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Inaugural Address

by

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Faculty of Natural and Agricultural Sciences

Topic:

Nuclear material: 'from the belly to the grave'

Thursday, 22 August, 2019

18:15 for 18:30

Biographical notes

Prof Victor Tshivhase

Prof MV Tshivhase was admitted to the degree doctor of philosophy in physics (nuclear physics) at the University of Cape Town in 1997 for his work on "A study of Gamow-Teller strength using the $^{208}Pb(p,n)$ and $^{181}Ta(p,n)$ reactions at intermediate energy, E_p=122MeV" utilizing the neutron time-of-flight and plastic scintillators at the iThemba LABS cyclotron facility. In 1999, he participated in the gamma spectroscopic research using the Afrodite Gammasphere at the iThemba LABS. In 1999, he accepted the position of senior physicist at Eskom in the Pebble Bed Modular Reactor (PBMR) project where he modelled the neutron profile in the different PBMR cores. In 2003, he served in the PBMR project as the chief physicist where he studied and modelled the fission products retention capability of PBMR kernels of the triso fuel. In 2005, he joined PBMR (Pty) Ltd as a senior manager in the fuel group and managed the special projects section. In 2010 and 2018, he accepted the position of an Associate Professor and Full Professor, respectively, at the Centre for Applied Radiation Science and Technology of the North-West University where he developed and presented the following courses; BSc honours in nuclear physics, BSc honours in reactor science and taught physics at first year university level modules. In 2013, he completed Master of Business Administration degree at North-West University with dissertation titled "Acceptance model and use of technology in the Science and Technology domain". In 2014, he was appointed as the director of the Centre for Applied Radiation Science and Technology (CARST) facility, where he established the nuclear regulated, department of health regulated and environmental radiation facility housing alpha spectrometers, high purity germanium spectrometers, inductively coupled plasma mass spectrometer and Quantulus liquid scintilation counter one of the few of its kind in South Africa. In January 2017 he was appointed to represent South Africa in the Generation IV International forum as a Senior Industrial Advisory Panel member for a period of three years. CARST continues to fulfill its mandate; that of training and developing capacity for the nuclear industry. Currently 12 BSc honours, 17 master of science, 8 doctoral students in applied radiation science and 2 post-doctoral fellows are registered at the centre. Victor has supervised and graduated, 12 MSc and 3 PhD students between 2015 and 2019.

Presentation title

Nuclear material: 'from the belly to the grave'

NUCLEAR MATERIAL: 'FROM THE HEART OF THE GRAVE'

INAUGURAL ADRESS

PRESENTED BY
PROFESSOR MAKINDELELE VICTOR TSHIVHASE
PhD in Physics (Nuclear Physics) (UCT)

ON

22 AUGUST 2019

AT

NORTH WEST UNIVERSITY MAFIKENG CAMPUS
SOUTH AFRICA

Introduction

An inaugural lecture is a formal ceremony held for a newly appointed professor. Newly appointed professors are expected to give their inaugural lectures within one year of starting their professorship. It provides newly appointed professors with the opportunity to inform colleagues, the campus community and the general public of their work to date, including current research and future plans.

My former promoter and supervisor Prof David Aschman entitled his inaugural lecture 'Science and Simplicity'.

Job 10:19 "If only I had never come to be, but had been carried from the womb to the grave." The title of my lecture more than 30 years down the line is nuclear material: 'from the belly to the grave'. Isaiah 46: 3,4a "Listen to Me, O house of Jacob, all the remnant of the house of Israel, who have been sustained from the womb, carried along since birth. Even to your old age, I will be the same, and I will bear you up when you turn gray." This lecture is being presented at a time when the minister of energy and minerals resources have just assured us that it is not doom and gloom with nuclear power in South Africa.

The Centre for Applied Radiation Science and Technology was established as a collaboration effort between North-West University and nuclear industry (PBMR, iThemba LABS, DoE, DMR, ESKOM, NNR and Necsa) to develop capacity for by the nuclear industry. As an employee of one of the stake holder companies, part of my duties was to offer courses and supervise research for the graduates, the task that I assumed on full basis since 2010. In the process of the research areas in the nuclear fuel cycle that would need attention would be highlighted. Let us go through the progress and achievements as demonstrated by the body of knowledge developed during the research training process.

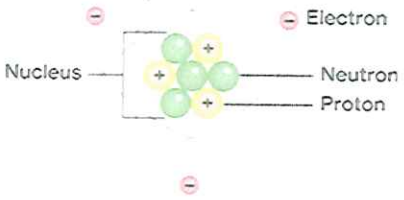

Figure 1: The atomic nucleus

Rutherford's atomic model shown in figure 1, became known as the nuclear model. In the model the nuclear atom, the protons and neutrons, which comprise nearly all of the mass of the atom, are located in the nucleus at the center of the atom. The electrons are distributed around the nucleus and occupy most of the volume of the atom.

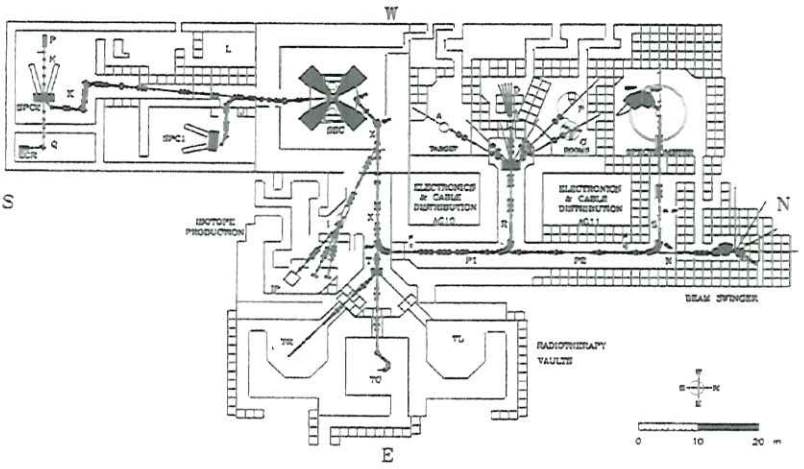

Figure 2: The layout of the NAC cyclotron (Tshivhase, 1992)

To probe the structure of the nucleus targets were bombarded with proton and measure the emerging neutron (Tshivhase, 1992). For (p,n) reactions to be used as a probe of nuclear structure, then it was important to understand the relationship between beta-decay transition strengths and the (p,n) reaction on a nucleus with a resolvable transition to a state for which the beta-decay strength has been measured. These cases are rare for medium mass nuclei. One such case occurs in the nucleus ^{51}V. The beta-decay strength for the weak Gamow-Teller 'transition to the ground state of ^{51}Cr has been measured to have log ft = 5.3893 ± 0.0016 (Auble, 1978). The $J^P = \frac{7^-}{2}$ ground state of ^{51}Cr is well separated from the other excited states, and the transition from the $\frac{7^-}{2}$ ground state in ^{51}V can be measured in a (p,n) reaction on a monoisotopic Vanadium target using a neutron time of flight spectrometer. The cross-section is small, and thus good resolution is needed to see this state above background. The MSc thesis (Tshivhase, 1992) described a study of the reaction ^{51}V(p,n) at proton beam energies of 90, 120, 160 and 200 MeV, and detection angles of 0°, 2° and 4° It was carried out at the National

Accelerator Center (iThemba LABS), Faure, South Africa, using a neutron time-of-flight spectrometer.

Measurement of this ground state transition with its known beta-decay strength then enables extracting the Gamow-Teller strength to the excited states in a model independent way. The magnitude and distribution of Gamow-Teller strength for ^{51}V provide a test for a shell model calculation. A sum rule predicts the Gamow-Teller strength to be1given by $B(GT.) - B(GT_{+}) = 3(N - Z) = 15$ for the $^{51}_{23}V_{28}$ nucleus. The $B(GT_{+})$strength will be zero in a nucleus with complete Pauli blocking, but a shell model calculation predicts a $B(GT_{+}) = 5$.

The zero degree (p,n) spectra will contain some (L > 0) strength, and so not all the observed cross-section corresponds to the (L=0) Gamow-Teller or Fermi strength. A limited angular distribution can be used to test whether the observed cross-section is consistent with (L=0) strength. However a full multipole decomposition, based on angular distributions, is complicated and difficult, and highly model dependent, and was beyond the scope of the MSc work.

At MSc level, the $^{51}V(p,n)^{51}$ Cr reaction was studied at four different proton beam energies namely 90, 120, 160, and 200 MeV. The experiment was performed in the angular range between 0 and 4°, using the beam swinger facility at National Accelerator Centre(NAC) at Faure, near Cape Town. The cross sections of the ground state, Isobaric Analog State, and the giant Gamow-Teller resonance were calculated at 0° for each beam energy. The ratio of the cross section of the giant Gamow- Teller resonance to the cross section of the Isobaric Analog State were studied at beam energies 90, 120, 160 and 200 MeV, and beam angles 0, 2 and 4°. The Gamow-Teller strength was estimated for energies 120, 160 and 200 MeV. The fractions of Fermi and Gamow –Teller strength in the Isobaric Analog State were also estimated.

At PhD level, the Gamow-Teller strength was measured in $^{208}Pb(p,n)^{208}Bi$ and $^{181}Ta(p,n)^{181}$ W reactions at an incident proton energy of 122 MeV. The experiment was performed using the beam-swinger facility at the National Accelerator Centre, Faure, South Africa. The time-of-flight (TOF) technique was employed with a flight-path of 100 m. Detectors comprised three stacks of four rectangular bars of NE 102A plastic scintillators. The outgoing neutrons were observed at laboratory angles, θ_{Lab}= 0°, 2°, 4° and 10°.

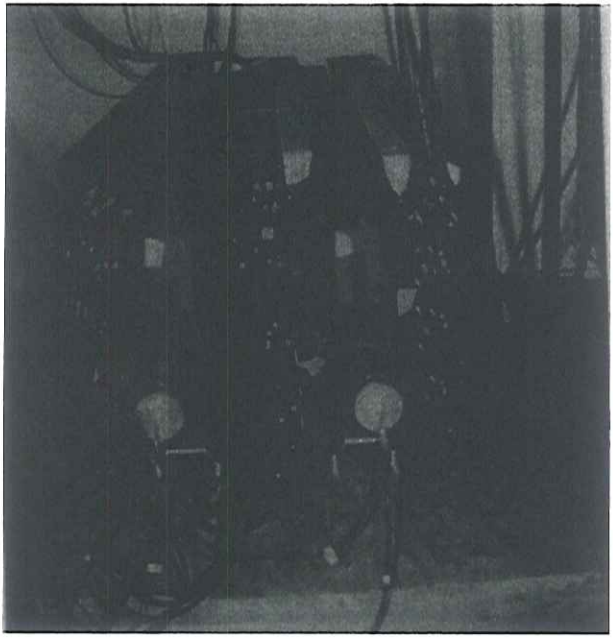

Figure 3: The orientation of the three stacks of four NE102A plastic scintillation detectors with two veto counters between the stacks facing the beam (Tshivhase, 1997).

A multipole decomposition analysis of spectra associated with ^{208}Pb(p,n)^{208}Bi and ^{181}Ta(p,n)^{181} W reactions was performed using the results of distorted-wave impulse approximation (DWIA) calculations. The spectra associated with the two reactions were decomposed into L=0, 1 and 2 transfer components. The major contribution to the spectra were found to be L=0, with a very small L=2 multipole transfer contribution.

The spectra were modelled with a combination of symmetrical Gaussians and a polynomial background. The GT strength was extracted by normalizing the cross section of the GT states to the cross section of the isobaric analogue state.

The $\sum B(GT)$ strength associated with the ^{208}Pb(p,n)^{208}Bi and ^{181}Ta(p,n)^{181}W reactions was found by summing the individual GT strength in the 0-23 MeV and 0-20 MeV excitation regions respectively. The $\sum B(GT)$ strength associated with the ^{208}Pb(p,n)^{208}Bi and ^{181}Ta(p,n)^{181}W reactions were found to be less than the values

predicted by the $3(N - Z)$ sum rule, being 81± 10% and 78±3% of the sum rule strength respectively.

Nuclear fuel cycle

Electricity in South Africa is generated from coal-fired power stations, hydroelectric power station, recently constructed wind turbines, new solar and nuclear power station.

In nuclear power stations a nuclear reactor is used to produce electricity. An example of a nuclear power plant in operation in South Africa is Koeberg nuclear power plant in Cape Town shown in figure 4, with Table mountain in the background.

Figure 4: Koeberg nuclear power station

As an illustration a nuclear reactor uranium-235 is needed to generate the required energy. Where do we get this uranium-235?

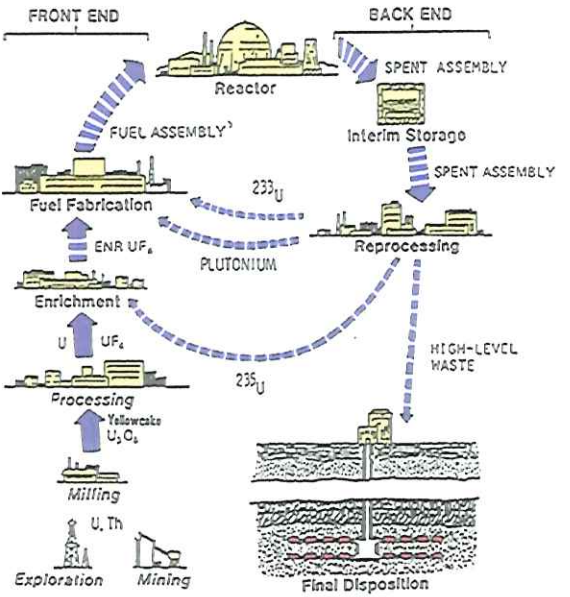

Figure 5: Nuclear fuel cycle

Figure 5 presents the nuclear fuel cycle which basically describes uranium's transformation from ore into nuclear fuel and, eventually, the handling of waste products. The nuclear fuel cycle is made up of two components: The front end and the back end.

The front end describes the processes that are involved in generating the fuel that is used in the nuclear reactor and it involves the following processes:

Mining

Depending on the depth and concentration of the uranium source, and the conditions of the surrounding rock, mining companies will extract uranium ore in one of three ways: open pit mining, underground mining or in-situ recovery. Nuclear material, which is basically natural uranium and natural thorium, is mined. Natural uranium is composed of three natural isotopes, all of which are radioactive. There is uranium-238 (99.275%), uranium-235(0.72%), and uranium-234(0.0055%). The useful isotope in the reactor is uranium-235. However, the natural abundance of this isotope is not good enough for a sustained chain reaction which is necessary of nuclear power generation. This means before the natural uranium can be used in the reactor,

the percentage of the uranium-235 isotope needs to be increased in a process call enrichment. Uranium ore, as it is mined from the ground, is not directly useable for power generation. Much processing must be carried out before uranium can be used efficiently to generate electricity.

Milling – To extract the uranium, the ore is crushed in a mill and ground to a fine slurry. The slurry is then leached in sulfuric acid, which produces a solution of uranium oxide (U_3O_8). The concentrate of this solution is called **yellowcake**.

Refining – A series of chemical processes separate the uranium from impurities, producing high-purity uranium trioxide (UO_3).

Conversion – UO_3 is converted to uranium dioxide (UO_2) for use in heavy water reactors, or to uranium hexafluoride (UF_6) for enrichment, before it can be used in light water reactors.

Enrichment - 50 boys and 10 girls in a class, 17% girls in the class. If you remove 25 boys from the class then you end up with 25 boys and 10 girls, then there is 29% girls in the class. In this case, then the class is enriched of girls from 17% to 29%.

Uranium-235 is the uranium isotope that can be used in fission, but it makes up only 0.7% of naturally occurring uranium, which is not concentrated enough for light water reactors. So, enrichment processes increase the concentration of ^{235}U to about 3% – 5%. After undergoing enrichment, the UF_6 is chemically transformed back into UO_2 powder.

Fuel manufacturing – Natural or enriched UO_2 powder is pressed into small cylindrical pellets, which are then baked at high temperatures, and finished to precise dimensions.

Electricity generation – Fuel is loaded into a reactor, and nuclear fission generates electricity. After fuel is consumed, it is removed from the reactor and stored onsite for a number of years while its radioactivity and heat subside.

Optional chemical reprocessing – After a period of storage, residual uranium or by-product plutonium, both of which are still useful sources of energy, are recovered from the spent fuel elements and reprocessed.

Disposal – Depending on the design of the disposal facility, the nuclear fuel may be recovered if needed again, or remain permanently stored. At some point in the future the spent fuel will be encapsulated in sturdy, leach-resistant containers and permanently placed deep underground

where it originated. Figure 6 shows a low-level and intermediate level waste disposal facility at Vaalputs.

Figure 6: Vaalputs nuclear waste disposal site

Problem statement for some few studies

South Africa is rich in mineral resources (Wendel, 1998). The history of mineral extraction dates back to the discovery of diamonds at Kimberley in 1871 and the discovery of gold-bearing conglomerate on Langlaagte farm near Johannesburg in 1886.

In the process of sorting out extracted minerals like gold, uranium is recovered as a by-product and also as the main product in uranium mines. Uranium is a naturally occurring element that emits radiation with the main isotope, ^{238}U decaying with a half-life (the time it takes the material to decay to half its original value) of 4.5×10^{9} years. It undergoes radioactive decay into a long series of 13 different radionuclides before finally reaching a stable state in ^{206}Pb (Canada Nuclear Association). These radionuclides emit alpha or beta radiation and some also emit gamma radiation of widely varying energies. The mineral by-products and unwanted minerals are stored in the tailings storage facilities (TSF) during the period of the operation of the mine until rehabilitation or reclamation (Hossner and Hons 1992). Unfortunately the mining industry, in South Africa mostly left behind a huge number of un-rehabilitated mines and TSF (Audit Report, 2009). The TSF are rich in uranium as a common element in nature and other radioactive elements.

People, due to lack of accommodation in the cities have built houses in close proximity to the old mines in some cases without residential zoning by the government and National Nuclear Regulator radiation clearance (Winde, 2002; Winde and Walt 2004). Examples of such scenarios are presented in figure 8 and figure 9. Once there are settlements close to these abandoned mine dumps, there exists the chance of recreational exposure, especially for children. Figure 10 shows children swimming in a pool that has developed over an abandoned mine dump. The mine tailings usually contain significant amounts of radioactive and toxic elements and therefore, there is a risk that the children swimming in such pools are being exposed to high levels of radiation. There has also been media coverage of the issues of radiative contamination, especially in the Johannesburg area. This creates a situation of confusion and fear within the public, especially those living next to the abandoned mine dumps. This therefore creates a huge needs for studies which will shed light on the radiological risks posed by the mine dumps, if any.

Figure 7: Location of the Tudor Shaft mine dump, in Krugersdorp, South Africa

Figure 8: Informal houses at a distance of less than one meter from the TSF

Figure 9: Commercial building located right next to a TSF

Figure 10: Children swimming in potentially contaminated water which has collected on top of a TSF

Figure 11: News coverage of how the media perceive the mine dumps in Johannesburg

Figure 12: Scientist carrying out dose rate assessment to determine a gross estimation of the level of radiation at Tudor Shaft

Literature review

South Africa has been a mining country for over a century and even though the minerals being mined have changed in quantities over that period, mining is still a major part of the South African economy. Gold mining has been the major mining activity in South Africa, especially in the Witwatersrand Basin. Gold mining began in the general area of Johannesburg 1886 (Werdmüller, 1986). The gold occurred in 1 to 2 m thick tabular conglomerate layers of the Witwatersrand Super-group, which extends in an east–west direction over a strike length of about 45 km (Naicker et al., 2003). Mining activities led to the formation of a large conurbation centred on Johannesburg, which as of 2011 holds a population of 4.3 Million people (Statistics SA, 2016).

Uranium is a radioactive heavy element, with average natural background concentrations that range from <2 to 4 mg/kg (Turekian and Wedepohl, 1961). However, in the gold deposits of the Witwatersrand basin, uranium is enriched to levels of up to 1 000 mg/kg (0.1 %). Compared to uranium ores with grades of about 0.3 - 6 % (3 000 - > 60 000 mg/kg) mined in Canada and Australia, this is considered as low-grade ore and therefore not economically viable to mine outright (McLEAN, 1994, Wilson and Anhaeusser, 1998). Due to the low grade, the uranium that occurred with the gold in the Witwatersrand basin was mined as a byproduct of the gold mining enterprise. This was a method that was used to offset some of the mining costs associated with the gold and therefore improve profits. The first uranium recovery plant was commissioned in 1952. The recovery of uranium during the gold mining went on until the early 1990s, at which point over 170 000 tons of U_3O_8 were recovered and sold (Ford, 1993, Wymer, 2001). Around the early 1980s the price of uranium in the world market steadily declined, reaching a point where it was no longer economically sound to recover uranium from the tailings anymore (Venter, 2001). This therefore led to a steady decline in the recovery of uranium from gold mining operations (Wendle, 1998, Wilson and Anhaeusser, 1998). Initially there were 26 mines, feeding 18 Uranium recovery plants, but only three mines and four plants were left by 1995, producing about 1 500 tons of U_3O_8 per year (Wilson and Anhaeusser, 1998). That figure was reduced further to less than 1 000 tons per year in 2001 (Venter, 2001).

The Witwatersrand ores contain much higher concentrations of uranium compared to the metal of interest which is gold, with gold-uranium ratios ranging from about 1:10 to 1:100. Without recovery therefore, there is a relatively large amount of uranium that is brought to the surface by gold mining. The uranium recovery process, which used sulfuric acid, was able to remove

90% of the uranium in the ore leaving only 10% in the mine dumps (Ford, 1993, Wendle, 1998). This means that mine dumps which were created from operations where there was no uranium recovery contain about 10 times more uranium than those from operations where uranium was recovered. There were some mines in which even during the period when uranium recovery was being done and was economically good, no recovery was being done. This was due to the fact that in some of the mines, the concentration was too low for any economic value and therefore the recovery was never done. Nowadays there are therefore two classifications of mine dumps in terms of uranium concentrations, those which were leached and those which were never leached. The ones that were never leached are therefore expected to have elevated concentrations of uranium than those which were leached. Around 2002, there was still a lot of uranium being disposed into mine dumps (about 6 000 tons of uranium per year) from gold mining in South Africa (Winde and de Villiers, 2002).

Since the beginning of the mining operations in the Witwatersrand basin, more than six billion tons of tailings have been produced (Janisch, 1986, Robb and Robb, 1998, Robb et al., 1998, Wymer, 2001). The average uranium concentration in these tailings is about 100 mg/kg, translating to over 600 000 tons of uranium oxide being exposed to the open environment. This estimation doesn't even take into account the amount of uranium in slimes dams, which contain even higher concentrations of uranium that the mine dumps (Winde and de Villiers, 2002). Mine dumps and slimes dumps cover an estimated surface area in the Witwatersrand of about 400 km^2. This value just go to show the extent of environmental scare that gold mining has left in the region and the scale of rehabilitation work that still needs to be done (Robb and Robb, 1998).

Initially radioactive pollution from gold mining was never considered a problem because the amount of radiation and radioactive material were probably considered insignificant. From the inception of an independent regulatory body, the National Nuclear Regulator (NNR) in 1990, radiological hazards associated with mining operations were being regulated. In 1995 the Department of Water Affairs conducted country-wide surveys and identified several "hot spots" of radioactive water pollution (Winde et al., 2004). Guideline limits for radioactive pollution in water are expressed as radioactivity concentrations, measured as the number of nuclear disintegrations per second (Bq) in one liter of water (Bq/L). The effect that radiation has on the human body is expressed as an effective dose per year (mSv/year). These

measurements can be related to the uranium mass concentration (g/L) (WHO, 2006). In terms of water quality, the uranium, radium and radon nuclides are of practical importance.

Irradiation of the human body from external sources is mainly by gamma radiation from radionuclides of the ^{238}U and ^{232}Th series and from ^{40}K present at different levels in soils. Natural environmental radioactivity and the associated external exposure due to gamma radiation depend primarily on the geological and geographical conditions. The specific levels of terrestrial environmental radiation are related to the type of rocks from which the soils originate (Momcilovic´, Kovacevic´ & Dragovic, 2010).

Natural radioactivity exists on earth: contributed by primordial radionuclides (present when the earth was created), and cosmo-genic radionuclides (formed as a result of cosmic ray interaction). Radioactivity is defined as the spontaneous emission of subatomic particles (α-rays and β-rays) and high-frequency electromagnetic radiation (γ-rays and X-rays) by radioactive elements (ICRP, 2008; Tykva & Sabol, 1995). An emission of this type is referred to as 'radioactive decay' or, nuclear transition. Reason for the phenomenon of radioactivity is the quest for nuclear stability. It was Becquerel who discovered radioactivity in 1896 through the fogging of photographic plates by an unknown radiation emanating from a uranium bearing rock (Eisenbud & Gesell, 1997). All food contains some natural radioactivity - radionuclides such as ^{40}K, ^{210}Po, ^{226}Ra which occur naturally in the soil, are incorporated metabolically into plants and ultimately find their way into food and water (Eisenbud & Gesell, 1997). The three major decay series of naturally occurring radionuclides are shown in table 1

Table 1: The ^{238}U, ^{235}U and ^{232}Th decays series showing both the major decay mode and the half-life of the radionuclides

Nuclide	Half-life	Major radiation	Nuclide	Half-life	Major radiation	Nuclide	Half-life	Major radiation
^{238}U	4.5×10^{9} a	α	^{235}U	7.03×10^{8} a	α	^{232}Th	1.41×10^{10} a	α
^{234}Th	24 d	β	^{231}Th	25.5 h	β	^{228}Ra	5.75 a	β
^{234}Pa	1.2 m	β	^{231}Pa	3.3×10^{4} a	α	^{228}Ra	6.1 h	β
^{234}U	2.4×10^{5} a	α	^{227}Ac	21.8 a	α, β	^{228}Th	1.91 a	α
^{230}Th	7.5×10^{5} a	α	^{227}Th	18.7 d	α	^{224}Ra	3.66 d	α
^{226}Ra	1.600 a	α	^{223}Ra	11.4 d	α	^{220}Rn	55.6 s	α
^{222}Rn	3.8 d	α	^{219}Rn	3.96 s	α	^{216}Po	0.15 s	α
^{218}Po	3.1 m	α	^{215}Po	1.78 ms	α	^{212}Pb	10.6 h	β
^{214}Pd	27 m	β	^{211}Pd	36.2 m	β	^{212}Bi	60.6 m	α, β
^{214}Bi	20 m	β	^{211}Bi	2.17 m	α	^{212}Po	0.3μs	α
^{214}Po	160 μs	α	^{207}Th	4.77 m	β	^{208}Th	3.1 m	β
^{210}Pb	22 a	β	^{207}Pb	(stable)		^{208}Pb	(stable)	
^{210}Bi	5 d	β						
^{210}Po	140 d	α						

Radionuclides released to the environment as a result of human activities add to the exposure received from natural radionuclides. These radionuclides are called TENORM for technologically enhanced naturally occurring radioactive material. Ionizing radiation is a health hazard and contributes towards adverse biological effects. Once present in the environment, these radionuclides can make their way into the food chain through two general pathways: the aquatic pathway, which involves entry into the food chain via water (IAEA, 1989); these radionuclides move along with water through lakes, the underground water, rivers and get deposited on the surrounding soil or rocks. Plants and fish absorb the radionuclides in

water the same way they absorb minerals, depending on chemical properties of the nuclides. The second pathway through the environment is the atmospheric pathway when radionuclides are released into the air by human activities. They later fall back on land and may settle on the surface of plants. Animals may eat these plants; they therefore ingest the radionuclides on these leaves. Eventually the plants and animals will become food for people and therefore they provide a pathway for radionuclides to humankind (Sedumedi, 2003).

The radioactive dose received by any individual depends upon a number of factors, such as time, location, the pathway taken by the radionuclides through the environment and the characteristics of the individual. These characteristics include physiological parameters (e.g. breathing rate), dietary information (e.g. consumption rate and type of food), residence data (e.g. ventilation of house), use of local resources (e.g. agricultural resources), recreational activities (e.g. swimming), and any other individual-specific information that is necessary to estimate annual dose. In the assessment on doses, a specific set of these characteristics is referred to as an exposure scenario (ICRP, 2005).

Radioactive equilibrium

Radioactive equilibrium is a term that is applied to a decay chain series, that is, a parent with all of its daughter nuclei. Radioactive equilibrium is when all the daughter nuclei in a decay chain series, decay at the same rate as they are produced (Prince, 1979). One very common and useful state of equilibrium is the secular equilibrium. When a decay chain series is in a state of secular equilibrium all the daughter nuclei decay at the same rate as the parent nuclei. Figure 3 shows one of the oldest radioactive equilibria in nature, the secular equilibrium between ^{238}U and its daughters. In secular equilibrium, presented in figure 10, the parent has a very long half-life compared to all its daughters and therefore its decay constant is much lower compared to its daughters, $\lambda_P << \lambda_D$ (Burcham, 1973; Cember & Johnson, 2009; Faires & Boswell, 1981; Krane, 1988). λ_P can be estimated to be zero. The activity of radioactive nuclei is given by equation (1) and that of daughter nuclei in a decay chain series is given by equation (2) (Lapp & Andrews, 1972; Lilley, 2001);

$$A = N\lambda \quad (1)$$

where: A= Activity, N= number of radioactive nuclei and λ= decay constant

$$N_D(t) = N_P(t_0)\frac{\lambda_P}{\lambda_D - \lambda_P}(e^{-\lambda_P t} - e^{-\lambda_D t}) \quad (2)$$

In secular equilibrium this equation can be simplified into equation (3) (Krane, 1988; Lapp & Andrews, 1972):

$$N_D(t) = N_P(t_0)\frac{\lambda_P}{\lambda_D}(1 - e^{-\lambda_D t}) \quad (3)$$

with time the $e^{-\lambda_D t}$ term will become negligible and the number of daughter nuclei will decay at a constant rate as illustrated by equation (4) (Cember & Johnson, 2009; Lapp & Andrews, 1972; Turner, 2007):

$$N_D(t) = N_P(t_0)\frac{\lambda_P}{\lambda_D} \quad (4)$$

Thus at a state of secular equilibrium the daughter and parent have the same activities as can be seen in equation (5):

$$N_D\lambda_D = N_P\lambda_P \quad (5)$$

where:

N_D = number of daughter nuclei

N_P = number of parents nuclei

λ_D = decay constant of daughter

λ_P = decay constant of parent

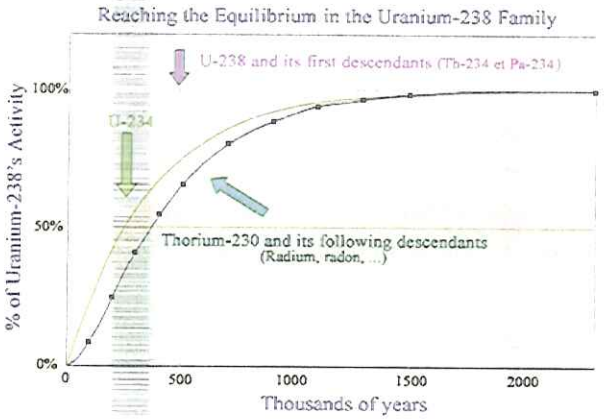

Figure 13: Secular equilibrium between ^{238}U and its daughter nuclides (la radioactivite, 2014)

Radioactivity detection and measurement

A fundamental feature of nuclear processes is that the energy released is larger than the binding energies of atomic electrons. Any emitted particles will have sufficient energy to ionize atoms. Nuclear radiation is called "ionizing radiation" and detecting this ionization allows us to observe nuclear processes. Radiations that interact with matter via the electromagnetic force, i.e., electrons, charged particles and photons, can directly ionize or excite atoms. These radiations are readily detected (Oregon State University, 2010).

There are various types of instruments used to detect radiation and all of them depend on the ionizing nature of 'ionizing radiation'. Even though these detectors differ in their fundamental functioning, several common criteria are used to evaluate and compare them. These are as follows:

1. The sensitivity of the detector- this property has to do with what type of radiation and the energies the detector can detect. For example solid scintillation detectors are used for α-particles from radioactive-decay because they can't penetrate the detector covering.

2. The energy resolution of the detector- this has to do with the ability of the detector to measure the energy of the particle striking it as accurately as possible, say for example if two gamma-rays of energy 1.10 MeV and 1.15 MeV strike the detector, will it be able to distinguish between them?

3. The time resolution of the detector or its pulse resolving time- addresses things like the dead time, how long the detector takes to process an incident hit and get ready for a new one. The shorter, the better.

4. The efficiency of the detector- if for example 1000 gamma-rays strike the detector, how many will be detected. High efficiency reduces uncertainty and allows for shorter counting times (IAEA, 2004; Oregon State University, 2010).

Types of detectors

a) Gas Ionization detectors- these detectors take advantage of the fact that radiation ionizes gases and produces ion pairs. These pairs can be separated and collected.

Application of a potential gradient between the two electrodes in a gas-filled ion chamber causes the cations move to the cathode and the anions move to the anode and this creates a measurable pulse (IAEA, 2004; Knoll, 1989).

b) Semiconductor detectors- in these detectors the incident radiation interacts with the detector material, a semiconductor, usually Si or Ge, to create hole-electron pairs. The hole-electron pairs are collected by charged electrodes and the electrons move to the anode and holes to the cathode, creating a measurable electric pulse. The important feature of semiconductor detectors is their superior energy resolution (Bertolini & Coche, 1968; Goulding & Pehl, 1974; IAEA, 2004).

c) Solid Scintillators- the energy of incoming radiation is transferred into fluorescent molecules in a crystalline solid. The absorbed energy causes excitation of the orbital electrons in the material. The electrons lose the excitation energy as light in the visible or near ultra-violet range of the electro-magnetic spectrum. A photomultiplier tube is used to convert the photons into photo-electrons, which are amplified through a series of secondary electron emission via a series of dynodes. The result is a big enough pulse to be measured (Ortec-Online n.d.; IAEA, 2004; Oregon State University, 2010).

d) Liquid scintillators- similar operation to solid scintillation detectors, only difference being that the radioactive sample and the fluorescent material are dissolved in a liquid medium, usually a non-polar solvent. The energy of nuclear radiation first excites the solvent molecules. This excitation energy eventually appears as photons emitted from the fluor (fluorescent material) following an intermediate transfer stage. The photons are then detected using a photomultiplier system as in solid scintillators (Flakus, n.d.; IAEA, 2004; Oregon State University, 2010).

e) Nuclear emulsions- ionizing radiation from a sample interacts with the silver halide grains in a photographic emulsion to cause a chemical reaction. Subsequent development of the film produces an image and so permits a semi-quantitative estimate of the incoming radiation (IAEA, 2004).

High Purity Germanium Detectors

In gamma spectroscopy the main aim is to detect photon energies with different energies and be able to distinguish between the different energies. Gamma photons have high energies, in

the order of hundreds of keV to a couple of MeV (Boukhenfouf and Boucenna, 2011). To be able to detect a photon and its approximate energy, that particular photon must first enter the germanium crystal and then interact with the atoms of the crystal material to depletion, leading to the deposition of all of its energy within the crystal. Photons of high energy don't interact easily, they therefore have a high mean free path. This therefore means that they will need a greater length of crystal material to deposit their energy (higher depletion depth) than lower energy photons. Germanium crystals of normal purity can only achieve a few mm in terms of depletion depth (Povinec et al., 2001)

Radiation dosimetry

Radiation is always around us, from the sun, the dust and other sources, even inside us, as we inhale some radioactive particles in dust and ingestion of material (Harvey, 1969; Turner, 2007). Radiation exposure is described as the amount of ionization that X-rays or γ-rays produce in air, and its unit is the roentgen (R) and it is equivalent to 2.58×10^{-4} C/kg (IAEA, 2007). Exposure is not very important in radiation dosimetry because it doesn't have any indication of the biological effect in living tissue.

Absorbed dose is defined as the amount of dose absorbed by a specific mass of target organ. The absorbed dose is expressed in the unit, gray (Gy), where 1 Gy is equal to I joule of absorbed energy per 1 kg of irradiated target (Cember & Johnson, 2009; Lilley, 2001; Noz & Maguire, 2007). The absorbed dose can also be expressed in the form of equation (6) (IAEA, 2007):

$$D = \frac{d\bar{e}}{dm}, \qquad (6)$$

where d*e* is the mean energy imparted by *ionizing radiation* to matter in a volume element and d*m* is the mass of matter in the volume element. The absorbed dose can be expressed in another unit called the '*rad*'(radiation absorbed dose). The *rad* is the original unit and is defined as an absorbed energy of 100 erg per gram. Equation (7) shows its relationship to the *gray* (Martin & Harbison, 2006):

$$1\,rad = 0.01\,Gy = 1\,centigray\,(cGy) \qquad (7)$$

The absorbed amount of energy just gives a very small idea of the biological effect of the radiation absorbed by the target. The biological effect depends on other factors that are related to the type of radiation and the target organ where the radiation is being absorbed (Cember & Johnson, 2009). Different types of radiation have different effects on living organisms. High

LET (linear energy transfer) radiation like alpha particles will cause more damage than gamma rays because they will deposit a large amount of their energy over a very short distance and thus over a very small volume, while gamma rays which are low LET will deposit very little energy over a longer path and thus less energy per unit volume (Lilley, 2001). Relative biological effectiveness (RBE) was introduced as a dimensionless quantity of the amount of absorbed dose of ionizing radiation relative to that of X-ray or gamma radiation of a particular energy to provide the same biological response (Noz & Maguire, 2007). The RBE is a complicated factor and has been normalized into the radiation weighing factor (W_R) by the ICRP and NCRP. Table 2 shows a list of radiation weighing factors for different radiation types and different energies (ICRP, 1991).

Table 2: Radiation weighting factors for different radiation types and energies (ICRP, 1991; Noz & Maguire, 2007)

Type of radiation	Energy range	Weighting factor (W_R)
Photons, electrons, positrons, muons	All energies	1
Neutrons	<10 keV	5
	>10 keV to 100 keV	10
	>100 keV to 2 MeV	20
	>2 MeV to 20 MeV	10
	>20 MeV	5
Proton	<20 MeV	5
Alpha particles, fission fragments, non-relativistic heavy nuclei	<20 MeV	20

In order to determine the effect of the nature of the radiation by the weighting factor in Table 2, a unit called the ***equivalent dose*** (H_T) is specified. This is the amount of the dose ($D_{T,R}$) absorbed over a tissue or organ (T) due to radiation (R) and is given equation (8) (Cember & Johnson, 2009; Eisenbud & Gesell, 1997; Lilley, 2001):

$$H_T = \sum_R w_R D_{T,R} \quad (8)$$

The '***Sievert***' (*Sv*) is used to express the equivalent dose when the absorbed dose is in units of *gray* (*Gy*); thus one Sievert is also equal to one joule per kilogram (Choppin, Liljenzin & Rydberg, 2002; Eisenbud & Gesell, 1997; Knoll, 2000). In addition to the radiation types and energy, the biological effect to radiation is concerned with the sensitivities of irradiated organs or tissues. The variation of radiation sensitivity of each organ is taken into account in the contribution of the equivalent dose in all tissues and organs of the body. The new terms the ***effective dose*** (***E***) and the ***tissue weighting factor*** (w_T) are introduced and given in Table 3. The definition of the effective dose is the sum of the equivalent doses weighted by the tissue weighting factors for each tissue, as given in equations (9) and (10) (Cember & Johnson, 2009; Martin & Harbison, 2006):

$$E = \sum_T w_T H_T \quad (9)$$

and can also be written as:

$$E = \sum_T w_T \sum_R w_R D_{T,R} \quad (10)$$

Table 3: Tissue weighting factors (ICRP, 1991; Martin & Harbison, 2006)

Tissue or Organ	Tissue Weighting factor, w_T
Gonads	0.20
Colon	0.12
Lung	0.12
Red bone morrow	0.12
Stomach	0.12
Bladder	0.5
Breast	0.5
Oesophagus	0.5
Liver	0.5
Thyroid	0.5
Skin	0.1
Bone surfaces	0.1
Remainder	0.5

Dose limits

ICRP has done some research on the dosage that people receive and calculated all the risk factors. Those calculations led to recommendations on the amount of dose that different groups of people may receive to keep the risk factors as low as reasonably possible. Table 4 shows those recommendations made:

Table 4: Recommended occupational and public dose limits (Cember & Johnson, 2009; ICRP, 1991; Noz & Maguire, 2007)

Application	Dose limit	
	Occupational	Public
Whole body	20 mSv per year, averaged over a defined period of 5 years	1 mSv per year
Annual equivalent dose in		
Lens of the eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hand and feet	500 mSv	–

Radiological risk assessment parameters

The most important parameter in radiological impact assessment is the yearly dose received by an individual. The dose rate in air can be calculated from the radioactivity concentrations of the natural radionuclides in soil samples. The mean activity concentrations of ^{238}U, ^{232}Th and ^{40}K ($Bq.kg^{-1}$) in the soil samples are used to calculate the absorbed dose rate given by equation (11) (Beck, 1972; Belivermis, Kikic, Cotuk & Topcuoglu, 2010; Turhan & Gundiz, 2008):

$$D = (0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K) \quad (11)$$

D is the absorbed dose rate in $nGy.h^{-1}$, A_{Ra}, A_{Th} and A_K are the activity concentration of ^{226}Ra (^{238}U) assuming secular equilibrium in the ^{238}U decay-series, ^{232}Th and ^{40}K, respectively. The dose coefficients in units of $nGy.h^{-1}$ per $Bq.kg^{-1}$.

The absorbed dose can be considered in terms of the annual effective dose equivalent from outdoor terrestrial gamma radiation which is converted from the absorbed dose by taking into account two factors, namely the conversion coefficient from absorbed dose in air to effective

dose and the outdoor occupancy factor. The annual effective dose equivalent can be estimated using equation (12) (Beck, 1972; Turhan & Gundiz, 2008; Chang, Koh, Kim, Seo, Yoon, Row & Lee, 2008):

$$AEDE\ (\frac{\mu Sv}{yr}) = D(\frac{nGy}{h}) \times 8760\ h \times 0.2 \times 0.7\ Sv.Gy^{-1} \times 10^{-3} \quad (12)$$

AEDE is the Annual Effective Dose Equivalent in μSv/yr, D is the dose rate in air, 8760 h is the number of hours in a year, 0.2 is the outdoor occupancy factor and 0.7 is a dose conversion factor for adults.

The yearly dose from the ingestion of radionuclides also contributes to the amount of dose received per annum. It can be calculated using equation (13):

$$\text{Yearly Dose} = \text{Yearly Consumption} \times \text{Specific Activity} \times \text{Dose Conversion Factor} \quad (13)$$

The radiological impact of ^{226}Ra, ^{232}Th and ^{40}K can also be assessed using the radiological index known as radium equivalent activity (Ra_{eq}). The radiological index is extensively used to analyse the hazards associated with radiation. Equation 14 is used to calculate this index. The drawn estimation thereof is that the following radionuclides produce the same gamma-ray dose rate, 370 Bq.kg^{-1} of ^{226}Ra, 259 Bq.kg^{-1} of ^{232}Th and 4810 Bq.kg^{-1} of ^{40}K.

$$Ra_{eq}(\text{Bq.kg}^{-1}) = A_{Ra} + 1.43A_{Th} + 0.077A_{K} \quad (14)$$

Where the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in Bq.kg^{-1} are represented by A_{Ra}, A_{Th} and A_K. The acceptable maximum value of the radium equivalent activity is 370 Bq.kg^{-1} which corresponds to an effective dose of 1 mSv/year for the general public.

Another parameter that is used in radiological risk assessment is the external hazard index. The maximum recommended value is aimed at restricting the radiation exposure from natural radionuclides in an area to the acceptable dose equivalent limit of 1 mSv.yr^{-1}.

$$H_{ex}=\left(\frac{A_{Ra}}{370}\right) + \left(\frac{A_{Th}}{259}\right) + \left(\frac{A_K}{4810}\right) \quad (15)$$

The external hazard index must not be greater than one in order to maintain the insignificance of radiation hazard. The upper limit of radium equivalent activity of 370 Bq.kg^{-1} matches the maximum allowed value of H_{ex}.

Materials for research: Special emphasis on gamma spectrometry

The equipment used for gamma analysis consisted of: Canberra Model GCW 2021 HPGe Well detector shown in figure 11, with relative efficiency of 20%. The resolution: FWHM @ 122 keV < 1.2 keV and FWHM @ 1332 keV < 2.1 keV and Well size: 10 mm diameter: 40 mm depth Aluminium end cap with a 2002 CSL preamplifier. It has an ultra-low background, top loading lead shield with a thickness of 100 mm. The inner dimensions are 279 mm diameter x 406 mm height, weighing 1100 kg. It has an inner lining of graded tin and copper to reduce X-rays background from lead shield interaction with gamma radiation from samples. For spectrum acquisition and analysis, Genie 2000 software was used, with a Canberra Model DSA 1000 Digital Spectrum Analyser, featuring: Integrated desktop Multi-channel Analyser, which includes DSP based pulse processing, 16 K Channel spectrum memory, multi range HVPS, digital stabilizer, USB & RS-232 serial interface.

Figure 14: Gamma spectrometry system at CARST

Energy and Peak efficiency calibration

Energy calibration is basically matching a channel number or range of channels to a particular gamma ray energy. In this study this was achieved by measuring a combination of point sources covering the energy range 59.54 keV to 1332.5 keV (^{241}Am, ^{57}Co, ^{137}Cs, ^{54}Mn and ^{60}Co). The gain of the system was set to 0.5 keV per channel. Strong point sources were used which allowed for shorter counting times. The centroids of the peaks were then plotted against the channel numbers on the MCA, producing the plot shown in figure 11.

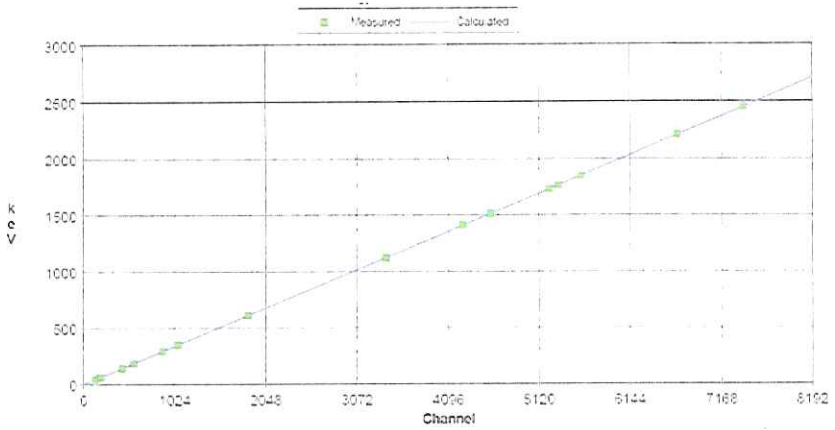

Figure 15: Energy calibration curve for the well-type HPGe detector used for gamma spectroscopy at CARST

For peak efficiency calibration two methods were used for quality assurance purposes. In the first method, LabSOCS sample and source geometry composer was used to do an efficiency calibration. This method is a simulation software from Genie 2000 which utilizes libraries and the given geometries as well as sample matrix to estimate the efficiencies at different energies using Monte Carlo methods. In the second method two standards, IAEA-RGU-1 and a ^{133}Ba-^{152}Eu standard in a Marinelli beaker geometry were used for calibration. The efficiencies at given energies were calculated according to equation (16) and plotted as a function of energy (Murray et al., 1987) and presented in figure 12.

$$\varepsilon(E) = \frac{N_c}{t \times Y \times m \times A}, \qquad (16)$$

where:

N_c is the net peak area of the peak under consideration,

t live time of the measurement,

Y the gamma emission probability of the calibration nuclide at the energy,

m mass of standard spiked into sample,

A source activity at the time of measurement.

^{152}Eu decay with a cascade of gamma rays at different energies and due to the proximity of the sample to the detector, two different gamma rays from a cascade might reach the detector at

the same time, resulting in coincidence summing. The detector adds energies of the two gamma rays and record the sum as a separate peak in the spectrum leading to loses at the original peaks. Corrections for the different gamma ray lines were effected using values obtained by Anas & Molham (2015), Schima & Hoppes (1983) and Dias et al. (2002) as well as simulation based corrections using Genie 2000 software.

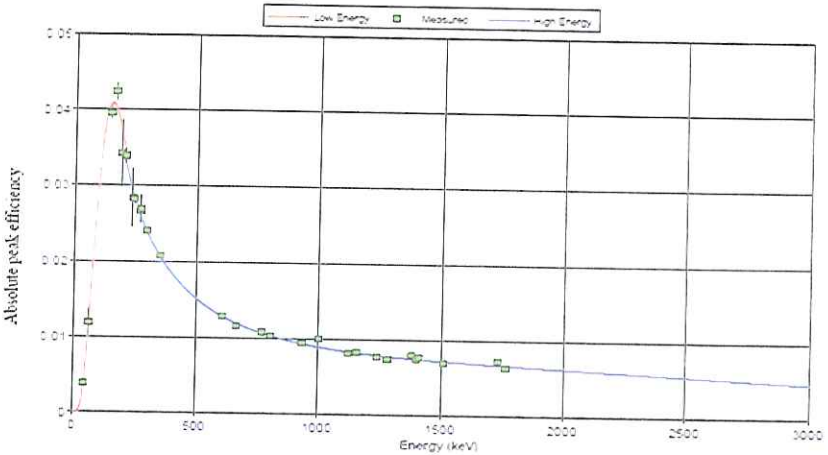

Figure 16: Full energy peak efficiency calibration for the HPGe detector setup at CARST

Completed research

My research over the last five years covered: Primary research field 1. Physical sciences, and 2. Technologies & applied sciences with secondary research field (a) Environmental studies (b) Atomic, molecular and nuclear physics, and (c) Physics, with the specialisation areas:

1. Environmental radioactivity:

The doctoral degree "effectiveness of Ion Exchange, Reverse Osmosis and Coagulation and Filtration in the removal of Radioactivity from Acid Mine Drainage" of Dlamini TC was produced in 2019. The aim of the study was to assess the effectiveness of ion exchange, reverse osmosis and coagulation filtration, three of the best available treatment methods, in the removal of radioactivity and heavy metals from Acid Mine Drainage (AMD) and make

recommendations on the most appropriate method among the three that South Africa can employ in the treatment of AMD.

According to the findings of this study ion exchange is the best method for the removal of both radioactivity and heavy metals from AMD, producing small amounts of solid waste and high radioactivity and metal removal rates.

The work "the effect of uranium speciation on the removal of gross alpha activity from acid mine drainage using anion exchange resin" has been published in the accredited and refereed/peer reviewed article in the Journal of Radioanalytical and Nuclear Chemistry, https://doi.org/10.1007/s10967-018-6354-7 ISSN 1588-2780.

The Master of Science degree "transfer of radionuclides and toxic elements from the Princess mine dump to water in Roodepoort, South Africa" of Dlamini SG was awarded in 2015. The research was aimed at determining the transfer of radionuclides and toxic elements from the Princess Gold Mine dump to water in the Roodepoort area, South Africa. The study focused mainly on the dump and considered it as the main (only) source of pollution to the water. The estimated radiological dose due to direct ingestion of the untreated water was calculated for all the age groups. For children, <1year, it ranged from 1.27 to 10.20 mSv/a, for 1 to 2 year olds, from 0.26 to 4.29 mSv/a, for 2 to 7 years, from 0.20 to 3.33, for 7 to 12 years, from 0.19 to 3.27 mSv/a, for 12 to 17 years, from 0.29 to 5.53 mSv/a and for adults >17 years, from 0.27 to 4.52 mSv/a. The dose limit set by Strahlengschutz-Komission of 0.500 mSv/a, the WHO screening value of 0.100 mSv/a and the 0.25 mSv/a set by the South African National Nuclear Regulator were exceeded by the maximum annual levels from the water samples in this research. Radionuclides identified and measured by alpha spectrometer were identified as ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Po, ^{235}U, ^{227}Th, ^{223}Ra, ^{232}Th, ^{228}Th and ^{224}Ra.

The work "Radionuclides and toxic elements transfer from the Princess Dump to the surrounding vegetation in Roodepoort South Africa: Potential radiological and toxicological impact on humans" have been published in the accredited and refereed/peer reviewed article in the Journal of Environmental Radioactivity 153 (2016) 201-205, www.sciencedirect.com/science/article/pii/S0265931X15301867.

The work "Chemical Toxicity of Surface-Based Drinking Water Sources Due to Natural Uranium Pollutant Around Princess Gold Mine Environs in Roodepoort, South Africa." has been published in the accredited and refereed/peer reviewed article in the Journal of Expo and

Health 8: 457 pp 1 - 8. doi 10.1007/s12403-016-0203-0. http://link.springer.com/article/10.1007/s12403-016-0203-0.

The work "Hazards index analysis gamma emitting radionuclides in selected areas of Erongo region around the uranium mine sites" have been published in the refereed/peer reviewed article in the Journal of Environmental Science and Management (JESAM) (ISSN 0119-11449) Vol 19, No 2 (2016) https://journals.uplb.edu.ph/index.php/JESAM/article/view/1551

The Master of Science degree "radioactive soil contamination from the coastal towns of Walvis bay and Swakpomund in the vicinity of uranium mine sites of Erongo region Namibia" M Zivuku was awarded in 2015.

Radioactive soil contamination is one of the major causes of external gamma rays exposure in many places including the coastal towns of Walvis Bay and Swakopmund in the Erongo region of Namibia. Gamma radiation emitted from natural occurring radioisotopes such as ^{238}U, ^{232}Th and ^{40}K series and their decay products are present in all ground formations and these represent the main external source of irradiation to the human body. Since the estimated radiological impact assessment factors are lower than the world permissible United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR), there seems to be no potential radiological health hazard associated with the soils of Walvis Bay and Swakopmund towns. This shows that the risk due to radiation contamination in Erongo region is low.

The Master of Science degree "Mapping of gamma–emitting radionuclides from Princess Mine Dump and the potential radiological effects on human beings" of Magagula MM was awarded in 2015.

The study was carried out at the Princess dump, an old abandoned mine tailing storage facility in the Witwatersrand region of South Africa. It was aimed at identifying the NORMs in the dump and their activity concentrations using a High Purity Germanium detector. It is recommended that the detailed dust transfer measurements be undertaken in the vicinity of the communities so as ensure that final recommendation can be drawn to assure the safety of the public living in the nearby communities.

The doctoral degree "Radiological Assessment of Naturally Occurring Radioactive Materials and Heavy Metals around the Uranium Mining Area in the Central District of Botswana" of Mashaba M was awarded in 2019.

The study was carried out in the central district of Botswana around Letsibogo dam and the surrounding communities of the new uranium mine. Mining has been identified as one of the main potential sources of exposure to naturally occurring radioactive materials (NORMs) and heavy metals. For foodstuff, the results revealed that the levels of radioactivity in most food samples are insignificant and will not pose any radiological hazard from consumption except for ^{232}Th and ^{40}K which indicated elevated values in vegetable samples that are above the world average value of 290 μSv/y. The cancer risk for people living in the study area, as a result of heavy metal in soil, water, foodstuff and dust was also evaluated. For non-carcinogenic risk, the HI values were found to be 1.5, 27.5 and 1.5 for As, Cr and Cu respectively. These values are greater than 1, which indicate a potential health risk of As, Cr and Cu to the residents of the study area. The ingestion pathway was the greatest contributor to non-carcinogenic risk with an HI value of 27.5 driven by Cr in food samples.

2. Nuclear security

The doctoral of science degree "Designing a physical protection system for the 444TBq ^{60}Co irradiation source at the Centre for Applied Radiation Science and Technology" was awarded to Dr Arwui C in 2017.

The accelerated technological change experienced by the world at the outset of the twenty-first century including technologies used in the nuclear field can pose serious risks to public health, property and the environment if not controlled and handled appropriately. Nuclear and other radioactive materials are being used in a growing variety of settings to advance development in most Countries. The EASIM code's results increased from zero (0) to a minimum of 0.55 and a maximum of 0.69 for sabotage scenario of F2C and a minimum of 0.54 to a maximum of 0.80 for theft scenario of F2C, F2A and F2E, thus indicating an increased level of overall effectiveness for the proposed PPS.

The work "Modeling a Physical Protection System for the 444 TBq ^{60}Co Irradiation Source at the Center for Applied Radiation Science and Technology, Mafikeng, South Africa" have been published in the refereed/peer reviewed article in the Journal of Physical Security 9(1), x-x+28, https://www.scribd.com/doc/ ISSN 2157-8443.

The work "Planning for nuclear security: Design Basis Threats and physical protection systems" have been published in the accredited refereed/peer reviewed article in the Journal SA Crime. Quarterly n.61 Pretoria Sep. 2017

http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1991-38772017000300006
ISSN 2413-3108

3. Applied radiation physics

The Master of Science degree "Evaluation of uptake of ^{65}Zn as a radiotracer in plants using different application techniques to enhance crop productivity" was awarded to Ms Gwala O in 2018.

The activity concentrations of ^{65}Zn in the different parts of the tomato plants was measured with the aim of tracing the uptake and compartmentalization of zinc. There was no correlation observed between the amount of zinc applied to seeds and the amount taken up for priming and coating with and without mycorrhizal inoculation.

There was a positive correlation between the amount of zinc applied to the soil and the amount of zinc taken up for the soil application technique. The zinc introduced for each seed was accounted for because a closed system was used during the experiment. A mass balance between the activity that was introduced and the activity in the plants and soil was obtained (for randomly picked samples) which gave credibility to the results.

4. Theoretical and applied nuclear physics

The masters of Science degree "Establishment of Zr (Zirconium) blood Plasma model" was awarded to Mr Basinyi T in 2016.

This study was carried out in an effort to verify 89Zr as a new safe and effective nuclide for immuno-PET imaging. In recent years, immuno-PET imaging has been of increasing importance in cancer diagnostics due to its rare abilities.

5. Nuclear waste minimization and management

The nuclear material generated in nuclear facilities and nuclear reactors in some case have to be separated from alloys and encapsulated in the material with the required properties. I am working with two MSc students specifically on the project of selecting the properties and strength of the material and on the recovery process.

The research is being carried out under the following topics:

(i) Recovery of uranium from aluminum alloys

(ii) Geopolymer to enhance future pressed cementitious material used in AHTR

Planned and ongoing research

My ongoing research and aim over the next five years will be focused on five core areas. The main themes for the next five years are as follows though some work is ongoing on some of the research themes:

(a) Environmental radioactivity

Environmental radioactivity is a growing field in environmental studies and my research is at the forefront in South Africa. As an expert in the area of environmental radioactivity, I have a long term plan to explore the physics principles behind the transfer of NORMs from mine dumps and the impact on the surrounding populace. To achieve these objectives. I am currently doing research on the potential transfer of radionuclides from former uranium mines to surface and ground water sources profiling of NORMs in areas surrounding uranium mines in South Africa, Botswana, and Malawi, and develop a database required by the nuclear regulators of the respective countries and the IAEA. Currently I am supervising five PhD students in this area:

(i) An investigation of radionuclides and toxic metals concentrations in particulate matter (PM) around Uranium and Gold Mining towns of Erongo region: Namibia,
(ii) Primordial radionuclides evaluation and health dose impact in groundwater, soil and food crops in the lower Swakop river, Erongo region, Namibia
(iii) Investigation of the transfer of naturally occurring radioactive materials from the Morupule Coal mine and the Morupule-B Coal Thermal Power Station in Botswana, to the surrounding environment,
(iv) Environmental radioactivity profiling of NORMs in the surrounding areas of Kayelekera uranium mine, Malawi,
(v) Evaluation of natural radionuclides and heavy metals in and around Mupane gold mine, Botswana
Five MSc students working on:
(i) Evaluation of the level of naturally occurring radioactive materials in soil samples at Mudimeli coal mine, Limpopo province, South Africa,

(ii) Radioactive toxicity in ground and surface water around the Rand uranium mine in Krugersdorp, South Africa,

(iii) Radioactive toxicity in ground and surface water around the Carletonville gold mine, South Africa,

(iv) Radiological risk assessment of ground water around the Serule area of Botswana. Botswana International University of Science and Technology (in collaboration with Botswana International University of Science and Technology, and

(v) Measurement of Natural Radioactivity levels in Serule Soils, in collaboration with Botswana International University of Science and Technology

(b) Applied radiation science

In this area I am doing research on optimizing X-ray radiography by improving image quality objective and reducing radiation dose absorption. I am also investigating the use of radiotracers such ^{65}Zn to improve nutrient absorption and sequestration in important South African crops. Lastly, I am also working on Extraction and Accelerator Mass Spectroscopy of in-situ cosmogenic ^{10}Be harvested from dolerites towards understanding river incision. I have three MSc students working on applied radiation science,

(c) Nuclear security

I am doing research on the development of new techniques and policies for nuclear safeguards of material. I am supervising one PhD and two MSc students on the development of these techniques for the abovementioned purpose under the following topics:

(i) Characterisation of the UF_4 unburnts materials using NDA techniques for safeguards purposes in collaboration with South African Nuclear Energy Corporation

(ii) Assessment of Aerodynamic Separation Process and regulation by Nuclear Suppliers Group

(iii) Nuclide inventory, radiation shielding and nuclear criticality safety calculations, for radiochemical uranium recovery on MTR isotope-production target-plate process residue and spent fuel

(d) Nuclear Technology

(i) The radon monitors required to measure the radon in different places have to be calibrated every year. There is no radon chamber that is operational for that purpose in South Africa at

the moment. I have one MSc student currently working on the project to design the radon chamber for calibration purposes. The design of a radon chamber for the calibration of radon monitors at the Centre for Applied Radiation Science and Technology.

(ii) There is a need to sterilize and extend shelf life of fresh produce. I have embarked on a project to acquire Cobalt-60 source that will be used to study the operation and doses of the equipment at the laboratory scale before upgrading industrial scale. The first phase of this project is complete where I developed the Planning for nuclear security: Design Basis Threats and physical protection systems and a publication of the same title in the accredited and peer reviewed journal. SA Crime Quarterly n.61 Pretoria Sep. 2017 http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1991-38772017000300006

ISSN 2413-3108. One PhD was produced from this work. The next phase and long term project will be to install and commission the ^{60}Co source.

List of MSc and PhD graduates

1	Moreosele TA	Dr V Tshivhase and Dr T Tshepe	MSc	2002
2	Basinyi T	Prof V Tshivhase and Prof JR Zeevaart	MSc	2016
3	Dlamini SG	Prof M Mathuthu and Prof VM Tshivhase	MSc	2015
4	Dlamini TC	Prof M Mathuthu and Prof VM Tshivhase	MSc	2015
5	Magagula MM	Prof V Tshivhase and Prof M Mathuthu	MSc	2015
6	Radebe M	Prof V Tshivhase and Dr NB Ndlovu	MSc	2019
7	Moabi HP	Prof V Tshivhase and Dr VL Mbele	MSc	2019
8	Mojaki PM	Prof V Tshivhase and Dr NB Ndlovu	MSc	2019
9	Mokgele TD	Prof V Tshivhase and Dr R Koen	MSc	2019
10	Morebantwa PP	Prof V Tshivhase and Dr Elizabeth Stassen	MSc	2019
11	Keetile TP	Prof V Tshivhase and Mr RB Nshimirimana	MSc	2019
12	Gwala O	Prof V Tshivhase and Prof JR Zeevaart	MSc	2018
13	Zivuku M	Prof V Tshivhase and Prof NA Kgabi	MSc	2015
14	Dlamini TC	Prof V Tshivhase and Dr PP Maleka	PhD	2019
15	Mashaba M	Prof V Tshivhase and Prof A Faanhof	PhD	2019
16	Arwui C	Prof V Tshivhase	PhD	2017

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