DEVELOPMENT OF AN ADVANCED NEUTRON ACTIVATION ANALYSIS PROTOCOL AT THE UNIVERSITY OF UTAH NUCLEAR ENGINEERING FACILITY

by

Todd Hansen Sherman

A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

in

Nuclear Engineering

Department of Civil and Environmental Engineering

The University of Utah

December 2012

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The thesis of **Todd Hansen Sherman**

has been approved by the following supervisory committee members:

Tatjana Jevremovic	, Chair	**May 18, 2012**
		Date Approved
Dong-OK Choe	, Member	**May 18, 2012**
		Date Approved
Haori Yang	, Member	**May 18, 2012**
		Date Approved

and by **Paul Tikalsky** , Chair of

the Department of **Civil and Environmental Engineering**

and by Charles A. Wight, Dean of The Graduate School.

`

ABSTRACT

This thesis encompasses the experimentation and development of neutron activation analysis protocols for the University of Utah Nuclear Engineering Program (UNEP). The University of Utah TRIGA Reactor (UUTR) was used as a neutron source to activate various materials to examine the inorganic elements. The *Activity Estimator* calculator was developed to approximate the activities of activated isotopes. Gamma ray activities, from activated samples, were acquired and measured on high purity germanium gamma spectroscopy detectors. Using the data collected from the gamma spectroscopy activated isotopes were identified and quantified. The activities from the identified isotopes were used to calculate the elemental concentrations of the sample materials using the *Elemental Concentration Calculator* and *SRM Ratio Calculator*. Complete NAA protocols and procedures were developed for a wide variety of materials and uses such as: criminal forensics, metals in soil, rock and water as well as minerals in fruits and vegetables.

TABLE OF CONTENTS

`

LIST OF TABLES

`

`

LIST OF FIGURES

`

ACKNOWLEDGEMENTS

I would like to thank Dr. Tatjana Jevremovic for guiding me through my thesis research. I would also like to thank Dr. Dong-Ok Choe and Dr. Haori Yang for their support, advice and guidance. My deepest gratitude is extended to my wife, my parents and my dear children for their patience, love and support. I am grateful to Energy*Solutions* for providing me with an internship and fruitful environment where I was able to learn about gamma spectroscopy that directly contributed to my thesis research. I would like to express my thanks to my friends and colleagues, Avdo Cutic, Phil Babitz, Jason Rapich, Steve Burnham and Jesse Reeves for their friendship, support and teamwork.

`

CHAPTER 1

INTRODUCTION

1.1 Motivation

Neutron Activation Analysis (NAA) is highly valuable yet nondestructive method providing the elemental composition for an examined sample. The sample can be almost from any origin and of any type. During the neutron irradiation the isotopes present in material sample become activated through neutron capture. The University of Utah Nuclear Engineering Program (UNEP) houses Mark I General Atomics ® TRIGA Reactor (UUTR), which is licensed to operate at the maximum power of 100 kW_{th}. The UUTR, operating for last 35 years, is utilized as an abundant neutron source for various nuclear related experiments. However, the reactor was seldom used for NAA, and no NAA protocol has ever been established during these 35 years of the UUTR use and operation. The motivation for this research therefore, was to develop and establish the NAA protocol inclusive of required procedures, and with the goal to investigate inorganic elemental compositions tailored toward multiple applications. Developing this new and advanced NAA protocol at UNEP would provide, never before existing opportunities for a wide array of experiments thus advancing research, education and

training, but as well in providing a ground for entrepreneurial efforts toward commercial, industrial and agricultural entities.

The NAA protocols that were considered as a main goal of this thesis research were instrumented neutron activation analysis (INAA) and delayed gamma neutron activation analysis (DGNAA) that employs delayed gamma spectroscopic counting of the irradiated samples that have not been chemically altered.

1.2 Thesis Objectives

The objectives of this thesis are to:

1. *Establish the NAA methods* for various applications and research avenues of great interest to faculty and students at UNEP. This new NAA line is envisioned to support the expansion of currently existing research, and provide the ground for new research and training development as well as in establishing entrepreneurial links to state's agricultural, industrial, geological and other similar entities.
2. *Develop the NAA protocol* (to include the NAA pre-estimator, manual, and steps for calibrating the instrumentation). In other words, the objective is to develop the NAA protocol and procedures for step-by-step procedures in carrying out NAA experiments leading to accurate results and accurate interpretation of the analysis. The NAA protocol includes: the *NAA Sample Activity Estimator*, the *NAA Manual*, *the Elemental Concentration Calculator* and the *Manual for step-by-step instructions on instrument calibrations with Quality Assurance (QA) and Quality Control (QC) instructions*.
3. *Create an NAA data library for a number of different types of materials* as a part of the NAA protocol development and benchmarks. The library is to be included into the

NAA manual to be used as a base for any future NAA at the UUTR. The library is planned to include at least the following: a number of various lime stone samples, different concrete samples, analysis of food products (fruits, veggies, meet, vitamins and similar), samples to potentially be found at crime-scene (hair, nails, shampoo, nail polish, bricks, dust, car paints, glass), and some of the beauty products.

1.3 Organization of the Thesis

The basics of NAA theory and physics behind are discussed in Chapter 2. In this Chapter the use of NAA in test and research reactors as well as the errors associated with NAA are discussed. In addition, the gamma spectroscopy and how it is coupled with NAA is reviewed in this Chapter. In Chapter 3 an overview of the UNEP facilities used for NAA is presented. The experimental data collected during the course of this research are presented and discussed in Chapter 4. This includes the UUTR flux mapping, calibration of the gamma detectors, and the analysis of error propagation. The NAA *Activity Estimator* and *Elemental Concentration Calculator* are both described in Chapter 5. In Chapter 6 the newly developed and benchmarked NAA protocol is described. Very important aspect of defining the minimal detectable levels (MDL) or the lowest detectable concentrations for each element is discussed in this Chapter. In Chapter 7 examples from the number of NAA experiments are presented and discussed. The conclusion of this research is given in Chapter 8, while suggestions for future work are listed in Chapter 9.

CHAPTER 2

NEUTRON ACTIVATION ANALYSIS (NAA)

2.1. Literature Review

Neutron Activation Analysis (NAA) was first proposed in 1936 by George Charles de Hevesy when he found that materials containing rare metals became radioactive after being exposed to neutron sources (Levi, 1985). De Hevesy then began to implement this technique to produce radioisotopes as medical biological tracers. Since then, the NAA has been used for a wide variety of applications.

In archeology, NAA is frequently used to fingerprint the artifacts in verifying their authenticity and track their origins. One example illustrating the effectiveness of the NAA in fingerprinting the archeological samples is found in 2009, at the University of Mainz in Germany where the group of scientists irradiated 20 samples from reverse glass paintings to identify the place and date of origin (Sanchez, Hampel, & Riederer, 2009). Through both, long term and short term irradiations, in a TRIGA Mark II reactor, isotopes from 23 elements were revealed which were used to characterize the glass matrix composition. The glass compositions were compared to other glasses from known locations and periods in validating their origins.

The Budapest Neutron Centre in Hungry teamed up with La Universidad Simon Bolivar in Venezuela to create a database of Pre-Columbian pottery figurines and their possible origins (Sjao-Bohus, et al., 2006). This study included nearly 800 figurines from the Valencia Lake Basin and Los Roques Archipelago regions of Venezuela. Using NAA, it was determined that the artifacts were most likely from pre-Hispanic time and therefore were not the modern replicas.

Environmental toxicity can be evaluated through NAA as well. Plants and animals are often good environmental 'monitors'. Samples can be collected to test for the presence of inorganic toxins. Mosses, tree barks, tree rings and lichens have been used for decades to track pollution levels over various time periods. In the Netherlands such biological specimens were analyzed using NAA to examine the presence of heavy metal pollution contents in air (De Bruin, 1990).

This study, carried out in the 1980s, identified 34 different metals that were found in the specimens that could have come from industrial pollutions. The findings were plotted over a map of the Netherlands to graphically show the regions of high and low concentrations of heavy metals presented in the air.

Evaluation of heavy metal contamination of soil is another field where NAA has been regularly utilized. For example, several hundred soil samples taken across the island of Jamaica were studied through NAA to determine various heavy metals concentrations especially the presence of cadmium (Grant, Lalor, & Vutchkov, 1998). The study revealed significant levels of contamination due the heavy mining industry and pollutions from the metal extraction processes.

NAA is often applied to criminal forensics. For example, the death of Napoleon Bonaparte was investigated using the NAA to determine if he died from arsenic poisoning. Hairs, which were taken immediately after his death, were exposed to neutrons and analyzed through the NAA to determine the arsenic concentrations (Weider, 1999). The results indeed verified that Napoleon had received significant doses of arsenic prior to his death.

NAA is also used to investigate bullets and gunshot residues at crime scenes. For example, in 1964 NAA was used to investigate the assassination of President John F. Kennedy. Bullet fragments recovered from the crime scene as well as the rifle of Lee Harvey Oswald were irradiated in a reactor at the Oakridge National Laboratory to analyze if the compositions matched (Guinn, 1979). The NAA report was included in the official investigation report issued by the Warren Commission, which confidently identified Oswald as the President's assassin.

Nutrition information on biological specimens can be derived from the mineral information based on NAA. For example, the Sao Paulo Nuclear and Energy Research Institute, (Instituto de Pesquisas Energeticas e Nucleares), IPEN, regularly conducts experiments to characterize the mineral nutritional levels of the people past and present in Brazil; bone and hair samples from deceased individuals are irradiated to determine mineral deposition and potential toxicity in Brazil. The results aid in identifying regions where malnutrition, toxic exposure and other health risks are concern.. NAA, therefore, can be an extremely powerful tool in studying chronological biological nutrition and presence of minerals in ancient and modern societies.

NAA is a powerful tool for finding the elemental composition for both, gross inorganic and trace metal compositions in various sample types. In other words, the NAA can be used to find the trace elements and thus characterize the matrix of a material. In addition, it can also be used to identify contamination of elements that should not be present in industrial, commercial and agricultural products. For example, the National Institute of Standards and Technology (NIST) has developed several techniques to detect and identify toxins in biological materials (Paul, 2011). Arsenic is a particular element of interest because of its biological hazard,(The Dr. Oz Show). NAA could be a useful tool to detect and quantify arsenic in any food sample.

This thesis summarizes the best practices of the NAA use, and reflects on many of these and yet novel applications in regard to science, technology, industry as well as our daily lives.

2.2. NAA Theory and Physics

Neutrons interacting with a nucleus of an atom may either be scattered or captured to form a compound nucleus (Jevremovic, 2009). One of these interactions is neutron capture, in which a neutron is absorbed by the nucleus. The capture thus increases the mass number of the nucleus:

$$X_A^Z + n_0^1 \rightarrow X_A^{Z+1} \qquad 2-1$$

This newly generated isotope is usually unstable. Neutron activation converts nuclide into new isotope. For example, some nuclides, such as titanium-49 would capture

a neutron and become titanium-50, which is a stable, naturally occurring isotope. However, a titanium-50 can capture a neutron to become titanium-51, which is unstable; titanium-51 will decay to vanadium-51 and become a new element.

The ability of a nucleus to capture a neutron depends upon the nuclear properties of the nucleus and probability of neutron capture. It is completely independent of all chemical, electrochemical and magnetic properties of the nucleus, which makes NAA virtually independent of chemical and electromagnetic properties of the examined sample.

Many nuclides, upon capturing a neutron, become unstable and undergo a nuclear transmutation and or radioactive decay in becoming stable. Such radioactive decays can involve one or more of the following modes: beta emission, positron emission, electron capture and/or isomeric transition. Each of these events can be accompanied with the emission of one or more gamma photons, as illustrated in **Figure 2-1**. These high energy photons can be detected and counted using gamma spectroscopy detectors (as discussed in Section 2.5).

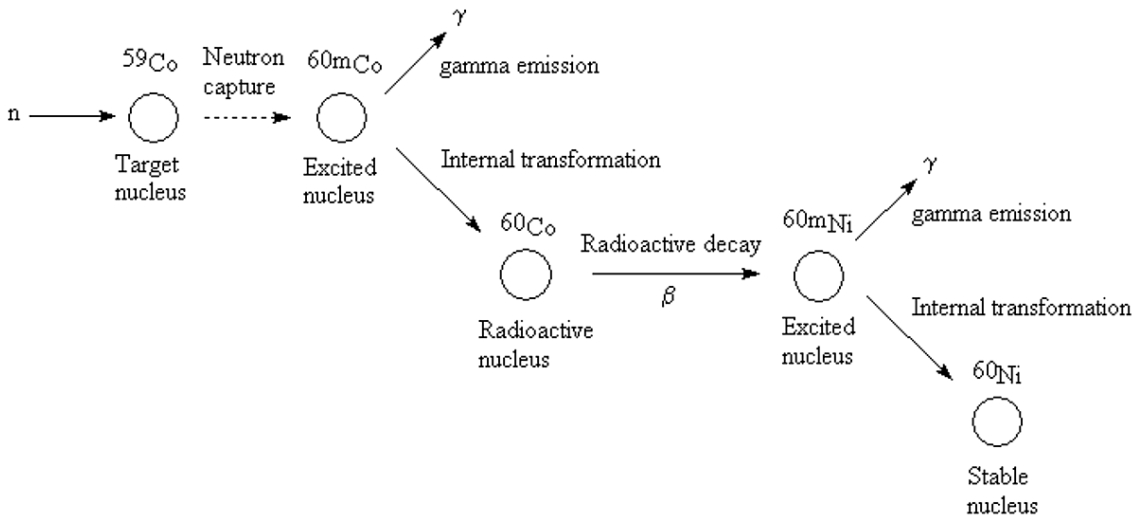


Figure 2-1 Neutron capture by Co-59 and radioactive decay of the formed Co-60 (Wikipedia - Neutron Activation Analysis)

Decaying nuclides emit signature gamma photons, which are used to identify the isotope. Most of the activated isotopes during NAA produce gamma rays as they decay, which makes them easy to detect.

Nuclear events such as radioactive decay or neutron interactions are characterized by the probability of occurrence. Measured nuclear properties such as half life and cross section determine the probability of whether an event will occur over time. Eq (2-2) defines the probability of decay for a single nuclide called decay constant (λ):

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

$$\lambda: decay\ constant\ \left(\frac{1}{sec}\right)$$

$$t_{\frac{1}{2}}: half\ life\ (sec)$$

The product of the decay constant and the number of radioactive nuclei of a given isotope, gives the total number of probable decays per second, which is the activity of that nuclide, and expressed in the unit of Becquerel's (Bq) is equal to:

$$A = \lambda n \qquad 2-3$$

$$A: total\ activity\ (Bq)$$

$$n: number\ of\ atoms\ (atoms)$$

$$\frac{dn}{dt} = -\lambda n \qquad A(t) = A_0 e^{-\lambda t} \qquad 2-4$$

$$t: decay\ time\ (sec)$$

The probability for a neutron to interact with a nucleus is expressed as microscopic cross section (σ). This property is represented as a cross sectional area measured in barns. One barn is equal to 10^{-24} cm^2. Smaller cross section units is defined as an outhouse (10^{-30} cm^2) and a shed (10^{-48} cm^2); these units are rarely used (The Language of the Nucleus). An integrated cross section over a number of nuclei (N) in a target per unit volume is defined as macroscopic cross section (Σ):

$$\Sigma = N\sigma \qquad 2-5$$

$$\Sigma: macroscopic\ cross\ setion\ \left(\frac{1}{cm}\right)$$

$$N: atom\ density\ \left(\frac{atoms}{cm^3}\right)$$

$$\sigma: microscopic\ cross\ setion\ \left(\frac{cm^2}{atom}\right)$$

Neutron cross section is not a constant value, but a variable dependent on the speed (or energy) of the interacting neutron and on the nuclear properties of the target material. The neutron capture cross section tends to increase as the neutron energy

decreases. Therefore, the probability that a nucleus will capture a slower neutron is usually higher than the probability of capturing a fast neutron. However, there are exceptions, especially in the resonance region where large cross sections for capture can be observed. **Figure 2-2** shows the neutron capture cross section for Au-197.

$$A_D(t_{decay}) = \phi n \sigma \left(1 - e^{-\lambda_D t_{irr}}\right) \qquad 2-7$$

$$A_D(t_{decay}): activity\ of\ activated\ daughter\ isotope\ (Bq)$$

$$\lambda_D: daughter\ decay\ constant\ \left(\frac{1}{sec}\right)$$

$$A\ \left(\frac{decays}{sec}\right)$$

$$= \phi \left(\frac{neutrons}{cm^2 * sec}\right) n(atoms) \sigma \left(\frac{cm^2}{atom}\right) 1\ absorption\ \left(\frac{atom}{neutron}\right) 1\ decay\ \left(\frac{decay}{atom}\right)$$

Eqs (2-6) and (2-7) are assuming the mono-energetic neutrons. More accurate activation equation taking into account a range of neutron energies is obtained by integrating over all the energies:

$$R = n \int_0^\infty \phi(E) \sigma_{absorption}(E)\, dE \qquad 2-8a$$

$$R: reaction\ rate\ \left(\frac{neutron\ interactions}{sec}\right)$$

$$A_D(t_{irr}) = \left(1 - e^{-\lambda_D t_{irr}}\right) \sum_{i=0}^{N} n_i \phi_i \sigma_{i,absorption} \qquad or$$

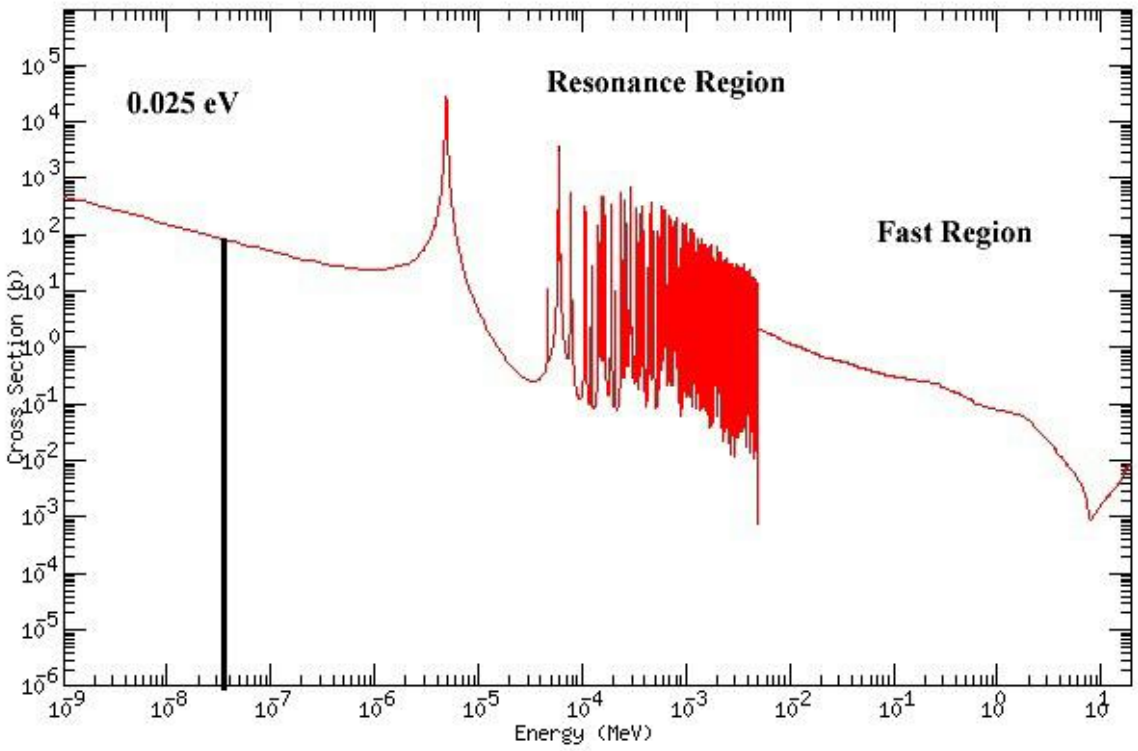


Figure 2-2 Au-197 neutron capture cross section (http://atom.kaeri.re.kr/)

$$A_D(t_{irr}) = n_P\left(1 - e^{-\lambda_D t_{irr}}\right) \int_0^{\infty} \phi\, \sigma_{absorption}\, dE \qquad 2-8b$$

$$n_P: number\ of\ parent\ atoms\ (atoms)$$

Combining Eqs (2-4) and (2-7) the activity of the remaining generated daughter isotopes after irradiation and decay is obtained as follows:

$$A_D\left(t_{decay}\right) = \phi n \sigma \left(1 - e^{-\lambda_D t_{irr}}\right) e^{-\lambda_D t_{decay}} \qquad 2-9$$

The absorption cross sections (σ) are affected by the temperature of the sample material (Jevremovic, 2009); therefore:

$$\sigma(T) = \frac{\sqrt{\pi}}{2}\sigma\sqrt{\frac{293}{T}} \qquad 2-9$$

$$\sigma: microscopic\ cross\ section\ at\ 293\ K\ \left(\frac{cm^2}{atom}\right)$$

$$T: temperature\ (K)$$

The number of parent atoms can be calculated from:

$$n_P = m\frac{N_A}{A_m}A_{\%} \qquad 2-10$$

$$m: mass\ (g)$$

$$N_A: Avogadro's\ number\ \left(\frac{atoms}{mole}\right)$$

$$A_m: atomic\ mass\ \left(\frac{g}{mole}\right)$$

$$A_{\%}: atomic\ abundance\ ratio$$

The modified NAA equation containing all the variables based on the "one-group" activation theory is:

$$A_D(t_{decay}) = \phi\left[\frac{\sqrt{\pi}}{2}\sigma_P\sqrt{\frac{293}{T}}\right]m\frac{N_A}{A_m}A_{\%}(1-e^{-\lambda_D t_{irr}})e^{-\lambda_D t_{decay}} \qquad 2-11$$

$$\sigma_P: parent\ microscopic\ absorption\ cross\ section\ at\ 293\ K\ (cm^2)$$

If the activity of the isotope, at a given time (t), is measured and the irradiation time and flux are known, then the mass of the original parent element (m), mass concentrations (C), as well as the number of original atoms (n_P) can be calculated using the modified NAA relations as follows:

$$n_P = \frac{A_D(t_{decay})}{\phi\sigma_P(1-e^{-\lambda_D\, t_{irr}})e^{-\lambda_D\, t_{decay}}} \qquad 2-12$$

$$n(atoms) = \frac{A\left(\frac{decays}{sec}\right)}{\phi\left(\frac{neutrons}{cm^2 * sec}\right)\sigma\left(\frac{cm^2}{atom}\right)1\ absorption\ \left(\frac{atom}{neutron}\right)1\ decay\ \left(\frac{decay}{atom}\right)}$$

$$m = \frac{A_D(t_{decay})}{\phi\sigma_P\frac{N_A}{A_m}A_{\%}(1-e^{-\lambda_D t_{irr}})e^{-\lambda_D t_{decay}}} \qquad 2-13$$

$$C = \frac{A'_D(t_{decay})}{\phi\sigma_P \frac{N_A}{A_m} A_{\%}(1 - e^{-\lambda_D t_{irr}})e^{-\lambda_D t_{decay}}} \qquad 2-14$$

$$C: mass\ concentration\ \left(\frac{g}{g} or \frac{g}{mL}\right)$$

$$A'_D: specific\ daughter\ isotope\ activty\ \left(\frac{Bq}{g\ or\ mL}\right)$$

Many of the activated isotopes only decay or transmute once to reach a stable state, but others go through multiple decays or combinations of transmutations and decays to reach a stable state. For example, calcium-46 is activated to calcium-47 which decays to scandium-47. Scandium-47 then decays to titanium-47 that is stable. Both the scandium and calcium isotopes can be measured using gamma spectroscopy and can be used to calculate the original number of calcium-46 atoms. Calcium-47 is the daughter isotope and scandium-47 is the granddaughter isotope. This is also the case for many metastable isotopes. Following equations show how granddaughter isotopes can be used to calculate the number of parent atoms (Leslie, 2008):

$$\frac{d\, n_G(t)}{dt} = \phi\sigma_P n_P - \lambda_D n_D(t) - \lambda_G n_G(t) \qquad 2-15$$

$$n_D: number\ of\ daughter\ atoms\ (atoms)$$

$$\lambda_G: granddaughter\ decay\ constant\ \left(\frac{1}{sec}\right)$$

$$n_G: number\ of\ granddaughter\ atoms\ (atoms)$$

$$A_G(t) =$$

$$\frac{n_P(0)\sigma_P\phi}{(\lambda_D-\lambda_G)}\left[\lambda_D\left(1-e^{-\lambda_G\, t_{irr}}\right)e^{-\lambda_G\, t_{decay}}-\lambda_G\left(1-e^{-\lambda_D\, t_{irr}}\right)e^{-\lambda_D\, t_{decay}}\right] \quad 2-16$$

$$A_G: activity\ of\ granddaughter\ isotope\ (Bq)$$

$$n_P = \frac{A_G(t_{decay})}{\frac{\sigma_P\phi}{(\lambda_D-\lambda_G)}\left[\lambda_D\left(1-e^{-\lambda_G\, t_{irr}}\right)e^{-\lambda_G\, t_{decay}}-\lambda_G\left(1-e^{-\lambda_D\, t_{irr}}\right)e^{-\lambda_D\, t_{decay}}\right]} \quad 2-17$$

$$C = \frac{A'_G(t_{decay})}{\frac{\sigma_P\phi}{(\lambda_D-\lambda_G)}\frac{N_A}{A_m}A_{\%}\left[\lambda_D\left(1-e^{-\lambda_G\, t_{irr}}\right)e^{-\lambda_G\, t_{decay}}-\lambda_G\left(1-e^{-\lambda_D\, t_{irr}}\right)e^{-\lambda_D\, t_{decay}}\right]} \quad 2-18$$

$$A'_G: specific\ granddaughter\ isotope\ activty\ \left(\frac{Bq}{g\ or\ mL}\right)$$

In the case of nonmonoenergic neutrons, the mass of the parent element can still be calculated without knowing the neutron energy spectrum. This can be achieved by irradiating the sample together with the unknown sample material, and using the assayed standards containing known concentrations of the same element assuming they are all exposed to same neutron beam. The mass/concentration of the standard can be multiplied by the ratio of the activity of the unknown sample over the activity of the standard. The result is the mass/ concentration of the unknown sample. By using a certified standard the need to integrate over all neutron energies, as well as the neutron cross sections, can be avoided altogether (Overview of Neutron Activation Analysis) as follows:

$$\frac{m_{Standard}}{m_{Sample}} = \frac{A_{sample}}{A_{standard}} \quad 2-19$$

$$C_{sample} = C_{Standard} \frac{m_{Standard}}{m_{Sample}} \frac{A_{sample}}{A_{standard}} \qquad 2-20$$

2.3. NAA Using Research Reactors

A neutron source is required for the NAA experiments. Some sources for neutrons include deuterium-tritium neutron generators or man-made heavy isotopes like californium-252. Most facilities that do a lot of NAA use small test and/or research reactors. Samples that are inserted into a reactor core irradiation facility are bombarded with neutrons at the neutron flux usually ranging from 10^7 to 10^{15} neutrons/ cm^2 – sec (Oak Ridge National Laboratory).

UNEP houses a General Atomics ® TRIGA Mark I Reactor (UUTR). This is one of about 35 TRIGA reactors presently operating worldwide and one of 13 found in the USA (TRIGA Reactors). Each TRIGA reactor is licensed to operate at certain power ranging from 100 kW to 16 MW (General Atomics Electronic Systems). The UUTR is licensed to operate at the maximum power of 100 kW.

General Atomics designed and manufactured the TRIGA reactor with the idea to "*design a reactor so safe … that if it was started from its shut-down condition and all its control rods instantaneously removed, it would settle down to a steady level of operation without melting any of its fuel*" (General Atomics Electronic Systems). The TRIGA is the most popular research reactor in the world and have been used for countless radiation experiments and applications. General Atomics recently completed the newest TRIGA reactor in Morocco and is currently constructing another one in Thailand (TRIGA Reactors).

Research and test reactors have multiple applications in both academic and commercial fields. Many universities operate such reactors, but non-academic entities utilize them as well like DOW Chemical, the United States Geological Survey and several national labs (TRIGA Reactors).

The IAEA published a report from an Advisory Group meeting held in 1998 (IAEA, 2001). The following subjects were central themes of this meeting:

1. Current trends in NAA;
2. The role of NAA compared to other methods of chemical analysis;
3. How to increase the number of NAA users through interaction with industries, research institutes, universities and medical institutions;
4. How to reduce cost and to maintain quality and reliability;
5. NAA using low power reactors.

One of the main conclusions from this meeting was a suggestion in making the NAA process quicker and more efficient so as to better compete with chemical analytical methods.

Research reactors can be outfitted with various irradiation facilities and chambers both inside and outside the reactor core depending on the demands of the experiments and tests. Moreover, the power of the reactor, and in turn the neutron/ gamma fluxes, can be adjusted. Relatively easily facilities are often designed and placed according to the neutron energy(s) that are best for the type of irradiation, i.e., fast vs. thermal irradiations.

Other neutron generating sources such as naturally occurring radioactive sources for example, lack the flexibility and adaptability found in research reactors as well as the range of neutron fluxes and energy spectra. Many research reactors around the world are

used for NAA experiments. **Figure 2-3** compares several research reactors that have one or more irradiation facilities dedicated to NAA.

2.4. Errors Associated with NAA

The NAA is accompanied with measurement errors that are somewhat unique when compared to other analytical techniques:

Material homogeneity is probably the greatest bane of any elemental analysis method. Most procedures involving large samples require numerous sampling in an attempt to obtain a "representative sample" of the entire specimen or material (either the individual results are averaged, or the individual aliquots are combined into a composite sample, and the results are assumed to be representative of the entire material).

This is widely acceptable when examining large samples that cannot be tested as a whole. Furthermore, it is also recognized that the results may encompass large errors compared to the true values of the whole sample.

Large sample neutron activation analysis (LS-NAA) such as large rocks, entire pottery artifacts and industrial components require special facilities for neutron irradiation and gamma spectroscopic counting (Baas, 2004).

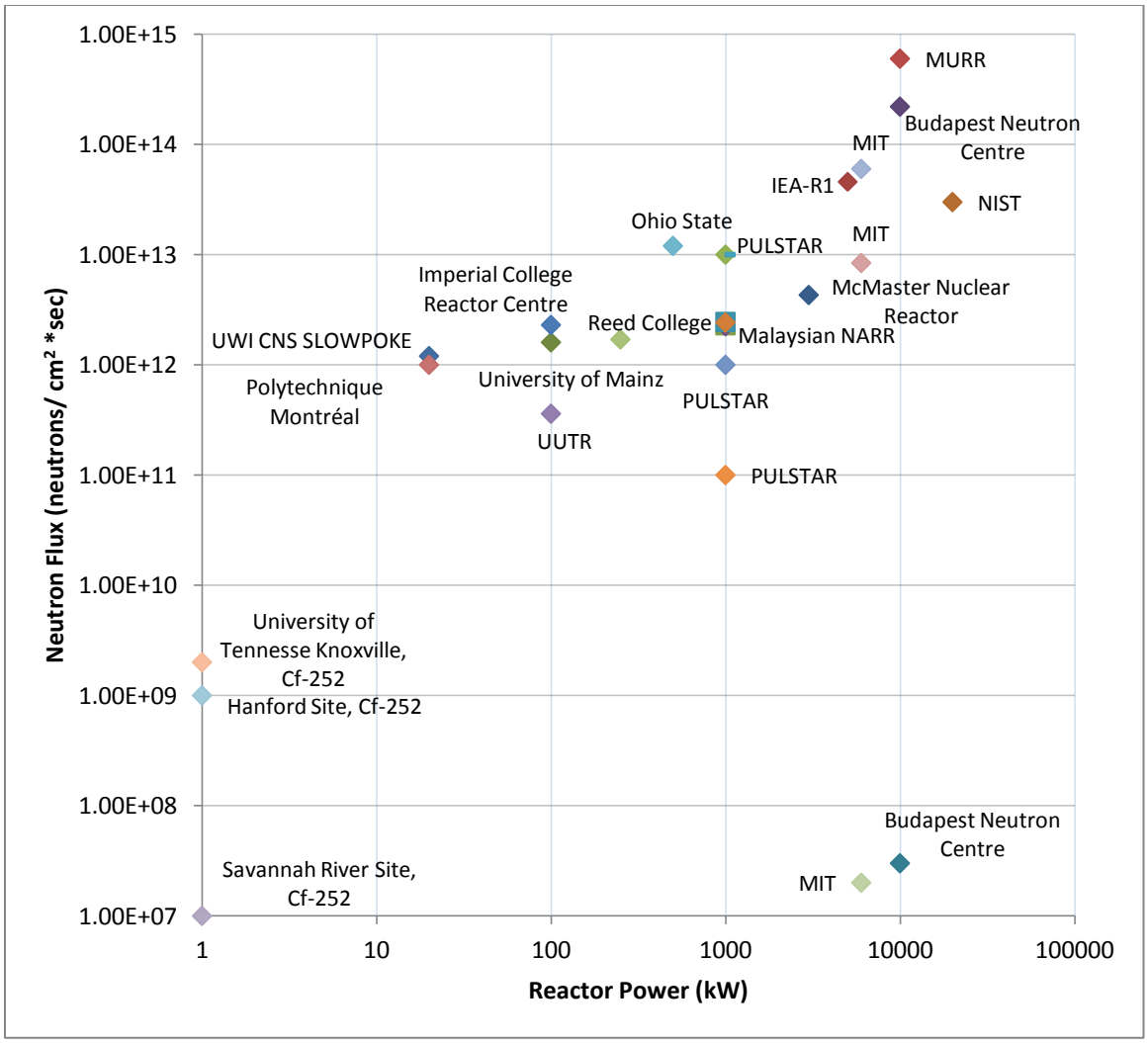


Figure 2-3 Summary on neutron sources for NAA based on research reactors and Cf-252

The whole sample is required to be irradiated in a custom designed facility and then counted and analyzed (Baas, 2004). In these cases, the homogeneity of the sample is not a significant concern, neither are the obstacles of large sample sizes. Therefore, the same size presents a source of error associated with NAA. Many irradiation facilities are quite small and cannot accommodate for large volumes or oddly shaped specimens. This means that in order to obtain adequate sized aliquot the sample must be cut down to smaller size. This may be undesirable if the sample has great historical, monetary or intrinsic value. This leads back to the errors associated with the sample homogeneity.

Many of the naturally occurring elements have multiple stable isotopes, but tend to have only a few that are activated and detectable isotopes. It would be easier if all the naturally occurring isotopes could be activated and accounted for. For example, iron has four stable isotopes (Fe-54, Fe-56, Fe-67 and Fe-58). Yet only Fe-58, the least abundant of the four, activates to a strong gamma emitting isotope, Fe-59. This means that the identification and quantification for the entire iron element is dependent upon the Fe-58 concentration which may or may not be accurate. For example, the mass concentration of iron could be derived from calculating the approximate number of Fe-58 atoms present in the sample. Fe-58 has a reported natural abundance of 0.282% of all the iron isotopes (Decay data search). But if the Fe-58 in the sample does not have that abundance then the calculated iron concentration produces an error. Isotopic ratios may be of a particular issue for samples that are altered such as enriched uranium or extraterrestrial samples that may not have the same isotopic ratios as those found on earth.

Most gamma emitting isotopes generate gamma photons with signature energies, but some isotopes share same gamma energies with others. This creates several

interferences for the gamma spectroscopy analysis. These interferences can be accounted for and partially eliminated. For example, both Cr-51 and Ti-51, share a dominate energy peak at 320 keV. The half life of Ti-51 is a few minutes while it is almost four weeks for Cr-51. A spectrum having a 320 keV peak can be counted two times; the second count being several hours or days later. If the 320 keV still shows up at about the same intensity, then it can be deduced that the activated isotope is Cr-51 and not Ti-51. In other cases additional energy lines can be used to identify and quantify the isotopes that share energies. Gd-153 and Sm-153 both share energy peaks at 103.2 keV and are often found together in the same samples. The detector and the analytical software cannot distinguish the origin of these photons, so the 103.2 keV peak will have the combined counts coming from both isotopes.

Counting the sample again a few hours later will not resolve this issue since both nuclides have half lives greater than one day. In this case, the 103.2 keV peak must be ignored all together. Gd-153 must then be identified and quantified from another energy peak, 97.4 keV. Meanwhile, the Sm-153 isotope should have to be deemed present, by the person reviewing the data, but unquantifiable due to interferences.

To be able to *confidently identify and quantify a decaying isotope*, the detector must be able *to see* and *distinguish* a certain number of counts at given energy lines. In other words, the nuclide must have a minimal detectable activity (MDA) to be positively recognized. The activity of a nuclide is dependent upon, and proportional to, the number of activated nuclides. Even if the MDA is met and the isotope is identified, a very low activity will result in relatively large errors. This must be taken into account when activating isotope sample to be able to confidently identify and quantify its elemental

composition. The sample must either be irradiated for a longer period to create a higher activity or counted for a longer period of time at detector. The longer the counting time, the lower the MDA's the errors tend to be.

The quality of many elemental analysis techniques is subject to the matrix interferences of the samples being analyzed. Such interferences can greatly affect the detection and quantification of the components of interest. The quality of NAA experiments typically is not affected by sample composition; therefore, there exists few matrix interferences. However, there are situations when sample matrix interferences are inevitable. These conditions exist when a very large concentration of an isotope, or multiple isotopes, with extremely large absorptions cross sections are present in the sample. In such cases the isotope(s) with large cross sections have high probability of capturing neutrons that would otherwise be captured by other nuclei. For example, nuclei with such large neutron absorption cross sections are cadmium, boron and gadolinium. These interferences can only be eliminated by chemically separating the different elements. This is known as radiochemical neutron activation analysis (RNAA). Thus, such samples should be counted multiple times to eliminate interferences with isotopes with relatively large actively and relative short half lives.

When a spectrum of examined sample is dominated by a few high activity isotopes, the energy peaks from the isotopes with lower activities tend to get buried in Compton continuum as seen in **Figure 2-4**.

Section 2.5 addresses issues of how to avoid large detector dead times and Compton interferences and in turn increase the quality of the gamma spectroscopy acquisition and analysis.

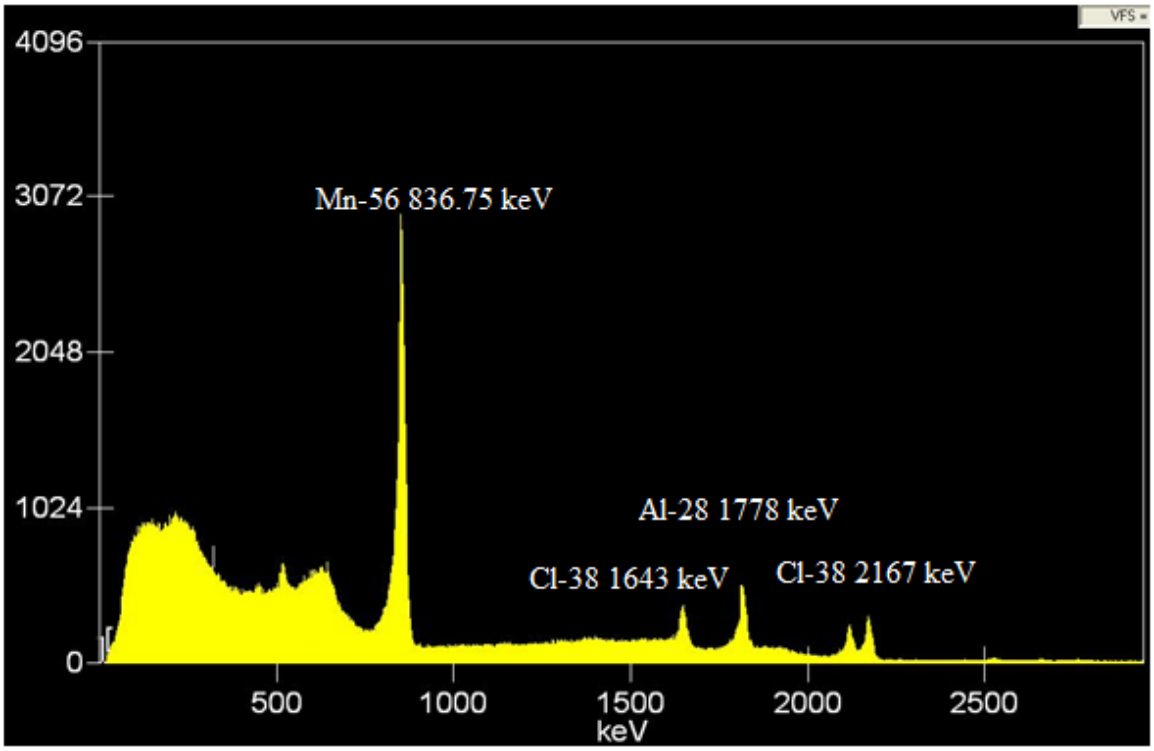


Figure 2-4 NAA spectrum with poor resolution due to high dead time caused by the high activity of Mn-56

Most gamma emitting isotopes generate gamma photons at unique energies that have been observed and recorded in various database libraries such as the NuDat database managed by the Brookhaven National Laboratory (NuDat 2.6). The energy peaks found in a sample's spectrum are then associated with known peaks of isotopes in the libraries to identify the presence of the isotopes.

2.5. Gamma Spectroscopy

Gamma spectroscopy is the method that is used to count and thus identify the high energy gamma radiation emitted from an activated sample. Modern semiconductor

detectors have the ability to *see* a wide range of gamma energies and also be able to distinguish narrow and different gamma energies. A high purity germanium crystal (HPGe), shown in **Figure 2-5**, is based on the semiconductor that absorbs the gamma photons emitted from the sample.

An HPGe has a voltage applied across the crystal; when a photon is attenuated or absorbed into the crystal, the photon liberates electrons through one of the following interactions: the photoelectric effect, Compton effect or pair production. **Figure 2-6** shows dominating photon interactions as a function of atomic number.

Figure 2-7 shows gamma spectroscopy equipment used for counting and analysis. After interactions the liberated electrons flow across the voltage and create a current.

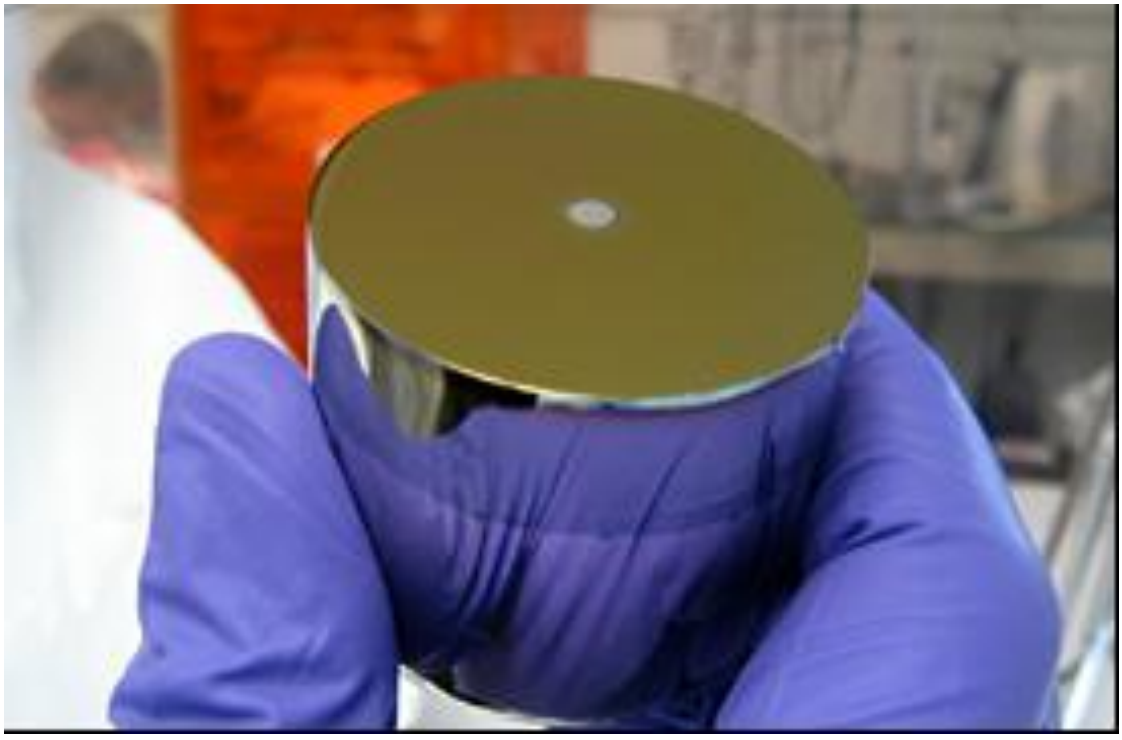


Figure 2-5 Example of a HPGe crystal (http://www.thephotonist.net/)

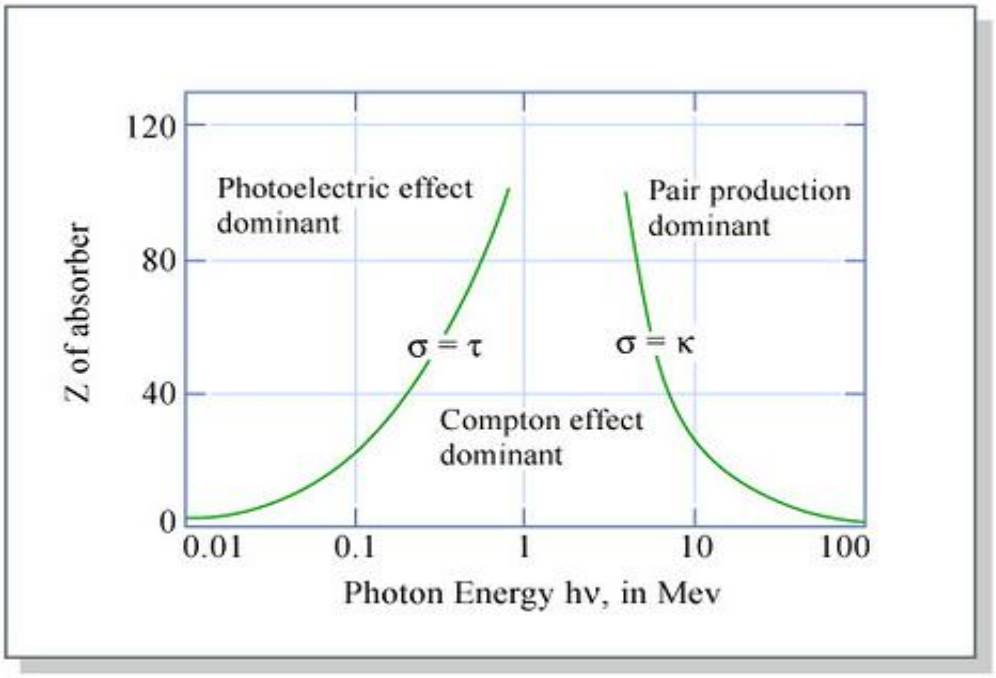


Figure 2-6 Photon interactions with matter probability as a function of material Z number (http://www.ilo.org/)

Figure 2-7 Nonshielded and shielded HPGe detectors at UNEP

The current is then amplified and sent to a multichannel analyzer, which counts and records the signal pulses. Each photon count is 'placed' into a bin or channel according to its energy. The collection of all of the counts in all of the channels forms a spectrum of energies as shown in **Figure 2-8**.

The counting, as well as all the data collected for the spectrum, is controlled, acquired and maintained on the MCA. This means that the MCA operates independently of the software; thus, it does not require the software to be turned on or active to function. Modern MCA's contain a high voltage power supply (HVPS), amplifier and analog-to-digital-converter (ADC) all in one apparatus like for example the Canberra DSA-1000, DSA-2000 and LYNX MCA's. Prior to the compact MCA unit, a rack containing HVPC, AMP, ADC and AIM components in a nuclear instrumentation module bin (NIM). **Figure 2-9** shows Canberra NIM based MCA and a new LYNX.

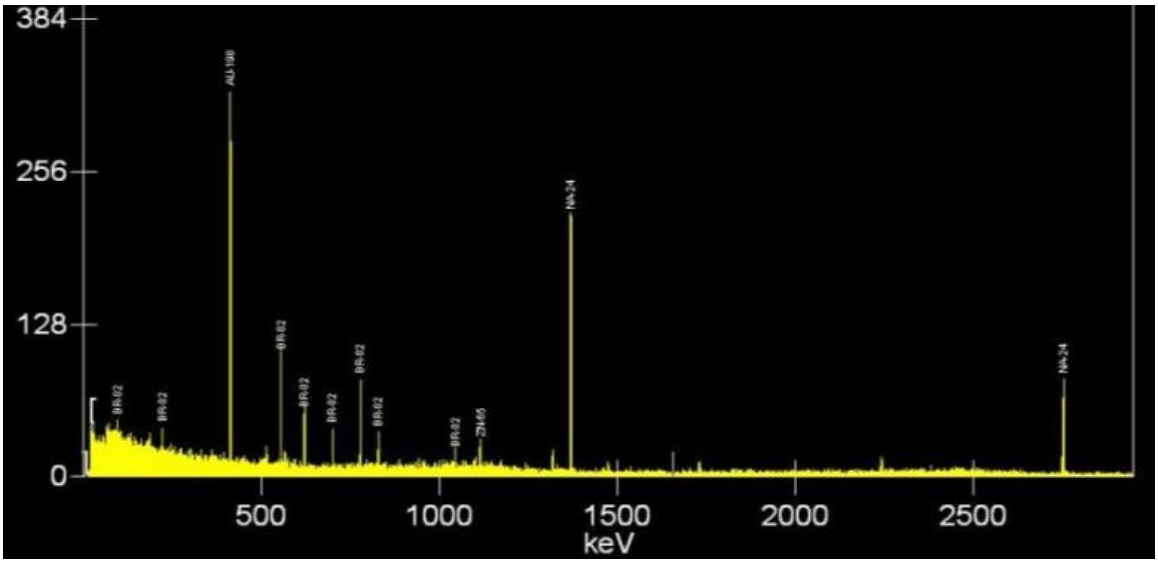


Figure 2-8 NAA spectrum of an irradiated hair sample showing Na-24, Zn-65, Br-82 and Au-198 energy lines

Figure 2-9 Canberra NIM based MCA and Lynx MCA as found at UNEP in 2012

HPGe detectors are very sensitive and moderately efficient. Ideal counting activities are in the range of micro – nanocuries even though HPGe detectors are sensitive enough to identify and quantify in the sub-pCi range (given that the MDA can be achieved). Isotopes with activities greater than one μCi per sample that are placed directly on the face on the detector tend to saturate an HPGe and cause very large dead times. If the detector is saturated then this causes a delay in the electronic refreshing or urn over time. This delay is known as “dead time”.

The dead time is expressed as the percentage of the time that the detector is not actively counting due to saturation from high quantities of incoming gammas. If the live counting time is preselected to be for example 100 seconds and the dead time is 10%, then the actual real counting time takes 110 seconds. Choosing a different counting geometry could greatly reduce the dead time and thus improve the resolution of the counting.

HPGe detectors are favored over other detectors for having superior energy resolution. This means that the energy peaks are very distinct and have very narrow Gaussian full width half maximum (FWHM).

The HPGe has a far better resolution, which makes it much easier to locate and identify the energy peaks on the spectrum compared to the one coming from NaI detector.

In order to maintain as high energy resolution as possible, and keep the counting time relatively short, the dead time must be kept low. To do this, the source is to be placed at different counting geometries. This may be as simple as increasing the distance between the source and the detector. By doing this the solid angle occupied by the detector decreases, thus, diminishing the intensity of the net number of photons that the detector is exposed to.

Gamma spectroscopy itself can be used not only for NAA but also for detecting naturally occurring radiation. Many of the uranium and thorium daughters emit gamma photons, which are easily observed on a gamma spectrum. For example, **Figure 2-10** shows the naturally occurring gamma emitting isotopes found in a Utah limestone specimen.

Not all activated nuclides emit gamma photons during decay. There are some isotopes that are strictly beta emitters, but these are far fewer in number than those that emit gammas as part of their decay or transmutation. These isotopes can be detected and counted using liquid scintillation counting (LSC) and beta spectroscopy, but these techniques are rarely used within the NAA.

Therefore, the NAA and gamma spectroscopy represent powerful techniques used to analyze materials and elemental composition.

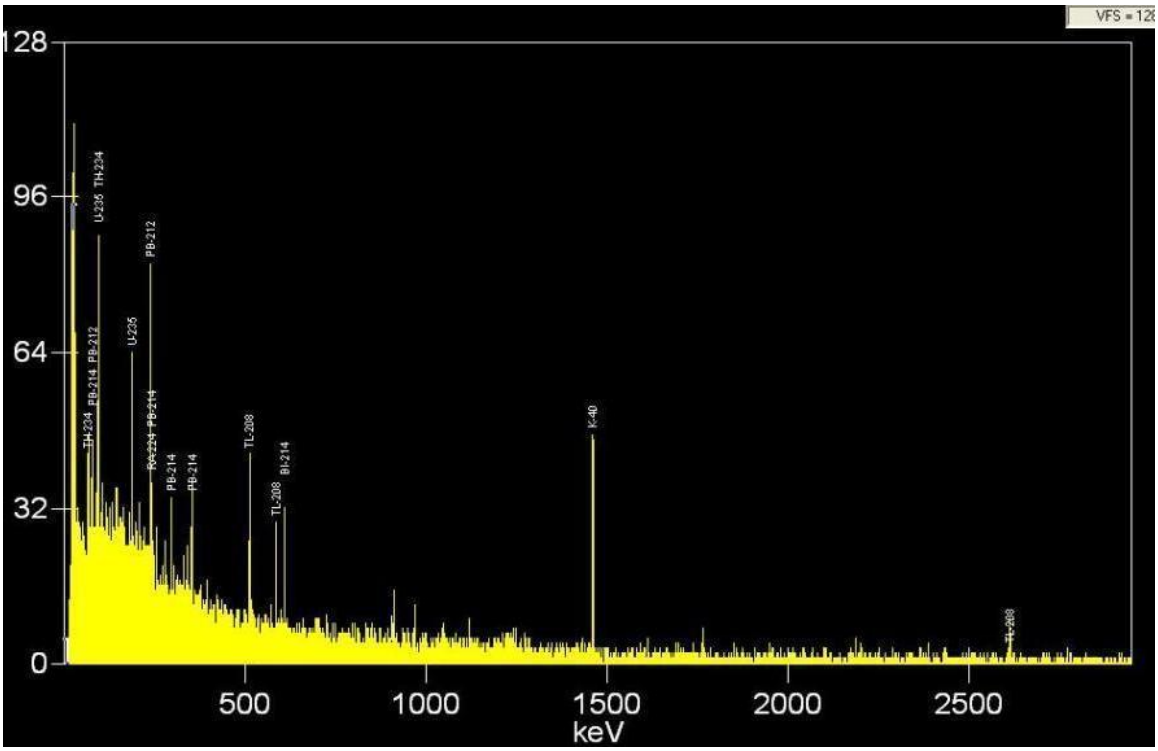


Figure 2-10 Passive gamma spectrum of Utah Limestone showing K-40, Pb-214, Bi-214, Th-234 and U-235

CHAPTER 3

UNEP NAA FACILITIES

3.1 UUTR - TI

The University of Utah TRIGA Reactor (UUTR), as shown in **Figure 3-1,** is the primary neutron source for nuclear experiments at the University of Utah Nuclear Engineering Program (UNEP). The UUTR is a General Atomics ® Mark I TRIGA reactor. TRIGA stands for Training, Research, Isotopes, General Atomics. The UUTR is a pool type reactor that is licensed to operate at maximum power of 100 $kW_{th.}$

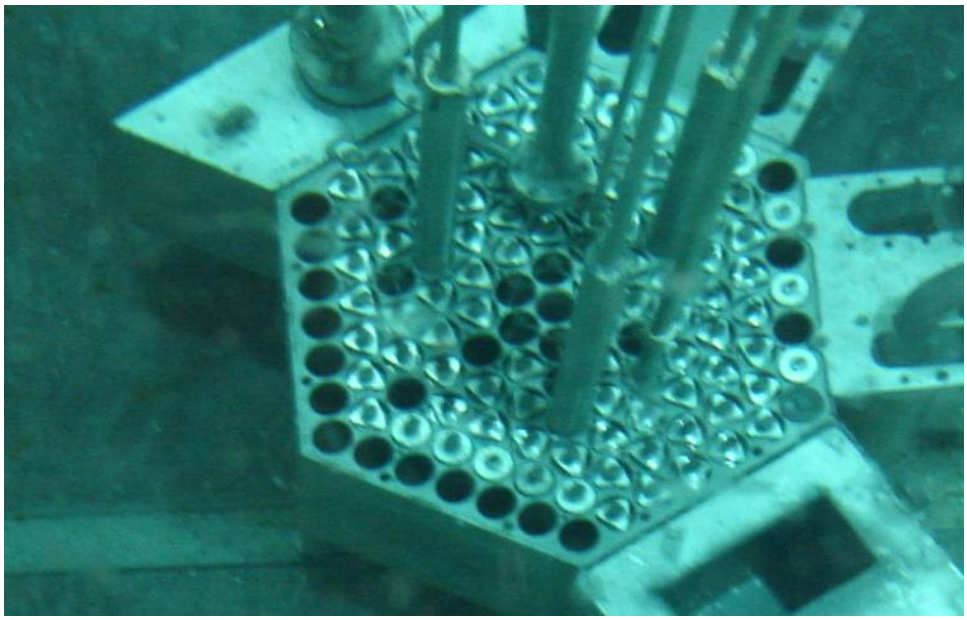


Figure 3-1 Top view of the UUTR Core

The UUTR went critical for the first time in 1975. The reactor has been in operation ever since. As shown in **Figure 3-2**, the UUTR has few irradiation ports; the port used for the NAA is called the thermal irradiation port (TI).

Neutron flux in the TI is primarily in thermal neutron energy range. The kinetic energy of a thermal neutron is about 0.025 eV, which results in a speed of 2200 m/sec

$$KE = \frac{1}{2}mv^2 = kT \qquad 3-1$$

$$KE: kinetic\ Energy\ (joules\ or\ eV)$$

$$m: mass\ (kg)$$

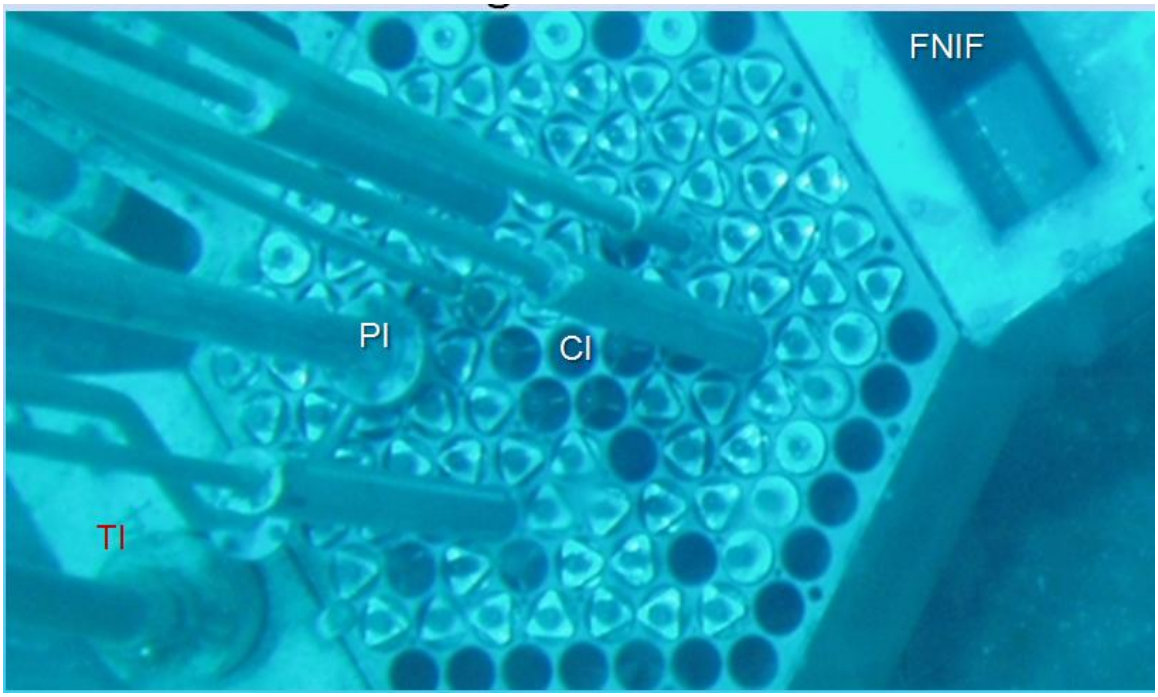


Figure 3-2 - UUTR core, heavy water elements (D_2O_ and irradiation facilities: Thermal Irradiator (TI), Central Irradiator (CI), Fast Neutron Irradiation Facility (FNIF) and Pneumatic Irradiator (PI)

$$v: velocity\ \left(\frac{m}{sec}\right)$$

$$k: Boltzmann's\ constant \quad k = 8.6173\ x\ 10^{-5}\ \frac{eV}{K}$$

$$T: temperature\ (K)$$

$$1\ Joule = 1\frac{kg\ \mathrm{m}^2}{sec^2} = 6.2415\ x\ 10^{18}\ eV$$

$$m_{neutron} = 1.6749\ x\ 10^{-27} kg$$

$$v = \sqrt{\frac{2KE}{m}} \qquad 3-2$$

$$v = \sqrt{\frac{2(0.0252\ eV)}{1.6749\ x\ 10^{-27} kg} * \frac{1\ J}{6.24151\ x\ 10^{18}\ eV}} = 2196\frac{m}{s}$$

$$T = \frac{KE}{k} \qquad 3-3$$

$$T = \frac{0.0252\ eV}{8.6173\ x\ 10^{-5}\ \frac{eV}{K}} - 273K = 19.4°\ C$$

Neutrons born in fission are fast with a average energy of about 2 MeV. As an example **Figure 3-3** shows neutron fission spectrum from U-235. The neutron fission spectrum shows the need to slow or moderate, the neutrons born in fission to the lower, 0.025 eV thermal, energy range. Activation through thermal neutrons can be improved by increasing the ratio of thermal to fast neutrons as well as the ratio of thermal to epithermal neutrons, as known as the cadmium ratio.

With correct selection of materials to the TI provides thermal neutron environment applicable for NAA experiments.

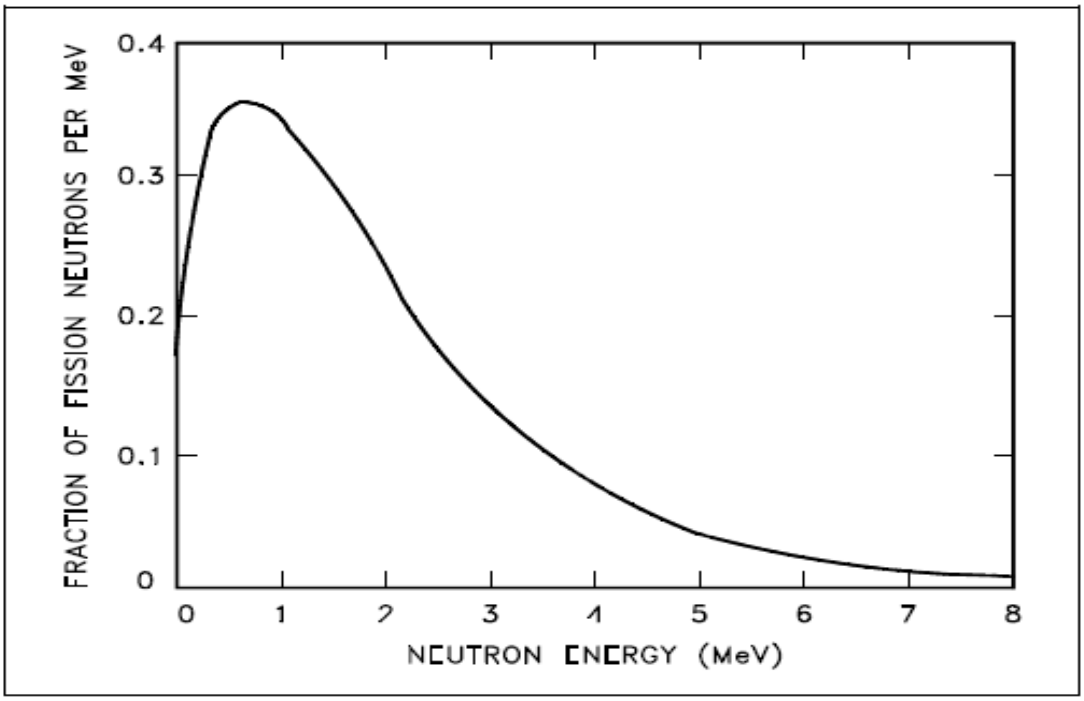


Figure 3-3 Neutron fission energy spectrum from U-235 [http://knowledgepublications.com]

Thermal flux at the UUTR's TI was experimentally measured to be at the order of 3.6 x 10^{11} neutrons /cm^2-sec at 90 kW_{th}. Cadmium ratio experiment and the MNCP5 simulation showed that the TI has a cadmium ratio of about 4.2 (Noble, 2012).

3.2 Gamma Spectroscopy Equipment

NAA is a valuable tool for many different applications, but much of the overall quality of the analysis and protocol depend on the gamma spectroscopy.

As of 2012, at UNEP there are multiple high purity germanium (HPGe) detectors used for NAA and passive gamma spectroscopy. In total there are two Ortec ® and six Canberra ® HPGe detectors.

In addition, there is four Canberra GC-2020 p-types detectors, donated by Energy*Solutions*, which were originally part of an *in situ* object counting system (ISCOCS). These detectors are powered and operated by two nuclear instrumentation module (NIM) bin racks. The GC-4020, as shown in **Figure 3-4,** is the main gamma spectroscopy system in 2012.

The GC-4020 is operated by Canberra DSA-2000 multichannel analyzer (MCA) which is controlled by the Genie 2000 v3.1 software. The DSA-2000 has the capacity to operate an 8K (8192) channel spectrum ranging from nearly 40 keV to about 2950 keV.

Canberra BEGe-3830 broad energy HPGe with a LYNX MCA shown in **Figure 3-5** is used for NAA and passive gamma spectroscopy. The LYNX MCA has the ability to operate a 32K channel spectrum rather than the traditional 8K.

Figure 3-4 UNEP NAA station with GC-4020 HPGe, DSA-2000 MCA and computer system (Counting Station #8, UNEP as of 2012)

Figure 3-5 Canberra BEGe 3830 and LYNX MCA system (Counting Station #4, UNEP as of 2012)

CHAPTER 4

EXPERIMENTAL PROCEDURES AND DATA ACQUISITION

4.1 UUTR Thermal Irradiator Flux Mapping

The neutron flux (ϕ) is important for quality NAA experimentation and analysis. Specific activity of the activated isotope daughter depends on neutron flux and is defined by the equation as follows:

$$A_D'(t_{irr}) = \phi n \sigma \left(1 - e^{-\lambda_D t_{irr}}\right) \qquad 4-1$$

$$A_D' : specific\ activity\ of\ activated\ daughter\ isotope\ \left(\frac{Bq}{g}\right)$$

$$\phi : neutron\ flux\ \left(\frac{neutrons}{cm^2\ *\ sec}\right)$$

$$n : specific\ number\ of\ atoms\ of\ a\ given\ element\ or\ nuclide\ \left(\frac{atoms}{g}\right)$$

$$\sigma : microscopic\ cross\ setion\ \left(\frac{cm^2}{atom}\right)$$

$$t_{irr} : irradiation\ time\ (sec)$$

$$\lambda_D : daughter\ decay\ constant\ \left(\frac{1}{sec}\right)$$

Neutron flux in UUTR TI facility is assessed throughout many experiments. One of the experiments included irradiating high purity nickel wire inside of a polypropylene vial, the same one as used in the NAA experiments.

After irradiation, the wire was cut from the bottom up into six one cm long-segments, weighed, and counted on the GC-4020 detector for five (5) minutes each. Given the measured activity, the initial activity directly after irradiation (A_0) was calculated following:

$$A_0 = \frac{A(t_{decay})}{e^{-\lambda_D t_{decay}}} \qquad 4-2$$

$$t_{decay}: decay\ time\ (sec)$$

The activated isotope used to measure the nickel was Ni-65 and easily identified in all the spectra as illustrated in **Figure 4-1.** In addition to nickel, f cobalt was identified through Co-60m energy peaks.

It was assumed that the epithermal flux would have a negligible contribution to the activity of the Ni-65 since the cross sections in the epithermal neutron energy range, 1 eV to 10 keV, is significantly smaller than that for the thermal energy as indicated in the cross section plot from **Figure 4-2.** There are no spikes in the epithermal range like the Au-197 nuclide has (**Figure 2-4**) that would cause even a small a epithermal flux to contribute to the total activity. It takes a significantly larger epithermal flux to add to the activity of activated Ni-65.

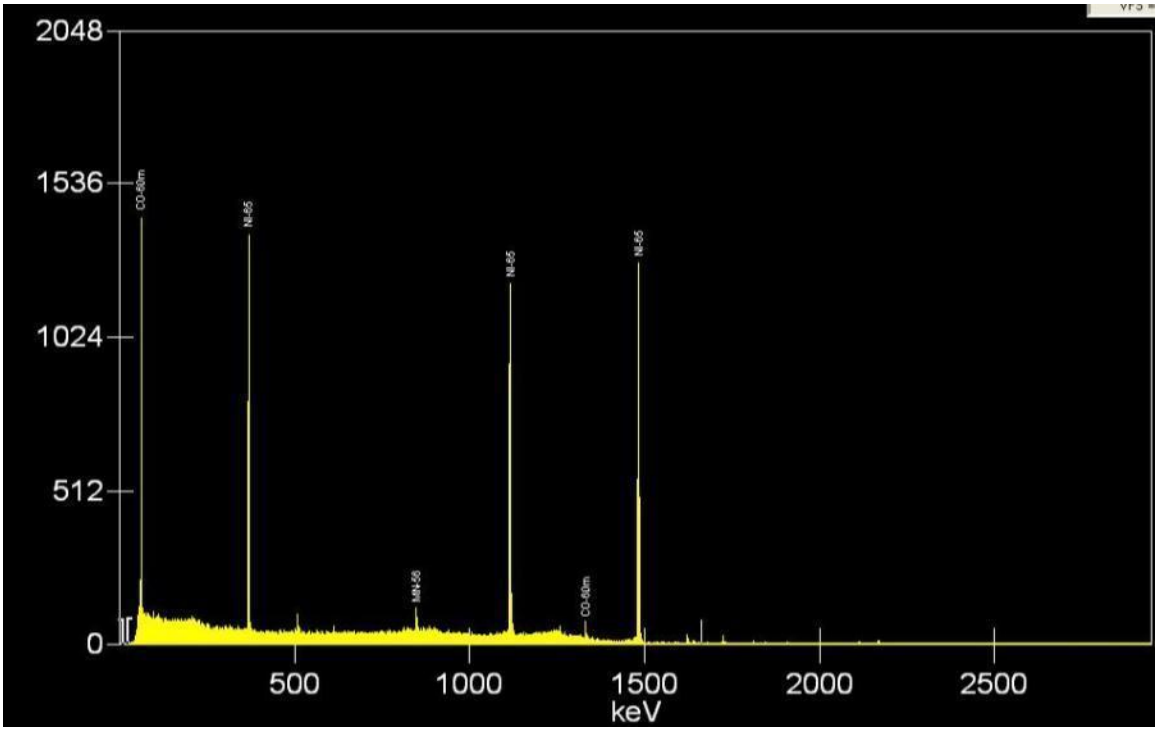


Figure 4-1 Gamma spectrum of irradiated nickel wire showing the presence of Ni-65 and Co-60m

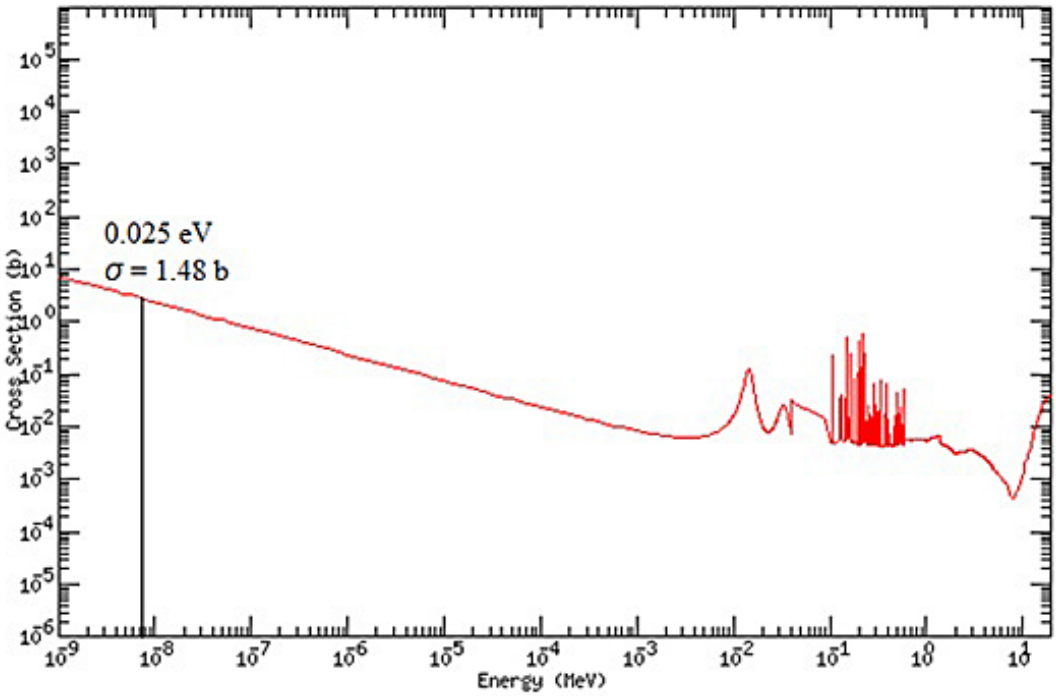


Figure 4-2 Nickel-64 absorption cross section (http://atom.kaeri.re.kr/)

Using the following equation, the thermal neutron flux is calculated for each segment assuming a nickel content of 99.99% and a natural abundance of 0.926% for Ni-64 (at the temperature of 20° C):

$$\phi = \frac{A_D(t_{decay})}{\left[\frac{\sqrt{\pi}}{2}\sigma_P\sqrt{\frac{293}{T}}\right] m \frac{N_A}{A_m} A_{\%}(1 - e^{-\lambda_D t_{irr}})e^{-\lambda_D t_{decay}}} \qquad 4-3$$

$$\phi: neutron\ flux\ \left(\frac{neutrons}{cm^2\ *\ sec}\right)$$

$$\sigma_P: parent\ microscopic\ absorption\ cross\ section\ at\ 293\ K\ (cm^2)$$

$$T: temperature\ (K)$$

$$m: sample\ mass\ (g)$$

$$N_A: Avogadro's\ number\ \left(\frac{atoms}{mole}\right)$$

$$A_m: element\ atomic\ mass\ \left(\frac{g}{mole}\right)$$

$$A_{\%}: element\ atomic\ abundance\ ratio$$

The results from the nickel flux mapping experiment are shown in **Figure 4-3** illustrating the thermal neutron flux profile in the TI.

The expected neutron flux value is 3.6 x 10^{11} neutrons/ cm^2-sec ± 10% in the TI of the UUTR. The thermal neutron flux varies usually from 3.43 to 4.12 x 10^{11} neutrons/ cm^2-sec with an average of 3.76 x 10^{11} neutrons /cm^2-sec which shows the natural variance in imperially collected data.

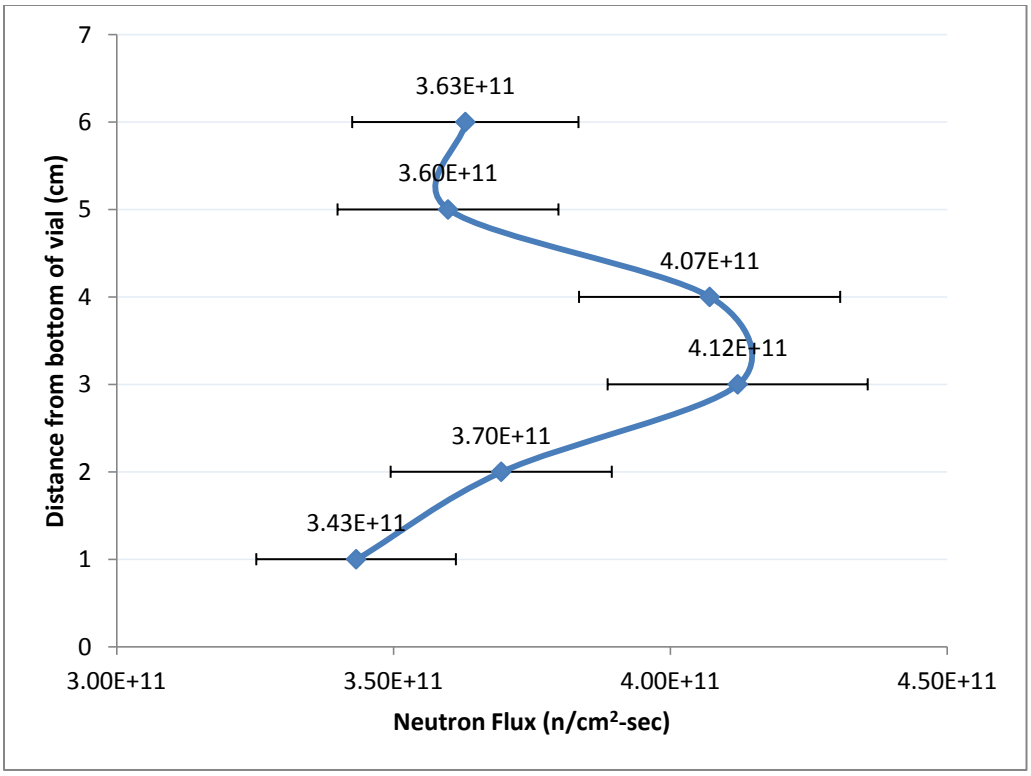


Figure 4-3 Measured thermal neutron flux profile in a polypropylene vial at the TI using nickel wire

4.2 Calibration of Gamma Detectors

Obtaining results from an NAA experiment is not merely dependent upon the conditions of the irradiation, but upon the quality of the gamma spectroscopy counting and identification. To ensure quality and accurate gamma spectroscopy results, the HPGe detectors must be used properly and be correctly calibrated.

There are two types of calibrations that must be performed before any sample count takes place. To complete these calibrations, a certified multi-gamma standard(s) must be used. An energy calibration is performed to set the energy range of the generated spectrum. A multi-gamma standard contains many nuclei and thus many various energy

lines. The standard should be counted for at least 10 minutes. Longer counting times are preferred to reduce the error.

Once a standard has been counted the acquired spectrum can be used to perform an energy calibration. The peak energy data in the certificate file is used to assign the channels in the spectrum to corresponding energies. The energy calibration function in the Canberra Genie 2000 software looks for the energy peaks in the spectrum and correlates them, to the energies found in the certificate file. The peaks found in the spectrum are assigned a "peak centroid" value or in other words a channel where the center of the peak is located. The software can either assign this channel the energy of the corresponding peak automatically or the user can select the channel in which to assign that energy value. For example, a hypothetical certificate file contains the energies 50 keV, 100 keV, 500 keV and 1000 keV; the software finds peak centroids at channels 167, 333, 1665 and 3330 in the spectrum; then the channels may be assigned to those energy values. The software then calculates the approximate energy per channel ratio and assigns each channel a corresponding energy.

Energy calibration steps for Genie 2000 are as follows:

1. Count standard
2. Input the nuclides and energies in a certificate file
3. Select "Calibration" tab →Energy Full → By Certificate File
4. Select the saved certificate file
5. Set the "Expand On" function
6. Place the cursor over the highest point of the peak that is highlighted

7. Click the "Cursor" button (the highlighted energy will be assigned to that channel and the next energy in the list will be highlighted)
8. Repeat steps 6 and 7 unit all the peaks/ channels are set
9. Click "OK" and save

Calibrations are ideally performed using calibration standards that have been recently assayed and are less than two years old. As of summer of 2012, the UNEP HPGe detectors have been calibrated using two multi-gamma button standards from 1997 and 2004.

The older of the standards is from Isotope Products Laboratories ® and was assayed on August 1, 1997. The only remaining isotopes that are detectable from this standard are Cs-137 and Co-60. The newer standard is from Canberra and was assayed on January 20, 2005. This standard still has significant activities from the isotopes: Eu-155, Cs-137, Mn-54 and Zn-65, which are used for calibrations.

The energy calibrations were also performed using an activated NAA sample containing Na-24. The highest energy line for either of the certificates was 1332.5 keV. By adding the Na-24 two additional energy lines, 1368.6 keV and 2574.2 keV, were added to improve the accuracy in the higher energy range. **Figures 4-4** and **4-5** show the energy calibration curves for the GC-4020 and BEGe-3830, respectively. Energy calibrations are not required for all of the different counting geometries. A single energy calibration is sufficient. Typical energy calibrations range from 0 – 3000 keV using 8192 channels, but this range can vary according to the needs of the spectroscopy laboratory experiments.

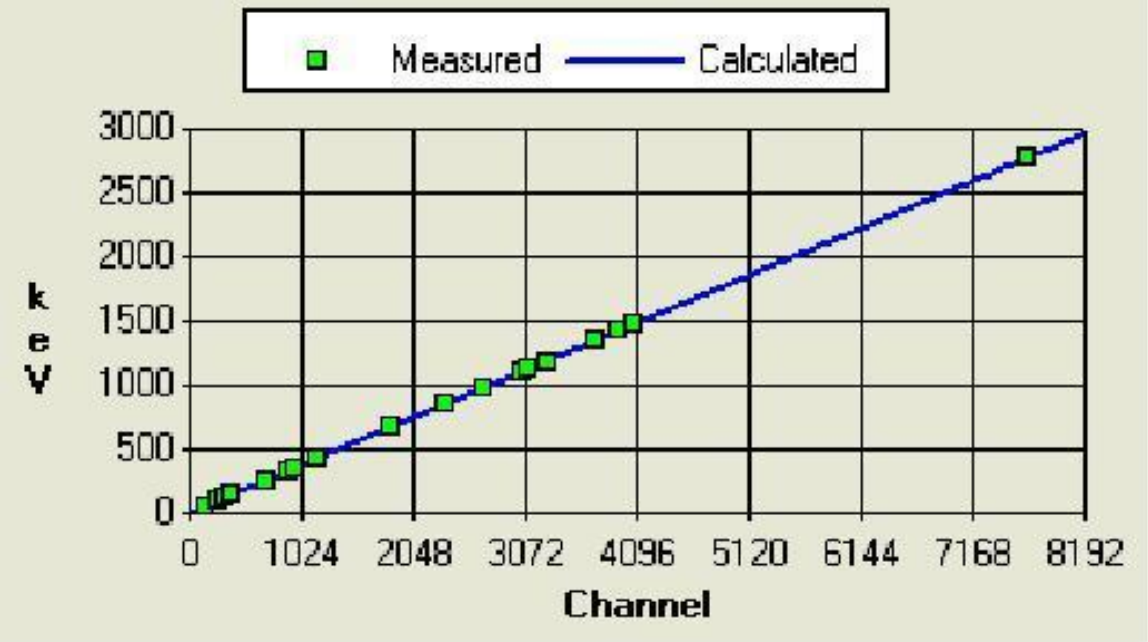


Figure 4-4 GC-4020 energy calibration curve plot

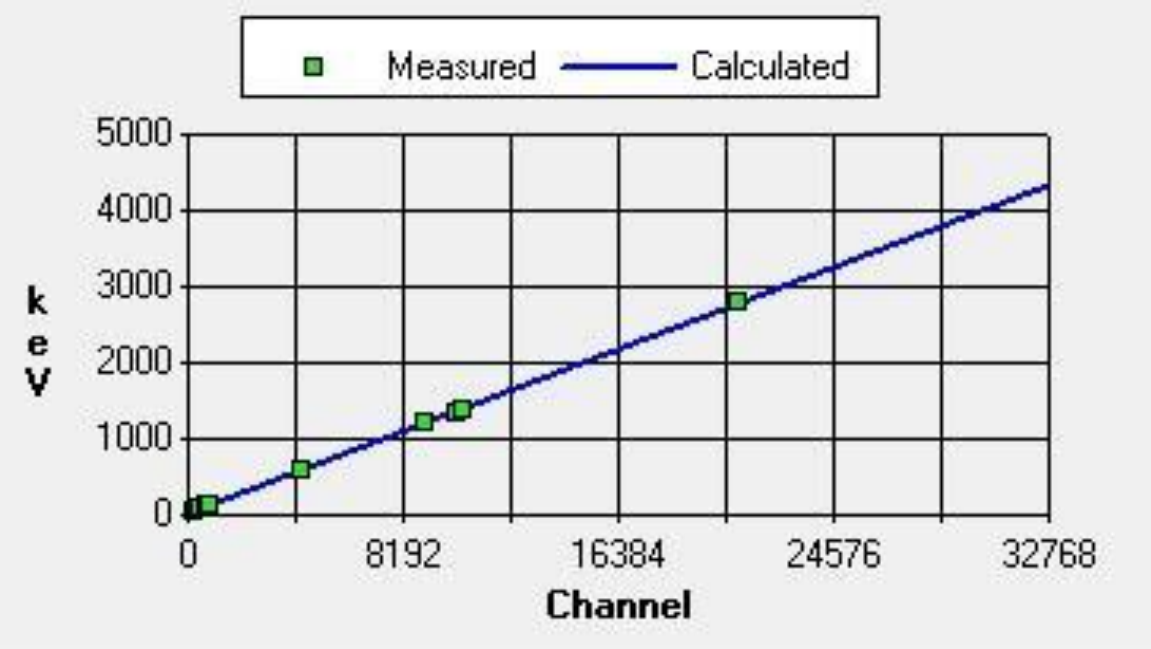


Figure 4-5 BEGe - 3830 Energy Calibration Curve plot

Efficiency calibrations are carried out similarly to the energy calibrations. An energy calibration must be completed before an efficiency calibration. Instead of assigning an energy value to a channel, a gamma emission rate is assigned to an energy peak from the spectrum. A spectrum from a standard presents many peaks at the energies of the corresponding isotopes. All of the counts associated with each individual peak are then summed up together. The real count rate is divided by the certified emission rate for each energy peak giving a calculated efficiency as follows:

$$\varepsilon = \frac{recorded\ counts}{emission\ rate} \qquad 4-4$$

$$\varepsilon: efficiency$$

This efficiency accounts for the detector intrinsic and the solid angle efficiency. The efficiency curve vs. energy is not linear like the energy calibration curve, but a polynomial curve. Using the individual efficiency points calculated from the peaks in the spectrum, the Genie 2000 software uses a curve fit algorithm to plot several curves that best fit the efficiency trends of the points. This is known as the efficiency curve. The user then selects the best fits for the "Dual", "Empirical" and "Linear" curve fitting operations.

Figure 4-6 shows the efficiency curve for the GC-4020 when point or button source is placed on the face of the detector.

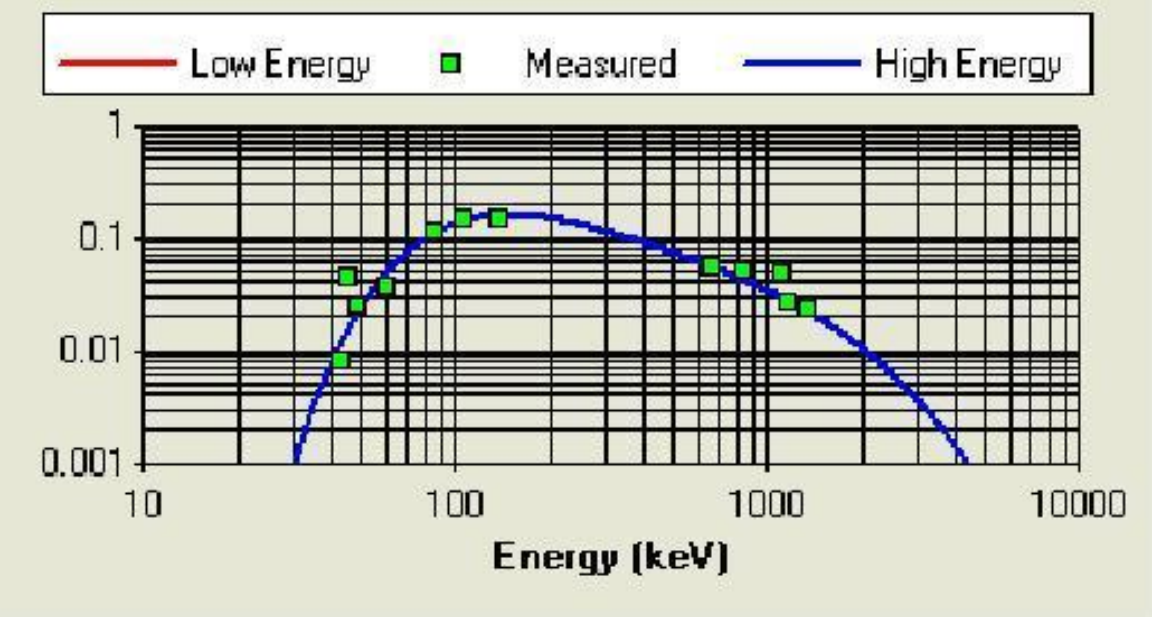


Figure 4-6 GC-4020 NAA geometry efficiency calibration curve plot

Efficiency calibration steps for Genie 2000 are as follows:

1. Count standard for a significant period of time
2. Input the nuclides and activities of each energy in a certificate file
3. Select "Calibrate" tab → Efficiency Full → By Certificate File
4. Select the saved certificate file
5. Click "Auto" (this will calculated the efficiency at each energy)
6. Click "Show Results"
7. Select the "polynomial" that best fits each curve plot
8. Click "OK"
9. Select "Calibrate" tab → Store

10. Name and store the efficiency calibration according to the geometry used

Efficiency curves must be generated for all counting geometries. Calibrated geometry efficiency curves can only be used for counting sources of similar shape and size. The sample shape and size and its distance from the detector are called counting geometry. A detector will have different efficiency for a point source placed at the center of the face of the detector compared to for example a 1 cm diameter sphere source, of the exact same activity, placed at the exact same position. Therefore, a different efficiency calibration is needed for all different geometries and positions that will be used.

Most NAA samples are small enough to be considered as button source, but vials, tubes, bottles, jars and similar, need their own calibrated geometries. For example, a vial filled with liquid would need a separate calibrated geometry as well as that same vial when filled with soil.

Multi-gamma standards can be manufactured of virtually any conceivable geometry, but it would get to be very expensive to create and purchase so many standards for so many geometries especially if the certified standard is only good for a few years. If many different geometries are to be part of regular gamma spectroscopic analyses then a "characterized detector" (such as an ISOCS detector) would be better option compared to purchasing multiple new custom standards each year.

A characterized detector is one that has been tested for many different point source geometries to establish an individual detector characterization file that would theoretically allow the detector to generate an efficiency curve for any geometry. Using a "characterization file", geometries of virtually any shape and size can be created. Canberra created an i*n situ* object count system (ISOCS) program in which custom

geometries can be created. Using ISOCS and a characterized detector, the need to purchase a large array of sources is then eliminated. Only simple check sources are to be used for quality assurance.

ISOCS is also used to generate efficiency curves in passive gamma spectroscopy to count large objects and structures like barrels, railroad gondolas and even entire reactor vessels.

In order to increase the efficiency and reduce the nuclide identification errors of the NAA gamma spectroscopy at UNEP, the custom nuclides libraries were created. Three different libraries have been used to identify the activated isotopes in an irradiated sample based on the irradiation conditions.

4.3 Sample Testing and Database Development

Much of the motivation for this research was to develop NAA protocols for practical applications. The following NAA protocols lines were developed:

 Soil and geology

 Metals and toxins in drinking water and waste water

 Precious metals and minerals in mining

 Nutritional mineral content and potential toxins in food

 Potential contamination of agricultural products

 Metal alloy identification

 Uranium content in soils

 Criminal Forensics: bullet lead, print chip, chemical residues etc.

 Petroleum: crude oil metal contamination

 Petroleum: noncombustible petro-product contamination

 Building materials: resistance to long term neutron activation

Building materials: neutron shielding

 Meteorite composition

 Metals and toxins in biological specimens

A number of materials and substances have been tested for each of the NAA lines. The NAA capacities (also discussed in Chapter 6) depend upon the ability to activate and confidently identify elements in the samples. Limiting factors such as: sample size, irradiation time, neutron flux, minimal detectable activity (MDA) (from the HPGe detectors) and number of samples that can be tested at the time, all affect the use of NAA at large. In total of 260 samples have been tested and analyzed. All of the data from these samples are complied as the NAA database. Future NAA experiments can be based upon

those that have already been done as part of this research. The database may also serve as an inspiration to obtain better results for these NAA tests or even explore new avenues of NAA that have not been developed under this research.

The database will serve as the foundation for the protocols and procedures for the various NAA lines. All future NAA experiments will be compared to the results found in the database.

4.4 Error Analysis in NAA

Errors are a part of every empirically conducted experiment and must be identified and accounted for in analyzing the data. Sources of errors were discussed in detail in Section 2.4. Most of these errors can be determined before the NAA experiment takes place. The errors coming from the gamma spectroscopy, like those associated with peak identification, its height and area, sample mass etc., are accounted for and calculated automatically in the measured nuclide activities found in the detector's analysis reports. Gamma spectroscopy error sources may originate from: calibration, sample counting, energy and nuclide identification, and sample mass/volume as well as calculated activity.

Errors associated with NAA represent the difference between calculated values and the actual values. The NAA procedure itself will include errors such as those associated with irradiation time, waiting time to reduce the sample activity, sample temperature and neutron flux. For example, the waiting time for the sample to reduce its activity is determined from the time when the sample leaves the TI until the time when the gamma spectroscopy acquisition is started. The time when the sample leaves the TI is measured by the clock at the UUTR reactor console. The acquisition start time is determined by the clock on the computer. These two clocks are not synchronized even

though their readings have been observed to be within one minute of each other. Therefore, the error introduced by reading these times is recorded to be plus or minus one minute. This discrepancy in time measurement could lead to an error in the original actual activity (A_0), which is required to calculate the sample mass concentration.

Genie 2000 reports will provide unit activities accompanied with their respective unit activity errors. The errors from the various components are propagated into the final mass concentration error (σ_C) as follows:

$$\sigma_x\left(\sigma_a, \sigma_b, \ldots \sigma_j\right) \qquad \frac{\sigma_x(a * b * \ldots e^{\pm kj})}{x} = \sqrt{\left(\frac{\sigma_a}{a}\right)^2 + \left(\frac{\sigma_b}{b}\right)^2 + \cdots \left(k\sigma_j\right)^2} \qquad 4-5$$

$$\sigma_C = C\sqrt{\left(\frac{\sigma_A}{A'}\right)^2 + \left(\frac{\sigma_\phi}{\phi}\right)^2 + \left(\frac{\sigma_T}{T}\right)^2 + \left(\lambda\sigma_{t_{irr}}\right)^2 + \left(\lambda\sigma_{t_{decay}}\right)^2} \qquad 4-6$$

$$\sigma_\phi : flux\ uncertainty\ \left(\frac{neutrons}{cm^2 - sec}\right)$$

$$\sigma_T : Temperture\ uncertainty\ (K)$$

$$\sigma_{t_{irr}} : irradiation\ time\ uncertainty\ (seconds)$$

$$\sigma_{t_{decay}} : decay\ time\ uncertainty\ (seconds)$$

$$\lambda : decay\ constant\ \left(\frac{1}{sec}\right)$$

$$C : mass\ concentration\ \left(\frac{g}{g}\right)$$

$$\sigma_C = C\sqrt{\left(\frac{\sigma_A}{A}\right)^2} \qquad 4-7$$

$$\sigma_C : mass\ concentration\ uncertainty\ \left(\frac{g}{g}\right)$$

$$\sigma_A: activity\ uncertainty\ (Bq)$$

Errors that cannot be entirely accounted for include sample homogeneity and atomic abundance (if different from the known values). As discussed in Section 2.4 sample aliquots can only be *assumed* to represent the entire sample.

Propagation of the various errors is important in reporting the results from any NAA experiment.

CHAPTER 5

NAA PROTOCOL AND NAA TOOLS DEVELOPED FOR THE UUTR

5.1. NAA Activity Estimator

As an integral part of the newly developed NAA protocol for UNEP, several NAA calculation tools have been created in support of the NAA lines. One of the newly developed tools is the *Activity Estimator* that provides the estimations of the activities for the isotopes to be activated during the NAA at the UUTR TI facility. The *Activity Estimator* was created for the following two primary reasons:

1) Assurance of a safe application of NAA protocols (never existed before over the course of 40 years of the use of UUTR). Since during the NAA isotopes are created, there is a need to be able to account for the potential activities and exposures from the generated isotopes as well as to determine the need for a potential long-term storage of the irradiated samples. Being able to predict the activities of each sample irradiated informs the NAA experimenter of potential risks and provides the guidelines to alter the irradiation of the samples if necessary. Different irradiation scenarios can be analyzed using the *Activity Estimator* so that the actual irradiation conditions are properly determined and beforehand, therefore assuring compliance with the overall newly established safety and preparedness culture at UNEP (starting fall of 2009). The

irradiation conditions such as: neutron flux, sample size, irradiation time and waiting time for sample to be counted, can all be adjusted using this tool.

2) Determine the most optimal irradiation conditions per sample. Other than avoiding potential radiological hazards, the *Activity Estimator* is also created to determine optimum irradiation conditions that would allow for as accurate as possible analysis and detection of target elements in the sample. A minimal detectable activity (MDA) must be observed by the high purity germanium (HPGe) gamma spectroscopy detectors in order for the activated isotopes to be identified. For example, if it is determined that arsenic concentrations in water must be below a certain limit to be acceptable, then *Activity Estimator* would be ideal to determine irradiation conditions to verify if arsenic is indeed below such concentrations. Various irradiation scenarios can be tested in the *Activity Estimator* (and later in the actual NAA experiments) to activate arsenic to the necessary MDA to confidently determine whether or not the concentration is above that concentration limit.

The *Activity Estimator, Elemental Concentration Calculator* and the *SRM Ratio calculator* are developed based on the NAA equations provided in Section 2.2.

The *Activity Estimator* was designed to be easy to use and understand. **Figure 5-1** shows a screen shot from one example from the Excel-based *Activity Estimator*: This example lists the activities for isotopes activated from a one gram sample containing Na, Ca, Mg, Ti, K, Fe, Sc, Cr and U; this sample was irradiated for 10 minutes at 3.6×10^{11} thermal neutrons per cm^2-sec and the waiting time for the sample to be counted was 300 seconds.

Sample Detail	*Sample Weight (g)*	*Temperature (°C)*	*Irradiation Time t_i (sec)*	*Decay Time t_d (sec)*	*Φ (neutrons/cm^2-s)*
	1	23	600	300	3.60E+11

Select (If Any) Additional Known Elements or modify composition in drop-down menus in the cells below	Estimated Concentration or change in Concentration (ppm or µg/g)	*Isotope*	*Predicted Unit Activity (µ Ci/g)*	*Total γ Activity (µ Ci)*	*The Red Scale shows the relative activity of the activated isotopes. The darker the shade the more the relative activity*
Sodium (Na)	2039			2.69E+01	
Calcium (Ca)	140725	Na-24	1.854E+00	1.85E+00	
Manganese (Mn)	200	K-40	3.742E-06	3.74E-06	
Titanium (Ti)	75	K-42	5.371E-01	5.37E-01	
Potassium (K)	4467	Sc-46	4.174E-04	4.17E-04	
Iron (Fe)	10490	Sc-46m	1.109E-04	1.11E-04	
Scandium (Sc)	2.3	Ca-47 -	5.692E-04	5.69E-04	
Chromium (Cr)	20	Ca-49	1.366E+01	1.37E+01	
Uranium (U)	4	Cr-51	2.370E-04	2.37E-04	
		Ti-51	2.878E-02	2.88E-02	
		Mn-56	1.072E+01	1.07E+01	
		Fe-59	3.789E-04	3.79E-04	
		Np-239*	1.210E-04	1.21E-04	
		U-239 -	5.169E-02	5.17E-02	

Figure 5-1 EXCEL based *Activity Estimator* showing relative activities using the red bars for easy "high activity" isotope identification. Yellow highlighted cells indicate information to be inputted by the user.

A "bar graph" in **Figure 5-1** provides to a user a visual representation of the relative activities of the activated isotopes. This can immediately help to identify nuclides with high activities that may present safety and/or counting problems due to dominating the spectrum and drowning out isotopes with smaller activities that need to be identified. The *Activity Estimator* uses the same "one-group" energy NAA equations as presented in Chapter 2 to estimate the activities.

The *Activity Estimator* contains data libraries for 194 isotopes from 70 elements that could potentially be generated in NAA at UUTR TI facility.

Data such as half lives, radiative capture cross sections (at 0.025 eV), branching ratios, atomic weight and natural isotopic abundances are included in these libraries.

These nuclides related data were extracted from various sources and compiled into the libraries: Korean Atomic Energy Institute (KAERI), NuDat (Decay Search), LBNL (LBNL Isotopes Projec) and Periodictable.com (Periodictable.com).

The *Activity Estimator* also supports formatting the irradiation procedures for each unique sample. By tailoring the procedure to meet the requirements of the sample analysis, rather than the other way around, the results can be improved. Results could be obtained much quicker, with higher degrees of confidence and smaller errors.

5.2. Elemental Concentration Calculator and SRM Ratio Calculator

The *Elemental Concentration Calculator* and *SRM Ratio Calculator* were developed to assist in completing the NAA experiments with faster and more consistent results. Once the activity from a decaying isotope has been measured it can be used to back calculate the original mass or mass concentration of the parent element in the sample and the corresponding errors. This is done using the mass concentration equations explained in Chapters 2 and 4, i.e., Eq (2-15), (4-6), (2-19) and (4-7).

This calculator is supported by the same libraries as those developed under the *Activity Estimator*. The measured activities of all of the identified nuclei are given in the custom arranged Genie 2000 ™ NAA reports. An example is shown in **Figures 5-2** and **5-3 –** a brief display regarding the sample information as well as its measured activities.

```
*************************************************************************
*****        G A M M A   S P E C T R U M   A N A L Y S I S          ****
*************************************************************************

Filename: C:\GENIE2K\CAMFILES\Todd\Water_and_Environmental\English_Waln

Report Generated On             : 10/27/2011  8:41:58 AM

Sample Title                    : English Walnut wood
Sample Description              : 10:05 - 12:01 PM 10/21/2011
Sample Identification           : wood
Sample Type                     : Environmental
Sample Geometry                 : NAA

Peak Locate Threshold           :  3.00
Peak Locate Range (in channels) :     1 - 65535
Peak Area Range (in channels)   :    60 -  8192
Identification Energy Tolerance :    1.150 keV

Sample Size                     :  4.296E-001 g

Sample Taken On                 : 10/27/2011  8:03:34 AM
Acquisition Started             : 10/27/2011  8:03:34 AM

Live Time                       :     1800.0 seconds
Real Time                       :     1801.0 seconds

Dead Time                       :   0.05 %
```

Figure 5-2 Sample information page of Genie 2000 ™ gamma spectroscopy report for irradiated walnut wood sample

```
*************************************************************************
*****   I N T E R F E R E N C E   C O R R E C T E D   R E P O R T   *****
*************************************************************************

                Nuclide       Wt mean         Wt mean
     Nuclide      Id           Activity        Activity
     Name      Confidence     (uCi/g   )      Uncertainty

     NA-24       0.986      1.008016E-003   3.435598E-005
     K-40        0.968      3.646183E-004   1.104048E-004
     K-42        0.902      1.678780E-003   1.311489E-004
     SC-46       0.989      4.119810E-005   1.336027E-005
  ?  SC-47       0.995      5.154540E-005   6.476483E-006
     CR-51       0.995      8.088258E-005   2.252434E-005
     BR-82       0.592      4.465859E-005   5.572522E-006
     RB-86       1.000      3.445918E-004   2.392568E-004
  ?  SN-117m     0.918      4.044260E-005   5.005802E-006
     SB-122      0.925      2.867332E-005   5.283760E-006
  ?  TE-123m     0.996      4.157853E-005   5.146611E-006
     LA-140      0.802      5.539106E-005   6.998127E-006
     SM-153      0.838      1.103788E-004   1.976429E-005
  X  IR-194      0.622
     AU-198      0.980      3.938648E-005   6.128377E-006
```

Figure 5-3 Reported nuclide activities of Genie 2000 ™ gamma spectroscopy report for irradiated walnut wood sample

The measured activities are calculated as weighted mean activity derived from all the identified energy lines associated with that isotope and their errors. The equations used in the software algorithms to calculate the weighted mean activities are:

$$A'_{mean} = \frac{\sum \frac{A'_i}{\sigma_i^2}}{\sum \frac{1_i}{\sigma_i^2}} \qquad 5-1$$

$$\sigma_{A\,mean} = \frac{1}{\sum \frac{1_i}{\sigma_i^2}} \qquad 5-2$$

$$A' : Specific\ activity\ \left(\frac{Bq}{g\ or\ mL}\right)$$

$$\sigma : error\ \left(\frac{Bq}{g\ or\ mL}\right)$$

The information from the irradiation conditions and the data reported in gamma spectroscopy report can be inputted into the *Elemental Concentration Calculator* to generate the mass concentrations and their errors. Using the information from the report of irradiated walnut wood as an example indicated in **Figures 5-4** and **5-5**, the elemental mass concentrations are calculated and the results are reported in the *Elemental Concentration Calculator*, as shown in **Figure 5-4**.

The *SRM Ratio Calculator* is used to determine elemental concentrations in the samples. It is based on the elemental concentrations and activities from the sample and

Date and Time of end of irradiation		Date and Time of start of acquisition				
4/1/2011 16:00		4/8/2011 20:45				
Temperature (°C)	*Irradiation Time t_i (sec)*	*Decay Time t_d (sec)*	*ϕ (neutrons/cm^2-s)*	*N_A (atoms/ mole)*	*σ t_{irr} (sec)*	*σ t_{decay} (sec)*
20	3600	621914	3.76E+11	6.02E+23	60	60

Isotope Entry	***Measured Activity (μCi/g)***	**Measured Parent Element**	**Measured Mass Concentration (%)**	**Measured Mass Composition (μg/g)**	***Activity uncertainty (μCi/g)***	**Mass Composition uncertainty (μg/g)**
K-40	1.027E-03	Potassium (K)			1.506E-04	#VALUE!
SC-46	3.998E-04	Scandium (Sc)	0.0000%	**0.371158**	9.205E-05	0.093363
Ca-47 -	1.759E-03	Calcium (Ca)	20.7837%	**207837.5**	1.743E-04	29465.43
Sc-47*	4.238E-03	Calcium (Ca)	40.4918%	**404918.1**	3.942E-04	55714.74
CR-51	3.039E-04	Chromium (Cr)	0.0005%	**4.839806**	5.926E-05	1.063782
FE-59	1.720E-04	Iron (Fe)	0.0846%	**846.0588**	1.775E-05	122.3712
ZN-65	2.231E-05	Zinc (Zn)	0.0005%	**5.13792**	1.399E-05	3.263279
Sr-85	5.177E-04	Strontium (Sr)	0.4160%	**4160.371**	3.985E-05	529.5815
Sb-122	7.031E-05	Antimony (Sb)	0.0000%	**0.272375**	1.359E-05	0.059444
BA-131	4.076E-04	Barium (Ba)	0.0200%	**199.5237**	1.736E-05	21.93901
CE-141	1.075E-04	Cerium (Ce)	0.0007%	**7.229942**	1.641E-05	1.324463
EU-152	7.914E-05	Europium (Eu)	0.0000%	**0.087374**	6.576E-06	0.011453
SM-153	3.406E-04	Samarium (Sm)	0.0000%	**0.1793**	2.399E-05	0.022134
Eu-155*	1.119E-05	Samarium (Sm)	0.0010%	**9.932129**	6.872E-06	6.180168
Lu-177, *	1.114E-04	Lutetium (Lu)	0.0001%	**0.722696**	4.673E-05	0.311809
Pa-233*	3.119E-04	Thorium (Th)	0.0002%	**2.034298**	1.192E-05	0.220394
Np-239*	1.263E-04	Uranium (U)	0.0001%	**1.391486**	1.537E-05	0.220445

Figure 5-4 EXCEL-based *Elemental Concentration Calculator* - results from irradiated walnut wood sample

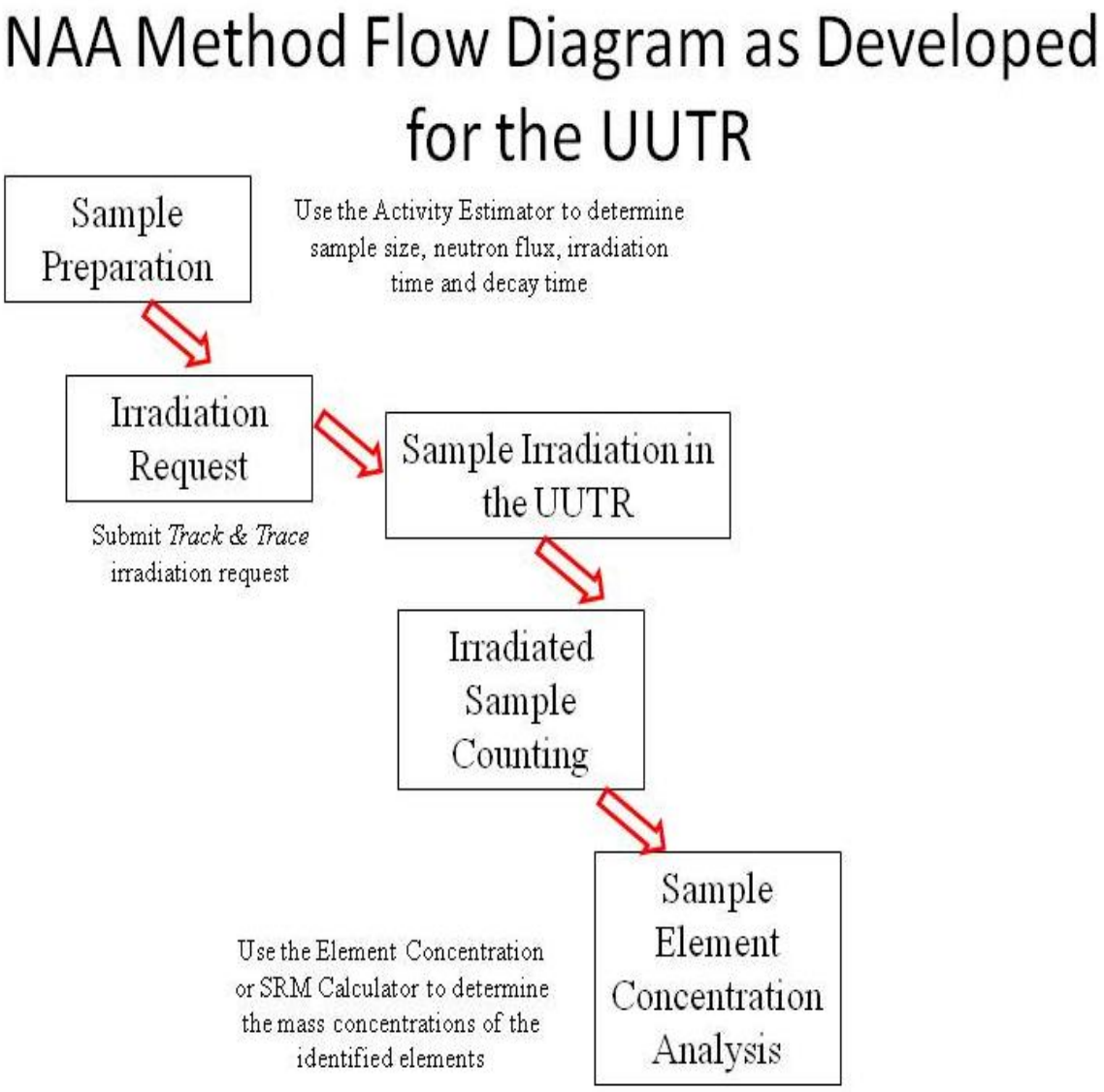


Figure 5-5 Flow diagram for NAA procedures applicable to UNEP

the standard reference material(s) (SRM), that are irradiated in tandem, to accurately calculate the unknown elemental concentrations.

This is described in Section 6.2. An SRM has certified elemental concentrations for each of the target analytes or elements of interest. This calculator can be more accurate than the *Elemental Concentration Calculator* because the activities are completely independent from neutron flux.

Complete instructions on using these calculators are found in the NAA Manual in **Appendix C**.

By merging the *Elemental Concentration Calculator* with the reported isotope activities the NAA process can be completed.

Therefore, an effort to streamline the NAA process is greatly advanced by using these tools: *Activity Estimator*, *Elemental Concentration Calculator*s and *SRM Ratio Calculator*.

The flow diagram of developed NAA procedures applicable to the UUTR is shown in **Figure 5-5**.

CHAPTER 6

DEVELOPED NAA PROTOCOLS

6.1. The NAA Specific Protocols

The scope of this research was to investigate and narrow down a few possible NAA areas for which UNEP could develop protocols, and then to establish and put into practice the standard operating procedures (SOP). An extensive literature survey provided valuable information on the NAA methods existing in USA (EPA/625/R-96/010a, 1999) and elsewhere (Hassan, 2008) and (Alnour, Ibrahim, & Fen, 2011). Based on such information and technical specifications of the UUTR TI facility, a list of NAA lines is suggested as described in previous chapter and in more details in this chapter.

It is well known that by performing, both, long and short irradiations on aliquots of the same sample more detailed and complete sample elemental composition is obtained. The short irradiations and short sample waiting times allow for detecting many of the isotopes with shorter half lives. While the long irradiations and long sample waiting times allow for detecting and identifying the isotopes with longer half lives.

The protocols for short and long irradiation times are developed based on the capacity and capability of the UUTR operational power and corresponding neutron flux as well as the UUTR irradiation port capacity, as follows:

- Short-term irradiations assume that sample is exposed to neutron flux at the UUTR TI for 0.5 – 20 minutes, at the reactor power of 90 kW_{th}. Such samples are then counted twice: firstly at t_{decay} = 1 – 10 min, and secondly at t_{decay} = 1 – 4 hr to find short lived ($t_{1/2}$ = 1 – 30 min) and medium lived ($t_{1/2}$ = 0.5 – 12 hr) isotopes. Often a lower reactor power is chosen (to lower the neutron flux) for high purity metals due to the large neutron capture probability.

- Long-term irradiations assume irradiation of a sample for 30 – 300 minutes; after irradiation the samples are left for at least 24 hours before counting. These samples also need to be counted at least twice to better identify the isotopes with long half lives ($t_{1/2}$ =12 – 48 hr) and those with very long half lives ($t_{1/2}$ > 2 days).

Different analysis sequence files (ASF) are used to analyze a spectrum and print a report (Canberra, 2004). These different ASF files contain different libraries of nuclides according to their half lives. An AFS files queues the Genie 2000 ™ algorithms to:

- Locate the peaks
- Sum the peak area counts
- Subtract out background counts
- Divide the sum peak areas by the efficiencies at the individual energies for the selected geometry
- Correlate the peak energies to the energies available in the selected library from the listed isotopes
- Calculate the activities and uncertainties of the identified isotopes

Custom ASF files are regularly used for short irradiations and long irradiations for isotopes with different half lives. When needed additional custom ASF files can be

created and used. Custom Genie 2000 ™ libraries that have been created and used in each ASF can be found in **Appendices B and C**. The NAA template is therefore developed to include the protocols for the following:

1. *Sample preparation*. A proper sample size must be selected for adequate irradiation and analysis. The sample size must be chosen based upon the limitations of: irradiation vial size, available gamma spectroscopy geometries, the number of samples to be irradiated at the same time and, *most important*, the total activity of the sample. The *Activity Estimator* should be used to help determine the sample sizes for both long and short irradiations. The sample should be weighed using 0.0001 g capacity analytical balance and placed in either a seal plastic pouch or a seal polyethylene vial.

2. *Sample irradiation.* Using the *Activity Estimator* the irradiation times should be determined prior to the actual irradiation of the samples. It should be noted that for most long-term irradiations the longer the irradiation time can provide better results but will be activating more isotopes to detectable levels. Errors associated with irradiation time and isotope activities decrease as well with longer irradiation times and higher activities (as described in Section 2.4). Short-term samples also benefit from longer irradiations, but if the samples contain large concentrations of Na, Al and/or Mn the spectrum will be dominated by their energy peaks and the associated Compton scattering which may be counterproductive to the analysis (**Figure 2-2**).

3. *Sample counting.* After irradiation the samples should be counted on HPGe gamma spectroscopy detectors. After a short-term irradiation, samples should be counted within 1 – 10 minutes after irradiation, and counted for 300 seconds (given the total sample activity is low enough that sample can be removed from the UUTR

immediately). The same sample should be counted again within 1 – 4 hours after irradiation for 600 – 1,200 seconds. After a long-term irradiation, the sample should not be counted until at least 24 hours of waiting time after irradiation, and then be counted for 1,800 – 3,600 seconds. The same sample should be counted again after 6 – 10 days after irradiation for 3,600 – 18,000 seconds. Longer counting times can be chosen if needed for lower MDA's and errors.

4. Sample analysis. The sample information (ID, description and mass) and irradiation times should be entered in the sample information page before the sample counting is done and saved. Once the sample counting is finished, the spectrum can be analyzed using one of the NAA ASF files: "UNEP NAA Short", "UNEP NAA Long" or "UNEP NAA Very long". This will generate a report containing the activities of the identified isotopes. These activities can be entered in the *Elemental Concentration Calculator* to compute the mass concentrations of the identified elements.

The developed methods within the protocols do not contain instructions tailored to every possible scenario, but are open to variations according to the specifics of the samples. These protocols recommend that the experimenters look at past irradiations, of similar sample composition, and determine how the future irradiations can be performed and possibly improved based upon the results of the previous NAA runs. The protocols also encourage the application of quality control (QC) measures in order to assure accurate results. QC measures may include irradiating a certified standard together with the sample(s) or spiking some samples with certified target analytes to determine accurate concentrations. QC measures may also include multiple NAA runs to be able to analyze

enough samples to confidently determine the average results for a large quantity of samples.

6.2. Benchmarking the Protocols by Irradiation of Standard Reference Materials

The quality and accuracy of developed NAA protocols is tested using the certified standards, i.e. the standard reference materials (SRM). The NAA procedures were applied to check if the results match with the assay results of the standard. In order to fully benchmark the methods of developed NAA protocol, SRMs with a matrix or composition was used; however when a similar standard matrix cannot be purchased a sample can be spiked with certified liquid analytes of the desired elements before irradiation.

Another way of benchmarking the NAA methods can be evaluated through numerical simulations using known codes such as but not limited to MCNP5/X, GEANT4 and similar. This may be especially useful with SRMs that cannot easily be purchased like some rare earth metals and transuranic elements.

6.3. Defining Minimum Detection Limits

Based on NAA very low trace levels of the elements can be detected. The lowest detectable concentration is referred to as the minimal detection level (MDL) or lowest limit of detection (LLD). The ability to detect the elements of interest defines the applicability of any elemental analytical technique. As the detection limits get lower and lower, the technique is considered better.

In order to determine the MDLs for NAA several factors must be considered: sample size, neutron flux, detector efficiency and signal to noise ratio (S/N). Larger neutron flux increases the probability that enough atoms of an element are activated to meet a detector's minimum detectable activity (MDA). The detector's ability to measure lower activities is the other factor in determining MDL. An element's MDL is directly proportional to the detector's MDA for the activated nuclide(s) of that element and S/N. Higher quality detectors with greater efficiencies and lower S/N can greatly augment the NAA process and lower the MDLs.

For significantly lower MDLs, multiple detectors can be placed in an array in which all the detectors count the same sample simultaneously. By placing the detectors in an array the solid angle greatly increases; therefore the effective counting efficiency for that geometry increases.

By counting a sample for a longer period of time, the MDA can be improved since the MDA is based upon the probability that emitted gamma photons will be captured by a detector. As many photons of the same energy are counted in a detector peaks rise above the continuum of the spectrum. The continuum counts are merely the counts from background radiation, scattered photons and electronic noise in the gamma spectroscopy system.

Compton scattering and backscattering contribute extensively to the continuum counts as illustrated in **Figure 6-1**. The Compton and backscatter waves or edges can drown out smaller peaks from nuclides with lower activities by lowering the S/N and raise the MDL for those nuclides because their peaks are inundated by the continuum and are not identified.

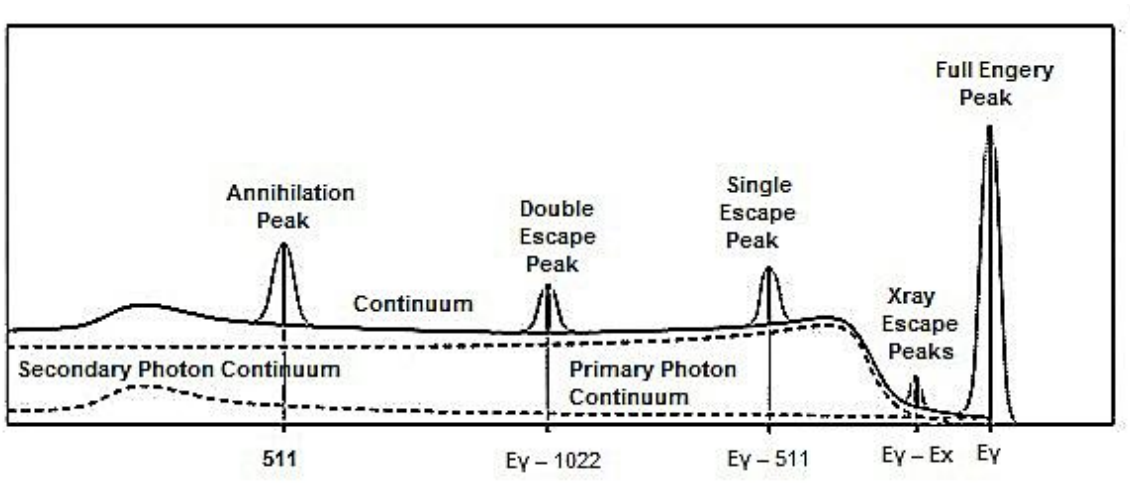


Figure 6-1 Gamma spectrum illustrating continuum spectra and Compton scattering (Nucleonica Wiki - Gamma Spectrum Generator)

The MDA's vary from spectrum to spectrum; they are not fixed values. Counting times and scattering waves affect the MDA, which is one of the reasons why irradiated samples need to be counted more than once. In latter counts many of the nuclides that cause the interferences, especially Na-24, will have decayed away, i.e. the activity will have decreased so much that interferences are minimized.

CHAPTER 7

NAA DATA LIBRARY AND DISCUSSION

This chapter summarizes the measurements developed into a first NAA library at UNEP from over 260 samples irradiated based on described NAA protocols. All tables are taken directly from the *Elemental Concentration Calculator*.[1] These values obtained using this tool, include the calculated mass concentrations expressed in both, the mass percentage and the parts-per-million, along with the mass concentration errors.

7.1. Soil and Geological Samples

Various geological samples have been tested to investigate what elements may be regularly detected in rock and soil specimens. Test samples included limestone, topsoil, sandstone, quartz monzonite and a number of different sand samples.

7.1.1 Limestone. Limestone samples were collected from several quarries around Utah they are analyzed to determine the trace elemental compositions. The trace elements are unique for different limestone from regions of origin. This helps to "fingerprint", or profile, each unique limestone specimen. **Figure 7-1** shows a sample of limestone collected from a limestone in southern Utah quarry near St. George. The measured

[1] The tables presented in this chapter are copied and pasted directly out of the EXCEL program. These tables do not represent final or official reports, therefore, significant figures is not taken into account nor the number of digits in this program. These tables are meant to present raw data to the program user. With this data the user can format a report as needed.

Figure 7-1 Limestone rock from southern Utah

gamma spectrum from a sample of irradiated a limestone sample is found in **Figure 7-2.** **Table 7-1** shows the calculated mass concentrations for all the identified elements from the *Elemental Concentration Calculator*. Limestone samples were among the first materials tested for this neutron activation analysis research project and also the last to be tested.

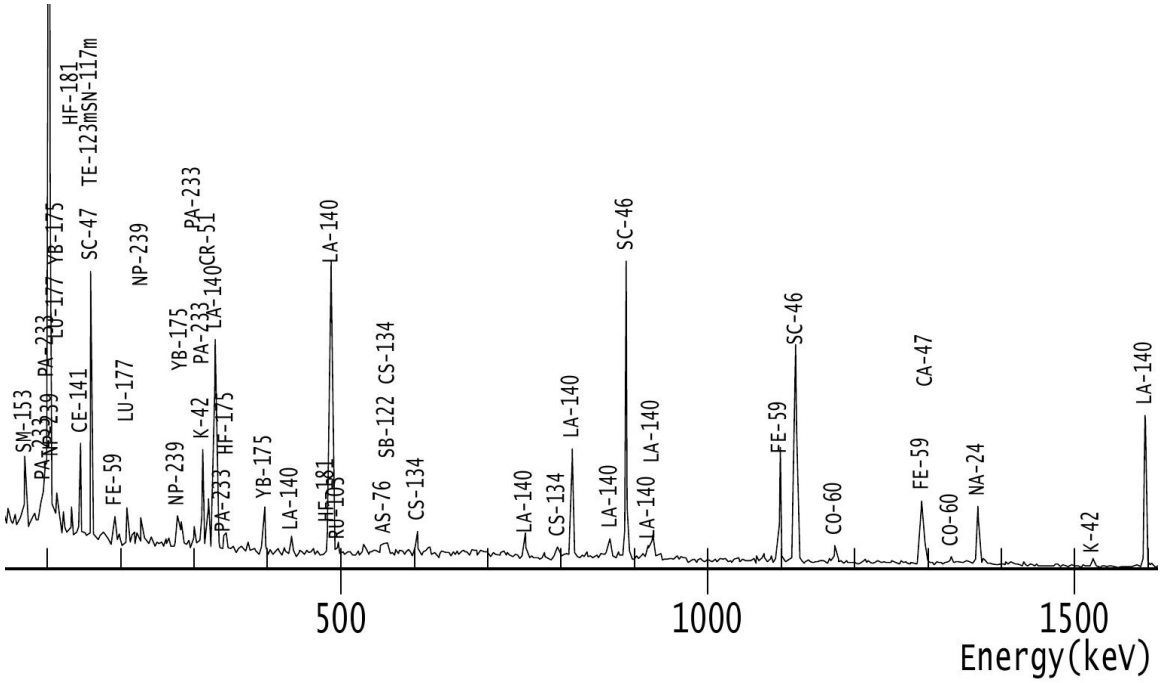


Figure 7-2 Spectrum from a 120 minute limestone irradiation showing peaks from 21 nuclides

Table 7-1 Limestone long irradiation results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	2.257E-03	Sodium (Na)	0.0611%	**610.9449**	1.246E-04	69.97173
K-42	1.638E-03	Potassium (K)	1.8265%	**18264.88**	4.025E-04	4846.955
SC-46	1.247E-02	Scandium (Sc)	0.0006%	**5.789713**	3.679E-03	1.803807
Ca-47 -	2.038E-03	Calcium (Ca)	12.0800%	**120799.8**	3.178E-04	22400.33
Sc-47*	1.528E-03	Calcium (Ca)	7.3044%	**73043.76**	2.807E-04	15293.51
CR-51	2.928E-03	Chromium (Cr)	0.0023%	**23.33019**	5.795E-04	5.176694
FE-59	1.001E-02	Iron (Fe)	2.4615%	**24615.2**	6.095E-04	2889.477
CO-60	5.095E-04	cobalt (Co)	0.0005%	**4.97498**	1.215E-04	1.287125
AS-76	2.830E-04	Arsenic (As)	0.0002%	**1.704429**	7.670E-05	0.492541
RU-103	2.760E-04	Ruthenium (Ru)	0.0010%	**10.22607**	5.969E-05	2.438529
Sb-122	1.588E-04	Antimony (Sb)	0.0000%	**0.309264**	5.694E-05	0.115145
CS-134	3.073E-04	Cesium (Cs)	0.0003%	**3.412936**	8.305E-05	0.983842
La-140	1.474E-02	Lanthanum (La)	0.0024%	**24.45317**	5.845E-04	2.638507
CE-141	1.099E-03	Cerium (Ce)	0.0037%	**36.96789**	2.395E-04	8.868595
SM-153	1.990E-02	Samarium (Sm)	0.0005%	**5.281334**	7.337E-04	0.5646
HF-175	2.431E-04	Hafnium (Hf)	0.0000%	**0.356449**	5.338E-05	0.086057
YB-175	5.861E-03	Ytterbium (Yb)	0.0002%	**2.036293**	8.174E-04	0.349877
Lu-177, *	2.292E-03	Lutetium (Lu)	0.0007%	**7.419747**	3.254E-04	1.289796
HF-181	3.196E-04	Hafnium (Hf)	0.0002%	**1.904041**	6.174E-05	0.414544
Pa-233*	2.233E-03	Thorium (Th)	0.0007%	**7.28429**	1.729E-04	0.923297
Np-239*	1.382E-03	Uranium (U)	0.0008%	**7.660875**	1.075E-04	0.972825

Limestone of any origin usually has gross compositions of Ca, Mg and K. The elements that are better for fingerprinting are those that are found in much small concentrations. Elements such as Co, Cs, Fe, Eu, Au and La would be better characterization markers. The concentrations of the major elements (Ca, Mg and K) can easily be altered when using limestone to make pottery or cement.

Profiling limestone quarry can be used for identify various products that may have originated from that quarry such as pottery, ceramic artifacts and concrete components.

7.1.2 Topsoil. Topsoil was collected from farm lands at various locations including Teton Valley Idaho and irradiated in the UUTR for NAA soil analyses. Most common inorganic elements are detectable via NAA and were easily identified in various geological samples through both the short and long irradiations with the exceptions of silicon, phosphorous and sulfur.

These elements have either rather small neutron absorption cross sections and or do not emit gamma photons. Si-32 has a very small cross section and also emits gamma photons that are not easily detected on the HPGe detectors because low emission intensities.

The Teton Valley soil was the first of the soils samples to be tested. **Figure 7-3** shows a farm plowing a field near where the samples were collected by Victor, ID. **Figure 7-4** and **Table 7-3** shows the measured spectrum and calculated mass concentrations from irradiated soil samples. **Table 7-2** list the irradiation parameters used for the experiment.

Figure 7-3 Teton Valley Idaho farmer plowing field of topsoil (Hunter)

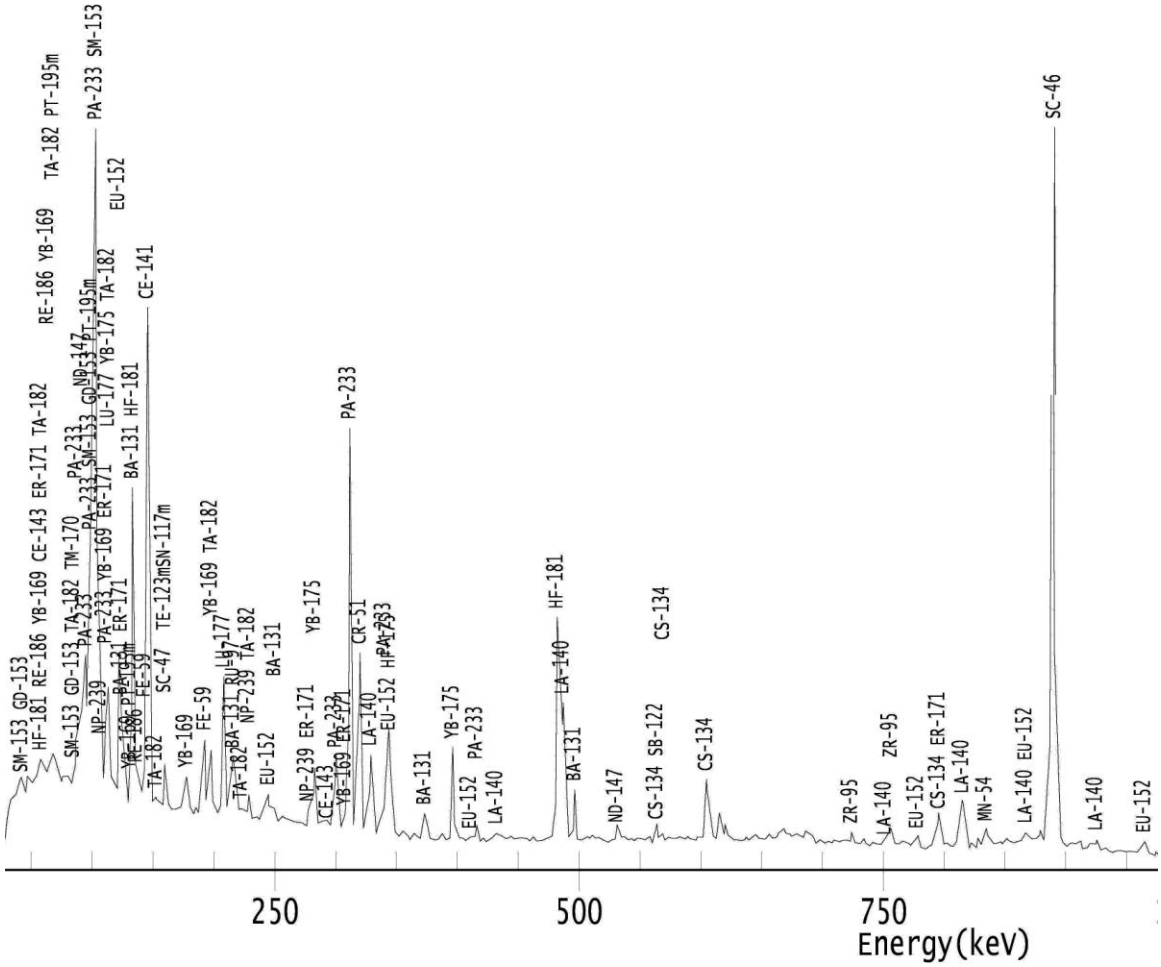


Figure 7-4 Spectrum for a 116 minute topsoil irradiation showing peaks from 44 different nuclides

Table 7-2 Teton Valley topsoil parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
Victor, ID topsoil	0.0678	6960	548,171	18,000	NAA

Table 7-3 Topsoil Long Irradiation NAA Results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	2.803E-01	Sodium (Na)	9.2221%	**92221.06**	2.442E-03	9291.102
K-40	3.939E-04	Potassium (K)	NA	**NA**	1.545E-03	NA
K-42	2.124E-02	Potassium (K)	29.7729%	**297728.6**	1.426E-03	35956.38
SC-46	4.445E-02	Scandium (Sc)	0.0021%	**21.3726**	1.048E-02	5.478604
Sc-47*	9.705E-04	Calcium (Ca)	4.8295%	**48295.09**	8.469E-05	6423.225
CR-51	1.869E-02	Chromium (Cr)	0.0155%	**154.5889**	1.287E-03	18.81824
MN-54	8.356E-04	Iron (Fe)	0.0000%	**NA**	1.742E-04	NA
FE-59	2.700E-02	Iron (Fe)	6.8862%	**68862.44**	7.001E-04	7138.726
CO-60	2.805E-03	cobalt (Co)	0.0028%	**28.33504**	1.050E-04	3.035288
SE-75	1.093E-05	Selenium (Se)	0.0001%	**0.772484**	2.172E-05	1.537212
AS-76	5.395E-03	Arsenic (As)	0.0037%	**36.88901**	3.433E-04	4.383957
BR-82	1.766E-03	Bromine (Br)	0.0017%	**16.6589**	6.703E-05	1.787689
RB-86	2.614E-02	Rubidium (Rb)	0.0522%	**522.1475**	1.394E-02	283.3379
Nb-95*	1.120E-04	Zirconium (Zr)	0.1955%	**1955.389**	4.712E-05	846.0374
Zr-95 -	7.486E-04	Zirconium (Zr)	0.1803%	**1803.257**	1.140E-04	328.9346
Mo-99 -	2.446E-04	Molybdenum (Mo)	0.0045%	**45.03256**	2.469E-05	6.410711
Tc-99m*	3.125E-04	Molybdenum (Mo)	0.0053%	**53.36638**	3.155E-05	7.59722
RU-103	4.976E-05	Ruthenium (Ru)	0.0002%	**1.912645**	1.015E-04	3.905285
TE-121	3.541E-04	Tellurium (Te)	0.1512%	**1511.954**	4.620E-05	248.8947
SB-122	2.537E-03	Antimony (Sb)	0.0005%	**5.302126**	1.340E-04	0.601415
TE-125m	6.027E-02	Tellurium (Te)	0.4877%	**4877.4**	1.559E-02	1353.392
BA-131	2.680E-03	Barium (Ba)	0.0685%	**685.2173**	1.146E-04	74.75563
CS-134	1.266E-03	Cesium (Cs)	0.0015%	**14.54778**	6.157E-05	1.622523
LA-140	9.987E-02	Lanthanum (La)	0.0182%	**182.0062**	1.045E-03	18.36712
CE-141	6.147E-03	Cerium (Ce)	0.0215%	**214.5466**	4.332E-04	26.31103
CE-143	1.116E-03	Cerium (Ce)	0.0278%	**278.1517**	8.494E-05	35.03752

Table 7-3 continued

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
ND-147	4.025E-03	Neodymium (Nd)	0.0140%	**139.523**	1.971E-04	15.58139
EU-152	2.709E-03	Europium (Eu)	0.0002%	**1.546999**	1.377E-04	0.174039
SM-153	1.215E-01	Samarium (Sm)	0.0035%	**35.31213**	1.993E-03	3.591309
YB-169	1.071E-03	Ytterbium (Yb)	0.0008%	**7.932717**	5.702E-05	0.901294
ER-171	3.224E-04	Erbium (Er)	NA	**NA**	5.105E-05	NA
HF-175	2.515E-04	Hafnium (Hf)	0.0000%	**0.382106**	8.497E-05	0.134657
YB-175	3.612E-02	Ytterbium (Yb)	0.0013%	**13.29927**	1.546E-03	1.451107
Lu-177, *	1.849E-02	Lutetium (Lu)	0.0061%	**61.11949**	7.620E-04	6.631685
HF-181	4.137E-03	Hafnium (Hf)	0.0026%	**25.55871**	1.988E-04	2.844105
TA-182	8.569E-04	Tantalum (Ta)	0.0003%	**2.988934**	1.477E-04	0.596211
RE-186	3.495E-03	Rhenium (Re)	0.0001%	**0.755658**	3.643E-04	0.109344
HG-197	8.195E-04	Mercury (Hg)	0.0001%	**1.395045**	5.038E-04	0.869023
HG-197m	6.032E-04	Mercury (Hg)	0.0015%	**14.9597**	4.502E-04	11.26543
AU-198	2.128E-06	Gold (Au)	0.0000%	**0.000253**	1.801E-05	0.002139
Pa-233*	1.215E-02	Thorium (Th)	0.0041%	**41.17428**	2.390E-04	4.211273
Np-239*	9.932E-03	Uranium (U)	0.0059%	**59.45049**	1.808E-04	6.064446

From this soil sample nearly 40 elements were identified through NAA. The concentrations of each of these elements were estimated using the *Elemental Concentration Calculator.* This was the first topsoil sample analyzed during this research study.

NAA can be used to profile inorganic compositions of geological sediments, rocks and soils. Such studies would be valuable to analyze mineral content, heavy metals contamination and general composition.

7.1.3 Sandstone. In addition to limestone and topsoil samples other types of stone were tested as well. **Figure 7-5** shows a specimen of sandstone collected near Moab, UT for NAA investigation. The measured spectrum and calculated mass concentration results are found in **Figure 7-6** and **Table 7-4**.

Figure 7-5 Sandstone rock from Moab, UT

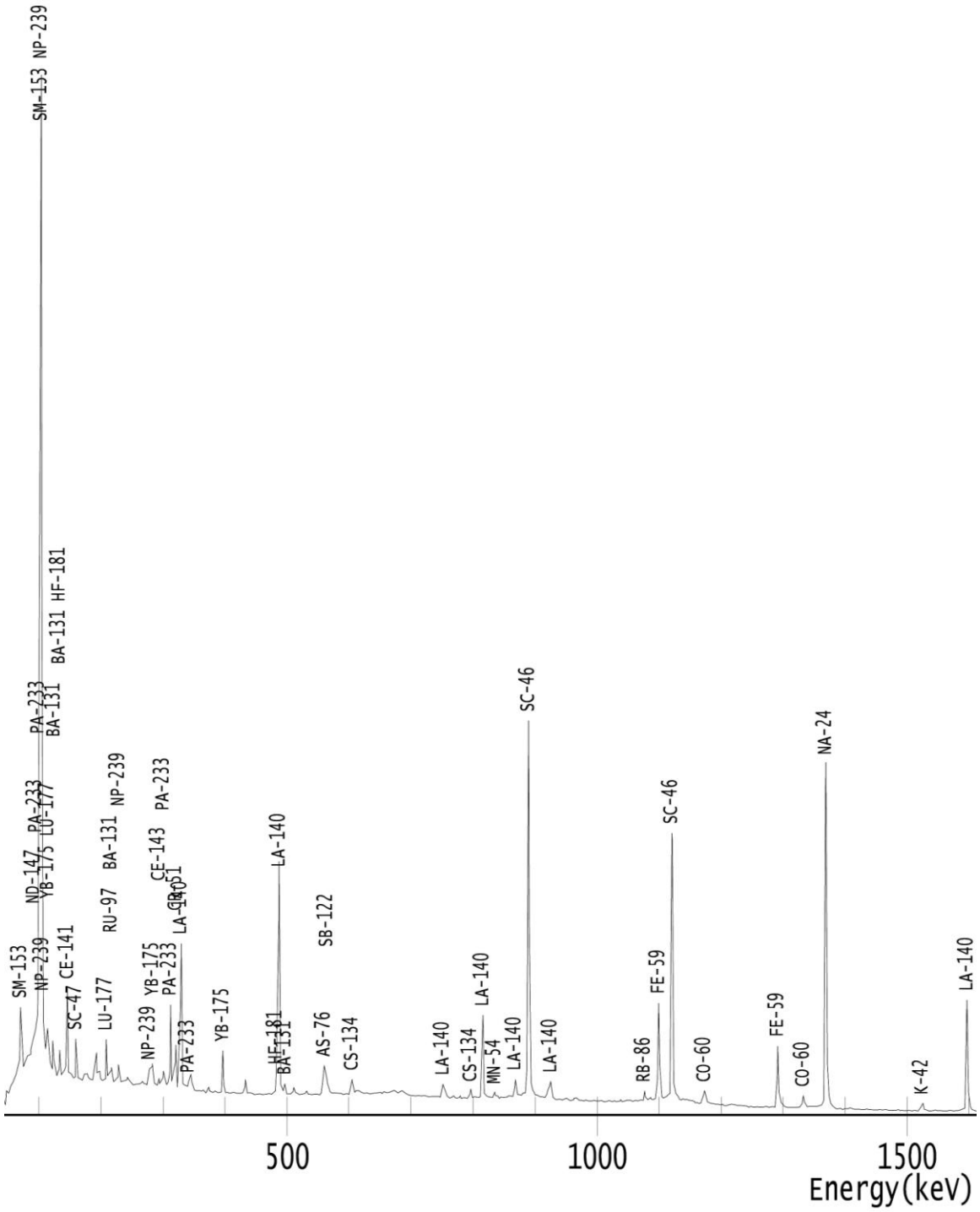


Figure 7-6 Sandstone taken from Moab, UT and irradiated for 92 minutes showing peaks from 24 nuclides

Table 7-4 Moab sandstone long irrdation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	4.854E-02	Sodium (Na)	1.1091%	**11091.27**	1.407E-03	1161.029
K-42	6.756E-03	Potassium (K)	5.8030%	**58029.57**	5.752E-04	7647.572
SC-46	2.185E-02	Scandium (Sc)	0.0013%	**13.18678**	4.988E-03	3.290059
Sc-47*	5.189E-04	Calcium (Ca)	3.1907%	**31906.62**	5.540E-05	4680.306
Cr-51	6.031E-03	Chromium (Cr)	0.0062%	**62.06054**	6.252E-04	8.964766
MN-54	2.518E-04	Iron (Fe)	0.0000%	**NA**	6.752E-05	NA
FE-59	1.609E-02	Iron (Fe)	5.1322%	**51322.43**	7.450E-04	5682.972
CO-60	1.426E-03	cobalt (Co)	0.0018%	**18.16299**	6.779E-05	2.020702
AS-76	1.643E-03	Arsenic (As)	0.0010%	**10.03602**	1.155E-04	1.231615
RB-86	9.021E-03	Rubidium (Rb)	0.0223%	**222.7295**	4.891E-03	122.8362
RU-97	1.278E-05	Ruthenium (Ru)	0.0005%	**5.218625**	2.714E-05	11.09354
SB-122	6.052E-04	Antimony (Sb)	0.0001%	**1.391432**	3.684E-05	0.1636
BA-131	5.242E-04	Barium (Ba)	0.0164%	**163.6322**	3.767E-05	20.22936
CS-134	5.316E-04	Cesium (Cs)	0.0008%	**7.698282**	4.221E-05	0.986513
LA-140	1.491E-02	Lanthanum (La)	0.0027%	**27.4456**	4.706E-04	2.89352
CE-141	1.427E-03	Cerium (Ce)	0.0062%	**62.07197**	1.335E-04	8.526077
CE-143	2.719E-04	Cerium (Ce)	0.0065%	**65.22773**	5.498E-05	14.73084
ND-147	7.976E-04	Neodymium (Nd)	0.0034%	**33.69687**	4.765E-05	3.942232
SM-153	2.529E-02	Samarium (Sm)	0.0008%	**7.5034**	3.181E-04	0.760639
YB-175	8.271E-03	Ytterbium (Yb)	0.0004%	**3.513027**	6.152E-04	0.439482
Lu-177, *	2.838E-03	Lutetium (Lu)	0.0012%	**12.429**	2.942E-04	1.795285
HF-181	5.470E-04	Hafnium (Hf)	0.0004%	**4.224045**	3.481E-05	0.502797
Pa-233*	3.132E-03	Thorium (Th)	0.0013%	**13.1944**	8.884E-05	1.378974
Np-239*	2.625E-03	Uranium (U)	0.0017%	**16.91999**	5.356E-05	1.736623

Over 20 elements were identified in the Moab sandstone sample including uranium and iron, both of which are very common in the Moab area. This particular specimen did not show any large concentrations of either element, which lead to believe that this is high quartz based sandstone.

Geological samples can be readily analyzed via NAA to determine inorganic elemental composition analysis. This can be applied to profiling the geological sample as well as investigating precious metal content as well as uranium and thorium.

7.1.4 Quartz monzonite. Quartz monzonite is a stone native to the Rocky Mountains and is found in the Salt Lake Valley in Utah with a large quarry in Little Cottonwood Canyon. This stone has been quarried and used in several local buildings including the LDS Salt Lake Temple, the John R. Park administration building at the University of Utah campus and the Utah State Capitol building.

Because of its use on the temple it is locally known as “temple granite”. Rock specimens were collected near the Little Cottonwood Canyon quarry and irradiated to examine what elements could be identified using NAA

Figure 7-7 shows the Little Cottonwood Canyon quartz monzonite quarry in full production during the late 1800s. **Figure 7-8** shows a quartz monzonite rock collected near the quarry. The measured gamma spectrum from a short irradiation of a quartz monzonite sample is seen in **Figure 7-9**. **Table 7-5** shows the results of the calculated mass concentrations of the various elements identified from the NAA irradiation and gamma spectroscopy measurement.

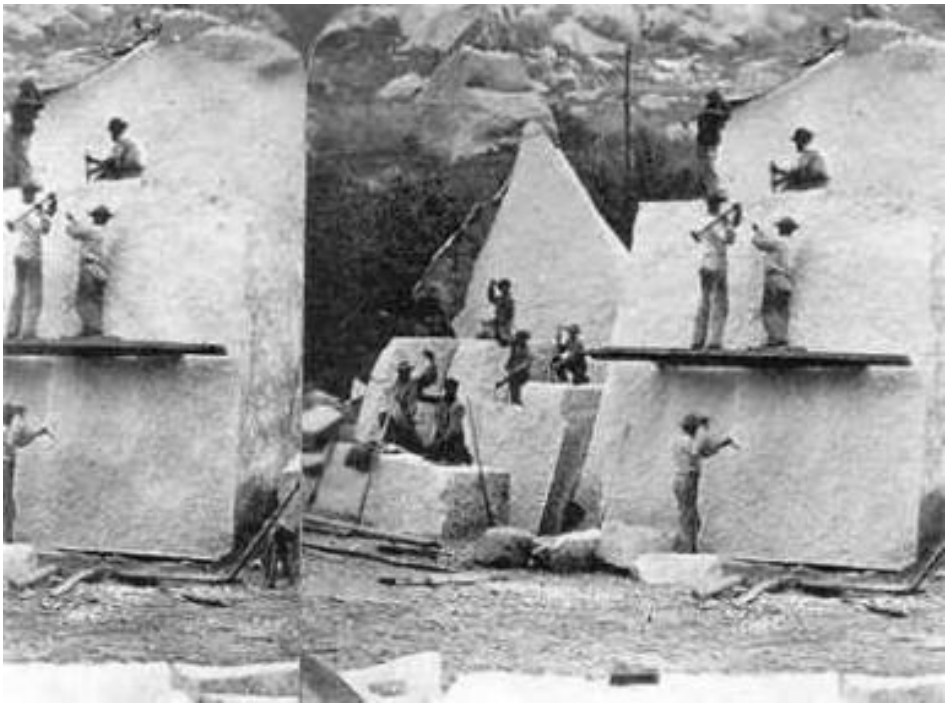


Figure 7-7 Little Cottonwood Canyon quartz monzonite quarry (http://www.believeallthings.com)

Figure 7-8 Quartz monzonite stone collectd for UNEP lab

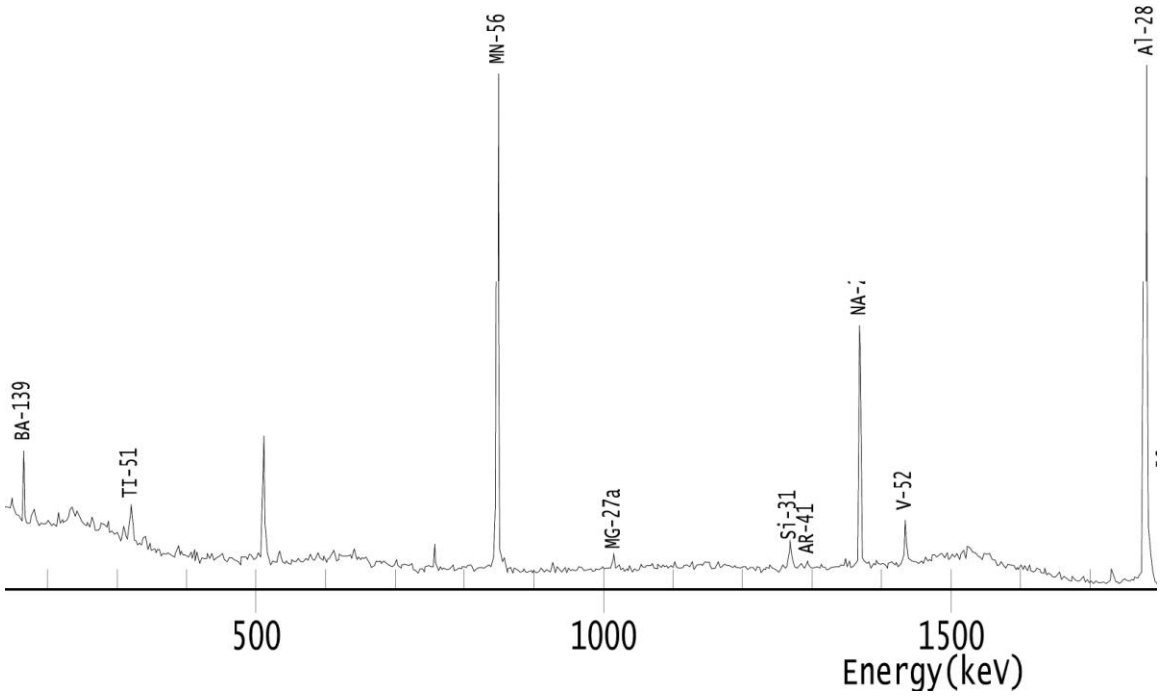


Figure 7-9 Quartz monzonite spectrum from a two minute irradiation showing peaks from nine nuclides

Table 7-5 Quartz monzonite short irradiation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	4.959E+00	Sodium (Na)	2.5905%	**25904.69**	2.545E-01	13506.49
MG-27	1.399E+00	Magnesium (Mg)	2.3465%	**23465.29**	3.922E-01	13837.87
Al-28	1.396E+02	Aluminum (Al)	16.3375%	**163375**	9.260E+00	85458.58
Si-31	9.318E+02	Silicon (Si)	NA	**NA**	2.039E+02	NA
AR-41	1.496E-01	Argon (Ar)	0.0142%	**142.1323**	6.584E-02	96.70228
TI-51	2.828E-01	Titanium (Ti)	0.4408%	**4408.04**	1.517E-01	3289.827
V-52	2.501E+00	Vanadium (V)	0.0138%	**137.7896**	2.942E-01	73.30834
MN-56	9.229E+00	Manganese (Mn)	0.0826%	**825.6975**	4.573E-01	430.371
BA-139	7.928E-01	Barium (Ba)	0.6834%	**6833.714**	4.716E-01	5394.099

The results from the short irradiation confidently identified eight elements. The activities from all the nuclides, except silicon-31, were accurately measured. Silicon is extremely difficult to quantify using NAA due to the small absorption cross section of silicon-30 and the weak intensity of the gamma emission coming from silicon-31.

NAA can be used to analyze local geological samples to evaluate their inorganic elemental compositions.

7.1.5 Sand. Sand specimens were collected from several local areas for NAA geological protocol development. Samples from the Great Salt Lake, Bear Lake, Madison County, Idaho sand dunes and Salt Lake County, UT were irradiated. These experiments helped determined whether the sand samples were either quartz or Ca/Mg based sediments.

Figure 7-10 shows two different sand samples collected for this research one from the shores of Bear Lake, ID and another from a pile of construction sand base in Salt Lake City, UT. **Figure 7-11** shows the acquired spectrum and **Table 7-6** shows the results of the calculated mass concentrations from an irradiated sand sample.

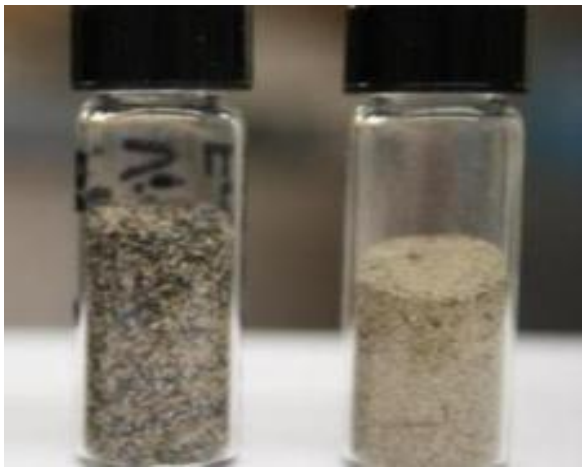


Figure 7-10 Sand specimens from Bear Lake, UT and Millcreek, UT

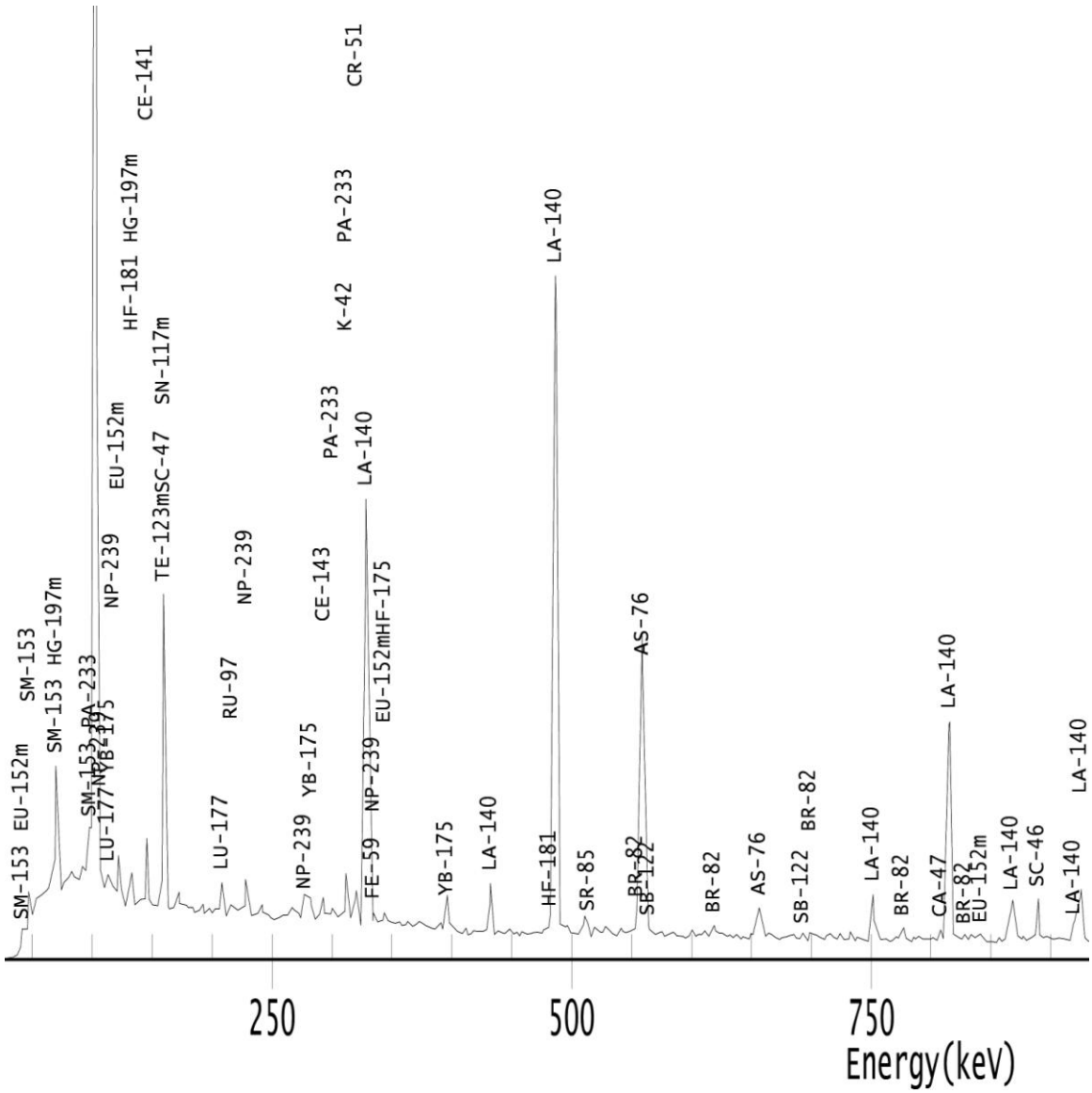


Figure 7-11 Bear Lake sand spectrum from a 116 minute irradiation showing peaks from 24 nuclides

Table 7-6 Bear Lake, UT sand long irrdation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
K-42	1.561E-02	Potassium (K)	0.2428%	**2427.509**	7.662E-04	271.234
SC-46	8.802E-04	Scandium (Sc)	0.0000%	**0.411675**	2.189E-04	0.110405
Ca-47 -	2.188E-03	Calcium (Ca)	8.2256%	**82255.82**	2.924E-04	13750.97
Sc-47*	1.128E-03	Calcium (Ca)	5.6490%	**56489.61**	8.669E-05	7140.644
CR-51	1.109E-03	Chromium (Cr)	0.0008%	**8.434229**	1.446E-04	1.388099
FE-59	1.386E-03	Iron (Fe)	0.3356%	**3356.271**	1.413E-04	480.1878
AS-76	5.982E-03	Arsenic (As)	0.0005%	**4.762735**	3.765E-04	0.564231
BR-82	3.051E-04	Bromine (Br)	0.0001%	**0.595285**	2.823E-05	0.08126
SR-85	1.110E-04	Strontium (Sr)	0.0446%	**445.9758**	1.986E-05	91.48163
RU-97	4.618E-05	Ruthenium (Ru)	0.0008%	**7.643483**	1.679E-05	2.883412
SB-122	1.844E-04	Antimony (Sb)	0.0000%	**0.164546**	3.040E-05	0.031761
LA-140	1.377E-02	Lanthanum (La)	0.0006%	**6.303447**	2.380E-04	0.641996
CE-141	3.599E-04	Cerium (Ce)	0.0012%	**11.6948**	5.424E-05	2.117933
CE-143	2.257E-04	Cerium (Ce)	0.0010%	**10.44268**	3.272E-05	1.841185
EU-152m	1.239E-03	Europium (Eu)	0.0000%	**0.076146**	1.672E-04	0.012808
SM-153	1.636E-02	Samarium (Sm)	0.0001%	**1.275214**	2.801E-04	0.129844
HF-175	3.683E-05	Hafnium (Hf)	0.0000%	**0.054119**	3.254E-05	0.048129
YB-175	1.994E-03	Ytterbium (Yb)	0.0000%	**0.421857**	2.753E-04	0.072018
Lu-177, *	9.115E-04	Lutetium (Lu)	0.0005%	**4.672238**	1.424E-04	0.867702
HF-181	1.555E-04	Hafnium (Hf)	0.0001%	**0.909585**	2.315E-05	0.163334
HG-197m	3.335E-04	Mercury (Hg)	0.0001%	**0.798583**	8.425E-05	0.217087
Pa-233*	3.056E-04	Thorium (Th)	0.0001%	**0.950036**	3.897E-05	0.154183
Np-239*	8.710E-04	Uranium (U)	0.0002%	**1.949382**	4.796E-05	0.223165

The bear lake sand long irradiation showed 21 different elements present in the samples. Higher concentrations of Fe were expected as well as Hg, but instead a significant concentration of Ca was identified showing that much of this sand came from limestone deposits.

Sand and sediment specimens can be analyzed through NAA to determine general inorganic elemental compositions as well as potential heavy metal contamination from local industrial waste pollutants.

7.2 Water

Water samples from Utah, Idaho, the Great Salt Lake as well as bottled waters have been irradiated to explore the presence of various minerals commonly found in water and investigate for heavy metal contamination.

Water samples in both environmental and municipal settings are regularly tested for dozens of reasons. These tests look for minerals, toxins, particles and gas levels for both safety and quality control purposes. NAA could possibly be used as part of the many analytical methods to regularly test water.

Tap water from Teton Valley Idaho was obtained and tested using NAA showing various minerals and metals in both long and short irradiations. **Figure 7-12** shows a picture of tap from a tap. The spectrum from an irradiated sample of tap water is shown in **Figure 7-13** and the results of the calculated elemental mass concentrations are found in **Table 7-8** and **7-10**. The irradiation parameters for this experiment are listed in **Table 7-7** and **7-9**.

Figure 7-12 Drinking water

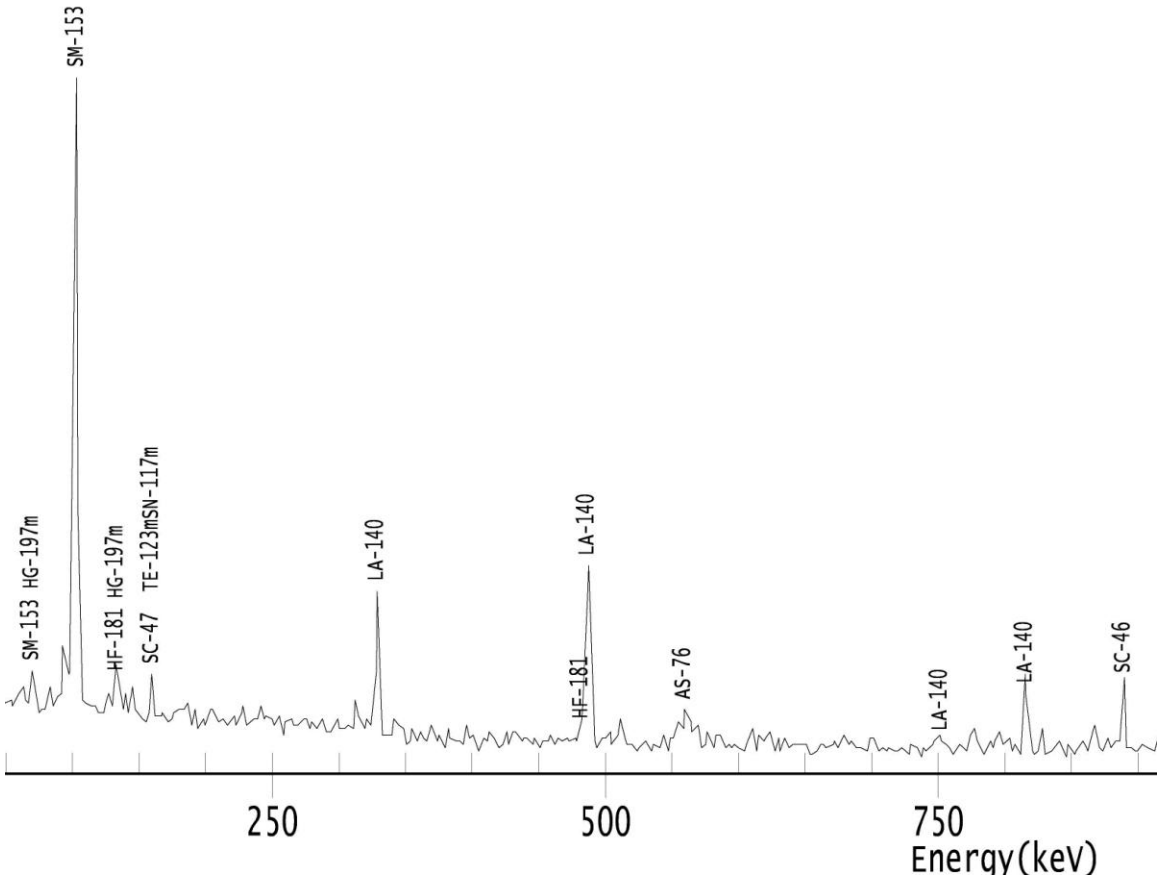


Figure 7-13 Spectrum for a 116 minute tap water irradiation showing peaks from 10 nuclides

Table 7-7 Drinking water long irradiation parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
Victor, ID drinking water	1.015	6960	511,192	18,00	NAA

Table 7-8 Drinking water long irradiation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	1.111E-03	Sodium (Na)	0.0009%	**8.862567**	2.298E-05	0.908239
SC-46	5.001E-05	Scandium (Sc)	0.0000%	**0.02339**	1.352E-05	0.006744
Sc-47*	1.815E-06	Calcium (Ca)	0.0091%	**90.89288**	2.010E-06	101.0684
FE-59	5.385E-05	Iron (Fe)	0.0130%	**130.3748**	1.551E-05	39.7743
ZN-65	3.855E-05	Zinc (Zn)	0.0005%	**4.552247**	2.506E-05	2.99411
AS-76	1.518E-05	Arsenic (As)	0.0000%	**0.012085**	4.112E-06	0.003492
LA-140	1.111E-04	Lanthanum (La)	0.0000%	**0.05088**	6.514E-06	0.005914
SM-153	2.062E-04	Samarium (Sm)	0.0000%	**0.016077**	1.227E-05	0.001876
HF-181	8.233E-06	Hafnium (Hf)	0.0000%	**0.048158**	1.948E-06	0.012377
HG-197m	4.627E-06	Mercury (Hg)	0.0000%	**0.011081**	5.620E-06	0.013504

Table 7-9 Drinking water short irradiation parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
Victor, ID drinking water	1.005	360	511,192	600	Spacer

Table 7-10 Drinking water short irradiation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	1.410E-02	Sodium (Na)	0.0024%	**24.42968**	3.440E-04	13.71942
MG-27	4.335E-03	Magnesium (Mg)	0.0015%	**14.92136**	1.731E-03	10.27503
Al-28	2.492E-01	Aluminum (Al)	0.0011%	**11.44738**	7.072E-03	6.430858
CL-38	1.215E-02	Chlorine (Cl)	0.0007%	**7.423009**	6.081E-04	4.181272
AR-41	1.079E-01	Argon (Ar)	0.0033%	**32.77732**	2.035E-03	18.40037
TI-51	3.652E-04	Titanium (Ti)	0.0001%	**0.849577**	1.423E-04	0.580294
V-52	1.593E-02	Vanadium (V)	0.0000%	**0.083656**	9.286E-04	0.047188
MN-56	2.184E-02	Manganese (Mn)	0.0001%	**0.632545**	9.666E-04	0.355997
CU-66	8.735E-03	Copper (Cu)	0.0000%	**0.355736**	6.320E-03	0.325728
BR-80	1.026E-02	Bromine (Br)	0.0000%	**0.139373**	2.104E-03	0.083252
IN-116m	8.799E-04	Indium (In)	0.0000%	**0.001341**	6.475E-04	0.001241

Irradiations from tap water revealed a variety of minerals that are common in water such as Fe, Na, k and Mg. Trace amounts of Hg and As where found in the Idaho tap water samples, but the exact concentrations could not be determined since no metals-in-water standard reference material were available for efficiency comparison.

NAA can be used to evaluate mineral contents found in water samples as well as metal contamination.

7.3 Food

NAA experiments have been proven to be effective in identifying and quantifying minerals in food and agricultural products. In addition to the common nutritional minerals found in food many other metals were regularly found to be present such as Al, V, Sc, Cs, Mo and Br. Many products were irradiation to verify the presence of such minerals as well as potentially harmful toxins and heavy metals such as Cd, Hg and As.

Figure 7-14 shows a picture of small red beans which was one of the types of food irradiated as part of this research. **Figure 7-15** shows the spectrum acquired from an irradiated sample of red beans. **Table 7-11** lists the parameters for the short irradiation experiment. **Table 7-12** and gives the results of the calculated mass concentrations of the identified elements. **Table 7-13** lists the parameters for the long irradiation experiment while **Table 7-14** and give the results of the calculated mass concentrations of the identified elements

Figure 7-14 Small red beans (www.healthygreenkitchen.com)

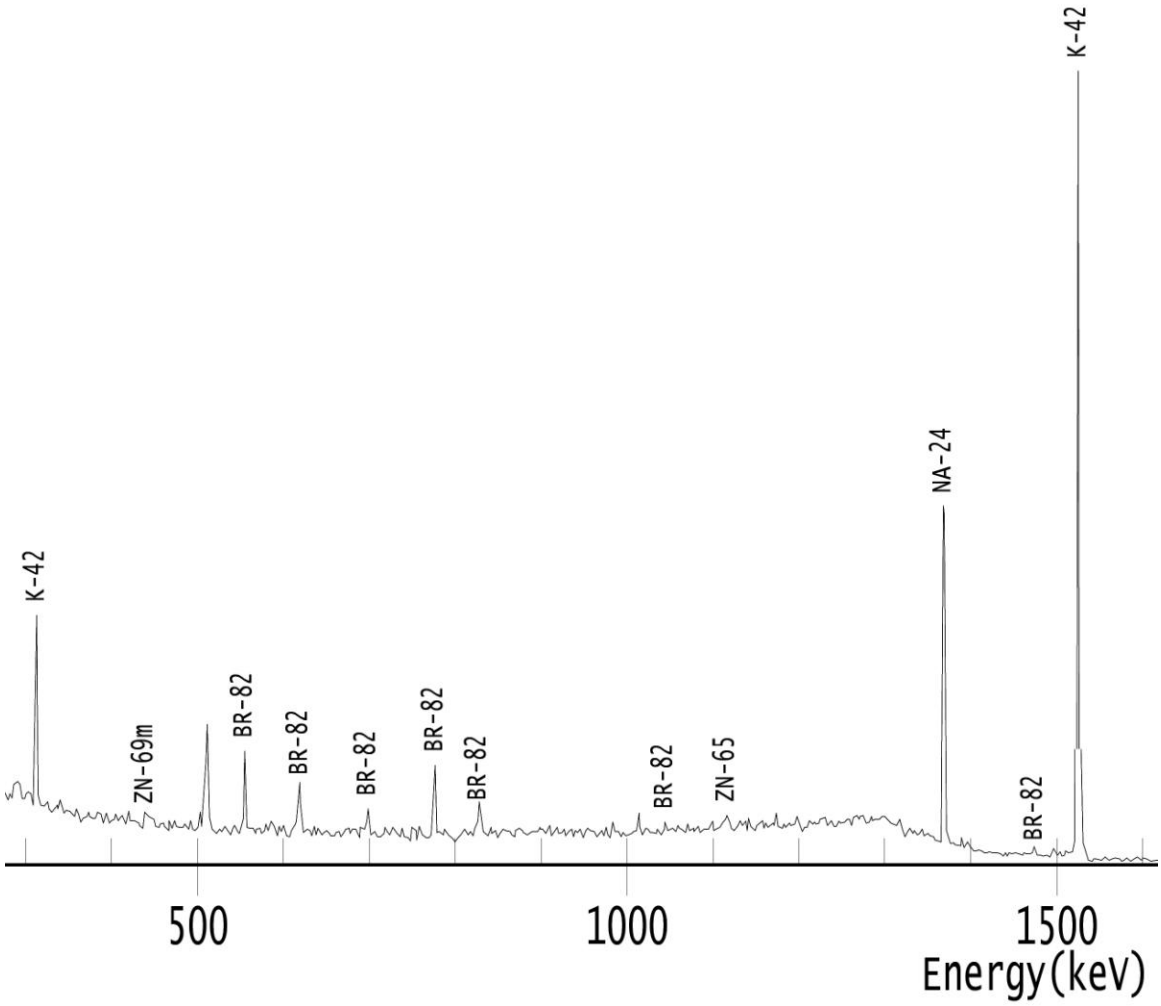


Figure 7-15 Spectrum from 5 minute irradiation of red beans showing peaks from 7 nuclides

Table 7-11 Red bean short irradiation parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
Red bean	0.2792	300	321	600	Spacer 2

Table 7-12 Red bean short irradiation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
MG-f27	3.163E-01	Magnesium (Mg)	0.1626%	**1626.006**	2.266E-02	487.9925
Al-28	3.907E-01	Aluminum (Al)	0.0056%	**55.91701**	1.331E-02	16.40753
CL-38	3.944E-01	Chlorine (Cl)	0.0305%	**305.4888**	6.230E-03	89.16246
AR-41	7.843E-02	Argon (Ar)	0.0029%	**29.13994**	3.211E-03	8.575961
K-42	1.136E+00	Potassium (K)	1.7970%	**17970.29**	2.471E-02	5251.826
V-52	1.250E-02	Vanadium (V)	0.0000%	**0.138185**	3.224E-03	0.053775
MN-56	3.148E-01	Manganese (Mn)	0.0011%	**11.08663**	9.970E-03	3.250118
CU-66	1.610E-01	Copper (Cu)	0.0012%	**11.8262**	5.085E-02	5.083082

Table 7-13 Red Bean long irradiation parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
Red bean	0.299	7200	352,807	1800	NAA

Table 7-14 Red bean long irradiation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	6.078E-03	Sodium (Na)	0.0052%	**51.51006**	1.860E-03	16.58619
K-42	1.017E-01	Potassium (K)	1.7145%	**17144.57**	3.404E-02	5988.871
ZN-65	4.288E-04	Zinc (Zn)	0.0049%	**48.94785**	2.867E-04	33.09326
Zn-69m	3.696E-05	Zinc (Zn)	0.0003%	**3.133358**	2.789E-05	2.385231
BR-82	4.884E-04	Bromine (Br)	0.0001%	**0.958712**	6.115E-05	0.153823

NAA irradiations showed several common minerals found in food products such as K, Zn Cu and Mn. Longer irradiations and count times would be effective to identify and quantify Fe, Se, and Mg concentrations.

Figure 7-16 shows a picture of white rice which is another type food product irradiated as part of this research. The irradiation parameters are given in **Table 7-15**. **Figure 7-17** shows the spectrum acquired from an irradiated sample of red beans and **Table 7-16** gives the results of the calculated mass concentrations of the identified elements.

Figure 7-16 Long grain white rice (trussty-jasmine.blogspot.com)

Table 7-15 White rice parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
White rice	1.472	6960	529,595	1800	NAA

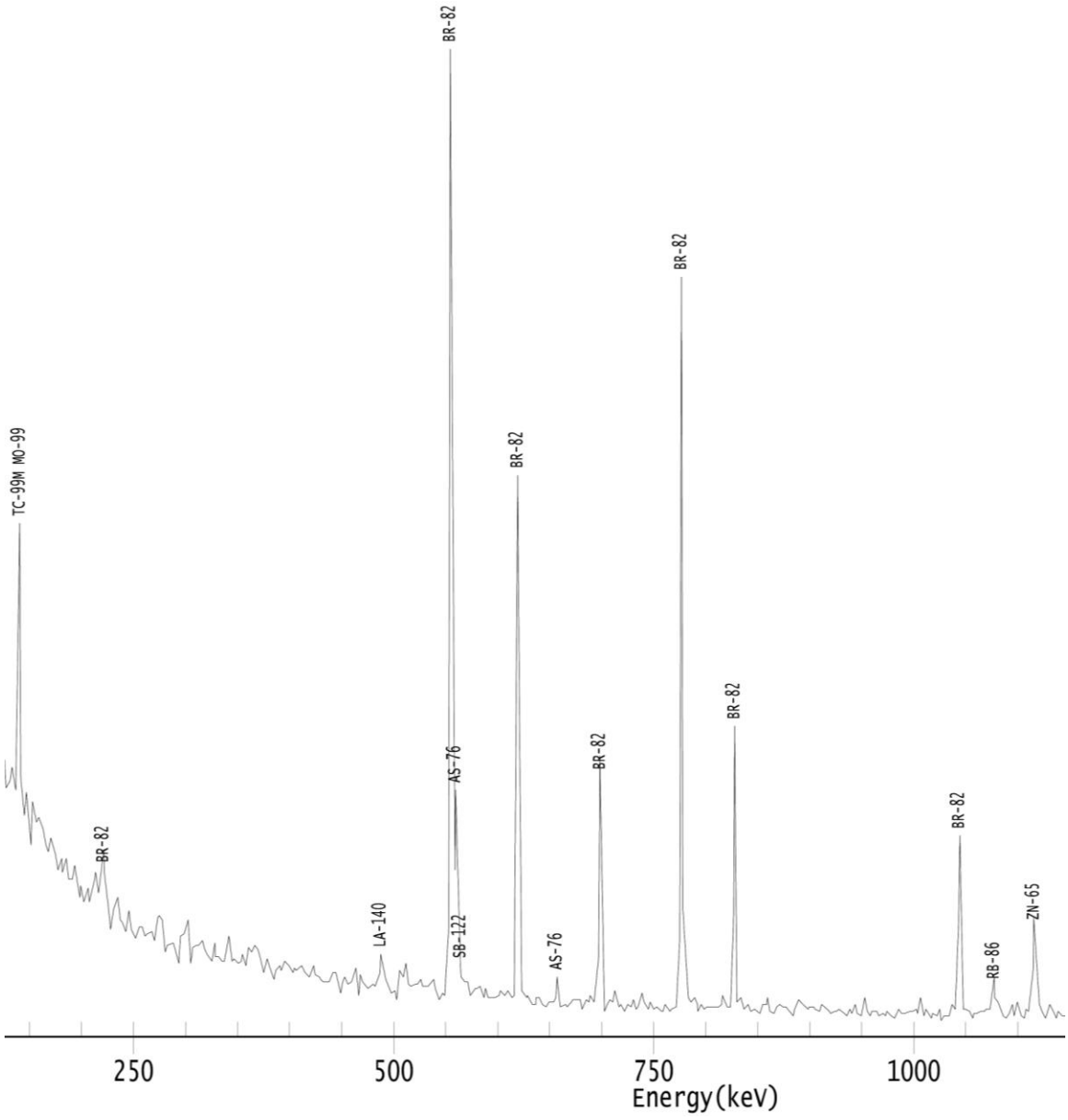


Figure 7-17 Spectrum from 116 minute irradiation fo white rice showing peaks from 8 nuclides

Table 7-16 White rice long irradiation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	2.439E-04	Sodium (Na)	0.0021%	**20.78461**	8.547E-06	2.209612
K-42	4.134E-04	Potassium (K)	0.1130%	**1129.708**	5.659E-05	191.7638
ZN-65	1.390E-04	Zinc (Zn)	0.0017%	**16.51568**	8.569E-05	10.31348
AS-76	1.232E-04	Arsenic (As)	0.0000%	**0.385621**	1.069E-05	0.051174
BR-82	4.523E-04	Bromine (Br)	0.0002%	**2.407045**	1.202E-05	0.249919
RB-86	3.262E-04	Rubidium (Rb)	0.0006%	**6.227802**	1.971E-04	3.814237
Mo-99 -	2.419E-05	Molybdenum (Mo)	0.0003%	**3.270928**	3.713E-06	0.599825
Tc-99m*	2.472E-05	Molybdenum (Mo)	0.0003%	**3.101139**	3.795E-06	0.568689
SB-122	1.098E-05	Antimony (Sb)	0.0000%	**0.016846**	2.937E-06	0.004814
LA-140	1.249E-05	Lanthanum (La)	0.0000%	**0.01378**	3.229E-06	0.003822
SM-153	2.015E-05	Samarium (Sm)	0.0000%	**0.003631**	1.330E-05	0.002423

Irradiations of white rice showed the presence of a few surprising elements such as Sb, and As. Further experiments could be conducted to look for these elements in other white rice samples and other types of rice as well.

NAA can be used to evaluate nutritional mineral contents of various food products like K, Na, Fe, Cu, Mg and Zn. Other trace metals and even toxic metals like As, Cd and Hg can be identified through NAA.

7.4 Metal Alloys

Metal ratios in alloy can easily be tested and verified via NAA. It should be noted that many elements in pure metals have relatively large radiative capture cross sections. Therefore, usually very small metal samples should be irradiated to avoid creating

excessively large activities. This applies to alloys containing large concentrations of the following metals: In, Mn, Cr, Co, Gd, Sc, Eu, Dy, Sb, La, Ir, Ag and Au. Extremely high activities can also be avoided by irradiating the alloys at lower fluxes shorter irradiation times. With low concentrations excessive activation of these metals is not an issue.

Figure 7-18 shows a picture spool of 40-60 solder wire. **Table 7-17** gives the irradiation parameters used for this experiment. **Figure 7-19** shows the spectrum acquired from an irradiated sample of 40-60 solder wire and **Table 7-18** gives the results of the calculated mass concentrations of the identified elements

Figure 7-18 40-60 solder wire

Table 7-17 40-60 solder parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
40-60 solder	0.046	6960	533,400	1800	NAA

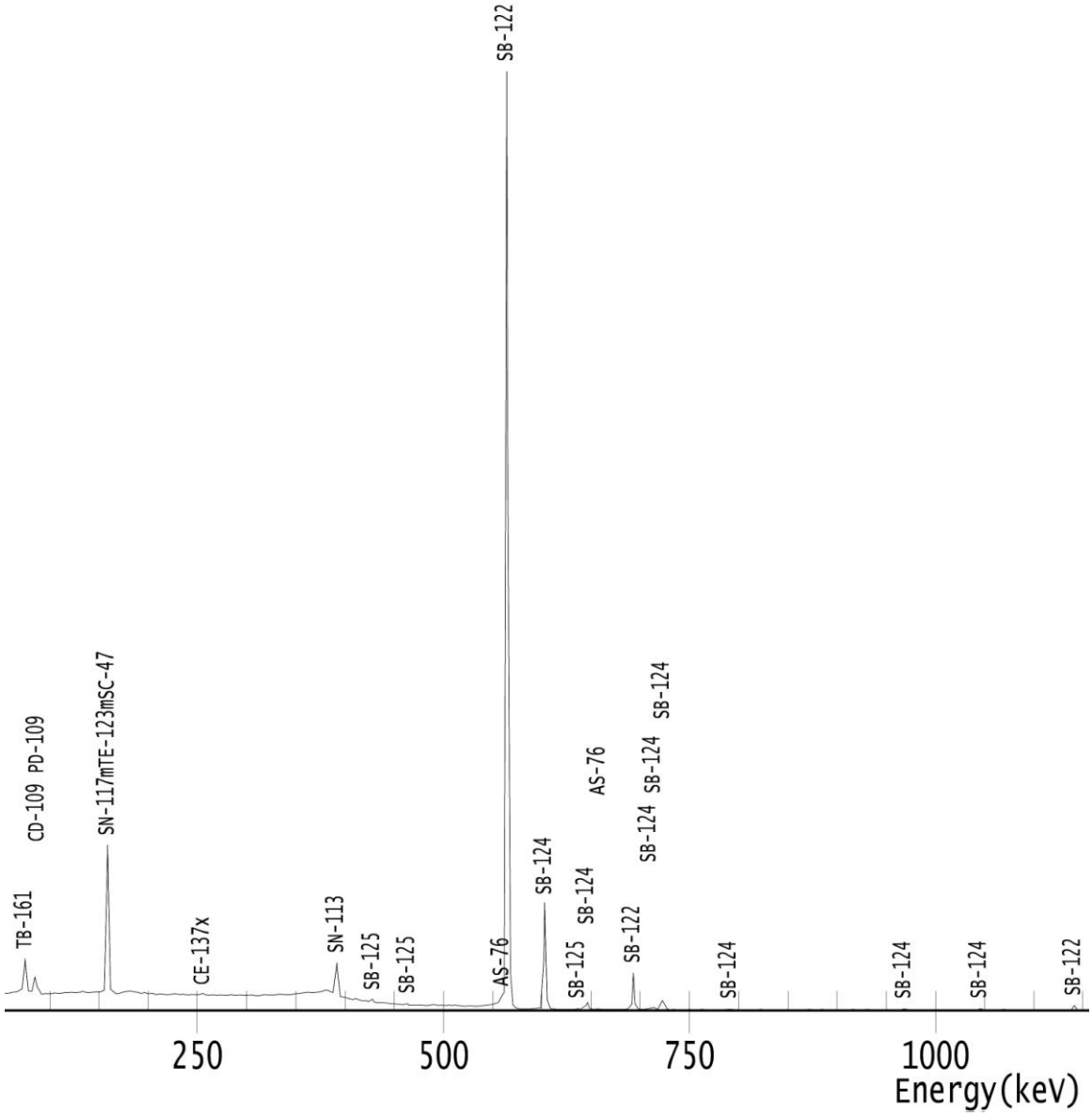


Figure 7-19 Spectrum from 116 minute irradiation of 40-60 solder showing peaks from 10 nuclides

Table 7-18 40-60 solder long irradiation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	6.130E-04	Sodium (Na)	0.0055%	**54.84588**	1.081E-04	11.1312
AS-76	1.956E-02	Arsenic (As)	0.0063%	**62.99579**	1.348E-03	7.669864
CD-109	1.090E-01	Cadmium (Cd)	194.7111%	**1947111**	6.929E-03	231357.1
PD-109	1.140E-01	Palladium (Pd)	192.7779%	**1927779**	1.420E-02	308392.5
SN-113	3.001E-02	Tin (Sn)	14.3593%	**143592.6**	2.137E-03	17670.72
Sn-117m	4.665E-02	Tin (Sn)	1.8385%	**18385.19**	3.165E-03	2227.363
SB-122	1.428E+00	Antimony (Sb)	0.2216%	**2215.743**	4.845E-02	234.758
SB-124	1.590E-01	Antimony (Sb)	0.2308%	**2307.66**	2.646E-03	234.7841
Sb-125*	7.338E-03	Tin (Sn)	38.7628%	**387628.4**	7.628E-04	56011.02
CE-137m	1.111E-02	Cerium (Ce)	1.0783%	**10782.82**	2.874E-03	2992.394
TB-161	1.859E-01	Gadolinium (Gd)	0.6746%	**6746.382**	1.884E-02	962.3751

40-60 solder wire consists of ~40% Sn and ~60% Pb. Many isotopes were identified from Sn and Sb. The results for the long irradiation show that the concentrations calculated from the Sn nuclides do not agree with each other showing the need of further investigations.

Metal alloys can be analyzed through NAA to determine the elemental mass concentrations and ratios of the various constituents found in alloys. By doing this the alloys can be identified and classified. Unwanted metal contamination an also be detected and analyzed

7.5 Uranium in Soil

To verify the uranium concentrations in soil, an additional calculator was created. This calculator uses the masses and activity ratios of an irradiated certified uranium-in-

soil standard and soil samples. Both were irradiated at the same time. This is an example of applying a QC measure to ensure the most accurate results. Irradiating a certified standard in tandem with a sample is a more accurate method to determine the mass concentration in the sample. This is especially true when there is a possibility of a significant variation in the flux of fast and or epithermal neutrons. The U-238 isotope has a few very large resonance radiative capture peaks between the energies of 17 – 24 keV, 33 – 41 keV and 63 – 68 keV. **Figure 7-20** plots the radiative capture cross section vs. neutron energy of U-238.

Having these epithermal absorption peaks caused the U-239 and Np-239 activities in the soil and standard samples to be three to four times higher than the values predicted

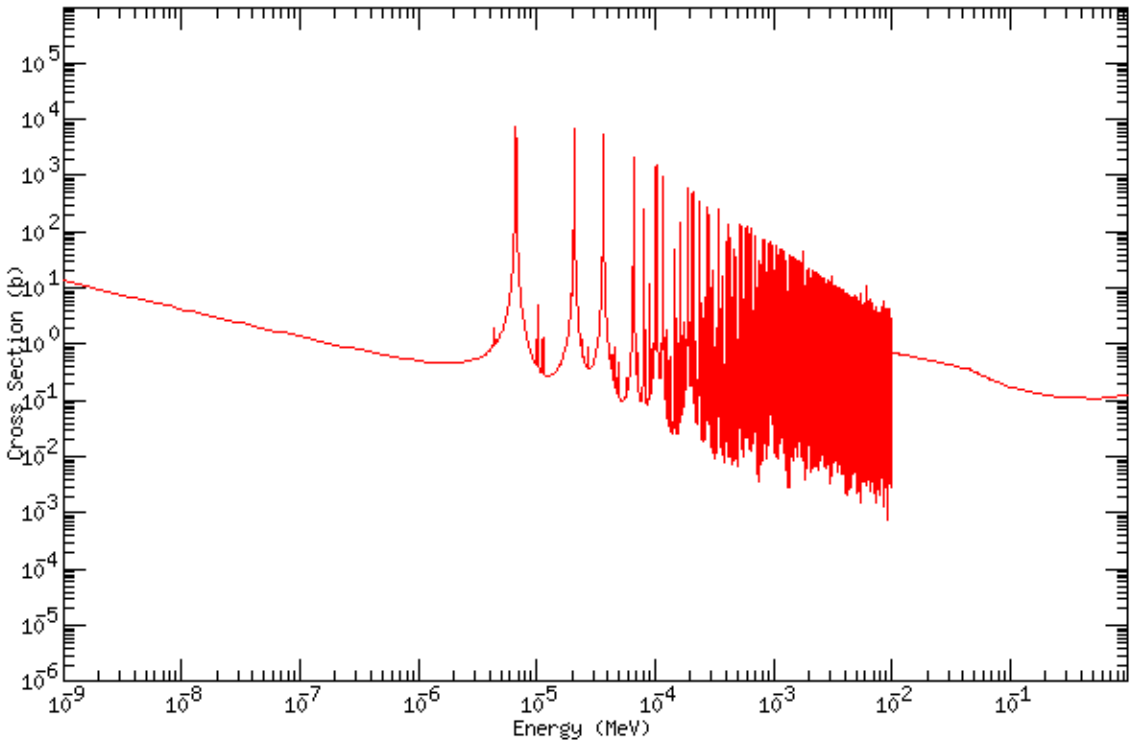


Figure 7-20 U-238 radiative capture cross section (http://atom.kaeri.re.kr/)

using the *Activity Estimator*. This also led to much higher mass concentration results which rendered the *Elemental Concentration Calculator* ineffective for calculating uranium concentrations. Therefore, a certified standard was purchased to precisely quantify uranium concentrations.

The irradiation parameters for the experiment are found in **Table 7-19**. **Table 7-20** and **7-21** shows the uranium concentration results from the *SRM Ratio Calculator* of an irradiated mining soil sample.

Table 7-19 Peruvian mining sample irradiation parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
FLS 11	0.5	7260	NI	1800	Tower

Table 7-20 Standard soil sample: uranium content from the NAA long irradiation

Standard			
	mass (g)	Select Standard	
	0.5014		
Isotope Entry	***Measured Activity (µCi/g)***	**Measured Parent Element**	**Assayed Concentration (mg/kg or ppm)**
Np-239*	2.7059E-01	Uranium (U)	182

Table 7-21 Peruvian mining soil sample: uranium content after the NAA long irradiation

Sample		
mass (g)		
0.5		
Measured Activity **(**μCi/g)	**Measured Parent Element**	**Calculated Concentration (mg/kg or ppm)**
8.3678E-02	Uranium (U)	56.43975139

Uranium and many other elements can be analyzed with NAA and a standard reference material (SRM). By irradiating simultaneously a sample and an SRM the elemental concentrations can be calculated by using the *SRM Ratio Calculator.*

7.6 Criminal Forensics

NAA has many applications in the fields of criminal forensics. The greatest advantage of NAA is the capacity to nondestructively analyze material evidence. After the sample has been analyzed via NAA, it can still be examined by other techniques.

For most forensic sample tests, using NAA, the methodology of element concentration analysis might not be the most effective method. Forensic evidence is frequently collected on/in mediums that could interfere with the NAA analysis and results. This is because the sample may simply be residue smears collected on clothe or tissue rather than measurable samples. Moreover, it is better to determine the elemental ratios using the activated nuclides.

Experiments to look into possible NAA applications for forensics at UNEP were performed to understand the potential forensic capacities of the UUTR. Such experiments

included bullet lead, gunshot residue, shampoo residue on hair, makeup residue, fingernail polish chips and paint chips.

Table 7-22 lists the irradiation and counting parameters used for the experiment. **Table 7-23** shows the results of the calculated elemental concentrations of an irradiated sample of hair, while **Table 7-24** gives the element/ gold ratios of many of the identified elements.

Table 7-22 Shampoo residues on hair parameters

Sample ID	Mass (g)	Irradiation time (sec)	Decay time (sec)	Counting time (sec)	Counting Geometry
Hair and shampoo 5	0.1908	5520	708.665	18,000	NAA

Table 7-23 Shampoo residues on hair long irradiation NAA results

Isotope Entry	*Measured Activity (µCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g)	*Activity uncertainty (µCi/g)*	Mass Composition uncertainty (µg/g)
NA-24	3.917E-04	Sodium (Na)	0.0000%	**0.057187**	1.799E-05	0.006327
CR-51	1.827E-04	Chromium (Cr)	0.0002%	**1.593155**	4.408E-05	0.416552
ZN-65	1.854E-03	Zinc (Zn)	0.0273%	**273.0791**	1.131E-03	168.7601
BR-82	2.103E-04	Bromine (Br)	0.0000%	**0.08605**	8.134E-06	0.009278
SB-122	1.898E-04	Antimony (Sb)	0.0000%	**0.081066**	1.258E-05	0.009769
SB-124	2.788E-05	Antimony (Sb)	0.0000%	**0.476267**	2.538E-06	0.064628
HF-181	3.273E-05	Hafnium (Hf)	0.0000%	**0.226841**	3.772E-06	0.034708
AU-198	1.170E-03	Gold (Au)	0.0000%	**0.027836**	9.817E-05	0.003648
HG-203	7.486E-06	Mercury (Hg)	0.0000%	**0.200274**	4.306E-06	0.116953

Table 7-24 Element/ Gold ratios froma long irradiaion of a hair sample

Element	Element/ Gold Ratio
Chromium (Cr)	53.2
Zinc (Zn)	9810
Bromine (Br)	3.1
Antimony (Sb)	2.9 or 17.1
Hafnium (Hf)	8.2
Mercury (Hg)	7.2

Criminal Forensic samples can be characterized via NAA by determining the elemental ratios of the identified elements found in a sample. These ratios can be compared to other materials to find a match.

CHAPTER 8

CONCLUSIONS

The objectives of this research were to establish the NAA methods and protocols using the UUTR irradiation facility and to develop necessary pre calculator tools allowing for accurate sample analysis (irradiation time, geometry, size, mass, and counting times). Based on these developed protocols, over 260 various samples were analyzed and the data are compiled into the NAA data library.

8.1 The NAA Precalculator Tools

The Excel-based activity calculator, called the *Activity Estimator,* is used prior to sample irradiation in order to provide information regarding the required sample irradiation times, desired neutron flux level and required waiting times. By applying the *Activity Estimator* the optimal experimental conditions can be designed beforehand to assist in obtaining the best results. The *Activity Estimator* also provides potential activities of the samples activated isotopes guiding the user to determine a proper sample waiting time before counting. Another Excel-based calculator developed to assist in the NAA protocols after the sample has been irradiated and counted via gamma spectroscopy is called *Elemental Concentration Calculator*. This tool provides the elemental concentrations of the elements that were identified through the gamma spectroscopy analysis. The use of these two calculators is explained in details in the NAA Manual

provided in **Appendix C.** In the Manual a list of instructions of how to start and complete the NAA is provided; it includes explanation on sample acquisition and preparation, sample irradiation, sample analysis and sample storage. Gamma spectroscopy calibration procedures, Quality Assurance (QA) and NAA Quality Control (QC) measures as also included explained.

8.2 The NAA Data Library

Various samples have been tested at UUTR with the goal to establish the NAA protocols for UNEP and test the accuracy of developed pre-calculator tools. The data collected from the analysis of over 260 samples were summarized into a data-library. The NAA experiments have been carried out to establish the optimal irradiation conditions, using the UUTR thermal irradiator, for various sample matrices. This data base can serve as a foundation to expand on individual areas of study. Another important contribution in developing the NAA data library is in learning what elements can and what elements cannot be easily detected.

Improvements on the NAA protocol can always be made. Using many standard reference materials (SRM) would greatly improve NAA protocols for UNEP. Applying SRM to every NAA procedure would aid in benchmarking new materials and matrices and verifying the overall results.

With the new NAA protocols in place UNEP will be able to support a wide range of new research and development.

`

CHAPTER 9

FUTURE WORK

9.1 Potential for Developing Other Types of NAA

The NAA protocols that were developed as a part of this thesis research represent instrumented neutron activation analysis (INAA) methods. This method employs delayed gamma spectroscopic counting on irradiated samples that have not been chemically altered. Potential for future research may include:

9.1.1 PGNAA. Several research and commercial NAA facilities employ a technique known as prompt gamma neutron activation analysis (PGNAA). This involves spectroscopy of the prompt gamma rays that are emitted during irradiation when nuclei capture neutrons (see **Figure 1-3**).

Such gamma spectroscopy also can detect the activated isotopes with half lives too short to be counted using delayed gamma INAA (Seabury & Caffrey). Typically these irradiations are performed at much lower fluxes and with the aid of special irradiation beam ports. Future NAA work could include investigations into developing PGNAA protocols and irradiation facilities at the UUTR.

9.1.2 Epithermal and fast neutron NAA. Using the UUTR Thermal Irradiator the target samples are irradiated largely with thermal neutrons with much fewer epithermal and fast neutrons. Additional NAA information can be gathered from samples by subjecting them to neutron fluxes composed primarily of either fast or epithermal

neutrons. Many nuclides have much lower detection limits using epithermal neutron activation analysis (ENAA) due to the lower signal to noise ratios of the ENAA gamma spectra (Frontasyeva & Steinnes, 1997).

Several nuclides such as Cd, As, Hg and Cr have higher activation potentials using higher energy neutrons compared to thermal neutron NAA (Win, 2004). Many interferences are greatly reduced by using an epithermal neutron flux instead of a thermal flux (Kiraly, Sanami, & Csikai, 2003). These interferences include relatively high activities from Na-24 and Mn-56 which drown out the peak of nuclides with smaller activities. Since Na-23 and Mn-55 have relatively low epithermal and resonance (n,γ) cross sections their activities tend to be much lower in ENAA spectra compared to INAA. Samples are often irradiated and compared using ENAA and INAA together.

9.1.3 Radiochemical neutron activation analysis. Most NAA experiments require minimal or no sample preparation prior to its irradiation, but with radiochemical neutron activation analysis (RNAA) chemical treatments are essential. Medical isotope activations are the most common uses for RNAA. Chemical treatments may include elemental separations so that only a certain target elements is left to be activated after separation.

RNAA is also used in some regular NAA experiments to remove interferences and or to obtain lower detection limits of target elements (Greenberg, 2008). Future research with respect to RNAA could possible include producing and analyzing medical radionuclides for medical research.

9.2 The Use and Expansion of the NAA Data Library

One of objective of this thesis research was to develop a primary NAA data library based on various sample types as detailed in Chapter 7. Based on this data library, more specific research is now possible to develop. Some examples include:

9.2.1 Correlation between soil minerals and crops production and quality. Agricultural products such as for example potatoes, tomatoes and apples derive their mineral content from the ground in which they are planted. Fertilizers are often applied to enrich the soils with vital nutrients for the plant and the products. NAA experiments could be carried out to analyze the mineral "uptake" from this process. This research could also be expanded to test and compare the effectiveness of different soil enriching techniques.

The local Utah and Idaho agricultural areas consist of large commercial farms and ranches as well as independent growers who sell their products at local farmers markets. NAA could be utilized to locally certify the mineral nutrition contents of test products as well support the studies to determine optimal soils and fertilizers for their individual growing needs.

9.2.2 Air quality. Air samples can be examined in industrial, mining and densely populated areas to monitor the pollution content especially the presence of heavy metals. NAA could be employed to analyze metal content deposited on air filters for both research and environmental quality studies.

9.2.3 Water quality. Many techniques are used to analyze the mineral and toxic metal content in drinking water, municipal and industrial waste water and environmental

waters. NAA could be complementary and often a competitive technique due to its high efficiency and short time required to obtain the final analysis.

9.2.4 Local mining and petroleum studies. State of Utah is known for many productive mining as well as oil and gas industries. These companies perform many analytical studies to determine the locations for prospecting and the purity/ quality of their product(s). NAA is commonly used throughout the world for such studies. Current NAA protocols can be easily adopted for these types of analysis.

9.3 Further Development of NAA Calculators

The *Activity Estimator* and *Elemental Concentration Calculator* developed as integral parts of the NAA protocols are based on the Microsoft EXCEL programs. These complex programs should be streamlined into JAVA to allow for applications on any computer operating system including even the smart phone and tablet apps. Additionally, the calculators can be accompanied with GEANT4 simulations of the UUTR TI in real-time.

APPENDIX A

NAA LONG IRRADIATION NUCLIDE LIBRARY

****
***** L I B R A R Y L I S T I N G R E P O R T *****
****

Filename: C:\GENIE2K\CAMFILES\NAA_LONG.NLB

Nuclide Library Description:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
NA-24	5.385E+004	1368.633*	0.040	100.0000	0.0000
		2754.600	0.080	99.9440	0.0040
K-40	4.030E+016	1460.750*	0.060	10.6700	0.1100
K-42	4.450E+004	312.350	0.250	0.3500	0.0240
		899.400	0.250	0.0520	0.0240
		1524.580*	0.080	18.8000	0.9000
SC-46	7.241E+006	889.277	0.003	99.9840	0.0010
		1120.545*	0.004	99.9870	0.0010
CA-47	3.919E+005	489.230	0.100	6.2000	0.9000
		807.860	0.100	6.2000	0.9000
		1297.090*	0.100	71.0000	9.0000
SC-47	2.890E+005	159.381*	0.015	68.3000	1.5000
CR-51	2.394E+006	320.084*	0.001	10.0800	0.2300
MN-54	2.697E+007	834.827*	0.021	99.9760	0.0010
CO-58	6.127E+006	810.775*	0.009	99.4480	0.0080
		863.959	0.009	0.6830	0.0110
		1674.730	0.010	0.5180	0.0080
FE-59	3.844E+006	142.652	0.002	1.0200	0.0400
		192.349	0.005	3.0800	0.1000
		334.800	0.200	0.2700	0.0100
		1099.251*	0.004	56.5000	1.5000
		1291.596	0.007	43.2000	1.1000
CO-60	1.663E+008	1173.216	0.000	99.9736	0.0000
		1332.486*	0.000	99.9856	0.0000
CU-64	4.572E+004	1345.770*	0.060	0.4730	0.0100
ZN-65	2.110E+007	1115.520*	0.000	50.6000	0.1000
ZN-69m	4.954E+004	438.634*	0.018	94.7700	0.2000
GA-72	5.076E+004	600.950	0.030	5.5400	0.1100
		629.960	0.040	24.8000	0.5000
		834.030*	0.030	95.6300	0.0700
		894.250	0.100	9.8800	0.1700
		1050.690	0.050	6.9100	0.1200
		1596.680	0.080	4.2400	0.0900
		1861.090	0.060	5.2500	0.0800
		2201.660	0.070	25.9000	0.5000
		2490.980	0.070	7.6800	0.2300
		2507.790	0.070	12.7800	0.2300
SE-75	1.035E+007	121.115	0.000	16.7000	0.6000
		136.000	0.000	59.2000	2.5000
		264.651*	0.000	59.8000	0.3000
		279.528	0.000	25.2000	0.3000
		400.646	0.000	11.4000	0.4000
AS-76	9.475E+004	559.100*	0.050	45.0000	2.0000
		657.050	0.050	6.2000	0.5000

		1212.920	0.050	1.4400	0.1100

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
AS-76	9.475E+004	1216.080	0.050	3.4200	0.2400
		1228.520	0.050	1.2200	0.1100
BR-82	1.271E+005	92.190	0.016	0.7200	0.0400
		221.480	0.002	2.2600	0.0700
		273.480	0.008	0.8000	0.0300
		554.348	0.002	70.8000	1.0000
		606.400	0.000	1.2110	0.0120
		619.106	0.004	43.4000	0.6000
		698.374	0.005	28.5000	0.4000
		776.517*	0.003	83.5000	1.2000
		827.828	0.006	24.0000	0.4000
		952.020	0.030	0.3680	0.0170
		1007.590	0.030	1.2710	0.0180
		1044.002	0.005	27.2000	0.4000
		1081.290	0.050	0.6180	0.0180
		1317.473	0.010	26.5000	0.4000
		1474.880	0.010	16.3200	0.2300
		1650.370	0.040	0.7430	0.0110
SR-85	5.602E+006	514.007*	0.002	96.0000	4.0000
RB-86	1.610E+006	1077.000*	0.400	8.6400	0.0400
SR-91	3.467E+004	652.900	0.200	8.0000	0.7000
		749.800	0.100	23.6000	1.7000
		925.800	0.200	3.8000	0.3000
		1024.300*	0.100	33.4000	2.3000
NB-94	6.406E+011	702.627	0.000	100.0000	0.0000
		871.099*	0.000	100.0000	0.0000
NB-95	3.022E+006	765.794*	0.010	100.0000	0.0000
NB-95m	3.118E+005	204.120	0.020	2.2000	0.3000
		235.680	0.020	24.1000	0.6000
ZR-95	5.531E+006	724.184	0.000	43.7000	0.8000
		756.715*	0.000	55.3000	1.1000
NB-97	4.326E+003	657.920*	0.100	98.3900	0.2000
		1024.500	0.300	1.0800	0.1000
RU-97	2.506E+005	215.680*	0.040	86.2000	0.4000
		324.550	0.070	10.2000	0.4000
ZR-97	6.084E+004	507.630	0.000	5.3000	0.6000
		743.360*	0.000	92.8000	0.3000
MO-99	2.374E+005	140.511	0.001	4.5200	0.2400
		181.063	0.008	6.0800	0.1300
		366.430	0.030	1.1500	0.0400
		739.580*	0.060	12.1300	0.1800
		778.000	0.200	4.3400	0.1300
		823.000	0.100	0.1320	0.0070
		961.000	0.100	0.1020	0.0050
TC-99M	2.167E+004	140.508*	0.000	89.0700	0.2400
RU-103	3.400E+006	497.080*	0.000	89.0000	5.0000
		610.330	0.000	5.6000	0.0000
AG-108m	4.008E+009	79.131	0.003	6.6000	0.5000
		433.937	0.005	90.5000	0.6000
		614.281	0.006	89.8000	1.9000
		722.938*	0.008	90.8000	1.9000

CD-109	4.009E+007	88.032*	0.000	3.7200	0.1100

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
PD-109	4.932E+004	88.040*	0.050	3.6000	0.4000
AG-110m	2.158E+007	657.762*	0.002	94.0000	0.4000
		677.623	0.002	10.3500	0.0800
		687.015	0.003	6.4400	0.0600
		706.682	0.003	16.4400	0.1000
		763.944	0.003	22.1400	0.0900
		818.031	0.004	7.3400	0.0400
		884.685	0.003	72.7000	0.3000
		937.493	0.004	34.3600	0.1200
		1384.300	0.004	24.2800	0.0800
		1505.040	0.005	13.0400	0.0500
SN-113	9.945E+006	391.688*	0.000	64.9000	0.7000
IN-114m	4.278E+006	190.270*	0.030	15.5600	0.0700
		558.430	0.030	3.2400	3.0000
		725.240	0.030	3.2400	3.0000
CD-115	1.925E+005	231.443	0.003	0.7400	0.0180
		260.896	0.003	1.9400	0.0400
		266.985	0.003	0.0900	0.0180
		336.240*	0.030	45.9000	1.0000
		492.351	0.004	8.0300	0.1900
		527.901	0.007	27.4000	0.6000
CD-115m	3.853E+006	484.471	0.015	0.2900	0.1100
		933.838*	0.004	2.0000	0.7000
		1290.585	0.011	0.9000	0.4000
SN-117m	1.175E+006	156.020*	0.030	2.1130	0.0120
		158.560	0.020	86.4000	0.4000
TE-121	1.450E+006	507.591	0.011	17.7000	0.6000
		573.139*	0.011	80.3000	2.5000
TE-121m	1.331E+007	212.190*	0.030	81.4000	1.1000
SB-122	2.333E+005	564.240*	0.040	69.3000	0.7000
		692.650	0.040	3.7800	0.1300
		1140.000	1.000	0.7400	0.2100
		1256.930	0.040	0.8000	0.0500
SN-123	1.116E+007	1088.640*	0.100	0.6000	0.1000
SB-124	5.201E+006	602.730*	0.003	97.8000	0.6000
		645.855	0.002	7.3800	0.0700
		709.320	0.013	1.3500	0.0210
		713.781	0.005	2.2700	0.0400
		722.786	0.004	10.7600	0.1200
		790.712	0.006	0.7430	0.0110
		968.201	0.004	1.8880	0.0220
		1045.131	0.003	1.8400	0.0400
		1325.512	0.005	1.6200	0.0400
		1355.175	0.022	1.0400	0.0400
		1376.110	0.050	0.5000	0.0400
		1436.563	0.006	1.2300	0.0500
		1488.886	0.024	0.6900	0.0300
		1690.980	0.004	47.3000	0.7000
		2090.942	0.007	5.5700	0.1100
SB-125	8.615E+007	176.334	0.011	6.7900	0.0700
		427.889*	0.015	29.4000	0.3000

		463.383	0.015	10.4500	0.1100

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
SB-125	8.615E+007	600.557	0.018	17.7800	0.1800
		606.641	0.019	5.0200	0.0600
		635.954	0.018	11.3200	0.1200
SN-125	8.329E+005	332.100	0.050	1.3100	0.0600
		469.850	0.050	1.3800	0.0700
		822.480	0.050	3.9900	0.1900
		915.550	0.050	3.8500	0.1800
		1067.100*	0.050	9.0400	0.2500
		1089.150	0.100	4.2800	0.2000
TE-125m	5.011E+006	109.270*	0.020	0.2820	0.0080
TE-127	3.366E+004	417.900*	0.100	0.9900	0.1000
TE-129	4.176E+003	459.600*	0.050	7.7000	0.6000
		487.390	0.050	1.4200	0.1100
TE-129m	2.903E+006	695.880*	0.060	3.0000	1.1000
BA-131	1.020E+006	78.755	0.013	0.7500	0.0300
		92.301	0.011	0.6400	0.0500
		123.803	0.012	29.1000	0.9000
		133.607	0.014	2.1900	0.0900
		216.090	0.030	19.9000	0.4000
		239.630	0.030	2.4100	0.0800
		246.920	0.060	0.6000	0.0500
		249.440	0.030	2.8100	0.1000
		373.250	0.030	13.3000	1.5000
		404.040	0.030	1.2900	0.0900
		486.480	0.040	1.8900	0.2100
		496.280*	0.030	44.0000	4.0000
		585.020	0.030	1.2300	0.0900
		620.050	0.030	1.5700	0.0900
		923.860	0.040	0.7000	0.0700
		1047.560	0.040	1.1940	0.0240
I-131	6.947E+005	80.183	0.010	2.6200	0.0500
		284.298	0.011	6.0600	0.0900
		364.480*	0.011	81.2000	1.2000
		636.973	0.010	7.2700	0.1100
TE-131m	1.080E+005	102.060	0.010	7.9000	0.3000
		149.710	0.010	5.1000	0.7000
		200.630	0.020	7.5400	0.2500
		240.930	0.010	7.5800	0.2400
		334.270	0.010	9.6000	0.3000
		665.050	0.030	4.3300	0.1500
		773.670*	0.030	38.1000	1.2000
		782.490	0.040	7.8000	0.3000
		793.750	0.030	13.8000	0.5000
		822.780	0.040	6.1100	0.2000
		852.210	0.030	20.6000	0.8000
		1125.460	0.040	11.4000	0.4000
		1206.600	0.040	9.7000	0.4000
BA-133	3.313E+008	81.000	0.000	33.0000	2.2000
		276.397	0.000	6.9000	0.4000
		302.839	0.000	17.8000	0.9000
		356.005*	0.000	60.0000	3.0000

		383.850	0.000	8.7000	0.4000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
BA-133m	1.400E+005	275.925*	0.007	17.5000	0.1000
XE-133	4.530E+005	80.997*	0.003	38.2700	0.7000
CS-134	6.507E+007	475.350	0.050	1.4600	0.0400
		563.227	0.015	8.3800	0.0500
		569.315	0.015	15.4300	0.1100
		604.699*	0.015	97.6000	0.4000
		795.845	0.022	85.4000	0.4000
		801.932	0.022	8.7300	0.0400
		1038.570	0.030	1.0000	0.0100
		1167.940	0.030	1.8000	0.0300
		1365.150	0.040	3.0400	0.0400
BA-135m	1.033E+005	268.218*	0.020	15.6000	0.4000
CE-137m	1.238E+005	254.290*	0.050	11.0000	0.5000
CE-139	1.189E+007	165.850*	0.000	80.3500	0.0800
LA-140	1.450E+005	328.762	0.008	20.6000	0.4000
		432.493	0.012	2.9100	0.0300
		487.021	0.012	44.3000	0.8000
		751.637	0.018	4.2500	0.0500
		815.772	0.019	22.9000	0.4000
		867.846	0.020	5.5900	0.0500
		919.550	0.023	2.7000	0.0400
		925.189	0.021	6.9300	0.0800
		1596.210*	0.040	95.4000	0.0800
		2347.880	0.050	0.8490	0.0100
		2521.400	0.050	3.4200	0.0500
CE-141	2.808E+006	145.440	0.000	48.4000	0.4000
PR-142	6.883E+004	1575.600*	0.500	3.7000	0.5000
CE-143	1.192E+005	57.356	0.007	11.7000	0.4000
		231.550	0.002	2.0500	0.0500
		293.266*	0.002	42.8000	0.5000
		350.619	0.003	3.2300	0.0400
		490.368	0.005	2.1600	0.0300
		664.571	0.015	5.6900	0.0700
		721.929	0.013	5.3900	0.0700
		880.460	0.010	1.0310	0.0130
ND-147	9.487E+005	91.106*	0.020	28.0000	1.1000
		531.016	0.022	13.1000	0.9000
PM-151	1.022E+005	104.840	0.010	3.5000	0.3000
		167.750	0.020	8.3000	0.6000
		177.160	0.010	3.8000	0.3000
		240.090	0.010	3.8000	0.3000
		275.210	0.020	6.8000	0.6000
		340.080*	0.010	22.5000	0.9000
		445.680	0.020	4.0000	0.3000
		717.720	0.080	4.1000	0.3000
EU-152	4.272E+008	40.000	0.001	59.0000	0.1300
		45.400	0.001	14.8000	0.1300
		121.783*	0.002	28.4000	0.4000
		244.699	0.001	7.4900	0.1300
		344.281	0.002	26.6000	0.3000
		367.790	0.001	0.8300	0.1300

		387.290	0.005	0.4600	0.0300

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
EU-152	4.272E+008	411.115	0.005	2.2300	0.0300
		443.976	0.005	2.7800	0.0700
		778.903	0.006	12.9600	0.1300
		867.388	0.008	4.1500	0.0900
		964.131	0.009	14.3400	0.2000
		1085.914	0.003	9.9200	0.1600
		1089.700	0.003	1.7100	0.1600
		1112.116	0.017	13.5500	0.2000
		1212.950	0.017	1.4000	0.2000
		1299.124	0.017	1.6300	0.2000
		1408.011	0.014	20.8700	0.1100
EU-152m	3.352E+004	40.100	0.030	21.6000	1.1000
		45.400	0.030	5.4000	1.1000
		121.780	0.030	7.2000	1.1000
		344.310	0.030	2.4000	0.3000
		841.630*	0.040	14.6000	2.1000
		963.370	0.040	12.0000	1.8000
		1314.670	0.040	1.5500	1.8000
		1389.000	0.040	0.7700	1.8000
GD-153	2.087E+007	41.540	0.000	38.9000	0.2000
		47.000	0.000	15.2000	0.2000
		69.673	0.000	2.5400	0.1100
		83.370	0.000	0.2110	0.0220
		97.432*	0.000	30.2000	0.6000
		103.181	0.000	21.4000	0.7000
SM-153	1.666E+005	69.674	0.001	4.8500	0.0700
		75.422	0.006	0.3500	0.0160
		83.367	0.003	0.2030	0.0130
		89.485	0.003	0.1790	0.0210
		97.429	0.003	0.8470	0.0110
		103.180*	0.001	31.4000	0.4000
EU-154	2.711E+008	123.068*	0.003	40.4000	0.8000
		247.932	0.015	6.8300	0.1300
		591.760	0.030	4.9100	0.0900
		722.300	0.000	20.0000	0.4000
		756.860	0.030	4.5000	0.0900
		873.200	0.030	12.0900	0.2200
		996.300	0.030	10.3400	0.1900
		1004.760	0.030	17.9000	0.4000
		1274.510	0.070	34.4000	0.7000
GD-159	6.682E+004	50.400	0.000	4.0000	1.1000
		58.000	0.010	2.3000	0.6000
		363.560*	0.030	11.0000	3.0000
TB-160	6.247E+006	86.788	0.000	12.8000	0.3000
		197.035	0.001	5.6100	0.1300
		215.646	0.001	4.4100	0.0900
		298.580	0.002	28.9000	0.6000
		879.383*	0.003	32.9000	0.6000
		962.317	0.004	10.5300	0.2000
		966.171	0.003	27.2000	0.5000
		1177.962	0.004	16.2000	0.3000

		1271.880	0.008	8.1300	0.1500

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
TB-161	5.944E+005	52.100	0.000	4.6500	0.2500
		57.196	0.002	1.7900	0.1100
		74.567*	0.000	10.2000	0.6000
HO-166m	3.787E+010	55.700	0.000	8.0000	0.5000
		80.574	0.008	12.7000	0.5000
		184.412*	0.006	72.0000	2.2000
		280.450	0.008	29.5000	0.9000
		410.930	0.020	11.2000	0.4000
		529.800	0.030	9.6000	0.3000
		570.980	0.030	5.4600	0.1600
		670.490	0.020	5.4400	0.1600
		711.680	0.020	54.7000	1.6000
		752.270	0.030	12.2000	0.4000
		810.280	0.020	57.5000	1.7000
		830.570	0.020	9.7000	0.3000
YB-169	2.767E+006	50.742*	0.000	94.4000	1.8000
		57.500	0.000	38.5000	1.0000
		63.010	0.000	1.1000	1.1000
		63.121	0.000	44.2000	1.0000
		93.615	0.000	2.6100	0.0600
		109.780	0.000	17.5000	0.4000
		118.190	0.000	1.8700	0.0400
		129.900	0.000	0.3000	0.3000
		130.524	0.000	11.3100	0.2100
		177.214	0.000	22.2000	0.5000
		197.958	0.000	35.8000	0.7000
		240.332	0.003	0.1138	0.0000
		261.079	0.000	1.7100	0.0300
		307.500	0.000	0.3000	0.3000
		307.738	0.000	10.0500	0.1900
TM-170	1.111E+007	51.354	0.001	1.2700	0.0800
		52.389	0.001	2.2400	0.1300
		59.400	0.000	0.9300	0.0600
		84.255*	0.000	3.2600	0.1600
ER-171	2.707E+004	50.742	0.000	23.3000	1.3000
		57.500	0.000	9.6000	0.6000
		111.621	0.004	20.5000	1.2000
		116.656	0.006	2.3000	0.1100
		124.017	0.004	9.1000	0.5000
		210.600	0.030	0.6400	0.0400
		277.430	0.050	0.5800	0.0300
		295.901	0.014	28.9000	1.4000
		308.291*	0.018	64.0000	3.0000
		796.550	0.130	0.6400	0.0300
		907.700	0.400	0.6300	0.0300
HF-175	6.048E+006	52.965	0.001	25.8100	0.1900
		54.070	0.001	45.4000	0.4000
		61.300	0.000	18.9000	0.4000
		343.400*	0.000	86.8600	0.0700
YB-175	3.620E+005	52.965	0.001	1.1000	0.1400
		54.070	0.001	1.9300	0.2400

		61.300	0.000	0.8000	0.1000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
YB-175	3.620E+005	113.803	0.004	1.9100	0.2500
		282.517	0.014	3.1000	0.4000
		396.322*	0.020	6.5000	0.8000
LU-177	5.797E+005	54.611	0.001	1.6400	0.1200
		55.790	0.001	2.8700	0.2000
		112.952	0.003	6.4000	0.4000
		208.359*	0.010	11.0000	0.8000
LU-177m	1.390E+007	54.611	0.001	32.7000	1.5000
		55.790	0.001	57.0000	3.0000
		63.200	0.000	24.0000	1.2000
		105.360	0.020	12.2000	1.3000
		112.952	0.003	21.8000	2.4000
		128.480	0.020	15.5000	1.8000
		153.250	0.040	18.2000	2.1000
		174.370	0.060	12.8000	1.5000
		204.060	0.060	14.5000	1.7000
		208.359*	0.010	62.0000	7.0000
		228.440	0.060	38.0000	5.0000
		281.780	0.070	14.2000	1.6000
		319.040	0.020	10.0000	4.0000
		327.660	0.080	17.8000	2.0000
		378.510	0.080	28.0000	4.0000
		413.700	0.040	17.0000	6.0000
		418.510	0.100	20.3000	2.3000
HF-179m	2.169E+006	54.611	0.001	29.7000	2.4000
		55.790	0.001	52.0000	5.0000
		63.200	0.000	21.8000	1.8000
		122.700	0.070	28.0000	1.6000
		146.150	0.070	27.4000	1.5000
		169.780	0.070	19.6000	1.2000
		192.660	0.110	21.7000	2.1000
		217.040	0.120	9.1000	0.8000
		236.480	0.140	19.0000	0.9000
		268.850	0.140	11.4000	0.8000
		315.930	0.140	20.5000	0.8000
		362.550	0.150	40.1000	1.7000
		409.700	0.200	21.7000	1.0000
		453.590*	0.200	69.0000	4.0000
HF-181	3.662E+006	56.277	0.001	9.0200	0.2400
		57.532	0.001	15.7000	0.5000
		133.021	0.019	43.3000	0.6000
		345.930	0.060	15.1200	0.1300
		482.180*	0.090	80.5000	0.5000
TA-182	9.887E+006	57.982	0.001	10.5600	0.2400
		59.318	0.000	18.4000	0.5000
		65.722	0.000	2.9200	0.0700
		67.200	0.000	7.8100	0.2200
		67.750*	0.000	41.2000	1.0000
		84.681	0.000	2.6500	0.0700
		100.106	0.000	14.1000	0.3000
		113.673	0.000	1.8800	0.0400

		152.431	0.000	6.9300	0.1300

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
TA-182	9.887E+006	156.388	0.000	2.6400	0.0500
		179.395	0.000	3.0800	0.0600
		198.353	0.000	1.4400	0.0300
		222.110	0.000	7.4900	0.1400
		229.322	0.001	3.6300	0.0700
		264.075	0.000	3.6100	0.0700
		1001.695	0.002	2.0700	0.0400
		1121.301	0.002	34.9000	0.6000
		1189.050	0.002	16.2000	0.3000
		1221.407	0.002	27.0000	0.5000
		1231.016	0.002	11.4400	0.2000
		1257.418	0.002	1.4900	0.0300
		1289.156	0.002	1.3490	0.0240
OS-185	8.087E+006	59.718	0.001	20.9000	0.3000
		61.140	0.001	36.2000	0.5000
		69.300	0.000	15.5000	0.4000
		646.116*	0.009	81.0000	1.0000
		874.813	0.013	6.6100	0.1600
		880.523	0.013	5.0000	0.1300
RE-186m	3.263E+005	57.982	0.001	1.5100	0.0500
		59.318	0.000	2.6300	0.0800
		63.000	0.001	1.7300	0.0800
		137.157*	0.008	8.2000	0.3000
W-187	8.539E+004	59.718	0.001	7.2000	0.3000
		61.140	0.001	12.5000	0.5000
		69.300	0.001	5.3600	0.5000
		72.002	0.004	11.1000	0.4000
		134.247	0.007	8.8000	0.3000
		479.550	0.022	21.8000	0.8000
		551.520	0.001	5.0800	0.5000
		618.260	0.040	6.2800	0.2200
		625.519	0.001	1.0900	0.5000
		685.730*	0.040	27.3000	1.0000
		745.216	0.004	0.2980	0.4000
		772.890	0.004	4.1200	0.4000
		864.550	0.004	0.3360	0.4000
RE-188	6.113E+004	61.487	0.001	1.3600	0.1000
		63.000	0.001	2.3500	0.1800
		155.032*	0.012	14.9000	0.6000
		632.980	0.020	1.2500	0.0500
OS-191	1.331E+006	63.287	0.001	16.1000	1.6000
		64.896*	0.001	28.0000	3.0000
		73.600	0.000	12.0000	1.2000
		129.431	0.005	25.7000	2.4000
IR-192	6.379E+006	66.832	0.002	4.5900	0.0900
		205.796	0.000	3.3000	0.1000
		295.958	0.000	28.6700	0.1000
		308.457	0.000	30.0000	0.0900
		316.508*	0.000	82.8100	0.2100
		468.072	0.000	47.8300	0.1700
		484.578	0.000	3.1800	0.1700

		588.584	0.001	4.5150	0.0150

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
IR-192	6.379E+006	604.415	0.000	8.2300	0.0600
		612.466	0.000	5.3090	0.0180
OS-193	1.098E+005	63.287	0.001	3.6700	0.2400
		64.896*	0.001	6.3000	0.5000
		73.039	0.012	3.2000	0.5000
		73.600	0.000	2.7200	0.1900
		138.920	0.030	4.3000	0.3000
		460.490	0.030	3.9500	0.2500
IR-194	6.894E+004	293.541	0.014	2.5200	0.4000
		328.448	0.014	13.1000	1.8000
		645.146*	0.020	1.1700	0.1600
		938.700	0.020	0.5990	0.1600
		1150.760	0.020	0.6010	0.1600
PT-195m	3.473E+005	65.122	0.002	22.5000	1.5000
		66.832*	0.002	38.3000	3.0000
		75.700	0.000	16.8000	1.2000
		98.900	0.020	11.4000	0.9000
		129.790	0.020	2.8300	0.2100
HG-197	2.309E+005	66.990	0.001	20.9000	0.1100
		68.804*	0.001	35.7000	0.1800
		77.680	0.002	30.7000	0.4000
HG-197m	8.568E+004	69.500	0.001	22.0000	0.4000
		80.300	0.000	7.3000	0.7000
		133.980*	0.050	34.0000	4.0000
		279.000	0.100	5.0000	0.5000
PT-197	6.588E+004	68.804	0.001	1.6800	0.1700
		77.350*	0.050	17.0000	2.4000
		191.437	0.010	3.7000	0.4000
AU-198	2.327E+005	68.895	0.002	0.8100	0.0700
		70.819	0.002	1.3800	0.1200
		80.300	0.000	0.6100	0.0500
		411.804*	0.001	95.5800	0.1200
		675.887	0.002	0.8040	0.0030
		1087.690	0.003	0.1590	0.0000
AU-198m	1.987E+005	66.990	0.001	27.5000	1.0000
		68.804	0.001	47.0000	1.7000
		78.000	0.000	20.6000	0.8000
		97.210	0.050	69.0000	4.0000
		180.310	0.050	65.0000	4.0000
		204.100	0.060	50.0000	4.0000
		214.890*	0.050	77.0000	1.0000
HG-203	4.026E+006	279.190*	0.000	77.3000	0.8000
BI-210m	9.909E+013	70.832	0.001	3.9000	0.4000
		72.871	0.001	6.5000	0.6000
		82.600	0.000	2.8900	0.2500
		265.600*	0.000	50.0000	5.0000
		304.700	0.000	28.0000	3.0000
		649.700	0.000	3.9000	0.4000
PA-233	2.330E+006	75.354	0.004	1.3900	0.0800
		86.814	0.003	1.9700	0.1200
		94.665	0.002	10.9000	0.4000

		98.439	0.002	17.7000	0.6000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
PA-233	2.330E+006	103.971	0.009	0.8700	0.0300
		111.000	0.000	8.2000	0.3000
		271.480	0.080	0.3280	0.0120
		300.340	0.020	6.6200	0.0600
		312.170*	0.020	38.6000	0.4000
		340.810	0.030	4.4700	0.0400
		375.450	0.040	0.6790	0.0080
		398.620	0.080	1.3900	0.0120
		415.760	0.040	1.7450	0.0160
NP-239	2.035E+005	61.460	0.050	1.0500	0.8000
		99.550	0.050	13.9000	0.8000
		103.760	0.050	22.3000	1.2000
		106.123*	0.002	22.9000	1.2000
		117.000	0.000	8.6000	0.6000
		209.753	0.002	3.2700	0.2400
		228.183	0.001	10.8000	0.6000
		277.599	0.001	14.2000	0.2000
		315.880	0.003	1.6000	0.1100
		334.310	0.002	2.0400	0.1800

* = key line

TOTALS: 104 Nuclides 532 Energy Lines

APPENDIX B

NAA SHORT IRRADIATION NUCLIDE LIBRARY

****
***** L I B R A R Y L I S T I N G R E P O R T *****
****

Filename: C:\GENIE2K\CAMFILES\NAA_SHORT.NLB

Nuclide Library Description:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
NA-24	5.385E+004	1368.630*	0.040	100.0000	0.0000
		2754.600	0.080	99.9440	0.0040
MG-27	5.677E+002	170.686	0.015	0.8000	0.1000
		843.760	0.030	71.8000	0.4000
		1014.440*	0.040	28.0000	0.4000
MG-27a	5.677E+002	1014.440*	0.040	28.0000	0.4000
Al-28	1.345E+002	1778.850*	0.000	100.0000	0.0010
Si-31	9.438E+003	1267.250*	0.500	0.0700	0.0100
CL-38	2.234E+003	1642.714	0.050	31.9000	0.1000
		2167.405*	0.050	42.4000	0.1000
AR-41	6.577E+003	1293.640*	0.040	99.1600	0.0300
K-42	4.450E+004	312.600	0.080	0.3360	0.0500
		1524.700*	0.080	18.0800	0.0500
TI-51	3.456E+002	320.076*	0.006	93.1000	0.4000
		608.550	0.050	1.1800	0.1000
		928.630	0.060	6.9000	0.4000
V-52	2.250E+002	1434.060*	0.010	100.0000	1.5000
MN-54	2.697E+007	834.827*	0.021	99.9760	0.0010
MN-56	9.283E+003	846.754*	0.020	98.9000	0.3000
		1810.720	0.040	27.2000	0.8000
		2113.050	0.040	14.3000	0.4000
		2522.880	0.060	0.9900	0.0300
		2657.450	0.060	0.6530	0.0300
FE-59	3.845E+006	192.349	0.005	3.0800	0.1000
		1099.251*	0.004	56.5000	1.5000
		1291.596	0.007	43.2000	1.1000
CO-60m	6.282E+002	58.603*	0.007	2.0359	0.0007
		1332.501	0.005	0.2400	0.0300
CU-64	4.572E+004	511.000	0.000	0.0000	0.0000
		1345.770*	0.060	0.4730	0.0100
NI-65	9.072E+003	366.270	0.000	4.6100	0.2000
		1115.520	0.000	14.8000	0.6000
		1481.840*	0.000	23.5000	0.8000
CU-66	3.072E+002	1039.200*	0.200	9.2000	1.8000
ZN-69m	4.954E+004	438.634*	0.018	94.7700	0.2000
ZN-71	1.426E+004	142.600	0.050	5.6000	0.6000
		386.280*	0.050	93.0000	3.0000
		487.340	0.050	62.0000	4.0000
		511.550	0.050	28.4000	2.1000
		596.070	0.070	27.9000	2.1000
		620.190	0.050	57.0000	4.0000
		753.410	0.070	3.3000	0.3000
		964.700	0.100	4.3000	0.5000
GA-72	5.076E+004	600.950	0.030	5.5400	0.1100

		629.960	0.040	24.8000	0.5000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
GA-72	5.076E+004	786.440	0.080	3.2000	0.0600
		834.030*	0.030	95.6300	0.0700
		894.250	0.100	9.8800	0.1700
		1050.690	0.050	6.9100	0.1200
		1464.000	0.070	3.5500	0.0600
		1596.680	0.080	4.2400	0.0900
		1861.090	0.060	5.2500	0.0800
		2201.660	0.070	25.9000	0.5000
		2490.980	0.070	7.6800	0.2300
		2507.790	0.070	12.7800	0.2300
GE-75	4.967E+003	264.660*	0.000	11.0000	0.0000
AS-76	9.475E+004	559.100*	0.050	45.0000	2.0000
		657.050	0.050	6.2000	0.5000
		1216.080	0.050	3.4200	0.2400
GE-77	4.068E+004	211.030	0.030	30.8000	1.0000
		215.500	0.030	28.6000	0.9000
		264.440*	0.030	53.9000	0.5000
		367.400	0.030	14.0000	0.4000
		416.330	0.030	21.8000	0.6000
		558.020	0.030	16.1000	0.4000
		631.820	0.030	6.9500	0.1800
		714.350	0.030	7.1700	0.1800
		1085.190	0.030	6.0500	0.1500
		1368.400	0.500	3.3000	0.4000
BR-80	1.061E+003	616.300*	0.500	7.0000	0.7000
		665.800	0.200	1.0800	0.1300
SE-81	1.107E+003	275.930*	0.040	0.5100	0.0600
		290.040	0.070	0.4300	0.0600
		828.270	0.050	0.2000	0.0300
SE-81m	3.435E+003	102.990*	0.060	9.8000	0.4000
BR-82	1.271E+005	221.480	0.002	2.2600	0.0700
		554.348	0.002	70.8000	1.0000
		619.106	0.004	43.4000	0.6000
		698.374	0.005	28.5000	0.4000
		776.517*	0.003	83.5000	1.2000
		827.828	0.006	24.0300	0.4000
		1044.002	0.005	27.2300	0.4000
		1317.473	0.010	26.4800	0.4000
		1474.880	0.010	16.3200	0.2300
BR-83	8.640E+003	529.640*	0.010	1.2000	0.5000
SE-83	1.338E+003	225.180	0.050	32.6000	1.5000
		356.700*	0.040	69.9000	1.5000
		457.410	0.100	3.4600	0.1700
		510.060	0.070	43.0000	3.0000
		553.200	0.210	3.3600	0.2300
		571.910	0.090	4.3000	0.3000
		664.800	0.100	3.2900	0.2300
		712.110	0.100	3.1000	0.3000
		718.030	0.100	15.0000	1.7000
		799.040	0.090	14.8000	1.6000
		836.520	0.090	13.0000	3.0000

		866.640	0.090	8.2000	0.9000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
SE-83	1.338E+003	883.610	0.100	7.2000	0.3000
		887.810	0.100	4.3000	0.6000
		1064.110	0.100	5.5000	0.5000
		1191.750	0.140	4.1300	0.1800
		1317.050	0.210	3.9800	0.2300
		1341.290	0.170	5.4000	0.5000
		1352.590	0.170	4.6100	0.2400
		1894.880	0.210	7.8000	0.4000
		2290.300	0.300	9.3000	0.4000
KR-85	1.613E+004	151.170*	0.030	75.4000	1.8000
		304.870	0.020	14.0000	0.4000
SR-85m	4.058E+003	151.194	0.015	12.9000	0.7000
		231.860*	0.020	84.4000	2.2000
RB-86	1.610E+006	1077.000*	0.400	8.6400	0.0400
SR-87m	1.009E+004	388.531*	0.003	81.9000	0.5000
RB-88	1.067E+003	898.030	0.040	14.0000	0.8000
		1836.000*	0.050	21.4000	1.3000
		2677.892	0.021	1.9600	0.1200
MO-90	2.041E+004	122.370	0.022	64.0000	4.0000
		162.930	0.090	6.0000	0.6000
		203.130	0.100	6.4000	0.6000
		257.340*	0.040	78.0000	4.0000
		323.200	0.180	6.3000	0.6000
		445.370	0.210	6.0000	0.7000
		511.000	0.000	49.6000	0.0000
		941.500	0.400	5.5000	0.7000
		1271.300	0.600	4.1000	0.5000
Y-90m	1.148E+004	202.510*	0.030	96.5800	0.1800
		479.530	0.040	90.7100	0.0700
SR-91	3.467E+004	652.300	0.300	3.0000	0.3000
		652.900	0.200	8.0000	0.7000
		749.800	0.100	23.6000	1.7000
		925.800	0.200	3.8000	0.3000
		1024.300*	0.100	33.4000	2.3000
MO-93m	2.466E+004	263.061	0.006	58.0000	3.0000
		684.673*	0.009	99.6900	0.0900
		1477.116	0.019	99.0000	0.5000
NB-95m	3.118E+005	204.120	0.020	2.2000	0.3000
		235.680	0.020	24.1000	0.6000
NB-97	4.326E+003	657.920*	0.100	98.3900	0.2000
ZR-97	6.084E+004	355.390	0.000	2.2700	0.0000
		507.630	0.000	5.3000	0.6000
		743.360*	0.000	92.8000	0.3000
		1147.000	0.000	2.6000	0.0000
MO-99	2.377E+005	140.508*	0.000	88.7000	0.2400
		181.063	0.000	6.2000	0.5000
		739.580	0.000	12.8000	0.8000
		778.000	0.000	4.5000	0.0000
TC-99M	2.167E+004	140.508*	0.000	89.0700	0.2400
MO-101	8.766E+002	80.930	0.040	3.8400	0.1800
		191.920*	0.030	18.8000	0.4000

		195.950	0.060	2.8600	0.1700

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
MO-101	8.766E+002	505.940	0.030	11.8000	0.8000
		590.100	0.190	5.6000	1.4000
		590.910	0.030	16.4000	1.6000
		695.600	0.090	7.2000	0.6000
		713.020	0.100	3.4000	0.3000
		877.390	0.040	3.4000	0.3000
		934.210	0.030	3.4000	0.3000
		1011.050	0.140	2.2600	0.2200
		1012.480	0.040	12.8000	0.8000
		1161.000	0.040	3.9700	0.2300
		1251.100	0.040	4.6000	0.3000
		1304.010	0.040	2.7800	0.1700
		1532.500	0.040	6.0000	0.4000
		2032.110	0.050	6.9000	0.4000
		2041.240	0.050	2.1100	0.1300
TC-101	8.520E+002	127.230	0.030	2.8600	0.2000
		306.830*	0.050	88.0000	6.0000
		545.060	0.050	6.0000	0.4000
RH-104m	2.604E+002	51.423*	0.002	48.2770	0.0050
		77.533	0.010	2.0800	0.0500
		97.114	0.003	2.9900	0.1500
AG-108	1.422E+002	623.970*	0.000	1.7600	0.2500
AG-108m	4.008E+009	433.937	0.005	90.5000	0.6000
		614.281	0.006	89.8000	1.9000
		722.938*	0.008	90.8000	1.9000
PD-109	4.932E+004	88.040*	0.050	3.6000	0.4000
PD-109m	2.814E+002	188.900*	0.100	55.9000	0.0000
AG-110m	2.158E+007	446.811	0.003	3.7500	0.0300
		657.762*	0.002	94.6000	0.4000
		677.623	0.002	10.3500	0.0800
		687.015	0.003	6.4400	0.0600
		706.682	0.003	16.4400	0.1000
		744.277	0.003	4.7300	0.0300
		763.944	0.003	22.2900	0.0900
		818.031	0.004	7.3400	0.0400
		884.685	0.003	72.7000	0.3000
		937.493	0.004	34.3600	0.1200
		1384.300	0.004	24.2800	0.0800
		1505.040	0.005	13.0400	0.0500
CD-111m	2.916E+003	150.825	0.015	29.1000	1.9000
		245.395*	0.020	94.0000	7.0000
PD-111	1.404E+003	59.820	0.080	0.5300	0.0700
		70.430	0.080	0.7800	0.1400
		289.800	0.100	0.1020	0.0130
		376.680	0.080	0.4400	0.0600
		509.100	0.600	0.2100	0.0400
		547.000	0.080	0.3700	0.0500
		580.000*	0.080	0.8400	0.0900
		623.200	0.100	0.2800	0.0400
		650.400	0.100	0.5500	0.0600
		709.800	0.200	0.1260	0.0180

		835.700	0.200	0.2700	0.0400

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
PD-111	1.404E+003	1388.500	0.200	0.5400	0.0700
		1459.000	0.300	0.5600	0.0700
PD-111x	1.980E+004	70.440	0.070	8.3000	1.7000
		172.180*	0.080	34.0000	4.0000
		391.300	0.100	5.4000	0.9000
		575.000	0.100	3.2000	0.6000
		632.800	0.200	3.6000	0.6000
		694.200	0.100	2.0000	0.3000
CD-115	1.925E+005	336.240*	0.030	45.9000	1.0000
		492.351	0.004	8.0300	0.1900
		527.901	0.007	27.4000	0.6000
IN-115m	1.615E+004	336.240*	0.030	45.8000	2.3000
IN-116m	3.265E+003	138.326	0.008	3.2900	0.1200
		416.860	0.030	28.9000	0.9000
		818.700	0.200	11.5000	0.5000
		1097.300	0.200	56.2000	1.2000
		1293.540*	0.040	84.4000	1.8000
		1507.400	0.200	10.0000	0.4000
		1753.800	0.600	2.4600	0.0800
		2112.100	0.400	15.5000	0.5000
CD-117	8.964E+003	89.730	0.010	3.2600	0.2200
		273.349*	0.018	27.9000	0.7000
		344.459	0.010	17.9000	0.6000
		434.190	0.017	9.8000	0.5000
		831.800	0.030	2.2600	0.1100
		880.710	0.017	3.9600	0.2200
		1051.700	0.100	3.7900	0.2200
		1303.270	0.030	18.4000	0.6000
		1576.620	0.030	11.2000	0.4000
		1723.060	0.030	2.0100	0.1000
CD-117x	1.210E+004	366.910	0.030	3.3300	0.2500
		564.397	0.016	14.7000	0.9000
		631.800	0.040	2.8000	0.2000
		748.060	0.030	4.5000	1.1000
		860.410	0.040	7.9000	0.4000
		931.370	0.040	3.6400	0.2500
		1029.060	0.030	11.7000	0.5000
		1065.980	0.030	23.1000	0.7000
		1234.590	0.030	11.0000	0.4000
		1339.300	0.500	2.0700	0.2400
		1432.910	0.030	13.4000	0.4000
		1997.330*	0.030	26.2000	0.5000
		2096.400	0.040	7.4400	0.2200
		2322.750	0.080	7.8600	0.2400
IN-117	2.628E+003	158.600	0.200	87.0000	9.0000
		552.900*	0.200	100.0000	10.0000
IN-117m	6.990E+003	158.600	0.200	15.9000	1.7000
		315.302*	0.013	19.1000	0.9000
SN-117m	1.175E+006	156.020	0.030	2.1130	0.0120
		158.560*	0.020	86.4000	0.4000
TE-121	1.450E+006	507.591	0.011	17.7000	0.6000

		573.139*	0.011	80.3000	2.5000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
SB-122	2.333E+005	563.930*	0.000	70.6000	0.4000
		692.800	0.000	3.7000	0.0000
SB-122m	2.526E+002	61.413*	0.001	54.0000	6.0000
		76.060	0.001	18.5000	2.1000
SN-123m	2.405E+003	160.330*	0.050	85.6000	2.0000
SN-125	5.712E+002	331.900*	0.200	99.6000	2.0000
SN-125x	8.329E+005	332.100	0.050	1.3100	0.0600
		469.850	0.050	1.3800	0.0700
		822.480	0.050	3.9900	0.1900
		915.550	0.050	3.8500	0.1800
		1067.100*	0.050	9.0400	0.2500
		1089.150	0.100	4.2800	0.2000
		2001.840	0.050	1.7900	0.0800
TE-127	3.366E+004	417.900*	0.100	0.9900	0.1000
I-128	1.499E+003	442.900*	0.000	17.0000	0.0000
		526.560	0.000	1.5800	0.0000
TE-129	4.176E+003	459.600*	0.050	7.7000	0.6000
		487.390	0.050	1.4200	0.1100
TE-129x	2.903E+006	695.880*	0.060	3.0000	1.1000
BA-131	1.020E+006	123.803	0.012	29.1000	0.9000
		133.607	0.014	2.1900	0.0900
		216.090	0.030	19.9000	0.4000
		239.630	0.030	2.4100	0.0800
		249.440	0.030	2.8100	0.1000
		373.250	0.030	13.3000	1.5000
		496.280*	0.030	44.0000	4.0000
BA-131m	8.760E+002	108.450*	0.160	55.0000	2.0000
I-131	6.947E+005	80.183	0.010	2.6200	0.0500
		284.298	0.011	6.0600	0.0900
		364.480*	0.011	81.2000	1.2000
		636.973	0.010	7.2700	0.1100
TE-131	1.500E+003	149.716*	0.005	68.9000	0.9000
		452.323	0.002	18.2200	0.2500
		492.660	0.010	4.8400	0.0700
		602.039	0.003	4.2000	0.0600
		948.542	0.004	2.2600	0.0400
		997.250	0.010	3.3400	0.0500
		1146.960	0.010	4.9600	0.0700
TE-131x	1.080E+005	81.140	0.020	4.0600	0.1400
		102.060	0.010	7.9000	0.3000
		149.710	0.010	5.1000	0.7000
		200.630	0.020	7.5400	0.2500
		240.930	0.010	7.5800	0.2400
		334.270	0.010	9.6000	0.3000
		665.050	0.030	4.3300	0.1500
		773.670*	0.030	38.1000	1.2000
		782.490	0.040	7.8000	0.3000
		793.750	0.030	13.8000	0.5000
		822.780	0.040	6.1100	0.2000
		852.210	0.030	20.6000	0.8000
		910.000	0.030	3.2900	0.1300

		1125.460	0.040	11.4000	0.4000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
TE-131x	1.080E+005	1206.600	0.040	9.7000	0.4000
BA-133m	1.400E+005	275.925*	0.007	17.5000	0.1000
CS-134m	1.045E+004	127.502*	0.002	12.7000	0.3000
BA-135m	1.033E+005	268.218*	0.020	15.6000	0.4000
CE-137m	1.238E+005	254.290*	0.050	11.0000	0.5000
BA-139	4.986E+003	165.850*	0.000	17.0000	6.0000
LA-140	1.105E+006	328.770	0.000	20.5000	0.3000
		487.030	0.000	45.5000	0.7000
		751.790	0.000	4.4000	0.0900
		815.850	0.000	23.5000	0.5000
		867.820	0.000	5.6300	0.0800
		925.240	0.000	7.0900	0.1100
		1596.490*	0.000	95.4900	0.0700
CE-141	2.808E+006	145.440	0.000	48.4000	0.4000
PR-142	6.883E+004	1575.600*	0.500	3.7000	0.5000
CE-143	1.192E+005	57.356	0.007	11.7000	0.4000
		231.550	0.002	2.0500	0.0500
		293.266*	0.002	42.8000	0.5000
		350.619	0.003	3.2300	0.0400
		490.368	0.005	2.1600	0.0300
		664.571	0.015	5.6900	0.0700
		721.929	0.013	5.3900	0.0700
ND-147	9.487E+005	91.106*	0.020	28.0000	1.1000
		531.016	0.022	13.1000	0.9000
ND-149	6.210E+003	58.883	0.020	1.2900	0.2200
		74.320	0.030	1.1100	0.2400
		74.660	0.100	0.9800	0.1600
		75.690	0.060	0.2280	0.0230
		97.001	0.012	1.4500	0.1200
		112.520	0.040	0.1190	0.0170
		114.314	0.011	19.0000	1.6000
		139.210	0.012	0.5100	0.0300
		155.873	0.009	5.9000	0.3000
		188.640	0.008	1.7900	0.1100
		192.026	0.009	0.5700	0.0300
		198.928	0.008	1.3900	0.0700
		208.147	0.009	2.5500	0.1000
		211.309*	0.007	25.9000	1.5000
		213.947	0.016	0.4000	0.0300
		229.566	0.009	0.4820	0.0230
		240.220	0.007	3.9400	0.2200
		245.720	0.050	0.8000	0.2100
		258.067	0.013	0.3760	0.0180
		267.693	0.008	6.0000	0.3000
		270.166	0.007	10.7000	0.5000
		275.437	0.011	0.6500	0.0300
		276.960	0.017	0.3420	0.0170
		282.456	0.010	0.6200	0.0300
		288.194	0.010	0.6900	0.0400
		294.802	0.010	0.5700	0.0300
		301.128	0.014	0.3760	0.0180

		310.979	0.013	0.5100	0.0240

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
ND-149	6.210E+003	326.554	0.010	4.5600	0.2100
		349.231	0.009	1.3800	0.0700
		366.634	0.014	0.5400	0.0300
		423.553	0.010	7.4000	0.5000
		425.220	0.030	0.2720	0.0150
		443.551	0.011	1.1500	0.0700
		540.509	0.010	6.6000	0.4000
		555.880	0.090	0.5900	0.0400
		556.830	0.090	0.4400	0.0600
		654.831	0.013	8.0000	0.5000
ND-151	7.464E+002	116.800*	0.010	43.4000	2.5000
		138.890	0.010	7.8000	0.5000
		170.760	0.020	3.2000	0.2100
		175.070	0.010	7.0000	0.5000
		255.680	0.010	16.4000	1.0000
		423.560	0.020	6.6000	0.4000
		736.230	0.030	6.6000	0.4000
		797.530	0.020	5.3000	0.3000
		1122.630	0.030	4.5000	0.3000
		1180.890	0.020	14.8000	0.9000
PM-151	1.022E+005	104.840	0.010	3.5000	0.3000
		167.750	0.020	8.3000	0.6000
		177.160	0.010	3.8000	0.3000
		240.090	0.010	3.8000	0.3000
		275.210	0.020	6.8000	0.6000
		340.080*	0.010	22.5000	0.9000
		445.680	0.020	4.0000	0.3000
		717.720	0.080	4.1000	0.3000
EU-152m	3.352E+004	121.780	0.030	7.2000	1.1000
		344.310	0.030	2.4000	0.3000
		841.630*	0.040	14.6000	2.1000
		963.370	0.040	12.0000	1.8000
EU-154m	2.760E+003	68.170*	0.010	37.0000	5.0000
		100.880	0.010	25.0000	4.0000
SM-155	1.326E+003	104.320*	0.005	75.0000	4.0000
		141.411	0.011	2.0100	0.0800
		245.730	0.050	3.7300	0.0200
GD-159	6.682E+004	50.400	0.000	4.0000	1.1000
		58.000	0.010	2.3000	0.6000
		363.560*	0.030	11.0000	3.0000
GD-161	2.196E+002	50.400	0.000	12.0000	2.3000
		56.290	0.012	3.7700	0.1600
		102.315	0.010	13.9000	0.8000
		165.213	0.015	2.5800	0.2000
		283.550	0.030	5.9500	0.2500
		314.920	0.020	22.7000	0.9000
		338.070	0.020	1.6800	0.1000
		360.940*	0.020	60.1000	1.5000
		480.120	0.020	2.6800	0.1500
DY-165	8.402E+003	47.550	0.000	4.7000	0.2100
		53.900	0.000	1.9200	0.2100

		94.700*	0.003	3.6000	0.4000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
DY-165	8.402E+003	361.680	0.020	0.8400	0.0900
		633.415	0.020	0.5700	0.0600
		715.328	0.020	0.5300	0.0600
YB-169	2.767E+006	50.742*	0.000	93.8000	1.8000
		57.500	0.000	38.5000	1.0000
		63.121	0.000	44.2000	1.0000
		109.780	0.000	17.5000	0.4000
		130.524	0.000	11.3100	0.2100
		177.214	0.000	22.2000	0.5000
		197.958	0.000	35.8000	0.7000
		307.738	0.000	10.0500	0.1900
ER-171	2.707E+004	50.742	0.000	23.3000	1.3000
		57.500	0.000	9.6000	0.6000
		111.621	0.004	20.5000	1.2000
		116.656	0.006	2.3000	0.1100
		124.017	0.004	9.1000	0.5000
		295.901	0.014	28.9000	1.4000
		308.291*	0.018	64.0000	3.0000
YB-175	3.620E+005	52.965	0.001	1.1000	0.1400
		54.070	0.001	1.9300	0.2400
		113.803	0.004	1.9100	0.2500
		282.517	0.014	3.1000	0.4000
		396.322*	0.020	6.5000	0.8000
HF-177m	3.084E+003	54.611	0.001	16.0000	0.7000
		55.790	0.001	28.1000	1.2000
		63.200	0.000	11.8000	0.6000
		214.000	0.000	40.0000	4.0000
		277.300*	0.000	75.0000	6.0000
		295.100	0.000	68.0000	6.0000
		311.500	0.000	58.0000	4.0000
		326.700	0.000	64.0000	7.0000
		572.400	0.000	7.0000	0.6000
		606.500	0.000	11.4000	0.9000
		638.200	0.000	19.8000	1.5000
LU-177	5.797E+005	54.611	0.001	1.6400	0.1200
		55.790	0.001	2.8700	0.2000
		112.952	0.003	6.4000	0.4000
		208.359*	0.010	11.0000	0.8000
YB-177	6.840E+003	54.070	0.001	2.5000	0.4000
		121.620	0.003	3.4000	0.5000
		150.392*	0.003	20.0000	3.0000
		1080.100	0.300	5.5000	0.7000
		1241.400	0.300	3.4000	0.5000
HF-179m	2.169E+006	54.611	0.001	29.7000	2.4000
		55.790	0.001	52.0000	5.0000
		63.200	0.000	21.8000	1.8000
		122.700	0.070	28.0000	1.6000
		146.150	0.070	27.4000	1.5000
		169.780	0.070	19.6000	1.2000
		192.660	0.110	21.7000	2.1000
		217.040	0.120	9.1000	0.8000

		236.480	0.140	19.0000	0.9000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
HF-179m	2.169E+006	268.850	0.140	11.4000	0.8000
		315.930	0.140	20.5000	0.8000
		362.550	0.150	40.1000	1.7000
		409.700	0.200	21.7000	1.0000
		453.590*	0.200	69.0000	4.0000
HF-180m	1.980E+004	54.611	0.001	10.0000	0.3000
		55.790	0.001	17.5000	0.5000
		57.535	0.007	48.5000	1.1000
		63.200	0.000	7.3600	0.2300
		93.319	0.009	17.3200	0.2100
		215.259	0.022	81.7000	1.0000
		332.302*	0.024	94.4000	1.2000
		443.192	0.019	83.3000	1.4000
		500.727	0.019	14.7300	0.1800
HF-181	3.662E+006	56.277	0.001	9.0200	0.2400
		57.532	0.001	15.7000	0.5000
		133.021	0.019	43.3000	0.6000
		345.930	0.060	15.1200	0.1300
		482.180*	0.090	80.5000	0.5000
TA-182m	9.504E+002	56.277	0.001	28.3000	1.3000
		57.532*	0.001	49.3000	2.2000
		65.200	0.000	20.8000	1.0000
		146.785	0.015	37.2000	2.5000
		171.586	0.015	49.0000	2.0000
		184.951	0.015	24.5000	1.8000
		318.400	0.050	6.9000	0.6000
RE-186	3.263E+005	57.982	0.001	1.5100	0.0500
		59.318	0.000	2.6300	0.0800
		63.000	0.001	1.7300	0.0800
		137.157*	0.008	8.2000	0.3000
W-187	8.539E+004	59.718	0.001	7.2000	0.3000
		61.140	0.001	12.5000	0.5000
		69.300	0.000	5.3600	0.2200
		72.002	0.004	11.1000	0.4000
		134.247	0.007	8.8000	0.3000
		206.242	0.018	0.1430	0.0060
		246.280	0.021	0.1190	0.0060
		479.550	0.022	21.8000	0.8000
		511.660	0.040	0.6470	0.0220
		551.520	0.040	5.0800	0.1700
		618.260	0.040	6.2800	0.2200
		625.519	0.010	1.0900	0.0400
		685.730*	0.040	27.3000	1.0000
		745.216	0.019	0.2980	0.0100
		772.890	0.050	4.1200	0.1400
		864.550	0.010	0.3360	0.0120
RE-188	6.113E+004	61.487	0.001	1.3600	0.1000
		63.000	0.001	2.3500	0.1800
		155.032*	0.012	14.9000	0.6000
		632.980	0.020	1.2500	0.0500
RE-188m	1.116E+003	59.718	0.001	18.2000	2.0000

		61.140*	0.001	32.0000	4.0000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
RE-188m	1.116E+003	63.600	0.030	21.6000	1.1000
		69.300	0.000	13.5000	1.5000
		92.430	0.030	5.2000	0.3000
		105.960	0.100	10.8000	0.6000
OS-190m	5.940E+002	61.487	0.001	5.7000	1.8000
		63.000	0.001	10.0000	4.0000
		71.400	0.000	4.2000	1.4000
		186.700	0.100	70.2000	0.6000
		361.200	0.100	94.8800	0.1000
		502.500	0.100	97.7900	0.0500
		616.500*	0.100	98.6200	0.0300
OS-191	1.331E+006	63.287	0.001	16.1000	1.6000
		64.896*	0.001	28.0000	3.0000
		73.600	0.000	12.0000	1.2000
		129.431	0.005	25.7000	2.4000
PT-191	2.506E+005	63.287	0.001	30.0000	2.5000
		64.896*	0.001	52.0000	5.0000
		73.600	0.000	22.3000	1.9000
		82.398	0.007	4.9000	0.7000
		96.517	0.009	3.3000	0.4000
		129.400	0.007	3.2000	0.5000
		172.190	0.020	3.5000	0.4000
		268.710	0.080	1.6500	0.2300
		351.170	0.030	3.4000	0.4000
		359.880	0.030	6.0000	0.7000
		409.440	0.020	8.0000	0.9000
		456.470	0.050	3.4000	0.4000
		538.870	0.050	13.7000	1.6000
		624.060	0.060	1.4100	0.1600
IR-192	6.379E+006	61.487	0.001	1.2140	0.0120
		63.000	0.001	2.0960	0.0200
		65.122	0.002	2.6800	0.0500
		66.832	0.002	4.5900	0.0900
		71.400	0.000	0.9000	0.0180
		75.700	0.000	2.0000	0.0500
		205.796	0.000	3.3000	0.0400
		283.267	0.001	0.2620	0.0050
		295.958	0.000	28.6700	0.1000
		308.457	0.000	30.0000	0.0900
		316.508*	0.000	82.8100	0.2100
		468.072	0.000	47.8300	0.1700
		484.578	0.000	3.1800	0.0300
		588.584	0.001	4.5150	0.0150
		604.415	0.000	8.2300	0.0600
		612.466	0.000	5.3090	0.0180
OS-193	1.098E+005	63.287	0.001	3.6700	0.2400
		64.896*	0.001	6.3000	0.5000
		73.039	0.012	3.2000	0.5000
		73.600	0.000	2.7200	0.1900
		138.920	0.030	4.3000	0.3000
		460.490	0.030	3.9500	0.2500

PT-193m	3.741E+005	65.122	0.002	4.3300	0.1800

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
PT-193m	3.741E+005	66.832*	0.002	7.4000	0.3000
		75.700	0.000	3.2300	0.1500
		135.500	0.030	0.1100	0.0000
IR-194	6.894E+004	65.122	0.002	0.2400	0.0300
		66.832	0.002	0.4200	0.0500
		75.700	0.000	0.1810	0.0200
		293.541	0.014	2.6000	0.4000
		300.741	0.014	0.3500	0.0500
		328.448*	0.014	13.1000	1.8000
		589.179	0.017	0.1400	0.0190
		621.971	0.019	0.3400	0.0500
		645.146	0.020	1.1700	0.1600
		938.690	0.030	0.6000	0.0800
		1150.750	0.050	0.6000	0.0800
		1183.490	0.050	0.3000	0.0400
		1468.910	0.070	0.1900	0.0300
PT-195m	3.473E+005	65.122	0.002	22.5000	1.5000
		66.832*	0.002	39.0000	3.0000
		75.700	0.000	16.8000	1.2000
		98.900	0.020	11.4000	0.9000
HG-197	2.309E+005	66.990	0.001	21.6900	0.1100
		68.804*	0.001	37.0700	0.1800
		77.351	0.002	18.0000	0.4000
		78.000	0.000	16.2000	0.3000
HG-197m	8.568E+004	66.990	0.001	2.0000	0.2200
		68.804	0.001	3.4000	0.4000
		68.895	0.002	9.8000	0.9000
		70.819	0.002	16.6000	1.4000
		80.300	0.000	7.3000	0.7000
		133.980*	0.050	34.0000	4.0000
		279.000	0.100	5.0000	0.5000
PT-197	6.588E+004	66.990	0.001	0.9800	0.1000
		68.804	0.001	1.6800	0.1700
		77.350*	0.050	17.0000	2.4000
		78.000	0.000	0.7300	0.0800
		191.437	0.010	3.7000	0.4000
		268.780	0.050	0.2300	0.0400
PT-197m	5.725E+003	53.100	0.020	1.0900	0.0300
		65.122	0.002	13.6000	0.6000
		66.832*	0.002	23.3000	1.0000
		66.990	0.001	0.2400	0.0300
		68.804	0.001	0.4000	0.0500
		75.700	0.000	10.2000	0.5000
		78.000	0.000	0.1770	0.0200
		130.000	0.000	0.1050	0.0140
		279.000	0.000	2.4000	0.3000
		346.500	0.200	11.1000	0.3000
AU-198	2.327E+005	68.895	0.002	0.8100	0.0700
		70.819	0.002	1.3800	0.1200
		80.300	0.000	0.6100	0.0500
		411.804*	0.001	95.5800	0.1200

		675.887	0.002	0.8040	0.0030

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
HG-199m	2.556E+003	68.895	0.002	18.0000	1.2000
		70.819	0.002	30.6000	2.0000
		80.300	0.000	13.5000	0.9000
		158.379*	0.000	52.3000	1.0000
		374.100	0.100	13.8000	1.1000
PT-199	1.848E+003	66.990	0.001	1.2000	0.1100
		68.804	0.001	2.0500	0.1800
		77.200	0.030	1.5000	0.4000
		78.000	0.000	0.9000	0.0800
		185.790	0.030	3.3000	0.5000
		191.690	0.030	2.4000	0.4000
		219.360	0.040	0.3900	0.0700
		225.880	0.040	0.1700	0.0300
		240.010	0.060	0.1800	0.0300
		246.460	0.030	2.2000	0.4000
		317.030	0.040	4.9000	0.7000
		323.600	0.060	0.2500	0.0500
		417.610	0.050	0.3900	0.0600
		425.340	0.070	0.1700	0.0400
		465.760	0.050	0.9300	0.1400
		468.090	0.050	0.9900	0.1900
		474.680	0.040	1.1500	0.1700
		493.750	0.030	5.7000	0.9000
		542.980*	0.040	14.8000	2.2000
		714.550	0.040	1.9000	0.3000
		791.740	0.040	1.0700	0.1700
		968.320	0.050	1.1000	0.1800
HG-205	3.120E+002	72.871	0.001	0.3000	0.1500
		203.750*	0.009	2.2000	1.0000
TL-206m	2.244E+002	70.832	0.001	9.4000	0.9000
		72.871	0.001	16.0000	1.5000
		82.600	0.000	7.1000	0.7000
		216.400	0.100	74.0000	4.0000
		247.200	0.100	8.6000	1.8000
		265.700	0.100	86.0000	0.0000
		453.300*	0.200	93.0000	6.0000
		457.200	0.500	22.0000	3.0000
		564.200	0.100	5.2000	0.9000
		686.500	0.200	90.0000	6.0000
		1021.500	0.200	69.0000	6.0000
		1139.900	0.300	6.0000	1.8000
PA-233	2.330E+006	75.354	0.004	1.3900	0.0800
		86.814	0.003	1.9700	0.1200
		94.665	0.002	10.9000	0.4000
		98.439	0.002	17.7000	0.6000
		111.000	0.000	8.2000	0.3000
		300.340	0.020	6.6200	0.0600
		312.170*	0.020	38.6000	0.4000
		340.810	0.030	4.4700	0.0400
		398.620	0.080	1.3900	0.0120
		415.760	0.040	1.7450	0.0160

TH-233	1.338E+003	86.480*	0.060	2.7000	0.0000

Library Title:

Nuclide Name	Half-Life (Seconds)	Energy (keV)	Energy Uncert. (keV)	Yield (%)	Yield Uncert.(Abs.+-)
TH-233	1.338E+003	459.222	0.007	1.4000	0.0000
NP-239	2.035E+005	61.460	0.002	0.9700	0.1500
		99.550	0.050	13.9000	0.8000
		103.760	0.050	22.3000	1.2000
		106.123*	0.002	22.9000	1.2000
		117.000	0.000	10.5000	0.6000
		209.753	0.002	3.2700	0.2400
		228.183	0.001	10.8000	0.6000
		277.599	0.001	14.2000	0.2000
		315.880	0.003	1.6000	0.1100
		334.310	0.002	2.0400	0.1800
U-239	1.410E+003	74.664*	0.001	50.0000	5.0000

* = key line

TOTALS: 131 Nuclides 681 Energy Lines

APPENDIX C

NAA MANUAL

University of Utah Nuclear Engineering Program Neutron Activation Analysis Handbook

INTRODUCTION

Neutron Activation Analysis (NAA) is a powerful tool in detecting, identifying and quantifying many different elements found in the various materials. NAA is based upon the phenomenon of neutron capture in which nuclei absorb neutrons and become radioactive. The decaying radio-nuclei emit gamma ray photons which are attenuated and counted using high purity germanium (HPGe) gamma spectroscopy detectors. The decaying nuclides are identified by the signature gamma photon energies emitted upon decaying.

Samples are irradiated using a strong neutron source. At the University of Utah Nuclear Engineering Program (UNEP) an experimental reactor is utilized as the neutron source. The University of Utah TRIGA Reactor (UUTR) is equipped with several irradiation facilities for various nuclear experiments including NAA.

This manual outlines the UNEP NAA protocol and procedures for most NAA experiments. Found within this manual include full gamma spectroscopy calibration and

operation procedures as well as NAA experiment procedures. Examples and results from previous irradiations are given as well.

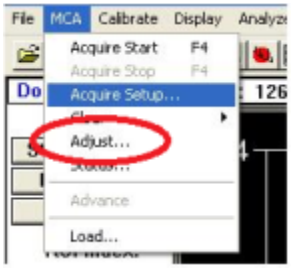
GAMMA SPECTROSCOPY

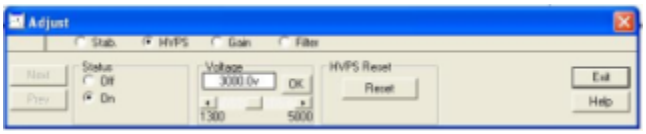
1. **Turning on a detector**
2. **Energy Calibration**
3. **Efficiency Calibration**
4. **Sample Acquisition, Information and Analysis**
5. **Regular QA Checks and Maintenance**
6. **Troubleshooting**

Figure 1 Non-Shielded and Shielded HPGe Detectors at UNEP

1. Turning a detector on

Turn the power switch to the on position on the MCA and wait for the machine to go through the start up diagnostics. Then open the Genie 2000™ Gamma Acquisition and Analysis program. Select the *Open Datasource* button and select *Detector*. Open the *MCA* tab and select *Adjust*. Turn the high voltage power supply (HVPS) *On:*





2. Energy Calibration

Gamma photons absorbed in the HPGe crystal are counted by the multichannel analyzer (MCA) and placed into bins or channels according to their energy. MCA's typically operate on 4096 (4K), 8192 (8K), 16,384 (16K) or 32,768 (32K) channel spectrums. An energy calibration assigns energy values to these channels.

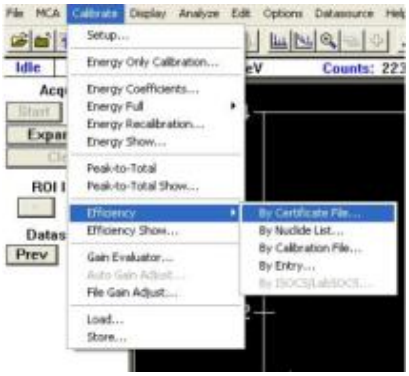
Energy calibrations should be performed using source with known nuclides and energy lines. Certified sources will list the assayed activities for each nuclide and often for each energy line. Certificate files can be created in which the nuclide and activity information is recorded for reference during calibrations.

An energy calibration must be performed before a detector can be used for actual gamma spectroscopy counting. The energy calibration can be change at any time and should be checked daily and regularly recalibrated at least once a year.

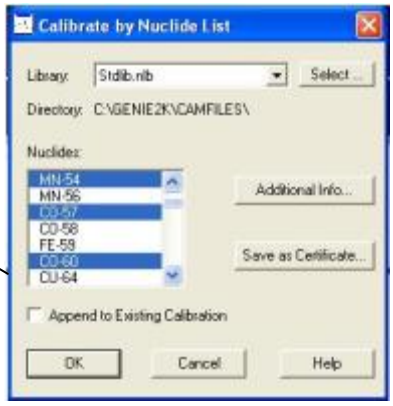
Typical gamma spectra range from 0 – 1500 keV for 4K spectra and 0 – 3000 keV for 8K and 16K spectra. These ranges can vary according to necessities of the laboratory.

1. Place source on detector and count until all energy lines are

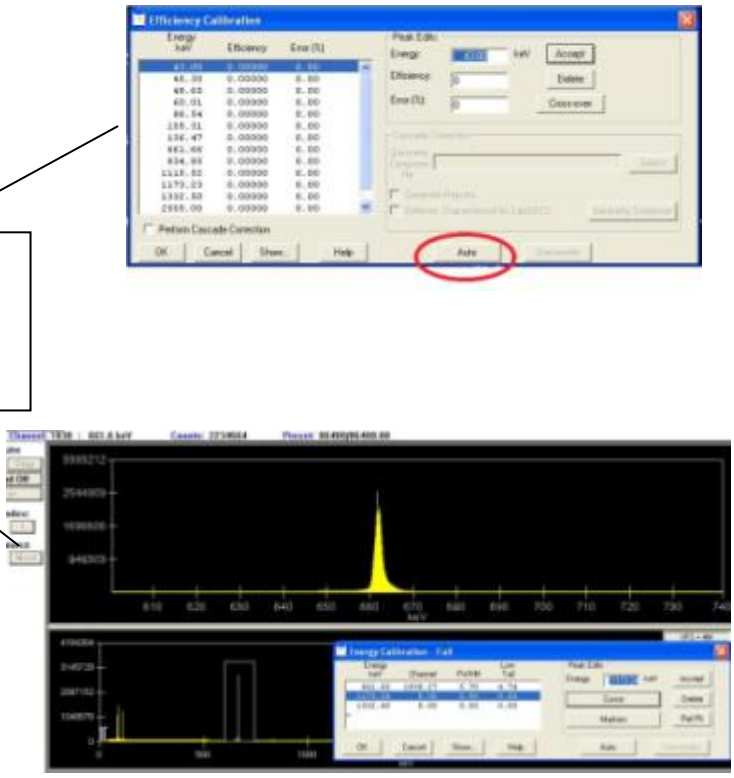
2. Select *Energy Calibration* and select



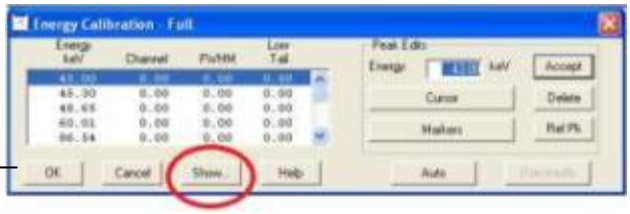
3. Select the appropriate Certificate file or nuclides used

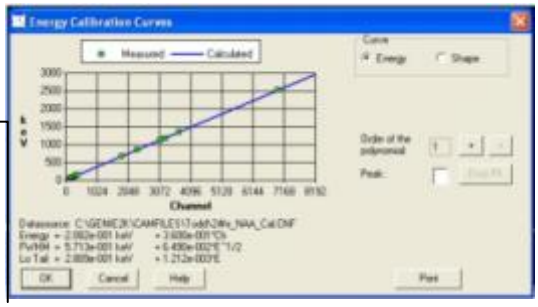


4. Select *Auto* or use the *Cursor* method

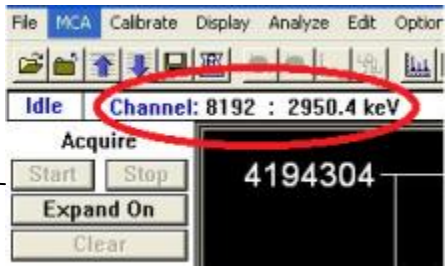


5. Select *Show* to verify that the energy



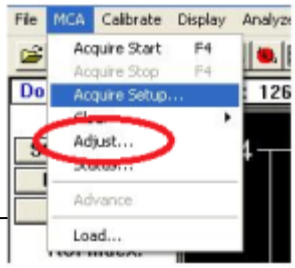


6. Verify that the range extends to the desired maximum energy by placing the cursor in the

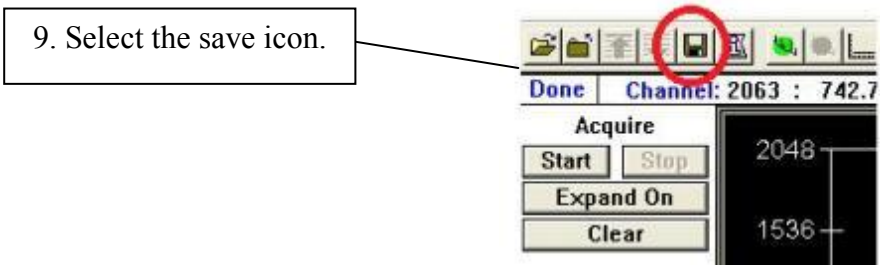


7. If the energy range is adequate go to step 10

8. Open the Gain Adjust to alter the spectrum. Increasing the gain will



9. Select *Clear* and *Start* to begin a new count. Repeat steps 8 and 9 until the desired energy range



3. Efficiency Calibration

The Efficiency calibration determines how the efficiently the detector counts the gamma photons at all the energies of the spectrum. This is done by counting certified gamma source(s). The activities of each of the energy lines from the gamma source are recorded in a certificate file. The efficiency at which the detector counts each energy line that is found is calculated. The energies for the rest of the spectrum is either interpolated or extrapolated.

The interpolated and extrapolated efficiencies for the entire spectrum is calculated using polynomial equations. The result of this equation is known as the "efficiency curve".

Efficiency curves must be generated for all counting geometries. A geometry can be as simple as a point source on the face of the detector or a bottle containing water. If the point source is moved at a known distance from the detector then this is a new geometry or if the bottle is filled with soil instead of water this is also a new geometry. All geometries must have their own efficiency curves.

Gamma spectroscopy samples must be counted using only geometries for which efficiency curves have been generated and saved. Otherwise the results from the counted

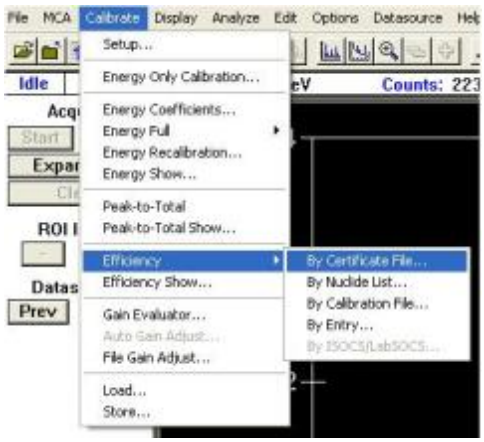
sample cannot be considered valid for quantification analysis only simply isotope identifications.

For many different shapes of geometries individual certified sources can be purchased or created to suit the gamma spectroscopy demands of the lab. Most NAA samples are assumed to be "disk" sources and should, ideally, be formed to represent a small disk or point source. By doing so this decreases errors and increases the accuracy of the measurements.

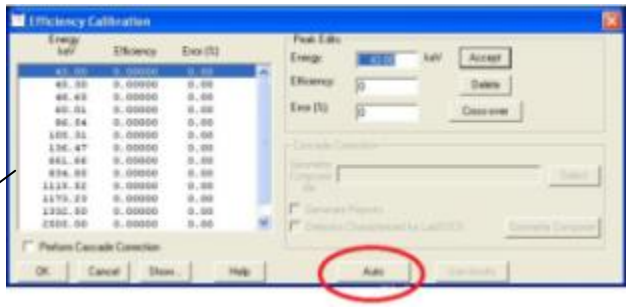
Efficiency calibrations should be checked regularly by counting and analyzing a check source in each geometry to verify the accuracy of the curves. This will part of the QA checks that should be performed to ensure regular and consistence results. Efficiencies should be check at least weekly and recalibrated at least once a year for each geometry.

1. Place source on detector and count until all energy lines are distinct and recognizable. Longer count times are strongly recommended since longer counts

2. Select *Efficiency Calibration*

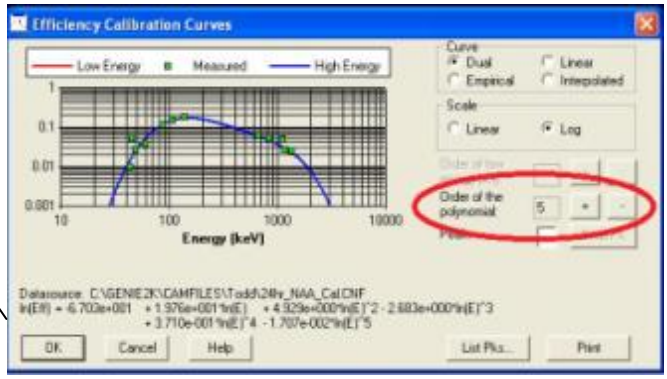


3. Select the appropriate certificate file



4. Select *Auto*

5. Select *Show* to select the efficiency curve polynomials that best represent the efficiency (with low errors) for



6. Select Store to save the calibration curve. Name the calibration according to the

4. Sample Acquisition, Information and Analysis

Gamma spectroscopy involves acquiring a spectrum of sample or material containing gamma emitting nuclides. To do so the sample must be "counted" on a HPGe detector. This is more involved than simply clicking "Start" in the acquire menu.

First the geometry (shape, size, matrix and distance from the detector) of that sample must have a calibrated efficiency curve generated. The samples mass and or volume must be measured beforehand as the analysis sequence file (ASF) will calculate a unit activity for each radionuclide identified. If a sample is irradiate, then the irradiation time and flux may also be valuable information to add to the sampled description.

All this data is to be inputted into the sample information tab either before, during or after counting but before the ASF is executed and an official report is generated. Multiple ASF's have been created according to the type of nuclides that may be seen. These include:

- Short irradiations
- Long irradiations with 1 – 5 day decay time
- Long irradiations with > 5 decay times
- Naturally occurring radionuclides from the U-238, U-235 and Th-232 decay chains
- U-natural only

Custom ASF's can be created as needed.

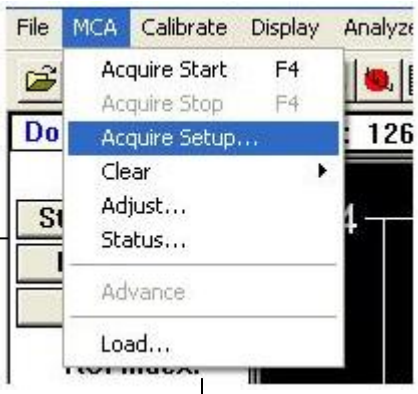
An ASF will contain several steps that are needed to fully analyze the gamma spectrum. These functions automatically find the peaks in the spectrum given a pre-assigned significance factor. A peak must have a Gaussian distribution (bell-curve shape) in order to be identified. The peak areas are then summed. Background counts at discrete energy peaks are subtracted out of the sum peaks if similar peaks were found in a QA background count. The peak areas are then divided by the efficiency at that energy corresponding to the energy curve for that geometry. The identified peaks are then correlated to the energies in the selected nuclide library and the measure activities are calculated.

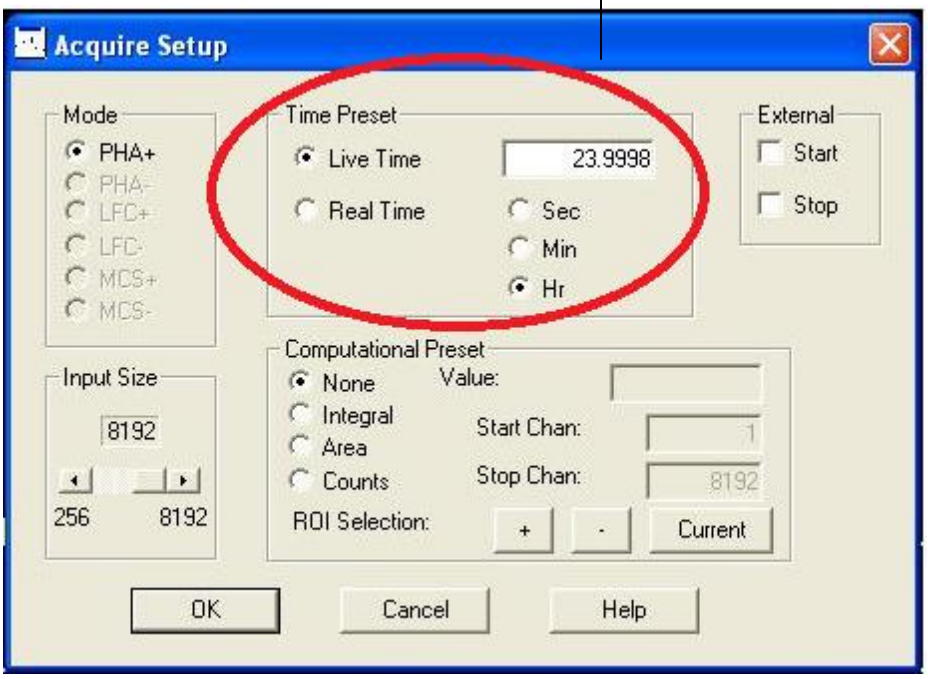
- Peak locate
- Peak sum
- Background subtraction
- Efficiency Correction
- Nuclide identification and activity calculations

Each of these functions can be performed individually if needed.

SAMPLE ACQUISITION

1. Define the desired counting time prior to



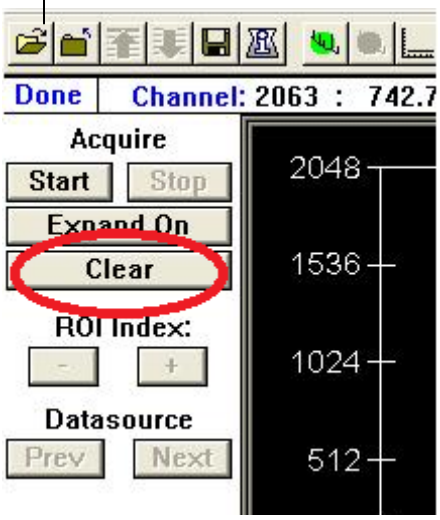


2. Place sample on detector and select

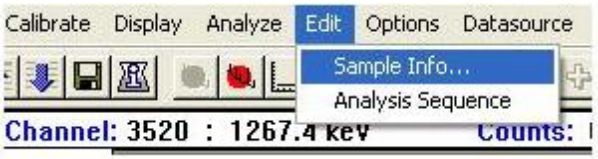
3. Verify that the dead time is below 2% for the GC-4020 to maintain adequate peak resolution.

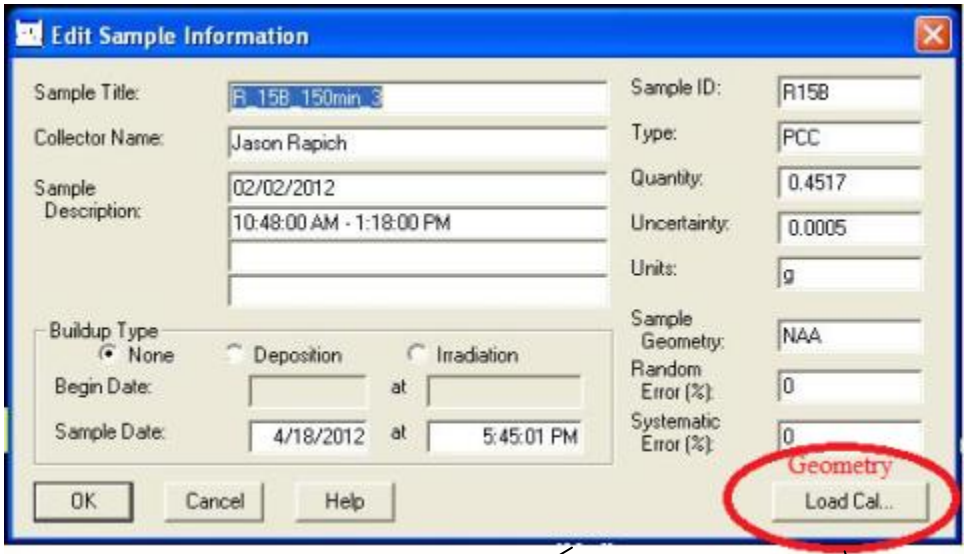
NOTE: high dead times do not affect the

4. If the dead time is higher than 2% then the sample needs to be placed at a greater distance from the detector. Once this done *Clear* the spectrum and the count will start over.

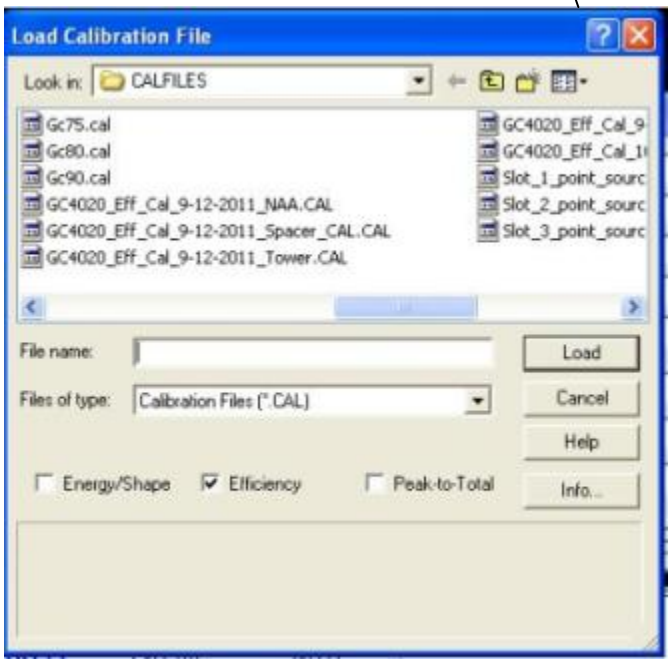


5. Input the sample information: Title, ID,

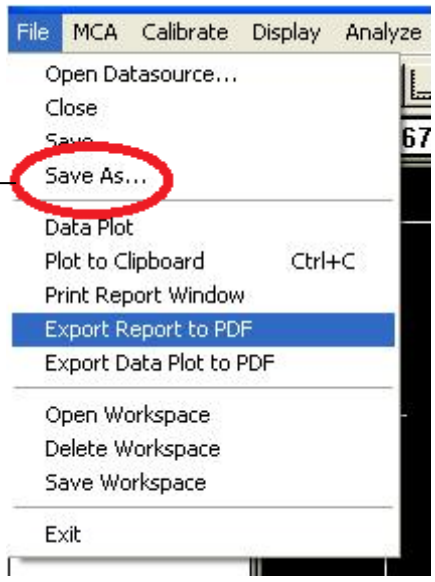




6. Select the appropriate Geometry



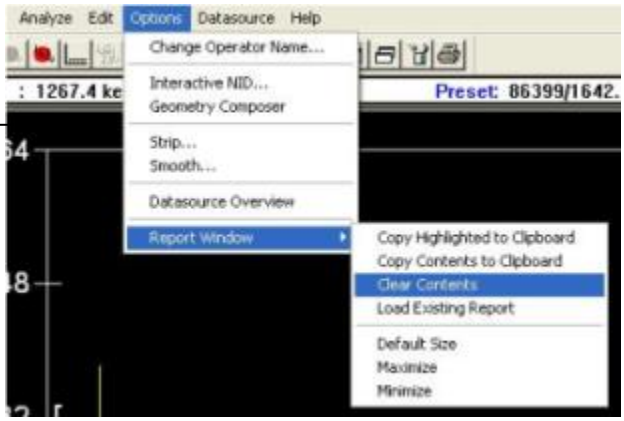
7. Once the count is complete *Save As* the in the appropriate



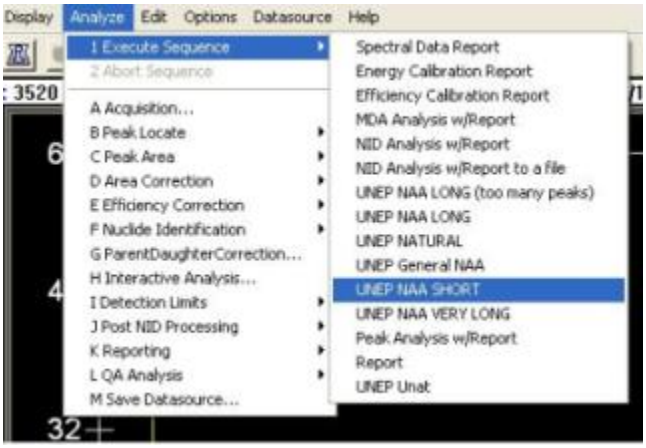
SAMPLE ANALYSIS

1. Open the saved file

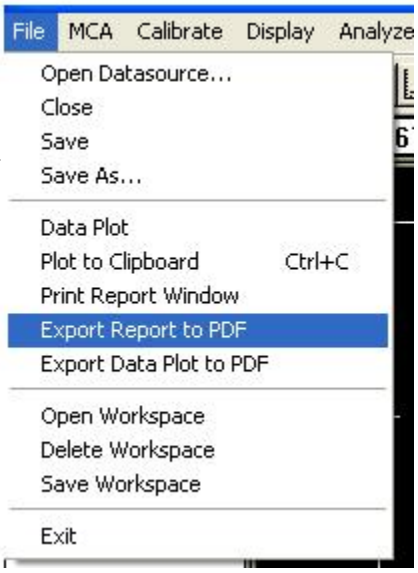
2. If other analyses were executed such as peak locate etc. *Clear Contents* on the



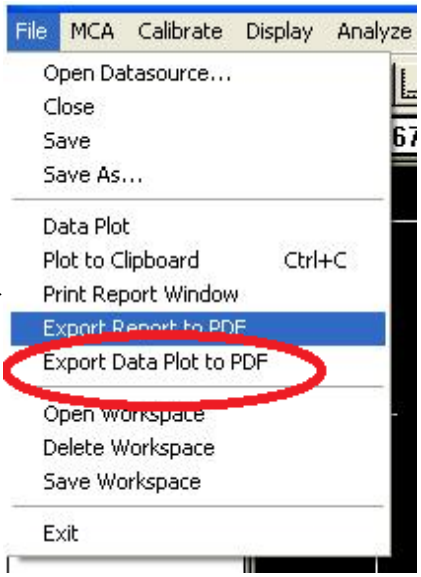
3. Review and verify the *Sample Info*, the execute the appropriate ASF



4. Export the report to the appropriate



5. If needed, export a plot of the spectrum to the appropriate



6. Save and close

5. Regular QA Checks and Maintenance

LN2

Regular maintenance as well as QA checks and adjustments should be performed to maintain proper calibrations and optimal counting conditions.

The HPGe detectors are cooled by liquid nitrogen (LN2) that is held in 25 – 35 L dewars. Long probes called “cold fingers” extend from the HPGe crystal chamber down into the dewar. The dewar must be regularly refilled with LN2.

If a detector is not being used it needs to only be refilled once every 10 days. The LN2 will naturally evaporate at about a rate of 1 – 2 liters per day. If a detector is being used then it should be refilled every week. It would be better if refilled twice a week to maintain a more constant LN2 level.

NOTE: after a detector’s dewar is refilled the detector should be allowed to cool down and reach and equilibrium state for at least 1 hour before counting is started. The

energy gains may shift during this period and will need to be readjusted after the 1 hour cool down. The detectors do not need to shut down for refilling.

Energy QA Check

Daily energy QA checks should be performed to assure that the energy gains are in the proper channels. Differences in ambient temperature, LN2 levels and electronic issues can swift the energy gains.

The Energy QA check can be performed by counting a gamma emitting source on the detector for several minutes. After the source has been counting for a while a *Peak Located* function should be executed generating a report showing the identified peaks and their associated energies. Sources with higher energies tend to work better for this QA check since the gains shift logarithmically. This means that the lower energies hardly swift compared to the higher energies.

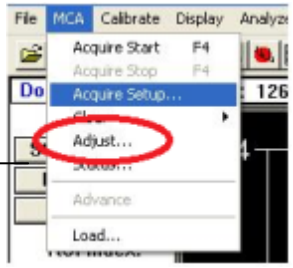
A Co-60 source works well for this QA check. The Co-60 energy lines (1173.2 and 1332.5 keV) are great energy reference peaks. The *Peak Locate* function will report the energies for these two peaks. If the energies are high or low the gains can be adjusted accordingly. See the **Energy Calibration** section to see how to adjust the gains. The gains should be adjusted to the correct energies ± 0.4 keV.

NOTE: if adjusting the energy gains does not correct the energy shifts or too many of the energy peaks consistently fall outside of the ± 0.4 keV range then a energy

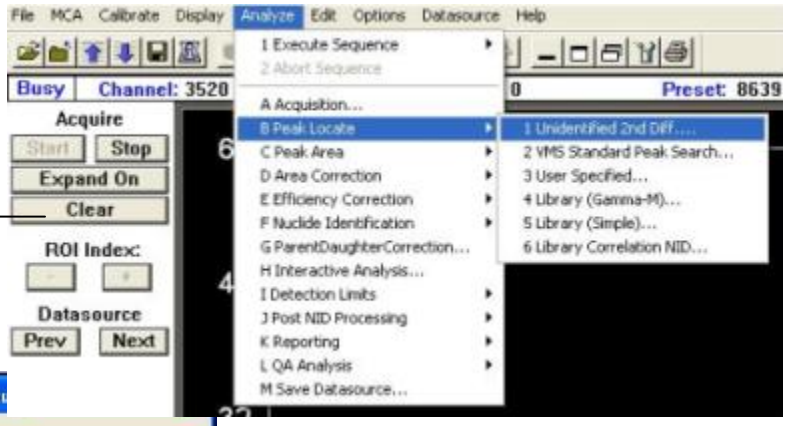
recalibration may be necessary. It could also indicate that source is too strong. Experience has shown that sources with significantly higher activities shift the gains up for that spectrum. Recalibrations are not needed in this case.

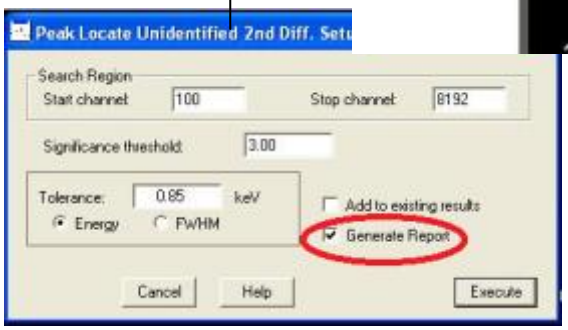
1. Place source on the detector and *Start* the count.

2. Open the Gain Adjust to alter the spectrum. Increasing the gain will



3. Select the Generate Report box and execute





4. Review the energies on report if needed adjust the gains accordingly and select *Clear*.

```
*************************************************************
*                P E A K    L O C A T E    R E P O R T      *
*************************************************************

 Detector Name:  DET01
 Sample Title:   24
           Peak Locate Performed on:  5/13/2012  11:52:39 PM
           Peak Locate From Channel:     100
           Peak Locate To Channel:     32768
           Peak Search Sensitivity:      3.00

 Peak    Centroid     Centroid      Energy        Peak
  No.     Channel   Uncertainty     (keV)     Significance

    1      554.68       0.2369       72.81         4.11
    2      570.68       0.1865       74.91         7.26
    3      647.05       0.2509       84.96         3.91
    4     1909.99       0.3069      251.11         3.03
    5     5563.77       0.2370      731.29         3.15
    6     8916.99       0.0630     1172.94        18.58
    7    10127.53       0.0691     1332.19        13.00

Adjacent peak noted
```

5. If no adjustments need select *Save*.

Energy Resolution QA Check

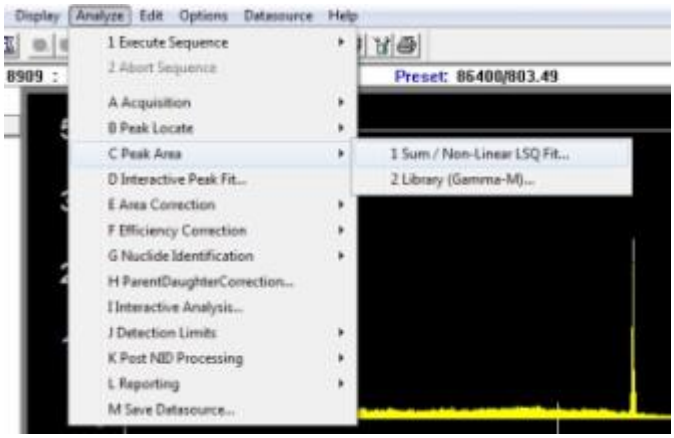
The energy resolutions (how fat the peaks are) will greatly affect the quality of the detector and the overall analyses. Energy resolution checks should be performed daily along with the energy checks. Poor resolutions can indicate: detector vacuum leaks, bad MCA rise times, detector damage and incorrect voltage.

The energy resolutions can be checked using a source with higher energies such as a Co-60 source. The source should be counted for several minutes then the *Peak Locate* and *Peak Sum* functions. Verify that the resolutions are near a FWHM of 2. The GC-4020 FWHM is typically slightly higher than 2 and the BEGe-3830 FWHM should be under 2.

A thermal cycle should improve resolutions, but if chronic resolution issues persist after a few thermal cycles then the manufacturer should be consulted for repairs.

1. Complete steps 1 and 2 from the

2. Select the *Peak Area* function



3. Review the Peak Area report to verify the FWHM

P E A K A N A L Y S I S R E P O R T

Detector Name: DET01
Sample Title: 24
Peak Analysis Performed on: 5/13/2012 11:52:56 PM
Peak Analysis From Channel: 100
Peak Analysis To Channel: 32768

Peak No.	ROI start	ROI end	Peak centroid	Energy (keV)	FWHM (keV)	Net Peak Area	Net Area Uncert.	Continuum Counts
1	548-	580	554.64	72.80	0.64	1.07E+002	14.27	2.27E+002
2	548-	580	570.88	74.94	0.65	2.16E+002	19.68	2.25E+002
3	641-	656	647.05	84.96	0.49	7.93E+001	24.60	2.38E+002
4	1904-	1915	1909.99	251.11	0.17	-5.86E+000	15.47	1.35E+002
5	5555-	5572	5563.77	731.79	0.37	1.09E+001	14.46	1.04E+002
6	8892-	8941	8916.99	1172.94	2.75	5.66E+003	85.33	5.38E+002
7	10101-	10153	10127.53	1332.19	3.23	4.80E+003	79.50	5.16E+002

Efficiency QA Check

Efficiency calibration QA checks should be performed on weekly basis. This ensures that the efficiency calibrations are still valid. Over time the HPGe crystals can degrade and lose efficiency. Other issues like poor resolution and incorrect voltage will greatly affect the efficiencies and should be dealt with.

If the efficiency issues cannot be resolved through a thermal cycle a recalibration may be required. If chronic efficiency issues persist the manufacturer should be consulted.

An efficiency QA check can be performed by counting and analyzing a certified source as a sample. The reported activities should be compared to the original certified activities.

Thermal Cycling

Thermal Cycling is a common remedy for many of the HPGe detectors issues. The HPGe crystals can be warmed up to room temperature indefinitely without any degradation or loss of quality. CANBERRA® recommends regular thermal cycles for their HPGe's.

A thermal cycle consists of powering down the detector and removing it from the cryostat dewar and allowing it to warm up to room temperature for at least 24 hours. Afterwards the detector is replaced in the dewar again and recalibrated. The detector should be allowed to cool down for at least 6 hours before reapplying the high voltage.

Thermal cycles help to improve energy resolutions and efficiencies and are recommend to be performed at least once a year.

6. Troubleshooting

Often times troubles arise that are frustrating and difficult to resolve if the operator does not know how to resolve the issues. The following are common issues that have been encountered.

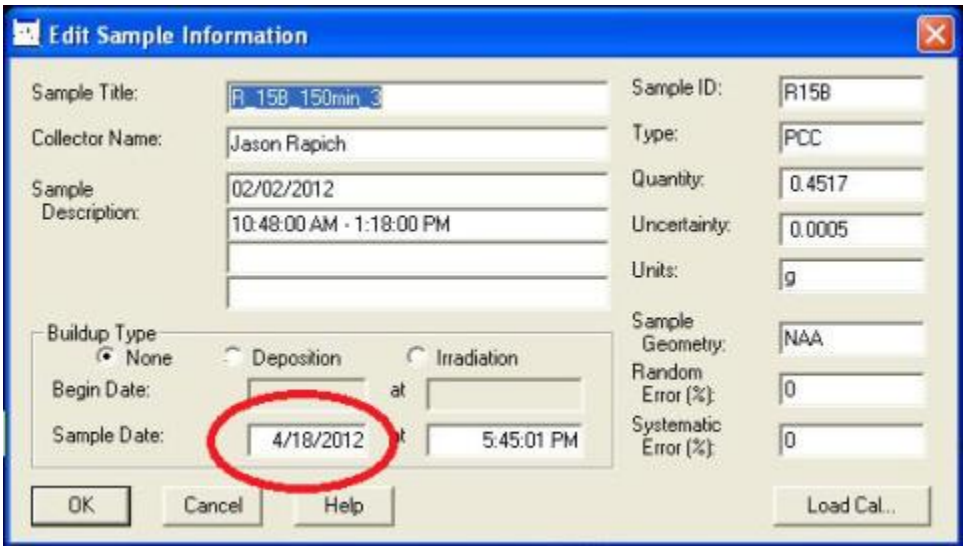
Energy peaks are not identified

Reasons:

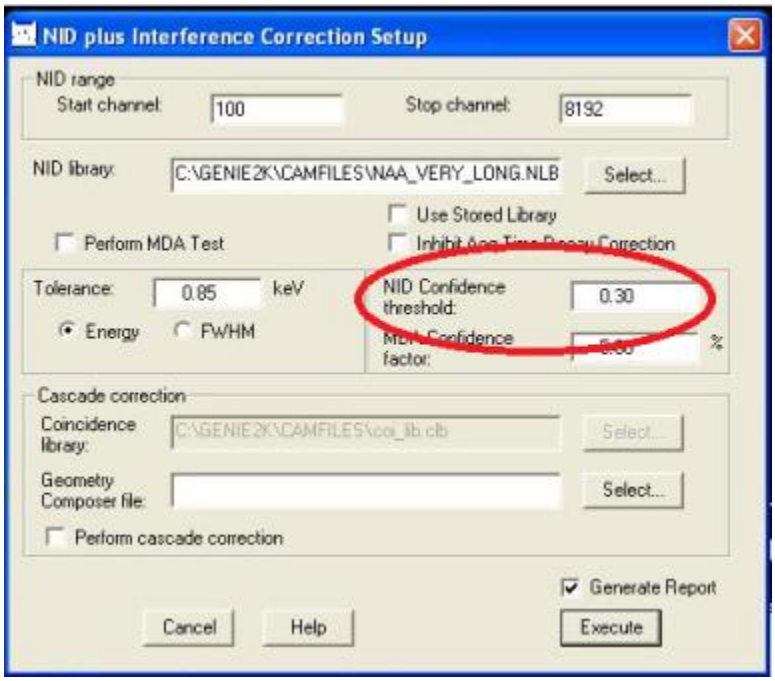
- Sample date and time are incorrect.
- Too few peaks are identified to reach a confidence ID of 0.3
- Peak energies are too far away from where they should be
- Peaks for that nuclide are not found in the library being used

Solutions:

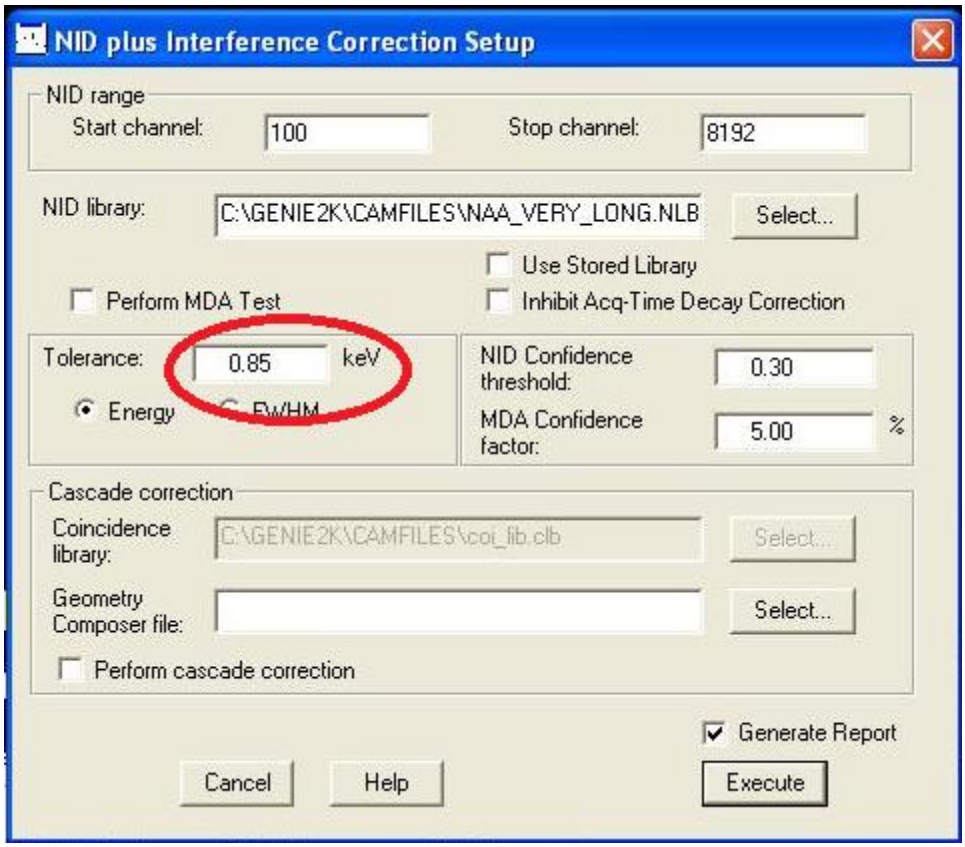
- Enter the proper sample date and time in the *Sample Info* section



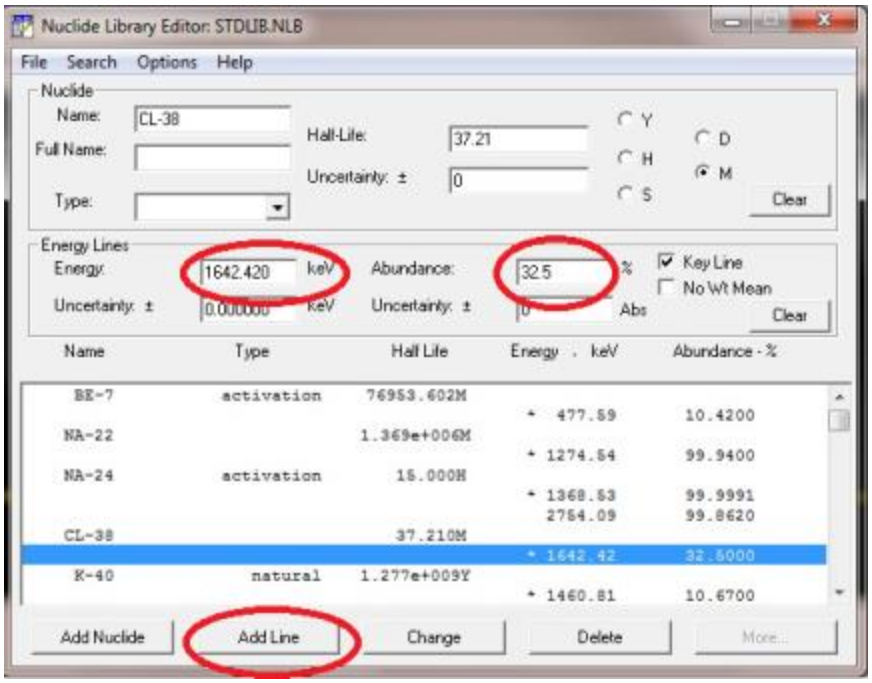
- Lower the NID Confidence Threshold



- Increase the energy tolerance



- Add the energy line to the library



<u>Too many peaks in the spectrum to complete analysis</u>

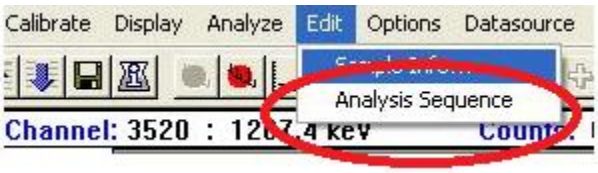
Reason:

- Too many peaks are located in the spectrum and are overwhelming the analyze algorithm

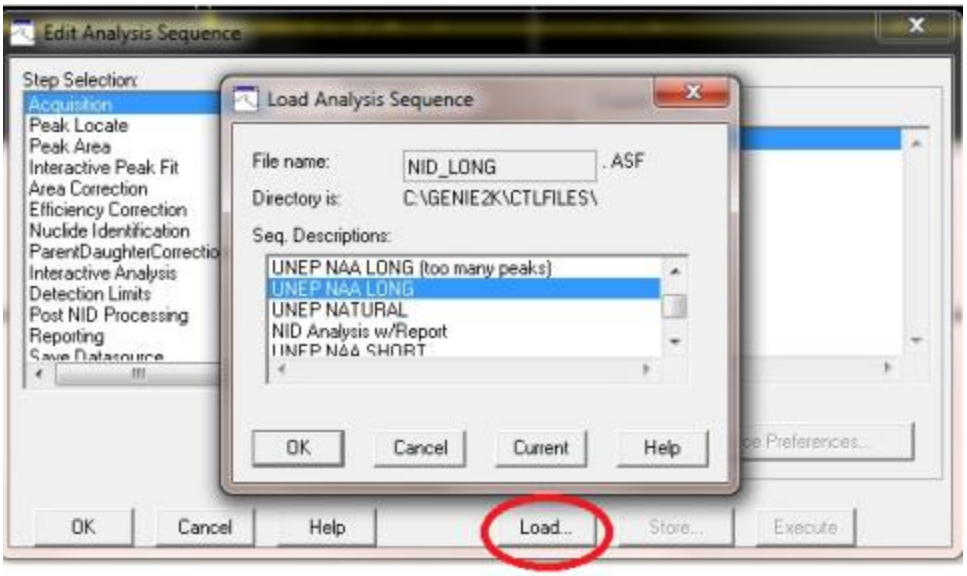
Solution:

- Lower the number of peaks identified by raising the Threshold Significance

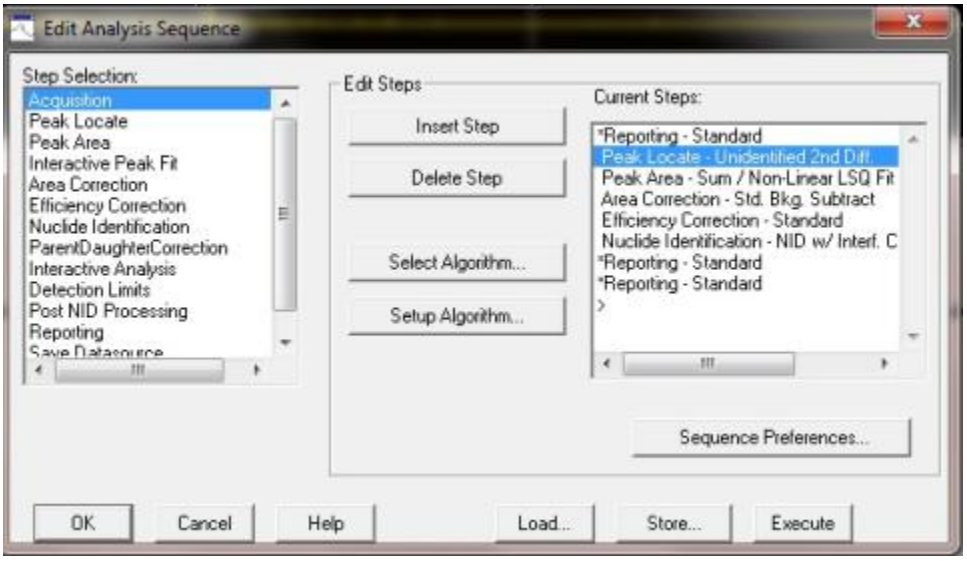
Select *Analysis Sequence*



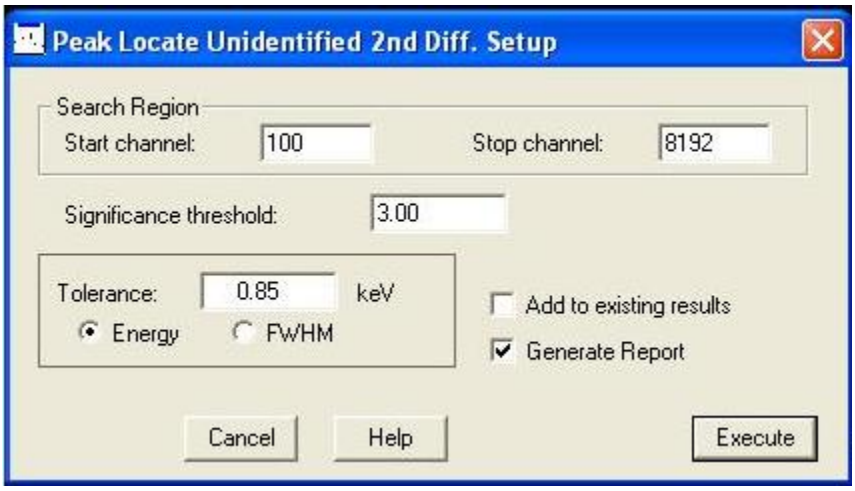
Load the proper ASF



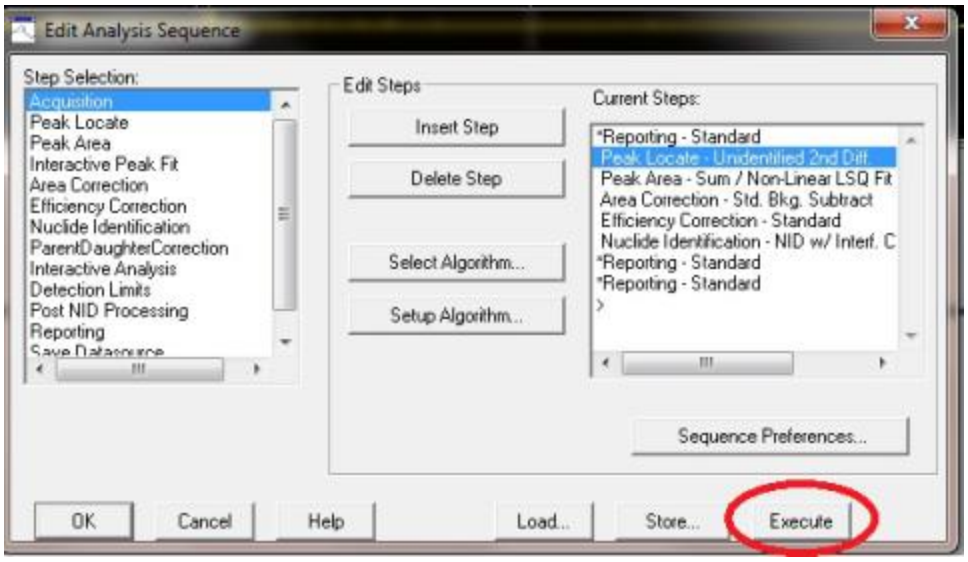
Select the *Peak Locate* Function



Change the Significance threshold to a higher number



Execute the ASF



<u>Cannot save a count from the detector view</u>

Reasons:

- Too much information exists in the report window

Solutions:

- Clear Contents from the report window
- Re-calibrate the energy spectrum of the save spectrum using nuclides found in the spectrum

NAA SAMPLE IRRADIATION AND ANALYSIS

1. **Sample Acquisition**
2. **Sample Preparation**
3. **Determining Irradiation Conditions**
4. **QC operations**
5. **Sample Irradiation**
6. **Sample Analysis**

1. Sample Acquisition

Sample can be gathered from an infinite number of sources. What is important to take into account is that contamination be minimized. If possible samples should be collected using gloves and placed in individual containers. Organic materials may begin to decay and this also should be taken into account.

2. Sample Preparation

Collected samples should be placed in a plastic vial or pouch for irradiation. This container should only be handled with gloves before and after irradiation. The plastic container should be sealed to prevent any loss of material.

3. Determining Irradiation Conditions

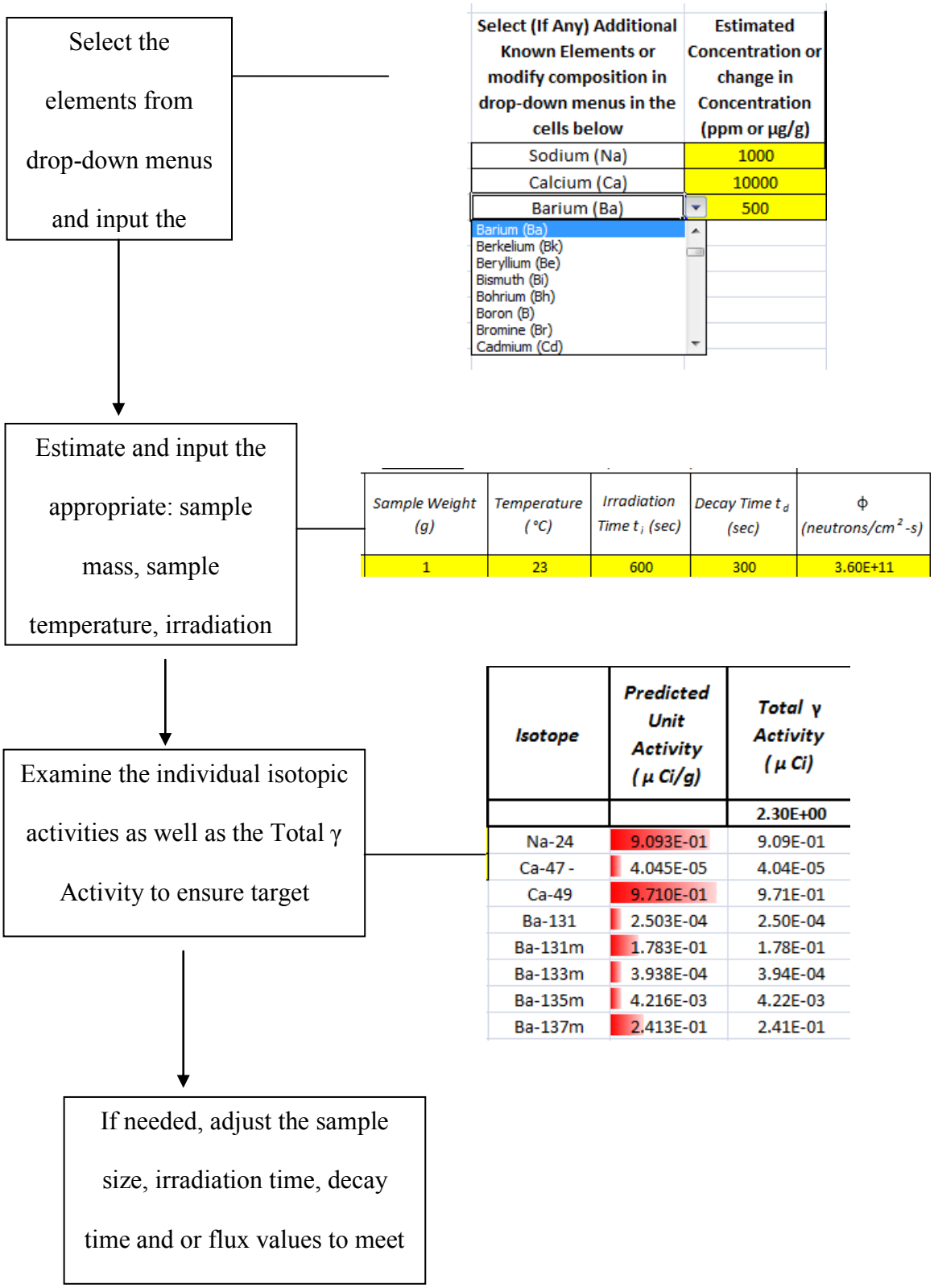
To determine the proper sample size, irradiation time and decay the *NAA Activity Estimator Calculator* should be used. Total activities should be kept below 10 μCi at the time of counting as to not saturate the detectors. Total activities from 0.25 – 2 μCi are preferable.

Sample sizes, except for aqueous liquids, should be kept to < 2.5 g unless a proper geometry can be created for such a sample. Sample may be to be doubly contained and sealed in necessary.

Long and Short irradiations should be consider depending on the element(s) that need to be analyzed. High purity materials, like metals, may need to be irradiated at lower fluxes to prevent excessively high activities.

Longer irradiation times will lead to low detection limits and often lower uncertainties. Samples containing significant concentrations (>1%) of Na should have special considerations because of the spectral interferences that Na-24 causes for both long and short irradiations.

Activity Estimator flow diagram



4. QC operations

All gamma spectroscopy QA checks should be performed prior to counting. See the **Regular QA Checks and Maintenance** section.

Standard Reference Materials (SRM) should be irradiated in tandem with the sample(s) for best quality control (QC) measures if high accuracy concentration results are desired. SRM will provide a certified reference of selected elements. The activities of the elements in the SRM can then be used in the *SRM Ratio Calculator* for high accuracy elemental concentration results.

5. Sample Irradiation

A formal request for sample irradiation should be submitted to the Reactor Supervisor longer later than one week prior to irradiation. The irradiation times should have already been determined using the *Activity Estimator* with this information in the request form. Upon approval the samples will be irradiated in the University of Utah TRIGA Reactor Thermal Irradiator as outlined in the request.

6. Sample Analysis

5. Sample should be counted multiple times on an HPGe detector in accordance with the **Sample Acquisition, Information and Analysis** section.

Short irradiations can be ran for 0.5 – 20 minutes, at a reactor power of 90 kW_{th}, and counted several times (first at t_{decay} = 1 – 10 min and the second t_{decay} = 1 – 4 hr) to find short lived ($t_{1/2}$ = 1 – 30 min) and medium lived ($t_{1/2}$ = 0.5 – 12 hr) isotopes.

Long term irradiations can run for 30 – 300 minutes and allowed to decay for at least 24 hours before counting. These also need to be counted at least two times to better identify the isotopes with long half lives ($t_{1/2}$ =12 – 48 hr) from those with very long half lives ($t_{1/2}$ = 2 + days).

Using the information generated in the analysis report the *Elemental Concentration Calculator* or the SRM Ratio Calculator can be used to determine the elemental concentrations of the activated and identified elements.

Elemental Concentration Calculator instructions

Take the irradiation times and the acquisition time from the first page of the report

```
*******************************************************************************
*****        G A M M A   S P E C T R U M   A N A L Y S I S          *****
*******************************************************************************


Filename: C:\GENIE2K\CAMFILES\Todd\Water_and_Environmental\English_Waln

Report Generated On             : 10/27/2011  8:41:58 AM

Sample Title                    : English Walnut Wood
Sample Description              : 10:05 - 12:01 PM 10/21/2011
Sample Identification           : Wood
Sample Type                     : Environmental
Sample Geometry                 : NAA

Peak Locate Threshold           :  3.00
Peak Locate Range (in channels) :     1 - 65535
Peak Area Range (in channels)   :    60 -  8192
Identification Energy Tolerance :    1.150 keV

Sample Size                     :  4.296E-001 g

Sample Taken On                 : 10/27/2011  8:03:34 AM
Acquisition Started             : 10/27/2011  8:03:34 AM

Live Time                       :     1800.0 seconds
Real Time                       :     1801.0 seconds

Dead Time                       :   0.05 %


             Energy Calibration Used Done On       : 10/25/2011
             Efficiency Calibration Used Done On   : 10/20/2011
             Efficiency ID                         :
```

Input this information the top of the calculator. The yellow cells indicate that the operator needs to input some information. The uncertainty values (σ) can be estimated according the ability to measure such values. For example the long irradiations are timed using a clock with no seconds displayed. Therefore, the uncertainty could be as much as 60 seconds for the irradiation time.

Date and Time of end of [illegible]		Date and Time of start of acquisition					
10/21/2011 12:01			10/27/2011 8:03				
Temperature (°C)	Irradiation Time t_i (sec)	Decay Time t_d (sec)	Φ (neutrons/cm^2-s)	N_A (atoms/mole)	σt_{irr} (sec)	σt_{decay} (sec)	σ_Φ (neutrons/cm^2-s)
22	6960	504154	3.76E+11	6.0221419E+23	60	60	3.31E+10

Isotope Entry	Measured Activity (μ Ci/g)	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (μg/g or ppm)	Activity uncertainty (μ Ci/g)	Mass Composition uncertainty (μg/g or ppm)	
Na-24	1.0082E-03	Sodium (Na)	0.0062%	62.12067981	3.4256E-05	5.884400352	9.47%
K-42	1.6788E-03	Potassium (K)	0.3097%	3097.152123	1.3115E-04	365.4286128	11.80%
Sc-46	4.1198E-05	Scandium (Sc)	0.0000%	0.019629304	1.3360E-05	0.006598031	33.61%
Sc-47*	5.1545E-05	Calcium (Ca)	0.2472%	2471.759792	6.4765E-06	379.761539	15.36%
Cr-51	8.0883E-05	Chromium (Cr)	0.0001%	0.646474193	2.2524E-05	0.188888361	29.22%
Br-82	4.4659E-05	Bromine (Br)	0.0000%	0.207597699	5.5725E-06	0.031748543	15.29%
Rb-86	3.4459E-04	Rubidium (Rb)	0.0007%	6.530325116	2.3926E-04	4.570751184	69.99%
Sb-122	2.8673E-05	Antimony (Sb)	0.0000%	0.040956978	5.2838E-06	0.00837121	20.44%
La-140	5.5391E-05	Lanthanum (La)	0.0000%	0.05429742	6.9981E-06	0.008373116	15.42%
Sm-153	1.1038E-04	Samarium (Sm)	0.0000%	0.017774381	1.9764E-05	0.003549556	19.97%
Au-198	3.9386E-05	Gold (Au)	0.0000%	0.003182335	6.1284E-06	0.000569526	17.90%

Input the nuclides, their activities and uncertainties from the interference corrected report

```
Interference Corrected Activity Report    10/27/2011  8:41:59 AM   Page  4

*************************************************************************
*****   I N T E R F E R E N C E   C O R R E C T E D   R E P O R T   *****
*************************************************************************

                Nuclide       Wt mean          Wt mean
      Nuclide     Id          Activity         Activity
      Name     Confidence     (uCi/g   )      Uncertainty

      NA-24       0.986      1.008016E-003   3.435598E-005
      K-40        0.968      3.646183E-004   1.104048E-004
      K-42        0.902      1.678780E-003   1.311489E-004
      SC-46       0.989      4.119810E-005   1.336027E-005
   ?  SC-47       0.995      5.154540E-005   6.476483E-006
      CR-51       0.995      8.088258E-005   2.252434E-005
      BR-82       0.592      4.465859E-005   5.572522E-006
      RB-86       1.000      3.445918E-004   2.392568E-004
   ?  SN-117m     0.918      4.044260E-005   5.005802E-006
      SB-122      0.925      2.867332E-005   5.283760E-006
   ?  TE-123m     0.996      4.157853E-005   5.146611E-006
      LA-140      0.802      5.539106E-005   6.998127E-006
      SM-153      0.838      1.103788E-004   1.976429E-005
   X  IR-194      0.622
      AU-198      0.980      3.938648E-005   6.128377E-006

      ? = nuclide is part of an undetermined solution
      X = nuclide rejected by the interference analysis
      @ = nuclide contains energy lines not used in Weighted Mean Activity

      Errors quoted at  1.000 sigma
```

Date and Time of end of irradiation		Date and Time of start of acquisition					
10/21/2011 12:01		10/27/2011 8:03					
Temperature (°C)	*Irradiation Time t_i (sec)*	*Decay Time t_d (sec)*	*Φ (neutrons/cm^2-s)*	*N_A (atoms/mole)*	*σ t_{irr} (sec)*	*σ t_{decay} (sec)*	*σ_Φ (neutrons/cm^2-s)*
22	6960	504154	3.76E+11	6.0221419E+23	60	60	3.31E+10

Isotope Entry	*Measured Activity (μCi/g)*	Measured Parent Element	Measured Mass Concentration (%)	Measured Mass Composition (µg/g or ppm)	*Activity uncertainty (μCi/g)*	Mass Composition uncertainty (µg/g or ppm)	
Na-24	1.0082E-03	Sodium (Na)	0.0062%	62.12067981	3.4256E-05	5.884400352	9.47%
K-42	1.6788E-03	Potassium (K)	0.3097%	3097.152123	1.3115E-04	365.4286128	11.80%
Sc-46	4.1198E-05	Scandium (Sc)	0.0000%	0.019629304	1.3360E-05	0.006598031	33.61%
Sc-47*	5.1545E-05	Calcium (Ca)	0.2472%	2471.759792	6.4765E-06	379.761539	15.36%
Cr-51	8.0883E-05	Chromium (Cr)	0.0001%	0.646474193	2.2524E-05	0.188888361	29.22%
Br-82	4.4659E-05	Bromine (Br)	0.0000%	0.207597699	5.5725E-06	0.031748543	15.29%
Rb-86	3.4459E-04	Rubidium (Rb)	0.0007%	6.530325116	2.3926E-04	4.570751184	69.99%
Sb-122	2.8673E-05	Antimony (Sb)	0.0000%	0.040956978	5.2838E-06	0.00837121	20.44%
La-140	5.5391E-05	Lanthanum (La)	0.0000%	0.05429742	6.9981E-06	0.008373116	15.42%
Sm-153	1.1038E-04	Samarium (Sm)	0.0000%	0.017774381	1.9764E-05	0.003549556	19.97%
Au-198	3.9386E-05	Gold (Au)	0.0000%	0.003182335	6.1284E-06	0.000569526	17.90%

SRM Ratio Calculator

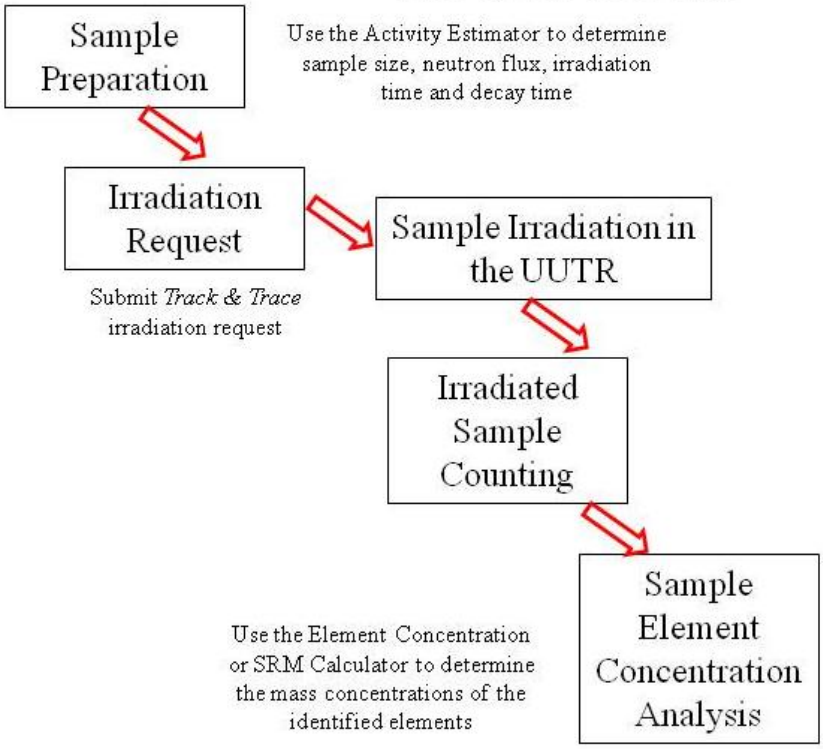
This calculator takes the activities from the same element in both the SRM and the sample as well as the certified mass concentration from the SRM. With these values the mass concentration for this element can be determined in the sample

SRM			
	mass (g)	Select Standard	
	0.3208		
Isotope Entry	***Measured Activity (µCi/g)***	**Observed Parent Element**	**Assayed Concentration (mg/kg or ppm)**
K-40	2.6068E-04	Potassium (K)	2250
Sc-46	1.4593E-02	Scandium (Sc)	
Sc-47*	1.1919E-04	Calcium (Ca)	2940
Cr-51	2.6668E-02	Chromium (Cr)	295
Mn-54	6.0842E-05	Iron (Fe)	7620
Co-58	1.3355E-04	Nickel (Ni)	346
Fe-59	3.3195E-03	Iron (Fe)	7620

Co-60	1.0878E-02	cobalt (Co)	145
Zn-65	2.1544E-03	Zinc (Zn)	383
Se-75	1.2330E-03	Selenium (Se)	118
Sr-85	7.7766E-05	Strontium (Sr)	263
Tc-99m*	3.8083E-03	Molybdenum (Mo)	73.8
Ag-110m	3.9139E-04	Silver (Ag)	30.3
Cd-115 -	5.8044E-04	Cadmium (Cd)	150
Sb-122	1.4699E-02	Antimony (Sb)	44.8
Sb-124	6.2994E-03	Antimony (Sb)	44.8
Ba-131	6.6076E-04	Barium (Ba)	741

	Sample			
	mass (g)			
	0.1607			
	Measured Activity **(**µCi/g)	**Observed Parent Element**	**Calculated Concentration (mg/kg or ppm)**	**Calculated uncertainty**
K-40	1.0269E-03	Potassium (K)	**17693.32414**	2595.524235
SC-46	3.9983E-04	Scandium (Sc)	**0**	0
SC-47	4.2377E-03	Calcium (Ca)	**208668.6379**	19412.48331
CR-51	3.0388E-04	Chromium (Cr)	**6.710588403**	1.308712142
		Iron (Fe)		
		Nickel (Ni)		
FE-59	1.7202E-04	Iron (Fe)	**788.2658384**	81.31758811
		cobalt (Co)		
ZN-65	2.2306E-05	Zinc (Zn)	**7.916080217**	4.963326777
		Selenium (Se)		
SR-85	5.1771E-04	Strontium (Sr)	**3495.227427**	269.0516922
		Molybdenum (Mo)		
		Silver (Ag)		
		Cadmium (Cd)		
SB-122	7.0307E-05	Antimony (Sb)	**0.427763091**	0.082672373
		Antimony (Sb)		
BA-131	4.0764E-04	Barium (Ba)	**912.5921995**	38.85471865

NAA Method Flow Diagram as Developed for the UUTR



NAA Equations

$A = activity\ in\ (Bq) or \left(\frac{decays}{second}\right)$

$A' = specific\ activity\ in\ (\frac{Bq}{g})$

$A_0 = activity\ at\ t = 0\ (Bq)$

$N = number\ of atoms$

$N_A = Avogado's\ number$

$t_{1/2} = half\ life\ (seconds)$

$\sigma = microscopic\ cross\ section\ barns * (10^{-24} cm^2)$

$\phi = thermal\ neutro\ flux\ \left(\frac{neutrons}{cm^2 - sec}\right)$

$\Sigma = macroscopic\ cross\ section\ \left(\frac{1}{cm}\right)$

$\lambda = decay\ constant\ \left(\frac{1}{second}\right)$

$t_{irr} = irradation\ time$ (seconds)

$t_{decay} = decay\ time$ (seconds)

$m = mass\ (grams)$

$C = concentration\ \left(\frac{grams}{gram}\right)$

$A_m = Atom\ is\ mass\ \left(\frac{g}{mole}\right)$

$M_m = Molar\ mass\ \left(\frac{g}{mole}\right)$

$A_{\%} = isotopic\ abundance\ (\%)$

$T = Temperature\ (K)$

$R = reaction\ rate\ \left(\frac{events}{second}\right)$

$subscripts\ P = parent, D = Daughter, G = Granddaughter$

$$A = N_P \sigma_P \phi \left(1 - e^{-\lambda_D t_{irr}}\right) e^{-\lambda_D t_{decay}}$$

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

$$N = m\frac{N_A}{A_m}, atomic\ ratio\ \frac{N_A}{M_m}$$

$$A(t_{decay}) = N\sigma\phi\left(1 - e^{-\lambda\, t_{irr}}\right) e^{-\lambda\, t_{decay}}$$

$$N_D\left(t_{decay}\right) = \frac{N_P \sigma_P \phi \left(1 - e^{-\lambda_D\, t_{irr}}\right) e^{-\lambda_D\, t_{decay}}}{\lambda_D}$$

$$N_P = \frac{A_D\left(t_{decay}\right)}{\sigma_P \phi (1 - e^{-\lambda_D\, t_{irr}}) e^{-\lambda_D\, t_{decay}}}$$

Activation to unstable daughter and stable granddaughter

$$\frac{d\, N_P(t)}{dt} = \phi \sigma_P N_P - \lambda_D N_D(t)$$

$$N_D(t_{decay}) = \frac{N_P \sigma_P \phi}{\lambda_D - \sigma_P \phi}\left(e^{-\sigma_P \phi\, t_{irr}} - e^{-\lambda_D\, t_{irr}}\right)e^{-\lambda_D\, t_{decay}}$$

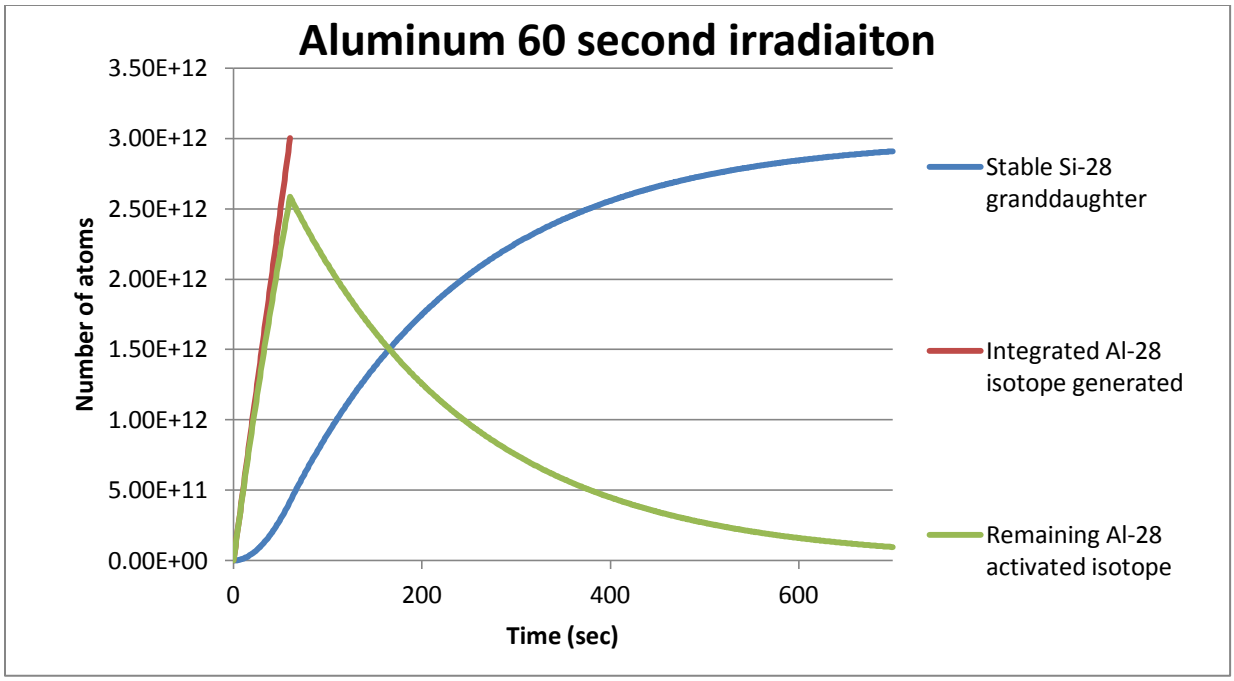
$$A_D(t_{decay}) = \frac{N_P \sigma_P \phi}{\lambda_D - \sigma_P \phi}\lambda_D\left(e^{-\sigma_P \phi\, t_{irr}} - e^{-\lambda_D\, t_{irr}}\right)e^{-\lambda_D\, t_{decay}}$$

$$= N\sigma\phi\left(1 - e^{-\lambda\, t_{irr}}\right)e^{-\lambda\, t_{decay}}$$

$$N_P = \frac{A_D(t_{decay})}{\frac{\sigma_P \phi}{\lambda_D - \sigma_P \phi}\lambda_D(e^{-\sigma_P \phi\, t_{irr}} - e^{-\lambda_D\, t_{irr}})e^{-\lambda_D\, t_{decay}}}$$

$$C = \frac{A_D{}'(t_{decay})}{\phi\left[\frac{\sqrt{\pi}}{2}\sigma_P\sqrt{\frac{293}{T}}\right]\frac{N_A}{A_m}A_{\%}(1 - e^{-\lambda_D t_{irr}})e^{-\lambda_D t_{decay}}}$$

$$\sigma_C = C\sqrt{\left(\frac{\sigma_A}{A'}\right)^2 + \left(\frac{\sigma_\phi}{\phi}\right)^2 + \left(\frac{\sigma_T}{T}\right)^2 + \left(\lambda\sigma_{t_{irr}}\right)^2 + \left(\lambda\sigma_{t_{decay}}\right)^2}$$



Activation to unstable daughter and unstable granddaughter

$$\frac{d\,N_G(t)}{dt} = \phi\sigma_P N_P - \lambda_D N_D(t) - \lambda_G N_G(t)$$

$$N_G(t_{decay}) = \frac{N_P\sigma_P\phi}{\lambda_G(\lambda_D - \lambda_G)}\left[\lambda_D\left(1 - e^{-\lambda_G\, t_{irr}}\right)e^{-\lambda_G\, t_{decay}}\right.$$

$$\left. - \lambda_G\left(1 - e^{-\lambda_D\, t_{irr}}\right)e^{-\lambda_D\, t_{decay}}\right]$$

$$A_G(t_{decay}) = \frac{N_P\sigma_P\phi}{(\lambda_D - \lambda_G)}\left[\lambda_D\left(1 - e^{-\lambda_G\, t_{irr}}\right)e^{-\lambda_G\, t_{decay}}\right.$$

$$\left. - \lambda_G\left(1 - e^{-\lambda_D\, t_{irr}}\right)e^{-\lambda_D\, t_{decay}}\right]$$

$$N_P = \frac{A_G(t_{decay})}{\frac{\sigma_P \phi}{(\lambda_D - \lambda_G)}\left[\lambda_D(1 - e^{-\lambda_G t_{irr}})e^{-\lambda_G t_{decay}} - \lambda_G(1 - e^{-\lambda_D t_{irr}})e^{-\lambda_D t_{decay}}\right]}$$

$$C = \frac{A_G{}'(t)}{\frac{N_A}{A_m} A_{\%} \frac{\left[\frac{\sqrt{\pi}}{2}\sigma_P\sqrt{\frac{293}{T}}\right]\phi}{(\lambda_D - \lambda_G)}\left[\lambda_D(1 - e^{-\lambda_G t_{irr}})e^{-\lambda_G t_{decay}} - \lambda_G(1 - e^{-\lambda_D t_{irr}})e^{-\lambda_D t_{decay}}\right]}$$

$$\sigma_C = C\sqrt{\left(\frac{\sigma_A}{A'}\right)^2 + \left(\frac{\sigma_\phi}{\phi}\right)^2 + \left(\frac{\sigma_T}{T}\right)^2 + \left(\lambda\sigma_{t_{irr}}\right)^2 + \left(\lambda\sigma_{t_{decay}}\right)^2}$$

$$C_{sample} = C_{Standard}\frac{m_{Standard}}{m_{Sample}}\frac{A_{sample}}{A_{standard}} \qquad 2-20$$

REFERENCES

Alnour, I. A., Ibrahim, N., & Fen, I. H. (2011). The accuracy of the absolute NAA method based on the analysis of standard reference materials (SRMs). *analysis of standard reference materials (SRMs) , 6* (17), 4169-4175.

Baas, H. W. (2004). *Neutron Activation Analysis of Inhomogeneous Large Samples - An Explorative Study.* Delft, Netherlands: Delf University of Technology.
Brazilian Journal of Physics. (n.d.). Retrieved February 20122, from Brazilian Journal of Physics: http://www.scielo.br/scielo.php?pid=S0103-97332010000100008&script=sci_arttext

(2004). Genie 2000 V3.1 Users Manual. In Canberra. Meriden, Conneticut: Canberra.

De Bruin, M. (1990). Applying Biological Monitors and Neutron Activation Analysis in Studies of Heavy-Metal Air Pollution. *IAEA Bulleting , 32* (4), 22-27.

Decay data search. (n.d.). Retrieved February 2012, from Decay data search - NuDat database:
http://nucleardata.nuclear.lu.se/Scripts/database/nudat/Nuclide.idc?el=Fe&prod=

Decay data search - NuDat database. (n.d.). Retrieved 2011, from The Lund/LBNL Nuclear Data Search: http://nucleardata.nuclear.lu.se/database/nudat/
(1999). *Determination of Metals in Ambient Particulate Matter Using Neutron Activation*

Analysis (NAA) Gamma Spectromentry. U.S. Environmental Protection Agency, Center for Environmental Research Information. Cincinnati, OH: U.S. Environmental Protection Agency.

Error Propagation tutorial.doc. (n.d.). Retrieved March 2012, from Foothill College PSME:
http://www.foothill.edu/psme/daley/tutorials_files/10.%20Error%20Propagation.pdf

Frontasyeva, M. V., & Steinnes, E. (1997). Epithermal Neutron Activation Analysis for Studying the Environment. *International Symposium on Harmonization fo Health Related*

Environmental Measurements Using Nuclear and Isotopic Techniques. Hyderabad, India.

Gamma Spectrum Generator. (n.d.). Retrieved March 2012, from Nucleonica Wiki:
http://www.nucleonica.com/wiki/index.php?title=Help:Gamma_Spectrum_Generator

General Atomics Electronic Systems. (n.d.). Retrieved February 2012, from General Atomics Electronic Systems: http://www.ga-esi.com/triga/about/index.php

Grant, C. N., Lalor, G., & Vutchkov, M. K. (1998). Neutron activation analysis of cadmium in Jamaica. *Journal of Radioanalytical and Nuclear Chemistry , 237* (1-2), 109-112.

Greenberg, R. R. (2008). Pushing the limits of NAA: Accuracy, uncertainty and detection limits. *Journal of Radioanalytical and Nuclear Chemistry , 278* (2), 231-240.
Guinn, V. P. (1979). JFK Assassination: Bullet Analysis. *Analytical Chemistry , 51* (4), 484-493.

Hampel, G., Wortmann, B., Knorr, J., Kratz, J., Aguilar, A. L., Minouchelr, S., et al. (2009). Irradiation facility at the TRIGA Mainz for treatment of liver metastases. *Applied Radiation and Isotopes , 67* (7-8), 238-241.

Hassan, A. M. (2008). Modern Trends in Neutron Acitivation Analysis. Applications to some African Environmental Sampesl. *Proceedings of the 3rd Environmental Physics Conference.* Aswan, Egypt.

http://atom.kaeri.re.kr/. (n.d.). Retrieved 2011, from Korean Atomic Energy Research Institute: http://atom.kaeri.re.kr/

http://www.believeallthings.com. (n.d.). Retrieved April 2012, from Believe all things.com: http://www.believeallthings.com/3278/salt-lake-temple-foundation-stones/
Hunter, D. L. (n.d.). *Idaho Farmer Plowing Field*. Retrieved April 2012, from Flickr:

http://www.flickr.com/photos/daryl-hunter/4608111809/lightbox/

IAEA. (2001). Use of research reactors for Neutron Acitvation Analysis. *IAEA-TECDOC-1215.* Vienna.

Instituto de Pesquisas Energeticas e Nucleares. (n.d.). *Nuclear Science & Technology (2008).* Retrieved September 12, 2010, from Progess Report 2005 - 2007: http://www.ipen.br/conteudo/upload/201002021820590.4_nuclear_science.pdf

International Labour Organization. (n.d.). Retrieved March 2012, from International Labour Organization:

http://www.ilo.org/safework_bookshelf/english?content&nd=857170560
Jevremovic, T. (2009). *Nuclear Principles in Engineering* (2nd ed.). New York City, New York, USA: Springer.

Johnson, A. H., Lalor, G. C., Preston, J., Robotham, H., Thompson, C., & Vutchkov, M. K. (1996). Heavy metals in Jamaican surface soils. *Environmental Geochemistry and Health , 18*, 113-121.

Kiraly, B., Sanami, T., & Csikai, J. (2003). Advantages and limitations of thermal and epithermal neutron activation analysis of bulk samples. *Applied Radiation and Isotopes , 58* (6), 691–695.

Leslie, R. (2008). *Potential for Produciton of Porliferation Sensitive Materials in Research Reactors.* Australian Government, Australian Safegruards Support Program.

Levi, H. (1985). *George de Hevesy: life and work : a biography.* A. Hilger, 1985.

Neutron Temperature. (n.d.). Retrieved February 2012, from Wikipedia - Neutron Temperature: http://en.wikipedia.org/wiki/Neutron_temperature

New possible signal of dark matter subject of debate. (n.d.). Retrieved March 2012, from http://www.thephotonist.net/: http://www.thephotonist.net/2011/05/new-possible-signal-of-dark-matter-subject-of-debate/

Noble, B. (2012). Cadmium Ration MCNP5 Modeling and Measurements for UUTR Thermal Irradiator. *ANS Student Conference 2012.* Las Vegas, NV.

NuDat 2.6. (n.d.). Retrieved 2011, from NuDat 2.6: http://www.nndc.bnl.gov/nudat2/
Oak Ridge National Laboratory. (n.d.). Retrieved February 2012, from Neutron Sciences - Facts & Figures: http://neutrons.ornl.gov/about/facts.shtml

Overview of Neutron Activation Analysis. (n.d.). Retrieved February 2012, from University of Missouri Research Reactor: Archaeometry Laboratory: http://archaeometry.missouri.edu/naa_overview.html

Paul, R. L. (2011). Evaluation of Radiochemical Neutron Activation Analysis Methods for Determination of Arsenic in Biological Materials. *Analytical Chemistry , 83* (1), 152-156.

Periodictable.com. (n.d.). Retrieved 2011, from Periodictable.com: http://periodictable.com/

Sanchez, I. C., Hampel, G., & Riederer, J. (2009). Reverse paintings on glass - A new approach for dating and localization. *Applied Radiation and Isotopes* , 2113–2116.
Seabury, E. H., & Caffrey, A. J. (n.d.). *Explosives Detection and Identification by*

PGNAA. Retrieved April 2012, from inl.gov: http://www.inl.gov/technicalpublications/Documents/3480146.pdf

Sjao-Bohus, L., Mackowiak de Antezak Ma., M., Kasztovszky, Z., Greaves, E., Antezak, A., Simonits, A., et al. (2006). Neutron Activiation Analysis of Pre-Columbian Potter in Venezuela. *Journal of Physics: Conference Series 41* (pp. 408-416). Institute of Physics Publishing.

Table of Nuclides. (n.d.). Retrieved 2011, from Korean Atomic Energy Research Institute: http://atom.kaeri.re.kr/

The Dr. Oz Show. (n.d.). Retrieved February 2012, from The Dr. Oz Show: http://www.doctoroz.com/videos/arsenic-apple-juice

The Language of the Nucleus. (n.d.). Retrieved February 2012, from The Language of the Nucleus: http://www.nuclearglossary.com/nuclearglossary_reactions.html

TRIGA Reactors. (n.d.). Retrieved February 2012, from TRIGA Reactors: http://www.ga-esi.com/triga/about/install_usa.pdf

trussty-jasmine.blogspot.com. (n.d.). Retrieved April 2012, from trussty-jasmine.blogspot.com: http://trussty-jasmine.blogspot.com/2012/03/white-rice-and-type-2-diabetes.html#axzz1tPEcgvOf

Tsoulfanidis, N. (1995). Measurement and Detection of Radiation. Taylor & Francis.

Weider, B. C. (1999). Activation Analyses of Authenticated Hairs of Napoleon Bonaparte Confirm Arsenic Poisoning. *The American Jouranl of Forensic Medicine and Pathology , 20* (4), 378-382.

Wikipedia - Neutron Activation Analysis. (n.d.). Retrieved from Wikipedia: en.wikipedia.org/wiki/Neutron_activation_analysis

Win, D. T. (2004). Neutron Activation Analysis. *AU Journal , 8* (1), 8-14.

WWW Table of Radioactive Isotopes. (n.d.). Retrieved 2011, from LBNL Isotopes Project - LUNDS Universitet: http://ie.lbl.gov/toi/nucSearch.asp

www.healthygreenkitchen.com. (n.d.). Retrieved April 2012, from www.healthygreenkitchen.com: http://www.healthygreenkitchen.com/simple-seasoned-aduki-beans.html