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Kishor Paudel

Date _____

**GAMMA DOSE RATES AND POTENTIAL SOURCE TERM FROM
TENORM AT A MOLYBDENUM ORE PROCESSING FACILITY**

**By
Kishor Paudel**

**A thesis
Submitted in partial fulfillment
Of the requirements for the degree of
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Table of Contents

List of Figures.....	vii
List of Tables.....	ix
List of Abbreviations and Acronyms.....	xi
Glossary.....	xii
Abstract.....	xiii
Chapter 1. Introduction	1
1.1 Background	1
1.2 Objective	1
1.3 Thompson Creek Mining Company at Challis, Idaho.....	2
Chapter 2. Literature Review	5
2. 1 Molybdenum	5
2.1.1 What is Molybdenum?	5
2.1.2 Chemical properties.....	6
2.1.3 History of Molybdenum	6
2.1.4 Applications:	7
2.1.5 How are molybdenum metal products made?	8
2.2Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). 11	
2.2.1 Natural Radioactivity	11
2.2.2 EPA concerns about TENORM	12
2.2.3 Sources of TENORM	14
2.2.4 TENORM monitoring concerns	16
2.2.5 Management of NORM.....	16
2.2.6 TENORM Wastes	17
2.3 Radiation and Mining.....	18
2.3.1 Ra-226 content of Rocks and ores.....	19
2.3.2 Monazite	20
2.3.3 Natural radioactivity in ore	21

2.3.4 Natural Radioactivity in the Ocean	22
2.3.5 Radiation in Food	22
2.4 Decay chains	24
2.4.1 Radioactive Decay.....	24
2.4.2 Natural Decay series.....	26
2.4.3 Radon gas and Radon loss.....	29
2.4.4 K-40.....	30
2.4.5 Rubidium-87 (Rb-87).....	31
2.5 TENORM Standards and Guidelines.....	32
2.5.1 International Atomic Energy Agency (IAEA)	33
2.5.2 EPA vs NCRP guidelines on TENORM	33
2.5.3 Standards for Uranium and Thorium Mill Tailings	34
2.6 Hypothesis:	35
Chapter 3: Methods and Materials.....	36
3.1 GammaTRACER	36
3.2 Reasons for choosing GammaTRACER in this project.....	37
3.3 High Purity Germanium (HPGe) Gamma Detectors.....	40
Chapter 4: Results and Discussions	45
4.1 Photon Dose Rates at Various Locations	45
4.2 Results obtained from Thompson Creek Mining Company.....	47
4.3 Results obtained from High Purity HPGe Gamma Detectors	56
4.3.1 Efficiency determination:	56
4.3.2 Activity of Identified radionuclides	59
4.3.3 Photon dose rate:	62
4.3.4 Comparison of GammaTRACER results with gamma detector result:.....	72
Chapter 5. Feasibility and Cost Analysis of future measurements	72
Chapter 6: Conclusions	75
Chapter 7: Future work	77
References	78
Appendix.....	82

List of Figures

Figure 1.1 Diagram of Molybdenum extraction facility	4
Figure 2.1 Diagram of Molybdenum.....	5
Figure 2.2 Flowchart describing molybdenum metal production in mill.....	10
Figure 2.3 Radioactive in growth.....	24
Figure 3.1 Picture of GammaTRACER.....	36
Figure 3.2 Detector Response at Higher dose rate.....	39
Figure 3.3 Detector Response at Lower Photon rate GF1142 vs. GF1159.....	40
Figure 3.4 Geometry used to count samples in gamma detector.....	41
Figure 4.1 Dose rates at various locations GF1142.....	46
Figure 4.2 Dose rates measured by GF1159.....	46
Figure 4.3.1 Photon dose rates at Scavenger Tail (ST).....	48
Figure 4.3.2 Photon dose rate at under little thicker.....	48
Figure 4.3.3 Photon dose rates at De-agglomeration.....	49
Figure 4.3.4 Photon dose rates at Rougher Concentrate.....	49
Figure 4.3.5 Photon dose rates at Stock tank 7.....	50
Figure 4.3.6 Photon dose rate at Re grind #1.....	50
Figure 4.3.7 Photon dose rates in between leach tank 3 & 4.....	51
Figure 4.3.8 Photon dose rates at Dust Scrubber.....	51
Figure 4.3.9 Photon dose rates at End of the Lab.....	52
Figure 4.3.10 Photon dose rates at Pyrite Rougher concentrate.....	52

Figure 4.4 Recount of Photon dose rates at PRC using GF1142.....	53
Figure 4.5 Recount of photon dose rates at PRC using GF1159.....	54
Figure 4.6 Efficiency of ore and water at various heights.....	57
Figure 4.7 Empirical efficiencies of ore samples at various heights.....	58
Figure 4.8 Activity of various geometry.....	60
Figure 4.9 Total Computed Photon dose rates for various samples.....	65
Figure 4.10 Contribution of various radionuclide in total photon dose rates.....	66
Figure 4.11.1 Percentage Photon dose rates from sample ore ST.....	67
Figure 4.11.2 Percentage Photon dose rates from sample ore PT-I.....	67
Figure 4.11.3 Percentage photon dose rates from sample ore PT-II.....	68
Figure 4.11.4 Percentage photon dose rates from sample ore PRC.....	68
Figure 4.11.5 Percentage photon dose rate sample ore FF-I.....	69
Figure 4.11.6 Percentage Photon dose rates from sample ore FF-II.....	69
Figure 4.11.7 Percentage photon dose rate from sample ore RT.....	70
Figure 4.11.8 Percentage photon dose rates from sample ore CT.....	70
Figure 4.11.9 Percentage photon dose rates from sample ore FT.....	71

List of Tables

Table 2.1 Industrial Applications of Molybdenum Category 1: Steel.....	7
Table 2.2 Annual estimated effective dose equivalent	12
Table 2.3 Industry Sectors and Associated NORM and TENORM.....	15
Table 2.4 Average Uranium Concentration in various rocks.....	20
Table 2.5 Natural radioactivity found in ore.....	21
Table 2.6 Natural radioactivity found in various oceans.....	22
Table 2.7 Natural radioactivity in food.....	23
Table 2.8 Properties of the radioactivity of the U-238 decay chain.....	27
Table 2.9 Properties of the radioactivity of the Th-232 decay chain.....	28
Table 2.10 Properties of the radioactivity of the U-235 decay chain.....	29
Table 2.11 Calibration Information for GammaTRACER.....	39
Table 3.1 LabSOCS TM and GESPECOR® input parameters for gamma detectors	44
Table 4.1 photon dose rate measured in various places.....	45
Table 4.2 Ore sample information.....	55
Table 4.3.1 Radionuclides with average activity for geometry CT.....	60
Table 4.3.2 Radionuclides with average activity for geometry PT-I.....	60
Table 4.3.3 Radionuclides with average activity for geometry PRC.....	61
Table 4.3.4 Radionuclides with average activity for geometry PT-II.....	61
Table 4.3.5 Radionuclides with average activity for geometry FF-I.....	61
Table 4.3.6 Radionuclides with average activity for geometry FF-II.....	61
Table 4.3.7 Radionuclides with average activity for geometry RT.....	62
Table 4.3.8 Radionuclides with average activity for geometry ST.....	62
Table 4.3.9 Radionuclides with average activity for geometry FT.....	62

Table 4.4 Gamma ray constants for various radionuclides.....	63
Table 4.5 Computed photon dose rates per hour per kilogram of various samples.....	64
Table 4.6 comparison of GammaTRACER and gamma detector result.....	73
Table 5.1 Cost estimation of installation of GammaTRACER.....	74

LIST OF ABBREVIATIONS AND ACRONYMS

EML	Environmental Monitoring Laboratory
EPA	Environmental Protection Agency
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IEER	Institute for Energy and Environmental Research
IMOA	International Molybdenum Association
NAS	National Academy of Sciences
NCRP	National Council on Radiation Protection and Measurement
NORM	Naturally Occurring Radioactive Material
TENORM	Technically Enriched Naturally Occurring Radioactive Material
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USGS	United States Geological Survey

Glossary

1. **Absorbed Dose:** Absorbed dose means energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are rad and the gray.
2. **Activity:** The activity of a source is defined as the rate at which a source of unstable nuclei decays measured in decays per second. The unit of activity is Bq which is decay per second.
3. **Dose rate:** The dose of ionizing radiation delivered per unit time. For example rems or Sieverts per hour.
4. **Gammas particles:** A gamma ray is an ionizing radiation in the form of electromagnetic energy, no charge and no rest mass. They have very high penetrating capability.
5. **Ionizing radiation:** Ionizing radiation is the radiation with enough energy so that during an interaction with an atom, it can remove tightly bound electrons from the orbit of an atom.
6. **Mill:** A plant in which ore is treated for the recovery of valuable metals, or the concentrations of valuable minerals for shipment to smelter or refinery.
7. **Milling Ore:** Ore that contains enough valuable minerals to be treated.
8. **Mining:** The process or industry of obtaining coal or the other minerals from a mine.
9. **Photon:** A particle representing a quantum of light or other electromagnetic radiation. A photon carries energy proportional to the radiation frequency but has zero rest mass.
10. **Radiation:** The emission of energy as electromagnetic waves or as moving subatomic particles, especially high-energy particles that cause ionization.
11. **Radionuclide:** A radioactive nuclide.
12. **Source Term:** Amount of radioactive materials released or the amount of the radioactive material available to cause exposure.

ABSTRACT

Natural radioactive substances are ubiquitous and may need to be monitored to prevent potential harmful effects to human health. Molybdenum does not occur in native state, but is obtained from the ores by mining and milling processes. The goal of this project was to measure photon dose rates at a Molybdenum processing facility. GammaTRACER, an autonomous measuring probe for the continuous measurement of photon dose rate, was used. Out of 10 chosen locations, one was found to have both variable and elevated photon dose rates. Ore samples throughout the milling process were collected and counted on two high purity gamma detectors. Ore samples were counted in gamma detectors after one month apart to find if they were originally in equilibrium. Different natural radionuclides with different concentrations were found that might be associated with the specific GammaTRACER measurements. They were: K-40, Pb-212, Bi-214, Pb-214, and Tl-208. Based on the HPGe gamma detector results, in-growth and decay were not observed in the ore samples.

Chapter 1. Introduction

1.1 Background

The goal of this study was to measure the photon dose rates at various places in Thompson Creek Mining Company's milling facility near Challis, Idaho and to determine sources of dose rates throughout the process. Finding which type of radionuclides and the pathway of exposure were additional goals. An autonomous radiation detection device, was used to measure photon dose rate in and around the facility. Two HPGe gamma detectors were used in the laboratory to measure radionuclide content in process ore samples.

Radioactive substances are natural and permanent feature of the environment. The risk associated with the radiation can be restricted but is impossible to eliminate entirely. There are some radiations produced because of human activity and may present some hazards to the people and the environment. It is important to identify the radionuclides, natural or man-made, which are sufficiently present as to pose a risk of detrimental effects to the humans and the environment.

1.2 Objective

The objective of this research project was to identify areas of elevated or variable photon dose rates and to suggest if any radionuclides and decay products might be primarily responsible for the measured photon dose rates. With this in mind it was a secondary goal to understand if continuous monitoring of the industrial setting could lend some useful real time industrial information by correlating dose rate to some useful understanding of process of chemical composition at different stages of production.

1.3 Thompson Creek Mining Company at Challis, Idaho

According to the corporate website, technically, Thompson Creek Mining Company is a mine, a mill and a major producer of surface molybdenum. The Thompson Creek Mining Company is located in the Bayhorse mining district about 20 air miles southwest of Challis, Idaho. It is the fourth- largest primary molybdenum mine in the world. One hundred twenty two million pounds of proven and probable contained molybdenum is available in this region (Thompson Creek 2015).

The mine began its operation in 1983. Thompson Creek uses conventional open- pit mining methods with large electric- powered shovels that can each move up to 100,000 tons of waste rock and ore per day. The shovels load ore into 200- ton trucks to be hauled to a site-mill. A molybdenum disulfide concentrate is processed from the ore through a series of crushing, grinding and floatation operations (Thompson Creek 2015). Daily throughput of ore at mill averages close to 28,000 tons per day. Most of the molybdenum disulfide concentrate produced at the mine is further processed into technical grade molybdenum oxide at the Langeloth Metallurgical Facility in Pennsylvania. A small portion of the concentrate of molybdenum is packaged at the mine and sold directly to customers (Thompson Creek 2015).

Materials containing NORM usually have a mixture of different radionuclides which are all capable of making some degree of contribution to worker and public exposure (European Commission 1999). All of these potentially harmful radionuclides need to be monitored and identified.

Average grade of molybdenum at Thompson Creek Mining Company at Challis, Idaho has been 0.1 to 0.13% Mo for well over 100 million tons of ore production (Worthington 2003). Thompson Creek Mining Company was the facility where the complete spectrum of photon dose rates were counted using GammaTRACER (see Figure 1.1 for a flowsheet for the concentrator in the facility).

THOMPSON CREEK MINING COMPANY QUALITY MANUAL

SECTION: APP. C

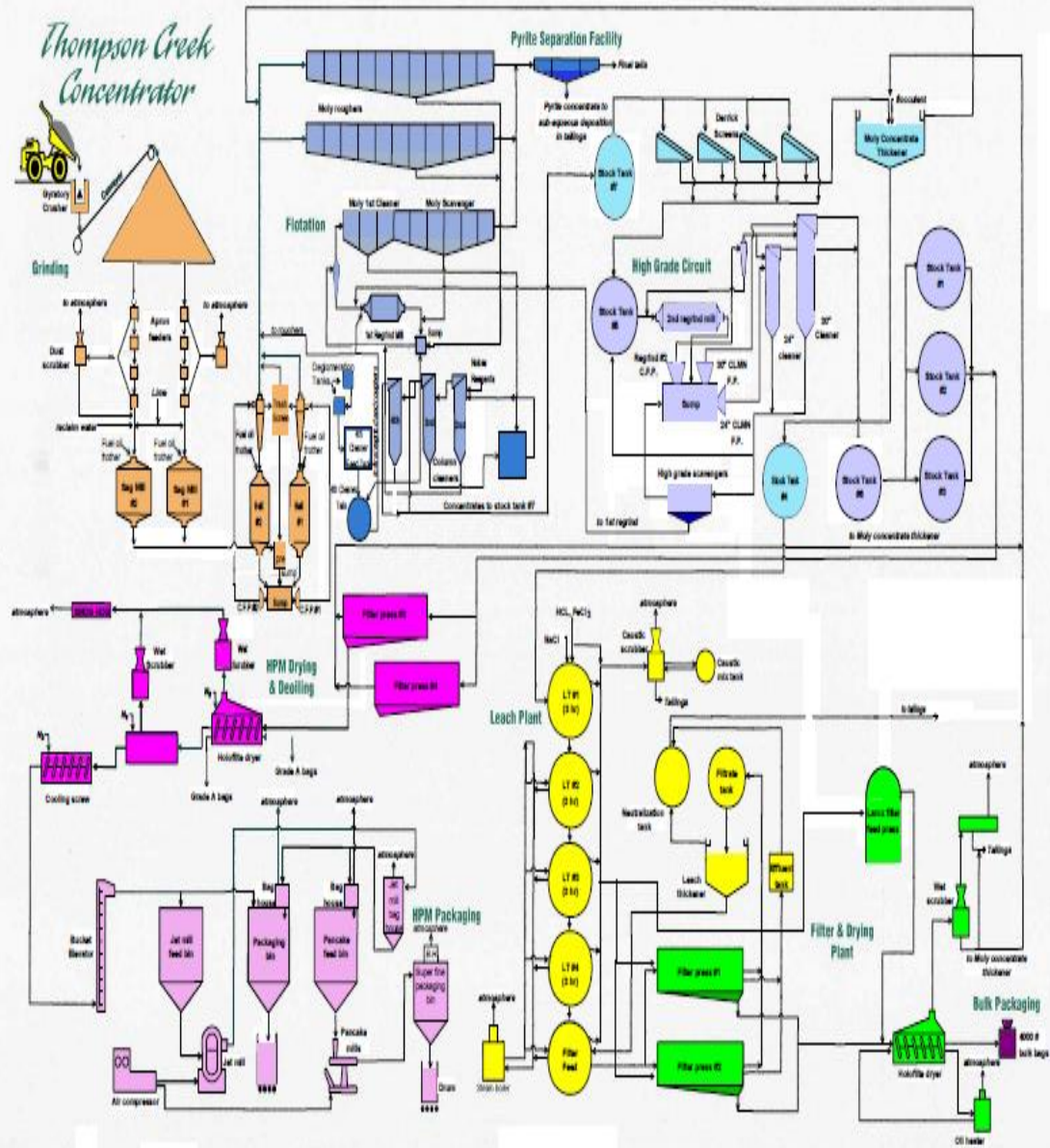
THOMPSON CREEK CONCENTRATOR FLOWSHEET

PAGE 1 OF 1

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Figure 1.1 Diagram of Molybdenum extraction facility (Source: Dr. BJ Bryant)

Chapter 2. Literature Review

2. 1 Molybdenum

2.1.1 What is Molybdenum?

Molybdenum is a group 6 transition metal in the periodic table. Molybdenum does not naturally occur in the native state but is obtained from the ores molybdenite, wulfenite, ferrimolybdate and jordicite (Gharehbaghi 2011). Molybdenum is an essential trace element for humans and animals. It was established that the daily Molybdenum requirement of human is approximately 25.0 μg or possibly less while an intake of 150 μg per kg body weight might be toxic (Gharehbaghi et.al 2011). Figure 2.1 shows the picture of crystalline molybdenum (Source: International Molybdenum Association). According to USGS, The United States has a total reserve of 2.70 million metric tons of Molybdenum, the rest of the world has a 6 million tons of molybdenum reserves. The leading producers in 2008 were the United States, China, Chile, Peru, and Canada (USGS 2010).



Figure 2.1 Picture of crystalline molybdenum

2.1.2 Chemical properties

Atomic Number: 42

Isotopes: 11

Melting points: 2610 degree Celsius

Boiling point: 4825 degree Celsius

Molybdenum metal is a silvery white, very hard transition metal, but is softer and more ductile than tungsten. Molybdenum has one of the highest melting points among all pure elements. Molybdenum reacts slowly with acids. Seven naturally occurring isotopes of molybdenum are: molybdenum-92, molybdenum-94, molybdenum-95, molybdenum-96, molybdenum-97, molybdenum-98, and molybdenum-100 (Lentech 2014).

2.1.3 History of Molybdenum

Molybdenum was discovered by Carl Wilhelm Scheele, a Swedish chemist, in 1778 in mineral known as MoS_2 which was confused as a lead compound. Molybdenum was isolated by Peter Jacob Hjelm in 1781. Today, most molybdenum is obtained from molybdenite. Molybdenum is also obtained from byproducts of mining and processing tungsten and copper. Molybdenum remained mainly a laboratory curiosity until the 19th century, when technologies for the extraction of commercial quantities became practical. In 1981, French company Schneider & Co. first used molybdenum as an alloying element in armor plate steel (IMOA 2014).

2.1.4 Applications:

Molybdenum is a valuable alloying agent because it helps in hardening and toughness of quenched and tempered steel. It also increases the strength of steel at high temperature. Molybdenum has various industrial applications, such as: alloying agent in steel and cast iron, pigment for printing ink, catalysts, and solid lubricants (Barvinyuk 2004). Molybdenum powders are used in circuit inks for circuit boards, and in microwaves devices and heat sink for solid state devices. Table 2.1 shows various industrial and other applications of Molybdenum (General Moly 2014).

Table 2.1 Industrial Applications of Molybdenum Category 1: Steel

Category	Applications
Full Alloy	Construction and Automotive industries, shipbuilding, heavy machinery, offshore pipeline
Stainless	Fuel tanks, Chemical and petroleum refineries, desalination plants
Carbon	Construction equipment and building, and transportation
Tool	Steels that cut other steels, extremely hard pieces of metal
HSLA	High strength, Low Alloy, Oil and Gas pipeline, construction and automotive industries, bridges

Category: Other Metallurgical

Super alloys	Supercharges, aircraft engines, gas turbines, chemical and petroleum plants
Cast Iron	Diesel engine motor blocks and cylinder heads, mining milling and crushing equipment
Mo Metals and Alloys	Auto parts, light bulb filament, glass manufacturing, heads shields

Category: 3 Non- Metallurgical

Catalyst	Petroleum hydro-processing and desulfurization
Lubricants	High performance base oils, greases, synthetic fluids coating, friction products
Pigment	Paints, links, plastic, and rubber products, ceramics
Other Chemical	Smoke suppressants, PVC, metal-based suppressants

2.1.5 How are molybdenum metal products made?

Molybdenum melts at a high temperature and oxidizes at a low temperature, which makes it difficult to extract molybdenum by using traditional smelting processes. Instead, a series of grinding and separating processes are required to isolate MoS_2 (molybdenum disulfide). The isolated materials contains up to 90 % of MoS_2 and the remaining unseparated mineral is roasted in air to produce MoO_3 (molybdic oxide) which is later converted to sulfuric acid for chemical separation. The roasted product is called Technical oxide or Tech oxide, and contains 57% MO and less than 0.1% S (IMO A 2013).

The Tech oxide is first dissolved in ammonium or sodium hydroxide, and the solution is processed by precipitation and filtration, solvent extraction or a combination of both to remove impurities. High-purity ammonium molybdate (ADM) is extracted by crystallization or precipitation and filtration. ADM is the starting material for molybdenum metal powder production. The molybdate can be heated to high temperature in air to produce high-purity molybdic oxide. ADM or calcined oxide undergoes a two stage chemical reduction in hydrogen gas to create pure molybdenum metal powder. The first stage occurs in the temperature range of 450-650 degree Celsius as shown in the Figure 2.2, and reduces the input materials to MoO_2 , often called brown oxide. The second stage reduction is performed in 1000-1100 degree Celsius range which results in molybdenum metal powder that is typically 99.7% Mo (IMOA 2013).

Substantial quantities of powder are pressed and sintered into pellets or other simple shapes placed with other filled molds in a cold isostatic press. After pressing at pressures of approximately 200 MPa, the ingots are removed from the molds and sintered in hydrogen at 1700-1800°C. Hydrogen is an ideal atmosphere on which to sinter molybdenum because it chemically reduces absorbed oxygen and surface oxides on the powdered particles. Mill processing of molybdenum metal can be performed on standard equipment. Most of the mill products are finished at ambient temperatures (IMOA 2013).

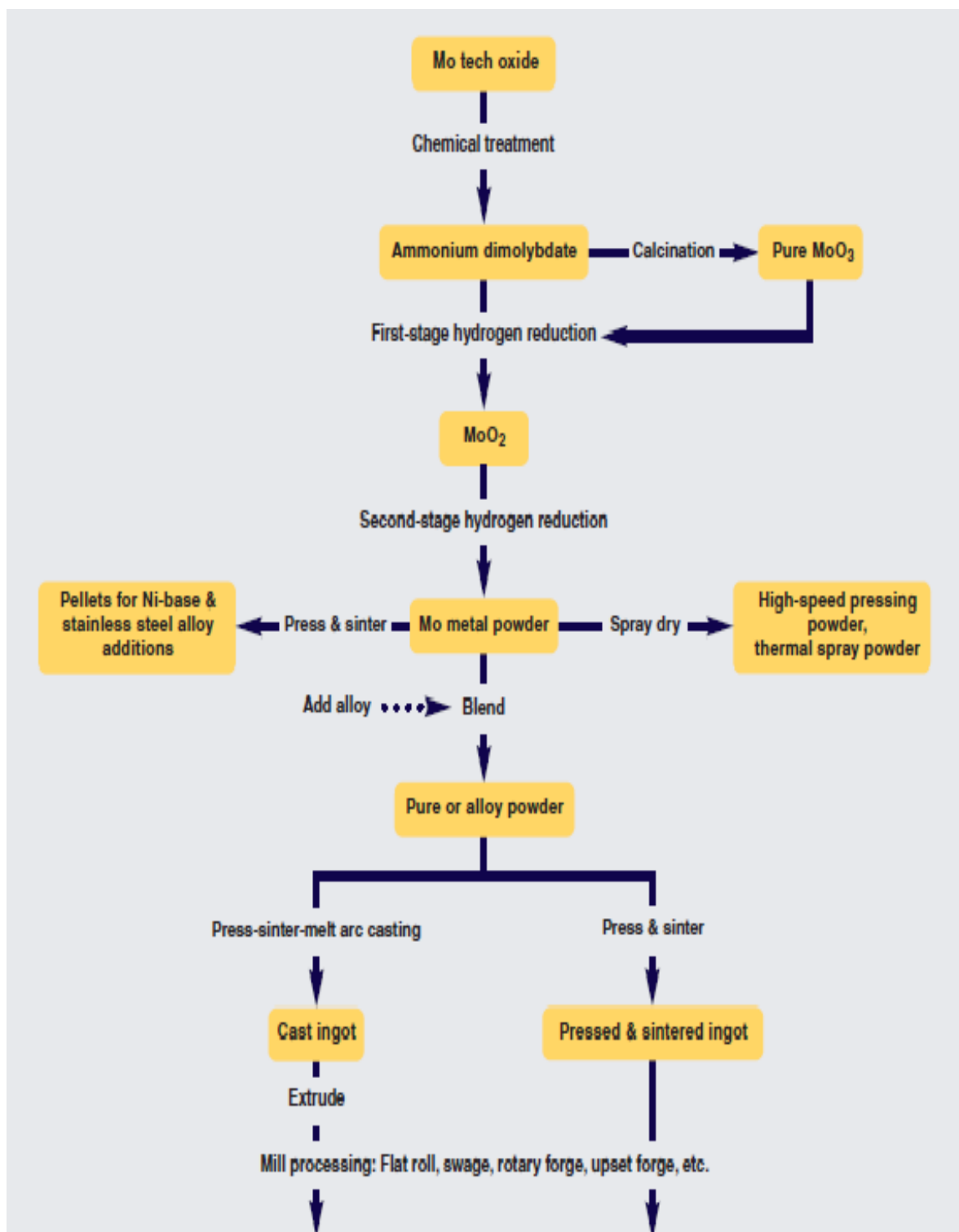


Figure 2.2 Flowchart describing molybdenum metal production in mill (IMO 2013).

2.2 Technically Enhanced Naturally Occurring Radioactive Materials (TENORM)

2.2.1 Natural Radioactivity

Natural radiation can't be ignored when quantifying and qualifying radiation involved in mining and milling places. Natural radionuclides, and hence radiation is present throughout molybdenum processing facilities.

Natural radioactivity originates from extraterrestrial sources as well as from radioactive elements in the earth's crust. Out of 340 nuclide found in nature, 70 are radioactive. All elements having atomic number greater than 80 possess radioactive and all the elements heavier than 83 are radioactive (Eisenbud and Gesell 1997).

NORM is an acronym for Naturally Occurring Radioactive Materials that potentially includes all radioactive elements present in the environment. The radionuclides uranium-238 (U-238) and thorium-232 (Th-232) have decay times (half-lives) which are comparable with, or larger than, the age of the earth, so they have always been present in the earth's crust and within the tissues of all the living species (Australian radiation Protection 2012). Table 2.2 shows the total estimated effective dose equivalent from natural sources of natural radiation.

There are other naturally occurring nuclides, such as C-14, which are produced continuously by nuclear reactions between high energy particles with oxygen and nitrogen in the earth's atmosphere (Gilmore 2008). Exposure to naturally occurring radiation is responsible for the majority of an average person's yearly radiation dose and is not therefore not considered health and safety concern (ARPANSA 2014).

Table 2.2 Annual estimated effective dose equivalent (NCRP 95 and NCRP 160)

Source	Average annual effective dose equivalent		NCRP 160	
	(μ Sv)	(mrem)	(μ Sv)	(mrem)
Inhaled (Radon and Decay Products)	2000	200	2290	229
Other Internally Deposited Radionuclides	390	39	310	31
Terrestrial Radiation	280	28	190	19
Cosmic Radiation	270	27	270	27
Rounded total from natural source	3000	300	3100	310
Rounded total from artificial Sources (Medical, industrial, etc)	600	60	3100	310
Total	3600	360	6200	620

All the naturally occurring radionuclide are concentrated or translocated because of various human activities and might possess some hazard to people and the environment. These materials are known generally as technologically enhanced naturally occurring radioactive materials or TENORM (EPA 2000).

2.2.2 EPA concerns about TENORM

EPA concerns about TENORM for three reasons are given below (EPA 2012)

- 1) It has the potential to cause elevated exposure to radiation.
- 2) People may not be aware of TENORM materials and need information about them.
- 3) Industries that generate these materials may need additional guidance to help manage and dispose them off in ways that protect people and the environment and are economically sound.

Naturally occurring radioactive materials (NORM) are ubiquitous throughout the earth's crust. " Human manipulation of NORM for economic ends, such as mining, ore processing, fossil fuel extraction, and commercial aviation, may lead to what is known as technologically enhanced naturally occurring radioactive materials," often called TENORM (Verrier 2009). Human activities such as mining and milling of ores, extraction of petroleum products, use of groundwater for domestic purposes, and living in houses alter the natural background of radiation either by moving naturally occurring radionuclide from inaccessible locations to locations where human are present or by concentrating the radionuclide in the exposure environment (NAS 1999).

Most of TENORM contains trace amounts of radionuclide and is part of our everyday life. Some TENORM, however, contains significant amount of radionuclides that can cause harmful effects (EPA 2000). The only reason that the Environmental Protection Agency is concerned about TENORM is because of its potential for harmful exposure to humans and the environment. Before 1998, the term used for these radioactive materials was, Naturally Occurring Radioactive Materials (NORM). Based on more current industry and regulatory practice, the term TENORM now is considered more appropriate (EPA 2000).

2.2.3 Sources of TENORM

NORM primarily consists of material containing K-40 and radionuclides belonging to the primordial series. The principal primordial series are radionuclides of heavy elements belonging to the radioactive series headed by the three long-lived radionuclides: uranium-238 (uranium series), uranium-235 (actinium series), and thorium-232 (thorium series) (EPA 2012). All these naturally occurring radionuclides have numerous radionuclides in their decay chain before reaching a stable end point, lead. At background concentrations, the naturally occurring radionuclides in the uranium, actinium, and thorium series contribute about one-half of the natural background external radiation. More than 80% of total natural background radiation is contributed by radon (ICRP 1991).

According to the US Environment Protection Agency, “the ultimate source of primordial radionuclides in the environment is earth’s crust and its underlying mantle”. Table 2.3 shows some radionuclides released by TENORM industries. Selective movement of some materials from the mantle to the crust usually resulting from fluid movement driven by temperature differences has caused heterogeneous organization of chemical elements in the crusts (Association of state and territorial solid waste management officials (ASTSWMO 2011)). Redistribution has also occurred as a result of weathering, sedimentation, and chemical interactions in the crust. As a result, K-40, uranium and thorium series nuclides tend to concentrate in certain minerals and certain geologic formations (EPA 2012). Human activities like milling, mining increases the concentration of natural radiation present in the ore samples.

Table 2.3 Industry Sectors and Associated NORM and TENORM

Industrial Sector	NORM or TENORM	Radioactive Series
Uranium mining	Waste overburden or low grade ore	U, Th
Other metal mining	Waste overburden	U, Th
Metal ore processing	Slag and sludges	U, Th
Metal welding and fabrication	Metal alloys and products	Th
Metal casting, grinding or sand-blasting	Foundry sands or casting molds, grinding or shot with zircons	U, Th
Phosphate fertilizer and phosphorus production	Waste phosphogypsum scale, residuals, slag	Ra-226, U, Th
Oil and gas production	Process brine water treatment sludge, scale in equipment, storage tank bottom sludge, gas refining separation process	Ra-226, U
Geothermal energy generation	Brine residuals and scale	Ra-226, U, Th
Drinking water treatment	Sludge and ion exchange resins	Ra-226, U, Th
Waste water treatment	Sludge	Ra-226, U, Th
Paper and pulp production	Scale and sludge	Ra-226, U, Th
Coal combustion for energy generation	Bottom and fly ash	Ra-226, U, Th
Decorative or optical glass	Slag and coating residuals	U, Th
Stone cutting and polishing	Certain base rock (e.g., granite) with high U/Th series	U, Th
Building materials	Certain construction materials (e.g. gypsum and stone (e.g. granite)	Ra-226, U, Th
Chemical industry and use	Potassium compounds	K-40

** Table is adapted from Association of State and Terrestrial Solid waste Management officials (ASTSWMO-2011).

2.2.4 TENORM monitoring concerns

Two things to be considered while monitoring TENORM are given below (Mining Industry Advisory Committee in Australia (MIAC 2010)).

1. The possibility for the radionuclide in the material mined or processed to change their physical and chemical characteristics due to the treatment of the material. Also, the possibility of change in their concentration and distribution in the local environment.
2. Possible pathways of exposure of workers, public and the environment.

2.2.5 Management of NORM

An important consideration for regulatory bodies is whether there is a need to regulate activities involving NORM, and at what activity concentration a regulatory approach is necessary. For normal exposure, it is usually unnecessary to regulate materials with radionuclide of natural origin with activity concentrations below 1000 Bq/kg (ARPANSA 2012). Under these conditions, it can be anticipated that doses to members of the public are unlikely to exceed about 1 mSv/year (IAEA 2004). It is appropriate for the regulatory body to take such exposure into consideration if the individual radionuclide concentration in the material exceeds about 1000 Bq/kg. However, the goal of this project was not to involve the management of NORM.

According to the Mining Industry Advisory Committee in Australia (MIAC), “employees working in groups are not monitored individually. Instead, their dose are monitored in a group of 5 people which is 4 mSv/year”. If a group exceeds 4mSv/year, they need to be

monitored individually (Mining Industry Advisory Committee (MIAC) 2010). For employees who are expected to receive doses between 1 and 4 mSv/year, a combination of group and individual monitoring can be used. However, the goal of this project did not include monitoring occupational exposure.

2.2.6 TENORM Wastes

TENORM wastes are the radioactive residues from extraction, treatment, and purification of minerals, petroleum products, or other substances obtained from parent materials that may contain elevated concentrations of primordial radionuclides (Eisenbud & Gesell 1977). Levels of NORM found in ores depends more on geologic formation or region than on the particular type of mineral being mined (Pontedeiro 2010). NORM has potential to become TENORM because of various human activities.

TENORM wastes also include any natural radioactive materials made more accessible by the action of man. Each year thousands of metric tons of TENORM wastes are generated from a wide variety of processes. Especially wastes are created because of uranium and phosphate mining. Some of the TENORM radionuclide produced after processing results in orders of magnitude higher than the parent materials (EPA 2012).

The mining of uranium ores produces small and large amount of waste materials termed as TENORM. These TENORM inventories include mining overburden and waste rock as well as evaporation pond sludge and scales. These waste materials typically contain radionuclide of radium, uranium, and thorium. Radioactive levels in in-situ leachate evaporation ponds are between 0.111 Bq/g to 7.4 Bq/g (3 pCi/g to 200 pCi/g). However, other solid TENORM wastes generated in uranium mining can reach radioactivity levels between 11.1

Bq/g to 111 Bq/g (300 pCi/g to 3000 pCi/g) (ASTSWMO 2011). However, waste management of TENORM wasn't the goal of this project.

2.3 Radiation and Mining

There are various methods involved in the process of mining and ore processing. The detailed assessment of the behavior of radionuclides is necessary to establish potential pathways of radiation exposure. Some situations involves physical processing (e.g. crushing, electrostatic separation) where change in the behavior of radionuclide is less likely. The only concern in these situations is the concentration of material and the dust. People working at places that involve fine grinding might run a risk of inhalation of dust with some level of radon and thorn (MIAC 2010).

Uranium mining releases radon from the ground into the atmosphere. Open-pit and in-situ mining sites are monitored by federal agencies and are found to pose low risk to the public. However, underground mining possesses greater potential of radon gas exposure to the public and the workers. Mines and mine wastes can release radionuclides, including radon and, other pollutants to streams, springs, and drinking water sources (EPA 2015).

Uranium mining which was closed before the mid-1960s, is of particular concern. In many cases, these mines were left un-attended and unclaimed and the wastes are still piled near the mines. Weathering might carry the radioactive dusts into drinking water sources by means of wind. Also, there are cases of unclaimed uranium mine wastes being used for house construction, which creates significant radon and radiation hazard for the inhabitants (EPA 2012). In uranium mines, radiological hazards are primarily a result of the airborne

radionuclides which consist of radon and its short lived progeny, Po-218, Pb-210, Bi-214 and Po-214 (Ahmed 2010).

The milling process recovers about 95% of the uranium present in ores. The leftover contains several naturally- occurring radioactive elements, including uranium, thorium, radium, polonium, and radon. They might also contain a number of hazardous elements, such as arsenic (EPA 2012).

EPA has used its authority under a number of existing environmental laws to regulate sources of TENORM. Most of the radionuclides are regulated under the authority of the Atomic Energy Act (AEA). However, AEA does not cover TENORM unless it is specifically designated as source material, such as uranium and thorium ore (EPA 2012).

2.3.1 Ra-226 content of Rocks and ores

Ra-226 is present in all rocks and ores in various amounts. Igneous rocks tend to contain higher concentrations of Ra-226 than sandstones and limestone (Eisenbud & Gesell 1997). The concentration of radium in limestone is (1500 Bq/kg to 49 Bq/kg) in igneous rock, as shown in Table 2.4. Ra-226 is generally in an equilibrium with U-238 and these values are consistent with the range of 7-60 Bq/kg for U-238 (UNSCEAR 1958).

Table 2.4 Average Uranium Concentration in various rocks (Solon 1956)

Rock Type	PPM	pCi/g	Bq/kg
Acid Igneous	3.0	0.99	37
Intermediate igneous	1.5	0.50	18
Basic igneous	0.6	0.20	7.3
Ultra basic igneous	0.03	0.010	0.37
Meteorites	0.003	0.0010	0.037
Phosphate rock (Florida)	120	40	1500
Phosphate rock (N.Africa)	20-30	6.6-10	240-370
Bituminous shale (TN)	17-26	17-26	610-980
Normal granite	1.3	1.3	49

2.3.2 Monazite

The minerals used as the commercial source of rare earths contain elevated level of thorium decay series and uranium decay series. In such mineral, monazite, thorium concentrations are sufficiently elevated to warrant its being used as a commercial source of thorium. Monazite is a highly insoluble rare earth mineral that occurs in some beach sand together with the mineral ilmenite, which gives the sand characteristic black color. Monazite occurs in heavy-mineral sand deposits, vein type deposits in granite and low grade tin ores. Monazite has the highest thorium content (IAEA 2011).

2.3.3 Natural radioactivity in ore: Table 2.5 shows the natural radioactivity that is found in a volume of ore that is 1 square mile by 1 foot deep. The volume is estimated to be $7.894 \times 10^5 \text{ m}^3$ and the density of ore is estimated to be 1.58 g/cm^3 . Table 2.5 shows that amount of Thorium, Potassium, and Radon in ore are 40 Bq/kg, 400 Bq/kg and 10 kBq/m^3 respectively.

Uranium is found in all rocks and ores. The typical concentration of Uranium and Thorium in earth's crust is around 10 parts per million (Metcalf 1996). The acid igneous rocks contain uranium concentration on the order of 3 PPM, about 100 times greater than that in the ultra-basic igneous rocks. The phosphates rock of Florida and south –east Idaho and neighboring areas contains as much as 120 ppm of uranium. The typical concentration of uranium in rock is 0.5 to 4.7 PPM in the common rock types (Solon et al., 1956). Table 2.5 shows that concentration of uranium in soil is 25 Bq/kg.

Table 2.5 Natural radioactivity found in soil (ISU 2005)

Nuclide	Activity used in calculations	Mass of Nuclide	Activity found in the volume of ore
Uranium	0.7 pCi/g (25 Bq/kg)	2,200 kg	0.8 curies (31 GBq)
Thorium	1.1 pCi/g (40 Bq/kg)	12,000 kg	1.4 curies (52 GBq)
Potassium-40	11 pCi/g (400 Bq/kg)	2000 kg	13 curies (500 GBq)
Radium	1.3 pCi/g (48 Bq/kg)	1.7 g	1.7 curies (63 GBq)
Radon	0.17 pCi/g (10 kBq/m ³) ore	11 µg	0.2 curies (7.4 GBq)
Total:			>17 curies (>653 GBq)

** Natural radioactivity found in a volume of soil that is 1 square mile, by 1 foot deep. The volume of soil used was $7.894 \times 10^5 \text{ m}^3$. Density of soil used was 1.58 g/cm^3 .

2.3.4 Natural Radioactivity in the Ocean: Water on earth including that in the sea has some radionuclides in it. Table 2.6 shows the natural radioactivity by the ocean (NAS 1971). Uranium, potassium, tritium, carbon-14 and Rubidium-87 are the major naturally occurring radionuclides which are found in oceans.

Table 2.6 Natural radioactivity found in various oceans

Nuclide	Activity used in calculation	Activity in Ocean		
		Pacific	Atlantic	All Oceans
Uranium	0.9 pCi/L (33 mBq/L)	6×10^8 Ci (22 EBq)	3×10^8 Ci (11 EBq)	1.1×10^9 Ci (41 EBq)
Potassium 40	300 pCi/L (11 Bq/L)	2×10^{11} Ci (7400 EBq)	9×10^{10} Ci (3300 EBq)	3.8×10^{11} Ci (14000 EBq)
Tritium	0.016 pCi/L (0.6 mBq/L)	1×10^7 Ci (370 PBq)	5×10^6 Ci (190 PBq)	2×10^7 Ci (740 PBq)
Carbon 14	0.135 pCi/L (5 mBq/L)	8×10^7 Ci (3 EBq)	4×10^7 Ci (1.5 EBq)	1.8×10^8 Ci (6.7 EBq)
Rubidium 87	28 pCi/L (1.1 Bq/L)	1.9×10^{10} Ci (700 EBq)	9×10^9 Ci (330 EBq)	3.6×10^{10} Ci (1300 EBq)

** Table is adopted from Idaho State University's radiation information network

2.3.5 Radiation in Food: Everything we eat is radioactive. The common radionuclides found in food are potassium, radium, uranium and their progeny. Table 2.7 gives a list of common foods and their levels of potassium and radium.

Table 2.7 Natural radioactivity in food (Eisenbud & Gesell 1997)

Food	K-40 pCi/kg	Ra-226 pCi/kg
Banana	3,520	1
Brazil Nuts	5,600	1,000-7,000
Carrot	3,400	0.6-2
White Potatoes	3,400	1-2.5
Beer	390	---
Red Meat	3,000	0.5
Lima Bean	4,640	
raw		
Drinking water	---	0-0.17

2.4 Decay chains

2.4.1 Radioactive Decay

Most of the naturally radioactive materials and many fission products undergo decay through a series of transformation rather than in a single step. Until the final step, these radionuclides emit energy or particles with each transformation and become another type of radionuclides (EPA 2012). Radionuclide decay chains are important in planning for the management and disposal of radioactive waste. As radioactive decay processes are continuous, the concentration of the original radionuclide decreases, while the concentration of their decay products increases and then decreases as they undergo transformation as illustrated in Figure.2.3 The increasing concentration of decay products and activity is called ingrowth (EPA 2012).

To completely understand the buildup process it is essential to know the radioactive decay data. Once the parent radionuclide involved in the process is identified, the daughter progeny involved in the process of radiation exposure can be inferred.

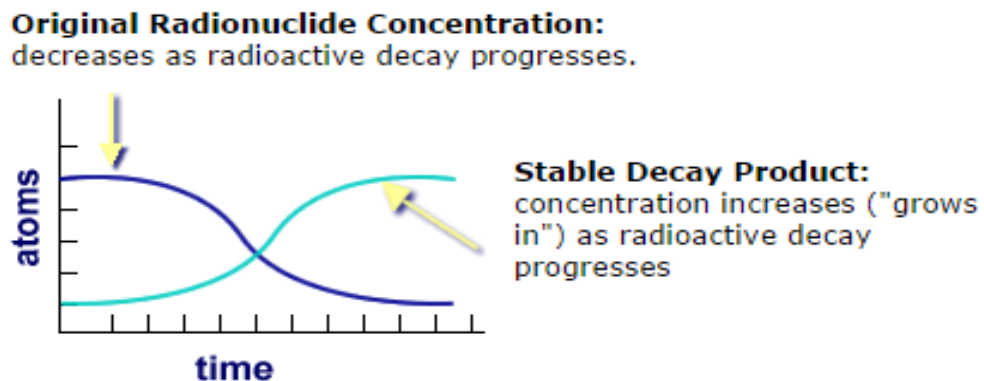


Figure 2.3 Radioactive in growth (EPA 2012)

Natural decay chain consists of three radionuclides; uranium-238, uranium-235, and uranium-234. A fourth family member of naturally occurring nuclide, neptunium series, which originates in the parent element Pu-241. These radionuclides are known to exist briefly after their formation because of their short half-life of 14 years. The only surviving member of the neptunium series is Bi-209 which is nearly stable with a half-life of 2×10^8 years (Eisenbud and Gesell 1997).

The nucleus of radioactive elements is unstable and transforms into other elements typically emitting particles. Each of these nuclides decays to unstable daughter particles leading to a whole series of nuclides that terminate in a stable lead. Under normal circumstances, in a naturally occurring material, the ratio of U-235 and U-238 is fixed and all nuclides in each of the series are in equilibrium. This process of emission of particles from a nucleus is known as radioactive decay. It is often accompanied by emission of the gamma radiation (IEER 2014).

2.4.2 Natural Decay series

2.4.2.1 The Uranium Series – U-238

U-238 decays through a series of steps to become a stable form of lead (see Figure 2.3). U-238 have the longest half-life of 4.4 billion years. U-238 comprises 99.25% of natural uranium. U-238 decays by alpha emission into Th-234, which itself decays by beta emission to protactinium-234 (Pa-234), which decays by beta emission to U-234 and so on. Table 2.9 shows the important properties of the radionuclide of the U-238 decay chain.

In some cases, the half-life of a particular intermediate parent nuclide is less than that of the daughter (Pa-234/U-234, for example). If we are only dealing with Pa-234, we would expect there to be no radioactive equilibrium. However, for sources older than 10 half-lives of the longest lived progenitor, the half-life of each component, in this case the Pa-234 is effectively that of the U-238 series. This means that the measurement of any of the nuclides in the decay chain can be taken as an estimate of the U-238 activity as well as the other nuclides in the chain (Gilmore 2008). After a series of alpha and beta decays as shown in Table 2.9, the final stable isotope lead-206 is formed (IEER 2014). There are 14 radionuclides in the chain as shown in Table 2.8 so the total activity of such a source will be 14 times that of the parent, or of any individual nuclide (ARPANSA 2012).

Table 2.8 Properties of the radionuclides of the U-238 decay chain

Nuclide	Half-Life	Radiations
U-238	4.4 Billion Years	α
Th-234	24 Days	β
Pa-234m	1 Minute	β
U-234	250,000 Years	α
Th-230	75,000 Years	α, γ
Ra-226	16,00 Years	α, γ
Rn-222	3.8 days	α, γ
Po-218	3 Minutes	α, γ
Pb-214	27 Minutes	β, γ
Bi-214	20 Minutes	β, γ
Po-214	$1.6 * 10^{-6}$ Seconds	α, γ
Pb-210	22 Years	β, γ
Bi-210	5 Days	β, γ
Po-210	138 Days	α, γ

2.4.2.2 The thorium series- Th-232

The thorium decay series is shown in Table 2.9. There are a total of 10 decay stages with six of them releasing alpha particles (ignoring the number of minor decay branches). Four nuclides can be easily measured by gamma spectrometry; Ac-228, Bi-212, Pb-212 and Tl-208.

Table 2.9 Properties of the radioactivity of the Th-232 decay chain 2012)

Nuclide	Half-life	Radiations
Th-232	14 Billions Years	α, β, γ
Ra-228	6 Years	β
Ac-228	6 Hours	β, γ
Th-228	2 Years	α
Ra-224	4 days	α, γ
Rn-220	1 Minutes	α
Po-216	0.1 Seconds	α
Pb-212	10 Hours	β, γ
Bi-212	1 Hour	α, β, γ
Po-212	3×10^{-7} Seconds	α, β, γ
Tl-208	3 Minutes	β, γ

** Table is adopted from Australian radiation protection and nuclear safety agency (ARPANSA 2011).

2.4.2.3 The actinium series- U-235

U-235 comprises 0.72% of natural uranium. The decay series is shown in Table 2.10 and is comprises of 11 decay stages with the emission of seven alpha particles (ignoring the number of minor decay branches). Within this series, only U-235 can be measured itself. Th-227, Ra-223, Rn-219 can be measured with high uncertainty. Measurement of daughter

nuclides can provide useful information confirming the direct U-235 measurement or giving insight into the disruption of the decay series. The total activity of the nuclides in this series is eleven times that of the U-235 activity.

Table 2.10 actinium decay series – 235 U (Gilmore 2007)

Nuclide	Half- Life	Radiation
U-235	7.04*10 ⁸ Y	α, γ
Th-231	1.06 d	β, γ
Pa-231	3.28*10 ⁴ y	α, γ
Ac-227	21.77 y	β
Th-227 & Fr-223	18.72 d/ 22.0 m	α, γ / β, γ
Ra-223	11.44 d	α, γ
Rn-219	3.96s	α, γ
Po-215	1.78 ms	α
Pb-211	36.1 m	β, γ
Bi-211	2.14 m	α, γ
Tl-207	4.77 m	β
Pb-201	stable	None

2.4.3 Radon gas and Radon loss

Ra-226, a member of the U-238 decay chain, decays by alpha- particle emission and has a half-life of 1600 years. Radon is a noble gas and occurs as non-polar, monoatomic molecules. All the decay series discussed previously have, within them, a radon isotope. Radon is an inert gas. It can normally be trapped within a solid sample. Radon can escape by grinding the sample and most of it decays rapidly because of its short

half-life. In reality, this would alter the total activity of the sample and the total dose rate from the sample. However, the half-life of Rn-219 in the actinium series, and the half-life of Rn-220 in the thorium series, are very short and even though radon escapes, equilibrium will be reestablished (Gilmore 2007).

The seventh nuclide in the U-238 series decay chain is Rn-222, with a half-life of 3.8 days. After a loss of Rn-222, there is ample time for the decay of the daughter nuclides preceding Pb-210 before re-growth of the Rn-222. Loss of radon would affect total activity. We can solve this by encapsulating the sample and waiting for about 10 half-life of Rn-222 to allow equilibrium--say one month (Gilmore 2007).

2.4.4 K-40

Out of three naturally occurring radioactive potassium, only K-40 is unstable having a half-life of 1.3 billion years. K-40 decays by beta-particle emission to Ca-40 (89%) and by electron capture to Ar-40 (11%), and produces 1.46 MeV gamma rays after electron capture decay. K-40 is present at 0.0117% by mass in natural potassium. The specific activity of potassium is 20 kBq/kg. The presence of potassium in ore varies from 0.3% to 4.5%. The activity concentration varies from 90 to 1400 Bq/kg. Some basalts and sand are low in potassium whereas granites and other basalts have higher concentration of potassium. About 110 Tbq of potassium is added to the soil of the United States in the form of fertilizers (Guimond 1978). Seawater contains K-40 at 11 kBq/m³. K-40 is the predominant radioactive component in common foods and humans because of its relative abundance and mobility. Its energetic beta-particle emission causes it to be an important contributor to the dose in humans from natural radionuclides (NAS 1999).

Potassium in humans is under homeostatic control and is little influenced by environmental variations. A person who weighs 70 kg contains about 140 g of potassium, most of which is in muscles. Potassium content of the human body is around 4 kBq. NCRP has estimated that K-40 delivers annual dose of 18 mrem to the soft tissues and 14 mrem to the bone.

2.4.5 Rubidium-87 (Rb-87)

The primordial beta- emitting radionuclide Rb-87 with a half-life of 4.75×10^{10} y is present in the environment and the human tissue. The average annual effective dose equivalent from Rb-87 is 0.3-0.6 mrem (UNSCEAR).

2.5 TENORMs Standards and Guidelines

The Conference of Radiation Control Program Directors (CRCPD) created a special commission to develop and suggest state regulations for the control of TENORM. Its 1978 task force on natural radioactivity contamination problems (CRCPD 1978), prepared in cooperation with EPA's office of Radiation Programs, one of the first assessments of the scope of the problem and the potential radiation control measures. Since 1990, CRCPD has published Suggested State Regulations for the Control of Radiation (SSRCR). CRCPD has drafted TENORM regulations as part N of SSRCR (Reynolds 1995). A summary of part N CRCPD 1997 are given below (NAS 1999).

1. An annual total effective dose equivalent (excluding radon and its progeny) because of operations, uses, or transfers of TENORM should not exceed 1mSv (100 mrem) for the general population.
2. Use, transfer or disposal of TENORM is to be conducted to prevent accumulation of radon in residential structures, schools, and public building in concentrations exceeding 150 Bq/m³ (4 pCi/L).
3. For radium-bearing TENORM, materials containing Ra-226 or Ra-228 at less than 0.2 Bq/g (5 pCi/g) are exempt from licensing.
4. Land may not be released for unrestricted use where the soil concentration of Ra-226 or Ra-228 (averaged over any 100 m² and to a depth of 15 cm) exceeds 0.2 Bq/g (5 pCi/g).
5. Disposal methods used within uranium mill tailings regulated under 40 CFR 192 are generally acceptable for TENORM.

2.5.1 International Atomic Energy Agency (IAEA)

The recommended exemption levels for naturally occurring radionuclide other than radon are, as given by IAEA given below. In each case, all decay products are assumed to present and in equilibrium.

1. Natural uranium or Thorium: an activity concentration of 1 Bq/g (27pCi/g) and a total activity of 103 Bq (27 nCi).
2. Ra-226: an activity concentration of 10 Bq/g (270 pCi/g) and a total activity of 104 Bq (270 nCi).
3. Ra-228: an activity concentration of 10 Bq/g (270 pCi/g) and a total activity of 105 Bq (2.7 μ Ci).
4. Pb-210: an activity concentration of 10 Bq/g (270 pCi/g) and a total activity of 104 Bq (270nCi).

Each case discussed above are assumed to be present and in equilibrium.

2.5.2 EPA vs NCRP guidelines on TENORMs

EPA has issued proposed federal guidance on radiation protection of the public that includes an annual dose limit of 1mSv (100 mrem) for all controlled sources combined, including human- made radionuclide and TENORM other than indoor radon (EPA 1994).

In contrast, NCRP developed separate recommendations that remedial actions should be undertaken when the annual dose from natural sources only, other radon, exceeds 5mSv

(500 mrem). Although, direct comparison of EPA and NCRP guidelines is not straightforward, the proposed EPA guidance, which applies to all sources to TENORM combined, should in most cases be considerably more restrictive than NCRP's recommended- action level (NAS 1999).

2.5.3 Standards for Uranium and Thorium Mill Tailings

EPA's current standards for uranium and thorium mill tailings can be found in 40 CFR part 192. These standards are concerned with control and cleanup of residual radioactive materials at or near inactive uranium- and thorium processing sites. Standards for uranium and thorium mill tailings do not apply to TENORM, because they apply only to radioactive materials regulated under the Atomic Energy Act. However, because mill tailing contain naturally occurring materials radionuclides, the standards can be used as a model for regulating TENORM. The following statements summarize the applicability of the various guidelines and regulations to TENORM, except the guidance for indoor radon (NAS 1999).

1. Existing federal guidance on radiation protection of the public and EPA guidelines apply to all sources of exposure to TENORM, except indoor radon.
2. Standards for radioactivity in drinking water 40 CFR part 141 apply to TENORM from any source.
3. Standards for liquid discharges from mines or mills used to produce or process uranium, radium, and vanadium ores in 40 CFR part 1440 apply to TENORM for specified sources.
4. Standards for cleanup of radioactivity contaminated CERCLA sites in 40 CFR part 300 apply to TENORM.

2.6 Hypothesis

Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) are prevalent throughout the process. Some elevation and variation in photon dose rate was expected. Laboratory results can be associated and correlated with dose measurements. GammaTRACER results can be correlated with industrial data. Some of the hypothesis made for this project are listed below:

Null Hypothesis ($H_{1,0}$): NORM is enriched to TENORM.

Alternative Hypothesis ($H_{1,a}$): TENORM is not present in ore samples.

Decision rule 1: It will be considered that TENORM is present in soil samples only if the activity of the radionuclide is greater than two times its activity of background uncertainty.

Chapter 3: Methods and Materials

3.1 GammaTRACER

GammaTRACER is an autonomous measuring probe for the continuous measurement of gamma dose rates for environmental monitoring. Energy saving chip technology enables maintenance-free use of GammaTRACER for at least five years. Measured values can be obtained of any time via an interactive infrared interface. The communication and analyzing software Gamma View enables access to the stored data.

GammaTRACER is equipped with two independent counter channels which are each complemented with a Geiger- Muller counter tube. The actual complement of the counter tubes depends both on the indicted dose rate quality as well as on the desired measuring range (Genitorn manual). Figure 3.1 shows the photograph of GammaTRACER.



Figure 3.1 Photograph of GammaTRACER

GammaTRACER can be carried anywhere and can be used to count continuously for 5 years without any maintenance. The GammaTRACER can be used to measure gamma photon dose rates continuously in a chosen time frame. It can measure photon dose rates in ten minutes intervals and can also point out maximum and minimum values of measured photon dose rates for each interval. Variation of photon dose rates can be easily measured with the GammaTRACER since it gives time and date of maximum measured dose rate.

3.2 Reasons for choosing GammaTRACER in this project

Radioactive and radioactive substances are natural and permanent features of the environment. The risk associated with the radiation can be restricted but not eliminated entirely (IAEA 1996). The first thing people need to do to prevent radiation exposure is to measure the radiation exposure. Once the amount of radiation exposure and pathway of radiation is known, ways for radiation restriction can be planned. It was important for this project to find a suitable low maintenance portable detector to measure a radioactivity at the Thomson Creek Mining Company.

Thomson Creek Mining Company is located several hours away by automobile from Pocatello, Idaho. It was impractical to travel and count natural radioactivity every day. Since GammaTRACER is a portable device, two units were shipped from the ISU campus once a month. GammaTRACER probes were kept in various parts of the facility. They were then sent back to EML every month to transfer the collected data for analysis. The process was repeated for 5 months until sufficient data was collected. Below are some other reasons for choosing the GammaTRACER in this project.

1. Available at EML and can be used free of cost.
2. An autonomous measuring probe.
3. Cheap and highly portable device.
4. Good tool for environmental monitoring of natural radiation.
5. Environmental monitoring in areas with weak infrastructure.
6. Sensitivity range of 20 nSv/hr – 10 mSv/hr which is appropriate for measuring low levels of natural radiation.
7. Dose rate variability in the process of natural radiation can be predicted easily.

Disadvantages of using GammaTRACER

1. Models of GammaTRACER used on this project were vintage and only work with the Windows 95 operating system.

Two GammaTRACER units with serial numbers, GF1142 and GF1159, were used for two weeks in 10 minutes interval to measure the gamma dose rates at Thompson Creek Mining Company. Table 2.11 shows the calibration information. Appendix A shows the detail calibration information of GammaTRACER. According to the calibration certificates, both types of tracers should respond in a similar manner. However, slight differences in the detector response were observed. Detectors response at high photon dose rates was found to be similar for both detectors. Figure 3.2 shows that both detectors were equally sensitive when they were exposed to higher photon dose rates. At lower photon dose rates, however, some discrepancy between detectors were observed. Figure 3.3 shows that GF1159 gave higher number of the photon dose rates compared to GF1142. For given place and time, GF1159 was found to be 14% efficient than GF1142.

Table 2.11 Calibration Information for GammaTRACER

Instrument	GF1159	GF1142
Sensitivity range	20nSv/h – 10 mSv/hr	20nSv/h – 10 mSv/hr
Energy Range	48keV to 200 MeV	48keV to 200 MeV
Date of calibration	04/09/2014	04/15/2014
Calibration Source	Cs-137 at 662 KeV	Cs-137 at 662 KeV

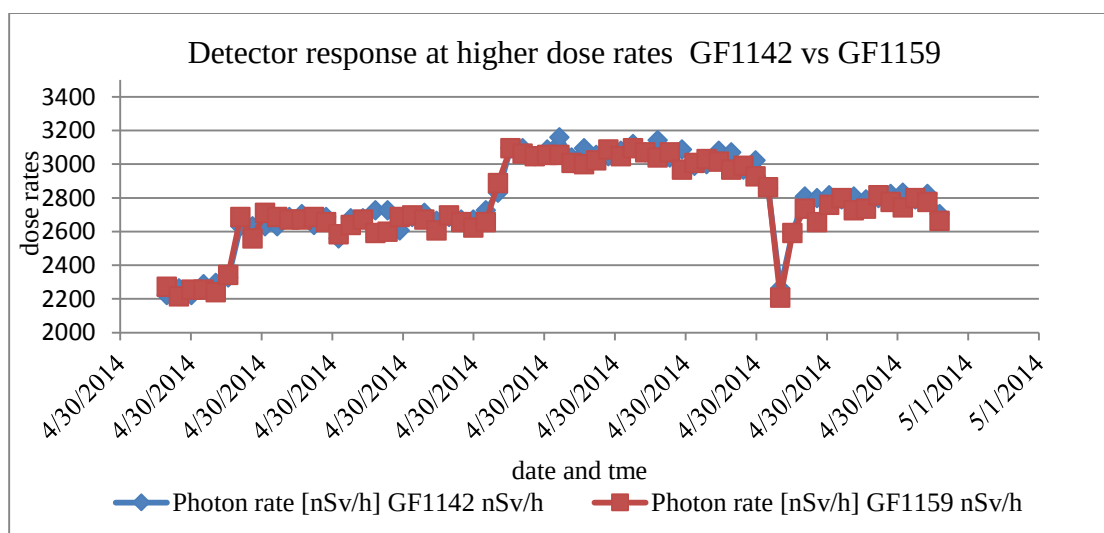


Figure 3.2 Detector response at higher dose rates GF1142 vs GF1159

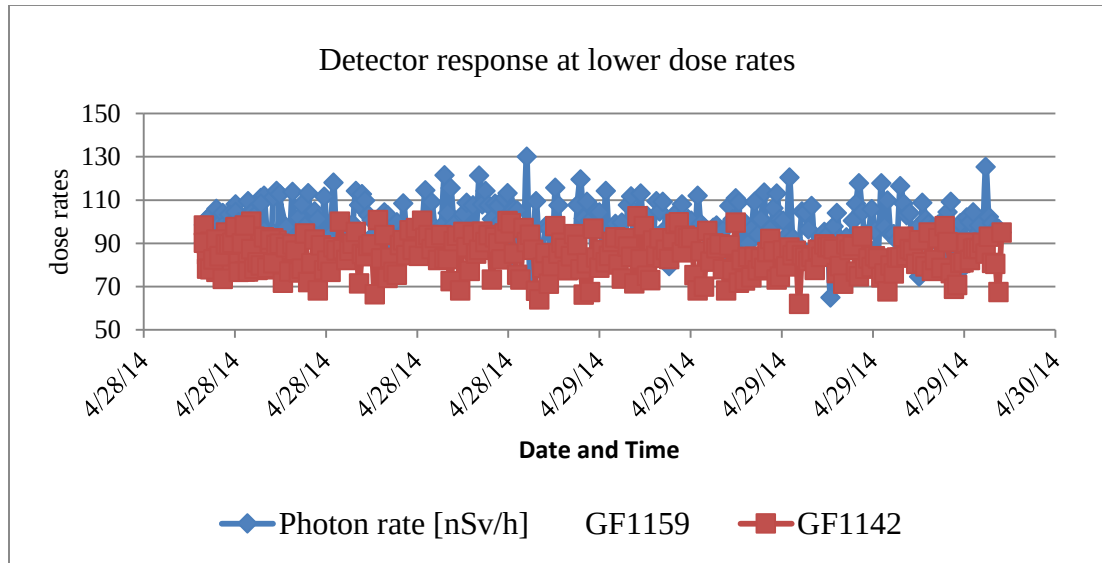


Figure 3.3 Detector response at lower dose rates GF1142 Vs GF115

3.3 High Purity Germanium (HPGe) Gamma Detectors

High purity germanium (HPGe) gamma detectors are widely used detectors to identify and quantify radionuclides because of their superior energy resolution. Spectra of energy distributions emitted as a result of radioactive decay are arranged by channels which indicate the values of energies (Gilmore 2008). Peak area indicates the number of counts from which quantity of radionuclide can be determined. Before counting samples, it was necessary to perform energy and efficiency calibrations of the HPGe systems. In order to calibrate the spectrometer properly, calibration standards should be prepared with matrices of similar composition and density, similar concentration for the radionuclide, and in the same geometry as the real samples.

Efficiency calibration of the detector refers to the detection of gamma rays from the given source. Usually, the efficiency of the source detector decreased with the increased photon

energy. Calibration is done using sources with known gamma-energies to assign photon energy to each channel on the system. Resolution calibrations are done in the detecting system. Full width at half maximum (FWHM) can be done to get qualitative information. The calibration standard sources are normally made in the shape of a cylinder, Marinelli beaker or other radially symmetrical object. Fisherbrand™ wide- mouth polypropylene Jars were used as shown in the Figure 3.4. The jar has a total capacity of 500 mL with a height of 9.6 cm (3.8 inch). The color of the jar used was natural as shown in the picture.



Fig 3.4 Geometry used to count samples in gamma detector

Absolute and Relative Efficiency

Absolute efficiency of a detector (ϵ) can be determined by the equation below

$$\text{Efficiency} = \frac{\text{NetArea}}{(\text{Livetime})(\text{Activity})(\text{Yield})} \quad \text{Equation 3.1}$$

Where A is Activity in Bq.

$$A \text{ (Bq)} = \frac{\text{Net Area}}{(\text{Total Time}) * (\text{Efficiency}) * (\text{Yield})} \quad \text{Equation 3.2}$$

Equation 3.1 was used while computing the net activity of identified radionuclide. Relative efficiency is the ratio of absolute efficiency of a detector to the efficiency of a standard which is shown numerically,

$$\text{Relative efficiency} = \frac{\text{Absolute Efficiency(HpGe)}}{\text{Efficiencyof the standard Na(Tl)}} \quad \text{Equation 3.3}$$

Absolute peak efficiency of a detector is a function of many factors, such as gamma ray energy, sample size, sample density and source detector response and source- detector distance. In order to have good a result, the chemical composition, shape, density, and geometry of a counting sample needs to be compatible with a standard source. Sometimes, it is impossible to find a calibration source which is identical to the sample of interest. Under these circumstances, correction factors need to be applied when the differences are significant (Shi 2008).

These corrections can be performed either by empirical measurement or by Monte Carlo based computer software. Some example of commercially available software which can be used to perform these types of corrections are LabSOCSTM, ISOCSTM, GESPECOR[®],

and ORTEC-ANGLE[®]. Regardless of what software or algorithms are used, the uncertainty of these corrections is largely dependent on the accuracy of information about detector response and physical parameters, range of energies in the sample, and the geometries of the sample. Most calculations performed by Monte Carlo simulations are limited to radially symmetric geometries, such as cylinders and Marinelli beakers (Shi 2008).

For non-destructive counting of irregularly shaped samples, it may not be technically possible to obtain empirical correction factors for a specific geometry. Therefore, while counting irregularly shaped samples with no identical standard source available, it is only possible to estimate the efficiencies for the unrepresentative samples, either by empirical measurement or by software simulation such as WinnerTrack[™].

There were two HPGe gamma detectors available in EML to count ore samples. Canberra (GC2520 with relative efficiency 0.25) and Ortec (GEM-FX8530P4 with relative efficiency 0.449) detectors were used to count ore samples. The detectors will hereby be referred as “Canberra” and “Ortec”. Table 3.1 shows the input parameters for high purity gamma detectors which were used to count ore samples. In-order to find an efficiency correction factor for non-typical cylindrical ore samples, GESPECOR[®] was used for ORTEC and LabSOCS[™] was used for Canberra. The dead layer and detector holder thickness were finely tuned by changing thickness at various steps of 0.05mm to 0.1 mm to make the computed geometry closer to the true efficiency.

Table 3.1 LabSOCS™ and GESPECOR® input parameters for gamma detectors

	Canberra (cm)	Ortec (cm)
Crystal radius	2.55	4.245
Crystal length	5.2	3.35
Relative efficiency	0.25	0.449
inner contact radius	0.375	0.545
inner contact length	3.65	1
thickness of dead layer (face)	0.05	0.0001
thickness of dead layer (side)	0.05	0.05
distance from active face to window	0.5	0.5
detector holder face thickness	0.11	0.0015
detector holder side thickness	0.11	0.07
end cap diameter	7.6	10.8
end cap window thickness	0.15	0.09
end cap side thickness	0.15	0.15

** Efficiency for the 1332 KeV Co-60 line relative to 3" by 3" Na (TI) scintillation crystal

All the ore samples collected from Thompson Mining facility were counted in the Canberra (CAN) and Ortec (ORT) detectors for 60,000 seconds. Reasons for using high Purity gamma detectors in the project are discussed below.

1. Environmental Monitoring Laboratory at ISU has high purity gamma detectors which could be used free of cost.
2. The end cap material for Canberra was Aluminum whereas for Ortec it was carbon fiber. Ortec has a higher efficiency than that of Canberra.
3. Canberra was calibrated only in the region of 50 to 2000 keV.
4. Ortec has higher efficiency because of thin carbon fiber and wider energy range of 50 to 3000 keV.
5. Gamma detectors utilize nondestructive analysis for sample counting.
6. It is a relatively fast and inexpensive technique that gives immediate results.

Chapter 4: Results and Discussions

4.1 Photon Dose Rates at Various Locations

GammaTRACER was continuously measuring the dose rates in the air at the height of 30,000 feet while they were shipped after repair from Germany to Idaho. All the measured values of dose rates were transferred to find the dose rates of Frankfurt, Germany, and at high altitude. Also, photon dose rates of Pocatello background were measured using GammaTRACER. Figures 4.1 & 4.2 shows dose rates measured at Frankfurt, Idaho and at high altitude for both detectors.

The average values of detector measured dose rates measured by GammaTRACER at higher altitude were found to be 2770 ± 258 nSv/hr and 2750 ± 249 nSv/hr respectively. The average background dose rates of Pocatello and Frankfurt were found to be 134 ± 9.60 nSv/hr and 91.0 ± 9.01 nSv/hr respectively. Figure 4.1 shows that detector measured dose rates were higher in Pocatello than in Frankfurt Germany. Higher dose rates at Pocatello were due to higher altitude. Dose rates measured at higher altitude were found to be almost 33.0 times higher than the background values measured at Pocatello.

Table 4.1 detector measured dose rates in various places.

Unit	nSv/hr	nSv/hr	nSv/hr
where	GF1142 High Altitude	GF1159 High Altitude	Pocatello
MAX	3160	3090	143
MIN	2220	2210	86.0
AVERAGE	2770	2750	134

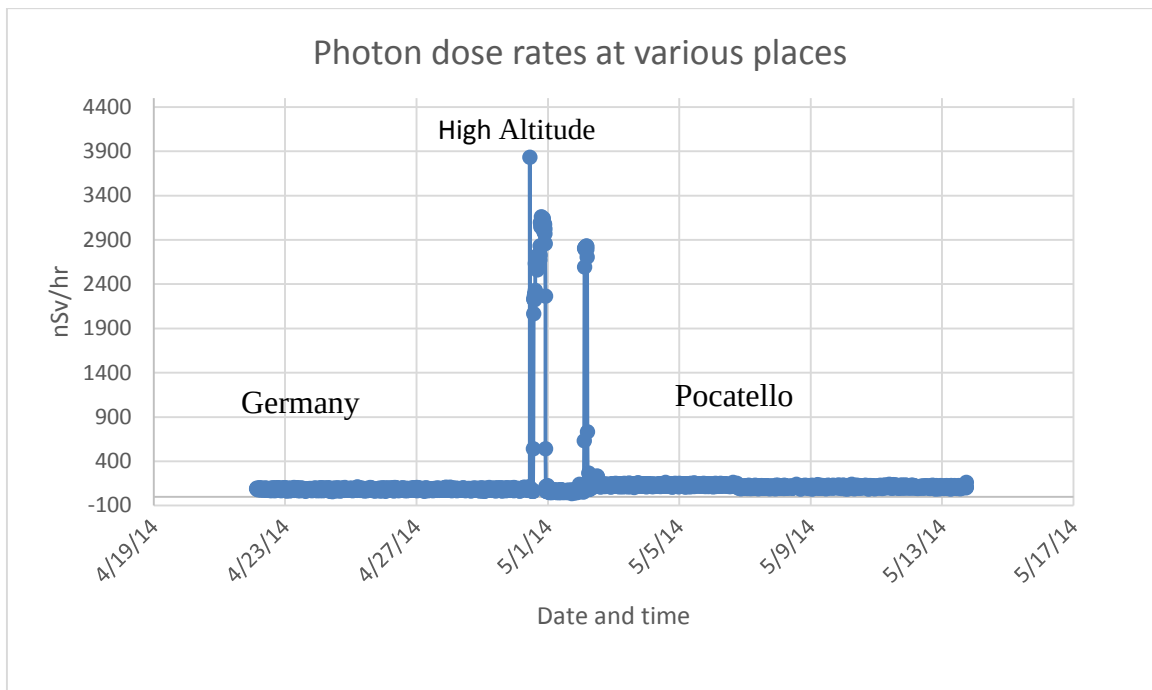


Figure 4.1 Detector measured photon dose rates by GF1142 at various locations

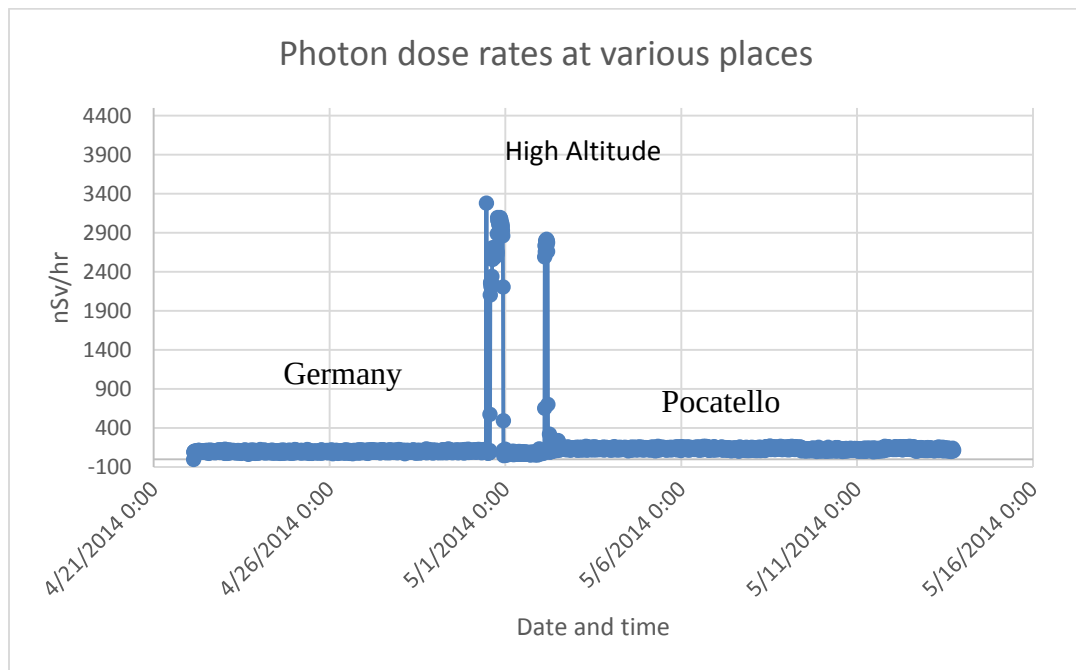


Figure 4.2 Detector measured photon dose rates by GF1159 at various locations

4.2 Results obtained from Thompson Creek Mining Company

The first phase of the result was obtained using GammaTRACER implanted at various locations in Thompson Creek Mining Company. Thompson Creek is a facility where there could be with numerous locations where GammaTRACER can be kept to monitor photon dose rates. Monitoring every point of the facility wasn't the main focus of interest of this project. Dr. BJ Bryant, Mill Tech Services Superintendent at Thompson Creek Mining Company, suggested the possible locations where there could be high probability of having elevated photon dose rates and variability of photon dose rates. About 10 locations were selected and photon rates were counted using GammaTRACER. GammaTRACERs were kept at various locations and counted every 10 minutes for about two weeks. The names of the location along with a series of obtained photon dose rates graphs are given in Figure 4.3.1 through 4.3.10. Figure 4.3.1 shows that photon dose rates at Scavenger tail were high at that period of time because of reagent choice they used at that period of time. They have added a xanthate collector (sodium isobutyl xanthate) to try to send FeS_2 to the concentrate. Rough flowchart of GammaTRACER locations inside the Thompson Creek Mining Company can be found in Appendix K.

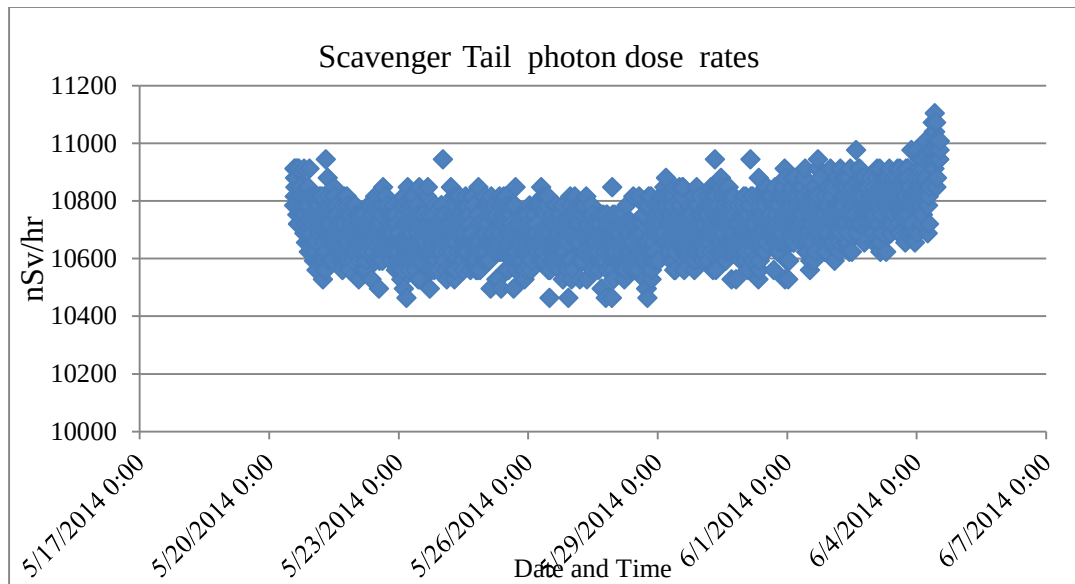


Figure 4.3.1 Photon dose rates at Scavenger Tail (ST)

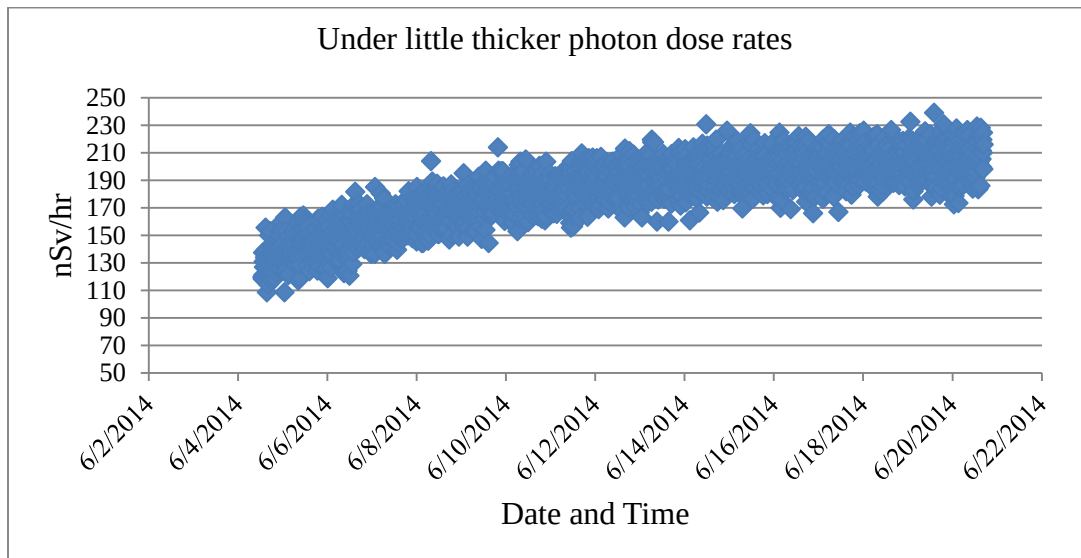


Figure 4.3.2 Photon dose rates at under little thickener

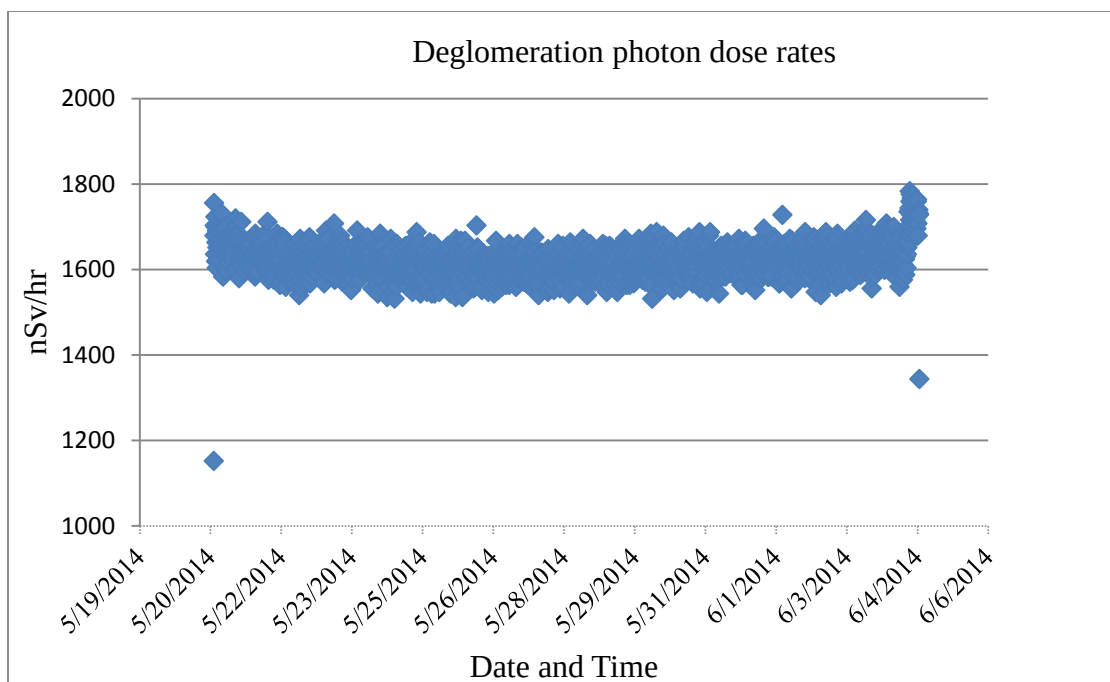


Figure 4.3.3 Photon dose rates at Deglomeration

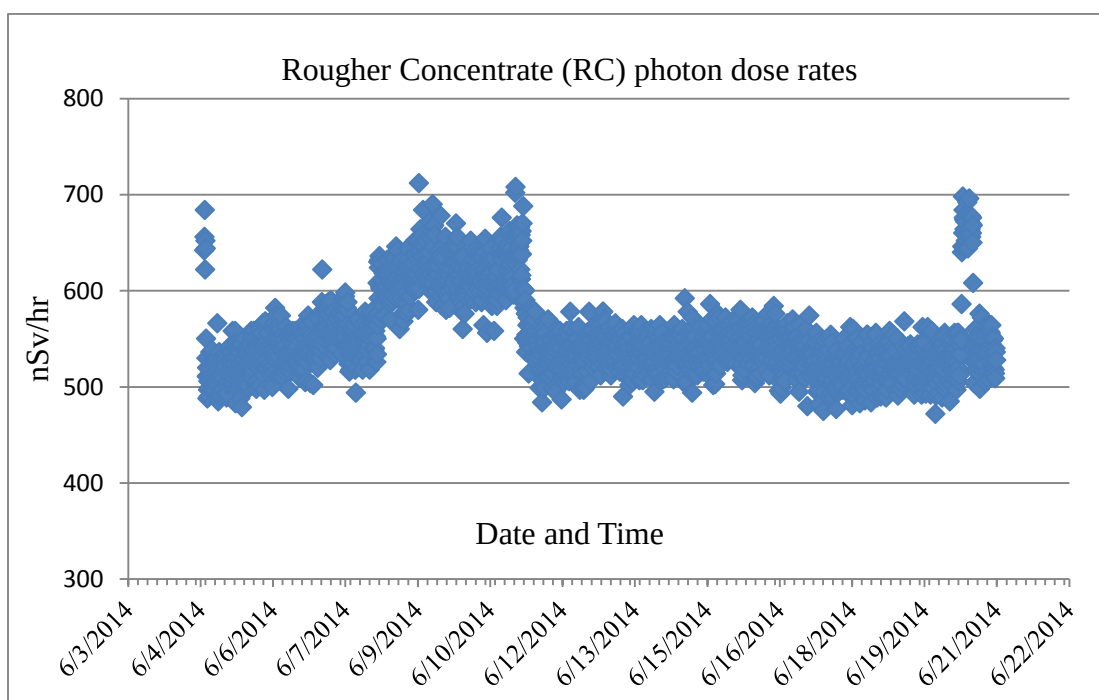


Figure 4.3.4 Photon dose rates at Rougher Concentrate

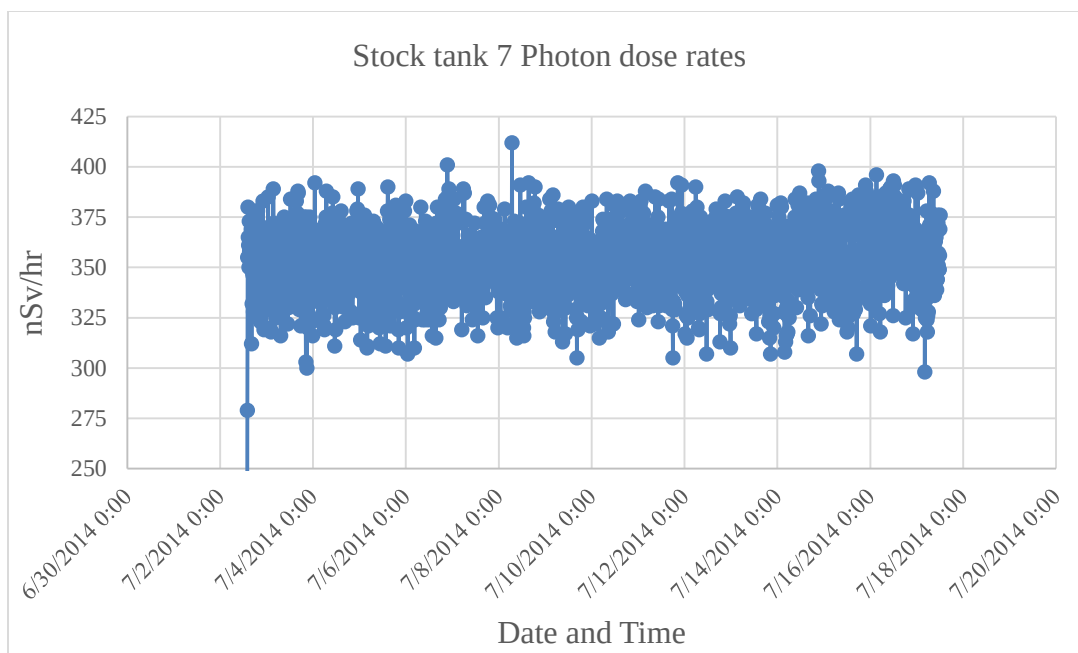


Figure 4.3.5 Photon dose rates at Stock tank 7

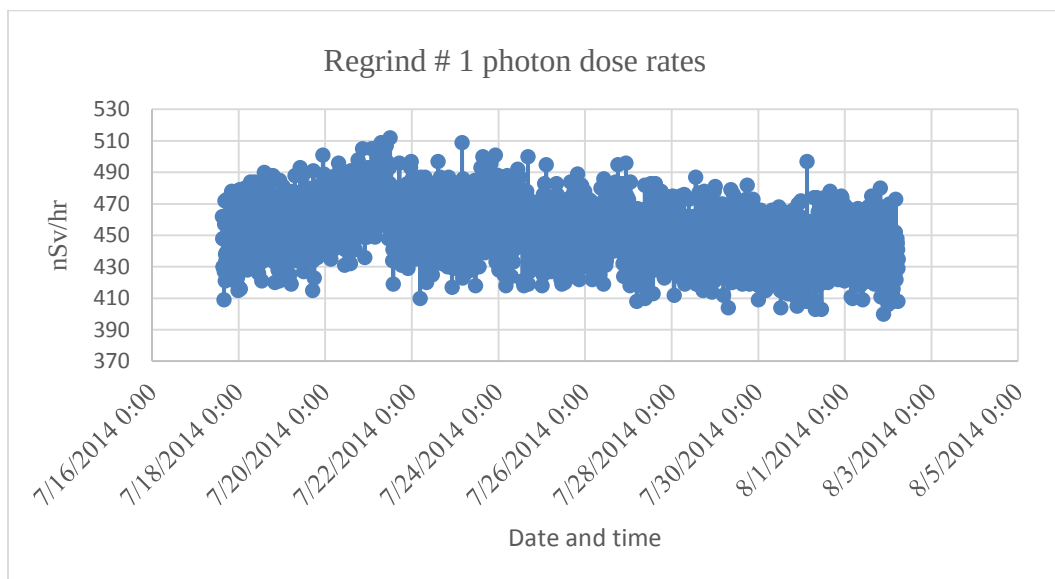


Figure 4.3.6 Photon dose rates at Regrind #1

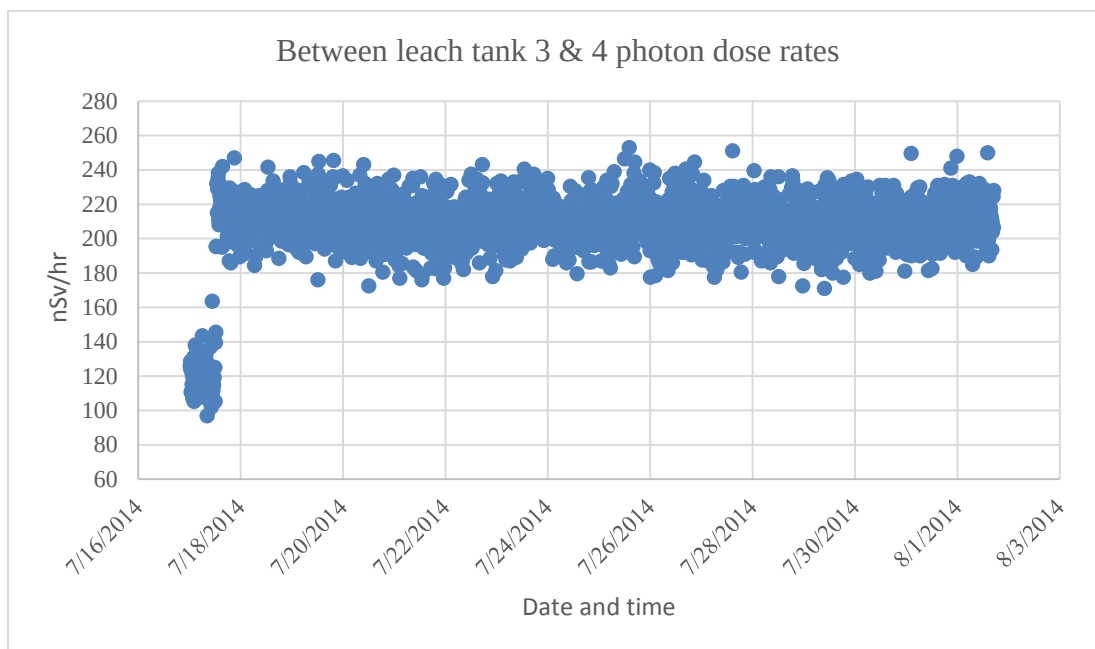


Figure 4.3.7 Photon dose rates in between leach tank 3 & 4

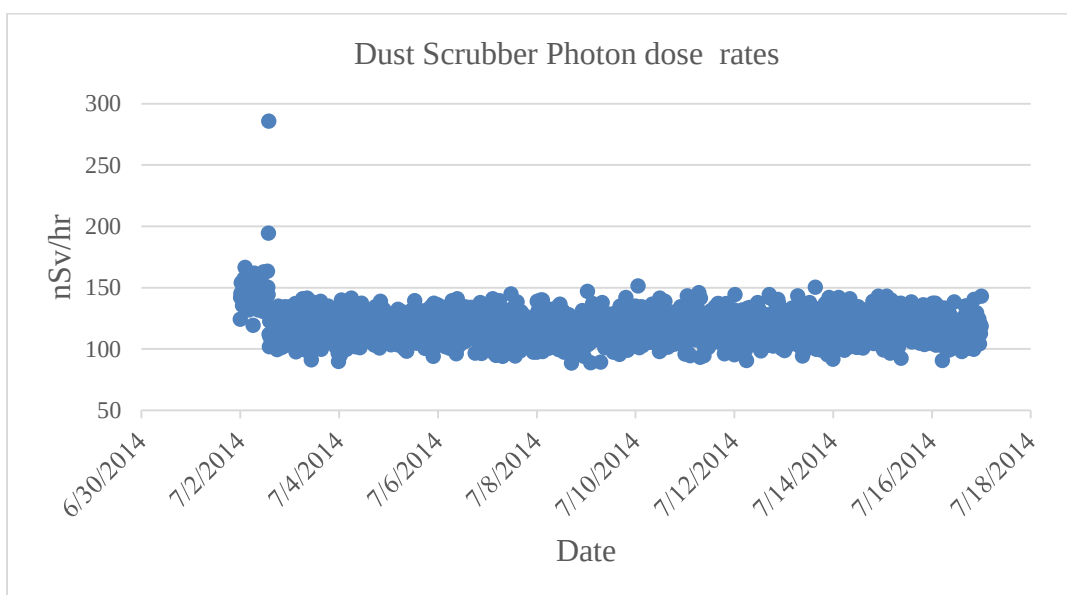


Figure 4.3.8 Photon dose rates at Dust Scrubber

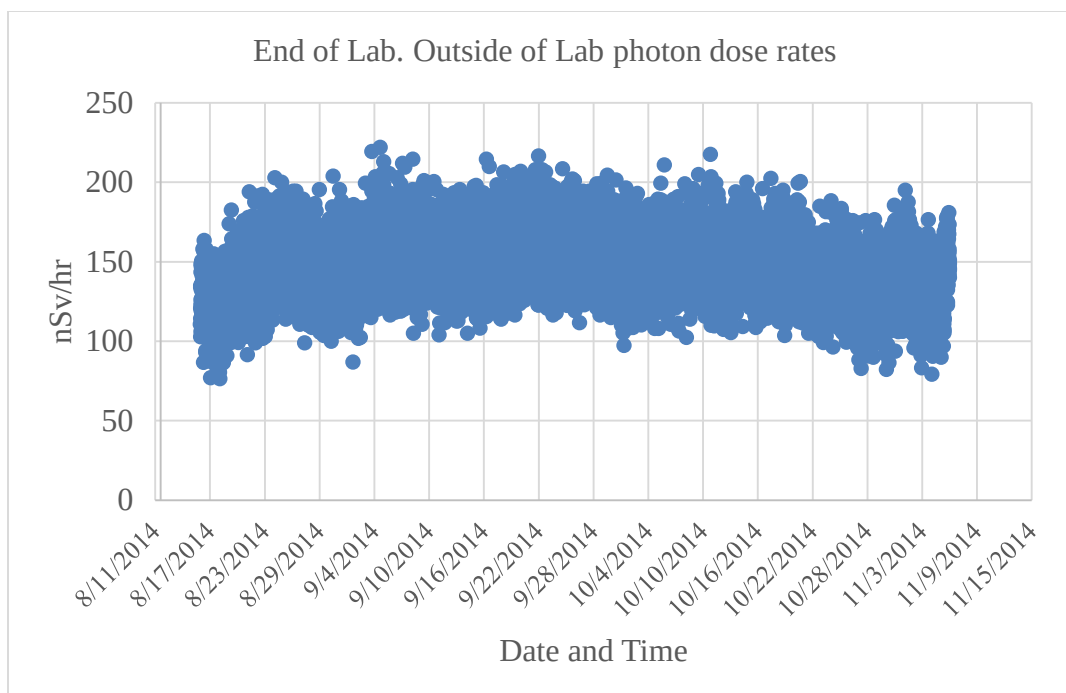


Figure 4.3.9 Photon dose rates at End of the Lab

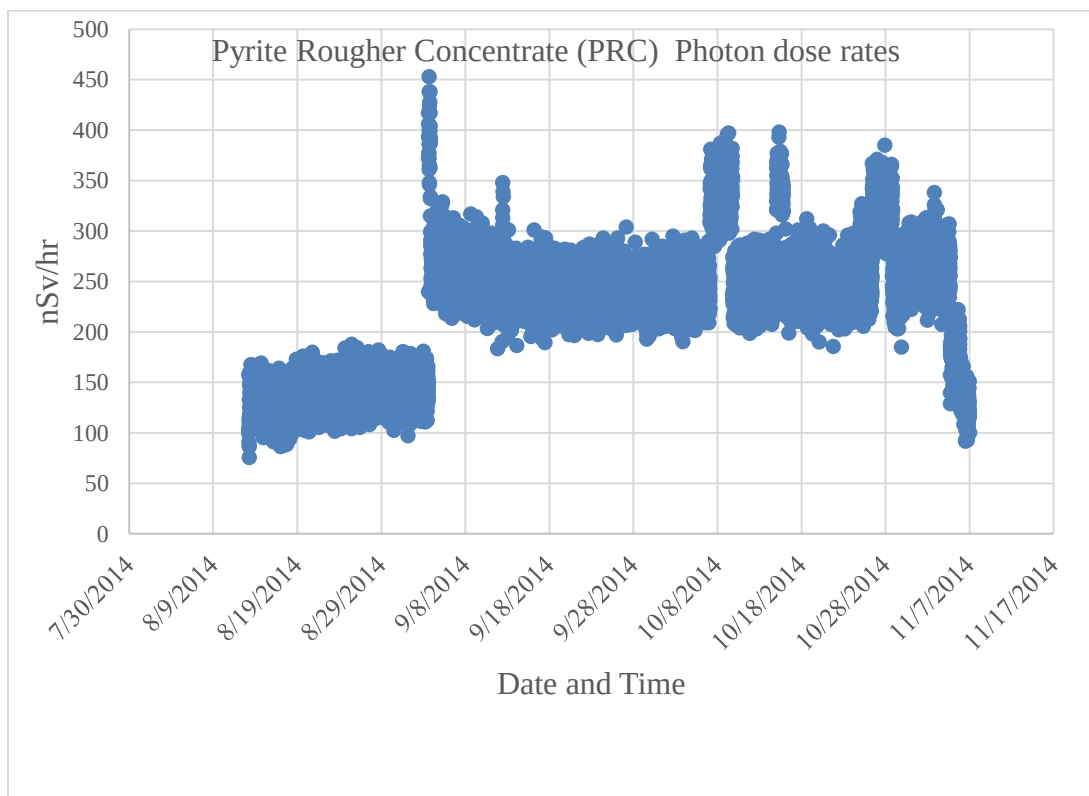


Figure 4.3.10 Photon dose rates at Pyrite Rougher concentrate

Out of 10 chosen locations, only one location Pyrite Rougher Concentrate (PRC) was found to be have variability of photon dose rates as shown in the Figure 4.3.10. The total photon dose rates obtained on all other locations were found to be comparable with Pocatello background dose rates (see Figures 4.1 to 4.9). Pyrite Rougher concentrate was the only place where variability in photon dose rates was obtained. For quality assurance purposes, a recount of the photon dose rates at PRC was performed for one month using both GammaTRACER. Figure 4.4 and 4.5 shows the recount of the photon dose rates at PRC using GammaTRACER. Graphs obtained for photon dose rates from both detectors supports the initial claim that PRC has both variability and elevated photon dose rates.

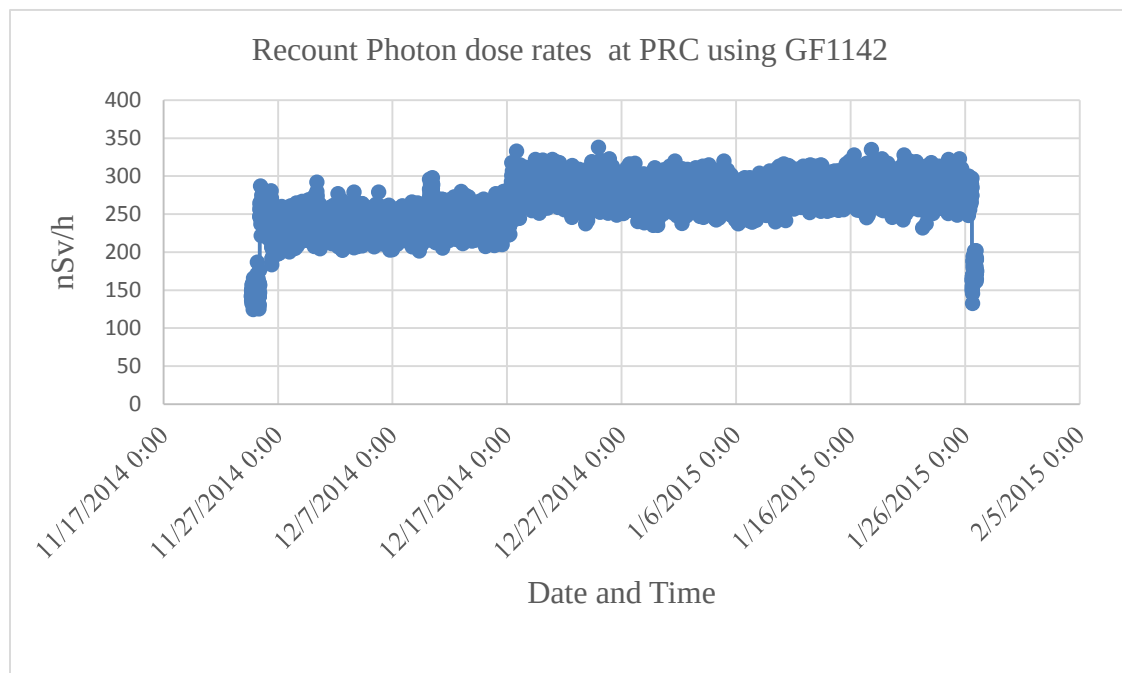


Figure 4.4 Recount of Photon dose rates at PRC using GF1142

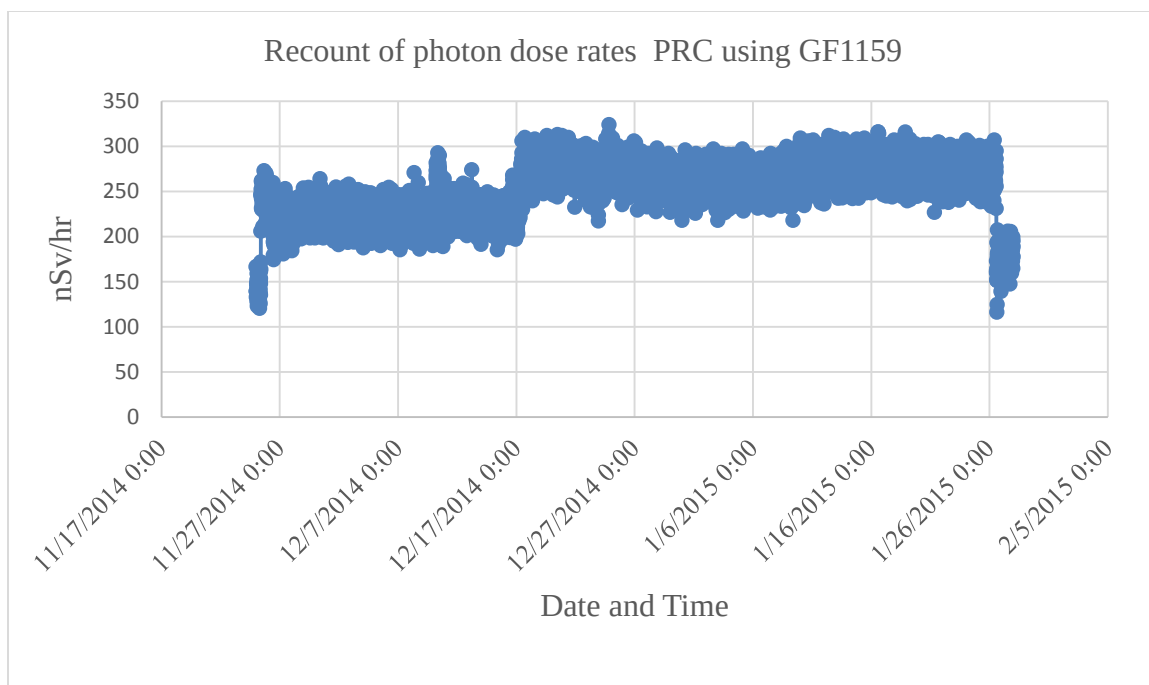


Figure 4.5 Recount of photon dose rates at PRC using GF1159

For further verification of the results, some ore samples were collected from locations inside the facility. Some of the ore samples collected represented same places where GammaTRACER were kept. For quality assurance purposes, two of the obtained ore samples were made split. Information regarding ore samples is given in the table 4.2. Dr. Bryant Bryan collected the samples and shipped to EML. Heights were different for each samples because Dr. Bryant shipped different amount of ores. Bulk densities were lower because of air space between the ore samples. I and II represents split of same locations. Collection date of all samples was December 25th 2014. First count of sample was done starting 27th December 2014. Second count of ore samples was done in last week of January 2015. Various locations with corresponding activity where ore samples were collected at Thompson Creek Mining Company can be found in Appendix J.

Table 4.2 Ore sample information

Location with Sample ID	Sample height (cm)	weight (g)	Bulk density (g/cm ³)
Rougher Tail (RT)	5.58	422.0	1.10
Pyrite Rougher Concentrate (PRC)	8.38	388.10	0.95
Scavenger Tail (ST)	0.70	28.40	0.90
Final Tail (FT)	0.70	41.10	1.03
Flotation Feed (FF-I)	7.62	476.10	1.10
Flotation Feed (FF-II)	7.62	463.00	1.07
Combined Tail (CT)	8.12	433.40	0.94
Plant Tail (PT-I)	7.87	499.50	1.11
Plant Tail (PT-II)	7.87	461.60	1.03

4.3 Results obtained from High Purity HPGe Gamma Detectors

4.3.1 Efficiency determination:

Various ore samples from different locations with different geometries were counted in HPGe gamma detectors. Energy calibration was done using a mixed gamma source available at EML. Efficiency calibration was essential to find out the exact activity and the identity of the radionuclides.

Even though the sample of interest was ore (rock and soil), a water source was used to determine the efficiency of various geometry samples from various locations. In order to verify there was no difference between sample ore and water samples in terms of efficiency, the efficiency of sample ore vs. water at various heights was created by using Lab-SOCS™. The bulk density of various geometry lines in between the range of 0.9 – 1.03 g/cm³.

Empirical efficiency was calculated by using the original certificate provided by the US Food and Drug Administration (FDA) (See Appendix C for original certificate). Figure 4.6 shows that the efficiencies between sample ore and water samples at various heights overlap. Requirement of density correction was rejected because the efficiency curve of sample ore vs. water for various geometries clearly overlap. Density of sample was not an issue while finding efficiency but height of the sample was.

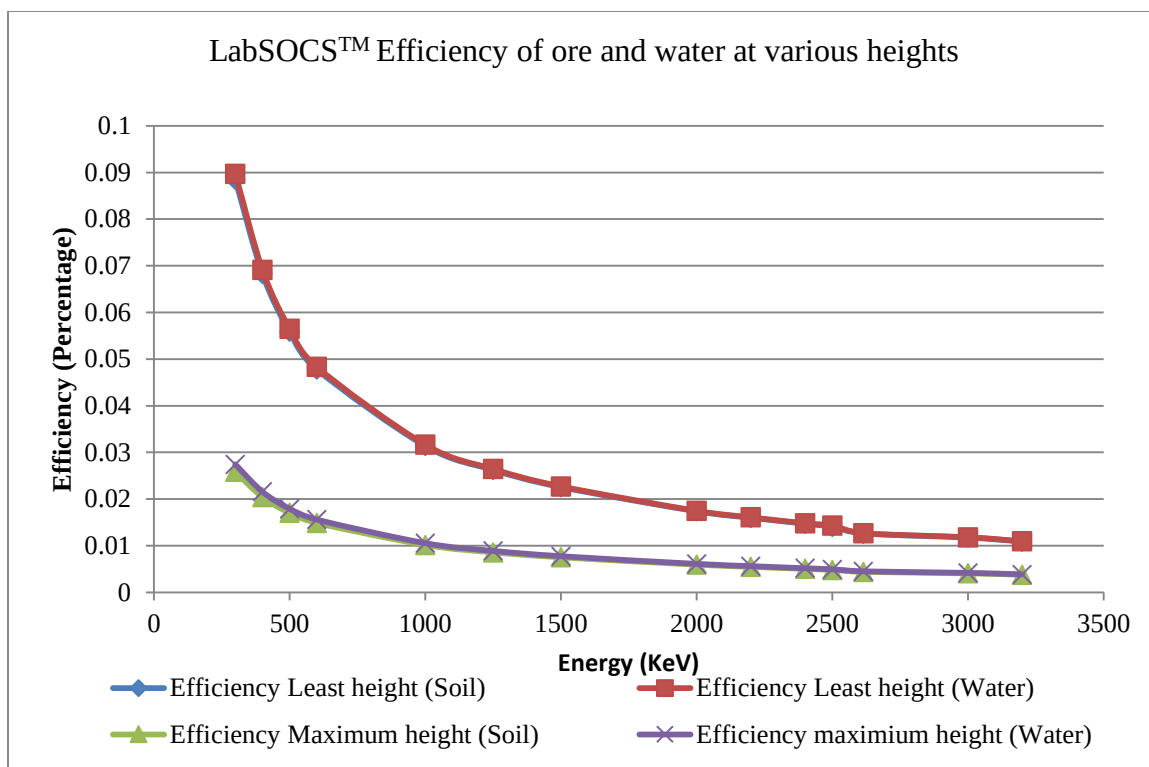


Figure 4.6 Efficiency of ore and water at various heights

Initially the plan was to use available software to determine the efficiency of ore samples with various geometries. LabSOCS™ and GESPECOR® were used to find out the efficiency of sample ore at various heights for Canberra and Ortec. In order to verify that efficiencies given by LabSOCS™ and GESPECOR® were trustworthy, a standard liquid calibration source was obtained from the US Food and Drug Administration (FDA). Graphs were plotted between empirical efficiencies and efficiencies obtained from GESPECOR® and LabSOCS™ for various geometry. GESPECOR® efficiency created for Ortec failed to match the empirical efficiency but, LabSOCS™ efficiency created for Canberra exactly matched the empirical efficiency (See Appendix D for empirical efficiencies vs. software efficiency at various geometries). In order to have a uniform result, empirical

efficiencies were used to find the exact activity concentration of the radionuclides responsible. Figure 4.7 shows empirical efficiencies generated from the FDA calibration standard at various ore heights. Exact values of efficiencies can be found in Appendix F. Figure 4.7 shows that geometries with lower heights were found to have higher efficiency values than the geometries with higher heights. Geometries with lower heights had less mass absorption than the geometries with higher heights which resulted in higher efficiency.

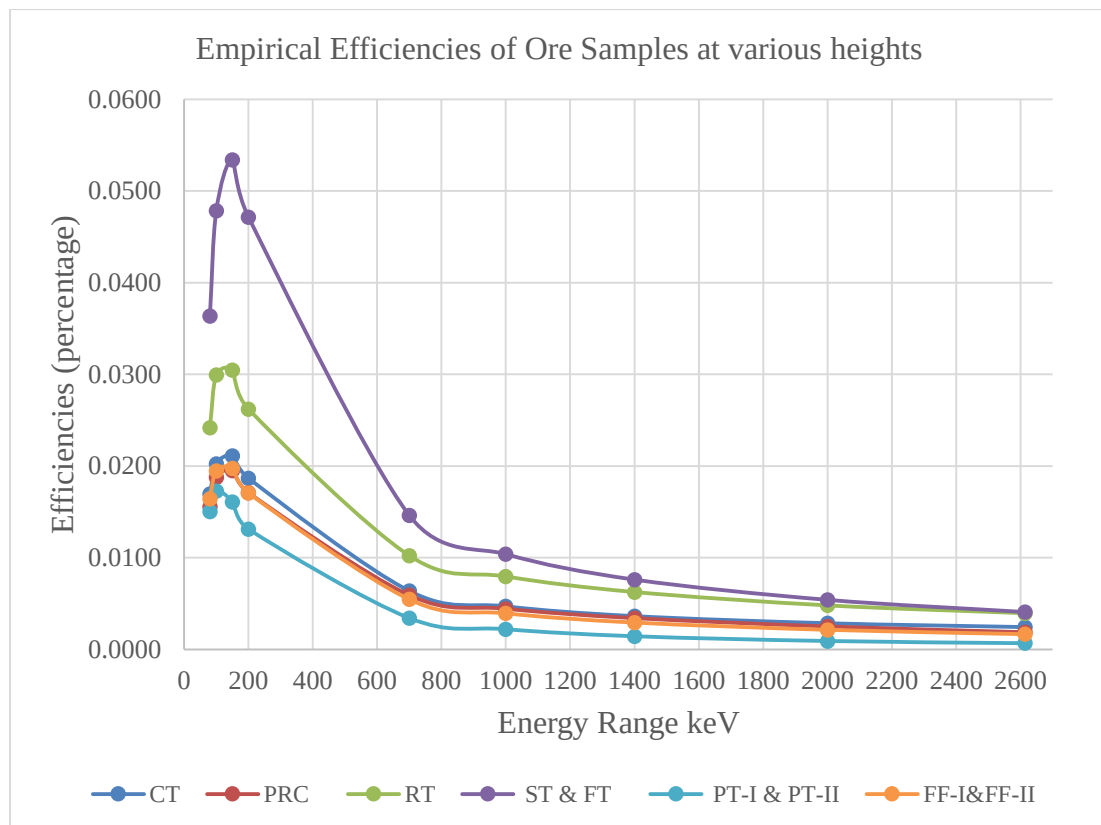


Figure 4.7 Empirical efficiencies of ore samples at various heights

4.3.2 Activity of Identified radionuclides

There were five common radionuclides identified in each sample. All the activity obtained from the first and second the count from Ortec and Canberra detectors were averaged. (See Appendix E for separate activity of radionuclide for 4 different counts). They were: K-40, Pb-212, Bi-214, Pb-21 and Tl-208. All the identified radionuclides can be correlated to Tables 2.3. Table 4.3.1 through 4.3.10 show the activity of different radionuclides in different ore samples. The values of background activity was found to be 0.00466 ± 0.000212 Bq/g. All the values of identified radionuclides were found to be higher than two times the uncertainty of background activity which satisfies the null hypothesis 1.

Figure 4.8 shows that the activity of K-40 was found to be dominant in most of the samples ranging from 0.923 – 1.09 Bq/g. Bi-214 was found in all geometries with very small activity except for PRC and ST. Bi-214 was found higher in the geometry PRC and ST with the activity of 0.209 & 0.316 Bq/g respectively. Tl-208 was found in each sample with very small activity but contributed a lot in photon dose rates because of a higher energy line. Some of the higher energy lines corresponding to Tl-208 were (860, 927, 982, 109, and 2614) keV. Pb-212 was found to be in each ore sample but had a negligible contribution to the total photon dose rates. Activity of Bi-214 & Tl-208 were found in lesser quantities but had significant contributions on the photon dose rates which will be discussed in next section.

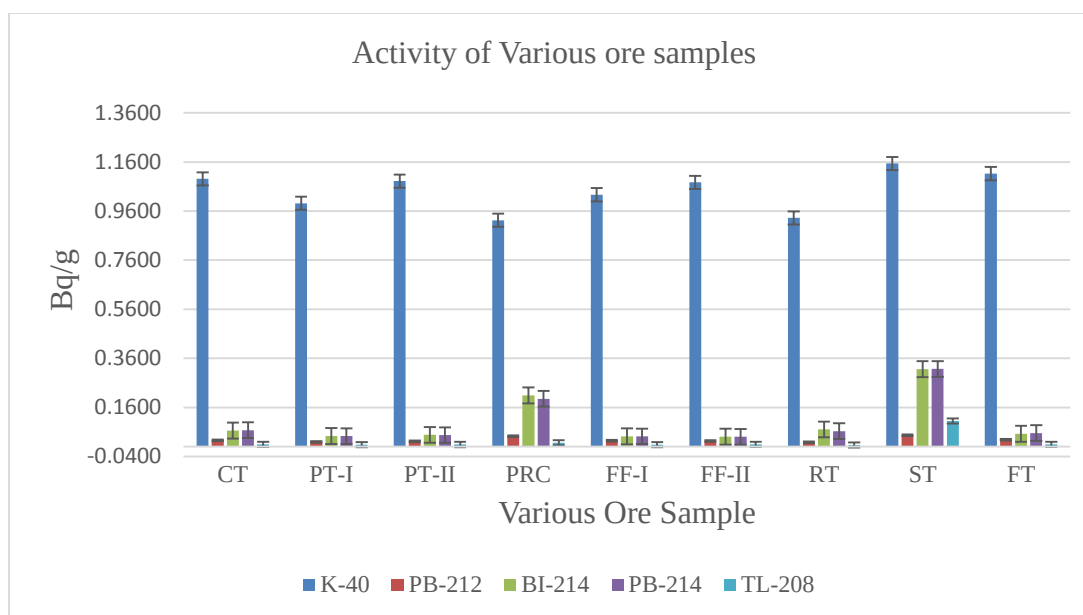


Figure 4.8 Activity of various Samples

Table 4.3.1 Radionuclides with average activity for sample CT

sample ID:CT	Average Activity Bq/g	Uncertainty
K-40	1.09E+00	2.90E-02
Pb-212	2.56E-02	9.81E-04
Bi-214	6.52E-02	4.34E-03
Pb-214	6.71E-02	1.47E-03
Tl-208	9.15E-03	1.18E-04

Table 4.3.2 Radionuclides with average activity for sample PT-I

Sample ID: PT-I	Average Activity Bq/g	Uncertainty
K-40	9.92E-01	2.18E-02
Pb-212	1.96E-02	5.77E-04
Bi-214	4.36E-02	8.83E-04
Pb-214	4.32E-02	7.74E-04
Tl-208	7.87E-03	7.95E-04

Table 4.3.3 Radionuclides with average activity for sample PRC

Sample ID: PRC	Average Activity Bq/g	Uncertainty
K-40	9.23E-01	1.70E-02
Pb-212	4.24E-02	4.24E-02
Bi-214	2.09E-01	3.22E-03
Pb-214	1.95E-01	1.95E-01
Tl-208	1.62E-02	1.35E-03

Table 4.3.4 Radionuclides with average activity for sample PT-II

Sample ID: PT-II	Average Activity Bq/g	Uncertainty
K-40	1.08E+00	2.38E-02
Pb-212	2.18E-02	6.98E-04
Bi-214	4.80E-02	9.63E-04
Pb-214	4.72E-02	8.30E-04
Tl-208	8.75E-03	8.69E-04

Table 4.3.5 Radionuclides with average activity for sample FF-I

Sample ID: FF-I	Average Activity Bq/g	Uncertainty
K-40	1.03E+00	2.26E-02
Pb-212	2.48E-02	7.26E-04
Bi-214	4.20E-02	8.65E-04
Pb-214	4.19E-02	1.83E-02
Tl-208	7.97E-03	1.39E-04

Table 4.3.6 Radionuclides with average activity for sample FF-II

Sample ID: FF-II	Average Activity Bq/g	Uncertainty
K-40	1.08E+00	2.36E-02
Pb-212	2.34E-02	5.75E-04
Bi-214	4.06E-02	8.52E-04
Pb-214	4.02E-02	6.99E-04
Tl-208	9.07E-03	8.17E-04

Table 4.3.7 Radionuclides with average activity for sample RT

sample ID: RT	Average Activity Bq/g	Uncertainty
K-40	9.32E-01	1.99E-02
Pb-212	1.84E-02	5.46E-04
Bi-214	7.02E-02	1.15E-03
Pb-214	6.34E-02	8.47E-04
Tl-208	7.16E-02	7.21E-03

Table 4.3.8 Radionuclides with average activity for sample ST

Sample ID: ST	Average Activity Bq/g	Uncertainty
K-40	1.15E+00	3.80E-02
Pb-212	4.63E-02	2.20E-03
Bi-214	3.16E-01	5.90E-03
Pb-214	3.17E-01	5.07E-03
Tl-208	1.04E-01	2.87E-02

Table 4.3.9 Radionuclides with average activity for sample FT

Sample ID: FT	Average Activity Bq/g	Uncertainty
K-40	1.11E+00	3.24E-02
Pb-212	2.88E-02	1.18E-03
Bi-214	5.27E-02	1.87E-03
Pb-214	5.55E-02	1.42E-03
Tl-208	9.82E-03	6.13E-04

4.3.3 Photon dose rates:

Some assumptions were made before computing photon dose rates from various samples. Computed estimates of the percentage contribution of radionuclides to dose rates were made without regard to true geometries considerations or point kernel methods. The point of interest was the percentage contributions to the doses, therefore simple point source dose estimates were computed at a distance of 1 meter. Gamma ray dose constants were used

while computing the values of photon dose rates at various locations. The gamma ray dose constant is defined as the dose rate at a specific distance from a given amount of a photon-emitting radionuclide (IEM 1997). Table 4.4 is the list of gamma ray constants for a variety of radionuclides, in units rem/hr at a distance of 1 meter from a 1Ci source. Total photon dose rates from one kilogram of the geometries were computed (See Appendix G for values of photon dose rates from both gamma detectors).

Table 4.4 Gamma ray constants for various radionuclides (IEM 1997)

Radionuclides	Gamma constant (Rem/hr) @ 1m from 1 Ci source	Gamma Constant (Sv/hr) @ 1m from 1 Ci Source
K-40	8.17E-02	8.17E-04
Pb-212	2.73E-01	2.73E-03
Bi-214	8.39E-01	8.39E-03
Pb-214	3.23E-01	3.23E-03
Tl-208	1.70E+00	1.70E-02

Table 4.5 shows the total photon dose rate per kilogram emitted by various samples. ST was responsible for the highest amount of photon dose rates per kilogram of sample i.e. 0.17 nSv/hr*kg. PRC was contributing photon dose rates of approximately 0.01 nSv/hr*kg. All other samples contributed nearly equal amount of photon dose rates ranging from 0.04-0.05 nSv/hr*kg.

Table 4.5 Computed photon dose rates per hour per kilogram of various samples.

Sample Geometry	nSv/hr*kg	Uncertainty (one Sigma)
ST	1.72E-01	3.87E-03
PT-I	4.08E-02	1.13E-03
PT-II	4.52E-02	1.30E-03
PRC	9.59E-02	7.57E-03
FF-I	4.22E-02	8.57E-04
FF-II	4.29E-02	1.25E-03
RT	4.68E-02	6.42E-03
CT	5.05E-02	5.52E-03
FT	4.70E-02	4.42E-03

Photon dose rates estimated from PT-I and PT-II were 0.041 and 0.045 nSv/hr*kg respectively as shown in Table 4.5. Photon dose rates emitted from FF-I & FF-II were 0.042 & 0.043 nSv/hr*kg respectively. Both of the splits were within two standard deviations to each other. Bi-214 was responsible for 22% of the total photon dose rates in PT- I and PT-II. Also, Bi-214 contributed 20% of the total photon dose rates in sample FT-I & FT-II. Potassium was found to be dominant in both splits (PT & FT) contributing about 55% of the total photon dose rates.

Computed total photon dose rates per kilogram given by different geometries were uniform for most of the samples (see Figure 4.9). For energy lines not associated with five common radionuclides, doses were computed using the fundamental principle (see Appendix I for calculation method). Only PRC and ST were significantly different than all other samples. Computed total photon dose rates were unchanged for each ore sample relative to the first and second counts because the samples were already in equilibrium at the first count. The initial concern about variability due to ingrowth or disequilibrium of activity of various

nuclides in the decay series was not supported by the gamma detector results. All the samples were found to be in equilibrium.

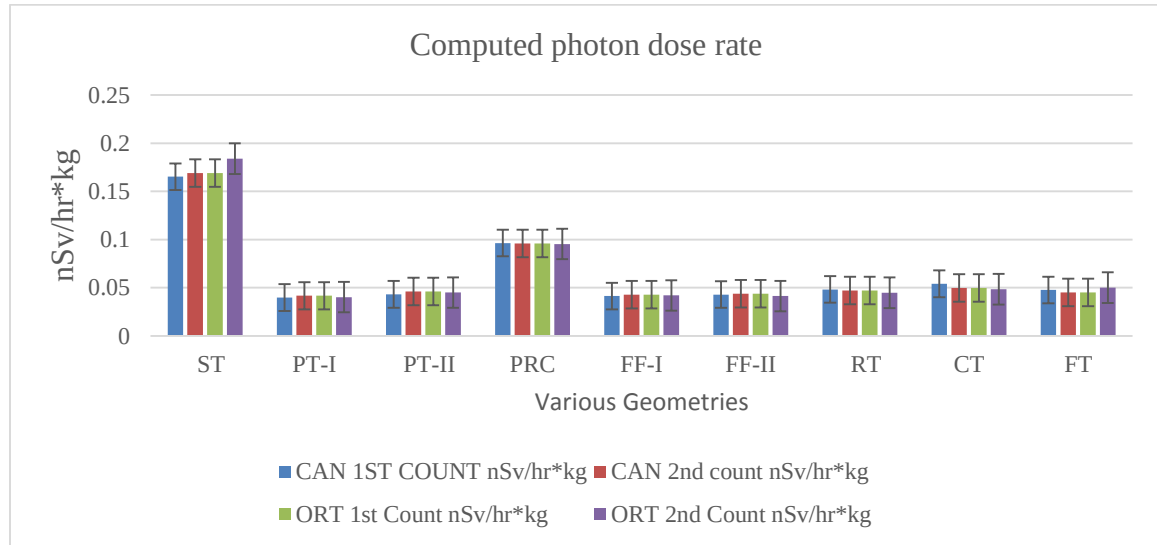


Figure 4.9 Total Computed Photon dose rates for various samples

Figure 4.10 shows that about 96% of the total photon dose rates could be attributed from the five radionuclides: K-40, Pb-212, Bi-214, and Pb-214 & Tl-208. Only 4% of total photon dose rates was contributed by identified peaks. Figure 4.10 shows the estimated percentage distribution of identified radionuclides which contributed to the total photon dose rates. In most of the samples except for PRC and ST, about 50% of the total photon dose rates were contributed by K-40 which supported the null hypothesis 2. In PRC and ST, Bi-214 was dominant and contributed about 50 and 40 percent of the total photon dose rates respectively. For samples PRC and ST, K-40 was responsible only for about 20% of the total photon dose rates.

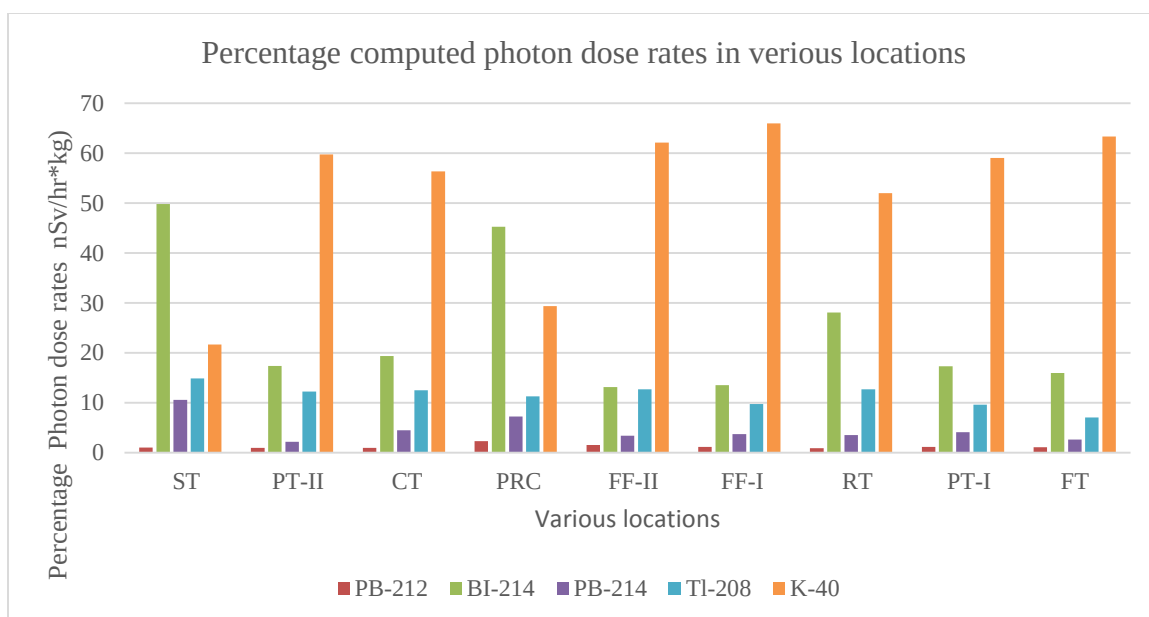


Figure 4.10 Contribution of various radionuclide in total photon dose rates

Pb-212 was identified in all of the geometries but contributed less than 2% of the total photon dose rates. Tl-208 was found to be present in all geometries. Percentage contribution of Tl-208 varied in each sample. In sample ST, Tl-208 contributed 28% of the total photon dose rates whereas in sample FT, Tl-208 contributed just 7% of the total photon dose rates. After K-40, Bi-214 was dominant in most of the samples.

In order to find which energy range was contributing the most photon dose rate, all the photon dose rates between the intervals of 100 keV were summed. Figure 4.11.1 through 4.11.9 shows the distribution of photon dose rates at various energy ranges. As predicted earlier, K-40 with energy range (1400-1500) keV, was found dominant in most of the samples. All the identified five radionuclides have several energy lines so, photon dose rates are distributed throughout the bar graph.

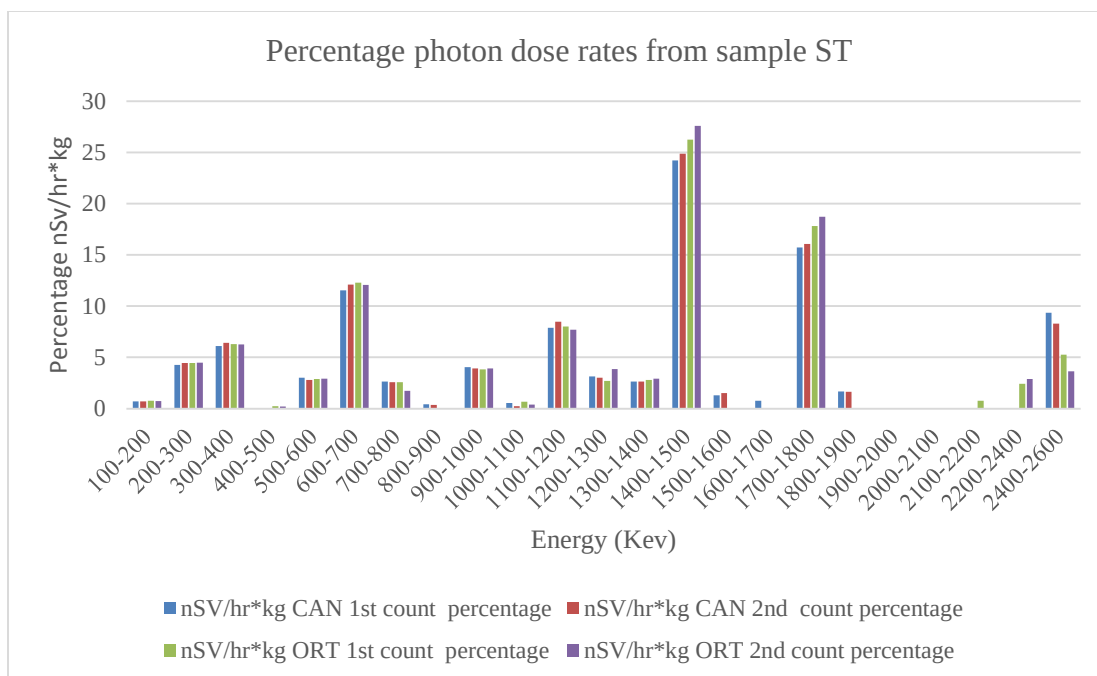


Figure 4.11.1 Percentage Photon dose rates from sample ore ST

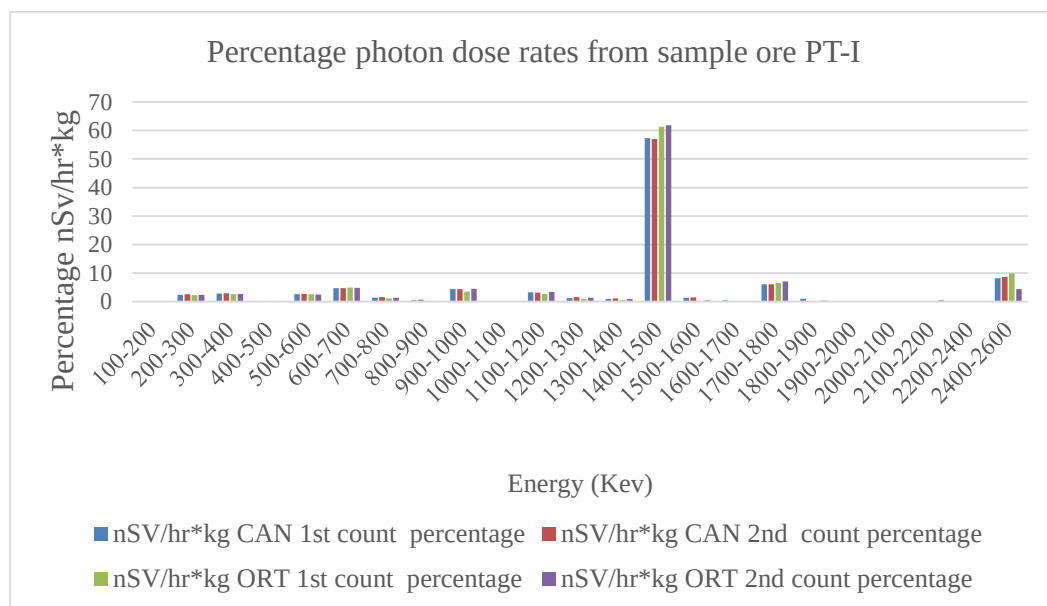


Figure 4.11.2 Percentage Photon dose rates from sample ore PT-I

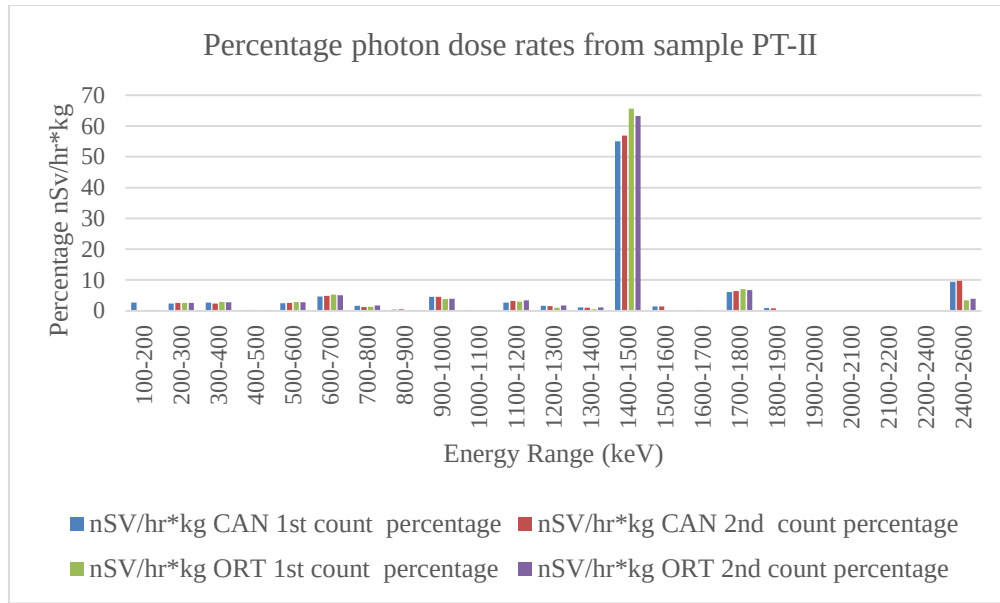


Figure 4.11.3 Percentage photon dose rates from sample ore PT-II

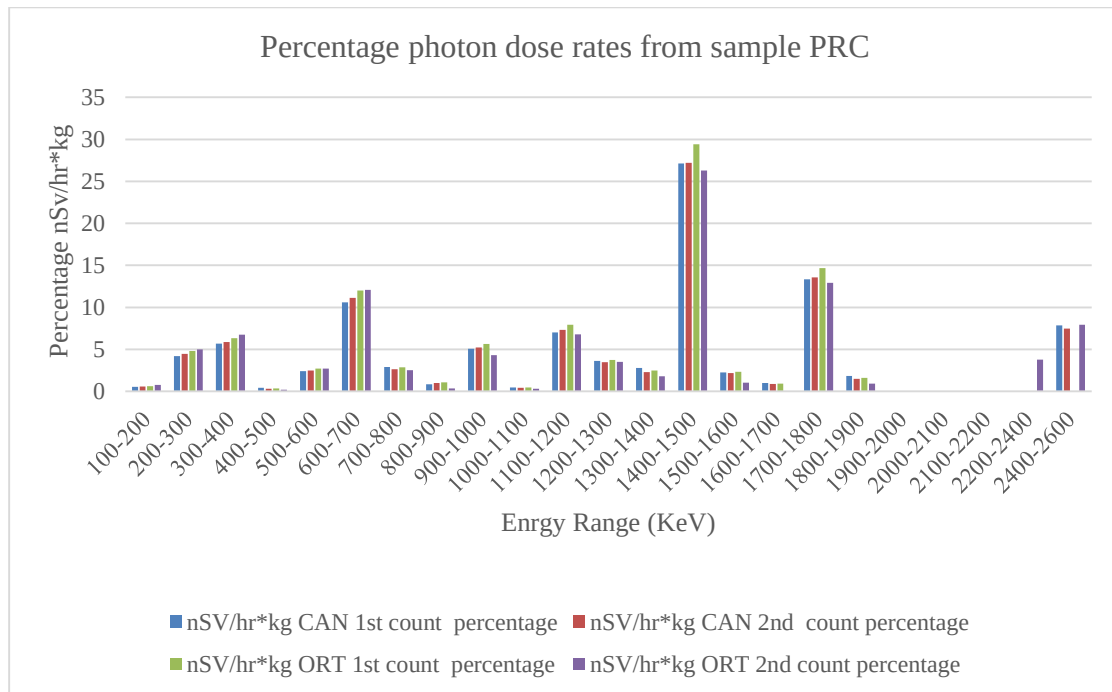


Figure 4.11.4 Percentage Photon dose rates from sample ore PRC

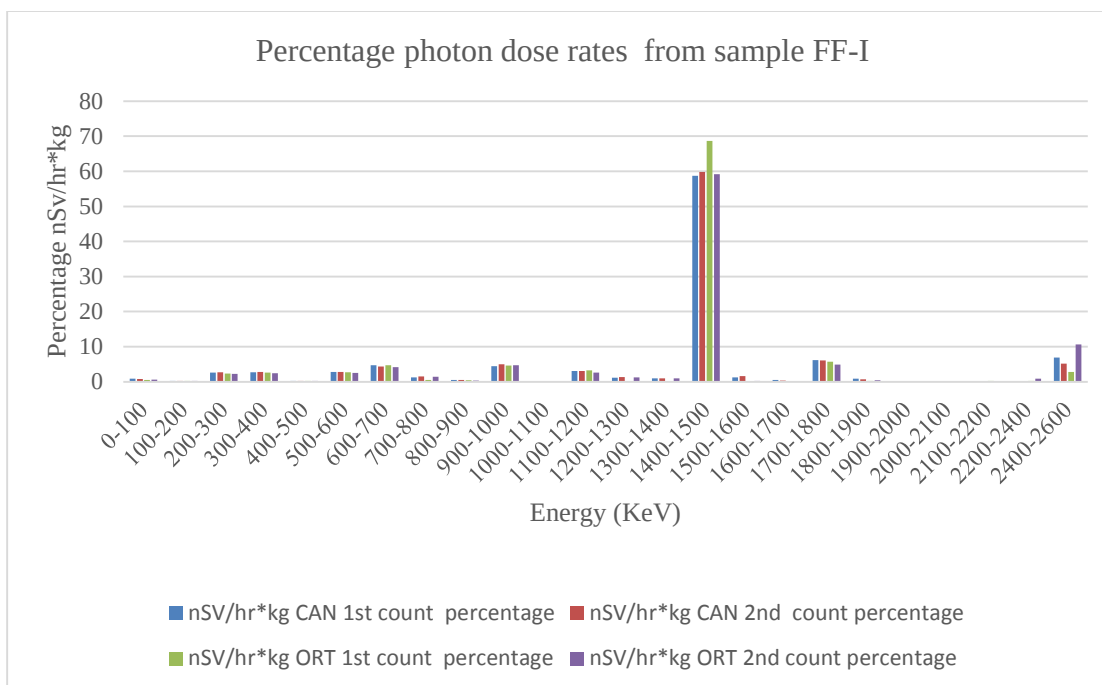


Figure 4.11.5 Percentage Photon dose rates sample ore FF-I

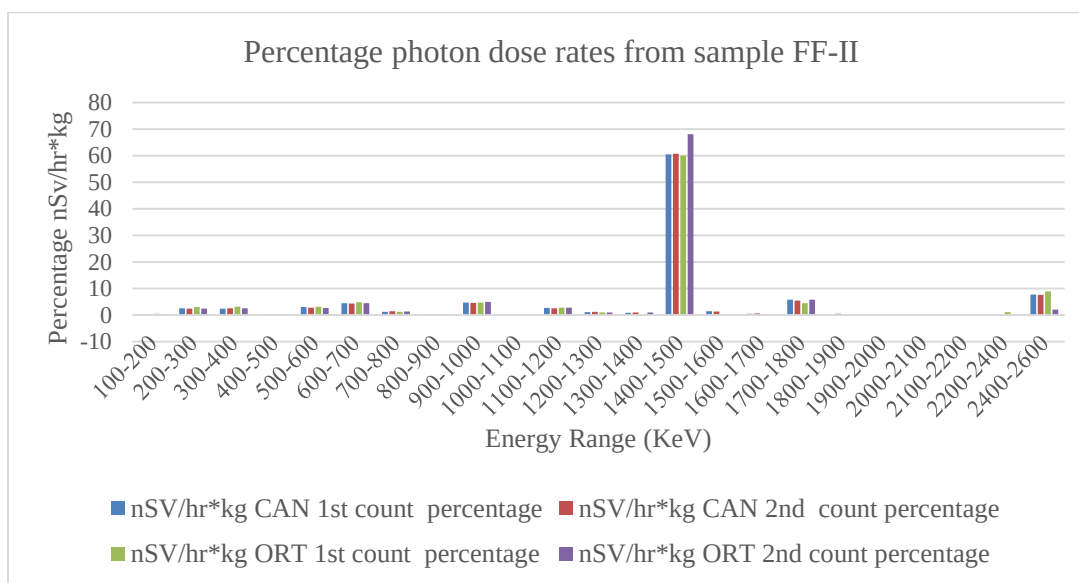


Figure 4.11.6 Percentage Photon dose rates from sample ore FF-II

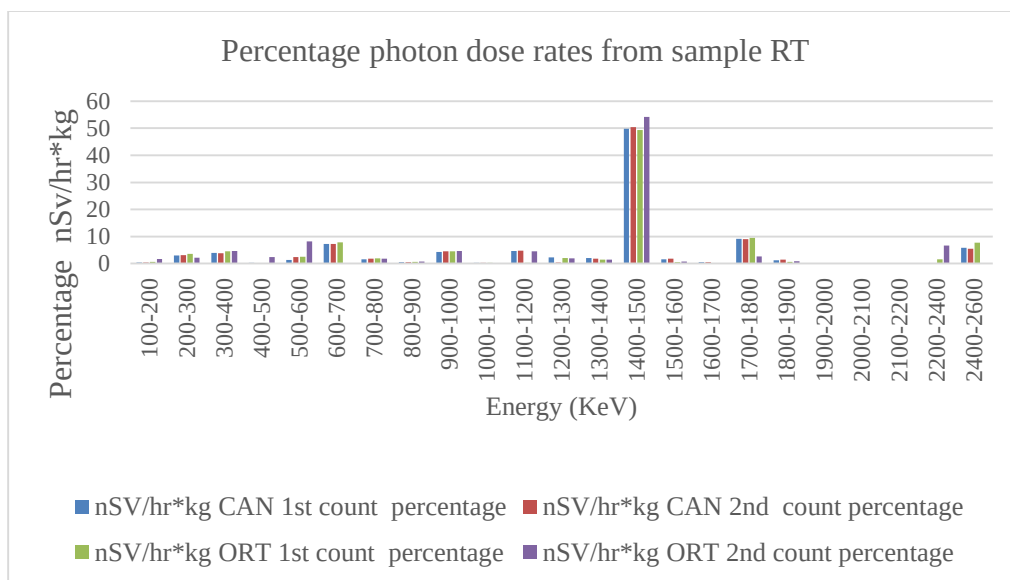


Figure 4.11.7 Percentage photon dose rates from sample ore RT

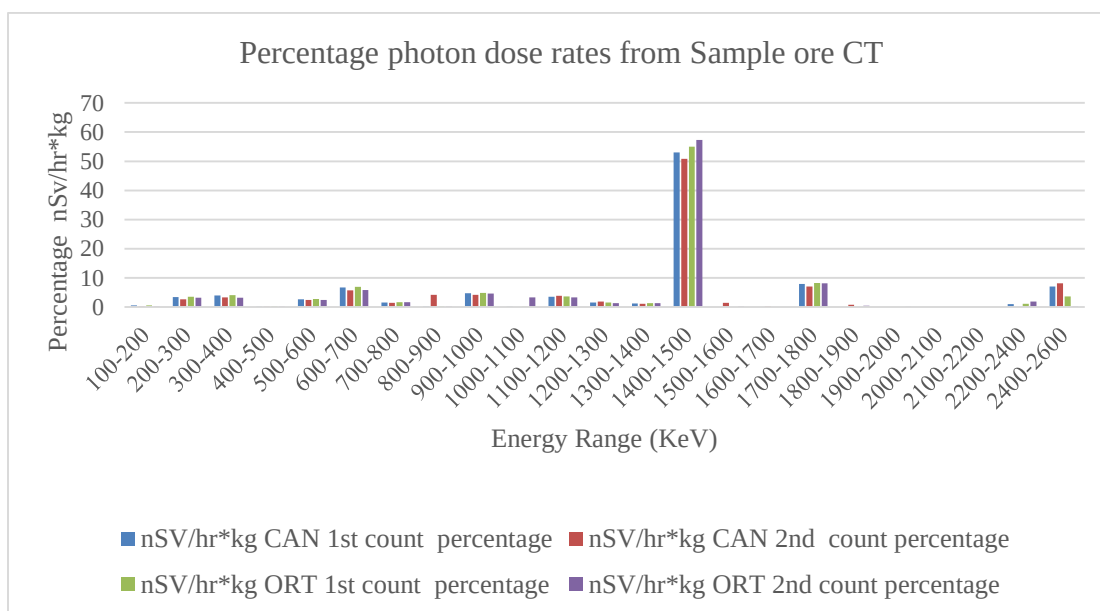


Figure 4.11.8 Percentage photon dose rates from sample ore CT

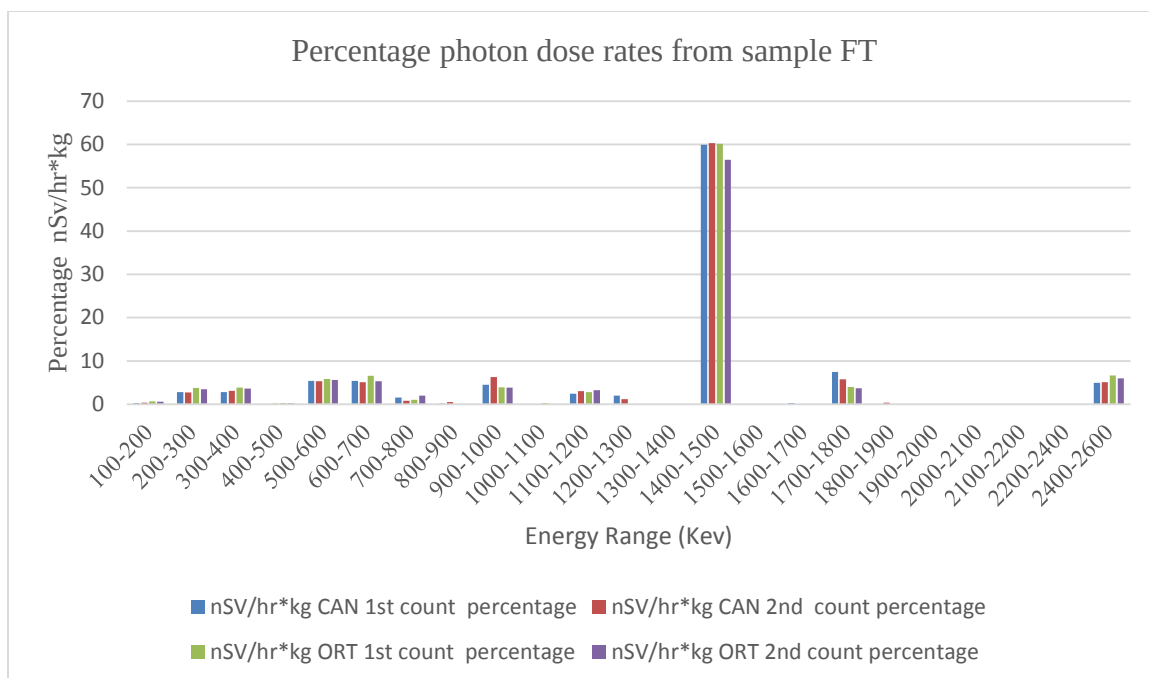


Figure 4.11.9 Percentage photon dose rates from sample ore FT

4.3.4 Comparison of GammaTRACER results with gamma detector result:

Pyrite Rougher Concentrate (PRC), Scavenger Tail (ST) and Rougher Concentrate (RC) were the locations where both GammaTRACERs were kept and ore samples were collected. It was extremely difficult to compare the results between the GammaTRACER and gamma detectors because of the following reasons.

1. Area and mass covered by the GammaTRACER were unknown.
2. Soil samples obtained for gamma detector may not accurately represent the area of soil covered by the GammaTRACERs.

Table 4.6 shows the comparison of GammaTRACER and gamma detector results. A factor of GammaTRACER dose rates values vs. GammaTRACER background dose rates values were obtained. Also, a factor of gamma detector dose rates vs. background dose rates were obtained. Location PRC was found to have a factor of about 2 in both cases. In location RT, obtained factor for GammaTRACER was 3.8 whereas, for gamma detector was 1.

Photon dose rates obtained in the location ST by GammaTRACER was 10714 nSv/hr. Values were high because of the reagent choice that was used at that period of time. A xanthate collector (sodium isobutyl xanthate) was added to attempt to send FeS_2 to the concentrate. The factor of GammaTRACER vs. background was 75 whereas, for gamma detector was only 3.89. The similarities between the results was that factors were high in both cases but was difficult to compare because samples weren't collected

at the same time as GammaTRACER measurements. From these results, it can be determined with relative certainty that no correction can be made from these GammaTRACER and ore sample measurements.

Table 4.6 shows the comparison of GammaTRACER and gamma detector results

Gamma dose rates nSv/hr						
Location	Gamma TRACER			Gamma Detector		
	Gamma TRACER	Background	Factor	Gamma Detector	Background	Factor
PRC	265	143	1.85	0.090	0.044	2.03
ST	10714	143	74.92	0.172	0.044	3.89
RT	551	143	3.85	0.047	0.044	1.06

Chapter 5. Feasibility and Cost Analysis of future measurements

Natural radiation is present everywhere. It would be worthy to keep GammaTRACER in several places inside the Thompson Creek Mining Company in order to monitor the continuous photon dose rates not only for assurance of workers and public safety but also for the possibility that a correlation may exist between radionuclide data and specific chemical and/or process parameters. The GammaTRAC is able to function as a real-time monitor of process or quality control. The GammaTRACER can be used to measure the continuous photon dose rates for long periods of time in a harsh environment with no maintenance. Equipment required and cost of the installation of GammaTRACER can be found in the Table 5.1. GammaTRACER can continuously count photon dose rates for 5 years without any maintenance (Saphymo GmbH 2015). Table 5.1 shows that total cost of installing GammaTRACER would be just \$21145 in five years. Manufacturer cost of GammaTRACER can be found on Appendix H.

Table 5.1 Cost estimation of installation of GammaTRACER

Equipment Required	Quantity	Price Per Quantity (\$)	Cost (\$)
GammaTRACER	5	2929.00	14645.00
Laptop	1	\$500.00	500
Software to process data	1	Free	0.00
Labor (\$20/hr)	1 Person- 5 hrs/month	6000	6000.00
Total Cost (\$)			21145.00

** Costs are estimated values.

Chapter 6: Conclusions

The initial claim of having temporal variable level of photon dose rates at a molybdenum facility wasn't supported by high purity gamma detectors results. Some elevated levels of photon dose rates were observed in various places inside the facility. All the collected samples were found to be in equilibrium. Based on the gamma detector results, no in-growth and decay was observed in ore samples. Collected samples must have been in an equilibrium state even before they were shipped to EML for analysis.

There were five different radionuclides identified by their photon emissions in each geometry: K-40, Pb-212, Bi-214, and Pb-214 & Tl-208. Activity of K-40 was found to be dominant in most of the samples ranging from 0.923 – 1.09 Bq/g. All the obtained activity of identified radionuclides in ore samples were found to be two times higher than their uncertainty. After K-40, Bi-214 was the dominant radionuclide in all samples.

Most of the total photon dose rates emitted from ore samples were contributed by K-40, Pb-212, Bi-214, and Pb-214 & Tl-208. K-40 was found to be contributing about 50% of the total dose in all ore samples except for two locations (PRC and ST). In PRC and ST, Bi-214 was dominant and contributed about 45 and 49 percentages of the total photon dose rates respectively. Pb-212 was identified in all ore samples but contributed less than 2% of the total photon dose rates. Tl-208 was found to be present in all ore samples. Percentage contribution of Tl-208 varied in each samples. In sample ST, Tl-208 contributed 25% of total photon dose rates whereas in sample FT, Tl-208 contributed just 7% of the total photon dose rates.

Mining and milling facilities at remote places can be monitored using GammaTRACER.

It is recommended that mining and milling facilities especially at remote places keep GammaTRACER or similar devices to monitor natural photon dose rates.

Chapter 7: Future work

Multiple ore sample collection throughout the process at the time when GammaTRACER are kept should be considered as a future work.

Initially the plan was to relate GammaTRACER results with ore samples. There were few reasons which made it difficult to relate GammaTRACER results with ore sample results.

They are:

- a. Amount of ore sample counted in gamma detector does not represent the amount of ore area covered by GammaTRACER.
- b. Area covered by GammaTRACER is unknown. Amount of ore responsible for photon dose rate obtained from GammaTRACER was unknown.

Obtaining the above listed information might be difficult and time consuming. More data obtained through additional ore samples would have been helpful to strengthen the result. But seasonal shut down of the facility in the winter and the remote location of the facility made it impossible for further collection of ore samples.

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Appendixes

Appendix A: GammaTRACER Calibration Certificates

A-1: calibration information for GF1159



GammaTRACER CERTIFICATE OF CALIBRATION

Instrument: GammaTRACER S/N GF1159
Sensitivity range: 20 nSv/h to 10 mSv/h - Hx
Energy Range: 48 keV to 2,00 MeV
Date of calibration: 09.04.2014
Calibration Source: Cs-137 at 662 keV
Reference Procedure: ANSI N 323A - 1997
Method of calibration: Four calibration points are checked on every unit.
A*: Verification of internal background correction 25 nSv/h
B: Verification of calibration factor 1965 nSv/h
C*: Verification of deadtime correction 66.300 nSv/h
D*: Verification of deadtime correction 7.410.000 nSv/h
*: not included in standard revision
Place of calibration: Saphymo GmbH Frankfurt/Germany
Calibration based on:
• the German national dose-rate standard at Physikalisch
• Technische Bundesanstalt (PTB) in Braunschweig
• the British National Radiation Protection Board (NRPB) in
Didcot, Oxfordshire
with a total error of less than 6 %.
These laboratories are cross-linked to all major national
calibration laboratories such as NIST and DOE/EML with un-
certainties in the order of 1 %.
Calibration tolerance: Specified by the factory +/- 6 % (tube 1) and +/- 15 % (tube 1)

Exact calibration levels and results:

	Counter tube 1	Counter tube 2
Target value:	1965 nSv/h	1965 nSv/h
Actual value:	1965 nSv/h	1948 nSv/h
Mean deviation:	0,00 %	-0,87 %
Calibration factor:	9,20 nSv/(h*cpm)	9,60 nSv/(h*cpm)
Intrinsic effect:	9,43 cpm	4,27 cpm

controlled by:
Petra Sattler

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BIC: FOLKDE33

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Postbank Frankfurt
IBAN: DE93 5001 0060 0998 8236 09
BIC: PANKDE33

A-2: calibration information for GF1142



GammaTRACER CERTIFICATE OF CALIBRATION

Instrument: GammaTRACER S/N GF1142
 Sensitivity range: 20 nSv/h to 10 mSv/h - Hx
 Energy Range: 48 keV to 2,00 MeV
 Date of calibration: 15.04.2014
 Calibration Source: Cs-137 at 662 keV
 Reference Procedure: ANSI N 323A - 1997
 Method of calibration: Four calibration points are checked on every unit.
 A*: Verification of internal background correction 25 nSv/h
 B: Verification of calibration factor 1965 nSv/h
 C*: Verification of deadtime correction 66.300 nSv/h
 D*: Verification of deadtime correction 7.410.000 nSv/h
 *: not included in standard revision
 Place of calibration: Saphymo GmbH Frankfurt/Germany
 Calibration based on:
 · the German national dose-rate standard at Physikalisch
 · Technische Bundesanstalt (PTB) in Braunschweig
 · the British National Radiation Protection Board (NRPB) in
 Didcot, Oxfordshire
 with a total error of less than 6 %.
 These laboratories are cross-linked to all major national
 calibration laboratories such as NIST and DOE/EML with un-
 certainties in the order of 1 %.
 Calibration tolerance: Specified by the factory +/- 6 % (tube 1) and +/- 15 % (tube 1)

Exact calibration levels and results:

	Counter tube 1	Counter tube 2
Target value:	1965 nSv/h	1965 nSv/h
Actual value:	1947 nSv/h	1943 nSv/h
Mean deviation:	-0,92 %	-1,12 %
Calibration factor:	9,74 nSv/(h*cpm)	9,42 nSv/(h*cpm)
Intrinsic effect:	4,80 cpm	5,59 cpm

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 BIC: PBNKDEFF

Appendix- B Photon dose rate at various places using GammaTRACER

Table B-1 Photon dose rates at Deglomeration using GF1159

	nSv/hr
Max Value	1784.23
Min Value	1152.13
Average	1619.88
Uncertainty	36.043

Table B-2 Photon dose rate at Under Little Thicker Using GF1159

	nSv/hr
Max Value	24112
Min Value	84.25
Average	167.27
Uncertainty	29.09

Table B-3 Photon dose rate at Scavenger tail (ST) using GF1142

	nSv/hr
Max Value	11104
Min Value	10464
Average	10714.446
Uncertainty	91.176824

Table B-4 Photon dose rate at Rougher Tail using GF1159

	nSv/hr
Max Value	712.00
Min Value	472.00
Average all values	551.49
Uncertainty	41.37

Table B-5 Photon dose rate between leach tank 3 and 4 using GF1159

	nSv/hr
max value	253.14
min value	97.13
Average	207.42
Uncertainty	20.02

Table B-6 Photon Dose rates at dust scrubber using GF1159

	nSv/hr
max value	286.29
min value	88.51
Average	118.77
Uncertainty	11.69

Table B-7 Photon dose rates at Stock tank 7 using GF1142

	nSv/hr
max value	412.33
Min Value	119.52
average	346.16
Uncertainty	40.21

Table B-8 Photon dose rates at Regrinding # 1 using GF1142

	nSv/hr
max value	512
Min Value	400
average	452.48
Uncertainty	18.34

Table B-9 Photon dose rates at Pyrite Rougher Concentration using GF1142

	nSv/hr
Max	420.13
Min	90.37
Avg	224.61
Uncertainty	55.89

Table B-10 Photon dose rates at End of Lab. Outside of Lab using GF1159

	nSv/hr
Max	203.5
Min	103.75
Avg	157.788
Uncertainty	13.63

Table B-11 Re-count of photon dose rates at Pyrite Rougher Concentration by GF1142

	nSv/hr
Max	338.24
Min	124.75
Avg	263.615
Uncertainty	27.92

Table B-12 Re-count of photon dose rates at Pyrite Rougher Concentration by GF1159

	nSv/hr
Max	324
Min	116.5
Avg	250.71
Uncertainty	28.79

Table B-13 Photon dose rates at various places

	nSv/hr	nSv/hr	nSv/hr
	GF1142 High Altitude	GF1159 High Altitude	Pocatello BKG
Max	3160.00	3096.00	143.50
Min	2224.00	2208.00	86.25
Average	2776.24	2750.52	8.258

Table B-14 Photon dose rates at Frankfurt Germany

Location	nSv/hr	nSv/hr
Germany	GF1159	GF1142
MAX	130.00	102.31
MIN	65.00	75.33
AVG	98.00	62.26

Appendix- C-1 FDA certificate used as a Quality Assurance



1380 Seaboard Industrial Blvd.
Atlanta, Georgia 30318
Tel: 404-352-2877
Fax: 404-352-2837
www.ezanalytic.com

CERTIFICATE OF CALIBRATION
Standard Radionuclide Source

98433

5 mL Liquid in Flame Sealed Vial

Customer: US FDA / WEAC
P.O. No.: FURMAN22AUG14/VS, Item 1 Product Code: 8401
Reference Date: 01-Jul-2014 12:00 PM EST Grams of Master Source: 0.064508

This standard radionuclide source was prepared using aliquots measured gravimetrically from master radionuclide solutions. Additional radionuclides were added gravimetrically from solutions calibrated by gamma-ray spectrometry, ionization chamber, or liquid scintillation counting. Calibration and purity were checked using a germanium gamma spectrometer system. At the time of calibration no interfering gamma-ray emitting impurities were detected. The gamma-ray emission rates for the most intense gamma-ray lines are given. Eckert & Ziegler Analytics (EZA) maintains traceability to the National Institute of Standards and Technology through a Measurements Assurance Program as described in USNRC Regulatory Guide 4.13, Revision 2, July 2007, and compliance with ANSI N42.22-1995, "Traceability of Radioactive Sources to NIST." EZA is accredited by the Health Physics Society (HPS) for the production of NIST-traceable sources, and this source was produced in accordance with the HPS accreditation requirements. Customers may report any concerns with the accreditation program to the HPS Secretariat, 1313 Dolley Madison Blvd., Ste. 402, McLean, VA 22101.

Nuclide	Gamma-Ray Energy (keV)	Half-Life, Days	Master	This Source	Uncertainty*, %			Calibration Method*
			Source* yps/gram		Type	u _A	u _B	
- Am-241	59.8	1.580E+05	—	6.648E+03	0.1	1.0	2.0	4π LS
Cd-109	88.0	4.614E+02	1.492E+05	9.626E+03	0.5	1.3	2.8	HPGe
Co-57	122.1	2.717E+02	8.097E+04	5.223E+03	0.4	0.7	1.6	HPGe
Ce-139	165.9	1.376E+02	1.148E+05	7.407E+03	0.4	0.9	2.0	HPGe
Hg-203	279.2	4.659E+01	2.749E+05	1.774E+04	0.3	0.8	1.7	HPGe
Sn-113	391.7	1.151E+02	1.589E+05	1.025E+04	0.4	1.2	2.5	HPGe
Cs-137	661.7	1.099E+04	1.023E+05	6.598E+03	0.7	1.2	2.8	HPGe
Y-88	898.0	1.066E+02	3.843E+05	2.479E+04	0.5	0.8	1.9	HPGe
Co-60	1173.2	1.925E+03	1.923E+05	1.240E+04	0.6	0.9	2.2	HPGe
Co-60	1332.5	1.925E+03	1.925E+05	1.242E+04	0.7	1.0	2.4	HPGe
Y-88	1836.1	1.066E+02	4.068E+05	2.624E+04	0.7	0.8	2.1	HPGe

* Master Source refers to Analytics' 8-isotope mixture which is calibrated quarterly.

Calibration Methods: 4π LS - 4 π Liquid Scintillation Counting, HPGe - High Purity Germanium Gamma-Ray Spectrometer, IC - Ionization Chamber. Uncertainty: U - Relative expanded uncertainty, k = 2. See NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results."

(Certificate continued on reverse side)

MGS Certificate Rev 6, 22 May 2014

Corporate Office
24937 Avenue Tibbitts Valencia, California 91355



Page 1 of 2

Laboratory
1380 Seaboard Industrial Blvd. Atlanta, Georgia, 30318

Figure C.1 FDA certificate given by Eckert & Ziegler

Appendix D various graphs for empirical Vs software efficiency

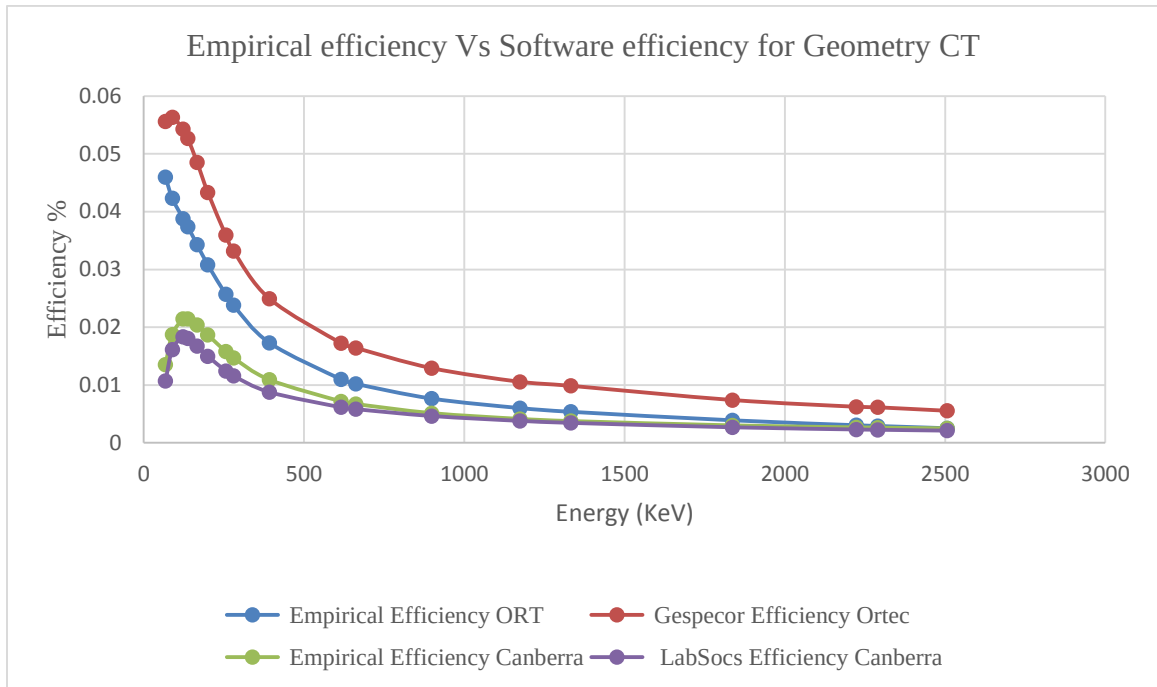


Figure D.1 Empirical Vs Software efficiency for the geometry CT

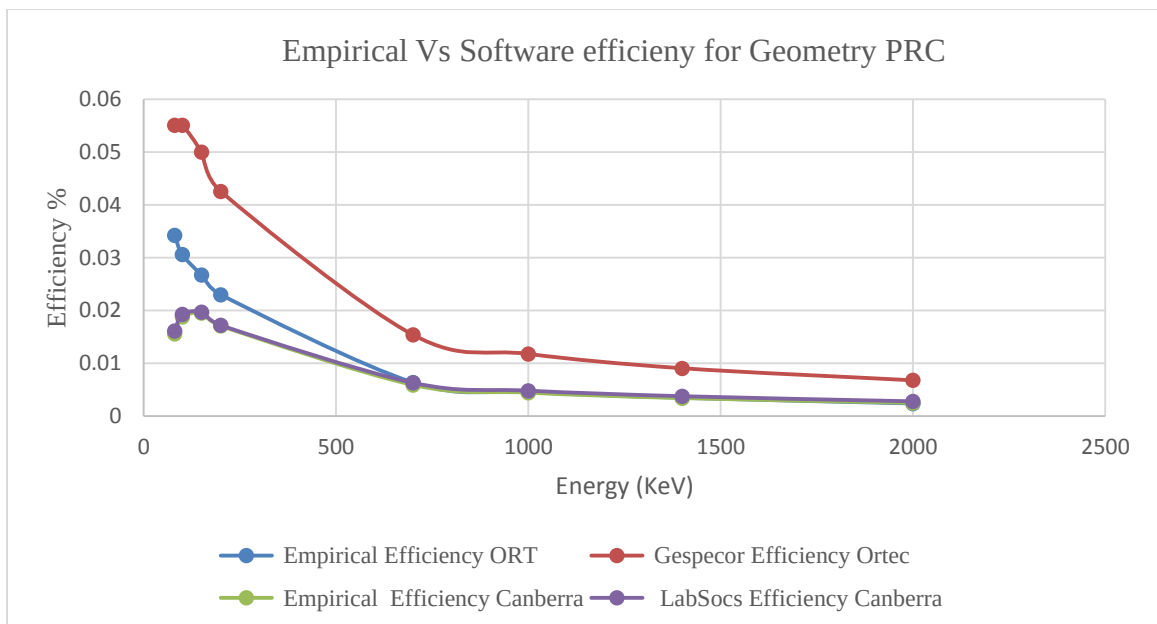


Figure D.2 Empirical Vs Software efficiency for the Geometry PRC

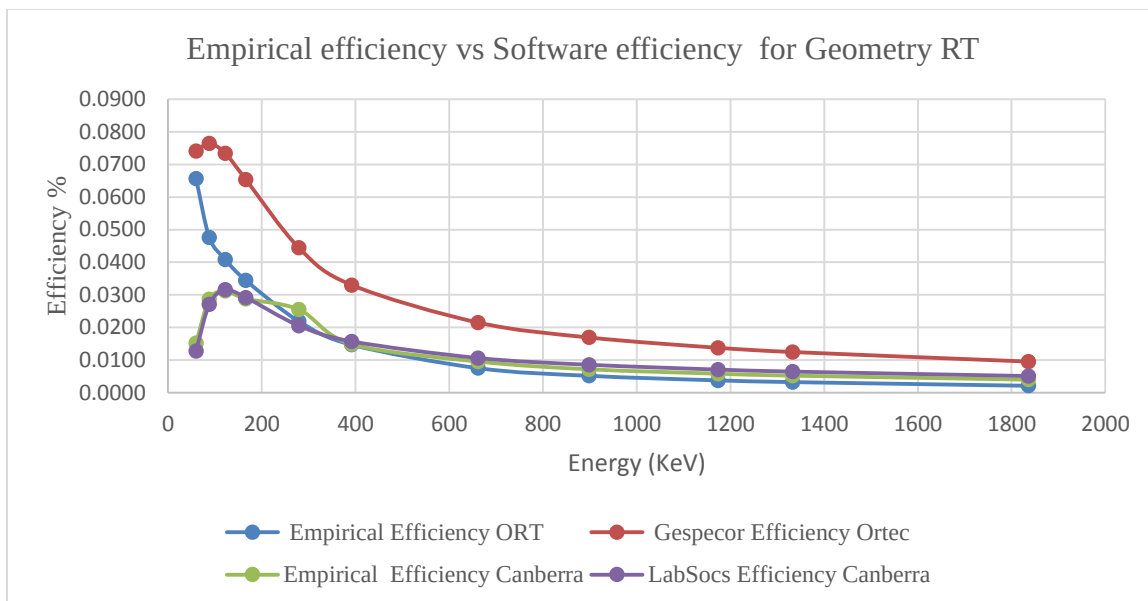


Figure D.3 Empirical Vs Software efficiency for the geometry RT

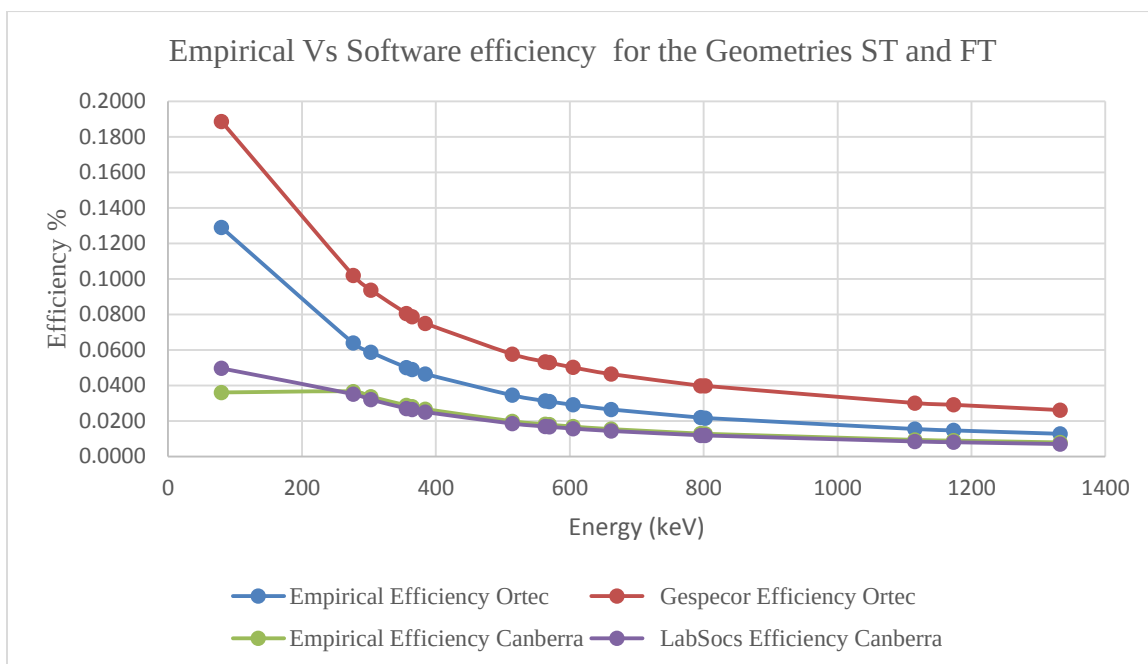


Figure D.4 Empirical Vs Software efficiency for the geometries ST and FT

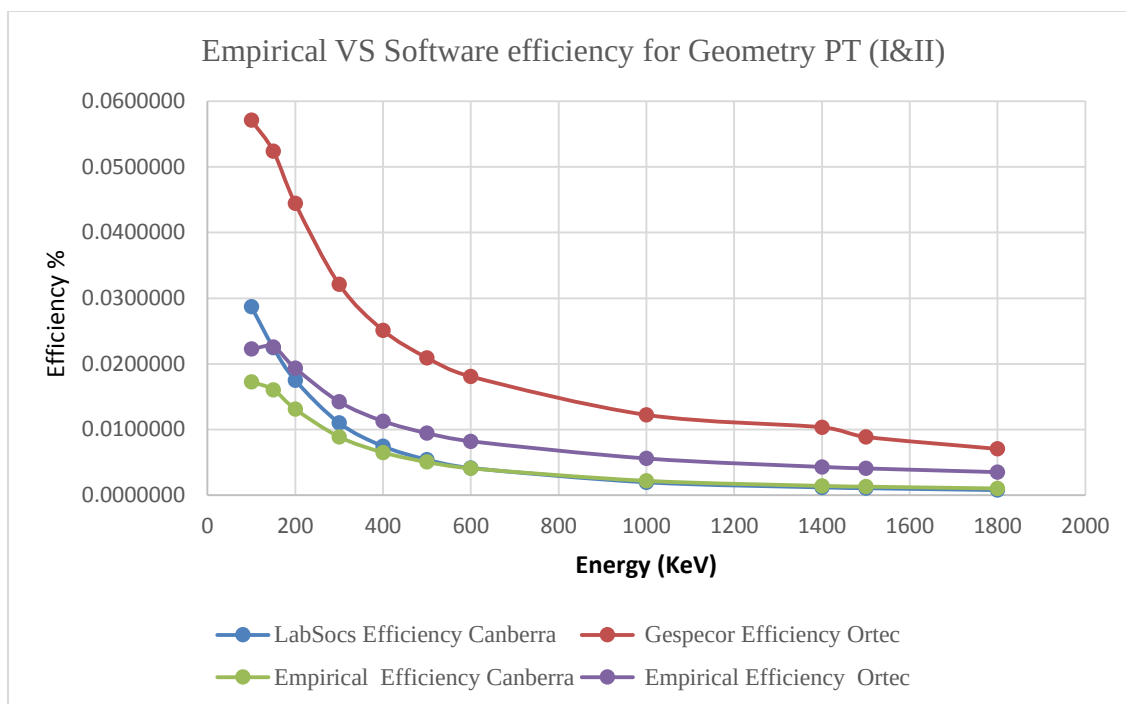


Figure D.5 Empirical Vs Software efficiency for the Geometry PT (I & II)

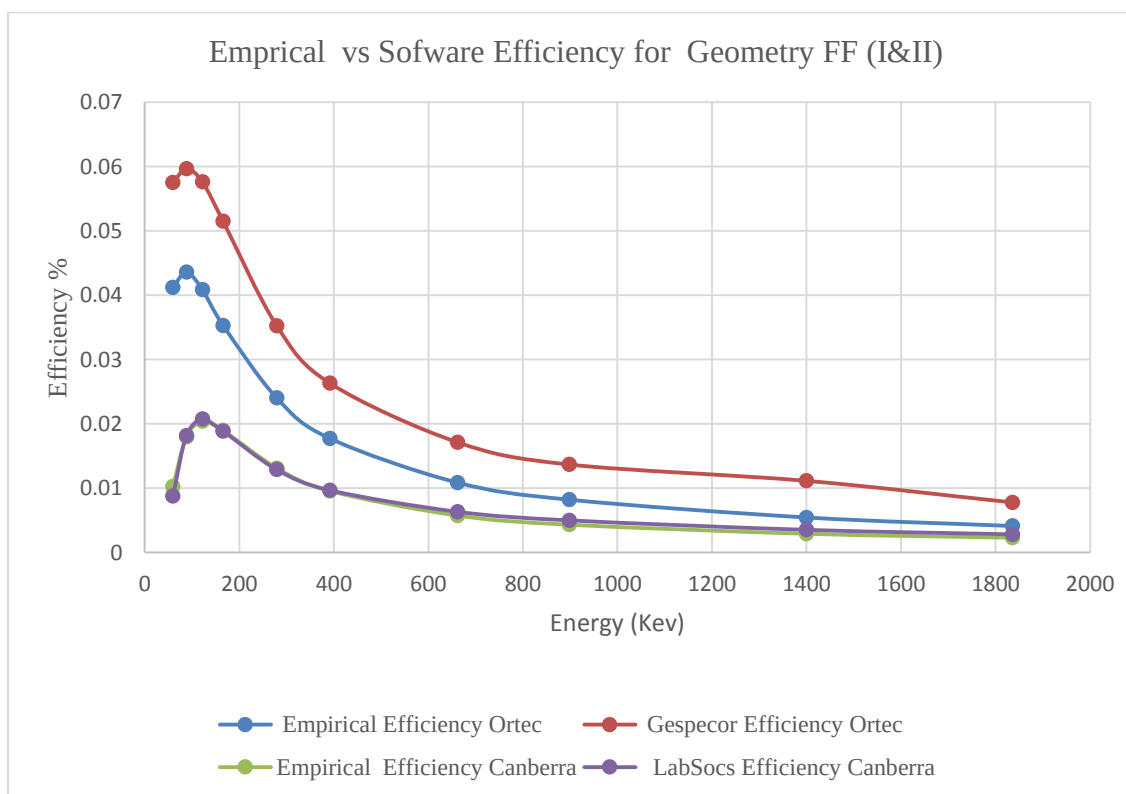


Figure D.5 Empirical Vs Software efficiency for the geometry FF (I & I)

Appendix: E Identified nuclides with activity for first and second count for Ortec and Canberra (1 sigma represents uncertainty)

Table E.1 Radionuclides found in sample CT in four different counts

FIRST COUNT (ORT)			SECOND COUNT (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.18E+00	2.57E-02	K-40	1.10E+00	2.39E-02
PB-212	2.68E-02	6.19E-04	PB-212	2.45E-02	5.65E-04
BI-214	6.91E-02	1.34E-02	BI-214	6.01E-02	1.16E-03
Pb-214	6.92E-02	9.74E-04	PB-214	6.27E-02	8.87E-04
TL-208	9.42E-03	8.26E-03	TL-208	9.07E-03	8.16E-03

FIRST COUNT (CAN)			SECOND COUNT (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.05E+00	2.24E-02	K-40	1.04E+00	4.40E-02
PB-212	2.59E-02	8.70E-04	PB-212	2.52E-02	1.87E-03
BI-214	6.87E-02	1.17E-03	BI-214	6.30E-02	1.66E-03
PB-214	6.67E-02	1.02E-03	PB-214	6.98E-02	3.00E-03
TL-208	8.69E-03	2.10E-03	TL-208	8.70E-03	9.62E-03

Table E.2 Radionuclides found in sample PT-I in four different counts

First Count (ORT)			Second Count (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	9.89E-01	2.20E-02	K-40	1.03E+00	2.28E-02
Pb-212	1.75E-02	5.44E-04	Pb-212	2.03E-02	4.87E-04
Bi-214	4.19E-02	8.88E-04	Bi-214	4.44E-02	9.53E-04
Pb-214	4.02E-02	7.35E-04	Pb-214	4.32E-02	6.86E-04
Tl-208	8.53E-03	8.14E-04	Tl-208	7.67E-03	7.02E-04

First Count (CAN)			Second Count (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	9.82E-01	2.14E-02	K-40	9.65E-01	2.11E-02
Pb-212	1.88E-02	5.04E-04	Pb-212	2.17E-02	7.74E-04
Bi-214	4.42E-02	8.55E-04	Bi-214	4.37E-02	8.36E-04
Pb-214	4.42E-02	8.55E-04	Pb-214	4.50E-02	8.18E-04
Tl-208	7.80E-03	9.07E-04	Tl-208	7.50E-03	7.59E-04

Table E.3 Radionuclides found in sample PRC in four different counts (1 sigma represents uncertainty)

First Count (ORT)			Second Count (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	9.62E-01	2.22E-02	K-40	1.00E+00	2.29E-02
Pb-212	4.59E-02	4.59E-02	Pb-212	3.52E-02	8.71E-04
Bi-214	2.05E-01	2.65E-03	Bi-214	2.18E-01	2.78E-03
Pb-214	1.95E-01	3.80E-03	Pb-214	1.67E-01	2.05E-03
Tl-208	1.79E-02	1.48E-03	Tl-208	1.58E-02	1.28E-03

First Count (CAN)			Second Count (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	8.10E-01	2.02E-03	K-40	9.19E-01	2.09E-02
Pb-212	4.27E-02	3.60E-03	Pb-212	4.60E-02	1.43E-03
Bi-214	2.11E-01	2.57E-03	Bi-214	2.01E-01	4.89E-03
Pb-214	2.03E-01	2.69E-03	Pb-214	2.15E-01	2.81E-03
Tl-208	1.53E-02	1.26E-03	Tl-208	1.58E-02	1.39E-03

Table E.4 Radionuclides found in sample PT-II in four different counts

First Count (ORT)			Second Count (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.07E+00	2.39E-02	K-40	1.13E+00	2.50E-02
Pb-212	1.89E-02	5.88E-04	Pb-212	2.31E-02	5.75E-04
Bi-214	4.45E-02	9.61E-04	Bi-214	4.87E-02	1.00E-03
Pb-214	4.35E-02	7.96E-04	Pb-214	4.86E-02	7.80E-04
Tl-208	9.37E-03	8.81E-04	Tl-208	9.23E-03	8.53E-04

First Count (CAN)			Second Count (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.06E+00	2.30E-02	K-40	1.08E+00	2.34E-02
Pb-212	2.32E-02	9.10E-04	Pb-212	2.21E-02	7.19E-04
Bi-214	4.80E-02	9.19E-04	Bi-214	5.06E-02	9.70E-04
Pb-214	4.73E-02	8.88E-04	Pb-214	4.94E-02	8.54E-04
Tl-208	8.28E-03	8.72E-04	Tl-208	8.12E-03	8.70E-04

Table E.5 Radionuclides found in sample FF-I in four different counts (1sigma refers to Uncertainty)

First Count (ORT)			Second Count (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.03E+00	2.30E-02	K-40	1.09E+00	2.41E-02
Pb-212	3.12E-02	9.70E-04	Pb-212	2.23E-02	5.63E-04
Bi-214	4.09E-02	9.34E-04	Bi-214	4.30E-02	8.60E-04
Pb-214	3.98E-02	1.17E-03	Pb-214	4.35E-02	1.17E-04
Tl-208	7.61E-03	8.70E-04	Tl-208	7.50E-03	8.28E-03

First Count (CAN)			Second Count (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	9.56E-01	2.09E-02	K-40	1.03E+00	2.24E-02
Pb-212	2.20E-02	5.58E-04	Pb-212	2.38E-02	8.12E-04
Bi-214	4.07E-02	8.18E-04	Bi-214	4.33E-02	8.47E-04
Pb-214	4.08E-02	7.02E-02	Pb-214	4.36E-02	7.99E-04
Tl-208	8.08E-03	2.05E-04	Tl-208	8.69E-03	1.80E-04

Table E.6 Radionuclides found in sample FF-II in four different counts

First Count (ORT)			Second Count (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.12E+00	2.49E-02	K-40	1.09E+00	2.41E-02
Pb-212	2.38E-02	5.75E-04	Pb-212	2.23E-02	5.63E-04
Bi-214	3.78E-02	8.95E-04	Bi-214	4.30E-02	8.60E-04
Pb-214	4.04E-02	6.87E-04	Pb-214	4.25E-02	7.12E-04
Tl-208	9.38E-03	7.45E-02	Tl-208	9.80E-03	7.50E-02

First Count (CAN)			Second Count (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.05E+00	2.27E-02	K-40	1.05E+00	2.27E-02
Pb-212	2.39E-02	5.79E-04	Pb-212	2.38E-02	5.84E-04
Bi-214	4.12E-02	8.27E-04	Bi-214	4.04E-02	8.25E-04
Pb-214	3.99E-02	6.99E-04	Pb-214	3.81E-02	6.99E-04
Tl-208	8.60E-03	2.20E+00	Tl-208	8.50E-03	9.22E-01

Table E.7 Radionuclides found in sample RT in four different counts

First Count (ORT)			Second Count (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	9.58E-01	2.09E-02	K-40	9.78E-01	2.13E-02
Pb-212	1.92E-02	4.60E-04	Pb-212	1.41E-02	4.45E-04
Bi-214	7.13E-02	1.20E-03	Bi-214	7.13E-02	1.22E-03
Pb-214	6.71E-02	8.92E-04	Pb-214	5.57E-02	8.44E-04
Tl-208	7.96E-03	6.81E-03	Tl-208	7.55E-03	6.81E-03

First Count (CAN)			Second Count (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	8.84E-01	1.85E-02	K-40	9.07E-01	1.89E-02
Pb-212	1.99E-02	6.22E-04	Pb-212	2.03E-02	6.57E-04
Bi-214	6.86E-02	1.02E-03	Bi-214	6.97E-02	1.14E-03
Pb-214	6.55E-02	8.30E-04	Pb-214	6.55E-02	8.22E-04
Tl-208	7.48E-03	6.98E-03	Tl-208	5.86E-03	8.22E-03

Table E.8 Radionuclides found in sample ST in four different counts

First Count (ORT)			Second Count (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.11E+00	3.62E-02	K-40	1.16E+00	3.70E-02
Pb-212	3.86E-02	1.48E-03	Pb-212	4.64E-02	1.53E-03
Bi-214	2.94E-01	5.76E-03	Bi-214	2.90E-01	5.80E-03
Pb-214	2.66E-01	4.21E-03	Pb-214	3.06E-01	4.53E-03
Tl-208	1.04E-01	2.58E-01	Tl-208	1.03E-01	2.38E-01

First Count (CAN)			Second Count (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.15E+00	4.02E-02	K-40	1.20E+00	3.86E-02
Pb-212	5.40E-02	2.88E-03	Pb-212	4.62E-02	2.91E-03
Bi-214	3.41E-01	6.04E-03	Bi-214	3.37E-01	6.00E-03
Pb-214	3.66E-01	5.88E-03	Pb-214	3.29E-01	5.65E-03
Tl-208	1.06E-01	3.26E-01	Tl-208	1.05E-01	3.26E-01

Table E.9 Radionuclides found in sample FT in four different counts

First Count (ORT)			Second Count (ORT)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.13E+00	3.16E-02	K-40	1.10E+00	3.12E-02
Pb-212	2.48E-02	8.55E-04	Pb-212	2.55E-02	8.52E-04
Bi-214	5.25E-02	1.90E-03	Bi-214	4.66E-02	1.53E-03
Pb-214	5.22E-02	1.22E-03	Pb-214	5.17E-02	1.21E-03
Tl-208	9.07E-03	3.12E-04	Tl-208	8.39E-03	1.60E-04

First Count (CAN)			Second Count (CAN)		
Radionuclide	Activity (Bq/g)	1 Sigma	Radionuclide	Activity (Bq/g)	1 Sigma
K-40	1.11E+00	3.33E-02	K-40	1.12E+00	3.36E-02
Pb-212	3.11E-02	1.85E-03	Pb-212	3.37E-02	1.17E-03
Bi-214	5.73E-02	2.00E-03	Bi-214	5.46E-02	2.05E-03
Pb-214	5.60E-02	1.67E-03	Pb-214	6.22E-02	1.56E-03
Tl-208	1.08E-02	9.90E-04	Tl-208	1.10E-02	9.90E-04

Appendix F: Empirical efficiencies at various heights

Energy (keV)	CT	PRC	RT	ST & FT	PT-I & PT-II	FF-I&FF- II
80	0.0170	0.0156	0.0242	0.0364	0.0150	0.0164
100	0.0202	0.0188	0.0299	0.0479	0.0173	0.0195
150	0.0211	0.0195	0.0305	0.0534	0.0161	0.0197
200	0.0187	0.0171	0.0262	0.0472	0.0131	0.0171
700	0.0064	0.0059	0.0102	0.0146	0.0034	0.0055
1000	0.047	0.0044	0.0080	0.0104	0.0022	0.0039
1400	0.036	0.0034	0.0063	0.0076	0.0014	0.0029
2000	0.0029	0.0025	0.0048	0.0054	0.0009	0.0021
2614	0.0024	0.0019	0.0039	0.0041	0.0007	0.0017

Appendix G: Calculations Photon Dose Rates

	CAN 1ST Count	CAN 2nd count	ORT 1st Count	ORT 2nd Count	Average
Sample ID:	nSv/hr*kg	nSv/hr*kg	nSv/hr*kg	nSv/hr*kg	nSv/hr*kg
ST	1.65E-01	1.69E-01	1.69E-01	1.84E-01	1.72E-01
PT-I	3.97E-02	4.17E-02	4.17E-02	4.02E-02	4.08E-02
PT-II	4.32E-02	4.62E-02	4.62E-02	4.50E-02	4.52E-02
PRC	9.64E-02	9.60E-02	9.60E-02	9.53E-02	9.59E-02
FF-I	4.13E-02	4.27E-02	4.27E-02	4.21E-02	4.22E-02
FF-II	4.29E-02	4.37E-02	4.37E-02	4.14E-02	4.29E-02
RT	4.83E-02	4.72E-02	4.72E-02	4.48E-02	4.68E-02
CT	5.41E-02	4.97E-02	4.97E-02	4.84E-02	5.05E-02
FT	4.77E-02	4.51E-02	4.51E-02	5.01E-02	4.70E-02

Appendix H

Table H-1 Description of recommended GammaTracer



Saphymo GmbH, Heerstraße 149, D-60488 Frankfurt
UST-IdNr.: DE-114 155 316 - Steuer Nr.: 047 243 15000

Idaho State University, ISU
Kishor Paudel, Graduate Student
785 S. Eighth Ave.
Postfach Campus Box 8106
83208 Pocatello, ID
USA

OFFER		
No.	Date	Page
AB150406	12.06.2015	1/4
Customer no.		VAT no.
Your contact		E-mail
Ingeborg Hohe-Dorst		ihohe-dorst@saphymo.de
Delivery to		End-user
		Overviewthesis Kishor Paudel - Ray Dunker
Dispatch		Incoterms

Further to your request from June 10, 2015, we are pleased to provide you our offer no. AB150406.

Pos.	Pcs.	Ref.	Description	Price/unit	Amount
1	1,0	P0000194	GammaTRACER Basic Battery powered dose rate measuring device with internal data logger for autonomous operation (typically 5 years). Adjustable measuring cycle time (1, 2, 5, 10, 15, 30, 60, 120 min), storage capacity 12.800 measurement values, i.e. 10 days at 1-min-measuring rate, respectively 3 years at 120-min-measuring rate. Simultaneous recording of the device temperature (via integrated temperature sensor) as well as many quality parameters, automatically cycle switch at free defined dose rate thresholds. Hermetically sealed housing. Measurement unit: Ambient dose equivalent rate (H*(10)) Measuring range: 20 nSwh up to 10 mSwh (two independent dose rate channels) operating temperature range: -20°C ... +50°C dimensions: (l x Ø): 660 mm x 60mm weight: approx. 1.000 g. Warranty: 36 months For detailed technical information see the comprehensive GammaTRACER brochure	2.929,00	2.929,00
Options:					
2	0,0	P0000203	Temperature extension for GammaTRACER Extension of the operating temperature range from standard	398,00	0,00

Saphymo GmbH
Tel.: +49-(0)69-97 65 14-0
Geschäftsführer
Laurent Schneider-Maunoury
HRB 22722 Frankfurt a. M.

Heerstraße 149
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Commerzbank AG
IBAN: DE69 5008 0000 0240 1770 00
BIC: DRESDEFF

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BIC: FFVBDEFF

Germany
sales@saphymo.de
Postbank Frankfurt
IBAN: DE93 5001 0060 0998 8236 09
BIC: PBNKDEFF

Appendix I

Calculations of Total Photon dose rate from basic Principal

Assumptions Made:

Point source was assumed at 1m distance.

Linear Absorption Coefficients of air (μ) = 3.5×10^{-3} per meter (Cember 1996. Page - 186)

Density of air at sea level and at 15 degree Celsius (ρ) = 1.204 kg/m^3

$$\text{Gammas/sec } (\gamma/s) = \frac{\text{Net Counts per sec}}{\text{Efficiency @ specific energy}}$$

For photon $1\text{Gy} = 1\text{Sv}$

For air, $\frac{\mu_{en}}{\rho} = 0.02906 \text{ cm}^2/\text{g}$ which is mostly valid within the range of 60 keV to 2 MeV (Cember 1996)

$$\frac{n\text{Sv}}{hr} = \frac{\frac{\gamma}{s} * \text{Energy(KeV)} * \mu_{en} / \rho}{\text{Area } (4\pi r^2)}$$

$$= \frac{\frac{\gamma}{s} * E(\text{KeV}) * 0.02906 \frac{\text{cm}^2}{\text{g}} * 1.6 * 10^{-16} \frac{\text{J}}{\text{keV}} * 10^3 \frac{\text{g}}{\text{kg}} * \frac{1\text{J}}{1\text{kg}} * \frac{1\text{Sv}}{1\text{Gy}} * 10^9 \frac{n\text{Sv}}{\text{Sv}} * \frac{3600\text{s}}{hr}}{4\pi (100\text{cm})^2}$$

Photon dose rates from specific energy per kg:

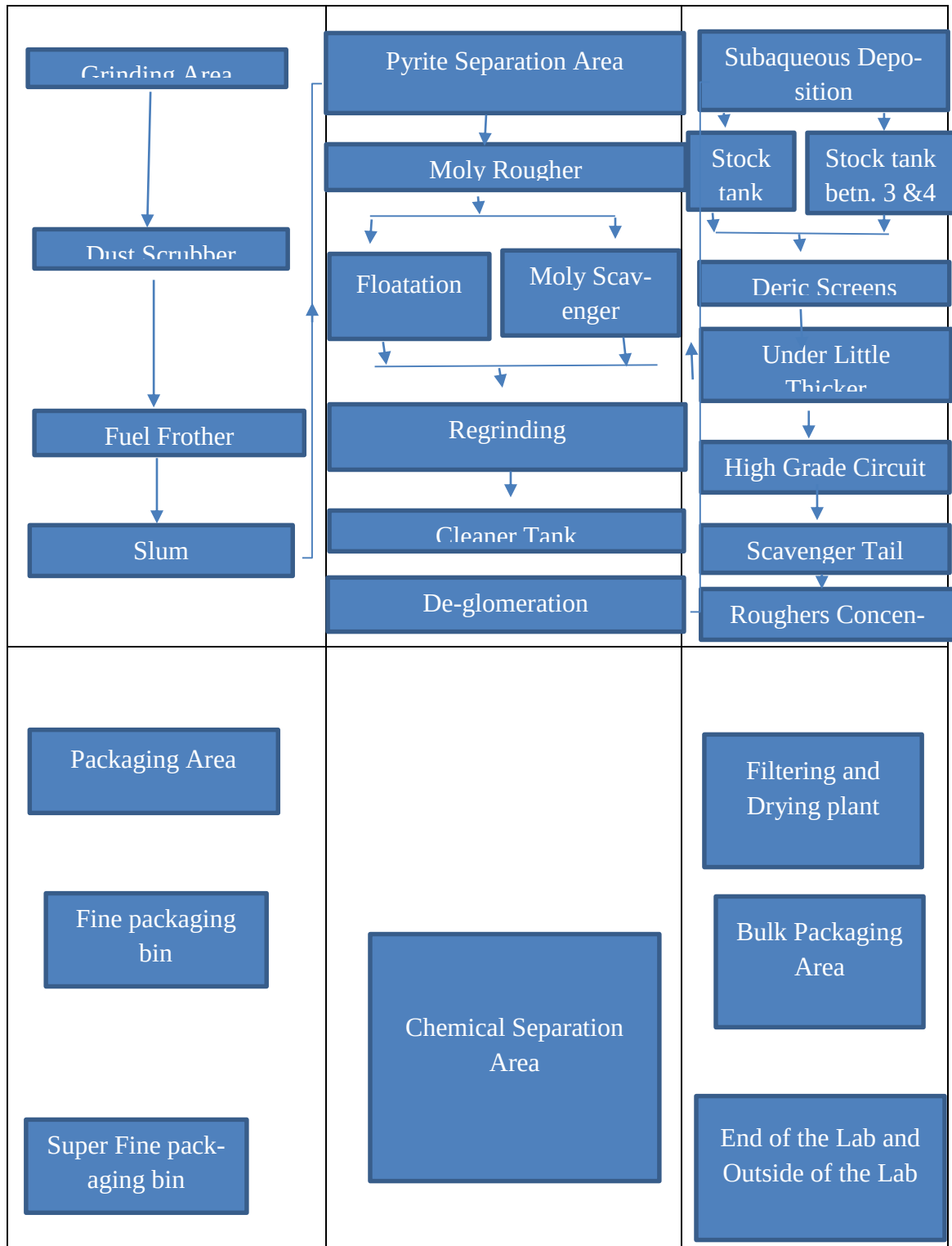
$$\left(\frac{n\text{Sv}}{hr} \right) = \frac{\gamma}{s} * E(\text{KeV}) * 1.33 * 10^{-7}$$

$$\text{Total photon dose rates } \left(\frac{n\text{Sv}}{hr} \right) = 1.33 * 10^{-7} \sum \left(\frac{\gamma}{s} \right) * \text{Energy(KeV)}$$

Appendix J various locations with corresponding activity where ore samples were collected at Thompson Creek Mining Company

1. FF=flotation feed-this is the feed to the plant. Ground ore that is floated in the Roughers.
2. RT=rougher tail-this is the tail from the initial float in the plant.
3. ST-Scavenger tail- this is the tail from flotation of the rougher concentrate.
4. CT-combined tail- this is the combination of RT and ST
5. FT feeds the pyrite plant
6. PRC-pyrite rougher concentrate-this is the concentrate from the pyrite plant.
7. PT-plant tail- this is the tail from the pyrite plant.

Appendix K: Flowchart of GammaTRacer locations inside the Thompson Creek Mining Company facility



** This flowchart is not official. This is a rough sketch of places where GammaTRACERs were located for the study. For official flowchart, refer to Figure 1.1.

