.

Water dependent pathways														
Radio-nuclide	Water		Fish		Radon		Plant		Meat		Milk		All pathways	
	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.	risk	fract.
²¹⁰ Pb	2.69E-18	0	5.80E-20	0	0.00E+00	0	2.67E-19	0	2.97E-20	0	2.43E-20	0	3.97E-18	0.0001
²⁰⁹ Po	4.11E-14	0.717	8.96E-15	0.1561	0.00E+00	0	4.02E-15	0.07	2.66E-15	0.0463	4.13E-16	0.0072	5.74E-14	0.9999
Total	4.11E-14	0.717	8.96E-15	0.1561	0.00E+00	0	4.02E-15	0.07	2.66E-15	0.0463	4.13E-16	0.0072	5.74E-14	1

Excess cancer risk entails contribution from decay daughter radionuclides.

APPENDIX K: LIST OF PRESENTATIONS & PUBLICATIONS FROM THIS STUDY

Oral Presentations

1. **Solomon, T.**, Mathuthu, M., & Kureba, C.O., (2020). Radiological risk assessment due to Naturally Occurring Radioactive Material (NORM) in the proposed radioactive waste storage area of Pilikwe, Botswana, using Radiometrical techniques. International Conference on the Management of Naturally Occurring Radioactive Material (NORM) in Industry, IAEA Headquarters Vienna, Austria. 19–23 October 2020, Ref. No: IAEA-CN-287; EVT1902890.
2. **Solomon, T.**, Mathuthu, M., & Kureba, C.O., (2020). Radiological risk assessment due to Naturally Occurring Radioactive Material from the proposed radioactive waste storage area of Pilikwe, Botswana using Residual Radioactivity (RESRAD) codes software. 2nd International Conference on Applications of Radiation Science and Technology, #ICARST2021, 19—23 April 2021, IAEA Headquarters Vienna, Austria.

Poster Presentation

1. **Solomon, T.**, Mathuthu, M., & Kureba, C.O., (2020). Radiological risk assessment due to Naturally Occurring Radioactive Material (NORM) in the proposed radioactive waste storage area of Pilikwe, Botswana. IRPA15, The 15th International Congress of the International Radiation Protection Association, 18-22 Jan 2021, COEX, Seoul, Korea, www.irpa2020.org

Publications

1. **Solomon, T.**, Mathuthu, M., & Kureba, C.O., (2020). Radiological risk assessment due to Naturally Occurring Radioactive Material (NORM) in the proposed radioactive waste storage area of Pilikwe, Botswana, using Radiometrical techniques. International Conference on the Management of Naturally Occurring Radioactive Material (NORM) in Industry, IAEA Headquarters Vienna, Austria. 19–23 October 2020, Ref. No: IAEA-CN-287; EVT1902890.
2. **Solomon, T.**, Mathuthu, M., & Kureba, C.O., (2020). Radiological risk assessment due to Naturally Occurring Radioactive Material from the proposed radioactive waste storage area of Pilikwe, Botswana using Residual Radioactivity (RESRAD) codes software. 2nd International Conference on Applications of Radiation Science and Technology, #ICARST2021, 19—23 April 2021, IAEA Headquarters Vienna, Austria.
3. **Tshegofatso Solomon**, Manny Mathuthu, Chamunorwa Oscar Kureba, Radiological exposure risk assessment due to ²¹⁰Po from the proposed radioactive waste storage area of Pilikwe, Botswana, International Journal of Scientific & Engineering Research Volume 12, Issue 3, March-202, ISSN 2229-5518.