

Calibration & Application of an NaI(Tl) Detector for Environmental Radiation Measurement



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Declaration of Authorship

I, KJ Lawrence, declare that this thesis and the work contained in it are my own. Further, I confirm that:

- This work was mainly done while in candidature for an Honours degree at this University.
- Where any part of this thesis has been submitted at this University or any other institution, this has been clearly stated.
- Where I have consulted published work from others, this is clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of these quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where this thesis is based on work done jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signature: *KJ Lawrence*

Date: April 6, 2026

Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less. - Marie Curie

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Abstract

Environmental gamma radiation originates from naturally occurring and anthropogenic radionuclides. These radioactive substances are hidden within the soil which surrounds us everyday, contributing to long-term radiation exposure. Gamma-ray spectroscopy has been widely used to monitor environmental radioactivity in many regions across the globe. Many studies focus primarily on regions with industrial or nuclear activity, leaving gaps in the understanding of radiation levels in rural areas and farmlands. This research aims to address this lack of regional data by measuring gamma emitting radionuclides in soil samples using a sodium iodide (NaI (Tl)) scintillation detector. The gamma spectrum was acquired from collected soil samples and analysis was done using GammaVision Software. Results show that Uranium-238 series dominates in both provinces, reflecting regional geology. Detected activities are used to calculate annual effective doses from terrestrial radiation. The dose rates of 0.269 and 0.129 mSv/yr for Nova Scotia and New Brunswick are in agreement with expected natural background levels. With no elevated background radiation and no evidence of nuclear contamination, the regions of interest pose no health concern.

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1 Introduction

Radiation is typically associated with mass casualty events, its effects felt in the immediate aftermath and decades later. While it has developed an ominous reputation, as we know it is there, but it remains undetectable to the human senses. In fact its effects can take years to present themselves, adding to its dangerous and unpredictable perception. What is less commonly known is that radiation is part of everyday life and a natural and unavoidable component of the environment originating from cosmic sources, terrestrial materials, or human influence. The radiation we experience daily is called background radiation and is composed of the sources above. Typically, background radiation levels are low and living things have adapted to live with its constant presence, allowing them to go about their everyday lives without the need for protection from this radiation. But the background radiation can vary from location to location due to the geological composition of the area, soil characteristics, history, and human influence. Understanding the composition and concentration of this radiation is important for assessing radiation exposure, investigating potential contamination pathways and establishing a baseline reference level for future monitoring.

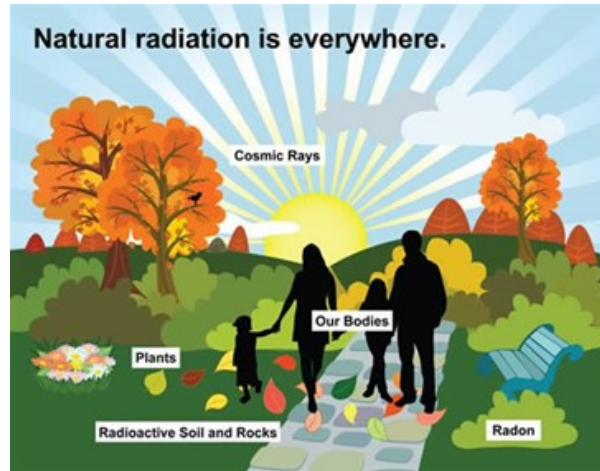


Figure 1: Sources of Natural Radiation[1]

1.1 The Critical Exposure Pathway

Soil serves as an effective source for measuring environmental radiation, as it can act as a reservoir for gamma-emitting radionuclides and as a medium through which they can be transported [2]. It is of great concern for public health that radionuclides present in soil may enter the food chain through crops and livestock, as well as contaminate water systems, adding to the importance of environmental radiation monitoring.

1.2 Targeted Radionuclides

1.2.1 Naturally Occurring Radioactive Materials

Earth is littered with varying concentrations of radioactive elements along its surface and inner layers. Majority of these radioactive elements have been present on Earth for thousands to millions of years. Today, they contribute to the radioactivity on Earth via their decay products. These parent and daughter nuclides are referred to as Naturally Occurring Radioactive Materials (NORMs) [3]. The nuclides referred to as such are isotopes of Uranium and their decay products, thorium and their decay products, and potassium [3]. These NORMs are present throughout soil, water, sediment, and rocks around the globe, and their abundance depends on the geological make up and human activity of the region. Human activity can increase the amount of NORMs present in our environment, increasing our exposure. Some of these activities include mining of ores, minerals, or fossil fuels and the processing of raw materials. The following map 2 shows the distribution of NORMs across Canada. The map shows a dominating presence of Uranium (U-238) and Thorium (Th-232) in Nova Scotia and New Brunswick. It's expected to see evidence of uranium and thorium in the collected soil samples from these regions.

Both uranium and thorium have incredibly long half-lives; because of this, it is extremely improbable that the NaI (Tl) detector will pick up an adequate amount of information to detect the presence of these radionuclides. However, their presence in the soil samples is revealed by the nuclides in their decay series [2]. The decay series nuclides emit many gamma-rays throughout their decay process. Most are of low intensity and not detectable by the scintillation detector. For that reason, only the detectable, high intensity gamma-rays are considered. These nuclides have much shorter half-lives, making them much more abundant in a soil sample and more likely to be detected. It is expected that the soil samples will contain several of these decay series nuclides and GammaVision is capable of reporting the activity for each of these nuclides.

Nuclide	Half-Life	Decay Mode	Emitted γ -ray	γ Intensity
U-238	4.5×10^9 years	α	2512.7 keV	65%
Th-234	24.1 days	β^-	63.29 keV	3.7%
Pa-234m	1.17 min	β^-	820.5 keV	97.57%
U-234	245.5×10^3 years	α	53.20 keV	0.123%
Th-230	75.38×10^3 years	α	67.67 keV	0.38%
Ra-226	1602 years	α	186.211 keV	3.57%
Rn-222	3.82 days	α	510 keV	0.076%
Po-218	3.1 min	α, β^-	-	-
Pb-214	26.8 min	β^-	351.932 keV	35.72%
At-218	1.5 sec	α	-	-
Bi-214	19.9 min	α, β^-	1268 keV	19.2%
Po-214	164.3 μ s	α	799.7 keV	0.0104%
Pb-210	22.2 years	α, β^-	46.539 keV	4.25%
Tl-210	1.3 min	β^-	799.6 keV	98.96%
Bi-210	5.01 days	α, β^-	265.5 keV	51%
Po-210	138 days	α	803.06 keV	0.00103%
Hg-206	8.32 min	β^-	304.896 keV	26%
Tl-206	4.2 min	β^-	453.3 keV	93%
Pb-206	Stable	-	-	-

Note: Radionuclides which do not emit gamma-rays are indicated by "-" in the respective columns.

Table 1: Uranium Decay Series Nuclides, Nuclide information sourced from IAEA [5]

Nuclide	Half-Life	Decay Mode	Emitted γ -ray	γ Intensity
Th-232	14.1×10^9 years	α	63.81 keV	0.263%
Ra-228	5.7 years	β^-	13.52 keV	1.6%
Ac-228	6.1 hours	β^-	270.235 keV	3.46%
Th-228	1.9 years	α	131.613	0.127%
Ra-224	3.6 days	α	240.986 keV	4.10%
Rn-220	55 sec	α	549.73 keV	0.114%
Po-216	0.14 sec	α	804.9 keV	0.0019%
Pb-212	10.6 hours	β^-	238.632 keV	43.6%
Bi-212	61 min	β^-	727.33 keV	6.67%
Po-212	3.0×10^{-7} sec	α	-	-
Tl-208	3.1 min	α	2614.511 keV	99.754%
Pb-208	Stable	-	-	-

Note: Radionuclides which do not emit gamma-rays are indicated by "-" in the respective columns.

Table 2: Thorium Decay Series Nuclides, Nuclide information sourced from IAEA [5]

1.2.2 Anthropogenic radionuclides

Other radionuclides present in our environment are a consequence of human activity. Classified as anthropogenic radionuclides, these nuclides find their way into our environment via the waste products of nuclear and industrial processes, nuclear decommissioning, and even frequent use of some chemical fertilizers [6]. Some common anthropogenic nuclides include: Cs-137, Co-60, Tc-99, and I-129 [6]. The samples collected for this work were taken from urban areas with no industrial or nuclear infrastructure in proximity. Therefore, it is not expected to detect significant amounts of these anthropogenic nuclides.

Nuclide	Half-Life	Decay Mode	Emitted γ -ray	γ Intensity
Cs-137	30.08 years	β^-	661.657 keV	85.1%
Co-60	1925.28 days	β^-	1173.228 keV, 1332.492 keV	99.85%,99.98%
I-129	1.57×10^7 years	β^-	7.51 keV	39.578%
Am-241	432.6 years	α	59.54 keV	35.9%

Table 3: Common Anthropogenic Nuclides, Nuclide information sourced from IAEA [5]

1.3 Gamma-Ray Spectroscopy with NaI(Tl) Detector

Gamma-ray spectroscopy is one of the most effective techniques for identifying and quantifying radionuclides. Gamma-rays emitted during radioactive decay processes are packaged into discrete energies, which serves as an identifier or fingerprint for each isotope. By measuring the energy spectrum of detected gamma-rays, it is possible to determine what radionuclides are present within the soil and the activity they possess. Additionally, gamma-spectroscopy is non-destructive, allowing for the preservation of the collected samples and the ability to measure them multiple times. This technique is particularly useful for the creation and monitoring of an environmental reference database.

Thallium activated sodium iodide detectors are commonly used in gamma-ray spectroscopy. NaI (Tl) detectors offer many advantages, including high detection efficiency of gamma-rays, good energy resolution, and relatively user friendly software. The elemental make up of the NaI (Tl) scintillation crystal makes it equipped to absorb gamma-rays and promote interactions such as Compton scattering, pair production, and photoelectric absorption. The scintillation process in the crystal produces lots of gamma-rays which can then be detected and converted into a measurable electric signal. Compared to other detector technologies like a High-Purity Germanium (HPGe) detector, which requires expensive cooling systems and regular maintenance, NaI (Tl) detectors are cost-effective, practical, and therefore a standard choice for radiation measurement.

1.4 Motivation

The motivation for the study is to contribute to the understanding of environmental radioactivity by measuring gamma radiation from soil samples using a NaI(Tl) scintillation detector. Despite its significance, there is limited publicly available data about gamma emitting radionuclides in soils from rural regions in New Brunswick and Nova Scotia. Establishing a baseline level is essential for assessing future environmental changes and evaluating potential contamination events. By analyzing gamma spectra and identifying characteristic energy peaks, my work aims to determine which radionuclides are present and contributing to the overall radiation detected. These measurements will provide valuable information about local regions and serve as a reference point for future gamma spectroscopy research.

Once the NaI detector has been used to measure the activity of radionuclides found in

the spectrum, these activity quantities will be converted into dosages. These calculated dosages will be compared to the average doses of radiation for Halifax and Canada, to see if they are within the quoted thresholds.

2 Background

2.1 Gamma-Ray interactions with Matter

Particle detection is dependent on the production of secondary particles that eventually produce an electrical signal. Typically, these secondary electrons are produced by ionization as a result of the introduction of an incident charged particle. Gamma-rays cannot be detected using the same method as they lack an electrical charge. Alternatively, Gamma-ray detection depends on other interactions, where the energy of the gamma-rays is transferred to electrons in the absorbing material[7]. It is crucial to choose a suitable material as the detector medium to ensure an acceptable number of electron-hole pairs are generated. These electron-hole pairs are then collected to produce an electrical signal.

Of interest are inelastic collisions of gamma-rays and surrounding atoms. This includes: photoelectric absorption, Compton scattering, and pair production.

2.1.1 Photoelectric Absorption

Photoelectric Absorption is a process in which gamma-rays excite inner shell electrons releasing them from the atom. The incident gamma-ray is completely absorbed by an inner shell electron (K-shell). If the gamma-ray has sufficient energy (E_γ) to excite the electron beyond the binding energy (E_b) of the electron shell, the electron will be ejected from the atom with some energy (E_e). The binding energy is dependent on the absorbing material, as the binding energy differs from element to element. The ejected electron is referred to as a “photoelectron” and is moving freely within the absorption material where it can continue to excite other electrons.

$$E_e = E_\gamma - E_b \tag{1}$$

The process of photoelectric absorption leaves a vacancy or “hole” in the inner electron shell which must be filled to maintain stability. This is done by electron rearrangement, where outer shell electrons shift down the energy shells of the atom. The outer shell electrons are not bound as tightly, so energy must be released to occupy the shells closest to the nucleus. The released energy takes the form of x-rays, also referred to as fluorescence[8]. As the electrons rearrange and energy of different quantities is released, a cascade of x-rays is produced. The energy of the x-rays is equal to the difference between the electron energy levels.

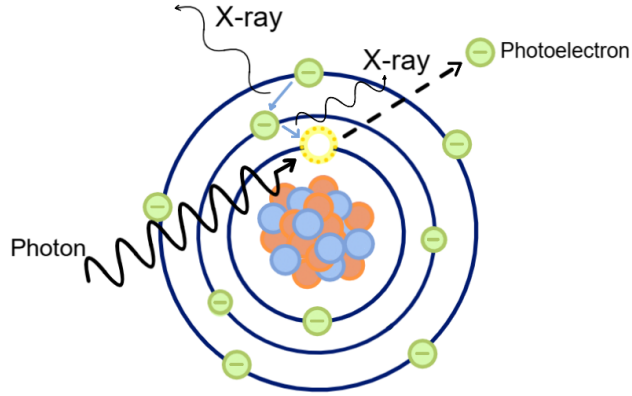


Figure 3: Photoelectric Absorption followed by the production of a Characteristic x-ray.

2.1.2 Characteristic x-rays

In this scenario the x-rays are produced by electrons moving between energy shells. This causes the x-rays to be released in a pattern which is unique to each element, hence their name “Characteristic x-rays”[8].

$$E_e = E_\gamma - E_K \quad (2)$$

2.1.3 Compton Scattering

Compton Scattering is the process of a gamma-ray transferring a portion of its energy to an atomic electron. An energetic gamma-ray collides with an electron bound to an atom. The angle at which this collision occurs dictates how much of the gamma-ray’s energy is transferred to the electron. Maximum energy transfer occurs during a head-on collision ($\theta = 180^\circ$), after which the electron will be ejected from the atom at some angle (ϕ) and is referred to as the recoil electron. In the case of a head-on collision the photon will always retain some energy and be scattered off similarly to the recoil electron. When the collision occurs at an angle less than 180° only a portion of the gamma-ray’s energy

is transferred to the electron. If the transferred energy is able to overcome the binding energy of the electron shell the electron will be ejected resulting in a recoil electron and scattered photon. If not, the electron will be put into an excited state but remain bound to the atom. When the electron returns to the ground state it will release the energy it received as a gamma-ray. Regardless of the scenario, the process of Compton scattering produces energetic electrons or, secondary gamma-rays which may go on to excite further electrons in the material[9].

$$E_e = E_\gamma - E'_\gamma \quad (3)$$

The energy of the scattered electron can be determined using 4:

$$E_{e^-} = \lambda' - \lambda = \frac{h}{mc}(1 - \cos \phi) \quad (4)$$

where, $\frac{h}{mc} = \lambda_c$ is Compton Wavelength.

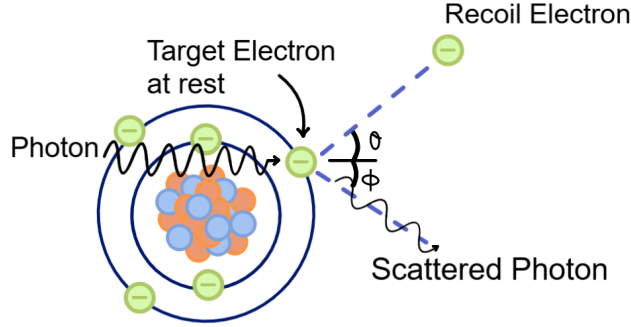


Figure 4: Compton Scattering resulting in a recoil electron and lower energy scattered photon.

2.1.4 Pair Production

Pair Production is the process of a gamma-ray transforming into an electron-positron pair (e^- , e^+). When a gamma-ray finds itself in the coulomb field of the atom's nucleus it is transformed into an electron and positron (anti-particle of an electron) through the conversion of energy into matter. For this to occur the initial gamma-ray must have a minimum energy equal to that of the rest energy of the particles created ($E_{min} = 1022keV$).

$$E_e = E_\gamma - 1022keV \quad (5)$$

[8] This process must also obey the conservation of energy and momentum, meaning the products must sum to zero. This results in the products having opposing values of one another which is why a particle anti-particle pair is produced. The products receive the same amount of energy from the gamma-ray as their masses are the same. The electron

and positron are scattered in different directions with equal amounts of energy. The electron will travel through the material dissipating its energy to surrounding electrons until it is brought to rest. However, the path of the positron is different.

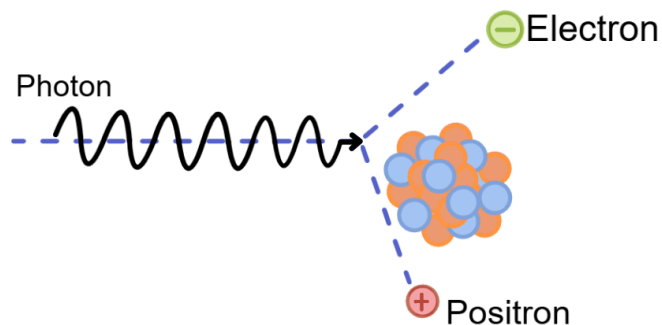


Figure 5: Pair production resulting in an electron-positron pair.

2.1.5 Annihilation

Positrons have a very short lifetime and very quickly donate their energy to surrounding electrons in the medium. Once the positron is almost at rest, it combines with an electron of the material. Then the process of annihilation occurs producing two gamma-rays from the combined electron and positron[7]. These gamma-rays are referred to as annihilation radiation. The two gamma-rays will then go one to interact with surrounding electrons or escape the material altogether.

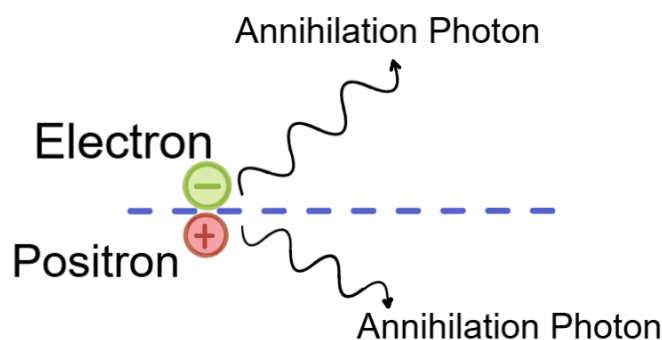


Figure 6: electron-positron annihilation, producing two identical gamma-rays.

2.1.6 Bremsstrahlung Radiation

As discussed, there are many different ways incident gamma-rays can produce energetic electrons. When these energetic electrons interact with the coulomb field of an atom's nucleus their energy is lost and appears as a continuum of photons. These photons

are within the energy range of x-rays and are referred to as Bremsstrahlung x-rays or Bremsstrahlung Radiation[8]. As the electron approaches the nucleus its path will be manipulated by the coulomb field surrounding the nucleus. The electron will be deflected around the nucleus and scattered away from it. The deflection causes a loss of energy from the electron which is released as an x-ray. The energy of this x-ray will depend upon the closeness of approach of the electron. When the electron closely approaches the nucleus, the x-ray will inherit a maximum amount of energy, this produces high energy x-rays. Moderate to low energy photons are produced by the deflection of the electron, and their de-acceleration is what causes the release of an x-ray. This is pictured in figure 7.

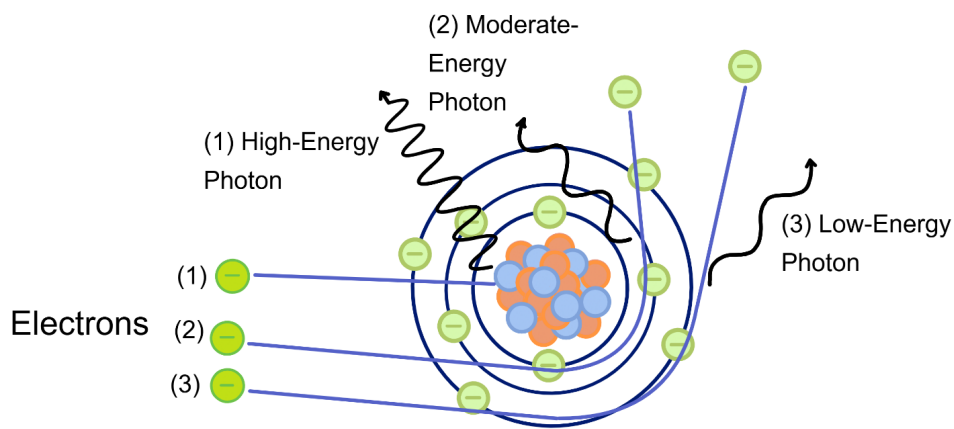


Figure 7: Different scenarios of Bremsstrahlung radiation production. resulting in low, moderate, and high energy gamma-rays.

2.1.7 Auger Effect

There are times when the energy released during the re-arrangement of electrons is not in the form of x-rays. Instead, this energy may be used to release an electron from the atom. This is referred to as the Auger effect, and the released electron is called an Auger Electron. This process is most probable in atoms with a low Z number. Auger electrons are mono-energetic and typically are of low energy as they are commonly emitted from the M or L shells. It is less common that an atom undergoes the Radiative Auger Effect, that being the production of an Auger electron and x-rays. In this case, the x-rays are produced from the daughter nuclide as electron rearrangement occurs after electron capture.

2.2 Radioactivity and Modes of Radioactive Decay

Radioactive decay is a spontaneous change within the nucleus of an atom that results in the emission of particles or electromagnetic radiation [7]. As this research investigates gamma radiation, understanding the processes from which they arise is crucial. Radionuclides are unstable forms of chemical elements which aim to achieve stability by one or more methods of decay. Some of these decay modes include alpha decay, beta-minus decay (β^-), positron decay (β^+), and electron capture (EC), with gamma-rays being released to attain stability. The instability in the nucleus is due to an imbalance of nuclear forces, meaning an imbalance between protons and neutrons. The conflict is between the strong force, which causes neutrons and protons to be attracted to one another, and the repulsive coulomb force which is caused by the closely packed protons in the nucleus. These unstable elements with an imbalance of protons and neutrons are classified as radioisotopes [7].

These radioisotopes are measured by their rate of disintegration, often in Becquerels (Bq) or Curies (Ci). This rate of disintegration is referred to as the activity of the sample. This amount will vary with time, so it is crucial to specify the time the activity was measured and to keep detailed records of any radionuclide sources, since an inaccurate time record can have significant effects on the labeled activity of a radionuclide [7].

The decay of these radionuclides is described in the decay equation, where the activity (A) of the radionuclide source (quantity of radionuclide atoms) is proportional to the number of nuclide atoms [7].

$$A = -dN/dt = \lambda N \quad (6)$$

The decay equation can be simplified into an exponential equation (7), where the activity of the source is denoted as A_0 and the activity after decay has occurred for some period of time, A . The decay constant (λ) is the probability of decay per unit time, with units of reciprocal time. The decay constant is inversely proportional to the mean lifetime (τ) of the radionuclide.

$$A = A_0 e^{-\lambda t} \quad (7)$$

$$\tau = \frac{1}{\lambda} \quad (8)$$

τ describes the average amount of time that the radionuclide can exist before its nucleus begins to decay. A shorter mean lifetime results in a higher decay constant, and a long mean lifetime indicates a shorter decay constant. Together, these two quantities make it possible to calculate the half-life of a radionuclide.

The half-life is the amount of time it takes for the radionuclide activity to decrease to half its original value (9). The exponential decay will continue until the radionuclide has reached stable conditions. The half life is unique to each radioisotope, some lasting decades and others minutes.

$$t_{1/2} = \frac{\ln 2}{\lambda} \quad (9)$$

2.2.1 β^- Decay

A beta particle (β^-) is an electron identical to any other; however, the term ‘beta particle’ is used specifically to refer to an electron that has been emitted during a nuclear decay process. Nuclides which undergo beta decay are neutron rich, an imbalance which is corrected during the decay process. During the decay process, a neutron is converted into a proton within the nucleus. This increases the atomic number by one and the nuclide drops down into a more stable state. The decay energy is shared between all decay products in an inverse ratio to their masses to conserve momentum. In this mode of decay, the beta particle and the anti-neutrino split almost all the decay energy and this can happen in many different proportions. This variability of energy between the beta particles and anti-neutrinos is the reason beta particles are not mono-energetic. We need not be concerned about the anti-neutrino as it is only detectable in very sophisticated detectors.



The decay of Cs-137 is a simple case of beta decay. As seen in its decays scheme diagram 8, 6.5% of all beta decays directly decay to the ground state to the daughter nuclide, stable Ba-137. Most beta decays (93.5%) decay to an excited nuclear state of Ba-137. From this excited state, gamma radiation releases an energy of 661.7 keV. Now de-excited, this processed has reached the ground state of stable Ba-137.

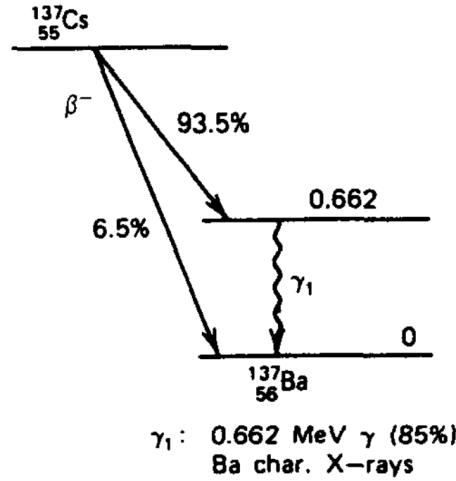


Figure 8: Decay Scheme of Cesium-137 [9]

Another example of beta decay is the decay of Co-60. This process is more involved as there are multiple gamma transitions. Many of the beta decays fall to the lower energy level, followed by the release of two gamma-rays, with energies 1173.3 and 1332.5 keV, to reach the ground state of stable Ni-60.

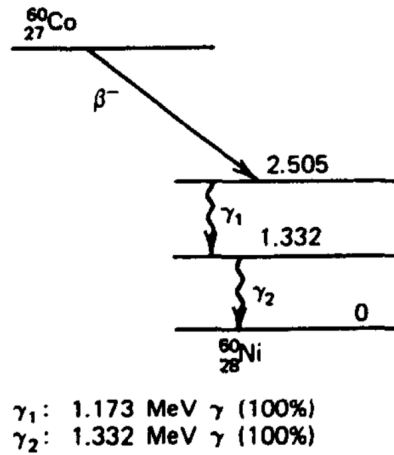


Figure 9: Decay Scheme of Cobalt-60 [9]

2.2.2 β^+ Decay

The complement to beta decay is known as positron (β^+) decay. This process involves the release of a positron, the anti-particle of an electron. Nuclides susceptible to β^+ decay are neutron deficient. Just as beta decay is the process of an electron being emitted from the nucleus, β^+ decay is the process of emitting a positron from the nucleus. However, β^+ decay is not as simple. If it were similar to beta decay, an extra proton would combine

with an electron, producing a positron which is emitted from the nucleus. But as it is commonly known, electrons are not found in the nucleus. To achieve this, the gamma-ray interaction of pair production must occur before positron decay. Pair production will release a free electron, which may go on to interact with the nucleus of a surrounding atom, inducing positron decay[9].

$${}^A_Z X \rightarrow {}^A_{Z-1} Y + \beta^+ + \nu \quad (11)$$

2.2.3 Electron Capture

A Caveat of β^+ decay is that it will only occur if 1022 keV of decay energy is available, as this is the energy threshold for pair production to occur. For neutron deficient nuclides without 1022 keV of decay energy available, an alternative decay process is possible. Instead of getting the free electron from the previous process of pair production, the nucleus can get the needed electron from an inner electron shell. The closest electron shell to the nucleus is called the K-shell, so the capture of a K electron is most likely and is the reason this process may also be called K-capture[9]. The probability of capturing an electron from the higher and less strongly bound shells (L, M, N, etc.) increases as the decay energy decreases. The loss of an electron from an electron shell will leave a vacancy which must be filled by an electron dropping down from surrounding shells. The effects of this electron shuffling process are detailed in 2.1.6.

$${}^A_Z X + e \rightarrow {}^A_{Z-1} Y + \nu \quad (12)$$

A decay process illustrating both positron decay and electron capture is the decay of Na-22. Most decays (90%) follow the path of positron decay, dropping down to an excited state of Ne-22. This will require the emission of a 1274.5 keV gamma-ray for the decay to reach the ground state of stable Ne-22. The other 10% of decays undergo electron capture which may produce x-rays as a by-product. The released positron will go on to annihilate with surrounding electrons (detailed in 2.1.5) giving rise to two 511 keV gamma-rays, which produce an annihilation peak visible in the gamma-ray spectrum of Na-22.

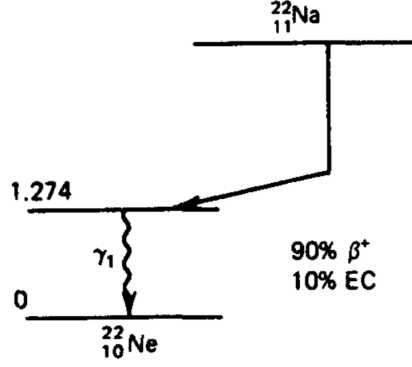


Figure 10: Decay Scheme of Sodium-22 [9]

2.2.4 α Decay

When dealing with elements of high atomic number ($Z > 83$) the preferred mode of decay is alpha decay. This process involves an “alpha particle” being emitted from the atom, producing a daughter nuclide of lower mass and charge, with the alpha particle (a He-4 nucleus) and an excess amount of energy Q . The quantity of energy is equal to the mass difference between the initial nuclide and products. This energy is shared between the products in a fixed proportion to conserve momentum [9]. When dealing with heavier nuclei alpha decay may result in the production of excited states in the daughter nuclide. These excited states will become stable by the emission of a gamma-ray.

$${}^A_Z X \rightarrow {}^{A-4}_{Z-2} Y + {}^4_2 \text{He} + Q \quad (13)$$

Useful examples of alpha decay are Ra-226 and Th-228. The radium nuclide decays directly to its ground state of Rn-222 majority of the time, with some decays going to an excited state of Rn-222 followed by the emission of a gamma-ray.

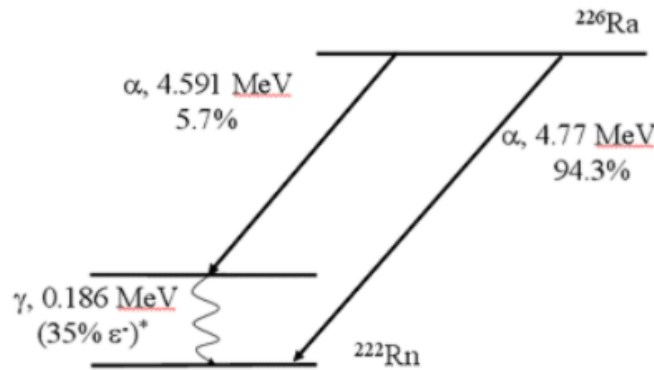


Figure 11: Decay Scheme of Radium-226[10]

Th-228 has several different pathways in which it may achieve stability. This occurs by the parent nuclide releasing an energetic alpha particle and directly arriving at the ground state. More probable is the release of a slightly energetic alpha particle followed by the decay landing on one of four excited energy states of Ra-224, followed by the emission of a gamma-ray to reach stability.

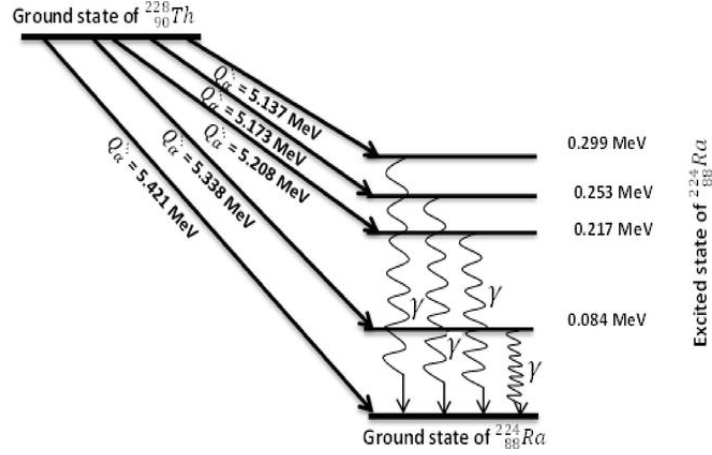


Figure 12: Decay Scheme of Thorium-228[11]

2.3 Features of a Gamma-Ray Spectrum

2.4 Partial Energy Scattering Features

Inelastic collisions between incident gamma-rays and electrons produce characteristic features in the gamma spectrum. These being the Compton continuum and Compton edge. Other times features are produced from extreme scattering or interactions with surrounding materials. These features are slightly different for each radionuclide, as they depend on the initial energy of the radionuclides gamma-ray [12].

2.4.1 Compton Continuum & Compton Edge

Compton scattering gives rise to two features within the gamma spectrum. The Compton continuum and the Compton edge. As discussed in section 2.1.3, Compton scattering results in an energetic electron and gamma-ray, whose energies are determined by the scattering angle. Within the scintillation material, Compton scattering will occur at all angles, which results in a number of inelastic collisions. Over a wide range of collision angles little to moderate energy is transferred to the recoil electron. This produces a shallow valley situated in the low energy region of the spectrum, referred to as the Compton

continuum.

A head-on collision occurs at $\theta = 180^\circ$, resulting in the gamma-ray donating as much of its energy to the recoil electron as possible and being scattered back towards its direction of origin. The recoil electron is scattered in the direction of incidence, sending it off to further interact with electrons in the scintillation crystal. Head-on Compton scattering produces a small peak at the higher energy extreme of the Compton continuum making the approach of its end. This is referred to as the Compton Edge.

When working with a spectrum of multiple radionuclides, the Compton scattering features may overlap. It is important to recognize these features to conduct necessary filtering and subtraction, allowing the software to identify true full-energy peaks and escape peaks.

2.4.2 Backscatter

The backscatter peak is a broad peak around 200 *keV*. It is caused by gamma-rays which have undergone Compton scattering with a surrounding material before entering the detector. The radiation source will emit energetic gamma-rays into the cavity created around the detector. The gamma-rays may interact with the surrounding shielding, which in this case is lead, the sample holder made from plastic, and air in the cavity above the detector. The backscatter peak is produced by gamma-rays which have undergone Compton scattering at a large angle ($180^\circ \leq \phi$) and then have gone on to be absorbed in the scintillation crystal. The large scattering angle causes the gamma-ray to lose most of its energy, which is why the backscatter peak is expected to appear in the lower energy range of the gamma spectrum preceding the internal Compton scattering features discussed above.

The energy of the backscatter peak can be approximated using equation 14[9]. This can be useful when checking the calibration of the detector. Ensuring that the calibration is well defined at lower energies and not just in the moderate to higher energy range where most full-energy peaks and escape peaks occur. Besides this, it is important that the backscatter peak be understood, again to ensure proper filtering and exclusion when performing the analysis of more complicated spectra as to not miss label spectrum

features.

$$hv'|_{\phi=180^\circ} = \frac{hv}{1 + (hv/m_e c^2)(1 - \cos \phi)} = \frac{hv}{1 + 2hv/m_e c^2} \quad (14)$$

2.4.3 x-ray Peaks

There are several atom particle interactions which result in a vacancy in one of the atom's inner electron shells. When this vacancy is corrected secondary radiation is released as x-rays which produce a peak characteristic of the radionuclide. As seen in the electromagnetic spectrum, x-rays are less energetic than gamma-rays. This is because the energy given to x-rays is determined by atomic binding energies, whereas gamma-rays acquire their energy from nuclear transitions, causing peaks produced by x-rays to be situated at the beginning of the gamma spectrum, typically within the range of $0-75\text{keV}$ [7].

Back scattered gamma-rays have the possibility to collide with electrons in the shielding material, lead. By the same processes discussed in earlier sections, it is possible this interaction results in the release of an x-ray. However, the x-ray will be a consequence of the shielding material instead of the radionuclide. This would then produce an x-ray peak, characteristic of the shielding material, independent of the radionuclide placed inside the detector.

2.5 Full-Energy Scattering Features

When a complete energy transfer occurs between a gamma-ray and electron, tall Gaussian shaped peaks appear in the gamma-spectrum. These peaks are the focus of the calibration as their area and location builds the calibration equations.

2.5.1 Full-Energy Peak

Photoelectric absorption results in the complete absorption of the incident gamma-ray by a surrounding electron. The complete energy transfer produces an electron with energy equal to that of the incident gamma-ray minus the binding energy of the electron shell. The energetic electron travels through the scintillation material, whose journey is picked up and recorded by the detector. As a result, a tall well-defined peak, centered at some energy, is recorded in the gamma spectrum, referred to as the photo-peak or full-energy

peak[7].

The full-energy peak can be thought of as a “fingerprint” for radionuclides. Each radionuclide releases a known quantity of energy which can be matched to the full energy peak in the gamma spectrum, allowing for identification of nuclides from a gamma spectrum and vice versa. The full energy peak reveals much about the detector’s performance such as information about the detector’s energy resolution from its width. Ideally, the peaks are narrow, making it possible to easily distinguish between multiple spectrum features. When resolution is poor, full-energy peaks will be much broader and can be caused by electronic noise, temperature instability or scintillator degradation. The overall shape of the peak should be symmetric and Gaussian -like, deviations from this will result in inaccurate counts and possible exclusion by the software, resulting in key information missing from the spectrum analysis. Characteristics of the full-energy peak, like its net counts and centroid, are required features for performing the energy and efficiency calibration, which is discussed further in the calibration section, 4.

2.5.2 Escape Peak

When working with high energy gamma-ray emitters it is possible to see peaks identical to full energy peaks centered at 511 *keV* and 1022 *keV*. These peaks are the product of pair production occurring in the scintillation crystal and are referred to as Escape peaks. When a radionuclide has 1022 *keV* or more energy available, it is possible for pair production to occur. This creates a positron-electron pair. The positron then annihilates with a surrounding electron producing two annihilation photons. When one of these annihilation photons escape the scintillator, gives rise to a Gaussian-like peak centered at 511 *keV*, referred to as the single-escape peak. When both annihilation photons escape, a double-escape peak is produced with the centroid 1022 *keV*, the sum of both photon’s energies. Similarly to full-energy peaks, the escape peaks are useful when performing the energy and efficiency calibration, their shape also revealing the quality of the hardware.

2.6 Background Radiation

Background radiation is a constant level of ionizing radiation present on Earth, which we are exposed to daily. Background radiation can be split into two main categories, cosmic

and terrestrial. Cosmic radiation originates from celestial bodies, mainly the sun, which travel through Earth's atmosphere down to the surface. A larger concentration of cosmic radiation is present in areas of a higher altitude due to less radiation being lost when having to travel a shorter distance. Terrestrial radiation originates from elements present in the soil and Earth's crust[1]. Their natural decay releases small amounts of ionizing radiation, leading to exposure.

When measuring samples, background radiation is detected and adds unwanted counts to the gamma spectrum. It produces a largely low energy gamma spectrum as it interacts with the scintillator and surrounding materials via Compton scattering[12]. This increases the areas of features in the spectrum tainting the actual results. This is specifically harmful when analyzing a spectrum as background radiation may increase the area of full-energy peaks, leading to misidentification by the software and inaccurate activity calculations. When working with low activity samples, background radiation can bury important features of the gamma spectrum, making results unusable.

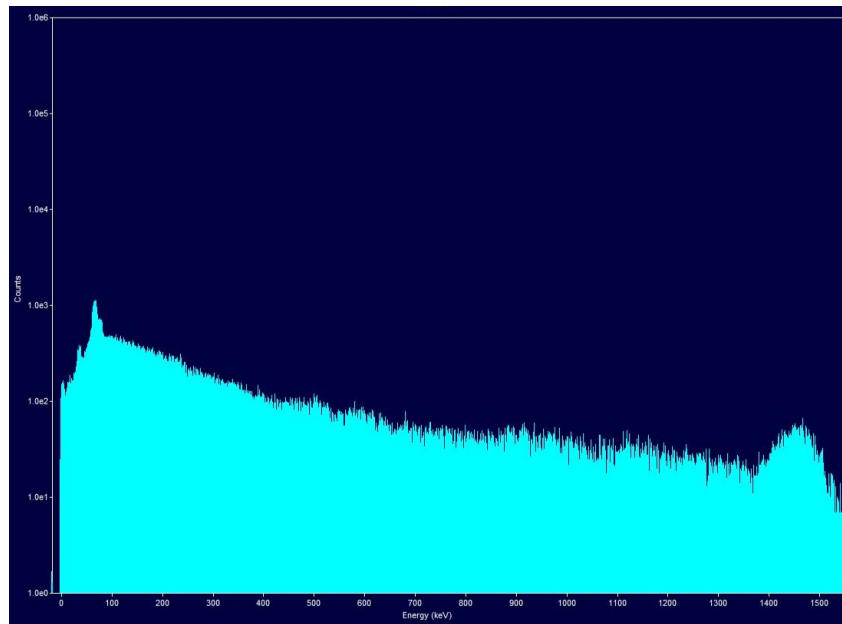


Figure 13: Background Spectrum, Jan 30th 2026

In gamma spectroscopy, there are several techniques to reduce the effects of background radiation. The physical measures used to reduce background radiation include a lead shielding with an added layer of plastic to minimize any leakage. The detector is placed in a controlled lab environment situated on the bottom floor, with the detector isolated from anything causing temperature fluctuations and sources of radiation.

3 Methodology

3.1 NaI(Tl) Detector System

The scintillation detector used to conduct this research was sold and distributed by Ametek Ortec [13]. The Thallium doped Sodium Iodide (Na (Tl)) Scintillation Detector is paired with a PhotoMultiplier Tube (PMT) and uses GammaVision-Version 8.10 Software to analyze the gamma spectrum. Scintillation is the process of light being emitted from a material when it is hit with ionizing radiation. The NaI crystal serves as the scintillation material in this detector, producing gamma-rays or flashes of light, proportional to the original radiation that entered the detector. These flashes of light are converted into electrical signals and are strengthened through a series of analyzing circuits. These detectors are used in many fields for radiation detection such as, security, environmental monitoring, and particle physics experiments.

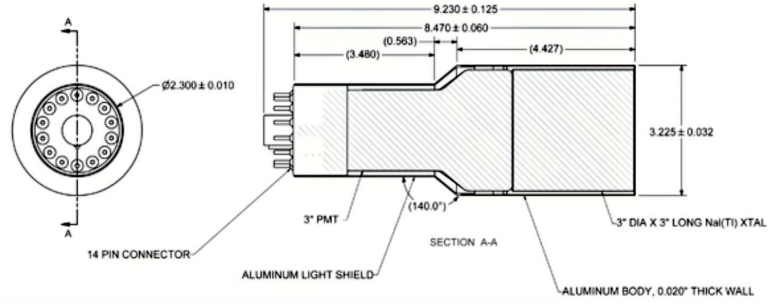


Figure 14: Dimension of the Series 905-4 Scintillation Detector, 3"×3" Crystal[13]

3.2 Components of a NaI(Tl) Detector

It is useful to think of the Scintillation detector in two different parts, the scintillation region and the PhotoMultiplier Tube, detailed in figure 15

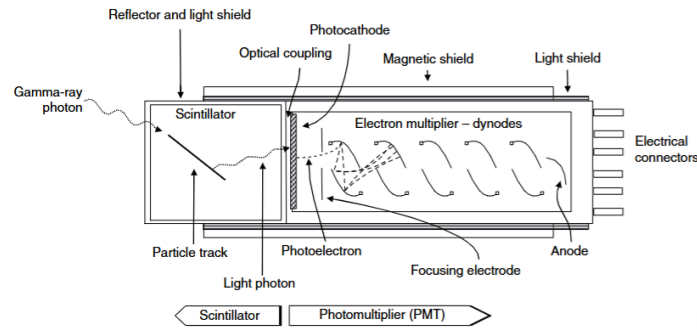


Figure 15: Side View of the Regions of a Scintillation Detector.[7]

3.3 Shielding

Surrounding the detector is shielding made from bricks of lead. This shielding is used to filter or block out background radiation from interacting with the detector. Optimum shielding for typical gamma spectrometry applications requires no more than 100mm of lead[7]. The shielding is made from sixteen $6'' \times 2'' \times 3''$ lead bricks providing approximately 50mm of lead shielding around the detector in all directions. The bricks were painted by an out of house professional to mitigate the health risks associated with working with lead. These bricks were used to build a $9'' \times 9''$ open ended rectangular prism. The lead shielding is housed within a $1''$ casing of plastic, providing another layer of protection and covering any gaps between the bricks. The plastic casing also serves as a guide for the top cap of the lead shielding. This cap is attached to a pulley system, allowing the cover to be raised or lowered using a crank. The detector and shielding are mounted atop a table. The surface of the table has a cavity allowing for the connection cables to reach the detector. The cavity is not shielded by any lead; this opening would be the cause for most of background radiation leakage. The research set up was constructed and designed by Head Machinist Steven MacDonald, now retired head lab instructor Jamie Powell, and Dr. Hossain Ahmed.

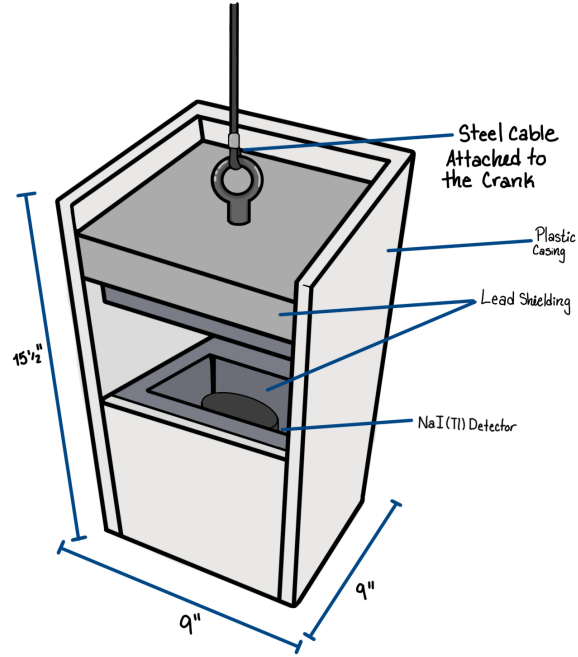
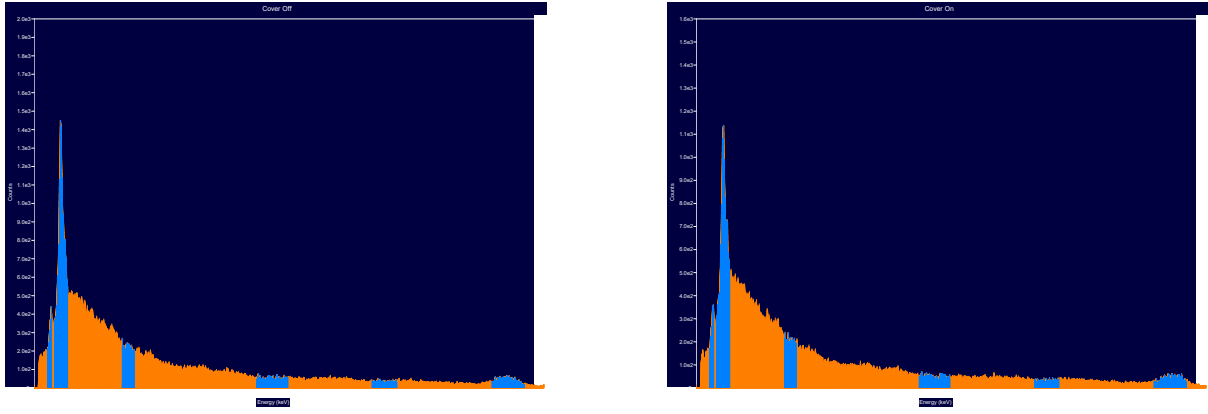


Figure 16: Constructed Set-Up around the NaI(Tl) Detector

To see how effective the shielding is in blocking background radiation a small experiment was conducted. If the shielding surrounding the detector is effective there should be less counts present in the spectrum of the fully enclosed detector. The detector was left to run with the lead cover off, leaving the detector exposed from above. The exposure background spectrum was then compared to gamma spectrum with the cover on. Both trials ran for one hour, allowing for ample time to collect sufficient counts. The results presented below.

Counts	Cover off	Cover on	Δ	%Shield
ROI 1	4355	3810	545	14.30%
ROI 2	26390	22370	4020	17.97%
ROI 3	6745	6122	623	10.17%
ROI 4	3539	3369	170	5.05%
ROI 5	1844	1660	184	11.08%
ROI 6	2760	2582	178	6.90%
Spectrum Sum	136479	122967	13512	11.00%

Table 4: Background Radiation Comparison



(a) Partially enclosed by lead shielding.

(b) Fully enclosed by lead shelling.

Figure 17: Different background radiation spectra showcasing the importance of shielding.

The data above shows a higher count rate for the trial with the cover off which aligns with the expected outcome. It can be seen that the shielding reduced the total background radiation counts by 11%. Re-affirming the shielding is effective in blocking some of the background radiation present in the detector's environment.

3.4 Scintillator Region

The scintillator region contains the most important part of the detector system, the scintillator crystal. The NaI (Tl) crystal is responsible for the conversion of ionizing radiation to visible light, producing a measurable signal. The scintillation material used in this research is a Thallium doped Sodium Iodide crystal an inorganic crystal manufactured to have a high light yield and energy resolution. The dimensions of the scintillator crystal are 3" in diameter by 3" in height, one of the larger scintillator sizes commercially available. Using a larger scintillator provides high sensitivity and detection probability, both of which are desirable for this research.

3.4.1 Beta Absorber

The first point of contact between the detector and any external radiation will occur at the beta absorber. The beta absorber is an external material used to stop any high energy beta particles from reaching the detector. Typically, the beta absorber is fabricated from plastic, which blocks the unwanted particles, as they have less penetrating power compared to gamma-rays[?]. This added layer of protection is useful as some source of gamma-radiation are also emitters of beta particles, such as the aforementioned Cs-137.

The beta absorber ensures that only the more penetrating gamma-rays enter the detector. Ensuring that the recorded signal is only produced by gamma-rays and that there is no interference from other emitted particles.

3.4.2 Casing and Internal Material

The scintillator crystal is enclosed within an aluminum casing. This casing is the crystal's main source of protection from environmental factors which could damage the material. Of greatest concern is moisture from the air, as NaI(Tl) is hygroscopic. Inside of the aluminum casing is a magnesium oxide coating on all surfaces but the exit face[?]. This coating reflects photons towards the exit of the scintillator region, towards the PMT. This is put in place to ensure the maximum amount of light is detected and not lost to the scintillation material.

3.4.3 Scintillation Crystal

As gamma-rays enter the detector they are absorbed by the NaI (Tl) crystal. Via the gamma-ray interactions, highlighted in 2.1, the gamma-rays release their energy to surrounding electrons. These interactions produce primary electrons which may go on to interact with other surrounding electrons (secondary electrons), exciting or ionizing them. With sufficient energy electrons will be excited to the conduction band of the atom, leaving a hole in its electron shell. The production of these electron-hole pairs is a crucial step in the scintillation process[7]. When the electron de-excites, it emits electromagnetic radiation near or within the visible range of light, producing a signal that can be detected by the PhotoMultiplier Tube (PMT).

NaI is a successful scintillator material as it has several key properties[7]:

- High ratio of electron-hole pairs produced per unit of gamma-ray energy.
- High Stopping Power (dE/dx) for gamma radiation. Meaning the material has a high density and atomic number.
- High transparency and refractive index similar to glass ($n=1.5$) for efficient coupling to the PMT.
- Short decay time of the excited states (order of $0.1\mu s$) to produce high count rates.

The NaI crystal used in the detector is doped with an activator. An activator is an impurity deliberately introduced into the lattice to strengthen its light production abilities[7]. Pure NaI has a large band gap, meaning a large amount of energy is needed to excite electrons to this state. Difficulty exciting electrons leads to weak signals produced in the detector. If an electron is capable of reaching the conduction band, it would still not produce a serviceable signal. The released electromagnetic radiation would be too energetic and not be within the visible range of light. The radiation would go on to be re-absorbed by the bulk of the scintillation material and not producing a signal in the PMT.

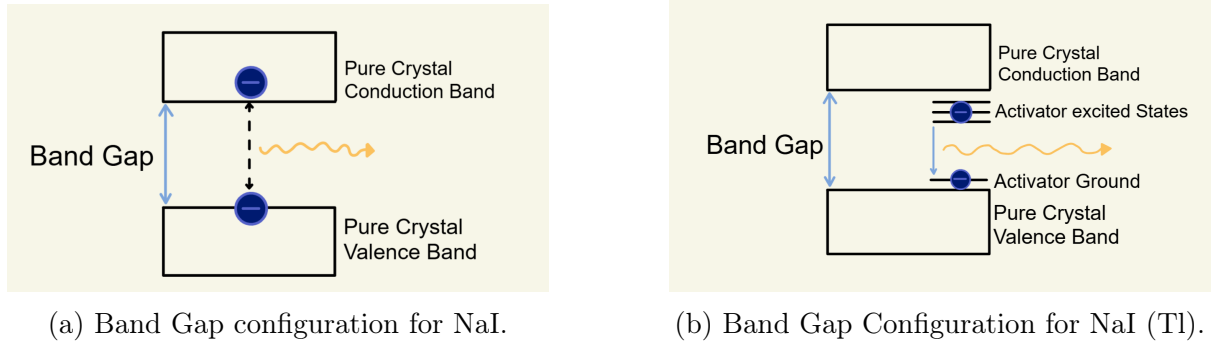


Figure 18: The effects of introducing an activator to the scintillator.

Introducing about 10^{-3} mole fraction of an activator can solve the above issues and unlock even more control over the scintillator light [7]. The activator creates energy levels within the crystal's band gap, also known as the forbidden band. These energy levels are activator ions capturing excited electrons and allowing them to combine with holes, producing photons in the visible light range. The mean lifetime of these excited states is shorter than that of NaI, having $\tau = 0.23\mu s$. [13] Different activator materials will produce different wavelengths, or colors of light allowing for manufacturers to tune the scintillation light to meet their needs. The activator is typically chosen to produce photons that will pair best with the PMT. An NaI crystal is typically paired with Thallium to better its light production abilities. However, even with this significant increase in light production NaI (Tl) will only achieve a light output of about 7% [13] as most of the energy is trapped inside the crystal lattice.

3.5 PhotoMultiplier Tube (PMT)

The output from the scintillation region must be measured and converted into an electrical signal. This process is carried out in the PMT, which is an evacuated, enclosed glass cylinder and has connections via a multi-pin plug at the anode end. The PMT con-

sists of three main components, the Photocathode responsible for the photon to electron conversion, the dynodes responsible for signal amplification, and finally the anode which collect the signal and passes it along to external processing systems.

3.5.1 Scintillator to PMT Connection & Photocathode

The scintillator is coupled to the PMT via a transition region made from glass. The scintillator is fabricated from an inorganic crystal which has a similar index of refraction to that of the glass. NaI (Tl) has a refractive index of $n=1.85$ [13], which pairs well with glass, $n=1.5$ [8]. This ensures a seamless transition from one region to another and minimizes the effects of refraction on the light output.

Immediately upon entry of the PMT the gamma-rays, of the visible light range, come into contact with the photocathode. The photocathode is a nanometer thin sheet of metal situated at the top of the PMT chamber. The metal used must have a very low work order function (ω_0). This allows the photocathode to easily release an electron for each incident gamma-ray via the process of photoelectric absorption. Most often used in scintillator systems is K_2CsSb activated with O_2 which has a work function of $\omega_0 = 2.5eV$ [?]. The photons must have sufficient energy to travel to the photocathode and overcome the work order of the metal; this minimum energy threshold helps reduce signals caused by afterglow or other low energy photons. The properties of the photocathode allow it to act as a filter within the detector, as well as be responsible for the conversion of photons to photoelectrons.

3.5.2 Signal Amplification

The newly produced photoelectrons are attracted towards the focusing electrode by the electric field in which generates. The photoelectrons are not tampered with at this electrode; they are simply collected and focused toward the first electrode of the electron amplification unit.

The photoelectrons are electrostatically focused onto the first of a series of electrodes within the PMT. The electrodes are coated with beryllium or Cs_3Sb due to their negative electron affinity [7] and into a chain down the PMT, these are known as dynodes. The photoelectrons travel down the chain of dynodes due to the increasing voltage potential

down the line. At each dynode, the incident electrons interact with the coating and causes additional electrons to be released. Due to the band structure of these materials, they essentially have no surface energy barrier. This allows them to release multiple electrons when a small quantity of energy is donated. Using a voltage divider circuit, the dynodes increase in voltage potential as secondary electrons travel further down the line, typical inter-dynode voltages range from 80 – 120V and PMTs use 10-12 stages of dynodes [7]. This increase in electric potential is to accelerate the continuously growing number of electrons to the following dynode. Overall, the dynodes are capable of amplifying the original electric signal by a factor of $10^4 - 10^6$ [7], producing an amplified electric signal capable of being analyzed and measured by further external electronics.

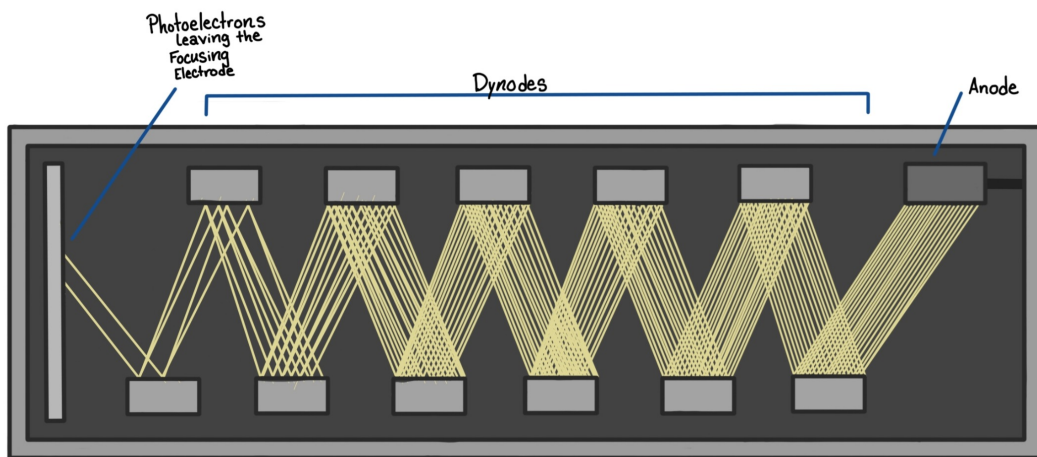


Figure 19: Dynode Configuration Demonstrating Signal Amplification.

3.6 Signal Processing and the GammaVision Software

The interaction of a gamma-ray with the NaI (Tl) detector produces a small amount of electrical charge at the output of the PMT. The anode situated at the end of the PMT, collects the electrons generated throughout the amplification process in the PMT. This provides an electrical signal that is proportional to the amount of energy deposited in the scintillation crystal by the initial ionizing radiation. This signal is small and travels very fast, requiring external electronics to extract, amplify and analyze it. The primary function of the electronic system is to collect this message, measure its magnitude and convert it into a form that can be processed and understood by the software.

Because the pulses generated by the detector are weak, maintaining a good signal-to-noise

ratio is important. Electronic noise can broaden peaks in the spectrum reducing energy resolution and making it more difficult to distinguish between radionuclides with similar gamma-ray energies. Each stage of the electrons from the PMT to the Multi-Channel Analyzer (MCA) must be optimized to preserve pulse shape and amplitude while minimizing the contributions from noise.

Once the signal leaves the detector it passes through amplifiers and pulse processing electronics. Amplifiers increase the pulse height to a level suitable for analysis, while the shaping circuits scale the signal to produce a consistent pulse form. Proper shaping helps reduce noise and improves resolution.

A drawback of this detection method is pile-up or random coincidence summing. This occurs when two or more gamma-rays are detected within the width of a single amplifier output pulse. If these pulses overlap the system could perceive them as a single event with an increased energy. This leads to inaccurate distorted peaks and incorrect spectral generation. Systems include pile-up rejection electronics to identify and discard such occurrences, improving the final spectrum's accuracy.

3.6.1 Multi-Channel Analyzer

In this research, GammaVision (ORTEC) software was used for spectral acquisition and analysis. It provides functions like automated peak searching, nuclide identification, energy calibration, efficiency calibration, defining regions of interest (ROIs), peak area calculations, and peak centroid determination. The energy calibration is typically performed using known gamma-ray energies to establish a relationship between channel number and energy, detailed in chapter 4. ROIs are set around peaks either manually or automatically, allowing calculation of gross and net peak areas where the net area does not include background counts[14]. Additional parameters such as full width half maximum (FWHM) and full width at fifth maximum can be used to assess peak shape and detector performance. The software can apply decay corrections and perform summing corrections when required[14].

The touched-up signals are sent to the MultiChannel Analyzer (MCA) from the anode in the PMT. The MCA measures each pulse and sorts them into discrete channels based on their amplitude. Because pulse height is proportional to the energy deposited in the

detector, the distribution of counts across channels forms the gamma-ray spectrum. This research uses a 1024-channel MCA system from Ortec[13]. MCA performance is affected by dead-time, a phenomenon that during pulse recording the system is temporarily unable to record additional events. Meaning any events which occur during this time will not be detected. Dead-time can lead to an underestimate of activity if not accounted for by longer run times and electronic corrections.

The MCA also incorporates several digital controls like lower and upper-level discriminators. These settings set minimum and maximum acceptable pulse values. Rejected pulses on the lower end of the spectrum are usually caused by electronic noise. On the other extreme the rejected pulses are typically caused by over-saturated signals[14]. There is also a digital offset adjustment that shifts the spectrum along the channel axis (x-axis) to optimize the displayed energy spectrum.

The software is powerful and relatively user friendly making it suitable research at the undergraduate level. Overall, the electronics and signal processing chain plays a critical role in converting the initial light pulse generated in the NaI(Tl) detector into a usable gamma-ray spectrum. Proper amplification, pulse shaping, pile-up control, and digital analysis ensure accurate identification and quantification of radionuclides present in the soil samples.

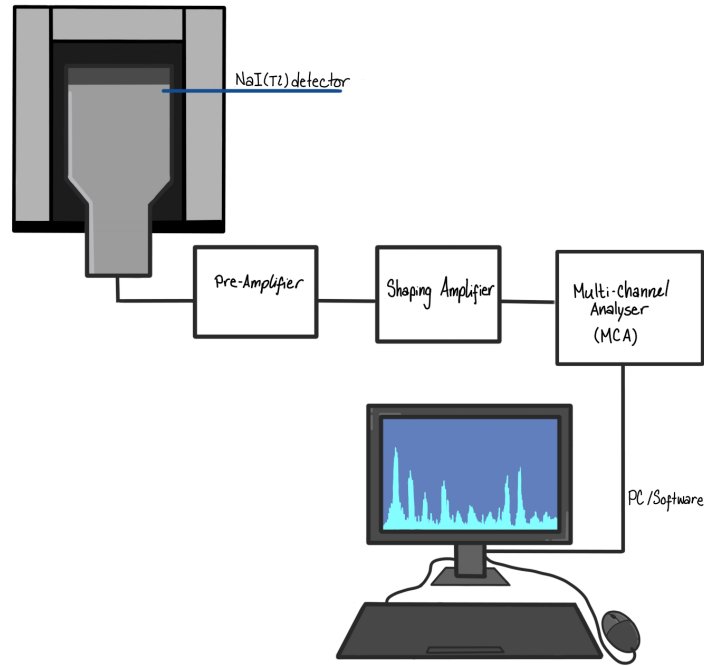


Figure 20: Signal Processing Chain

3.7 Soil Sample Collection and Measurement Protocol

Topsoil samples were collected from the Saint Francis Xavier University (StFX) campus in Antigonish Nova Scotia. Twelve samples were collected from locations spread across the campus with the goal of identifying any radionuclides present across the StFX campus. Three samples were collected in Fredericton New Brunswick, the area is newly developed with recently constructed apartment buildings, houses, and an elementary school. With one additional sample being collected from a suburban neighborhood close by the newly developed area. Additionally, a sediment sample was taken from Davidson Lake, Nackawic New Brunswick. All samples were collected and placed in a plastic container or large plastic bag; collection date and location were also recorded on the container.

3.7.1 Sample Preparation and Acquisition Protocol

All samples were placed in a convection drying oven for a minimum of forty-five minutes at 160°C to remove moisture. The samples were then strained several times using a clean aluminum sieve, removing large and fine debris: rocks, trash, insects. Before Acquisition, the soil was placed in a clean dry beaker (250ml or 1000ml PYREX beaker) and its mass recorded. This beaker is placed directly on top of the beta-absorber of the detector and enclosed by the lead shielding.

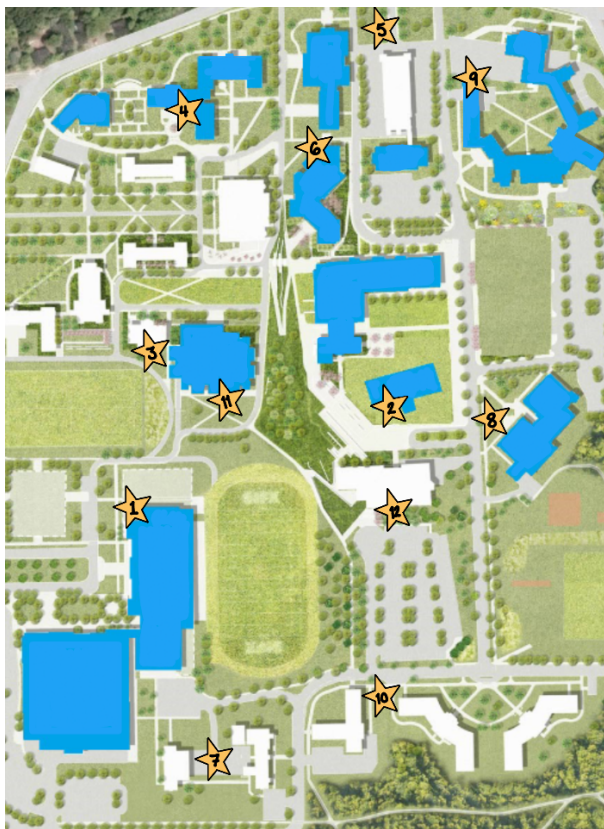


Figure 21: StFX Campus Soil Collection Locations

Campus Locations	
1.	Amelia Saputo Center
2.	Annex
3.	Bauer Theater
4.	Coady International institute
5.	St. Ninian's Cathedral
6.	Angus L. MacDonald Library
7.	FX Hall
8.	J. Bruce Brown Hall
9.	Immaculata Hall
10.	MacIsaac Hall
11.	Nasso Family Science Center
12.	Student Union Building

Table 5: StFX Campus Sample Locations



Figure 22: NB Soil Collection Locations

Campus Locations	
1.	Lawrence Residence
2.	Murray Ave.
3.	Cuffman St.
4.	Cuffman St. Construction Zone

Table 6: NB Sample Locations

Prior to each soil measurement the detector was turned on for an hour to allow the in-

ternal electronics to come up to temperature. Avoiding any thermal drift from affecting the sample's spectrum. Additionally, a short measurement of a calibration source was performed to check for any electronic drift, which could then be corrected using Gamma Vision's gain shift function. Once the software was identifying the proper radionuclides with the correct energy values the detector was set to measure the soil sample gamma spectrum.

Each soil sample spectrum was measured for one hour (3600 s) to achieve a high count-to-background ratio. Which is especially important for the soil samples as they will have a lower count rate compared to the calibration sources. It is crucial to have a strong spectrum so true gamma lines can be distinguished from background radiation remaining in the spectrum.

3.7.2 Background Radiation Correction

Despite taking physical steps toward minimizing the detector's exposure to background radiation, it is impossible to eliminate it completely. To account for what exposure there will be, the detector is used to measure a background spectrum. Using the same geometry as the sample measurements, the detector is enclosed within its lead shielding and is run for an hour, recording background radiation. It is not expected to see any large peaks in this spectrum as the majority of the gamma-rays interact via Compton scattering. It is possible to see higher counts at the beginning of the spectrum (lower than 100keV) caused by gammas scattering off the lead shielding, lead x-ray fluorescence. This background spectrum is stored within GammaVision's library and is subtracted from the soil sample spectra. This further helps reduce the contribution of background radiation in the actual sample spectra. Because background radiation is naturally produced its concentration changes daily. To account for this, on the same day the spectrum of a sample is measured a background spectrum is recorded too. This ensures that the proper number of counts are being subtracted.

4 Calibration and Detector Performance

In order to extract useful information from the detector, it must first be calibrated. This is done using several standard gamma-emitting sources with well known, well defined full-energy peaks. Co-60, Cs-137, and Na-22, all with activity 0.1 Bq, were the standard

sources used to construct the calibration for this NaI(Tl) detector. The Cs-137 and Co-60 gamma sources were placed in the detector side by side. The detector was run for an hour and a half measuring the emitted gammas. The shorter acquisition time is due to the increased emissions from these sources, as it doesn't take long to acquire sufficient counts with standard emitters. One and a half hours allows the detector to measure enough counts to have a sufficient signal-to-background ratio. This is convenient and reduces the probability of thermal fluctuations caused by the internal circuitry of the detector[8].

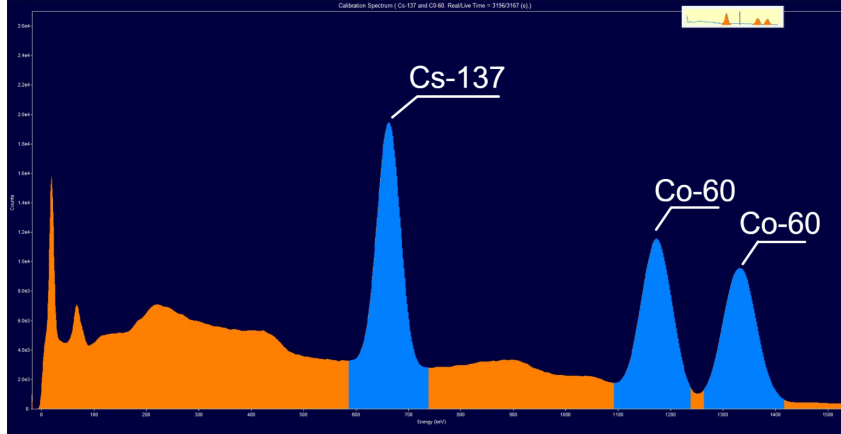


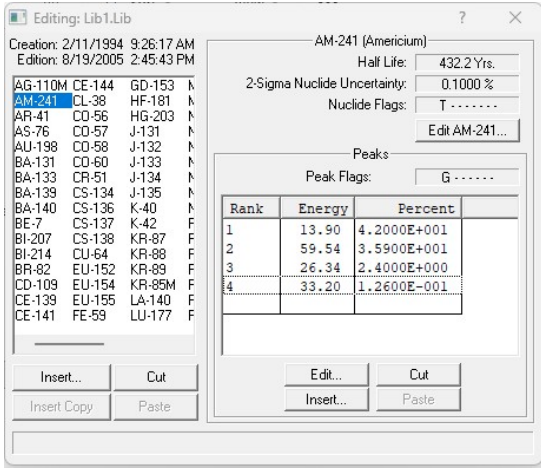
Figure 23: Calibration Gamma Spectrum consisting of Cs-137 and Co-60, July 2 2025

4.1 Energy Calibration

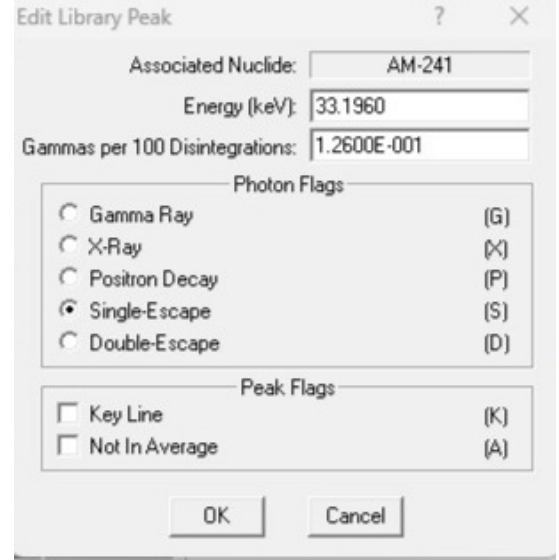
The energy calibration uses the full-energy peaks of the standard sources to assign the Analog-to-Digital Converter (ADC) channel numbers to a deposited gamma-ray energy. The detector produces an electrical pulse with a height proportional to the energy deposited by the gamma-ray. The ADC converts the pulse height into a digital number, the channel [7]. The NaI (Tl) detector and GammaVision software consists of 1024 channels which are organized along the x-axis of the gamma spectrum. In analyzing the gamma spectrum, the full-energy peaks are highlighted. Each channel which builds the Gaussian curve is selected and builds what it labeled as the Region Of Interest (ROI). The software calculates the mean position of the full-energy peak in the spectrum. It uses all counts highlighted in the ROI to find the channel corresponding to the peak's mean [14]. It is more commonly called the centroid of the full-energy peak ???. This centroid is a much more robust measurement than simply using the channel with the highest counts, its maxima, which is susceptible to drifting due to gain in the PMT or electronics, temperature fluctuations[7]. Peak centroids were used to determine calibration points as they provide a statistically robust estimate of the photo-peaks position.

$$PeakCentroid = \frac{\sum_{i=1}^h i \times c_i}{\sum_{i=1}^h i} \quad (15)$$

Stored in GammaVision, there are four pre-loaded nuclide libraries, all containing information on a variety of radionuclides. At the selected peak's centroid, GammaVision assigns the energy value of the characteristic or “fingerprint” gamma-ray to the channel, creating a calibration point in the spectrum. When multiple peaks in the spectrum are marked, a calibration curve can be built.



(a) Nuclides Stored in a Library File, showcasing the stored information for Am-241.



(b) Information stored about one possible gamma interaction from Am-241.

Figure 24: Nuclide Library stored in GammaVision.

The calibration spectrum for this detector is pictured in figure 23. It consists of Cs-137 and Co-60 which produce full-energy peaks in the mid to high energy range of the gamma spectrum. ROIs were marked around the full-energy peaks and the gamma energy assigned to the centroid using GammaVision’s nuclide library, Cs-137 $E = 661.61\text{keV}$, Co-60 $E = 1173.24\text{keV}$ and 1332.50keV . These three calibration points were then used to build a calibration curve. GammaVision saves and remember this file, uploading it to each blank spectrum before measurement of a new sample.

ROI	Range (keV)	Gross	Net	+/-	Centroid	FWHM	FW(1/5)M	Library	keV	Bq	+/-
1	586.16 740.32	886972	578915	2347	661.66	50.74	75.94	Cs-137	661.66	2264.38	9.18
2	1092.32 1241.02	539676	397281	1546	1173.33	65.41	96.31	Co-60	1773.24	2063.43	8.03
3	1264.74 1419.39	447676	356069	1286	1332.90	70.87	103.49	Co-60	1332.50	2041.23	7.37

Table 7: Calibration Spectrum: Full-Energy Peak Information, July 2 2025.

$$E = -17.8112 + 1.305972C + 0.000229332C^2 \quad (16)$$

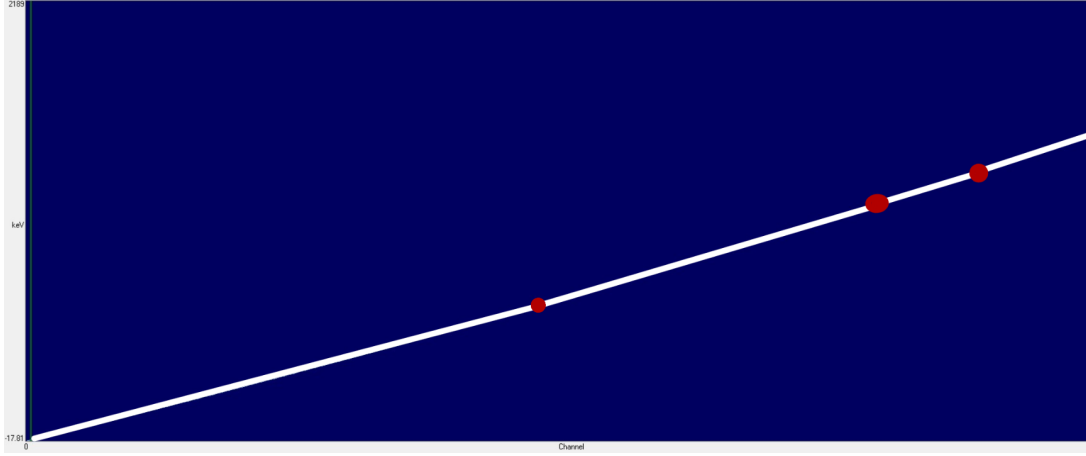


Figure 25: Energy v.s. Channel Graph Displaying the Energy Calibration Curve.

The energy range for the spectra spans 0 keV (channel 13.5) to 1558.2 keV (channel 1023). The calibration curve demonstrates linearity, which is the desired behaviour of the energy calibration. This can be seen by the small coefficient in the quadratic term of the equation and is visually evident when looking at the energy vs channel graph. Although the software is capable of deriving a calibration curve of higher order, the NaI system is designed for linearity; so, a quadratic fit is sufficient.

To test the quality of the calibration the detector was used to measure the Na-22 gamma spectrum. Using the calibration equation, the channel at which the single escape peak of Na-22 will appear can be estimated:

$$511\text{keV} = -17.8112 + 1.305972C + 0.000229332C^2$$

$$C = 379.6$$

The 511 keV single escape peak was located at channel 377.1, which indicates the calibration is behaving as expected.

Range (keV)	Centroid (Chan)	Δ	Centroid (keV)	Δ
438.13 586.16	377.1	2.5	511.15	0.15 keV

Table 8: Calibration Check: Na-22 Spectrum Information

4.2 Energy Resolution

While conducting the energy calibration, GammaVision also generates a FWHM (full width half maximum) curve. This characterizes the detector's ability to distinguish between closely spaced full-energy peaks. However, this ability is very limited in NaI(Tl) detectors due to statistical fluctuations in the scintillation light production [7]. The area of the peak is extracted from the marked ROI and used to calculate the FWHM. These values are calculated and recorded for each peak analyzed in the energy calibration and brought together to make a FWHM curve. This curve is also linear, as resolution improves with increasing energy and instability is expected at low energies. The manufactures of the scintillation detector have quoted the detector's resolution to be up to 8% [13], which is supported by the measured results. While the resolution evaluation is not as crucial as the energy calibration, it is still a useful tool for monitoring the detector's performance.

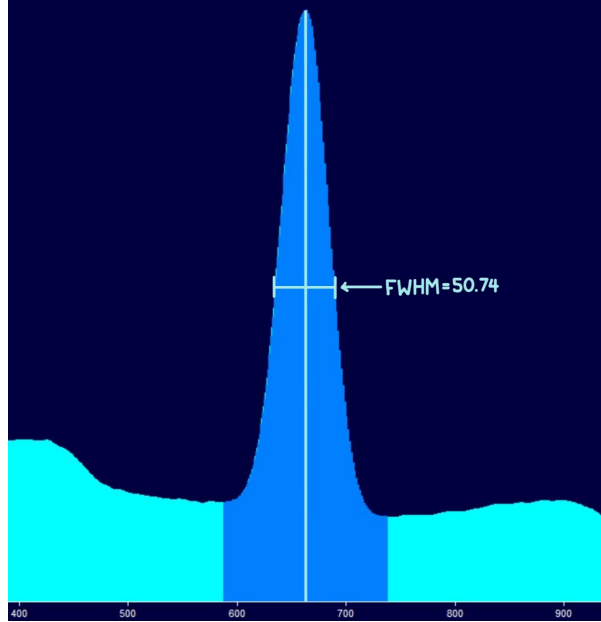


Figure 26: Illustration of FWHM of Cs-137

$$Res(E) = \frac{FWHM}{E} \times 100\% \quad (17)$$

Resolution of Cs-137:

$$Res(Cs - 137) = \frac{50.74}{661.66} \times 100\% \quad (18)$$

$$Res(Cs - 137) = 7.67\% \quad (19)$$

Channel	Energy (keV)	Fit (keV)	FWHM (keV)	Resolution
479.85	661.66	661.66	50.74	7.67%
799.70	1173.24	1173.24	65.41	5.58%
893.70	1332.50	1332.50	70.87	5.32%

Table 9: Energy/FWHM Table, July 7th 2025.

$$FWHM = 23.3513 + 0.024293C - 6.31488 \times 10^{-6}C^2 \quad (20)$$

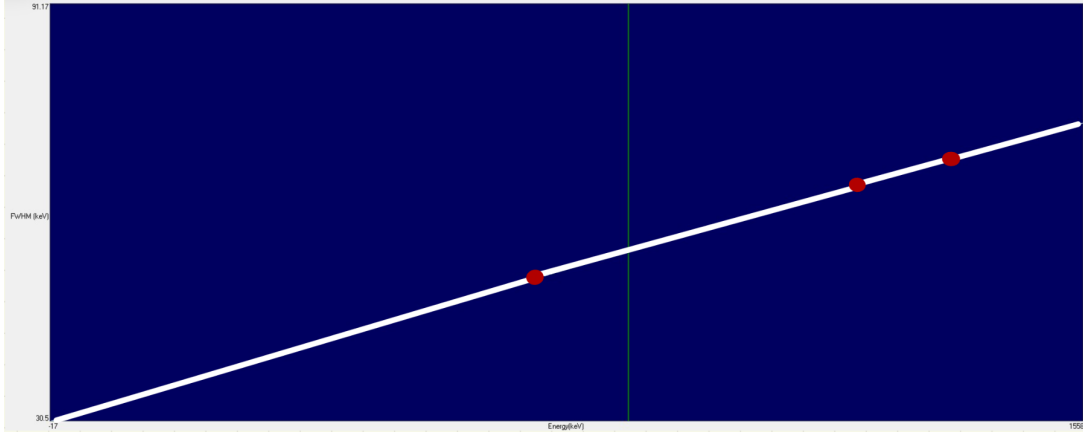


Figure 27: FWHM v.s. Energy Graph Displaying the FWHM Curve.

The curve, again, shows little contribution by the quadratic term. This is the desired result as the relationship is again expected to be linear. The resolution of each full-energy peak is calculated using equation 20 and fit into the range set by the manufacturer, all indicators that the detector is function as expected.

4.3 Efficiency Calibration

The efficiency calibration relates the detected counts in a full-energy peak to the number of gamma-rays emitted from the source during acquisition. This is crucial for determining the activity of the detected radionuclides, which can be seen in equation 23. Using the same calibration spectrum, consisting of Cs-137 and Co-60, the full-energy peaks are once again of great interest. Instead of the peak's centroid the software calculates the peak's net counts, counts remaining after the subtraction of the background spectrum. The raw counts are not sufficient on their own to provide the sample's activity. Information about the standard source is needed in combination with the net counts to determine the sample's activity. The information needed is the manufacturing date, initial activity, and

emission intensity. This is often referred to as the source’s certificate information, as it is standardized and certified to be true by the manufacturer.

Radionuclide	Activity (μCi)	Date	Absolute γ Intensity
Cesium-137	0.1	Sept. 16 2022	85.12%
Cobalt-60 (Peak 1)	0.1	Dec. 16 2022	99.85%
Cobalt-60 (Peak 2)	0.1	Dec. 16 2022	99.98%

Table 10: Certificate information of the Calibration Sources.

Using this information the activity at the time of measurement can be calculated by using equation ?? . The activity allows the system to determine the gamma emission rate throughout the acquisition. Comparing this to the measured counts produces a ratio which is the full-energy peak efficiency. Efficiency points are calculated for each full-energy peak in the spectrum using equation ?? and are then fit with a “linear” function, producing the efficiency calibration curve.

$$\epsilon(E) = \frac{N_{Ei}}{A_{Ei} \times B \times Lt} \quad (21)$$

$$\begin{aligned} \epsilon(Cs - 137) &= \frac{578915}{3434Bq \times 3196.46s \times 0.851} \\ \epsilon(Cs - 137) &= 0.06198 = 6.2\% \end{aligned}$$

Radionuclide	Activity at the time of acquisition (Bq)	Efficiency	Fit	Delta (Δ)
Cesium-137	3434	$6.1980E - 002$	$6.2358E - 002$	-0.6095%
Cobalt-60 (Peak 1)	2415	$5.1525E - 002$	$4.9805E - 002$	3.3378%
Cobalt-60 (Peak 2)	2415	$4.6120E - 002$	$4.7423E - 002$	-2.8264%

Table 11: Efficiency Table of the Calibration Spectrum, Jan 30_{th} 2026.

$$\epsilon = (e^{2.6867 - 0.776334 \ln(E)}) \quad (22)$$

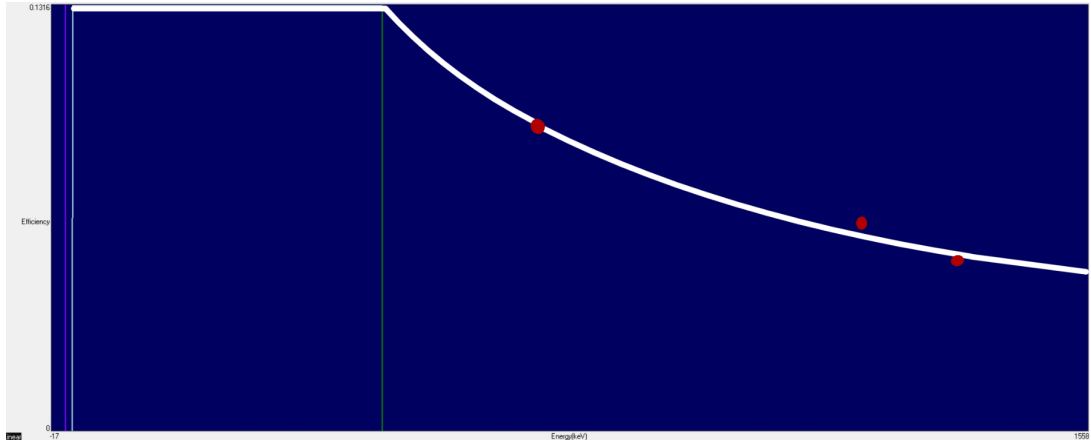


Figure 28: Efficiency vs Energy Graph displaying the Efficiency Curve.

The efficiency calibration worsens at higher energies as the probability of photoelectric absorption decreases as gamma energy increases[14]. At the beginning of the gamma spectrum the efficiency calibration may also have a poor performance as the low energy gamma-rays are susceptible to absorption by surrounding materials like the sides of the detector or material of the detector window[7]. Overall, the efficiency calibration of the detector follows the expected trends and is well suited for the laboratory use of this detector.

5 Results and Analysis of Soil Samples

5.1 Measured Spectra

The gamma spectra of soil samples appears differently than the standard gamma sources discussed when performing the calibration. The soil samples contain multiple gamma-ray emitting nuclides and background radiation. This produces a busy gamma spectrum with many full-energy peaks and overlapping x-ray peaks. Compton scattering features overlap one another, making it difficult to distinguish between the Compton continuum and Compton edge of each present radionuclide. Many radionuclides release x-rays, which appear at lower energies in the spectra. This can cause peak overlapping and noise early on in the spectra. Overall, the samples produce a cluttered raw spectrum, but the useful features - full-energy peaks - are distinguishable. Once background is subtracted the full-energy peaks can be identified and highlighted as an ROI. Similarly to the calibration, the full-energy peaks are essential for analysis and allow for identification of which radionuclides are present.

A total of 15 distinct radionuclides were identified across all sampling locations in Nova Scotia (n=13) and New Brunswick (n=4). These nuclides fall into three natural categories and one anthropogenic category:

Category	Nuclides Detected	Number
Uranium-238 Series	Ra-226, Pb-214, Bi-214, Th-234, Pa-234m,	5
Thorium-232 Series	Ac-228, Pb-212, Bi-212, Tl-208, Th-228	5
Primordial	K-40	1
Anthropogenic	Cs-137, Co-60	2
Total		15

Table 12: Summary of Radionuclides

GammaVision produces spectra as shown in sections 5.1.1 and 5.1.2 with energy along the x-axis and counts along the y-axis. The spectrum is shown in light blue. GammaVision displays the identified Radionuclides in orange and unknown peaks in pink. Highlighted in yellow is the sum of overlapping peaks.

5.1.1 StFX Samples

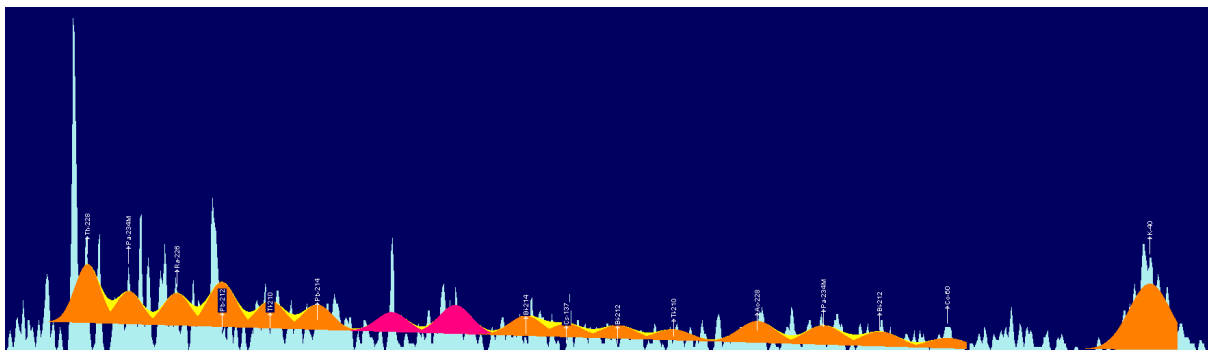


Figure 29: Amelia Saputo Sports Center Soil Sample

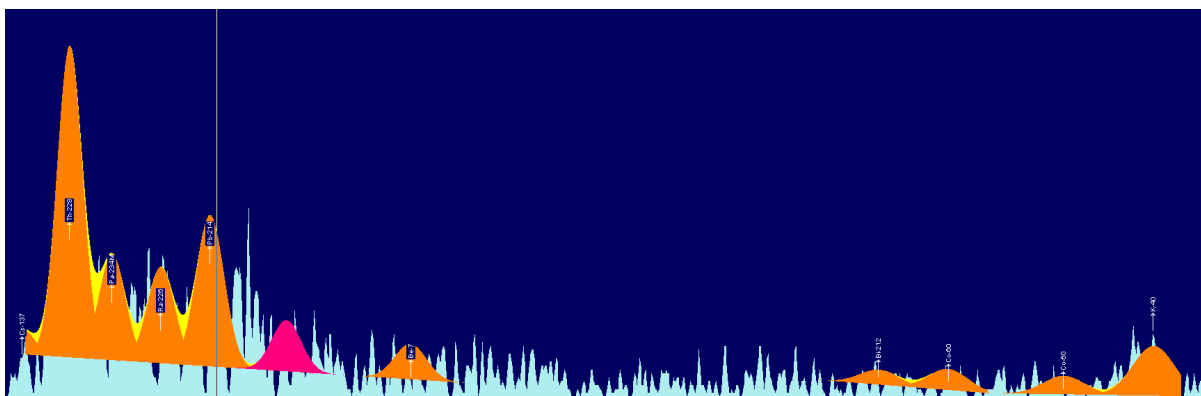


Figure 30: Annex Soil Sample

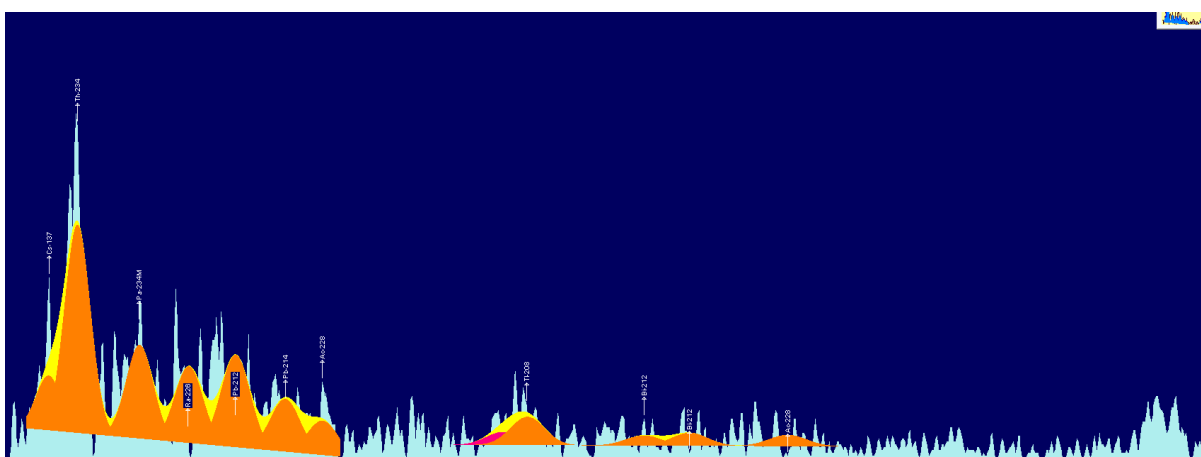


Figure 31: Bauer Theater Soil Sample

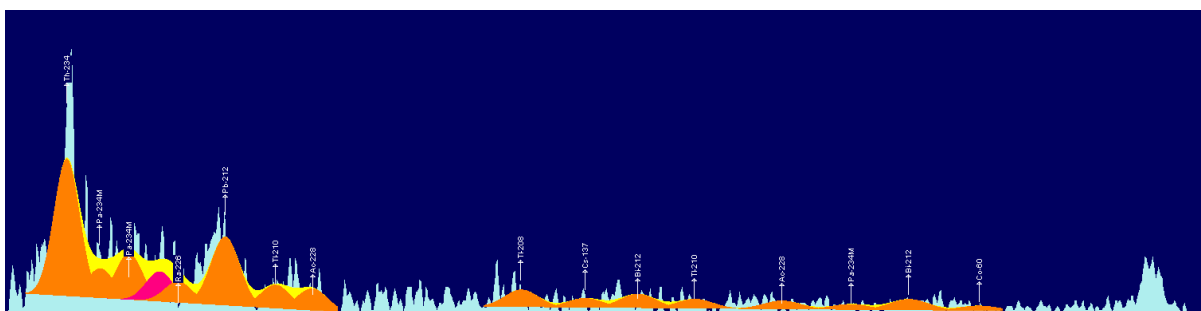
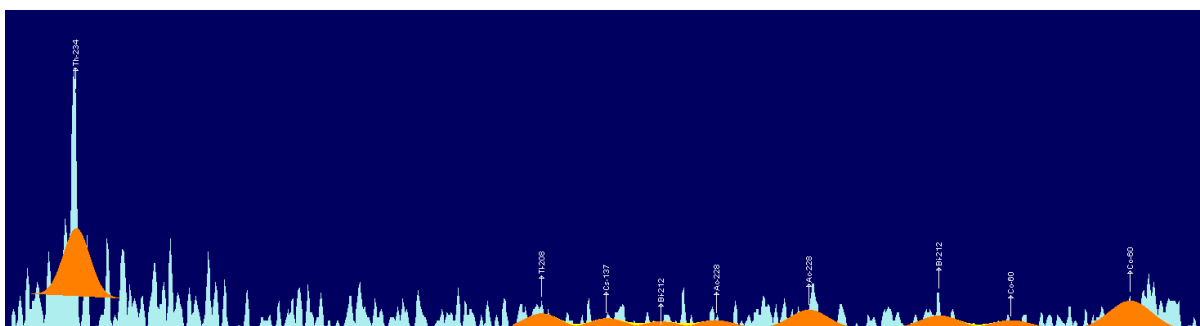
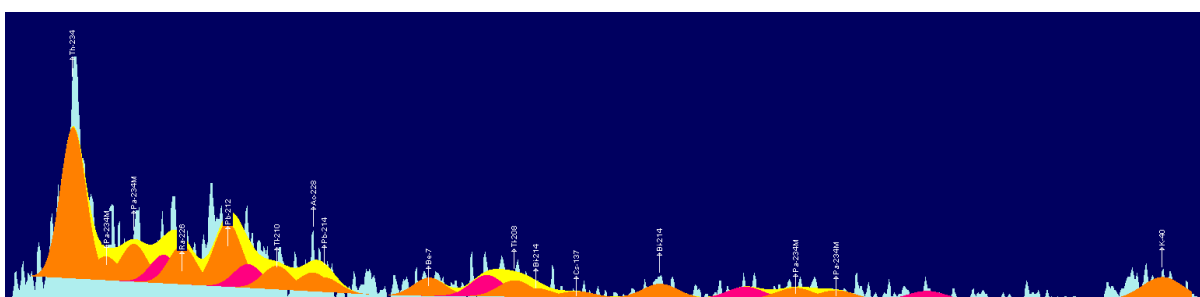
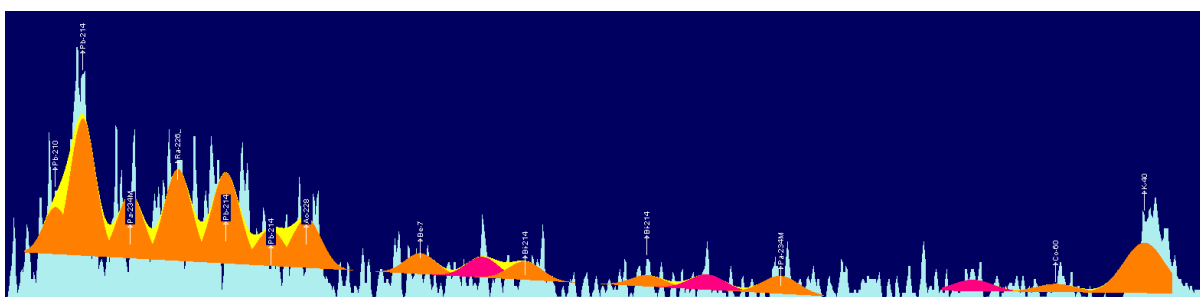
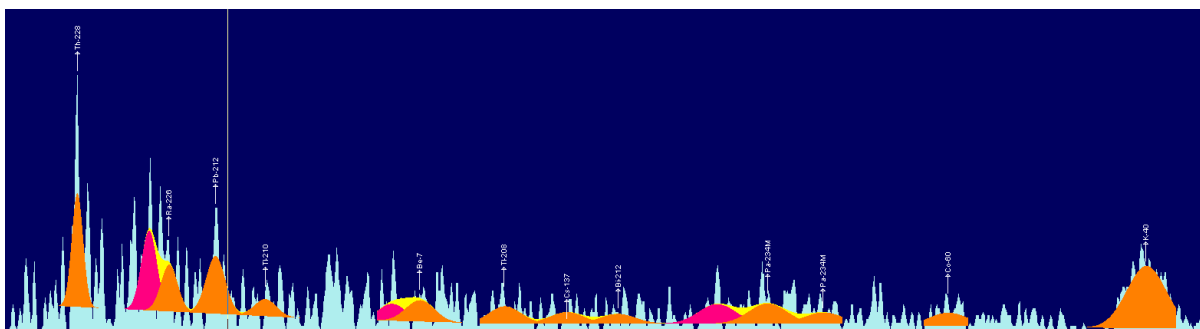


Figure 32: St. Ninian's Cathedral Soil Sample



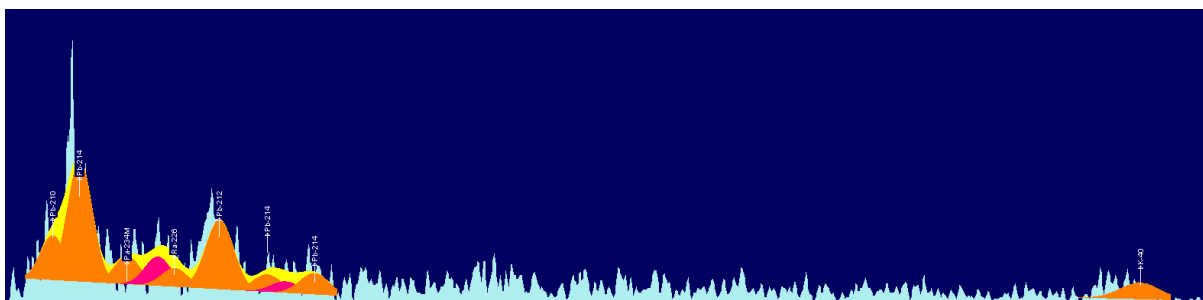


Figure 37: MacIssac Hall Soil Sample

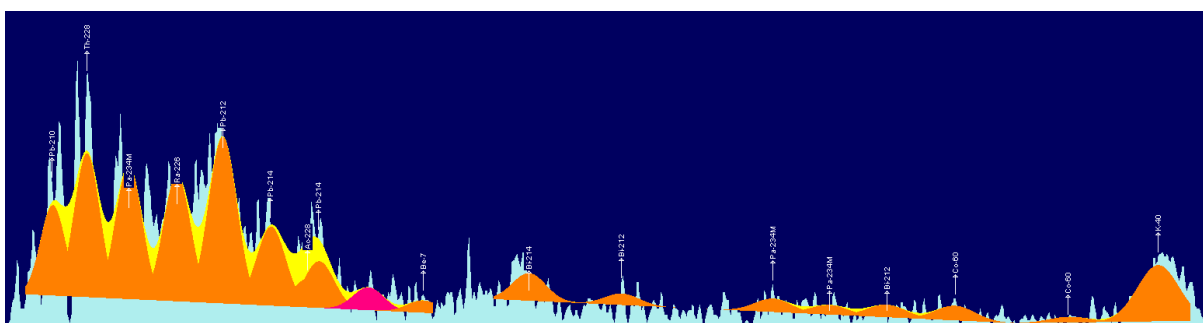


Figure 38: Nasso Family Science Center (NFSC) Soil Sample

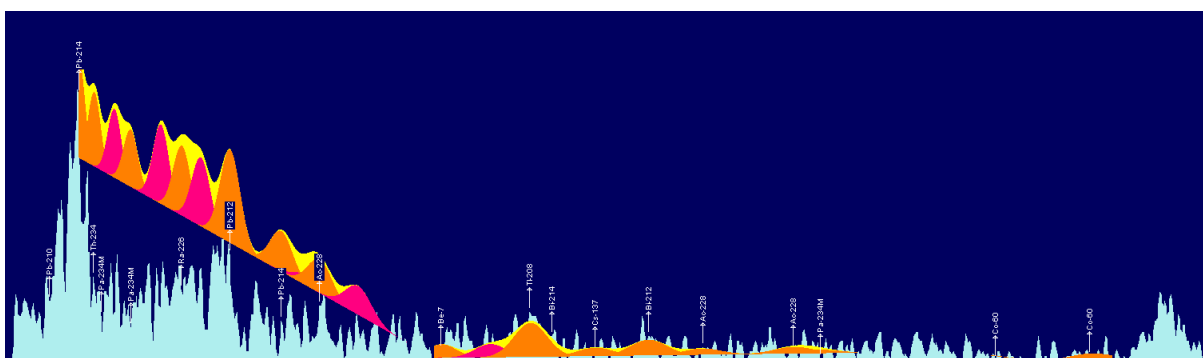


Figure 39: Student Union Building (SUB) Soil Sample

5.1.2 New Brunswick Samples

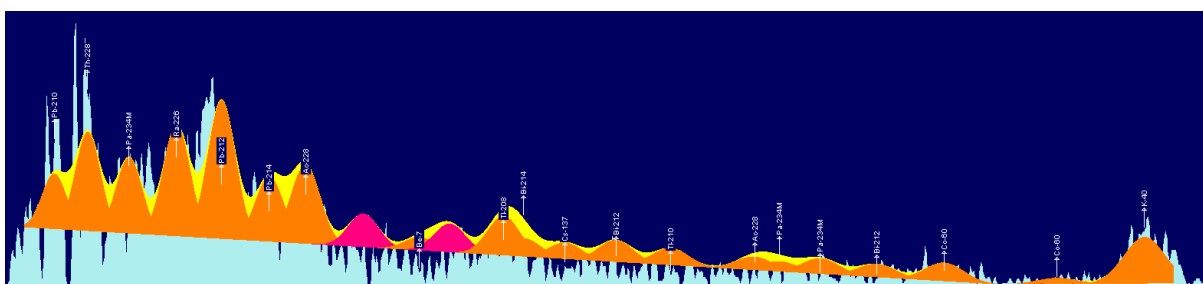


Figure 40: Cuffman St. Soil Sample

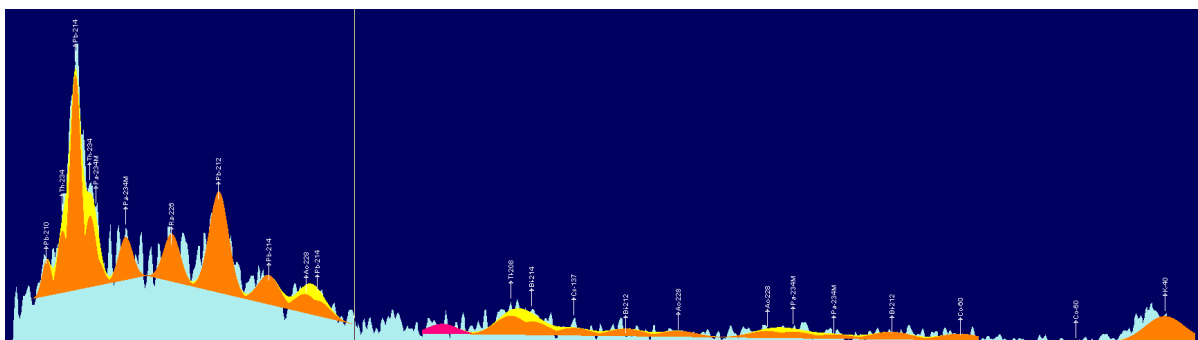


Figure 41: Cuffman St. Construction Site Soil Sample

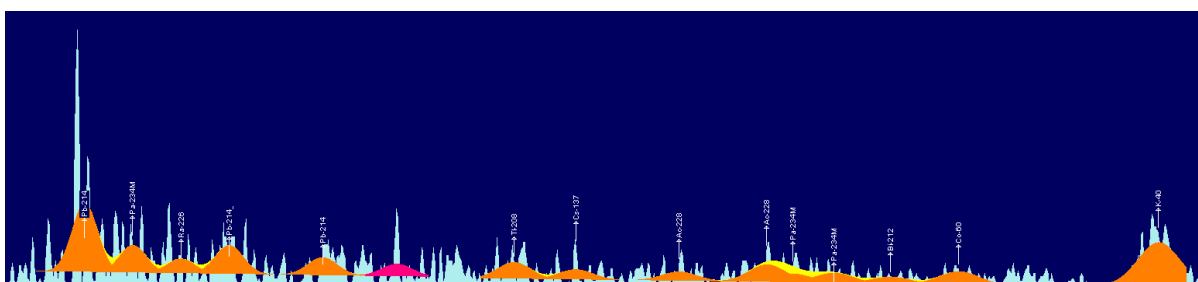


Figure 42: Murray Ave. Soil Sample

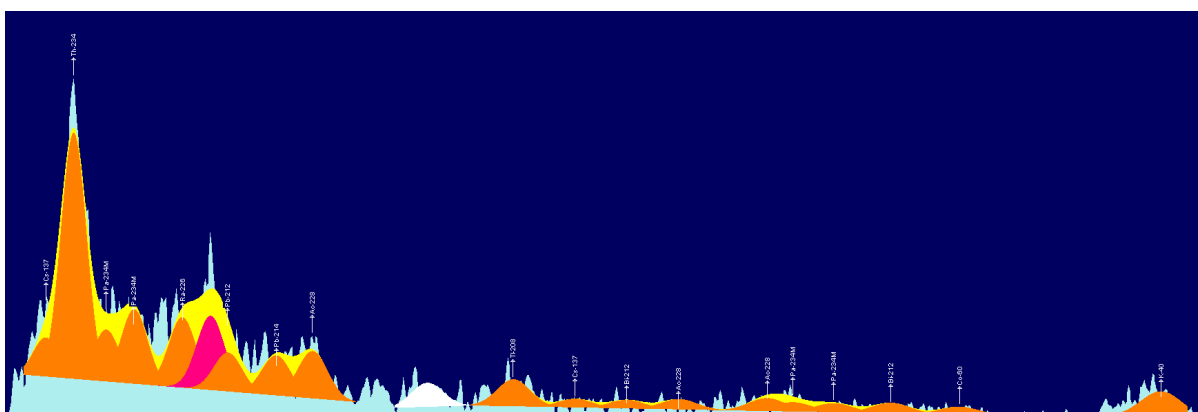


Figure 43: Lawrence Residence Soil Sample

5.1.3 Other Locations

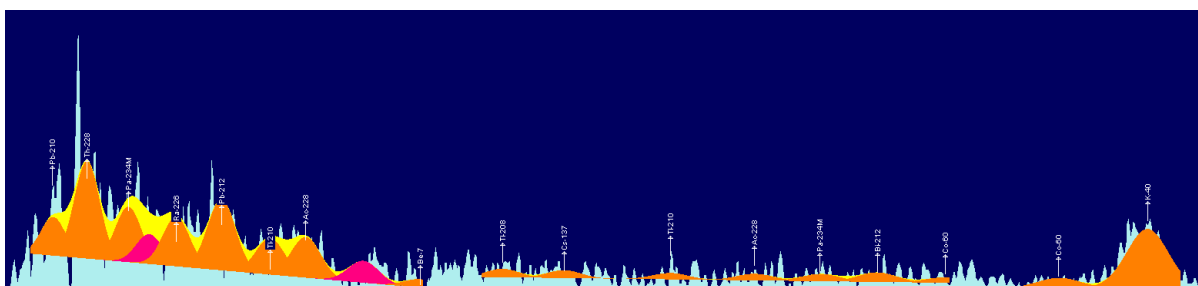


Figure 44: Sandy Cove Beach Sediment Sample, NS

5.2 Identified Radionuclides

Each gamma spectrum is analyzed using GammaVision and Maestro-PRO Software. Each spectrum was stripped of background radiation, using the subtract tool in GammaVision and the corresponding background spectra. GammaVision automatically searches the spectra for any significant peaks, marking ROIs, calculating its centroid channel, and converting it to an energy value using the energy calibration equation. GammaVision compares the energy to radionuclides in the uploaded nuclide library assigning the nuclide to the peak which best matches the information. In addition to GammaVision's automatic peak search, a manual search of the spectra is performed to ensure all peaks are marked within an ROI. GammaVision then performs the same calculations and comparisons, assigning a nuclide to the peak.

GammaVision either accepts or rejects the peaks based on how closely their shape and energy matched the selected nuclide from the library. GammaVision makes this decision based on the sensitivity level assigned to the detector. The rejection threshold was set to $\pm 5keV$. Measuring NORMs with an NaI (Tl) detector comes with some variability and uncertainty, which is why the peak sensitivity cannot be set too strictly, or no matches will be found within the spectrum. However, the analysis still needs to produce reliable results so the threshold was set so GammaVision would reject poorly assigned peaks.

Nuclide	Nova Scotia (n=13)		New Brunswick (n=4)	
	Count	Frequency (%)	Count	Frequency (%)
<i>Natural Decay Series</i>				
Pb-214	13	100	4	100
Ra-226	13	100	4	100
Pb-212	13	100	4	100
Ac-228	13	100	4	100
Bi-214	12	92	4	100
Th-234	12	92	4	100
Pa-234M	12	92	4	100
Tl-208	9	69	4	100
Bi-212	6	46	3	75
K-40	6	46	4	100
Th-228	5	38	4	100
<i>Anthropogenic</i>				
Cs-137	10	77	4	100
Co-60	9	69	4	100

Table 13: Detection Frequency of Radionuclides in Nova Scotia and New Brunswick Samples

5.3 Activity Calculation

GammaVision uses equation 23 to calculate the activity of each detected radionuclide.[14]

$$A_{Ei} = \frac{N_{Ei} \times TDC \times Mult \times RSF \times GeoFac \times AttCor}{Lt \times \epsilon(E) \times B \times Div \times m} \quad (23)$$

where N_{Ei} is the net counts of the nuclide at energy E. TDC is representative of any decay corrections imputed in the system. $Mult$ and Div are the multiplier and divisor entered into the system tab. RSF is the random summing correction factor. $GeoFac$ is the geometry correction factor. $AttCorr$ is the factor for attenuation correction. Lt is the live time of the acquisition (3600s). B is the branching ration of the nuclide. ϵ is the efficiency at energy E from the calibration curve. Finally, m is the mass of the measured soil sample in kg.

For the purposes of this research, most coefficients can be set to 1. Resulting in the

simplified activity formula.

$$A_{Ei} = \frac{N_{Ei}}{Lt \times \epsilon(E) \times B} \quad (24)$$

Activity Calculation of Pb-214 from Cuffman St. Fredericton NB.

$$A_{Pb-214} = \frac{962}{3600s \times 0.0831 \times 0.3572}$$

$$A_{Pb-214} = 9.00Bq$$

Activity Concentration of Pb-214 from Cuffman St. Fredericton NB.

$$A_{Pb-214} = \frac{962}{3600s \times 0.0831 \times 0.3572 \times 0.3689kg}$$

$$A_{Pb-214} = 24.40 \frac{Bq}{kg}$$

In total, GammaVision generated around 200 activity values. To clearly display the results, activities are grouped into nuclide series means which are then used to calculate the dosage. Activity levels are also shown as location means. However, these means cannot be used to calculate dosages because of the specific Decay Conversion Factor (DCF) assigned to each individual decay series, this is discussed further in 5.4.

Location	Sample Mass (kg)	U-238 Series (Bq)	Th-232 Series (Bq)	K-40 (Bq)
<i>StFX Campus</i>				
Amelia Saputo Center	0.1722	29.50	35.56	44.88
Annex	0.0755	33.21	35.75	-
Bauer Theater	0.2602	18.30	11.46	-
St. Ninian's Cathedral	0.1258	29.32	34.00	-
Coady International Institute	0.1759	25.11	8.12	30.90
FX Hall	0.1276	6.21	10.60	19.82
Immaculata Hall	0.1154	8.59	7.52	28.90
James Bruce Brown Hall	0.1669	20.34	3.15	23.60
Angus L. MacDonald Library	0.1356	11.50	38.15	-
MacIssac Hall	0.2202	7.63	4.60	-
NFSC	0.1356	13.18	22.00	-
Student Union Building	0.1599	8.07	4.96	-
<i>Nova Scotia</i>				
Sandy Cove Beach	0.3768	29.47	45.70	66.57
<i>New Brunswick</i>				
Cuffman St.	0.3689	43.17	50.14	44.10
Cuffman St. Construction Site	0.5910	18.88	41.93	51.00
Murray Ave.	0.5192	25.55	65.26	54.49
Lawrence Residence	0.7975	43.98	10.26	43.48

Table 14: NORM Nuclide Series Mean Activities

The same can be done for the Anthropogenic Nuclides. The following table excludes the Lawrence residence as it produced unusually high readings of anthropogenic radionuclides which would bias the results. This anomaly is further discussed in section 5.7.

Location	Sample Mass (kg)	Cs-137 (Bq)	Co-60 (Bq)
<i>StFX Campus</i>			
Amelia Saputo Center	0.1722	0.49	0.54
Annex	0.0755	-	0.35
Bauer Theater	0.2602	5.89	-
St. Ninian's Cathedral	0.1258	0.65	-
Coady International Institute	0.1759	0.37	-
FX Hall	0.1276	0.52	0.37
Immaculata Hall	0.1154	-	0.46
James Bruce Brown Hall	0.1669	0.38	-
Angus L. MacDonald Library	0.1356	0.44	0.56
MacIssac Hall	0.2202	-	-
NFSC	0.1356	-	0.47
Student Union Building	0.1599	0.46	-
<i>Nova Scotia</i>			
Sandy Cove Beach	0.3768	0.55	0.80
<i>New Brunswick</i>			
Cuffman St.	0.3689	0.96	1.06
Cuffman St. Construction Site	0.5910	0.98	0.90
Murray Ave.	0.5192	-	0.90

Table 15: Anthropogenic Nuclides Mean Activities

Summary of the Activities Detected in the Regions of Interest.

Nuclide Series	StFX Campus(Bq)	NS Samples(Bq)	NB Samples(Bq)
U-238	17.28	17.95	29.83
Th-232	19.85	22.50	49.34
K-40	28.37	33.95	48.27
<i>Anthropogenic</i>			
Cs-137	1.076	0.44	0.99
Co-60	0.35	1.16	0.97
Total	13.40	15.20	25.98

Note: NB Anthropogenic Activity Means do not include Lawrence Residence.

Table 16: Summary of Activity Means Sorted by location

The analysis of activities reveal that the mean total terrestrial activity from the sampled locations

Furthermore, the trace number of anthropogenic nuclides (Cs-137 & Co-60) detected are insignificant. These findings indicate that the studied areas exhibit no cautionary characteristics, as the observed activity concentrations are attributable to natural geological provenance and/or calibration source contamination. They do not represent a discernible public health concern above established background levels. This baseline characterization contributes valuable data to the regional radiation profile and confirms that the site remains within natural radiological equilibrium.

5.4 Dose Rates

As previously mentioned, humans interact with natural and artificial radiation daily. For this reason, the radiation in our surroundings is monitored heavily to determine our exposure. In Canada, the total average annual dose of background radiation is 1.77mSv/yr with 0.3mSv/yr of being attributed to terrestrial background radiation. This quantity of radiation does not cause concerning health effects as it is part of natural life and something the human body adapts to. What does cause concern is any radiation detected above this threshold. Many health agencies across the globe quote an additional 1mSv/yr of radiation (including environmental, industrial, and medical sources) above the regions background levels to be the safe maximum exposure for the public.[\[1\]](#).

The aim of this study is to see if the terrestrial radiation present at StFX University, NS, and NB is in accordance with the dose of 0.3mSv/yr currently quoted by the Canadian Nuclear Safety Commission. Additionally, we want to ensure there is no anthropogenic nuclide contamination in these locations surpassing the 1mSv/yr [\[15\]](#) limit of additional radiation exposure. Exposure is expressed in dosages, which specifically denotes the biological risks.

Exposure can be alternatively defined as a dose of radiation, that being the energy absorbed by the human body or by some material from ionizing radiation [\[15\]](#). The quantity of this dose is classified in two ways: absorbed dose [25](#) and effective dose [27](#). The absorbed dose describes the amount of ionizing radiation deposited into some medium and

is measured in joules/kg of the medium, more commonly called Grays (Gy)[16].

$$D = \frac{E}{m} \quad (25)$$

When measuring radiation from a sample, the absorbed dose is calculated from the activity concentration. The detector gives energy in the units of keV . So, absorbed dose can be alternatively expressed in keV/kg .

$$A_c = \frac{A}{m} = \frac{Bq}{kg} \quad (26)$$

The effective dose describes the radiation effects in a specific organ, tissue, or medium. This is because different materials have different radiation sensitivities. The effective dose utilizes a tissue weighting factor (w_T) [16] to specifically describe the dose delivered to one organ or tissue type, also measured in sieverts[16].

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R} \quad (27)$$

With environmental samples, the effective dose is calculated from the activity concentration, Dose Conversion Factors (DCF), and a time constant. The DCF is obtained from ICRP (Internal Commission of Radiological Protection) Publication 119 for single nuclides [17], and derived from UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) 2000 for natural decay series, with correction for surface contamination following UNSCEAR methodology [18].

Nuclide/Series	DCF ($\frac{Sv/yr}{Bq/kg}$)	Source Table
Cs-137	2.1×10^{-6}	ICRP 119 Table A.1 [17]
Co-60	1.3×10^{-5}	ICRP 119 Table A.1 [17]
K-40	6.2×10^{-6}	ICRP 119 Table A.1 [17]
U-238 series	8.5×10^{-6}	UNSCEAR 2000 Table 11 [18]
Th-234 series	1.1×10^{-5}	UNSCEAR 2000 Table 11 [18]

Highlight: UNSCEAR 2000 table values are converted to $\frac{Sv/yr}{Bq/kg}$ via $0.462nGy/h \times 0.7 \times 8760 \times 10^{-9} \times 3$ for the U-238 Series and $0.604nGy/h \times 0.7 \times 8760 \times 10^{-9} \times 3$

The dose calculation also requires an occupancy factor to estimate the rate of exposure. ICRP assumes outdoor occupancy of 0.2 for referencing adult individuals[17].

$$t_{occupancy} = \frac{4.8hrs}{day} \times \frac{365days}{year} = 0.2 \quad (28)$$

This adapted formula leads to an alternative effective dose calculation for environmental samples, the dose rate, which is based in the methodology of ICRP Publication 103 [19].

$$E = \sum_i A_{Ei} \times DCF_i \times t_{occupancy} \quad (29)$$

Effective Dose Calculation of Pb-214 from Cuffman St. Fredericton NB.

$$E = 24.40 Bq/kg \times 8.5 \times 10^{-6} \frac{Sv/yr}{Bq/kg} \times 0.2$$

$$E = 0.415 mSv/yr$$

Location	Sample Mass (mSv)	U-238 Series (mSv)	Th-232 Series (mSv)	K-40 (mSv)
<i>StFX Campus</i>				
Amelia Saputo Center	0.1722	0.309	0.441	0.278
Annex	0.0755	0.748	1.05	-
Bauer Theater	0.120	0.097	-	-
St. Ninian's Cathedral	0.1258	0.396	0.595	-
Coady International Institute	0.1759	0.243	0.102	0.218
FX Hall	0.1276	0.082	0.221	0.193
Immaculata Hall	0.1154	0.127	0.143	0.311
James Bruce Brown Hall	0.1669	0.207	0.042	0.175
Angus L. MacDonald Library	0.1356	0.144	0.619	-
MacIssac Hall	0.2202	0.059	0.046	-
NFSC	0.1356	0.165	0.357	-
Student Union Building	0.1599	0.086	0.068	-
<i>Nova Scotia</i>				
Sandy Cove Beach	0.3768	0.133	0.267	0.219
<i>New Brunswick</i>				
Cuffman St.	0.3689	0.238	0.299	0.148
Cuffman St. Construction Site	0.5910	0.054	0.156	0.107
Murray Ave.	0.5192	0.084	0.277	0.130
Lawrence Residence	0.7975	0.083	0.129	0.068

Table 17: NORM Nuclide Series Mean Effective Dosages

Location	Sample Mass (kg)	Cs-137 (mSv)	Co-60 (mSv)
<i>StFX Campus</i>			
Amelia Saputo Center	0.1722	1.20×10^{-3}	8.21×10^{-3}
Annex	0.0755	-	1.21×10^{-3}
Bauer Theater	0.2602	9.51×10^{-3}	-
St. Ninian's Cathedral	0.1258	2.15×10^{-3}	1.03×10^{-2}
Coady International Institute	0.1759	8.87×10^{-4}	-
FX Hall	0.1276	1.71×10^{-3}	7.59×10^{-3}
Immaculata Hall	0.1154	-	1.04×10^{-2}
James Bruce Brown Hall	0.1669	9.61×10^{-4}	-
Angus L. MacDonald Library	0.1356	1.37×10^{-3}	1.07×10^{-2}
MacIssac Hall	0.2202	-	-
NFSC	0.1356	1.50×10^{-3}	-
Student Union Building	0.1599	1.22×10^{-3}	-
<i>Nova Scotia</i>			
Sandy Cove Beach	0.3768	6.16×10^{-4}	5.55×10^{-3}
<i>New Brunswick</i>			
Cuffman St.	0.3689	1.10×10^{-3}	7.52×10^{-3}
Cuffman St. Construction Site	0.5910	6.94×10^{-4}	3.96×10^{-3}
Murray Ave.	0.5192	-	3.80×10^{-3}

Table 18: Anthropogenic Nuclides Mean Effective Dosages

Nuclide Series	StFX Campus(mSv)	NS Samples(mSV)	NB Samples(mSv)
U-238	0.235	0.223	0.190
Th-232	0.343	0.335	0.186
K-40	0.235	0.235	0.113
Total	0.270	0.269	0.129
<i>Anthropogenic</i>			
Cs-137	0.007	0.007	0.005
Co-60	0.002	0.002	0.0009
Total	0.0045	0.0045	0.003

Highlight: NB Anthropogenic Activity Means do not include Lawrence Residence.

Table 19: Summary of average effective dose rates sorted by Location

5.5 Comparisons

5.5.1 Thorium Uranium Dominance

Comparing the Nova Scotia and New Brunswick datasets reveals similarities and differences between the two provinces that reflect regional geology. To compare the concentrations of thorium-232 and uranium-238, the activity ratios were calculated using the mean activity from their respective decay series [20]. This ratio is calculated using:

$$R_{Th/U} = \frac{A_{Ac-228}}{A_{Pa-234M}} \quad (30)$$

where A_{Ac-228} is the activity of actinium-228 (911 keV gamma line), representing the thorium series, and $A_{Pa-234M}$ is the activity of protactinium-234M (1001 keV gamma line), representing the uranium series. Both nuclides are in secular equilibrium with their respective parents (Th-232 and U-238) due to their short half-lives relative to the parent half-lives, making them reliable proxies for the full decay chains. These peaks are also chosen because of their isolation within the gamma spectra; there are few other peaks in the gamma library which occur close to these gamma lines, leaving little chance of interference with these peaks, making them reliable for the ratio determination. For samples without the required radionuclides the Th/U ratio is determined using a secondary set of Nuclides, Pb-212 (238.6 keV Gamma line) for Thorium and Pb-214 (295 keV or 352 keV) for Uranium. Ratios less than one indicate uranium dominance and a ratio greater than one indicates thorium dominance.

Province	Th/U Ratio	Interpretation
Amelia Saputo Center	0.034	Strongly Uranium Dominated
Annex	0.065	Strongly Uranium Dominated
Bauer Theater	0.633	Uranium Dominated
St. Ninian's Cathedral	0.045	Strongly Uranium Dominated
J. Bruce Brown	2.630	Strongly Thorium Dominated
MacIssac Hall	1.966	Thorium Dominated
NFSC	0.049	Strongly Uranium Dominated
Student Union Building	0.759	Uranium Dominated
Cuffman St. NB	0.767	Uranium Dominated
Cuffman St. Construction Site	0.047	Strongly Uranium Dominated
Murray Ave. NB	0.759	Uranium Dominated
Lawrence Residence NB	0.345	Strongly Uranium Dominated
Sandy Cove Beach	0.027	Strongly Uranium Dominated
NB	0.050	Strongly Uranium Dominated
NS	0.027	Strongly Uranium Dominated

Table 20: Ratio of Th-232 and U-238 for distinction of dominance.

In Nova Scotia, the majority of locations are dominated by uranium which aligns with the known geological make up of this region. Two sites, J. Bruce Brown and MacIsaac Hall, are thorium dominated. This could be due to a difference in soil type, organic matter content, and the location's exposure to extreme weather which can affect the retention of radionuclides. All samples in NB show to be uranium dominated, which again agrees with the known geological make up of NB, as it is underlaid by uranium rich soils, particularly in the central and southern parts of the province [21].

Interestingly, the Th/U ratio remains consistent between provinces (0.05 in NS, 0.03 in NB), indicating that while absolute activities differ, the relative proportions of thorium to uranium are similar. This suggests that both provinces must have similar geological make-ups.

5.5.2 Anthropogenic Radionuclides

For anthropogenic nuclides, NB samples showed Cs-137 activities approximately twice the NS mean (0.97 Bq vs 0.47 Bq). Co-60 was also (0.84 Bq vs 0.55 Bq). However, as discussed previously it is believed that this apparent elevation reflects a combination of

laboratory background variability and small sample size. With only three NB samples available for comparison, a single sample with slightly higher carryover could skew the mean. The fact that the three NB samples cluster tightly (0.96-0.98 Bq) actually supports this, as they resemble a consistent background rather than variable environmental deposits. Future work will include expanding the sampling in NB. With additional samples, the apparent NB elevation in natural radioactivity could be confirmed or refined.

Overall, New Brunswick samples exhibit systematically higher natural radioactivity than Nova Scotia samples, consistent with the trends of bedrock geology [22, 21]. Anthropogenic nuclides also appear elevated in NB, though small sample size and calibration residue in the laboratory is likely the cause. These findings highlight the need for expanded sampling in NB to establish robust regional baselines.

5.6 NORMs

Overall, the naturally occurring radionuclides detected in this study reveal a region characterized by uranium-dominant geology, with localized thorium anomalies at two Nova Scotia sites. The consistent K-40 activities validate our methodology and confirm sample interpretations. The mean terrestrial radiation found for NS and NB are 0.269 and 0.129 mSv/yr which aligns well with the known terrestrial background radiation dose of 0.3 mSv/yr [1]. All natural radioactivity levels are within expected ranges for uncontaminated Maritime soils and pose no health concern.

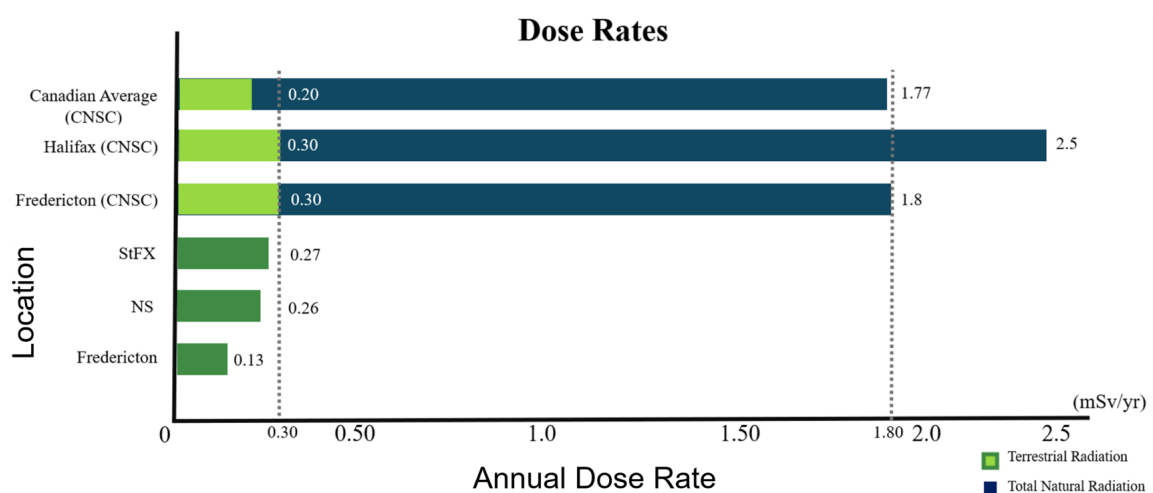


Figure 45: Bar graph comparing measured and known values for average terrestrial and total radiation.

5.6.1 Uranium-238 Series Nuclides

Uranium-238 is strongly detected across both provinces, dominating over Thorium-232. The mean activity ratio of Th/U is 0.03 in Nova Scotia and 0.05 in New Brunswick which indicates that uranium activity is higher than thorium activity across the provinces. The uranium dominance is expected as the maritime provinces are situated upon uranium geological formations. The consistency of uranium detection suggests that uranium enrichment is a regional characteristic rather than a localized phenomenon. This aligns with previously conducted geological surveys of the Maritime.

5.6.2 Thorium-232 Series Nuclides

While uranium dominance characterizes the region overall, two Nova Scotia locations deviated from this result: J. Bruce Brown and MacIsaac Hall International Institute. These locations process a Th/U ratio of 2.630 and 1.966, respectively. These represent localized thorium enrichment within a regionally uranium-dominant setting. It is possible that the reported thorium dominance is due to an analytical error. However, in these gamma spectra other thorium series peaks are correctly identified, making error an unlikely cause for the thorium dominance. Thorium dominance may be caused by imported soil with a higher thorium concentration as the sample was taken near an area of newly planted bushes. It is also possible the building materials like brick, and concrete, located around the areas from where this sample was taken contained thorium. Depositing trace amounts of thorium into the surrounding soil. Regardless of the origin, these anomalies are interesting but reveal no significant insight into the radioactive concentration of the soil. Even at Coady Institute, where thorium activity is three times higher than uranium, the absolute activity levels remain well within ranges typical for uncontaminated soils and pose no health concern.

5.6.3 Potassium-40

Potassium-40 was detected in 85% of Nova Scotia samples and 100% of New Brunswick samples, with activities ranging from 29.0 to 66.6 Bq. This consistency serves several important purposes such as internal quality control, baseline validation, and K-40 activities may act as a reference point comparing other nuclides. K-40 acts as a natural internal standard. If K-40 activities had shown extreme variation, it might indicate sample preparation issues or detector instability. The observed consistency confirms methodological reliability. The K-40 results thus validate that our samples are representative of typical

Maritime soils and that our measurement methodology is producing reliable data.

5.7 Anthropogenic Nuclides

Cesium-137 and Cobalt-60 were detected in the majority of samples, present in 77% and 69% of NS sites, respectively, and 100% of NB sites. The Nova Scotia samples produced Cs-137 activities all within a close range of one another (0.37-0.63 Bq) and span a range of different locations. This indicated the presence of the anthropogenic nuclide might not be environmental. Environmental Cs-137 from industrial or nuclear activities would show spatial variability based on precipitation patterns, soil type, and land use.

The near-identical activities observed in this study are inconsistent with environmental distribution. Furthermore, the activities have no correlation to the sample's mass indicating its origins may not be that of the soil sample. A realistic explanation for this trend is that these low, consistent activities represent trace residual contamination from recent repeated use of calibration standards. This aligns with the measurement protocol used for data collection. As a short measurement of the calibration sources, Cs-137 and Co-60 are conducted before the measurement of a soil sample to check for thermal drift in the detector. The New Brunswick samples exhibited the same characteristics but slightly elevated (0.89-0.96 Bq). With only three NB samples, the apparent elevation most likely a statistical error. A single sample with slightly higher values could skew the result. In summary, the Cs-137 and Co-60 detected in this study are attributed primarily to trace residual contamination from laboratory calibration sources rather than environmental fallout. Nonetheless, the effective dose attributed to anthropogenic radionuclides is well below the $1mSv/yr$ threshold set by the Canadian Nuclear Safety Commission [1] with dose rates being $0.0045mSv/yr$ and $0.003mSv/yr$ for NS and NB, concluding that there is no need for concern for human health at the locations measured in this study.

5.7.1 Lawrence Residence Anomaly

One location that indicated higher amounts of anthropogenic nuclides compared to the others was the Lawrence Residence. The sample yielded 10.16 Bq corresponding to Cs-137 (32 keV Gamma Line), higher than any other activity reading for an anthropogenic nuclide across all samples. This activity cannot be attributed to calibration source residue. Additionally, U-238, Th-232, and K-40 are all detected with the expected activity further

suggesting the high anthropogenic activity must be a genuine geological anomaly. It would be worth collecting and analyzing further samples from this location to determine how concrete this anomaly is. Despite the elevated activity, the calculated dose reveals that the anthropogenic nuclide does not raise concerns for human health and safety.

Radionuclide	Activity	Activity Concentration	Effective Dose
Cs-137	10.16 <i>Bq</i>	2.56 <i>Bq/kg</i>	$5.39 \times 10^{-3} mSv/yr$

Table 21: Lawrence Residence Characteristics

5.8 Limitations

While this study provides valuable baseline data, several limitations and sources of uncertainty must be acknowledged. The most significant being the small sample size, especially for New Brunswick ($n=4$). With only four samples, the mean values reported may not be an accurate reporting of the province’s radioactivity, as one extreme conclusion could skew the statistics. The elevation in NB should be considered preliminary until further samples can be collected and more robust results can be produced with a larger data set; even the thirteen NS samples cannot fully capture the radioactive profile of the province. Additionally, it would be useful to collect more samples from the same locations. This would allow us to check for detector consistency and to build a stronger sample for the location, especially in the case of the two Thorium dominated locations on StFX Campus, J. Bruce Brown and MacIsaac Hall. Re-sampling would help confirm whether these are true anomalies or a misstep during the analysis stage. Currently, most NS samples are from the StFX Campus. To build a better database for the province of NS more samples must be collected from other regions within the province. The same applies to NB as all samples are from Fredericton.

Sodium Iodide detectors have inherently poorer energy resolution compared to a high-purity germanium (HPGe) detector. The energy resolution of the NaI(Tl) detector used in this research is 7.67% at 661.6 keV, compared to, 0.2% for HPGe [7]. This drawback leads to peak overlapping, interference, and background continuum. These limitations are manageable by careful peak fitting and longer count times. However, if future work focuses on low-level contamination or precise quantification, HPGe would be the preferable instrument.

6 Conclusion and Future work

Overall, the objectives of this research were successfully achieved. The NaI(Tl) detector was calibrated and demonstrated performance capable of measuring low-activity environmental samples such as soil. For each sample collected on campus, both the activity concentration and corresponding dose rate were calculated and found to fall within the range deemed safe for human health by the Canadian Nuclear Safety Commission. These results establish a robust baseline for a campus radioactivity database that can be easily maintained and updated for long-term monitoring. The effective dose from NORMs was found to be 0.266 and 0.129 mSv/yr for NS and NB respectively. These values are below the known terrestrial background and indicated no radiological anomalies present within the areas investigated in this study.

Comparison between the two provinces reveals that uranium-series radionuclides dominate the gamma spectra, which aligns with the known geology of the region, as uranium bedrock formations underly both NB and NS.

Future studies should prioritize collecting additional samples from the Antigonish region to expand the existing database with the eventual goal of characterizing radioactivity across most of Nova Scotia. The same effort is recommended for Fredericton, New Brunswick, as the four samples collected in this study proved insufficient for drawing robust conclusions about the region's radioactive profile. Expanding the sample size may also help to further solidify the effective dose calculated for each area, bringing it closer to the expected value. Additional sampling in Fredericton is also needed to investigate the elevated Cs-137 activity observed at the Lawrence Residence. Finally, an error analysis should be conducted to quantify the accuracy and precision of the results presented here, thereby strengthening the reliability of the baseline data.

With the current detector capabilities, the next logical step is to apply this methodology to more complex samples, beginning with food products. Measuring the radiological concentration present in our dietary intake would establish a critical link between environmental radioactivity and potential human exposure. This progression from soil to food follows the order of the food chain-soil, plants, animals, humans. The natural progression through the food chain allows us to follow the radionuclide transfer from the ecosystem (soil) to plants to humans. Future work should focus on locally sourced foods which are

in direct contact with terrestrial radionuclides from soil, with later and samples including things such as fish or muscles from bodies of water, from which the sediment and surrounding soil is measured as well. Such a study would provide baseline data for effective dose via ingestion for residents of the region, complementing the external exposure data established in this work.

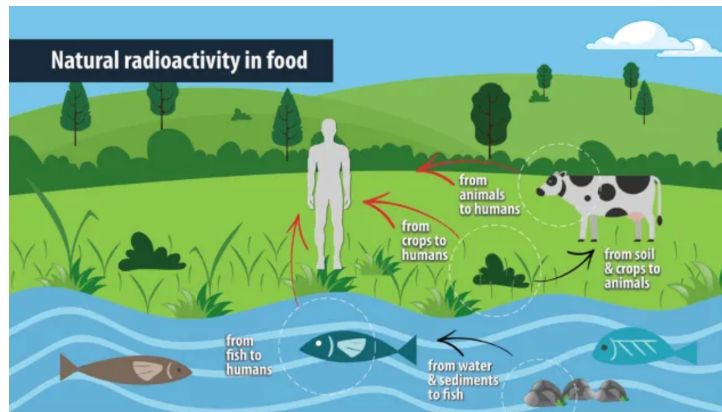


Figure 46: Radionuclide Pathway Through the Food Chain [10]

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A Appendix

A.1 Electromagnetic Spectrum

[h] The electromagnetic spectrum is the range of known electromagnetic radiation organized by frequency or wavelength. The spectrum divides electromagnetic radiation into different categories. Each form of radiation has its own set of characteristics, such as how it is produced, how it interacts with matter, and its applications. The low energy region of the spectrum houses radio waves and microwaves. These forms of radiation have the lowest frequency and the largest wavelengths ($10^3 - 10^{-2}m$). On the other extreme of the electromagnetic spectrum are x-rays and gamma rays. These forms of radiation have the shortest wavelengths ($10^{-10} - 10^{-12}m$)[23] and the highest energy. The energy of gamma-rays is commonly given in electron-volts ($1J = 1.602 \times 10^{-19}eV$).

The equation for calculating the energy of a photon:

$$E = h \times v \quad (31)$$

where,

$$v = \frac{c}{\lambda} \quad (32)$$

Gamma rays and x-rays are also known as ionizing radiation, which comes from their ability to ionize atoms. This process triggers a cascade of reactions throughout a material, which is a key occurrence in gamma spectroscopy.

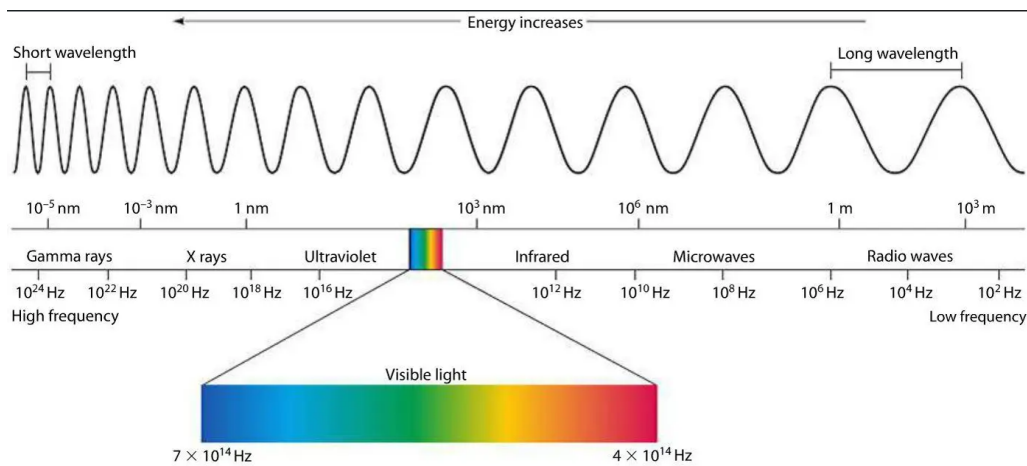


Figure 47: Electromagnetic Spectrum [23]

Table 22: Sampling Locations and Sample Information

Location	Mass (g)	Collection Date	Measurement Date	Latitude	Longitude
Annex, NS	75.5	2025-07-13	2026-01-25	45.61784	-61.99322
Cathedral, NS	125.8	2025-07-13	2026-01-23	45.62050	-61.99344
Library, NS	135.6	2025-07-23	2026-01-20	45.61973	-61.99437
MacIssac Hall, NS	220.2	2025-08-11	2026-01-22	45.61556	-61.99370
Coady Institute, NS	175.9	2025-07-23	2026-01-21	45.63309	-61.99020
J.B.B., NS	166.9	2025-07-30	2026-01-25	45.61760	-61.99246
Immaculata Hall, NS	115.4	2025-07-23	2026-01-27	45.62054	-61.99226
F.X. Hall, NS	127.6	2025-07-23	2026-01-23	45.61607	-61.99250
Bauer Theater, NS	260.2	2025-08-11	2026-01-23	45.61869	-61.99618
NFSC, NS	135.6	2025-07-30	2026-01-21	45.61771	-61.99521
S.U.B., NS	159.9	2025-08-11	2026-01-16	45.61739	-61.99357
Amelia Saputo, NS	172.2	2025-08-11	2026-01-20	45.61714	-61.99612
Sandy Cove Beach, NS	376.8	—	2025-02-05	44.624238	-65.766402
Cuffman St., NB	368.9	2025-08-20	2026-01-28	45.97406	-66.61257
Murray Ave., NB	519.2	2025-08-20	2026-01-28	45.972601	-66.610838
Construction Site, NB	591.0	2025-08-20	2026-01-29	45.973661	-66.612892
Lawrence Residence, NB	792.5	2025-08-20	2026-01-30	45.972364	-66.606358

A.2 Equations

[h]

$${}^A_ZX_N \quad (33)$$

where:

X is the element of choice

Z is the atomic number, or the number of protons

N is the number of neutrons

A is the mass number, $A = Z + N$

$$E_e = E_\gamma - E_b \quad (1)$$

where:

E_e is the energy of the photoelectron

E_γ is the energy of the released photon

E_b is the binding energy of the electron shell

$$E_e = E_\gamma - E_K \quad (2)$$

where:

E_e is the energy of the electron

E_γ is the energy of the released photon

E_K is the energy of the K-shell for the atom of interest

$$E_e = E_\gamma - E'_\gamma \quad (3)$$

where:

E_e is the energy of the recoil electron

E_γ is the energy of the incident photon

E'_γ is the energy of the scattered photon

$$E_e = \lambda' - \lambda \frac{h}{mc} (1 - \cos \phi) \quad (4)$$

where: E_e is the energy of the recoil electron

λ is the wavelength of the incident photon

λ' is the wavelength of the scattered photon

m is the mass of an electron. $m_e = 9.1 \times 10^{-31} kg$

ϕ is the scattering angle of the photon h is Plank's Constant

$$E_e = E_\gamma - 1022keV \quad (5)$$

where:

E_e is the energy of the electron

E_γ is the energy of the photon

1022keV is the energy threshold for pair production to occur

$$A = -dN/dt = \lambda N \quad (6)$$

where:

Activity is defined as the change in number of nuclei over the change in time.

λ is the decay constant, which is a measurement of decay per unit time for the particular element.

$$A = A_0 e^{-\lambda t} \quad (7)$$

where:

A is the activity after some period of time has passed

A_0 is the starting activity of the radionuclide

λ is the decay constant, which is a measurement of decay per unit time for the particular element

t is some unit of time that has passed

$$\tau = \frac{1}{\lambda} \quad (8)$$

where:

λ is the decay constant, which is a measurement of decay per unit time for the particular element

$$t_{1/2} = \frac{\ln 2}{\lambda} \quad (9)$$

where:

λ is the decay constant, which is a measurement of decay per unit time for the particular element

$${}^A_ZX \rightarrow {}^A_{Z+1}Y + \beta^- + \bar{\nu} \quad (10)$$

where:

X is the Parent nuclide

Y is the daughter nuclide

β^- is the released beta particle

$\bar{\nu}$ is the anti-neutrinos released in this interaction

$${}^A_ZX \rightarrow {}^A_{Z-1}Y + \beta^+ + \nu \quad (11)$$

where:

X is the Parent nuclide

Y is the daughter nuclide

β^+ is the released positron

$\bar{\nu}$ is the anti-neutrinos released in this interaction

$${}^A_ZX + e \rightarrow {}^A_{Z-1}Y + \nu \quad (12)$$

where:

X is the Parent nuclide

Y is the daughter nuclide

e is the captured electron

$\bar{\nu}$ is the anti-neutrinos released in this interaction

$${}^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + {}^4_2He + Q \quad (13)$$

where:

X is the Parent nuclide

Y is the daughter nuclide

${}^4_2He$ is the alpha particle released in the interaction

Q is a quantity of energy released during the process

$$PeakCentroid = \frac{\sum_{i=l}^h i \times c_i}{\sum_{i=l}^h i} \quad (15)$$

Where:

h is the high count channel

i is the channel number

l is the low count channel

c_i is net contents of channel i

$$E = a_1 + a_2C + a_3C^2 \quad (16)$$

where: a_1, a_2, a_3 are coefficients

C is a channel number

$$Res(E) = \frac{FWHM}{E} \times 100\% \quad (20)$$

where:

FWHM is the Full-Width Half Maximum value of the peak on interest

E is the energy of the peak

$$FWHM = b_1 + b_2C + b_3C^2 \quad (20)$$

where: b_1, b_2, b_3 are coefficients

C is a channel number

$$\epsilon(E) = \frac{N_{Ei}}{A_{Ei} \times B \times Lt} \quad (21)$$

where:

N_{Ei} is the net counts of the i^{th} peak

A_{Ei} is the activity of the i^{th} peak

B is the branching ratio of the nuclide of interest

Lt is the live time of the measurement trial

$$\epsilon = e^{a_1 + a_2 \ln(E) + a_3 (\ln(E))^2} \quad (??)$$

where:

a_1, a_2, a_3 are coefficients

E is the energy of the peak of interest.

$$A_{Ei} = \frac{N_{Ei}}{Lt \times \epsilon(E) \times B} \quad (23)$$

Where:

N_{Ei} is the net peak counts of the i^{th} peak

B is the branching ratio of the nuclide of interest

Lt is the live time of the measurement trial

$$A_c = \frac{A_{Ei}}{m} \quad (26)$$

Where:

A_{Ei} is the activity of the i^{th} peak

m is the mass of the sample in kg

$$E = \sum_i A_{Ei} \times DCF \times t_{occupancy} \quad (29)$$

where:

A_{Ei} is the activity of the i^{th} peak

DCF is the decay conversion factor from published sources [18],[17]

$t_{occupancy}$ is the outdoor occupancy factor

$$R_{Th/U} = \frac{A_{Ac-228}}{A_{Pa-234M}} \quad (30)$$

where:

A_{Ac-228} is the activity of the A_{Ac-228} peak from the spectrum

$A_{Pa-234M}$ is the activity of the $A_{Pa-234M}$ peak from the spectrum

$$E = h \times v \quad (31)$$

where:

h is Plank's constant, $h = 6.626 \times 10^{-34} Js$

v is the frequency of the photon

$$v = \frac{c}{\lambda} \quad (32)$$

where:

c is the speed of light, $c = 3.0 \times 10^8 \text{ m/s}$

λ is the wavelength of the photon