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**«НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ»**

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Направление подготовки 14.04.02 Ядерные физика и технологии
Отделение школы Отделение ядерного-топливного цикла

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

Тема работы
Эффективность регистрации фотонов спектрометром на основе полупроводникового детектора

УДК 539.122.16:539.1.074:681.777

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Томск – 2018 г.

Ministry of Education and Science of the Russian Federation
Federal Independent Educational Institution
"NATIONAL RESEARCH TOMSK POLYTECHNIC UNIVERSITY"

School of Nuclear Science & Engineering
(Specialty) 14.04.02. Nuclear Physics and Technology
Division for Nuclear Fuel Cycle

MASTER'S THESIS

Topic of the work
The Efficiency of Photon Registration by a Spectrometer Based on a Semiconductor Detector

UDC 539.122.16:539.1.074:681.777

Student

Group	Full name	Signature	Date
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ADVISORS:

Section "Financial Management, Resource Efficiency and Resource Saving"

Position	Full name	Academic degree, academic rank	Signature	Date
Associate Professor	Timur R. Rakhimov	Ph.D. Economics		

Section "Social Responsibility"

Position	Full name	Academic degree, academic rank	Signature	Date
Senior Lecturer	Verigin Dan	Ph.D.		

ADMIT TO DEFENSE:

Program Director	Full name	Academic degree, academic rank	Signature	Date
Nuclear Power Operations and Installations	Verkhoturova V.V.	Ph.D.		

Tomsk – 2018г

Expected learning outcomes of the Basic Educational Program (Master's Degree Program)

Learning outcome code	Learning outcomes (the graduate must be ready)
Professional competencies	
LO_1	To apply deep mathematical, natural scientific, socio-economic and professional knowledge for theoretical and experimental research in the field of the nuclear science and technology use
LO_2	To define, formulate and solve interdisciplinary engineering problems in the nuclear field using professional knowledge and modern research methods
LO_3	To plan and carry out analytical, simulation and experimental studies in complex and uncertain conditions using modern technologies; to critically evaluate the results
LO_4	To use the basic and special approaches, skills and methods for identification, analysis and solution of technical problems in nuclear science and technology
LO_5	To operate modern physical equipment and instruments to produce new materials, instruments, installations and systems
LO_6	To develop multivariate schemes for achieving the production goals, with the effective use of available technical means
Cultural competencies	
LO_7	To use the creative approach to develop new ideas and methods for designing nuclear facilities, as well as to modernize and improve the applied technologies of nuclear production
Core professional competencies	
LO_8	To study independently and to raise qualification continuously during all period of professional work.
LO_9	To know a foreign language at a level allowing to work in a foreign language environment, develop documentation, present the results of professional activity.
LO_{10}	To demonstrate independent thinking, to function effectively in command-oriented tasks and to have a high level of productivity in the professional (sectoral), ethical and social environments; to lead the team, form assignments, assign responsibilities and bear responsibility for the results of work.

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School of Nuclear Science & Engineering
Direction of Training 14.04.02. Nuclear Physics and Technology
Division for Nuclear Fuel Cycle

APPROVED BY:
Program Director

12.03.2018 Verkhoturova V.V.
(Signature) (Date) (Full name)

ASSIGNMENT
for the Master's Thesis completion

In the form:

Master's Thesis

Student:

Group	Full name
0АМ6И	Agyekum Ephraim Bonah

Topic of the work:

The Efficiency of Photon Registration by a Spectrometer Based on a Semiconductor Detector	
Approved by the order of the Director (date, number)	19.03.2018, №1882/c

Deadline for Completion of the Master's Thesis:	04.06.2018 г.

TERMS OF REFERENCE:

Initial data for work	Semiconductor detector based on a germanium detector, standard isotope source of cobalt-60, cesium-137, software Genie-2000 and LabSOCs, recommended literature.
List of the issues to be investigated, designed and developed	Statement of the purpose of the work, being developed the scope of the problem, its scientific, technical and practical significance. Searching methods for carrying out the experiment, the development of the research program and their implementation, the analysis of the results obtained
List of graphic material	Detector shielding drawing
Advisors on the chapters of the Master's Thesis	

Chapter	Advisor
Financial management, resource efficiency and resource conservation	Timur R. Rakhimov
Social responsibility	Verigin Dan

The names of sections that must be written in foreign languages: all work is done in English

Date of issuance of the assignment for Master's Thesis completion according to a line schedule	12.03.2018

The task was issued by the supervisor:

Position	Full name	Academic degree, academic status	Signature	Date
Senior Lecturer	Mikhail S. Kuznetsov	Ph.D.		12.03.2018

The assignment was accepted for execution by the student:

Group	Full name	Signature	Date
0AM6И	Agyekum Ephraim Bonah		12.03.2018

TASK FOR MASTER'S THESIS SECTION "FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE CONSERVATION"

Student:

Group	Name
0AM6И	Agyekum Ephraim Bonah

Institute	Nuclear Science and Engineering	**Department of**	Nuclear Fuel Cycle
Education Level	Master	**Direction / Specialty**	Nuclear Power Installations and Operation

References for "Financial management, resource efficiency and resource conservation":	
1. The cost of research: Logistics, energy, financial, information and human	*According to manual provided*
2. Norms and standards resource consumption	*According to manual provided*
3. used the tax system, tax rates, deductions, discounting and credit	*According to manual provided*
The list of questions for study, design and development:	
1. Evaluation of commercial and innovative potential STI	1. Potential consumers of research results 2. Analysis of competitive technical solutions from the perspective of resource efficiency and resource savings 3. SWOT-analysis **Perform** • Evaluation of the project readiness for commercialization • Methods for the commercialization of scientific and technological research
2. Development of the charter of scientific and technical project	• Objectives and outcomes of the project. • The organizational structure of the project. • Identification of possible alternatives
3. Project management planning: the structure and schedule of the budget, risk and procurement organization	• The structure of the work within the framework of scientific research • Determination of the complexity of work • Scheduling scientific research • The budget of the scientific and technical research (STR)
4. Defining resource, financial, economic efficiency	• Integral financial efficiency indicator • Integral resource-efficiency indicator • Integral total efficiency indicator • Comparative project efficiency indicator
List of graphic material	
1. *Segmentation of the market* 2. *Estimation of competitiveness of technical solutions* 3. *SWOT Matrix* 4. *Schedule and budget of the project* 5. *Assessment resource, financial and economic efficiency of the project*	

Date of issue of assignment	

Assignment given by consultant:

Position	Name	Degree	Signature	Date
Associate Professor	Timur R. Rakhimov	PhD		

Assignment received by student for implementation:

Group	Name	Signature	Date
0AM6И	Agyekum Ephraim Bonah		

TASK FOR SECTION
"SOCIAL RESPONSIBILITY"

To the student:

Group	Full name
0АМ6И	Agyekum Ephraim Bonah

School	Nuclear Science and Engineering	**Department**	Nuclear Fuel Cycle
Degree	Master	**Specialization**	Nuclear Power Installations and Operations

Input data to the "social responsibility":	
1. Describe workplace (work area) for occurrence of	– Harmful factors of the environment (microclimate, illumination, noise, vibration, electromagnetic fields, ionizing radiation); – dangerous factors of environment factors (electrical, fire and explosive nature).
2. Acquaintance and selection of legislative and normative documents on the topic	– electrical safety; – fire and explosion safety; – labor protection requirements when working on a PC. – radiation safety
The list of subjects to study, design and develop:	
1. Analysis of the identified harmful factors of the environment in the following sequence:	– The effect of the factor on the human body; – Reduction of permissible standards with the required dimensionality (with reference to the relevant normative and technical document); – Proposed remedies (collective and individual).
2. Analysis of identified hazards of the environment:	– Electrical safety (including static electricity, protective equipment); – fire and explosion safety (causes, preventive measures, primary fire extinguishing agents).

Date of issue of the task for the section according to the schedule	

Task issued by consultant:

Position	Full name	Scientific degree, rank	Signature	date
Senior Lecturer	Verigin Dan	PhD		

The task was accepted by the student:

Group	Full name	Signature	date
0АМ6И	Agyekum Ephraim Bonah		

Ministry of Education and Science of the Russian Federation
Federal Independent Educational Institution
«NATIONAL RESEARCH TOMSK POLYTECHNIC UNIVERSITY»

School of Nuclear Science & Engineering
Direction of training 14.04.02. Nuclear Physics and Technology
Division for Nuclear Fuel Cycle
Period of completion (fall/spring semester 2017 /2018)

Form of presenting the work:

Master's Thesis

SCHEDULED COURSE ASSESSMENT CALENDAR

for the Master's Thesis completion

Deadline for completion of the Master's Thesis:	04.06.2018

Assessment date	**Title of section (module) / type of work (research)**	**Maximum score of the section (module)**
04.06.2018	Literature Review	
04.06.2018	Methodology	
04.06.2018	Financial Management, Resource Efficiency and Resource Conservation	
04.06.2018	Social Responsibility	

Made by professor:

Position	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
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AGREED:

Program Director	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
Nuclear Power Installations Operations	Vera V. Verkhoturova	PhD		

Abstract

Key words: Engineering, efficiency, model, radiation, contamination, photon, gamma, activity, isotropic, geometry, LabSOCs, decommission.

The objective of the research is to experimentally study the influence of measurement parameters on the efficiency of photon registration by a semiconductor spectrometer.

The operations of decommissioning of nuclear installations are usually challenging due to lack of information about the position, identification and the radiological characteristics of residual radioactivity.

In this research, a description of the model of the radiation state of a nuclear facility is developed, the composition of the model is outlined, the problems of the formation of the engineering-radiation model of the nuclear facility are considered on the basis of the engineering model of radiation inspection and gamma radiation calculations depending on the radionuclide composition, the activity of radiation sources, and also their geometric sizes and shapes.

The efficiencies of various models in the LabSOCs software were evaluated and comparison between them were drawn and some recommendations. Good agreement was observed between the calculated, actual and certificate activities. It is an indication of the validity of the model used in this study. The slight discrepancies in the activity was as a result of the decay of Co-60 for the past eleven years. There is a decrease in more than 4 times the efficiency of detection of gamma quanta in the case when the transverse dimensions of the source exceed the dimensions of the detector, that can be compensated by measurements in close geometry.

This research can be applied in the nuclear decommissioning process for the identification of radionuclide composition for classifications and shielding purposes.

Economically, this will reduce the volumes of waste materials due to the segregation of contaminated materials from non-contaminated materials. Thereby reducing the cost involved in handling and storage of radioactive waste.

List of Abbreviations

GRB	Gamma Ray Burst
NDA	Non-Destructive Testing
PMT	Photomultiplier Tube
BiqGeSol	Bismuth Germinate
NaITl	Thallium Doped Sodium Iodide
MSV	Mean Square Voltage
STP	Standard Temperature and Pressure
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
MCP	Main Circulation Pump
NEW	Nuclear Energy Worker
CNSC	Canadian Nuclear Safety Commission
OSH	Occupational Safety and Health
WHO	World Health Organization
ALARA	As Low as Reasonably Achievable
OSHA	Occupational Safety and Health Administration
UNEP	United Nations Environment Program
LabSOCS	Laboratory Source-less Object Calibration Software

Table of Content

Introduction

The world's increasing population and industrialization requires a continuous, sustainable source of energy to sustain our energy demands. There is however the need to tackle this problem without any negative effect on humans and the environment, and this remains a great challenge to scientists, engineers and governments across the globe. For this reason, nuclear energy appears to be the best energy source which tackles the emission of green-house gases and less cost in generation. Most countries are now adding nuclear energy to their energy mix, there are a total of 442 reactors in the world. United States of America currently lead countries with higher number of reactors with Frances being the country with larger share of electricity generation by nuclear energy. China currently has the greatest number of reactors under operation. [1]

The era of atomic energy that began in the 1940s led to the creation of a large number of facilities, the operation of which has now been discontinued or involves the suspension of the operation of these facilities in the coming years. Decommissioning is the final stage in the life cycle of the nuclear facility, which is comparable in complexity and duration to a stage in the life cycle, such as operation.

Preparation for decommissioning of the atomic nuclear facility is a complex process involving several stages in which a local concept and decommissioning program is developed, a comprehensive engineering and radiation survey of the facility is conducted, from operation, work is carried out to decontaminate and dismantle the equipment and structures of the facility, to handle radioactive waste, and so on.

One of the main tasks in decommissioning radiation-hazardous and complex facilities like atomic nuclear facility is to ensure the safety of personnel, the public and the environment.

For these reasons, most enterprises mainly perform direct measurement monitoring of radioactive contamination of premises and the site of the atomic nuclear facility, while modern techniques and methods of radiation monitoring allow for the conduct of model monitoring of radioactive pollution of the environment on the basis of automation of all calculations and measurements.

Creation of a model of the radiation condition of the nuclear facility will allow to carry out a calculation forecast of changes in the radiation status at the site. It will ensure the fulfillment of design tasks, forecast the formation of radioactive waste, dose loads on staff, select the optimal version of the decommissioning operation. Visually navigate through information and visualization of data, preliminary refinement of equipment dismantling procedures, systems, designs, verification, testing and optimization of solutions laid down in the decommissioning project. This ultimately leads to a decrease in the economic costs of carrying out work on decommissioning of the nuclear facility.

The accumulated experience of designing and carrying out works on decommissioning of complex facilities (nuclear power plants, radiochemical plants, etc.), as well as mistakes made during the creation of decommissioning projects, led to the need to create tools that allow solving several tasks when developing a decommissioning project for nuclear facility, including reducing the time and cost of design, as well as exclude all kinds of collisions related to the mismatch of the real state of the facility with the project.

Such a tool should be the software and hardware system Digital Decommissioning, which includes various databases and models, an executive 3D model of the object combined with radiation characteristics, visualizing radiation fields and allowing to produce the necessary engineering, technological and radiation calculations in the development of the decommissioning project and the adoption of relevant design and technological solutions.

All sources can be divided into point and extended: linear, area and volumetric. In most cases, when calculating radiation, one has to deal with extended sources. The concept of an extended source covers all sources whose dimensions cannot be neglected in calculations. In contrast to point sources, the radiation field of extended sources depends on their shape and size, and in the case of bulk sources and on absorption processes (self-absorption) and scattering of radiation in the source material itself. Calculations from extended sources prove to be more complex and time-consuming than from point sources. Therefore, special methods for calculating exposure dose rate from extended sources have been developed.

Research Goal

Experimental study of the influence of measurement parameters on the efficiency of photon registration by a semiconductor spectrometer.

Tasks

1. Explore ways of detecting the photon radiation;
2. Study the types of efficiency in the registration of photons by semiconductor detectors;
3. Develop a measurement plan in the Genie-2000 software environment using the LabSOCs module;
4. Conduct measurements of samples in different geometries and develop recommendations.

Chapter 1

1.0 Literature Review

1.1 Interaction of Gamma with matter

The possibility of an interaction between the incoming γ-ray and the material in a detector relies on several different variables. It increases when the dimensions of the detector are increased, it also increases when the Z-value of the detection material increases. For higher energy incoming photon this chance of interaction decreases.

Idea about interaction of gamma rays with matter is necessary from the perspective of shielding against their consequence on biological matter. Gamma rays are ionizing radiations who's scattering by electrons and nuclei results in the creation of radiation field containing positive ions and negative electrons. These are the main forms of gamma interactions with matter: photo effect both in its photonuclear and photoelectric forms, electron positron pair production and Compton scattering. To a minor extent, Rayleigh scattering, Thomson scattering and photo fission also takes place. Each of them occurs differently. There are different forms of scattering depending on the quantum-mechanical properties of the gamma photons. Pair production takes place in the nucleus of the atom. Photoelectric effect can knock out atomic electrons whiles elementary particles are knocked out by photonuclear reaction in the nucleus. Decay process of radioactive isotopes emit Gamma rays. [2] Generation of intense gamma radiation fields by Gamma Ray Burst (GRBs) or Magnetars on a cosmic scale, could affect space travel and exploration works.

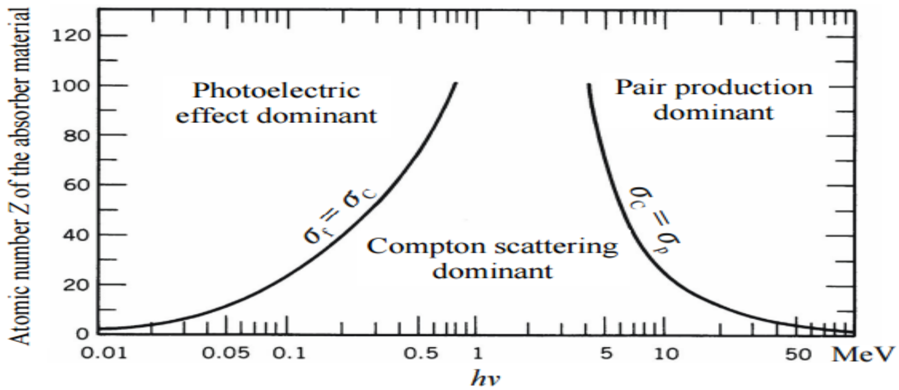

Figure-1 Interaction of Gamma with Matter

1.1.1 Gamma Photons Energy

The kinetic energy of a particle with zero rest mass such as gamma photon or neutrino can be given as:

$$E - hv = \frac{c}{\lambda} \tag{1.0}$$

Where: c is the speed of light

h is Planck's constant

λ is the wavelength of the electromagnetic radiation

Mass and energy are equal and convertible into each under in the theory of Relativity. Hence the total annihilation of particle of rest mass, m, in grams releases an energy E in units of ergs using the formula below:

$$E = mc^2[ergs] \tag{1.1}$$

A universal energy mass radiation equivalence equation can be written as:

$$E = mc^2 = hv = \frac{c}{\lambda} \tag{1.2}$$

This gives a relationship between electromagnetic radiation and mass as indicated below. This enables us to propose that a missing black mass and dark energy in the universe could be linked to electromagnetic radiation fields that permeate the known universe.

$$m = \frac{hv}{c^2} = \frac{1}{\lambda c} \tag{1.3}$$

This equation proposes that when radiation reaches very high frequencies or very short wavelength, it is similar to mass. The momentum of the photon is vector quantity and is given by the relation:

$$\vec{p}_\gamma = \frac{hv}{c} i = \frac{E_\gamma}{c} i \tag{1.4}$$

Interaction of gamma rays with matter leads to the generation of other charged particles such electrons and positrons at relativistic speeds. Considering the ratio of particle speed to speed of light we get:

$$\beta = \frac{v}{c} \tag{1.5}$$

With a rest mass of m_0, the particles relativistic parameters become:

$$m = \frac{m_0}{\left(1-\beta^2\right)^{1/2}} \tag{1.6}$$

$$T = m_0 c^2 \left(\frac{1}{\left(1-\beta^2\right)^{1/2}} - 1 \right) = mc^2 - m_0 c^2 \tag{1.7}$$

Where T, is the kinetic energy.

1.1.2 Compton Scattering

The most dominant of all gamma interaction with matter is the Compton scattering. A photon or gamma ray collides with a free electron which leads to elastics scattering. Momentum and energy cannot be conserved in a case whereby the photon is absorbed by the free electron at rest. Furthermore, electrons in matter are neither at rest nor free. Notwithstanding this, if the incident photon energy is greater than the binding energy of the electrons, which is its work function in solids or potential in gases, and also greater than the momentum of the interacting electron, then the state of the electron in a simple model could be assumed to be free and at rest. Under this situation, gamma ray can interact with a loosely bound electron by being scattered with an applicable loss in energy. [3]

A relativistic particle's total energy with respect to its momentum is from the equation below;

$$E^2 = \left(m_0 c^2\right)^2 + p^2 c^2 \tag{1.8}$$

$$E = +\left[\left(m_0 c^2\right)^2 + p^2 c^2\right]^{1/2} \tag{1.9}$$

Representing the energy of the preliminary gamma photon as E_γ and after collision $E_\gamma^{'}$ and scattering through an angle θ as illustrated in figure 1 below, applying the relativistic conservation of energy and momentum for such elastic collision produces the following relations:

Momentum conservation:

$$\frac{\overline{E_\gamma}}{c} = \frac{\overline{E_\gamma^{'}}}{c} + \overline{p} \tag{1.10}$$

Energy conservation:

$$E_\gamma + E_0 = E_\gamma^{'} + \left(E_0^2 + c^2 p^2\right)^{1/2} \tag{1.11}$$

Where $E_0 = m_0 c^2$ is the total energy of the electron when at rest = 0,511MeV, the mass of the electron is m_0.

Expansion of the vector equation describing conservation of momentum along the incident photon path and perpendicular is as shown below:

$$\frac{E_\gamma}{c} = \frac{E_\gamma^{'}}{c}\cos\theta + p\cos\varphi \tag{1.12}$$

$$0 = -\frac{E_\gamma^{'}}{c}\sin\theta + p\sin\varphi \tag{1.13}$$

Removing the angle φ by the use of this trigonometric identity:

$\cos^2\varphi + \sin^2\varphi = 1$,

$$p^2 c^2 = E_\gamma^{'} - 2E_\gamma E_\gamma^{'}\cos\theta + E_\gamma^{'2} \tag{1.14}$$

$$\frac{1}{E_\gamma} - \frac{1}{E_\gamma^{'}} = \frac{1-\cos\theta}{E_0} \qquad (1.15)$$

Equation 1.15 can be transformed into the equation below:

$$\Delta\lambda = \lambda^{'} - \lambda = \lambda_0\left(1-\cos\theta\right) \qquad (1.16)$$

Where: λ and $\lambda^{'}$ is the wavelength of the gamma photons before and after scattering respectively.

θ - is the angle of scattering of the gamma photon;

λ_0 - is the Compton wavelength of the electron.

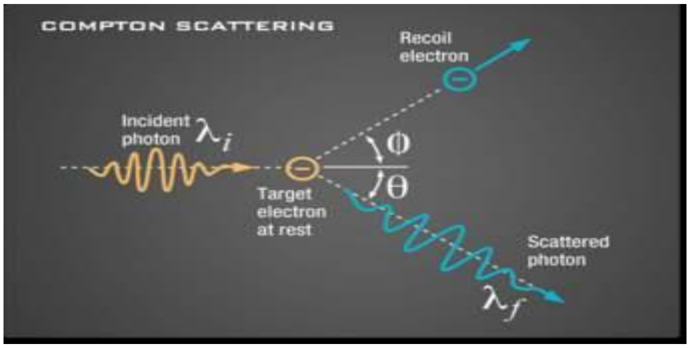

Figure 2- Compton scattering by gamma photon by free electron

Scattering through a very small angle $(\phi \approx 0)$, the energy of the incident gamma ray is slightly greater than the energy of the scattered gamma ray and the scattered electron takes little energy from the interaction. The energy gained by the scattered electron ranges from zero to a maximum using equation 1.18. It is however challenging to relate the Compton-scattering spectrum to the energy of the incident gamma ray. If a Compton scattering takes place in a detector, the scattered electron is generally stopped in the detection medium and an output pulse is produced by the detector which is proportionate to the energy lost by the incident gamma ray. Compton scattering in a detector yields a spectrum of output pulses from zero up to the maximum energy given by Equation 1.17.

$$E_e(\max) = \frac{E}{[1+\frac{m_0c^2}{2E}]} \approx E - \frac{m_0c^2}{2} = E - 256keV; \text{if } E >> m_0c^2/2 \qquad (1.17)$$

Since Compton scattering involves the minimum tightly bound electrons, the influence of the nucleus is fairly very little, therefore the probability of interaction is nearly independent of atomic number. The probability of interaction is subject to the electron density, which is proportional to Z/A and almost constant for all materials.

1.1.3 Pair production and Annihilation

Photoelectric and Compton effects illustrate two mechanisms of photon absorption, it is a process in which a photon gives all or some of its energy to a particle (generally within an atom). Photon absorption can be computed in terms of an absorption coefficient μ which is usually expressed in units of m^{-1} or cm^{-1} and can be defined by the equation below:

$$I(x) = I_0 \exp - \mu x \quad (1.18)$$

Where I_0 and $I(x)$ represents the photon intensities at the initial surface and at a depth x below the surface (usually measured in the direction of the incident beam). Hence the intensity decays exponentially. [4]

A photon with an energy of at least 1,02 MeV or two electron masses equivalent can create an electron-positron pair. Energy and momentum cannot be conserved in an empty space something must be there to absorb the momentum, it is however possible in the presence of a nucleus since the nucleus can take some energy and momentum. The figure 3 illustrates the formation of an electron positron pair. Photons with energies below 1,02 MeV cannot affect this process since they do not meet the threshold energy for pair production. However, photons with energies above this threshold have enough energy to create a particle pair and a kinetic energy from the remaining energies. There is the need for the process to fulfill one condition which is the conservation of momentum.

Taking the square root of equation 1.9 produces:

$$E = \pm\left[\left(m_0 c^2\right)^2 + p^2 c^2\right]^{1/2} \quad (1.19)$$

According to Dirac, the ambiguity of the sign in equation 1.19 is not by accident but the positive energies illustrates a particle of rest mass m and momentum p, whereas the negative energy states represent a particle of rest mass $-m_0$ and $-p$ as its momentum.

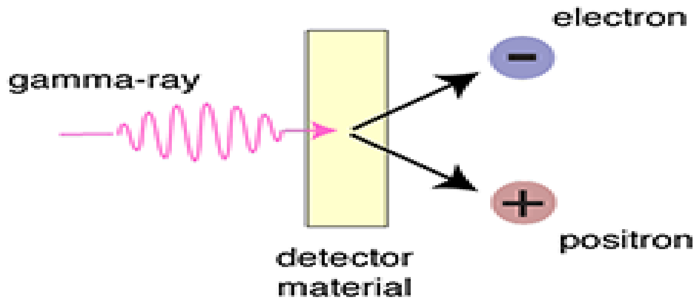

Figure 3 - Diagram of the basic interaction in a pair-production telescope [4]

There is also a possibility for an electron and a positron to form a positronium, this is an atom like structure in which one of the particles moves about their common center of mass. This structure is however, short-lived subject to the orientation of the particles with 10^{-10} and 10^{-7} seconds lifetime after which both annihilate. There is a rapid slowing down of the positron and electron by the absorber. The positron and electron combine after losing its kinetic energy in an annihilation process, this releases two gamma rays with energies of 0,511 MeV. There is the possibility for these lower energies to interact further with the absorbing material or escape. This interaction usually gives three peaks for high energy gamma rays in a gamma ray detector.

1.1.4 Photoelectric Effect

In photoelectric process the interaction is between a gamma photon and an orbital electron of an atom in which the photon completely disappears. The gamma photon transfers it kinetic energy to the electron and the electron is knocked out of it orbit. One of the outer electrons fills the vacancy created immediately whose transition is followed by the emission of characteristic x-rays, ultraviolet or visible regions of the electromagnetic spectrum. That electron is known as photoelectron. The atomic cross-section of the photoelectric dependence on the atomic number Z of the material and the photon energy. [5] The cross-section is approximately equal to equation 1.20 when the energy of the photon is of the order 100 keV.

$$\sigma_f \approx \frac{10^{-37} Z^5}{(hv)^{7/2}} \tag{1.20}$$

Where the cross-section σ_f is measured in m^2 and hv is the energy of the photon and is measured in MeV. The photon energy is shared between the kinetic energy of the knocked-out electron and the characteristic transition radiation in accordance with the conservation of energy equation:

$$E_\gamma = E_a + E_e + E_b \tag{1.21}$$

Where E_γ - is initial kinetic energy of the gamma photon,

E_a - Kinetic energy of the recoiling atom,

E_e - the knocked-out electrons acquired kinetic energy,

E_b - binding energy of the electron in the atom.

Figure 4 describes a photoelectric effect as a result of photon interaction with on orbital electron.

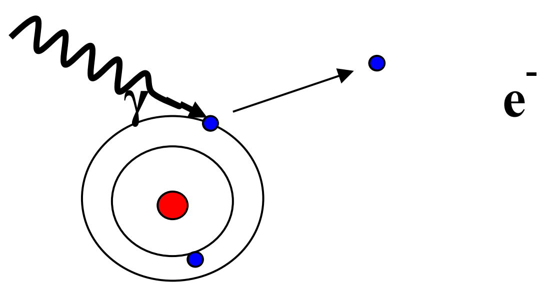

Figure 4- Photoelectric effect

1.1.5 Photonuclear Effect

The nucleons in the nucleus of an atom are bound with an energy ranging from 6 to 8 MeV. [6] This means a photon with an energy less than 6 MeV cannot initiate many nuclear reactions. Apart from a few short-lived low Z-nuclides such as N^{16} which possess energies that high. Photonuclear reactions are used in basic and applied sciences in nuclear and radiation physics and other related fields. [7] When a gamma-ray or photon is incident on a nucleus, the excited nucleus acts as any compound nucleus with an excitation energy. The most likely decay is emission of neutron (γ, n). After which the following reactions take part: (γ, 2n), (γ, 1p) and (γ, 2p). Nuclear level and half-life identifications, material analysis, determination of nucleon binding energy, radiation protection applications, dosimetry, assessment of absorbed dose, activation analysis, analyses of radiation, nuclear waste transmutations, physics of fusion and fission reactors, are examples to such studies. [8]

1.2.0 Sources of Radiation

There are different sources of radiation such as natural sources examples are: small radioactive sources, cosmic radiations, our surroundings background radiations and nuclear reactor. Our aim is to generally understand the effect of radiations and protect ourselves from them or minimize their impact in case they are considered excessive. In recent times, we create radioactive sources or particle beams from accelerators with some particular technical, scientific or medical applications in sight. Radiations are also generated from research reactors. Radiations from a source passes through some material medium which is either inserted for some specific reason or the material is there for reasons beyond control.

1.2.1 Detection of Radiation

There are transducers which record the passing or absorption of radiation. Optimization of the detector geometries, materials and configuration to attain the desired information of radiations is the work of scientists and engineers. This information could be the energies of the radiation, time at which they pass, the number and species of the radiation etc. it is on the bases of these applications that we design and build radiation detectors. The results or output of the detectors are sent into electronic modules which consists of both digital and analogue signal processing units. These units are designed to determine arrival times, energy deposits or spatial data of the different radiations passing through the detectors. [9] Figure 5 below illustrates a basic radiation detector system.

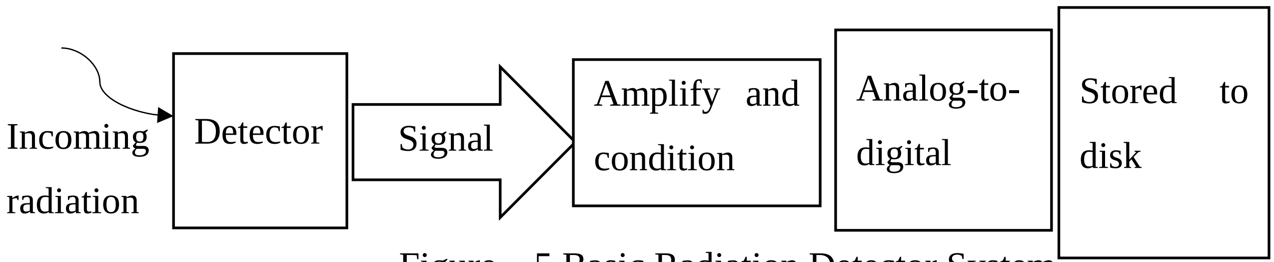

Figure – 5 Basic Radiation Detector System

1.2.2 Types of Gamma Ray Detectors

There are many types of detectors used to detect gamma ray and its energy. It is generally important to measure not only the amount of radiation coming from a sample but also its energy spectrum. Hence the detectors used in non-destructive testing (NDA) applications represents those whose output signal are proportional to the energy deposited by the gamma ray within the sensitive volume of the detector.

The following are some detector types:

a. Counters

    Gas filled detectors

    Scintillation detectors

b. Dosimeters

    Gas filled detectors

    Solid State detectors

    Scintillation detectors

    Thermo-luminescent detectors

    Film

c. Spectrometers

    Scintillation detectors

    Solid state detectors.

1.3 Scintillation Detectors

Luminescent material (liquid, solid or gas) which is viewed by an instrument that detects gamma ray induced light emissions (usually a photomultiplier tube, PMT) is the sensitive volume of a scintillation detector. The scintillation material could be organic or inorganic; however, the latter is more common. Some organic scintillators are as follows: plastics, liquids and anthracene. Plastics and liquids are less efficient compared to anthracene. Some common inorganic scintillators are cesium iodide, lithium iodide, zinc sulfide and sodium iodide. Sodium iodide and cesium iodide remains the most common inorganic scintillation detectors. [10]

Bismuth germinate (BiqGesOl) usually referred to as BGO is a new scintillation material and it has become common in applications where its high gamma counting efficiency and its lower neutron sensitivity is more than the considerations of energy resolution. [11] Ionized atoms in the scintillator material move to a lower-energy state when gamma rays interact in scintillator material and emit photons of light. The return of the atom to lower-energy states in a pure inorganic scintillator crystal with the emission of a photon is an inefficient process. The photons emitted are also usually too high in energy to lie in the range of wavelengths to which the PMT is sensitive. A little amount of impurities is added to all scintillators to improve the radiation of visible photons. Crystal de-excitations directed through these impurities generate photons that can activate the PMT. One significant result of luminescence through activator impurities is that the bulk scintillator crystal is translucent to the scintillation light. A common instance of scintillator activation in gamma-ray measurements is thallium-doped sodium iodide [NaI(Tl)]. It is transparent to its own scintillation emissions. Hence there is slight loss of scintillation light as a result of self-absorption, even in NaI(Tl) crystals of comparatively large size. Emission of scintillation light is isotropic therefore the scintillator is usually surrounded with a reflective material example is MgO to reduce loss of light which is optically coupled to the photocathode of a PMT. Scintillation photons incident on the photocathode free electrons through photoelectric effect which are then accelerated by a strong electric field in the PMT.[12] In the course of acceleration of these photoelectrons, there is collision with electrodes also known as dynodes resulting in release of additional electrons. The increase in electron flux is further accelerated to collide with succeeding electrodes, resulting in a large increase by a factor of 10^4 or more from its initial value at the photocathode surface. The amplified charge burst finally arrives at the output electrode of the tube. The initial amount of the charge freed at the photocathode is proportional to the magnitude of the surge. Additionally, as a result of the physics of the photoelectric effect, the primary number of photoelectrons liberated at the photocathode, is proportionate to the quantity of light incident on the phototube, which is also in turn, proportional to the quantity of energy deposited in the scintillator by the gamma ray. Hence, a production of an output signal which is proportional to the energy deposited by the gamma ray in the scintillation medium. The spectrum of deposited energies (even for a mono-energetic photon flux) is somewhat different, as a result of the occurrence of the Compton effect, photoelectric effect and several scattering phenomena in the scintillation medium and statistical fluctuations connected with all of these processes. [13]

Photomultiplier: This is an electron tube which holds two parts: photocathode (it is sensitive for light) in addition to an amplifier part. Photocathode: It transforms the light pulses to electron current. The amplifier amplifies the electron current to stronger values. The figure 6 below shows a diagram of Photomultiplier.

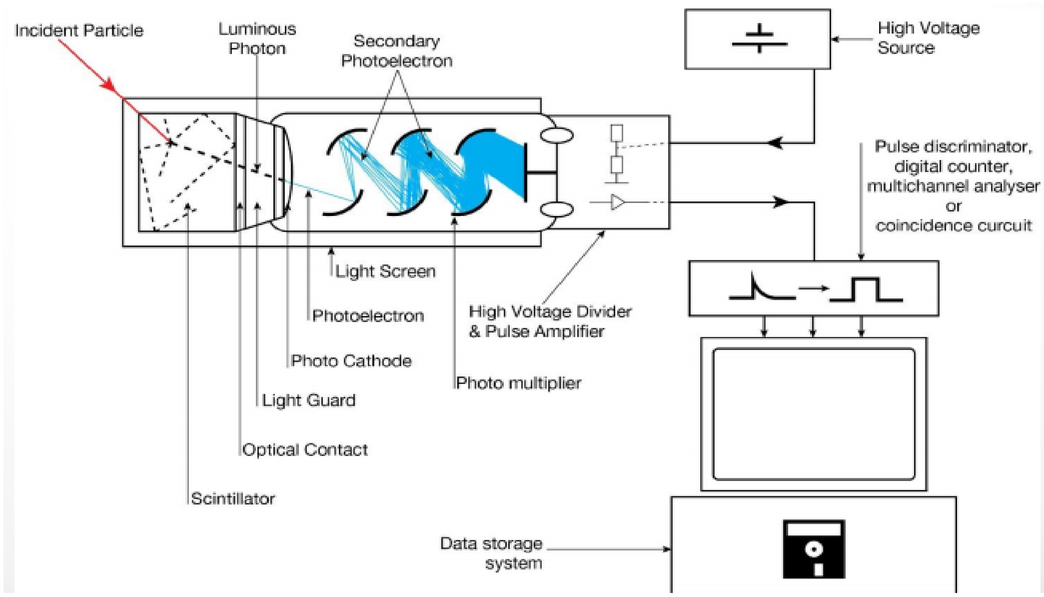

Figure 6 - Diagram of a photomultiplier [14]

1.4 Solid State Detectors

The term solid state detectors refer to certain groups of crystalline substances which shows measurable effects when introduced to ionizing radiation. Electrons exist in discrete energy bands which are separated by forbidden bands or gaps in these substances. Electrons are mostly in the valence and conduction bands. Transfer of charged particles or energy from photon to a valence band, an electron may raise it through the forbidden into the conduction or excitation band. A hole is then created which is analogous to a positive ion in a gas system. [15]

The charge generated by the photon interactions is collected directly in solid-state detectors. The energy resolution in solid state detector is far better than that in the scintillation detectors as a result, greater spectral detail measured. The sensitive volume is an electronically conditioned area in a semiconductor material where free electrons and holes move freely. The most widely used semiconductor material in solid-state is germanium, it possesses the most ideal electronic characteristics. Use of solid state detection medium have a significant advantage in many detection applications. When heavy charged particles are involved, then silicon diodes are the best for a large number of applications. The excellent timing characteristics of silicon diode detectors allows for a precise tracking and counting of charged particles in situations where measurement of energy is not required. The dimensions of the detector can be much smaller than alternatives for the measurement of high-energy electrons or gamma rays. Usage of semiconductor materials as radiation detectors also end up in a larger number of carriers for a given incident radiation event, hence a lower statistical limit on energy resolution than what is possible with other types of detectors. [16] Therefore, the best energy resolution practicable today is got through the use of such detectors. Electron-hole pairs are the basic information carriers which are created along the path taken by the charged particles through the detector as shown in the figure 7 below. A detection signal is formed by the collection of these electron-hole pairs by measuring them as charges at the electrodes of the sensor which proceeds to the amplification and discrimination stages. Further required features of solid-state detectors are a compact size, an effective thickness and relatively fast timing characteristics. Just like any other detector, it has shortcomings, including the limitation to small sizes and relatively high susceptibility of these devices to undertake performance degradation from radiation-induced damage. [17]

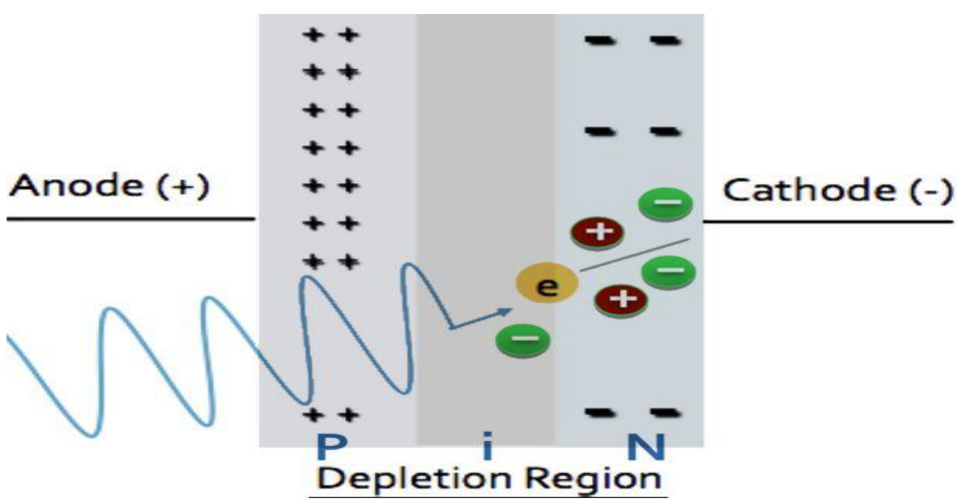

Figure 7- *Ionizing radiation forms electron-hole pairs in the intrinsic region resulting in a charge pulse*

1.5 Gas Filled Detectors

The pulsed operation of the gas filled detector shows the principle of fundamental radiation detection. Since the ionized particles of gases travel more freely compared to others, it is used in this detector. Examples of gases mostly used are helium and argon even though boron-tri-fluoride is used when the detector is used to measure neutrons. The negative charges are collected by the central electrode or anode which is insulated from the cathode and the chamber walls where positive charges are collected. A voltage is applied to the chamber walls and the anode. A capacitor in parallel shunts the resistor in the circuit in order that the anode is at a positive voltage with respect to the detector wall. [18]

Some gases along the path of travel of charged particles get ionized in the gas filled chamber. The anode attracts the electrons whiles the cathode attracts the positive charges. Collection of these charges decreases the voltage across the capacitor, resulting in a pulse across the resistor which is recorded by an electronic circuit. The electric field and its strength is determined by the voltage applied to the anode and cathode. Figure 8 is a schematic diagram of a gas-filled chamber with a central electrode.

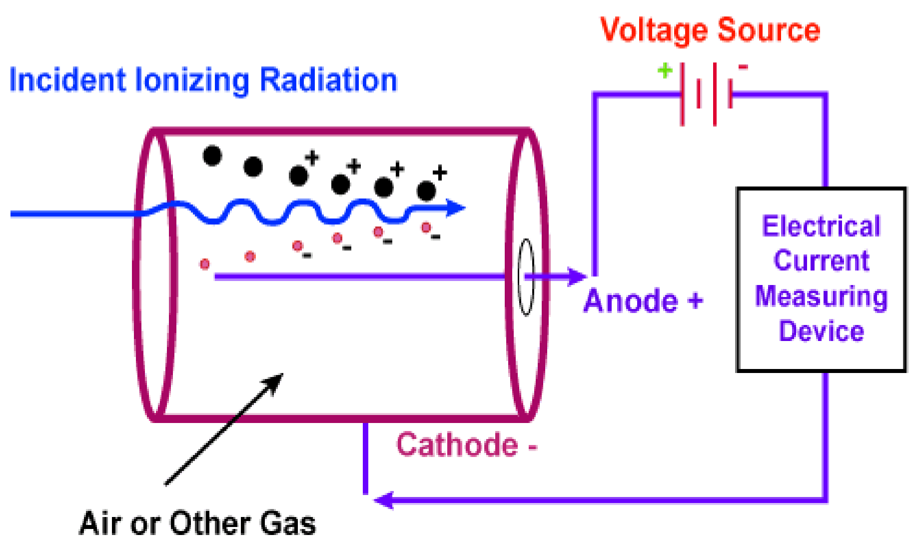

Figure 8- Schematic Diagram of a Gas-Filled Detector

1.6 General Properties of Radiation Detectors

1.6.1 Simplified Radiation Detector Model

The research took in to consideration a hypothetical detector that is subject to some type of irradiation. It firstly, focused on the interaction of a quantum or single particle radiation in the detector, this might for instance be a single gamma ray photon. The radiation must undertake interaction through one of the interactions discussed earlier in order for the detector to respond. The interaction or stopping time is very small (usually a few nanoseconds in gases and a few picoseconds in solids) as indicated in equation 1.22. Practically, this time is very short that the deposition of the radiation energy can be taken as instantaneous. The net outcome of the radiation interaction in a wide classification of detectors is the appearance of a given amount of electric charge inside the detector active volume. The simplified detector model therefore assumes that a charge Q, appears in the detector at time t = 0 coming from the interaction of a single particle or quantum radiation. This charge is then collected to form the basic electrical signal. Collection of the charge is usually attained through the imposition of an electric field within the detector, this makes the positive and negative charges generated by the radiation to flow in the opposite directions.

Time needed to completely collect the charge differs greatly from one detector to another. For instance, the collection time in an ion chamber can be very long as a few milliseconds, whiles it can be a few nanoseconds in a semiconductor diode detector. The mobility of the charge carriers in the detector active volume and the average distance required to travel before arriving at the collection electrodes determines the times. [19]

$$T = 1{,}2 \cdot 10^{-7} R \sqrt{\frac{m_A}{E}} \tag{1.22}$$

Where T is in seconds, m_A in amu, R in meters and E in MeV. This approximation is expected to be accurate for light charged particles (protons, alpha particles etc.) over much of the energy range of interest. It is not used for relativistic particles such as fast electrons.

Hence, we start with a model of a prototypical detector whose reaction to a single particle or quantum of radiation shall be a current that flows for a time equivalent to the charge collection time.

The charge Q, the total amount created in that interaction is equivalent to the time integral over duration of the current. Most quanta of radiation will interact over a period of time in any real situation. Cases can happen in which the current is flowing in the detector from more than one interaction in a given time if the irradiation rate is high. For purposes of this work, we assume that the rate is low enough so that every individual interaction gives rise to a current that is different from each other.

1.6.2 Modes Detector Operation

There are three basic modes of operation of radiation detectors namely: pulse mode, current mode and mean square voltage mode (MSV) sometimes called Campbelling mode. The most commonly applied mode is the pulse mode however, the current mode also finds many applications. The mean square mode is used in some specialized applications that uses a unique characteristic. The three modes are interrelated by their common reliance on the sequence of current pulses which are the output of the simplified detector mode even though all three modes are operationally distinct. Each individual quantum of radiation which interacts in the detector is recorded by the measurement instrumentation in pulse mode operation. Since the energy deposited in the detector is directly proportional to Q, the time integral of each current is recorded in most applications. Every detector used for measurement of energy of individual radiation quanta ought to be operated in pulse mode. Such applications are characterized as radiation spectroscopy.

Other situations may use simpler approach in the measurement: all pulses greater than a low-level threshold are recorded from the detector, regardless of the value of Q, this is referred to as pulse counting. This can be used in many applications where only the intensity of the radiation is needed, rather than sensing any changes in or data about the incident energy distribution of the radiation. Pulse mode becomes impossible or impractical at very high event rates. The period of time between adjacent events may become too small to carry out an adequate analysis, or the current pulses from consecutive actions may overlap in time. Under that situation, it is possible to revert to alternative measurements techniques which respond to the time average taken over many individual actions or events. This approach leads to the rest of the two modes of operation: current and MSV mode. [20]

1.6.3 Current Mode

Figure 9 below shows a current-measuring device (a pico-ammeter) connected across the output terminals of a radiation detector.

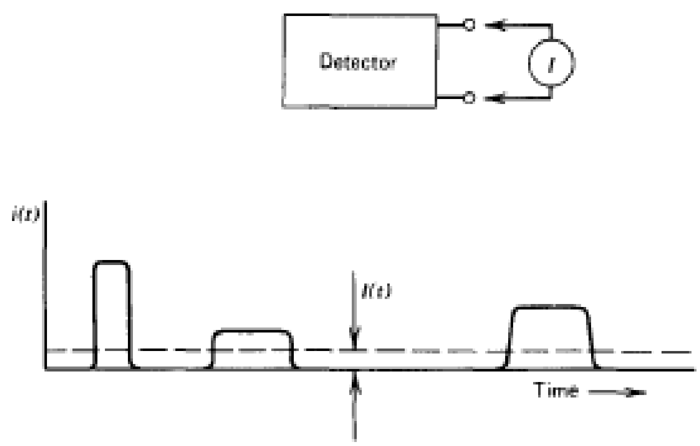

Figure 9 – Current measuring Device [9]

The recorded signal from the sequence of events will be a time-dependent current is given by the equation 1.23 below, in an assumption that the measuring device has a fixed response time T:

$$I(t) = \frac{1}{T}\int_{t=T}^{t} i(t')dt' \tag{1.23}$$

Since the response time T is usually long compared to the average time between each current pulse from the detector, this effect is to average out most of the fluctuations in the intervals between each radiation interactions and then record an average current that relies on the product of the interaction rate and the charge per interaction. The time average of each current best serve as the fundamental signal that is recorded in the current mode. The random fluctuations in the arrival time of the event creates a statistical uncertainty in this signal at any instant of time. The integration time T is similar to the measurement time in many occasions. Hence a selection of a bigger T will reduce the statistical fluctuations in the signal, however, it will also slow the response to rapid fluctuations in the rate or nature of radiations interactions. The average current is given by the product of the charge produced per event and the average event rate.

$$I_0 = rQ = r\frac{E}{W}q \qquad (1.24)$$

Where:

r = event rate

Q = E_q/W charge produced for each event

E = average energy deposited per event

W= average energy required to produce a unit charge pair (e.g., electron-ion pair)

q = 1.6 x 10^{-19} C

This average current can be rewritten as the sum of a constant current I in addition to the time-dependent changing component $\sigma_i(t)$ as shown in figure 10 below:

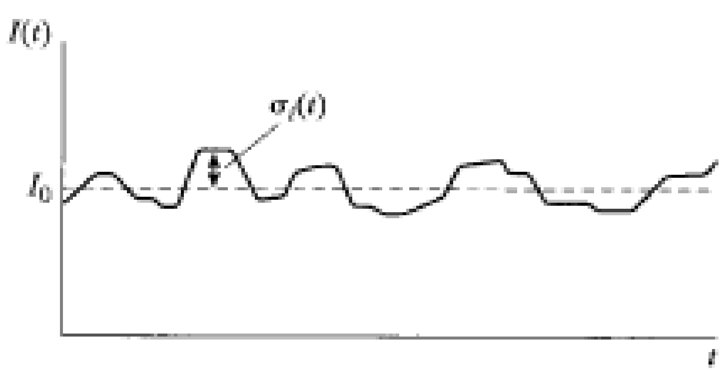

Figure 10 – Graph of current against time [9]

In this case, $\sigma_i(t)$ is an arbitrary time-dependent variable that occurs as a result of the arbitrary nature of the radiation actions interacting within the detector. A statistical measure of this arbitrary factor is the variance or mean square value, defined as the time average of the square of the variance between the fluctuating current $I(t)$ and the average current I_0. The mean square value is given by:

$$\overline{\sigma_i^2}(t) = \frac{1}{T}\int_{t-T}^{t}\left[I(t') - I_0\right]^2 dt' = \frac{1}{T}\int_{t-T}^{t}\sigma_i^2(t')dt' \qquad (1.25)$$

With a standard deviation as follows:

$$\overline{\sigma_i}(t) = \sqrt{\overline{\sigma_i^2}(t)} \qquad (1.26)$$

From Poisson statistics, standard deviation in a number of recorded events n over a given observation period of time given as:

$$\sigma_n = \sqrt{n} \qquad (1.27)$$

Consequently, the standard deviation in the number of events happening at a rate r in an effective measurement time T is as seen in the equation 1.28 [21]

$$\sigma_n = \sqrt{rT} \qquad (1.28)$$

1.6.4 Pulse Mode

In events when the rates are very high, current mode operation is used. In radiation dosimetry, detectors used are also usually operated in current mode. The mean square voltage mode is suitable in improving the relative response to large amplitude events and finds widespread application in reactor instrumentation. However, many applications are better served by protecting or preserving data on the amplitude and timing of each events that can be provided by only pulse mode. The input characteristics of the circuit to which the detector is connected determines the nature of the signal pulse produced from single event. The signal created depends on the preamplifier used, which is basically signified by the simple circuit shown here:

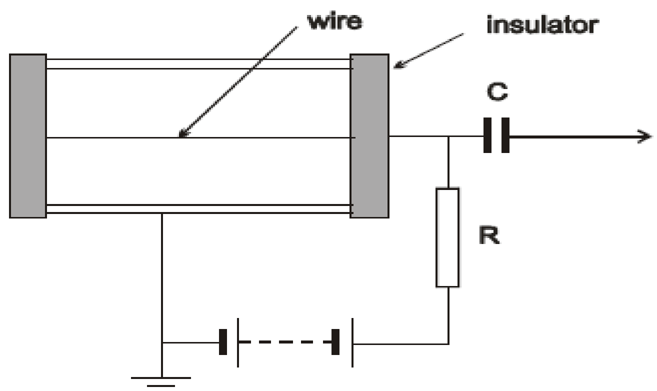

Figure 11 - Diagram of the simple circuit for a Gas-Filled Detector [22]

This is fundamentally a RC circuit. We measure the time-dependent voltage across the resistor [V(t)]. The value of RC impacts the shape of V(t).

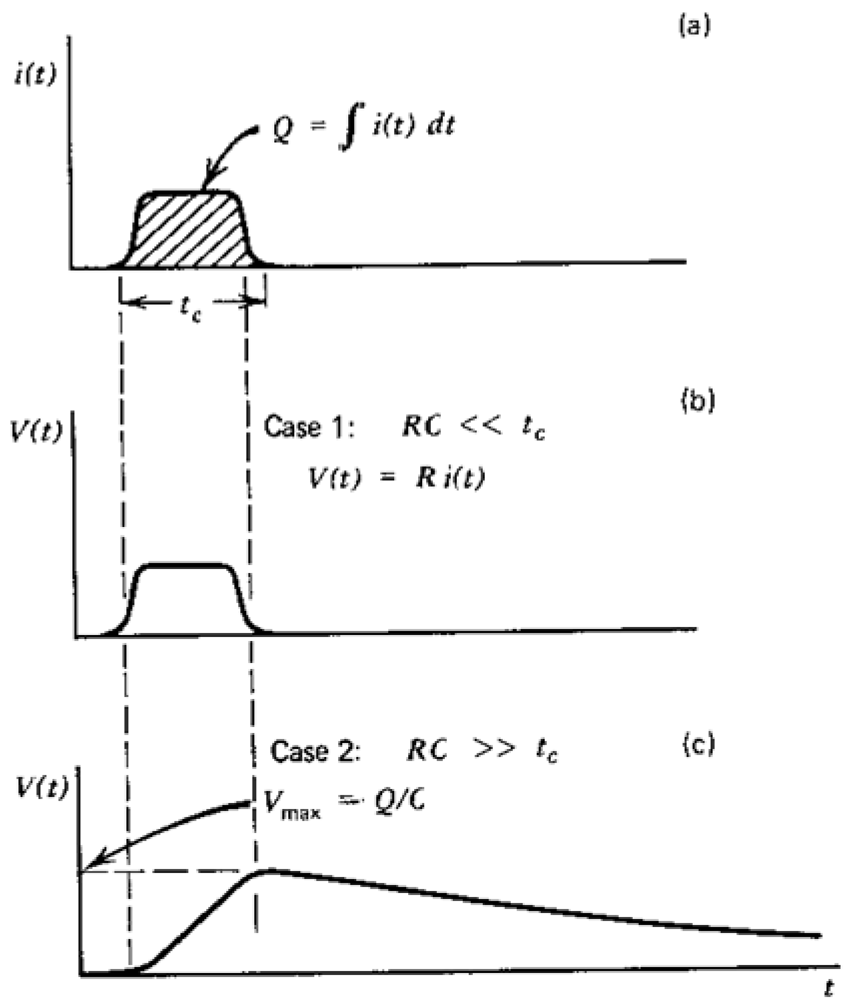

Figure 12 – (a) The presumed current output from a hypothetical detector (b) The signal voltage V(t) in the case of a small time constant load circuit (c) The signal voltage V(t) in an instance of a large time constant load circuit

The detector charge collection time determines the time the signal reach maximum whiles the time constant for the circuit determines the decay time of the pulse. A large RC offers an amplitude that is equivalent to the charge collected divided by *C*.

For this reason, the rate at which pulses are generated is proportional to the interaction rate of radiation, which in turn is proportional to the radiation emission rate. The height of every pulse is proportionate to the total of charge collected, which is usually related to the energy of the incident radiation. These two characteristics enable us to measure the energy spectra and emission rate of radiation from a source and will give us the opportunity to identify and quantify the source. [22]

1.7 Mean Square Voltage

Further studies of the statistical properties of the signal in current mode leads to the next mode known as the mean square voltage (MSV) mode. If the current signal sent through a circuit element that blocks the average current I and passes the fluctuating components $\sigma_i(t)$. The time average of squared amplitude of $\sigma_i(t)$ can then be calculated by providing additional signal processing elements.

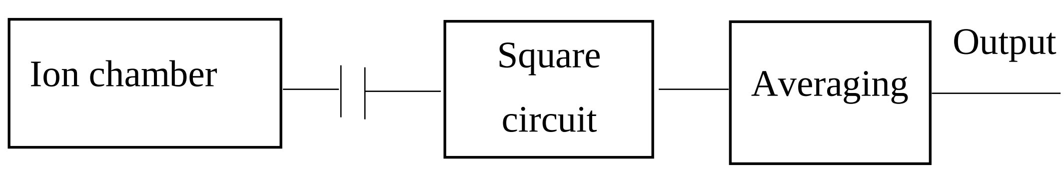

Figure 13 – Signal Processing Elements

This mode of operation is most suitable when measuring in a mixed radiation environment, a situation where the charge generated by one type of radiation are different from others. If simple current mode operation is selected, the measured current will linearly reflect the charges given by each type. However, in MSV mode, the derived signal is proportional to the square of the charge per event. The output of the current mode operation is a fluctuating current which can be regarded as a sum of a steady-state component and a time varying component. The MSV circuit stops the steady-state component and squares the amplitude of the varying component. The subsequent signal is proportional to the square of the charge that is generated by each incident particle of radiation, hence enhancing the difference between types of radiation. MSV mode is basically used for nuclear reactor instrumentation as a mean of measuring neutrons in high gamma background. The neutron flux in a reactor may be measured using this mode from source range to power range with a single channel. [23]

1.7.1 General Considerations in Gamma-Ray Spectroscopy

Gamma-ray photons are uncharged and therefore creates no direct ionization or excitations in the material in which it passes through. [24] For this reason, the detection of gamma rays is solely dependent on the energies that are transferred from the photon to the electrons in the absorbing material. These interactions are as detailed in chapter one, and represents sudden and major variations of photon properties, compared to the continuous slowing down of heavy charged particles through several simultaneous interactions. The nature of the incident gamma rays is determined by the fast electrons generated in the gamma interactions, this is because primary gamma-ray photons cannot be detected by the detector. The energies of these electrons are proportional to the energies transferred to the electrons by the gamma ray photons and will lose their energy after slowing down. The energy lost is through ionization and excitation of atoms in the absorber material and bremsstrahlung emissions. [25] For a detector to act as a spectrometer for gamma-rays, it must undertake two distinct functions. These functions are as follows: it must act as a conversion medium where the incident photons have a chance of interacting to produce one or more fast electrons, secondly, it must serve as a conventional detector for the secondary electrons. When it is assumed that the detector is large enough, then escape of secondary electrons is insignificant. Under this situation, the most penetrating secondary electrons will be generated with few MeV kinetic energy for incident gamma rays of a few MeV. The corresponding range in characteristic solid detector media is a few millimeters. If there is a total electron absorption it means that a detector minimum dimension is at least about a centimeter. In this case, only a little fraction of the secondary electrons created randomly in the volume of the detector lie within one range value of the surface and there is a probability of escape.

The penetration distance of a 1 MeV electron in standard temperature and pressure (STP) gases is longer in meters, so normal gas-filled detectors of practical size can never come close to absorbing all the secondary electron energy. [26]

1.8 Predicted Response Functions

1.8.1 Detectors with Small Size

The research looked at the behavior of the expected response of detectors with small size compared with the mean free path of the secondary gamma radiations generated in interactions of the original gamma rays. These secondary radiations comprise of Compton scattered gamma rays in addition to annihilation photons generated at the end of the tracks of positrons formed in pair production. [27] The condition of "smallness" is achieved when the detector sizes do not exceed 1 or 2 cm because the mean free path of the secondary gamma rays is usually of the order of several centimeters. At the same time, we maintain our original simplifying statement that all charged particle energy (photoelectron, Compton electron, pair electron, and positron) is totally absorbed in the detector volume. When the incident gamma energy is smaller than the value at which pair production can be formed, the spectrum forms only from the combined effect of photoelectric absorption and Compton scattering. [28] The continuum of energies corresponding to Compton scattered electrons is called the Compton continuum whiles the narrow peak relating to the photoelectrons is designated as the photo peak. Only single interactions take place for a small detector and the ratio of the photoelectric cross section to the Compton cross section in the detector material is the same as the ratio of the area beneath the photo peak to the area under the Compton continuum. The product of the pair production is shown in the electron energy spectrum if the incident gamma-ray energy is very high (several MeV). In the case of small detectors, the annihilation radiation escapes and the kinetic energies of the electron and positron are deposited. [29]

1.8.2 Transitional or Middle-size Detectors

Generally, detectors used in gamma-ray spectroscopy are neither small nor big. For traditional geometries where the gamma rays are incident the surface of the detector, even large-volume detectors look finite because some interactions will take place near the entrance surface. [30] Normal detector response functions combine some of properties and features related to partial recovery of the secondary gamma ray energy. The spectrum for low to medium gamma-ray energies is made up of a Compton continuum and photo-peak. However, the ratio of the area beneath the photo-peak to that beneath the Compton continuum is considerably improved over that for the very small detector as a result of the added contribution of multiple events to the photo-peak. When the incident gamma-ray energy is lower than the average energy of the Compton scattered photon will also be lower and the corresponding average distance of migration. For this reason, even detectors of moderate size will seem to be large and the relative area beneath the photo-peak increases with decreasing incident energy of the photon. [31]

The Compton continuum may effectively disappear at very low energies less than 100 keV. The possibility of multiple Compton scattering accompanied by escape of final scattered photon can result in a total energy deposition greater than the maximum for single scattering at medium energies. The shape of the continuum predicted for single scattering can be distorted by these multiple events as well as fill in the space between the

Compton edge and the photo-peak. A more complex situation arises when the energy of the gamma-ray is high enough to make a pair production. The annihilation photons may either undergo additional interactions within the detector or escape. The further interactions may result to either partial or full-energy absorption of either one or both of the annihilation photons. [32] These events lead to a single escape peak, this appears in the spectrum at an energy of 0,511 MeV below the photo-peak. A continuous range of other potentials exists where one or both of the annihilation photons are partly transformed to electron energy through Compton scattering and consequent escape of the scattered photon. Such events accrue in a broad continuum in the pulse height spectrum lying between the double escape peak and the photo-peak. [33] The expected response function for a real gamma-ray detector is determined by the shape, size and composition of the detector, and additionally the geometric details of the irradiation conditions. This means the response function will vary if a point gamma source is moved from a position close to a detector to a faraway detector. This change is as a result of the differences in the spatial distribution of the primary interactions which occur in the detector as the source geometry is altered. The Monte Carlo calculations simulates the histories really happening in the detector of the same size and composition to get the response function since it is complex to predict in detail. [34]

The photo-fraction is the ratio of the area beneath the photo-peak (or full energy peak) to that beneath the whole response function. It is a direct measure of the probability that a gamma ray that go through interaction of any kind in the detector eventually deposits its full energy. The complicating effect of Compton continua and escape peaks in the spectrum are minimized by large values of photo-fraction. The single and double escape peaks at high gamma-ray energies are fairly prominent parts of the response function and in certain cases become larger than the photo-peak. The ratio of the area beneath the single or double escape peak to the area beneath the photo-peak is also extensively quoted property of the response function that is useful in the description of complex spectra. [35]

1.8.3 Large Detectors

In a situation where the gamma rays are introduced close to the center of a very large detector, under an assumption that the detector dimensions are sufficiently large so that all secondary radiations involving Compton scattered gamma rays and annihilation photons also interact in the active volume of the detector and none escape from the surface. This condition translates into requiring a detector dimension in the form of many tens of centimeters in a typical gamma-ray energy which is too large for most practical cases. It is however helpful to notice how an increase in the size of the detector significantly simplifies the response function. When the first interaction is a Compton scattering, then the scattered ray will later interact within the detector at a different location. This subsequent interaction may also be a Compton scattering event which case a scattered photon of still lower energy is produced. Photoelectric absorption finally occurs and the history ends at that point. [36]

The primary and secondary gamma rays travel at the speed of light. The total elapsed time from start to finish will be less than nanoseconds when the secondary gamma rays' average migration distance is of the order 10 cm. This time is considerably less than the inherent response time of almost all practical detectors used in gamma-ray spectroscopy. The net effect is to create the Compton electrons at every scattering point and the final photoelectron in time coincidence. The sum of the responses due to each discrete electron will be the pulse produced by the detector. If there is a linear response by the detector to the electron, then a pulse is generated which is proportionate to the entire energy of the electrons produced along the history. Since there is no escape from the detector, the original energy of the gamma photon is the total energy of the electron energy. [37] The detector response is similar as though the original gamma –ray photon had gone through a simple photoelectric absorption in a single step. The total of the kinetic energies of the electron-positron pair and subsequent Compton and photoelectrons generated by interaction of the annihilated radiation should be equivalent to the original energy of the gamma-ray photon if the detector is bigger enough to prevent any secondary radiation from escaping. The detector response is hence proportional to the original gamma-ray photon energy. In conclusion, when the detector is adequately large and its response linearly reliant on electron kinetic energy, then the signal pulse is same for all gamma-ray photons of the same energy, notwithstanding the details of each individual history.

The detector response function is made up of a single peak as shown in figure 14 below. A response function with single peak enhances the ability to interpret complex gamma spectra involving different energies. Usually, the corresponding peak in the response function is referred to as photo-peak as in the small detector. Much more complex histories including multiple Compton scattering or pair production also add pulses that fall within this peak in addition to simple photoelectric events. This is called the full-energy peak since it takes into account all histories in which all of the original gamma-ray energy is fully transformed to electron kinetic energy. [38]

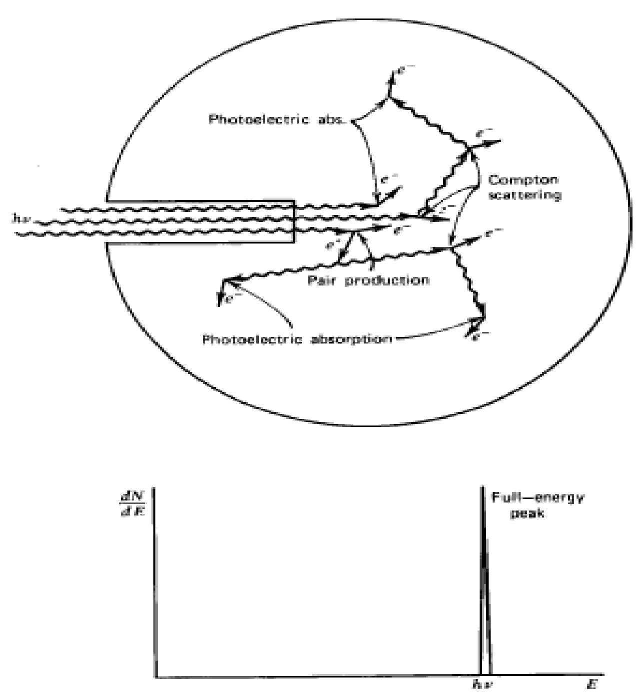

Figure 14 - The "large detector" extreme in gamma-ray spectroscopy [38]

1.9 Efficiency of the Detector

If a source of particle is located at a given distance from a detector as shown in figure 15 below, and the detector is connected to a pulse-type system. The sources maybe outside or inside the detector and may be isotropic (particles emitted with equal probability in all directions) or anisotropic (parallel beam of particles).

Let us consider that:

R – number of particles emitted per second by the source ("activity").

r – number of particles per second recorded by the scalar ("counting rate") corrected for dead time and background.

The measured rate, r, is related to, R, by the following equation:

$$r = f_1 f_2 f_{3.........} f_n R \qquad ((1.29)$$

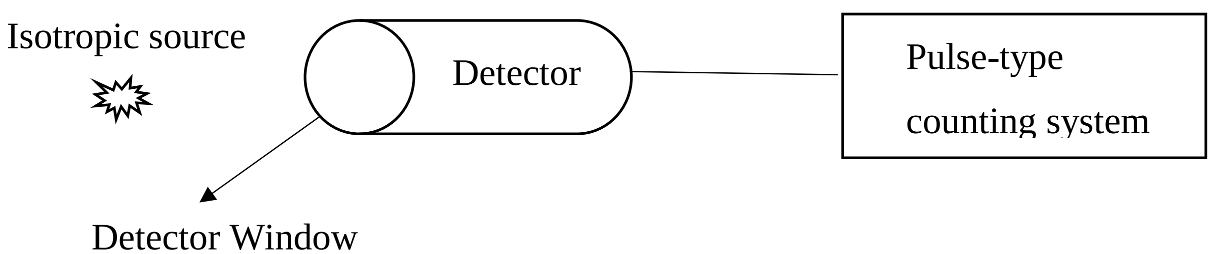

Figure 15 - An isotropic point-source counted by a pulse-type counting system

1.9.1 Effect of the Geometry

The impact of the geometry may affect the measurement in two forms: firstly, the medium between the source and the detector may either absorb or scatter some particles. Secondly, the source shape, the size, the detector and the distance between them determines the fraction of photons that will enter the detector to be counted.

Consider that the source and the detector are separated by an appropriate distance. The medium between them is usually air (which is low density medium). The effect of the air is dependent on the source-to-detector distance. If the source emits charged particles, all the particles suffer some energy loss, some may also be scattered in or out of the detector. If this outcome is significant for the measurement, it could be eliminated by placing the source and detectors in an evacuated chamber. However, if the use of evacuated chamber is prohibited by conditions of the measurement, then appropriate corrections should be applied to the results.

Consider an isotropic radiating point source at a defined distance from a detector window to demonstrate the concept of the solid angle. Only a portion or percentage of the emitted particles will enter the detector since the particles are emitted by a source with equal probability in all directions. That percentage is equivalent to the fractional solid angle subtended by the detector at the position of the source. In the general case of an extended source, the solid angle, Ω, is defined by [39]:

$$\Omega = \frac{number\ of\ \ particles\ entering\ the\ \ \mathrm{det}\,ector}{number\ of\ \ particles\ emitted\ \ from\ the\ source\ in\ all\ directions} \qquad (1.30)$$

1.9.2 Source Effects

Two source effects are deliberated on in this section: absorption of particles in the source (“self-absorption”), and the effect of the backing material that supports the source (“backscatter”), all of which are always significant in measurements of charged particles and are also important in x-ray measurements. Radioactive materials are deposited on a support material usually on thin deposits. Nonetheless, the deposit has a finite thickness which may cause absorption of some particles emitted by the source. Consider a source of thickness t as shown in figure 16, Particle (1) traverse the source deposit and enters the detector, yet Particle (2) is absorbed inside the source so it will not be counted. Consequently, source self-absorption will lead to a reduction of the counting rate r. Source self-absorption may be reduced to an inconsequential amount; however, it cannot be removed completely, and it is always vital for charged particles. In addition to changing the number of particles leaving the source, self-absorption, may also change the energy characteristics of the particles reaching the detector. Particle (1) in figure 16 successfully leaves the deposit, it however loses some energy as it goes through the deposit. This loss is important when the energy of the particle is the quantity being measured [40].

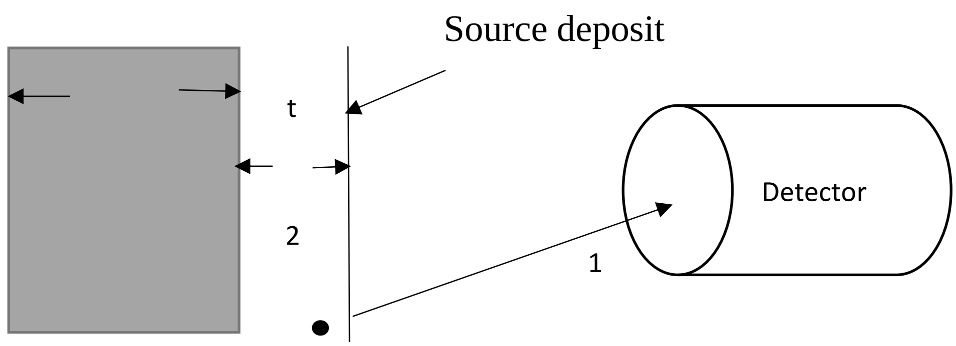

Figure 16 – Source self-absorption particles may be absorbed in the source deposit

The self-absorption factor, f_s is defined by:

$$f_s = \frac{number\ of\ \ particles\ leaving\ the\ source}{number\ of\ \ particles\ as\ \ produced\ by\ the\ source} \tag{1.31}$$

A source support material always supports the source. Even though the source support material is generally a thin layer, it may backscatter particles emitted in direction away from the detector as illustrated in figure 17. Assume that all particles entering the detector are counted, no self-absorption and there is no other medium present that might absorb or scatter the particles except the source support. Particle (1) in figure 17 is emitted towards the detector in the absence of source support material, whiles there is emission of particle (2) in the opposite direction. This is as a result of the presence of the support material, particle (2) may however backscatter and enter the detector.

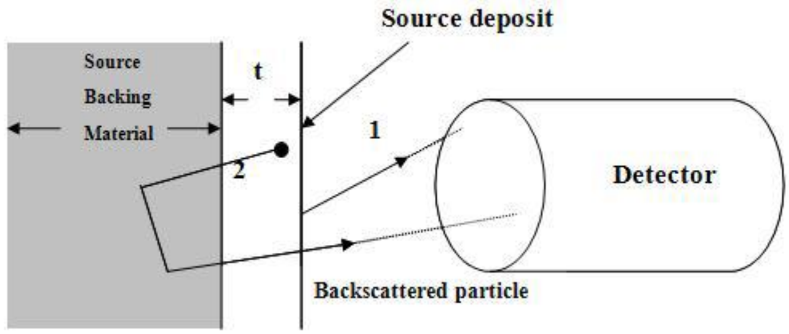

Figure 17 - The source backing material backscatters particles

The source backscattering factor, f_{back}, is defined by:

$$f_{back} = \frac{number\ of\ \ particles\ counted\ with\ source\ backing}{number\ of\ particles\ counted\ without\ source\ backing} \tag{1.32}$$

In most cases, the backscattering factor is important only for charged particles and it depends on the atomic number, thickness of the backing material and the kinetic energy of the emitted particles. [41]

1.9.3 Effect of the Detector

Measurement may be affected by the detector in the following forms: firstly, some particles may enter the detector and show no signal or it may generate a weak signal, lower than the discriminatory threshold. Secondly, if the source is located outside the detector outside the detector, the particle maybe absorbed or scattered by the detector window. [42]

1.10 Scattering and absorption due to the window of the detector

The source is located outside the detector in most measurements as shown in figure 18 below. The figure is an illustration of a detector, and the source of radiation is placed outside it, the radiation must penetrate the window of the counter and enter the detector in order to be counted. Interactions among the radiation and the material of the detector window may cause scattering and/or absorption, this is particularly important for low-energy charged particles. [43]

Generally, particles enter the detector through a window which is made up of a very thin layer (such as mica, glass or thin metal). Looking at figure 18, most of the particles, like particle (1), traverse the window and enter the counter. Nonetheless, there is a likelihood that a particle, such as particle (2), may be scattered at the window and never enter the counter, or may be absorbed by the window material such as particle (3). The window comprises of a material that covers the scintillator and makes it light-tight in the case of scintillation counters. In some applications, the source and the scintillator are placed in a light–tight chamber.

In semiconductor detectors, the window consists of a metallic layer covering the front face of the detector. Although this layer is extremely thin, it may still affect measurements of charged particles because of energy loss. In fact, there is no direct way to correct for the effect of the window. [44]

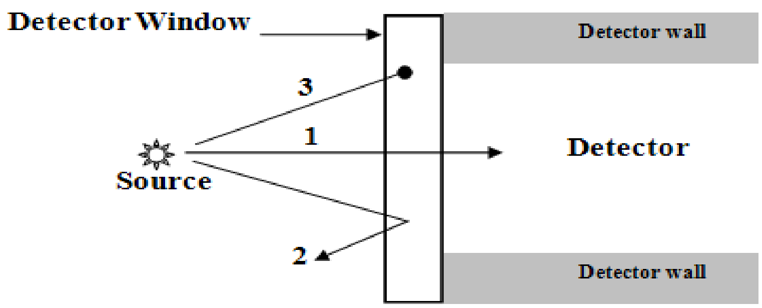

Figure 18 - The window of the detector may be scatter and/or absorb some of the particles emitted by the source

Counting of a particle when it enters a detector is a probability. Depending on it energy and type of the particle and size and type of the detector, it may go through without interaction, this is represented by particle (1) in figure 19. It may also produce a signal so small that it may be impossible to record with the available electronic instruments, as shown by particle (3), it may also be stopped from entering the detector by the window as represented by particle (4). In this arrangement, particle (2) has the best chance of being detected. This detector efficiency is also known as the intrinsic efficiency and it depends on the density and size of detector material, and type and energy of radiations and the electronics system. [45] The quantity that gives the fraction of particles being detected is the detector efficiency, ε, and is given by:

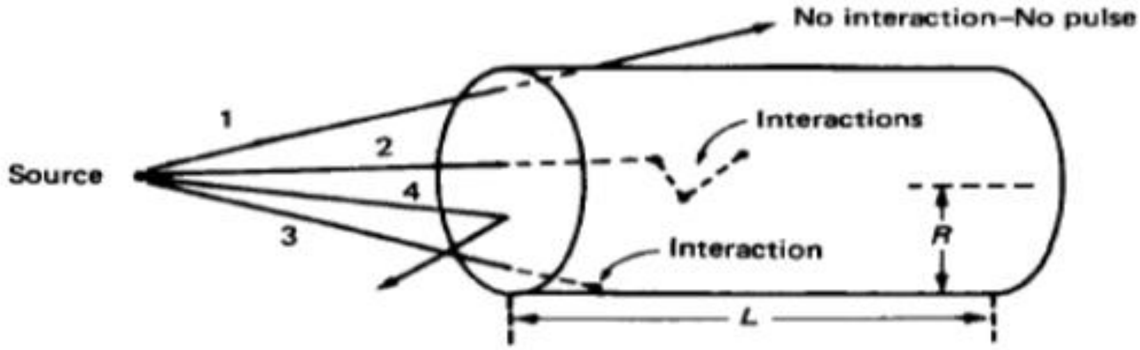

Figure 19 - Particles detected are those that interact inside the detector and produce a pulse higher than the discriminator level

1.11 Effect of size and density of detector material

If the probability of an interaction between the incident radiation and the material of which the detector is made increases the efficiency of the detector also increases. That probability increases also with detector size. However, larger size is of limited importance because the background increases proportionally with the size of the detector, and also because it is impractical to make large detectors in some cases. The probability of interaction per unit distance traveled is proportional to the density of the material. The density of solids and liquids is about a thousand times greater than the density of gases at normal pressure and temperature. Therefore, detectors made of solid or liquid materials are more efficient than those using gases. [46]

1.12 Effect of type and energy of radiations

Charged particles travelling through matter will always have coulomb interactions with the electrons and nuclei of that medium. Since the probability of interaction is virtually a certainty, the efficiency for charged particles will be close to 100 percent. Detectors for charged particles have an efficiency that is almost 100 percent notwithstanding their size or density of the material of which they are made. For charged particles, the detector efficiency is nearly independent of the particle energy (except for very low energies when the particles may be stopped by the detector window). Charged particles have a fixed range X. So, a detector can be made with a length L more than X. On the other hand, photons passing through a medium show an exponential attenuation, meaning that there is always a non-zero probability for a photon to traverse any thickness of material without any interaction. As a result of this property, detectors for photons have efficiencies less than 100 percent regardless of detector size and energy of the photon. [47]

1.13 Types of the detector efficiencies

1.13.1 The intrinsic efficiency

Intrinsic efficiency depends on the photon energy, the detector material type and the detector dimensions. It is the ratio between the number of photons recorded in the detector and the number of photons that enter the detector. [48]

1.13.2 The total (absolute) efficiency

The total efficiency is defined as the ratio between the number of photons that are recorded in the detector with any possible energy during a certain time interval and the number of photons that are emitted by the source in all directions during the same time interval.

1.13.3 The geometrical factor

When an isotropic radiating point source produces photons in all directions, only part of these photons will enter the detector window. The solid angle Ω is the angle between the source and the detector, it determines the geometrical factor. In general, Ω

depends on the shape of the source and the detector as well as the relative position between them. [49]

1.13.4 Relative efficiency

This is the efficiency of one detector, commonly a germanium detector relative to the efficiency of a standard detector (NaI crystal with 3 inches diameter and 3 inches length), each at a defined distance (25 cm) from a point source and for a single specified energy (1.33 MeV of ^{60}Co). [50]

1.13.5 Monitoring of Radiation in the Environment

Humans are exposed to ionizing radiation from a varied source, natural or artificial. The exposure levels of humans differ with the location and lifestyle, however, in many cases it is necessary to evaluate the radiation environment where humans live. The monitoring of Radon levels in certain areas exposure limits for radiation workers or pilots and inspection of radiation levels in food are just a few examples.[51] In the case of unintended release of artificial radiation into the environment, e.g. through waste from re-processing plants, accidents at nuclear power stations or atmospheric nuclear weapons testing it is obligatory to quickly assess the activity, radioisotope composition and localization of radioactive sources to prepare mitigating actions and to limit the exposure of the population to radioactive substances.

Fortuitously, for outreach and public engagement activities, inorganic scintillation counters very comparable to the ones used in professional backpack radiation surveys are readily obtainable from a variety of manufacturers. They are usually powered and read-out via USB with the results being displayed by the analysis software on an accompanying laptop, e.g. the NaI detector pictured in figure 20. By their very design they are practically rugged, easy to use and transportable hence can be easily used in nearly any outreach environment. By its very nature, radiation sources for demonstration purposes are readily available and fulfill the safe limits to be used in public, e.g. rock samples from areas with high natural background radiation, cosmic radiation or Potassium rich fertilizer.

Once set up, the detector systems are straightforward to use and to analyze, letting the general public to understand the work of nuclear, health or environmental physicists first hand. For small groups, undertaking a survey of the local radiation environment can also be quite useful, as are differences in the construction of different buildings. Lastly, investigating radiation emanating from everyday objects gives an illustration of the principle and a close connection to the audience, especially if informed beforehand that an analysis will be possible. Amongst the items used where wooden casks thought to belong to a nuclear physicist, watches with radium dials, Thorium lenses and various pieces of ceramics.

The use of a detector system with GPS functionality and automatic radiation mapping requires more specialized equipment and expert support, which is not always readily available for an outreach activity. When possible, it greatly enhances the audience participation and experience. When not possible, a display and explanation of radiation maps previously taken at the venue or elsewhere [52] proved to be beneficial and allows an in-depth discussion of natural and artificial radiation sources in the environment.

It should be mentioned, that Geiger counters offer a very valuable tool in detecting radiation in the environment. The difference between an audible signal and a scale usually enhances the experience. The clear shortcoming of a Geiger counter is its lack of spectroscopic capabilities. The comparison with a scintillation counter with spectroscopic capabilities is helpful and allows to increase from pure, quick dose measurements, of which both systems are capable, to a more detailed study and identification as well as better dose apportionment with a scintillation counter or a HPGe detector system. The sensor system described in the following section provides
a cost-effective spectroscopic system for similar studies.

Figure 20 - A size comparison between a traditional PMT based detector (upper system, using a 2” NaI and vacuum based PMT) and the SiPM coupled to a 30 mm long GAGG: Ce crystal [59]

Data about nuclide vectors in the environment is very essential for calculating and projecting future behavior and development of radioactive release (cloud of decaying radioactive nuclides with different half-life) in emergency situations. This method can help prevent vast impacts on areas close to reactor and radioactive material sites where such disasters could happen. [53]

Total number of reactors in operation in the world according to the International Atomic Energy Agency (IAEA) is 442, about 71 are under construction whiles 149 are currently out of service. These sites require enough monitoring for any emergency situation. This monitoring is aim at protecting human, environment and the future generation, which is the top priority. It is therefore impossible to abandon the information about spectrum, when it could essentially be measured and included in the recognition of nuclides, their decay chain and half-live in order to relocate humans or prevent the worst-case situations.

1.14 Impact of Ionizing Radiation on Biological Tissue

Absorbed dose of radiation can be expressed in two forms. The first is the physical quantity – an integral of absorbed incident radiation over time D, measured in Greys (1 Gy =1J/kg). Another form of expressing the absorbed dose is by its biological effect on tissues since the same dose in Grays can lead to different biological impact, this is because biological impact of such absorbed dose depends on the properties of the radiation. This quantity is generally called dose equivalent and it is actually an energy-scaled physical absorbed dose. It can be calculated as a weighted sum of the physical absorbed dose D, weighted by a factor W(E) which depends on the energy E,

$$H = W \cdot D = \sum_{i=1}^{n} w(E_i) D_{E_i} \tag{1.33}$$

Where D is a vector absorbed dose at the energies, D_{E_i}, W is a vector of weights $w(E_i)$ at energies E_i. The equivalent dose H is measured in Sievert (1 Sv=1J/kg) and it is the stochastic health effects of low levels of ionizing radiation on the human body. It is obtained from the physical quantity absorbed dose, it however takes into account the biological effectiveness of the radiation, which is reliant on the radiation type and energy. The choice of the biological impact factor W is reliant on a convention which are published by the International Commission on Radiological Protection (ICRP). The ambient dose rate equivalent is the most important standard for environmental monitoring: The ambient dose equivalent H*(10) at the point of interest in the real radiation field is the dose equivalent which would be produced in the related oriented and expanded radiation field at a depth of 10 mm on the radius of the ICRU sphere which is oriented opposite to the direction of incident radiation. An oriented and extended radiation field is an ideal radiation field which is extended and in which the radiation is also oriented in one direction. The biological impact when a tissue is exposed to radiation can be calculated by the total equivalent dose accumulated with time. [54]

The standards help manufacturers in calculating dose rate equivalents from incident radiations, fluence-to-dose rate conversion factors are generally provided. The dependence for H*(10) is illustrated in the figure below:

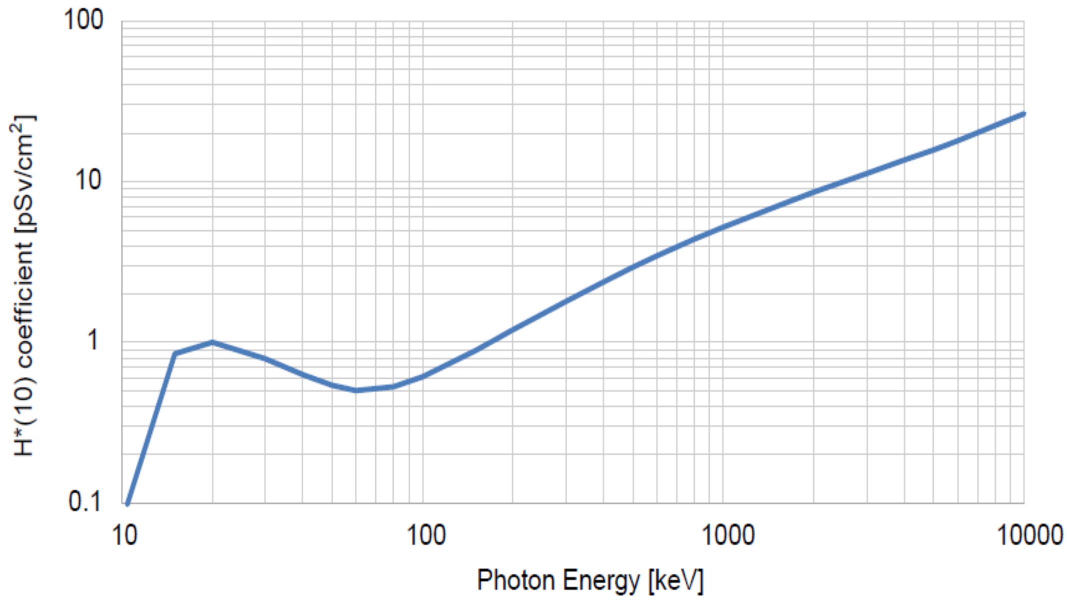

Figure 21- Conversion coefficients for the calculation of equivalent dose based on the incident gamma radiation fluence. Note the logarithmic scale on both axes [54]

There is great challenge in determining a technique to measure high dose rate. Quantum physics behind the techniques is the main preventive factor for the whole problem. In order to measure high doses and not to "saturate" the measuring medium (where interaction of the radiation with matter takes place and is essentially detected), the medium has to be of small size. Several researches deal with high flux measurements of gamma-rays (mostly in astronomical and medical applications), but only few mentions measuring of spectra under such conditions. [55]

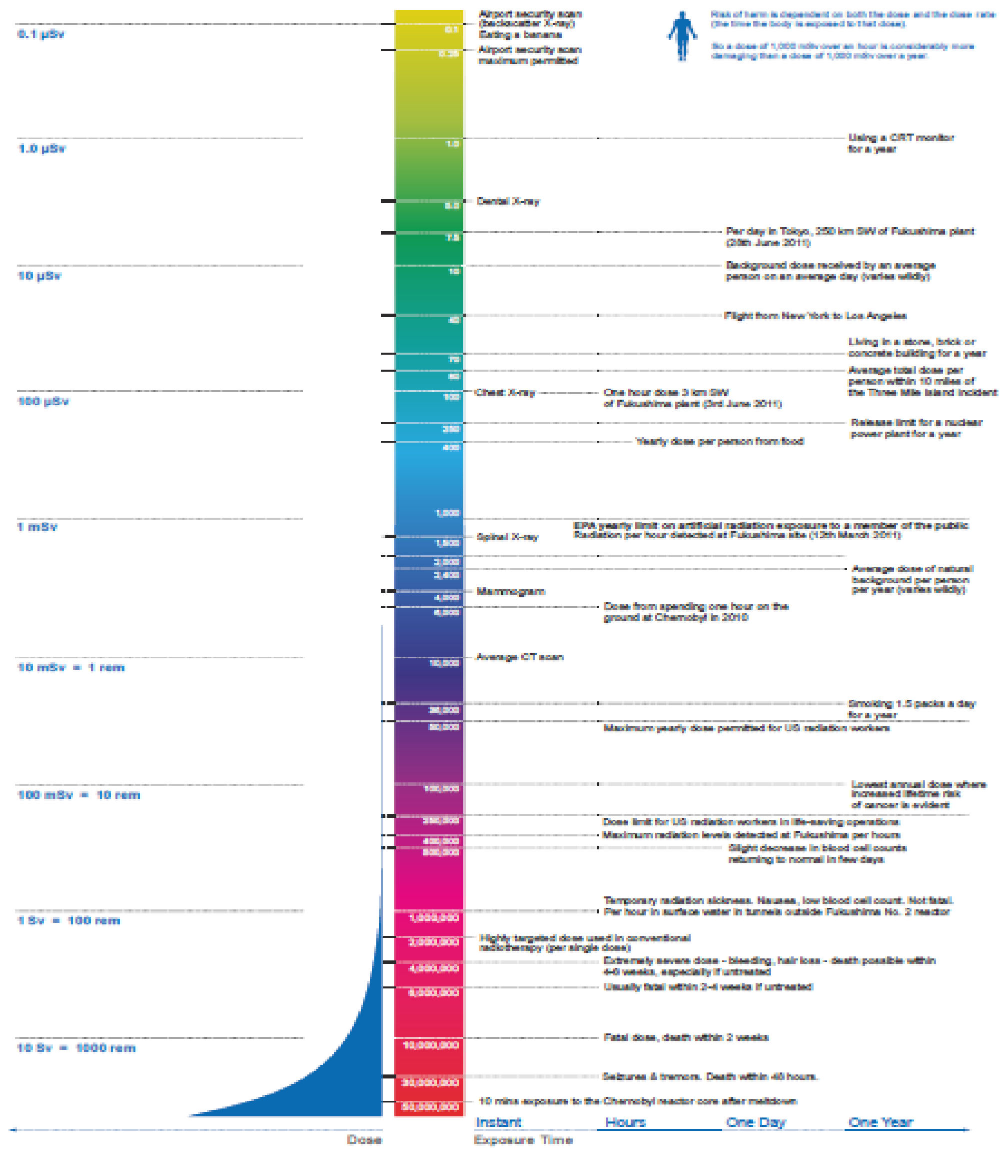

Figure 22 – Radiation dosage chart showing effects of the equivalent absorbed dose. The dose is shown in a logarithmic scale, the doses shown are averages [5]

Chapter 3

3.0 Financial management, resource efficiency and resource conservation Financial Management.

3.1 Pre-analysis

In this research, a description of the model of the radiation state of a nuclear facility is developed, the composition of the model is outlined, the problems of the formation of the engineering-radiation model of the nuclear facility are considered on the basis of the engineering model of radiation inspection and gamma radiation calculations depending on the radionuclide composition, the activity of radiation sources, and also their geometric sizes and shapes.

Methods for calculating radiation emanating from contaminated assemblies of the nuclear facility elements requiring maintenance or disassembly are considered as radionuclide sources of photon radiation having certain physical characteristics, such as dimensions and activity. Sources based on radionuclides are isotropic radiators. The geometric dimensions and shape of such sources can be very diverse in form and size.

3.2 Potential consumers of research results

A model of a gamma-scan detector with collimator to investigate radioactive contamination in a nuclear or radiochemical facility was done using Mathematical models to develop mathematical equations to calculate radioactive contamination.

This work is intended to reduce the time and cost of design, as well as exclude all kinds of collisions related to the mismatch of the real state of the nuclear facility with respect to contamination. This ultimately leads to a decrease in the economic costs of carrying out work on decommissioning of the nuclear facility.

Prospects for a good scientific research are measured by it commercial value and impact on development. Assessment of the economic value is a requirement for a search of funding for scientific research and commercialization of the project. The commercial value or attractiveness of scientific research is not only determined by it exceeding technical parameters over it previous developments. It however depends also on how quickly the developer will be able to find solutions to such questions as whether the product will be in demand by the market, what will be its price, to satisfy the consumer, what is the budget of the scientific project, etc.

Hence the idea behind this section under the Financial Management, Resource Efficiency and Resource Saving is to determine the prospects and success of a research project, to develop a mechanism for managing and supporting specific project solutions at the implementation stage [60].

It includes two parts in this dissertation which are, firstly, the cost of the detector in comparison with other existing detectors, its resource efficiency and

The section of financial management in this dissertation includes two sections, the first section is a pre-analysis of the project and evaluation of cost competitiveness of operating the project. The second includes a budgetary report of the scientific project.

3.3 Cost of Gamma portable gamma spectrometry system

Compact, hand-held, low-resolution spectrometers (Radioisotope Identifiers) cost between 16,000 – 30,000 Euro. Compact, portable high-resolution (electrically cooled HPGe-based) spectrometers cost typically about 70,000-100,000 Euro. Portable (but not compact) spectrometers can be assembled from separate parts, resulting in a system cost which is roughly 50-60% of the above costs. For detectors that are cooled by liquid nitrogen, the cost of the liquid nitrogen supply should be considered. If the detector is to be kept at operating temperature all of the time, then an automated liquid nitrogen filling system and additional work safety measures could be cost effective. The cost of suitable calibration sources and their registration and storage should be included.

3.4 Use for Nuclear Forensics

For on-site applications, high-resolution gamma spectrometry is mostly used to quickly identify radioactive material and obtain a rough idea about the isotopic composition of nuclear material. From the point of view of on-site identification techniques and handling of the material, usually four main categories are considered:

1. Naturally Occurring Radioactive Material (NORM),
2. Medical isotopes,
3. Industrial isotopes,
4. Special nuclear material, as well as any mixture of these four.

For the purposes of nuclear forensic investigations, IAEA Nuclear Security Series No. 2, “Nuclear Forensic Support” defines the categories of nuclear and other radioactive material as follows:

1. Unirradiated direct use material,
2. Irradiated direct use material,
3. Alternative material,
4. Indirect use material,
5. Commercial radioactive sources.

In some cases, specific radioisotopes can be identified using hand-held gamma spectrometers with built-in low-resolution or medium-resolution gamma detectors (based on NaI, $LaBr_3$, CdTe or CdZnTe crystals). These hand-held spectrometers typically employ algorithms to automatically identify radioactive material. They are simple to use and can be operated by first responders (e.g., customs and police officers, fire fighters) to detect, localize and perform initial identification of potentially illicit radioactive material. [61]

3.5 Resource Efficiency

According to the United Nations Environment Program (UNEP), resource efficiency is about ensuring that natural resources are produced, processed, and consumed in a more sustainable way, reducing the environmental impact from the consumption and production of products over their full life cycles. By producing more wellbeing with less material consumption, therefore resource efficiency enhances the means to meet human needs while respecting the ecological carrying capacity of the Earth (UNEP, 2012). With respect to this research, it is a computer base research hence does not require any material for it. It uses LabSOCs which requires time to learn and use.

Sustainable development be contingent on the long-term availability and environmentally sound production of fuel.

The high energy density of uranium (1 tonne of uranium is the energy equivalent of 14 000-23 000 tonnes of coal), the ease with which stocks can be sustained and the widespread geographical distribution of uranium resources all offer security of supply advantages. Previous uranium mining practices that created environmental matters are no longer licensed today. Recent extraction and processing procedures lessen impacts on people and the environment.

Even though uranium is perceived by some to be a limited resource with limited availability, the two previous periods of intense exploration (1940s and 1970s) stimulated by growing demand resulted in the identification of resources far beyond anticipated requirements. Over 2.3 million tonnes of natural uranium has been produced to date and identified uranium resources over the same period have generally increased. As of 2009, identified conventional uranium resources are adequate for 100 years of supply at current rates of consumption.

Arguments against nuclear energy often comprises the belief that accident risk and radioactive waste reduce the contribution of nuclear energy to sustainable development. Over 50 years of experience in OECD member countries demonstrates that responsibly managed nuclear power programs have a very low safety risk and much smaller impacts on the environment and public health than other sources of energy especially with respect to emissions and air pollution.

Radioactive waste is perhaps the most important issue when considering the use of nuclear energy. Advancement has been made in reducing the volume of final waste and next-generation reactors will burn fuel even more efficiently. However, remaining waste has to be addressed and long-term storage is currently the safest and most practicable solution. While such waste needs to be handled with care, above-ground storage in specially designed casks over the past 50 years has been handled with great success and minimal environmental impact. While there is no practical earnestness to implement geological storage of long-lived waste repositories, the construction and commissioning of such facilities prove that the goals of sustainable development can be met. It is also worth noting that radioactive waste represents less than 1% of the overall toxic waste generated by countries with nuclear energy industries. No other category of waste is recorded so precisely and stored so safely.

3.6 SWOT Analysis

SWOT analysis has four elements in a 2x2 matrix. Own strengths illustrate to the company where they are good and should pay attention on its development. By that companies can compensate for their own weaknesses and strengths of the head to obtain information about threats on the background of the future impact of the elimination purposes. Weaknesses can be eliminated by emphasizing the strengths. External opportunities can be obtained from the company's use of research and development activities, teaming with trusted partners and outsourcing some activities.

The table below is the SWOT Analysis of the research work.

Table 1 – SWOT Analysis of the research work

	Positive Factors	Negative Factors
Internal Factors	STRENGTHS 1. Detection of radioactive contaminations. 2. Environmental monitoring of radiation. 3. Does not require higher electrical energy to operate. 4. Simple to use. 5. Reduction in time of survey. 6. Moveable, it can be move from one place to other.	WEAKNESSES 1. Need technical know-how to operate at the facility. 2. Unable to identify some radioisotopes. 3. It effectiveness depends on the angle at which it is situated with respect to the source of the radiation source. 4. Detector efficiency depends on the sensitive volume of the detector, hence a slight change in the sensitivity of the detector volume will affect the efficiency of the detector

	Positive Factors	Negative Factors

External Factors	OPPORTUNITIES	THREATS
	1. Increasing number of radiochemical facilities which will need this equipment. 2. Need of new power generation capacity due to increased electricity demand and necessary replacement of old carbon-emitting power plants. 3. Tighter nuclear rules and regulations.	1. The Harsh weather conditions 2. High background radiations 3. Uncertainties in the construction cost i.e. increase in construction and raw material cost. 4. Nuclear security/terrorist threats to the nuclear infrastructure and materials. 5. Risk of accident during plants' operation, and corresponding risk perception following bad accident management. 6. Smaller market and strong competition from other products

The tables below show the Interactive matrix of the project:

Table 2 – Interactive matrixes of the project

Strengths of the project							
Project Opportunities		S1	S2	S3	S4	S5	S6
	O1	+	+	-	+	+	-
	O2	+	+	+	+	0	+

	O3	+	0	+	-	+	+

Weakness of the Project					
Project Opportunities		W1	W2	W3	W4
	O1	+	+	-	+
	O2	+	-	-	-
	O3	-	-	-	-

Strengths of the project							
Project Treats		S1	S2	S3	S4	S5	S6
	T1	-	-	-	-	-	-
	T2	-	-	-	0	-	+
	T3	-	-	-	-	-	-
	T4	-	-	0	-	+	0
	T5	-	-	-	+	-	-
	T6	-	-	-	-	-	-

Treats of the project							
Project Weakness		T1	T2	T3	T4	T5	T6
	W1	-	-	-	-	-	-
	W2	-	-	-	0	-	-
	W3	-	-	-	+	-	
	W4	-	-	0	-	+	0

Table 3 - SWOT-Analysis

	Strengths Strengths of the research project:	Weaknesses Weaknesses of the research project:
Opportunities	SO 1. Create more of such detection system to help in surveying at nuclear facilities. 2. Use it at radiochemical and nuclear facilities.	WO 1. Build more facilities to open up the market base. 2. Adhere strictly to rules and regulations in the use of nuclear materials.
Threats	ST 1. It can be used to survey radioactive contamination. 2. Simplify its use.	WT 1. Increase security at nuclear facilities. 2. Use good detecting material to enhance efficiency.

3.7 Evaluation of the project ready for commercialization

Table 4 – Evaluation of the project ready for commercialization

Criteria	Degree of elaboration in the research project	Level of developers existing knowledge
Scientific and technical potential is determined	4	3
Promising areas of commercialization of scientific and technological potential are identified	5	3
Industries and technologies (products and services) to offers on the market are identified	3	4
Commodity form (product form) of the scientific and technical basis for the presentation to the market is determined	1	2
Author is identified and protection of their rights is secured	5	3
Assessment of the value of Intellectual Property is done	4	5
Marketing research of potential markets is carried out	3	5
Business plan for commercialization of scientific development is developed	2	2
The ways of promoting scientific development to the market are defined	3	5
The strategy (form) the implementation of scientific development is developed	3	5
International cooperation potential and access to foreign markets are studied	2	3

Use of infrastructure support services to receive benefits is studied	3	2
Funding issues commercialization of scientific development are worked out	2	3
Team for the commercialization of scientific development is formed	5	3
Arrangements for the implementation of a research project are made	2	3
TOTAL POINTS	45	48

3.7.1 Method for the commercialization of scientific and technological research

Trade Patent Licenses

Research commercialization allows technology created during research activities to be further developed into marketable products for the benefit of the public. This is attained through technology transfer, which is a method by which technology, skills, or knowledge developed during research activities at the research institution are applied and used in another place. Technology transfer usually refers to transferring a technology between a research laboratory and a commercial partner, plus industry, academia, and state and local governments.

Patents include a legal monopoly granted to the inventor, licensee or assignee of the discovery and comprises a limited legal right to exclude others from making, using or selling that which has been patented for the duration of a patent.

Transfer to third parties the rights of intellectual property on a license basis. In the patent law distinguishing types of licenses: exclusive (simple), the exclusive, full license, sub-license, options. [62]

The technology transfer process characteristically will include:

1. Recognizing new technologies stemming from the research activities;
2. Protecting the intellectual property of technologies through patents and copyrights;
3. Forming marketing strategies to further develop and commercialize the technology to existing private sector companies or newly created startup companies.

This method of commercialization of the research will enable for engineering and implementation of technologies since this technology needs a lot of money to be implemented. This strategy will also formulate strategies to develop and commercialize to existing nuclear facilities and radiochemical facilities so as to realize the goal of the research.

3.8 Initiation of the Project

To reduce personnel and environmental burdens, it is required to develop a technology to ensure the safe, reliable, and rational decommissioning of commercial nuclear power plants. The developed technology is intended to be used at nuclear and radiochemical facilities. To achieve these purposes, this research seeks to develop a technology to detect and monitor radioactive contamination on techniques for decontamination, reactor dismantling, measurement of residual radioactivity in buildings and waste, waste recycling and decommissioning engineering. To achieve a preliminary reduction in the work-atmosphere dose-equivalent rate during dismantling work.

3.8.1 Objectives and Outcomes of the Project

The table below shows the project goals and results:

Table 5 – The goals and expected results for the research work

Project Objectives:	The research is to develop a gamma-scan with collimator to investigate differential radioactive contamination.

	Develop technological pipes or phantom objects at the nuclear power plants.
Expected results:	Develop a mathematical model to develop a model of a detector.
Requirements for project results:	Requirement:
	LabSOCS software
	Computer
	Mathematical model and Algorithm

3.9 The organizational structure of the project

The table shows the organizational structure and functions of the various participants.

Table 6 – Organizational structure and functions

#	Participant (Name, job position)	Role in the project	Functions	Labor costs per hour (Ruble)
1	Supervisor 1	Project Head and Supervisor	Responsible for the implementation of the project within the given resource constraints, coordinates the activities of the project participants.	300
2	Supervisor 2	Co-supervisor	Financial and Resource efficiency management under the project	300
3	Engineer	Researcher	In charge of formulating the work	100
TOTALS				700

3.9.1 Morphological matrix for research implementation alternatives

Characteristics	Variants				
	1	2	3	4	5
Base	University	Research Institute	Business Company		
Executives	Supervisor	Head of Lab	Research Director	Student	Engineer
Materials	Free	Bought			
Equipment	Free	Bought	Rented		
Software	Free	Bought			
Facilities (office)	Free	Bought	Rented		

3.9.2 Limitations and Assumptions of the Project

Project constraints - are all factors that can serve as a limited degree of freedom of members of the project team, as well as the "project boundary" - parameters of the project or product that will not be realized within the framework of this project.

Table 8 – Constraints and budget for the project

Factor	Limitations/ Assumptions
Project Budget	120000 Rubles
Source of funding	Internal
Duration of the project:	Three (3) months
Date of approval of the project management plan	5^{th} March, 2018
Date of completion of the project	01 May, 2018
Other limitations and assumptions *	Time limitations, time allocated for the research work was not enough.

	Limited access to the Monte-Carlo software.

3.10 Planning and Management of Scientific and Technical Project

3.10.1 Hierarchical structure of the project works

This research demands that a working calendar graph is drawn to represent activities undertaken during the course of the project. This was used to monitor and guide the progress of work.

The Gantt chart was used to map the distribution of the work carried out. Gantt chart is a type of bar charts which is used to illustrate the planned schedule of project, in which the works can be shown the extensive length of time, characterized by the dates of beginning and end of the implementation of these works.

Calendar schedule of R&D on the topic:

Table 9 – Gantt Chart

Work code (from WBS)	Type of works	Executive	T_k cal days	Duration of works									
				Mar		Apr			May			Jun	
				2	3	1	2	3	1	2	3	1	2
1	Compilation of technical specifications	Supervisor 1	4										
2	Developing of Research Structure	Engineer (graduate student)	2										
3	Study of the literature	Engineer (graduate student)	5										
4	Selecting the direction of research	Supervisor 1 and engineers	1										

5	Writing of Literature Review	Engineer/Student	12										
6	Developing of Research Method	Engineer/Student	8										
7	Review by Supervisor	Supervisor 1	4										
8	Corrections	Engineer	4										
9	Results and Discussions	Engineer	15										
10	Writing of Financial and Resource Efficiency	Engineer	6										
11	Social Responsibility	Engineer	4										
12	Conclusion	Engineer	6										
13	Pre-Defense	Engineer	1										
14	Final Defense	Engineer	1										

Calculation of material costs STR:

Material cost calculation is carried out according to the following formula:

$$C_m = (1 + k_{tr}) * \sum_{i}^{m} P_i * N_i \qquad (3.1)$$

Where

m – number of types of material resources consumed in carrying out scientific research;

N_i – the number of physical resources i-th species, planned to be used in carrying out scientific research (pieces, kg, m, mon.)

P_i – acquisition unit price i-th species consumable material resources (rubles / pc, rub / kg, rub / m, rub)

k_{tr} – coefficient taking into account transportation and procurement costs.

Table 10 – Material Cost of the Research

Name	Quantity			Price per unit., Rub.			Costs of materials**(Wm)**, Rub.		
	Alt.1	Alt.2	Alt 3	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3
Computer	1	1	1	28000	40000	50000	28000	40000	50000
Software	1	1	1	-	12000	12000	-	12000	12000
Electricity cost (kWh)		333	250	-	6	6	-	2000	1500
Pens	12	11	10	10	10	10	120	110	100
Note books	5	3	1	30	30	30	150	90	30
Printing	5	5	5	600	600	600	3000	3000	3000
Transpor-tation	15%						4690	8580	9995
Total							35961	65780	76625

The basic salary performers:

$$S_b = S_h * 8 \tag{3.2}$$

where S_h - basic salary of one employee per hour, rub/hour;
Hourly labor rate may vary depending on the type of executive in the research project.

$$S_b = 300 * 8 = 2400$$

Table 11 - Calculation of basic salary

#	Executives			Work, person-days.			Salaries per one person-hours, ths. Rub.			Total salaries at the rate (salary), ths. Rub.		
	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3
	Sup	L.T	R.D	70	65	60	21000	26000	30000	23730	29380	33900
Total:												

Additional salary:

$$S_{ad} = k_{ad} * S_b \tag{3.3}$$

where k_{ad} - factor of additional salary (taken at the design stage at 0.12 - 0.15)

$$S_{ad.1} = 0{,}13 * 21000 = 2730$$
$$S_{ad.2} = 0{,}13 * 26000 = 3380$$

$$S_{ad.3} = 0{,}13 * 30000 = 390$$

Contributions to these funds determined based on the following formula:

$$S_f = k_f * (S_b + S_{ad}) \quad (3.4)$$

where k_f - coefficient for payments to funds (SIF, PF, MIF).

Table 12 – Salary for the Research Work

Artist	Basic salary, rubles.			Additional salary, rubles.		
	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3
Project Manager	21000	26000	30000	2730	3380	3900
Student	-	-	-	-	-	-
ratio of contributions to social funds	27.1%	27.1%	30%	27.1%	27.1%	30%
Total amount of social fund payments, rubles						
Alternative 1	6431					
Alternative 2	7962					
Alternative 3	10170					

Overheads cost is calculated as follows:

Their value is determined by the following formula:

$$C_{ovh} = C_{total} * k_{ovh} \quad (3.5)$$

where

C_{total} – Total costs of the above cost items

k_{ovh} – Overhead coefficient, which can be taken at a rate of 16%.

$C_{ovh.1}$ = (35961 + 21000 + 2730 + 6431) * 0,16=10580 rubles

$C_{ovh.2} = (65780 + 26000 + 3380 + 7962) * 0{,}16 = 16499$ rubles

$C_{ovh.3} = (76625 + 30000 + 3900 + 10170) * 0{,}16 = 19311$ rubles

3.11 Budget of Scientific Research

Table 13 - Calculation of the budget cost of STI

Item	Amount, rub.		
	Alt.1	Alt.2	Alt.3

1. Material costs STR	35961	65780	76625
2. Costs of basic salary	21000	26000	30000
3. Costs of additional salaries	2730	3380	3900
4. Contributions to the social funds	6431	7962	10170
5. Costs of research and production trips	-	-	-
6. Outsourcing	-	-	-
7. Overhead costs	10580	16499	19311
8. Budget expenditures STI	**76702**	**119621**	**140006**

3.12 Effectiveness and efficiency

Effectiveness is measured based on the calculation of the integral index of the effectiveness of scientific research. It is done through weighted average of financial efficiency and resource efficiency.

Comparative evaluation of characteristics of the project alternatives

Integral financial efficiency indicator:

$$E_{fin}^{alt.i} = \frac{TC_i}{TC_{max}} \tag{3.6}$$

Where:

$E_{fin}^{alt.i}$- an integral index of financial efficiency,

TC_i- total cost of the $i - th$ alternative,

TC_{max}-the maximum total cost of research project.

Total cost of research at the university in ruble – 76702

Total cost of research at research institute in ruble– 119621

Total cost of research at business company in ruble – 140006

$$E_{fin}^{alt.U} = \frac{76702}{140006} = 0{,}548$$

$$E_{fin}^{alt.R} = \frac{119621}{140006} = 0{,}854$$

$$E_{fin}^{alt.B} = \frac{140006}{140006} = 1$$

Comparative evaluation of characteristics of the project alternatives:

Table 14 – Comparative evaluation of the project alternatives

Criteria	a_i Weight	b_i Score		
		Alt 1	Alt 2	Alt 3
1. Promotes growth user productivity	0,1	4	5	5
2. Ease of operation (corresponding to the requirements of consumers)	0,15	4	4	5
3. Interferences	0,15	3	4	4
4. Energy savings	0,20	4	2	3
5. Reliability	0,25	4	5	5
6. Material	0,15	3	5	5
TOTAL	1	22	25	27

Integral resource-efficiency indicator:

$$E_{res}^{alt.i} = \sum a_i * b_i \qquad (3.7)$$

$$E_{res}^{alt.1} = 4 * 0{,}1 + 4 * 0{,}15 + 3 * 0.15 + 4 * 0{,}20 + 4 * 0{,}25 + 3 * 0{,}15 = 3{,}70$$

$$E_{res}^{alt.2} = 5 * 0{,}1 + 4 * 0{,}15 + 4 * 0{,}15 + 2 * 0{,}20 + 5 * 0{,}25 + 5 * 0{,}15 = 4{,}10$$

$$E_{res}^{alt.3} = 5 * 0{,}1 + 5 * 0{,}15 + 4 * 0{,}15 + 3 * 0{,}20 + 5 * 0{,}25 + 5 * 0{,}15 = 4{,}45$$

Integral total efficiency indicator:

$$E_{total}^{alt.i} = \frac{E_{res}^{alt.i}}{E_{fin}^{alt.i}} \qquad (3.8)$$

$$E_{total}^{alt.1} = \frac{3{,}70}{0{,}548} = 6{,}752$$

$$E_{total}^{alt.2} = \frac{4,10}{0,854} = 4,800$$

$$E_{total}^{alt.3} = \frac{4,45}{1} = 4,450$$

Comparative project efficiency indicator:

$$E_{comp}^{alt.i} = \frac{E_{total}^{alt.i}}{E_{total}^{min}}$$

$$E_{comp}^{alt.1} = \frac{6,752}{4,450} = 1,517$$

$$E_{comp}^{alt.2} = \frac{4,800}{4,450} = 1,079$$

$$E_{comp}^{alt.3} = \frac{4,450}{4,450} = 1,000$$

Comparative development efficiency

Table 15 – Comparative efficiencies

№ p/p	Indicators		Alt.1	Alt.2	Alt.3
1	Integral financial efficiency indicator	$E_{fin}^{alt.i}$	0,548	0,854	1,000
2	Integral resource-efficiency indicator	$E_{res}^{alt.i}$	3,700	4,100	4,450
3	Integral total efficiency indicator	$E_{total}^{alt.i}$	6,752	4,800	4,450
4	Comparative project efficiency indicator	$E_{comp}^{alt.i}$	1,517	1,079	1,000

Conclusion

It can be concluded that the best place to conduct this research work is Alt. 1 which is the university, in order to attain resource and financial efficiency.

List of Publications

1. O. C. Joseph, E. B. Agyekum, B. K. Afornu, "Effect of Dual Surface Cooling on the Temperature Distribution of a Nuclear Fuel Pellet", www.scientific.net Key Engineering Materials, Vol. 769, pp. 296-310, 2018
2. Ephraim Bonah Agyekum, Yu Daneykin, Odii Christopher Joseph, Afornu Bright Kwame, Ansah Michael Nii Sanka *"Radiation Model of a Technological Pipe of Nuclear Power Plant"* Vol. 8 - Issue 3 (March 2018), International Journal of Engineering Research and Applications (IJERA), ISSN: 2248-9622, www.ijera.com
3. Modelling of Gamma-Scan with Collimator to Investigate Differential Contamination (Accepted for Publication, MEPHI, Journal)
4. Steady State Heat Transfer in Annular Nuclear Fuel Element Using ANSYS APDL: http://www.theijes.com/papers/vol7-issue2/I0702016873.pdf____DOI:10.9790/1813-0702016873
5. Analysis of Temperature Drop along the Radial axis in Steady State Heat Transfer of Nuclear Fuel Element using ANSYS APDL: http://ijpsat.ijsht-journals.org/index.php/ijpsat/article/view/234
6. Validation of Results of Analytical Calculation of Steady State Heat Transfer in Nuclear Fuel Element using ANSYS APDL: https://irjet.net/archives/V5/i1/IRJET-V5I1223.pdf
7. Analysis of Thermal Profiles of Various Power Extraction Limits in a PWR Heated Channel: https://www.irjet.net/archives/V4/i12/IRJET-V4I12315.pdf.