DETERMINATION OF ATTENUATION PROPERTIES OF SOME PETROLEUM PRODUCTS IN GHANA BY GAMMA RAY ABSORPTION TECHNIQUE

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DECLARATION

This thesis is the result of research work undertaken by AUGUSTINE OSEI in the Department of Nuclear Engineering, Graduate School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Dr. C.P.K. Dagadu and Dr. K.A Danso

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DEDICATION

I dedicate this thesis work to God Almighty, Rev. Eastwood Anaba and his wife Rev. Mrs. Rosemond Anaba, my mother Dora Boakye and my father Mr. Augustine Osei

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

(μ/ρ)	Mass attenuation coefficient
(μ_{en}/ρ)	Mass energy absorption coefficient
μ	Linear attenuation coefficient
keV	Kilo electron volts
MeV	Mega electron volts
I_0	Initial Intensity
I	Transmitted Intensity
γ	Gamma ray
$h\upsilon$	Energy of photon
Z	Atomic Number
l	Mean free path
Φ	Fluence
$\dot{\Phi}$	Flux
ψ	Energy flux
B	Buildup factor
Bq	Becquerel

Ci	Curie
Gy	Gray
Sv	Sievert
rad	Radiation absorbed dose
^{137}Cs	Caesium 137
NaI(Tl)	Sodium Iodide in Thallium
cpm	Count per minute
cpm	Count per second
GM	Geiger Muller
mCi	Microcurie
$\left(\mu_{tr}/\rho\right)$	Mass absorption transfer coefficient

LIST OF ABBREVIATIONS

NRRC	Nuclear Reactor Research Center
GAEC	Ghana Atomic Energy Commission
NIST	National Institute of Standard and Technology
GRAT	Gamma ray absorption Technique
A.T.K	Aviation Turbine Kerosene
N.D.E	Non Destructive Evaluation
E_B	Binding Energy
K. E	Kinetic Energy
HVL	Half value layer
AIP	American Institute of Petroleum
CDU	Crude Distillation Unit
RFCC	Residual Fluid Catalytic Cracking
TOR	Tema Oil Refinery

ABSTRACT

The mass attenuation coefficient $\left(\mu/\rho\right)$ and the mass energy absorption coefficient $\left(\mu_{en}/\rho\right)$are important parameters to characterise the penetration and the interaction of gamma rays in chemical materials such as hydrocarbons. Accurate determination of values of$\left(\mu/\rho\right)$ and $\left(\mu_{en}/\rho\right)$ are relevant in estimating certain important physical properties of petroleum products. In this study, gamma – ray absorption technique has been used to determine mass attenuation coefficients and mass energy absorption coefficients of the following petroleum products; Kerosene, Aviation Turbine Kerosene, Gasoline (Petrol) and Gasoil (Diesel). Gamma photon energy of 662 keV from a 30 mCi (^{137}Cs) source was utilised together with NaI (Tl) Scintillation detector and Ludlum ratemeter (Gamma Counter). The Theoretical values of mass attenuation coefficient and the mass energy absorption coefficient of each petroleum products was calculated. Experimental results were compared with theoretical ones showing a good correlation between methods. These attenuation properties can be used to determine some physical parameters of petroleum products such as density and hence check adulterations in petroleum products. The experimental values of $\left(\mu/\rho\right)$ of the petroleum samples range from 0. 0855 to 0.0911 (cm^2/g), the theoretical values of $\left(\mu/\rho\right)$were between 0.0916 and 0.0932(cm^2/g) with error deviation from 3% to 7%. The experimental and theoretical mass energy absorption coefficients$\left(\mu_{en}/\rho\right)$ recorded were in the range of 0.0330 to 0.0352(cm^2/g) and 0.0336 to 0.0342 (cm^2/g) respectively, having an error deviation between 1% and 3%.

CHAPTER ONE

INTRODUCTION

1.1 Background Study

With the extensive usage of radioactive isotopes in industries, medicine, and agriculture, the study of absorption of gamma radiation in chemical materials such as organic compounds has become an exciting field for researchers.

The knowledge of gamma ray attenuation coefficients in biological, chemical and other composite material is of immense significant practical interest for industrial, biological, chemical, agricultural, defense and medical applications (Chitralekha *et al*.,2005).

Accurate and detailed values of photon attenuation of materials are required to provide essential data in diverse fields such as industrial distillation column scanning, nuclear diagnostics (computerised tomography), nuclear medicine, radiation protection, radiation dosimetry, gamma ray fluorescence studies, radiation physics, shielding, and security screening, among others.

The values of photon attenuation coefficients serves as the basis for the calculation of penetration and energy deposition in shielding, biological and other dosimetric materials (Gounhalli *et al*.,2012). The basic quantities used in the assessment of the absorption and energy deposition by photons in materials are mass attenuation coefficient $\frac{\mu}{\rho}$ and mass energy absorption coefficient,$\frac{\mu_{en}}{\rho}$. The knowledge of mass attenuation coefficient $\frac{\mu}{\rho}$ and mass energy absorption coefficient,$\frac{\mu_{en}}{\rho}$ play a vital role in understanding the physical properties of compound materials. These quantities can be estimated theoretically and experimentally (Rao *et al*., 2013).

The mass attenuation coefficient $\frac{\mu}{\rho}$ is a measure of the average number of interactions between incident photons and matter that takes place in a given mass per unit area thickness of the substance under investigation (Hubbell and Seltzer, 1999). Mass energy absorption coefficient is a measure of the average fractional incident-photon energy deposited in an absorber due to interactions between photons and atoms in materials. According to Shakhreet *et al*., (2003), the coefficient of photon interaction of most significance to radiation dosimetry is the mass energy absorption coefficient.

Gamma ray absorption technique is increasingly being utilised and scientific study into the interaction of radiation with organic material such as hydrocarbons is alarmingly gaining grounds in several industrial applications.

1.2 Research Problem Statement

The mass attenuation coefficient, $\frac{\mu}{\rho}$ and mass energy absorption coefficient, $\frac{\mu_{en}}{\rho}$ of petroleum products are important parameters that can be used to estimate some physical properties of the petroleum products, such as; density (bulk density), water (moisture) content etc. These physical properties of the petroleum products can help in quality control analysis, classifying and branding petroleum products, checking levels of adulterations and also studying fuel contaminants.

Although these physical properties of petroleum products can be evaluated from their attenuation coefficients, there are no known methods of determining these attenuation properties of petroleum properties in Ghana. Furthermore, there are no known publications on the mass attenuation coefficients and the mass energy absorption coefficient of Ghanaian petroleum products; few researchers have considered this area of research. The research problem considered in this thesis was to determine the mass attenuation and mass energy absorption coefficients of some Ghanaian petroleum products.

1.3 Research Aim and Objectives

The aim of this research was to determine the attenuation properties of four (4) petroleum products; Kerosene, Gasoline, Diesel and Aviation Turbine Kerosene in Ghana using Gamma ray absorption technique.

The specific objectives of the research were to:

- Estimate the experimental mass attenuation coefficient and mass energy absorption coefficient of each of the petroleum products.
- Calculate the theoretical mass attenuation coefficient and mass energy absorption coefficient of each product.
- Verify and validate the theoretical results with the experimental results.
- Make suggestions and recommendation for further research into the use of radioactive application in the petroleum industry.

1.4 Research Relevance and Justification

The interaction of high energy photons with matter is very essential in industry, medicine and nuclear engineering. Knowledge of radioactive properties such as mass attenuation coefficient and the energy absorption coefficient play a significant role in understanding the physical properties of single-element materials as well as composite materials such as hydrocarbons. These parameters are useful in deriving many other physical parameters of the compound. The attenuation coefficient for gamma rays is an important parameter of absorbing media. Through the value of the mass attenuation coefficient, the density of materials (including hydrocarbons) can be determined. Ferraz, (1985) used the gamma ray attenuation coefficient to determine density and water content of some soil samples. The attenuation coefficient values can also be used to check adulterations in products including fuels. Chaudhari and Girase (2013) used gamma ray attenuation coefficient to check adulteration of some milk samples.

This research work focuses on the determination of mass attenuation coefficients and the mass energy absorption coefficients of Kerosene, Aviation Turbine Kerosene (A.T.K), Gasoline (Petrol) and Diesel (Gasoil). The methodology used in this work can serve as an alternative method for determination of the density, checking adulteration in fuels determining fuel contaminants in Ghanaian petroleum products.

Finally, there have not been much studies on the gamma ray interaction with petroleum products in Ghana, so this work will add up to the few literature in this area.

1.5 Scope of Research

The research involved the process of determining the radioactive attenuation properties of some petroleum products as they interact with incident gamma radiation. The radioactive attenuation parameters that was analysed were, the mass attenuation coefficient and the mass energy absorption coefficient. The determinations of these properties are done experimentally and theoretically. The experimental values were obtained through gamma ray absorption experiment and the theoretical values were obtained using data from Hubbell and Seltzer, (1999).

1.6 Structure of Thesis

Chapter One contains background information on why the study was done, research problem, relevance and objectives.

In Chapter Two, a review and detailed analysis of the relevant literature on the interaction of radiation with matter, linear attenuation, mass attenuation coefficient, radiation exposure, detection and measurements of radiations and review of the petroleum products used.

Chapter Three contains research methodologies of the laboratory procedures and the theoretical considerations. The results obtained for both experimental and the theoretical are presented and discussed in Chapter Four (4).

The conclusions of the study, recommendations and suggestions for further research are presented in Chapter Five (5). There are reference citations and Appendix of relevant data.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Analysis of the essentials of radiation interactions with matter has become a critical research area in Non Destructive Evaluation (NDE). The data on the attenuation of gamma rays and materials are essential for many areas of applications such as; scientific, engineering and industrial. An application for measurement of attenuation coefficient measurement in biological studies is the investigation of linear attenuation coefficient for *Rhizophora spp.* wood (Marashdeh *et al*.,2012).

The density of the *Rhizophora spp.* wood is comparatively close to water which is 1.029 ± 0.006 g/cm^3 and in view of this, the energy used must be low energy.

Singh *et al*., (2012) assessed the gamma attenuation of PbO-BaO-B_2O_3 glass system which is used in radiation shielding. The gamma energy used in the experiment were 511, 662 and 1274 keV. In his work, the results depicted that the mass attenuation coefficients increased linearly with the increase of the lead weight fraction in the absorber.

Gurdeep *et al*., (2010) analysed the mass attenuation coefficient of several materials namely bakelite, perspex, soil and water using a photon energy of 662 keV gamma ray. The gamma ray mass attenuation coefficients for industrial materials such as n-pentane, ethanol, toluene, olein, oil sludge, polyethylene, distilled water, cement were analysed using photon energies of 356 keV and 662 keV gamma ray by Susan (2004).

The gamma ray mass attenuation coefficients for several mono and disaccharides at different photon energies were studied by Chitralekha *et al*., 2015. The gamma ray energy absorption coefficients of H-, C-, N- and O-based samples of biological and chemical interest in energy range 200–1500 keV have been studied by Manjunathaguru and Umesh, 2009.

Mass energy absorption coefficient has critical role in the calculation of the radiation parameters such as absorbed dose in several fields including medical physics, industrial applications in NDT, agricultural irradiation technology, and other important fields (Hubbell, 1982).

Several amounts of energies are transferred into the medium in photoelectric absorption, Compton scattering, and pair production (Hubbell, 1996)

The mass energy absorption coefficients for photon energies of 662 and 1115 keV gamma rays in some fatty acids have been studied by Bhandal *et al*, (1994).The photon mass energy absorption coefficients for 1–100 MeV have been calculated by (Seltzer, 1993). The mass energy absorption coefficients for tumors have been studied by Maughan et al., (1999). Shakhreet *et al* in measured photon mass energy absorption coefficients of paraffins at a photon energy of 662 keV. (Shakhreet *et al*, 2003)

2.2 Gamma Radiation

Gamma radiations are high-energy photons emitted as one of the three types of ra36diation resulting from natural radioactivity. It is the most energetic form of electromagnetic radiation, with a very short wavelength high frequency. Wavelengths of the longest gamma radiation are less than 10 m, with frequencies greater than 1018 hertz. Gamma rays are very robust X-rays; the disparity between the two is based on their roots. X-rays are produced during atomic processes involving energetic electrons.

Gamma is radiated by excited state nuclei or other processes involving subatomic particles. It often escorts alpha or beta particles, as a nucleus emitting those particles may be left in an excited energy level.

The applications of gamma radiation are much the same as those of X rays, both in medicine and in industry. In medicine, gamma ray sources are used for the treatment of cancer and for other medical applications. Radioisotopes that emit gammas are also used as tracers in industry application; which include inspection of castings and welds, scanning of distillation columns etc.

2.2.1. Sources of Gamma radiation

Normal sources of gamma radiation prevalent on earth are made up of gamma decay from naturally occurring isotopes such as potassium-40, and also as a secondary radiation from various atmospheric collisions with cosmic particles. Natural sources that emit gamma radiations are lightning strikes and terrestrial gamma-ray flashes, which produce high energy radiations from natural high-energy voltages.

Gamma rays are produced by a number of celestial processes in which very high-energy electrons are created. Such electrons produce secondary gamma rays by the mechanisms of bremsstrahlung, inverse Compton scattering and synchrotron radiation. Prominent artificial sources of gamma radiations include fission in nuclear reactors, and high particle physics experimentations, such as neutral pion decay and nuclear fusion.

2.3 Interaction of Gamma radiation with matter

When a ray or beam of gamma photons coming from a source is incident on any material, they are attenuated as they traverse through the medium. The process may be an actual absorption process in which the photon reduces in intensity or the photon may be scattered out of the beam.

When gamma rays pass through materials, degree of absorption is dependent on the thickness of the absorber, the density of the material, and absorption cross section of the material. The total absorption depicts an exponential fall of intensity with distance which is denoted mathematically as;

$$I(x) = I_0 e^{-\mu x} \quad (2.1)$$

Where, x is the distance from the incident surface or the thickness of the absorber, μ is the absorption coefficient, measured in cm^{-1}, I_0 and I are the initial and transmitted intensity respectively(Duklin and Goetz, 2002).

Three methods mainly account for absorption of gamma (γ) rays.

These are;

- Photoelectric absorption
- Compton Scattering
- Pair Production

2.3.1 Photoelectric effect

In the process of photoelectric effect, a photon deposits all its inherent energy to knock off an electron in an inner shell from its parent atom. The gamma photon disappears in the process. The energy of the photon is used in whacking the electron out of the shell and giving it some residual kinetic energy.

Photoelectric process is most effective when the collision takes place with the most firmly bound electrons of a parent atom and cannot occur with liberal electrons as a third body is needed to share so as to preserve momentum (Hodgeman, 1961).

When incident photon having energy ofhvsurpasses the electronic binding energy (or ionization energy) E_B, the electron is evicted with a kinetic energy (K.E)

$$K.E = hv - E_B \tag{2.2}$$

The kinetic energy the electron receives equals the photon energy less the binding energy of the struck electron. This procedure, takes place entirely in the direct vicinity of the nucleus. So, the event only takes place with K or L shell electrons and it is more probable with substances of higher atomic number (Z). Conversely, when the photon energy is too high, a nucleus with a high Z cannot maintain the surplus of impulse either, that is why the photoelectric effect is evident up to a limited energy value.

The ejected electron also known as photoelectron can ionize other atoms again along its axis. The electrons freed from the activity of the photoelectron in their turn cause ionizations again along their routes. The formed electron gap in the struck atom is occupied by an electron from an outer shell.

2.3.2 Compton Scattering

The mechanism behind Compton scattering is that only a percentage of the photon energy is transferred from the mobile photon to an electron. The ejected electron, which is called Compton electron (recoil electron), reaches a certain momentum that is dependent on the energy transferred to the electron.

The rest of the energy moves as a photon of lower energy in another routes, and is therefore called a scattered photon. The scattered photon has a longer wavelength than the original because of the lower energy. The probability of Compton interaction surges linearly with scattering material's atomic number and decreases slowly with increasing photon energy.

In the average energies, Compton Effect is the most vital attenuation process. If a photon being scattered does not change its energy, then this process is called coherent scattering (or Raleigh scattering) Compton Scattering or Compton Effect is pictorially described by the Figure 2.1 below.

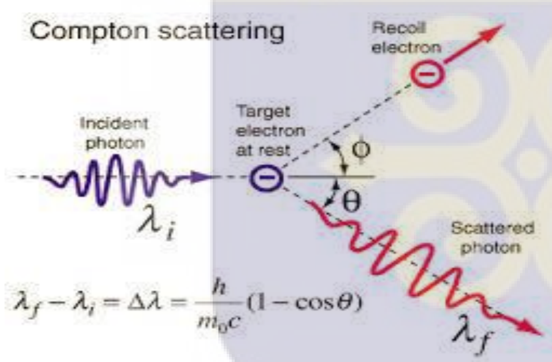

Figure 2.1 Compton Effect (www.hyperphysic.phystr.edu)

2.3.3 Pair Production

In pair production, a gamma ray with minimum energy of 1.022 *MeV* can create an electron-positron pair when it is under the impact of the strong electromagnetic field in the area of a nucleus. In this process the nucleus acquires a very small amount of recoil energy to conserve momentum, but the nucleus is otherwise unchanged and the gamma ray disappears (Jilley, 2001).

If the gamma ray energy exceeds 1.022 MeV, the excess energy is distributed between the electron and positron as kinetic energy. This process is comparatively not significant for nuclear material applications since most important gamma-ray experiments are done with energy below 1.022 MeV. The phenomenon of pair production can be seen in Figure 2.2 below

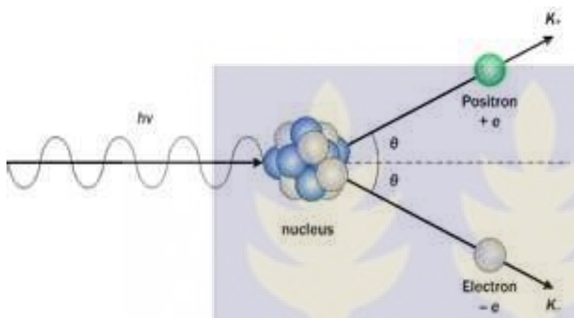

Figure 2.2 Pair Production (www.electrons.wikidot.com)

2.4 Attenuation of Photons

Photon beams navigating through a slab of material can be absorbed or scattered as already mentioned. The attenuation coefficient which is the property of the material defines how suitable a material or medium can be penetrated by beam of photons.

A high attenuation coefficient means that beam is rapidly attenuated as it moves through the medium, and a low attenuation coefficient means that the medium is relatively transparent to the beam. Attenuation coefficient is measured using units of reciprocal length.

2.4.1 Linear Attenuation Coefficient

The linear attenuation coefficient (μ) of a material defines the fraction of a beam of photonic rays that are absorbed or scattered per unit thickness of the material. The linear attenuation coefficients can be used to make a number of calculations. These include; intensity of the energy transferred through a material, intensity of the incident energy, thickness of the material. The type of material can be determined from the value of μ when the incident and transmitted intensity, and the material thickness are known.

Linear attenuation coefficient (μ) cm^{-1} is analysed with a carefully collimated beam of photon moving through a homogeneous material of thickness 't', the ratio of intensity of emerging beam from the source along the incident direction, to the intensity is given by the Beer Lambert law

$$I = I_0 e^{-\mu t} \tag{2.3}$$

Where I_O = Incident photon intensity

I = Transmitted photon intensity

t= Thickness of the material.

The linear attenuation coefficient is used in the contest of X-ray or gamma rays where it is represented by symbol μ and measured in cm^{-1}.

2.4.2 Mass Attenuation Co-efficient

The mass attenuation coefficient describes how a substance absorbs or scatters photon at a known wavelength, per unit mass. The ratio of linear attenuation coefficient (μ) to the density (ρ) is called the mass attenuation coefficient (μ/ρ) and has the dimension of area per unit mass (cm^2/g) (IUPAC, 2006).

The linear attenuation coefficient is the easiest absorption coefficient to measure experimentally, but it is not usually of great concern because of its dependence on the density of the interacting material. For example, at a given energy, the linear attenuation coefficients of water, ice, and steam are all different, even though the same material is involved.

The mass attenuation coefficient is independent of density. In the example mentioned above, water, ice, and steam will all have the same value of mass attenuation coefficient. This coefficient is often reported than the linear attenuation coefficient because it describes the gamma-ray interaction probability of an individual element.

2.4.3 Half Value Layer (HVL)

The material thickness that can attenuate about fifty percent (50%) of the incident energy is known as the half-value layer (HVL). The HVL is inversely proportional to the attenuation coefficient (μ) and the two values are related by equation 2.4 below.

Since μ is normally given in units of cm^{-1}, the HVL is commonly expressed in units of cm. (Akkurst *et al*., 2011)

$$HVL = \frac{0.693}{\mu} \tag{2.4}$$

Like the attenuation coefficient, the half value layer is also dependent on the photon energy. Increment of penetrating energy of a photon, will result in a further increase of a material's HVL.

2.4.4 Mean Free Path (l)

The average distance covered by radiation particle (photon) between two sequential collisions is commonly referred to as the Mean Free Path. In gamma ray radiography, the mean free path of a beam of mono-energetic photons is the average interval the photon journeys between consecutive collisions in the incident material. The mean free path depends on density of the material of concern and the energy of the photons (Brünglinghaus, 2002). Equation 2.5 shows the mathematical expression of the Mean Free path l of a photon

$$l = \mu^{-1} \left(\left({}^{\mu}/_{\rho} \right) \rho \right)^{-1} \qquad (2.5)$$

Where μ is the linear attenuation coefficient, ${}^{\mu}/_{\rho}$ is the mass attenuation co-efficient and ρ is the density of the material

2.4.5 Fluence (Φ)

The number of photons moving through a unit cross – sectional area of a material is referred to as the Fluence. It has units expressed in cm^{-1}. The particle fluence of a photon through a cross-sectional area is given by the expression (Woods and Pikaev, 2001)

$$\Phi = \frac{\text{photons}}{\text{Area}} \quad (2.6)$$

The fluence rate which is the rate at which photons or particles pass through a unit area per unit time is called flux. Flux is simply expressed as the fluence per unit time.

$$\dot{\Phi} = \frac{\text{photons}}{\text{Area} \cdot \text{Time}} \quad (2.6.1)$$

The flux has units of $\dot{\Phi}$ =$\text{cm}^{-2}\text{s}^{-1}$.

The amount of radiative energy passing through a unit cross sectional area of the incident material is known as the energy fluence. For a mono-energetic beam of photons, the energy fluence (ψ) is given as the product of the fluence and the energy per photon. (Podgosark, 2005)

$$\psi = \left(\frac{Photon}{Area}\right) \times \left(\frac{Energy}{Photon}\right) = \Phi E \quad (2.6.2)$$

The energy fluence ψ is expressed in units of energy per unit area, keV/cm^2 or Joules/m^2

2.4.6 Buildup Factor

Gamma photons experiencing scattering re-enter the detector in a broad beam calculation. Practically, accounts are taken of this effect by the introduction of a buildup factor B. The value of the buildup factor (B) is dependent on the nature and the thickness of the attenuating medium and on the energy of the incident gamma photon (Dhillon *et al*, 2012). The buildup factor (B) can be estimated by the following relation:

$$B = \frac{Actual\ \ gamma\ \ ray\ flux}{Flux\ obtained\ \ using\ the\ exponenti\ al\ law} \tag{2.7}$$

The practical attenuation law for gamma rays allowing B takes the form

$$I_x = I_0 B(\mu x. E_\gamma). e^{-\mu(E_\gamma)x} \tag{2.7.1}$$

E_γ is the energy of the gamma photon.

2.4.7 Gamma Ray Shield Design

The purpose of gamma radiation shield design analysis is to find the thickness of a material or a mixture of several materials that would attenuate the initial intensity of radiation exposure to a level that will not harm individuals in the vicinity of the exposed environment. The attenuation factor of a beam of initial intensity I_0 in a shield of thickness x is given by:

$$\frac{I_{(x)}}{I_0} = Be^{-\mu x} \tag{2.8}$$

By taking the natural logarithm of both sides of the equation we have

$$\mu x = -ln\left[\frac{1}{B}\left(\frac{I_{(x)}}{I_0}\right)\right] \tag{2.8.1}$$

If the needed attenuation factors are known, the needed thickness of shield can be estimated by

$$x = -\frac{1}{\mu}ln\left[\frac{1}{B}\left(\frac{I_{(x)}}{I_0}\right)\right] \tag{2.8.2}$$

2.5 Detection and Measurements of Gamma Radiations

For gamma radiation to be recognised for detection they must have some interaction with the medium through which they are moving, and that interaction must be measurable and recordable. Because of the electromagnetic nature of gamma radiation, they interact intensely with the charged electrons in the atoms of all matter.

The key process by which gamma ray is detected is by ionisation, where the gamma photons give up a part or all of its energy to orbital or inner electrons. The ionized electron collides with other atom and removes many more electrons. The liberated charge is collected either directly –as used in proportional counter or a solid-state semiconductor detector.-or indirectly, as used in Scintillation detector, in order to register the presence of the gamma ray and measure its energy. The final result is an electrical pulse whose voltage is proportional to the energy deposited in the detecting method.

2. 5.1 Radiation Measurements

There are different terms used for radiation measurement depending on whether the radiation come from a radioactive source, the radiation dose absorbed by a person, or the risk that a person will suffer health effects (biological risk) from exposure to radiation. The main purpose of radioactive emission is for the stability of the nucleus of the elements of concern

A radioactive atom gives off or emits radioactivity because the nucleus has too many particles, too many energy, or too much mass to be stable. The amount of radiation being emitted or given off by the unstable material is measured using the conventional unit called curie (Ci) or the S. I unit becquerel (Bq).

The radiation dose absorbed by a person; that is the amount of radiation energy deposited in human tissue by radiation is measured using the conventional unit rad or the S.I unit of gray (Gy). The biological risk of exposure to radiation is measured using the conventional unit rem or the S.I unit is Sievert (Sv) as demonstrated in Table 2.1

Table 2.1 Shows measurements table for radiations (www.patientsafetyauthority.org)

Quantity	Units	What is measured	Amount
Exposure	Roentgen or Coulombs/kg	Amount of charge produced in 1 kg of air by x - ray or gamma rays	$1R = 2.5 \times 10^{-4}\ Cb/kg$
Absorbed Dose	Rad Or Gray (Gy)	Amount of energy absorbed in 1 gram of matter from radiation	1rad = 100ergs/gram 1 Gy = 100 rad
Dose Equivalent	Rem Or Sievert	Absorbed dose modified by the ability of the radiation to cause	Rem = rad × Quality Factor 1Sv = 100 rem

2. 6 Biological Effects of Radiation

Biological damage effects associated with ionising radiation interactions with the atoms forming the cells by a process known as ionisation. As a result, radiation effects on humans proceed from the lowest to highest level in the human system.

Exposure to radiation can damage any molecule by ionisation; there are mainly two mechanisms by which radiation adversely affects biological cell known as direct and indirect effects.

With that of the indirect, for example if a radiation interacts with water, it may break the bonds that hold the water molecule together as a unit and it will subsequently produce fragments such as hydrogen (H) and hydroxyl (OH). These fragments may interact with other fragments or ions to form toxic substances, such as hydrogen peroxide (H_2O_2), which can contribute to the destruction of the cell.

2.7 Petroleum Distillates

Petroleum products are materials obtained from crude oil (petroleum) after processing in oil refineries. Unlike petrochemicals, which are a collection of well-defined and usually pure chemical compounds, petroleum products are complex mixtures. The majority of petroleum is converted to petroleum products, which includes several classes of fuels.

There are several products of crude; however this research work focuses on kerosene, gasoline, gasoil and aviation turbine kerosene (A.T.K).

2.7.1 Kerosene

Kerosene is a combustible hydrocarbon mainly liquid and often used as fuel in the industries. The name kerosene is derived from a Greek word (keros) meaning wax and was registered as a trademark by Abraham Gesner in 1854 before developing into global trademark Kerosene is extensively used to power jet engines and some engines of rockets. It is also useful commonly as cooking and lighting fuel (AIP, 2010).

Kerosene is a light pure liquid formed from hydrocarbons obtained from fractional distillation of petroleum between the temperatures of 150 ℃ and 275℃, producing a mixture with a density of 0.78- 0.81g/cm^3 composed of carbon chains that typically contain between 6 and 16 carbon atoms per molecule (Chris, 2007). It can be amalgamated with other petroleum products but immiscible in water. Kerosene contains a mixture of hydrocarbon liquids ranging from $C_{12}H_{26}$ to$C_{15}H_{32}$.

2.7.2 Gasoline (Petrol)

Gasoline is also known as Petrol. Gasoline is a clear liquid obtained by the fractional distillation of petroleum. It is commonly used as a fuel in internal combustion engines. The majority of a typical gasoline is made of hydrocarbons between 4 and 12 carbons atoms per molecule (commonly referred to as C4-C12). It is a blend of paraffins (alkanes), cycloalkanes (naphthenes) and olefins (alkenes) (Chen *et al*., 1993).

The density of gasoline ranges from 0.71- 0.77kg/L (NOAA, 2008). Octanes are a family of hydrocarbon that are typical components of gasoline. They are colourless liquids that boil around 125^{o}C. Another member of the octane family is iso-octane.

Gasoline has substantial impact on the environment, both in local effects (e.g. smog) and in global effects (e.g. effects on the climate). Gasoline is not a simple chemical compound; it is a mixture of different compounds. It is a complicated mixture of hydrocarbons having a boiling point between 49 and 204℃ with chemical formula between C_6H_{14} and $C_{12}H_{26}$ but a good average is octane or iso-octane which is C_8H_{18}. Octane is the simplest form of gasoline that is used for chemical analysis (Dabelstein, 2007)

2.7.3 Gasoil (Diesel)

In general, a diesel fuel is any liquefied fuel used in diesel engines, whose fuel ignition takes place, without spark, due to compression of the inlet air mixture and then injection of fuel. The most prevalent forms of diesel fuel are obtained from the fractional distillation of petroleum fuel oil. However, other diesel forms are not petroleum related, such as biodiesel (which is obtained from vegetable oil or animal fats), synthetic diesel oil (which is produced from any carbon containing material, including biomass, biogas, natural gas, coal etc). For easy reference, diesel derived from petroleum is referred to as Petrodiesel (Knothe *et al*., 2006).

Petroleum diesel or gasoil is composed of about 75% saturated and hydrocarbons and 25% aromatic hydrocarbons. The average chemical formula for common diesel fuel is $C_{12}H_{23}$ ranging from $C_{10}H_{20}$ to $C_{15}H_{38}$ (Gary and Handwerk, 1984).

2.7.4 Aviation Turbine Kerosene (A. T. K)

Aviation Turbine Kerosene or simply Jet fuel is a type of fuel used by the aviation industry. It is greatly sifted to get rid of all potential scum and has an advanced level of quality and purity than the other fuels.

Aviation fuel consist of mixtures of numerous thousand chemicals mostly hydrocarbons (paraffins, olefins, naphthenes and aromatics), additives such as antioxidants, and metal deactivators (www.oilandgasiq.com).

In the next chapter, the methodology used to carry out the work is thoroughly discussed.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

In this chapter, materials, sample preparation, methods, experimental setup, irradiation and counting of initial and transmitted intensities are discussed. Additionally, radiation source used for irradiation of the samples, the detector and radiation counter are also discussed.

3.1.2 Petroleum Samples

The materials used for this research are petroleum products obtained from Crude Distillation Unit (CDU) and the Residual Fluid Catalytic Unit (RFCC) of the Tema Oil Refinery (TOR). The specification of densities of each product was determined by the Quality Control Department of TOR. In all a total of four (4) petroleum products were used for the study.

The petroleum samples used in this study together with their respective densities are given in Table 3.1

The final sampling point of the finished products from the CDU and the RFCC of Tema Oil Refinery, Accra can be seen in Figure 3.1

Table 3.1 Petroleum samples and their respective densities

Distillation Unit	Petroleum Product	Density of Product (g/cm^3)
Residual Fluid Catalytic	Gasoline	0.744
Crude Distillation Unit	Aviation Turbine Kerosene	0. 823
	Kerosene	0. 825
	Gasoil	0.867

Figure 3.1 Sampling point of finished product from the CDU and RFCC of TOR.

Figure. 3.2 View of pipe lines to and from Sampling Points-TOR

3.1.3 Sampling Location – Tema Oil Refinery

The Tema Oil Refinery is the sole crude oil refinery in Ghana.Annually, 1,800,000 tonnes (2,000,000 tons) of refined petroleum products are used in the Ghanaian economy. The refinery's production reduces the cost of petroleum products imported into the country.

Ghana started commercial production of crude oil in December, 2010. The country's Jubilee oil field produces the high grade 'Sweet Light' oil. The installation processes 9,548 tonnes (10,525 tons) of crude oil daily. However, TOR was built to process lower grade crudes and cannot refine oil from the new local fields unless significant investment was made. The refinery has an output capacity of about 6,138 metric tonnes per day.

3.2. Equipment and Methods

3.2.1 Caesium 137 radiation source

The sample was irradiated with Caesium 137. Nonradioactive forms of Caesium occur naturally in several minerals. Radioactive Caesium 137 is produced when compounds such as uranium and plutonium arrest neutrons and undergo fission. This is very evident in nuclear reactors and nuclear weapons.

The splitting of Uranium and Plutonium after the neutron capture produces numerous fission products of which Caesium 137 is one of the products (Kocherov *et al*., 1997). It has a half-life of about 30 years and a specific activity of $3.2 \times 10^2\ Bq/g$ (Unterweger *et al*., 1992).

Caesium experiences high-energy beta decay, mainly to an excited nuclear isomer of Barium 137, which further undergoes gamma decay with a half-life of about 150 seconds.

The energies of both the beta decay of Caesium 137 and the immediate gamma decay of the excited Barium 137 compound are 512 keV and 662 keV respectively (Bunting, 1975)   Furthermore, Caesium is much more chemically reactive than many of the transition metal fission product. As a group 1 alkaline metal, Caesium is quite electropositive and quickly ionised by water (Holleman and Wiberg, 2001).

Caesium 137 is one of the most utilised radioisotopes in industry. Some of the industrial uses of Caesium 137 include;

- Moisture-density gauges, widely used in the construction industry.
- Levelling gauges, used in industries to detect liquids flow in pipes and tanks.

- Thickness gauging, for measuring thickness of a sheet metal, paper film and several products.
- Well logging devices in the dulling industry to help characterise sock strata.
- Industrial scanning of the petroleum distillation column

Caesium 137 is also used in medical radiotherapy to treat cancer.

3.2.2 NaI(Tl) Scintillation Detector

The theory behind Scintillation counters is the detection of the fluorescent radiation emitted when an electron returns from an excited state to the valence band due to absorption of energy from incident source. Through various processes, a gamma ray passing into the crystal may interact with it creating many visible and ultraviolent photons, also called scintillation.

To detect the scintillation photons, the crystal is located next to a photomultiplier tube (PMT) and the scintillation is enclosed in a reflective housing. The scintillation detector is contained in a thick shielding material in order to minimise the effect of background radiation.

Scintillation photons interactions with the photocathode emit electrons through photoelectric emission. High voltage supplies bias the cathode, dynodes and anode so as to fast-track electrons from the cathode through the series of dynodes to the anode collector.

Each incident electron hits a dynode with ample energy to remove around 5-10 (secondary) electrons from that particular incident dynodes. For each initial photoelectron, by the end of the chain, there are about 10^6 electrons at the anode. In most cases, the anode is connected to a charge sensitive preamplifier/amplifier which converts the residual charge to proportional height.

The anode of the photomultiplier tube can also be connected to a counter which converts the collective charges into counts per minute (cpm) or count per second (cps). The amount of photons or light produced in the scintillation counter is proportional to the amount of gamma ray incident in the crystal.

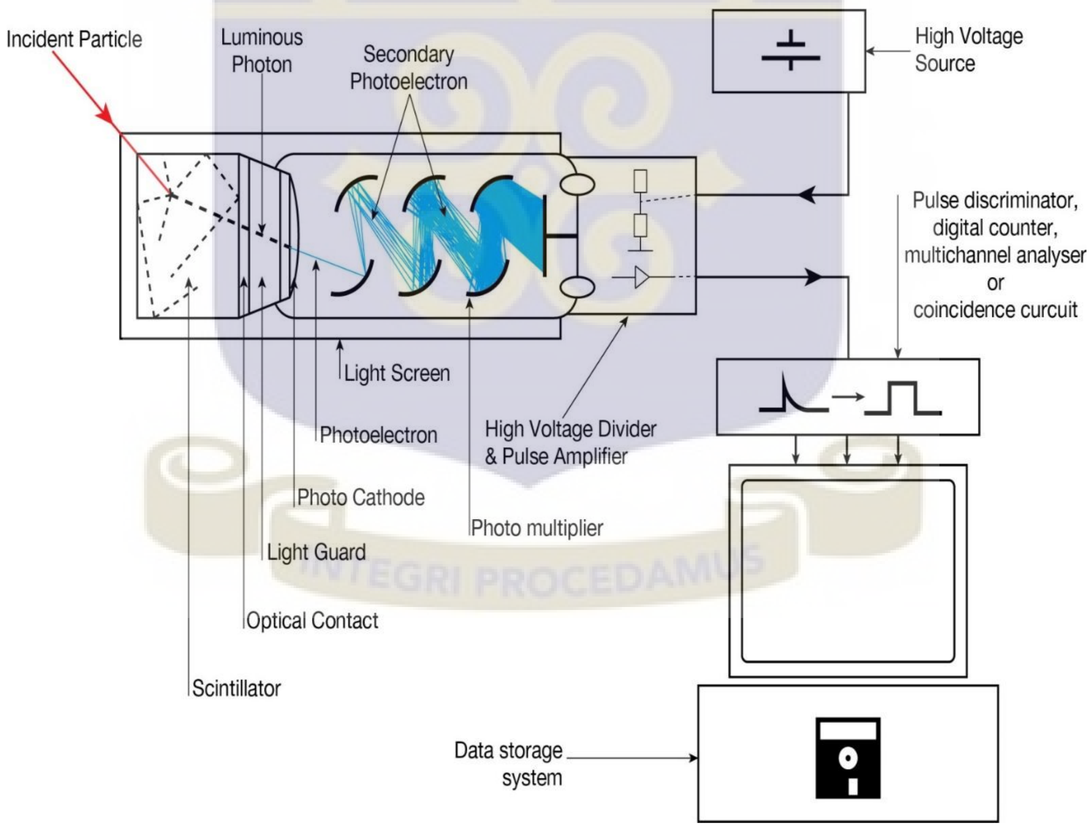

Figure 3.3 Schematic diagram of Na I (Tl) Scintillation Detector (www.wow.com)

Figure 3.4The NaI (Tl) Scintillation detector used in the experiment

3.2.3 Ludlum Model 16 Analyzer

The Ludlum Model 16 Analyzer was used for the experiment. It has complete electronic requirements for scintillation, proportional, or GM monitoring with the added feature of a window discriminator circuit.

A two-position switch, marked WIN IN/OUT allows the instrument to operate as a gross count rate-meter or as a single-channel analyzer. With the WIN switch in the OUT position, the discriminator level is controlled by the THR potentiometer, which is adjustable from 2 to 60 mV. In this mode, the instrument performs as a gross count rate-meter. With the WIN switch in the IN position, the WIN potentiometer controls the high discriminator level. The high discriminator level may be adjusted between the THR level and two times the threshold level (not to exceed 60 mV). Other features include AUD

ON/OFF and fast/slow (F/S) meter response switches, meter RESET and high voltage (HV) test buttons.

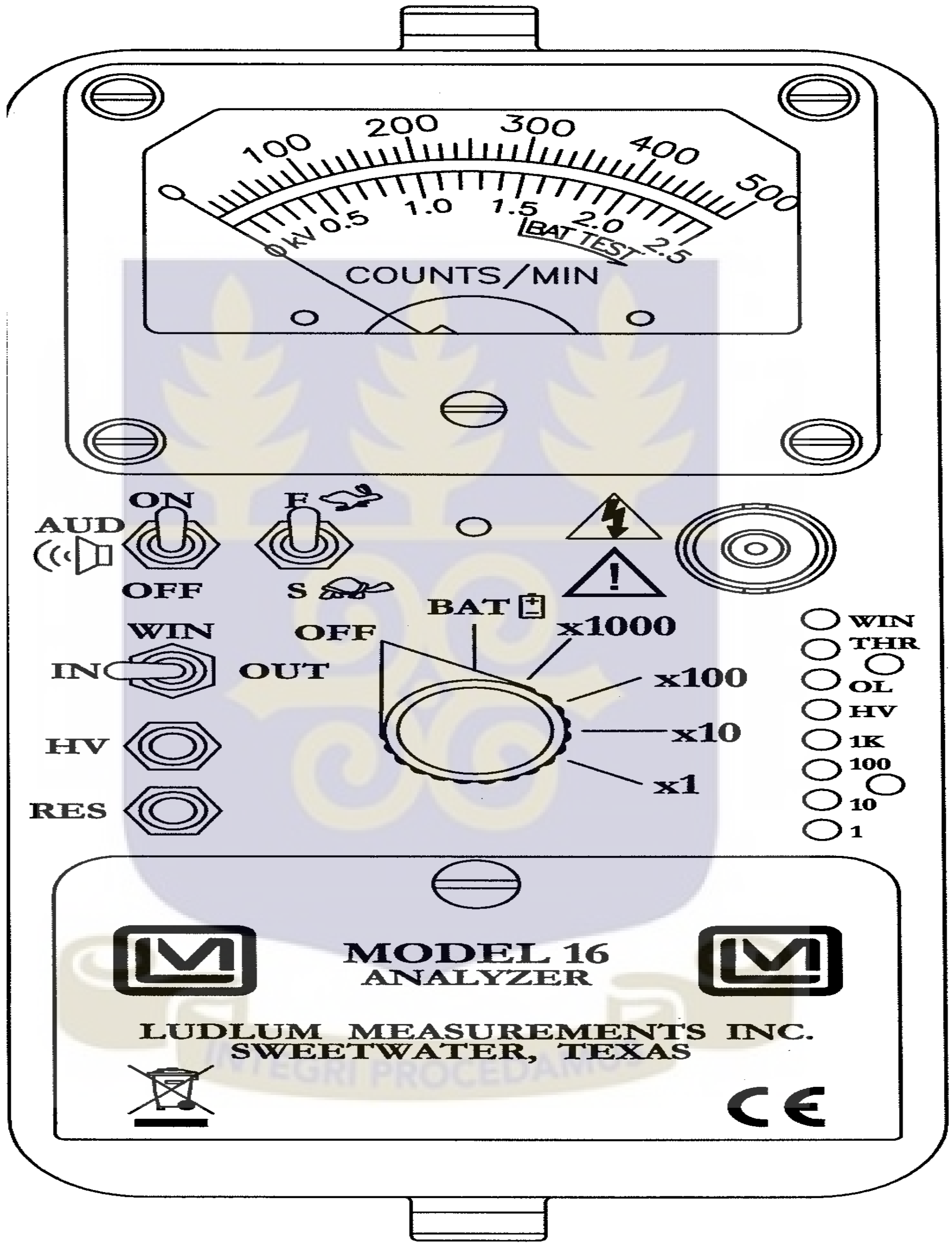

Figure 3.5 Schematic Diagram Ludlum Analyzer (Ludlum measurement, Inc. 2011)

3.2.3.1 Instrument Test

After inspecting the batteries, the instrument range switch was selected at ×1000 position, the AUD ON-OFF was also placed at the ON position and the WIN IN/OUT switched to the OUT position. The instrument speaker emits ″clicks″ relative to the rate of counts detected.

The range switch was rotated through the lower scales until the meter reading is indicated. While observing the meter, fluctuations between the fast and slow response time (″F/S″) positions were selected and variations in the display were observed.

According to Ludlum measurement, Inc. 2011, the ″S″ position should respond approximately 5 times slower than the ″F″ position; the slow response position is normally used when the instrument is displaying low numbers, which require a more stable meter movement. The fast response position is used at high rate levels.

The meter reset (RES) function was also checked by depressing the RES pushbutton and ensuring the meter needle drops to “0.” When the RES pushbutton was released the meter needle recovers to the original reading.

The high value, HV pushbutton was also depressed and it was noted that the meter indicated the high voltage set point.

3.2.3.2 Operating Point

The operating point of the instrument and probes are established by setting the probe voltage and instrument sensitivity between high value and threshold (HV and THR). The proper selection of this point is said to be the key to the instrument performance.

Efficiency, background sensitivity, and noise are fixed by the physical makeup of the given detector and rarely vary from unit to unit.

In setting the operating point, the final result of the adjustment is to establish the system gain so that the desirable signal pulses (including background) are above the discrimination level, and the unwanted pulses from noise are below the discrimination level, and are therefore, not counted.

Total system gain is controlled by adjusting either the instrument threshold or high voltage. Voltage affects control in the probe; THR (threshold) controls the amplifier gain. The operating point for each detector is set at a compromise point of sensitivity, stability, and background contribution.

3.2.3.4 Identification of Controls and Functions Range Selector Switch

There are six-positions switch marked: OFF, BAT, ×1000, ×100, ×10, and ×1.

Turning the range selector switch from OFF to BAT provides the operator with a battery check of the instrument. A BAT check scale on the meter provides a visual means of checking the battery-charge status (Ludlum measurement, Inc. 2011**).** Moving the range selector switch to one of the range multiplier positions (×1000, ×100, ×10, and × 1) provides the operator with an overall range of 0 to 500,000 cpm. Multiply the scale reading by the multiplier to determine the actual scale reading.

3.3 Experimental Setup and Measurements

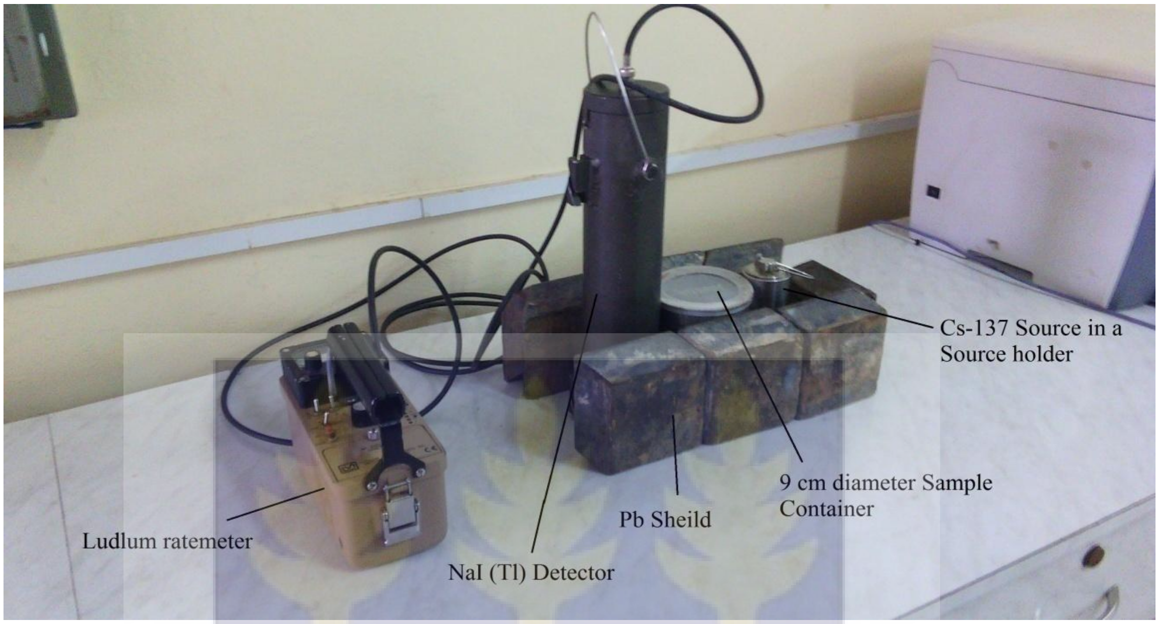

Figure 3.6 Experimental setup of tests

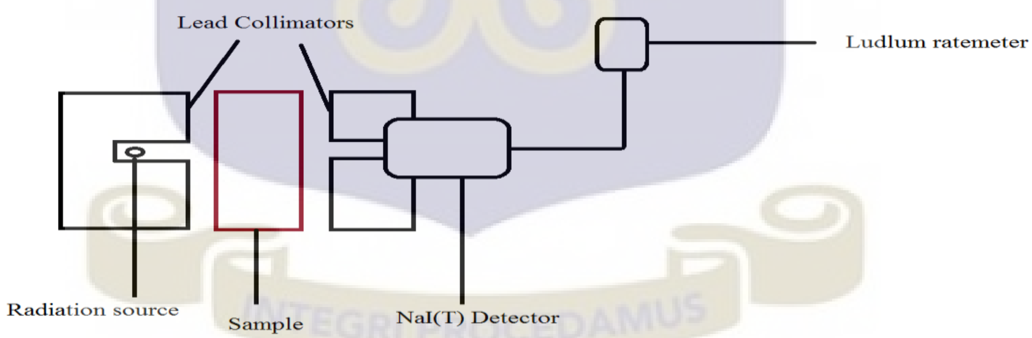

Figure 3.7 shows the schematic diagram of the experimental set up.

3.4 Irradiation and Counting

The petroleum products, each having a volume of 500 cm^3 were poured into an aluminium container with the help of a funnel. To avoid product contamination, each of the containers was cleaned with highly volatile light naphtha. Naphtha is used in petroleum industry for cleaning and blending of petroleum products.

Both the NaI (Tl) detector and the Ludlum analyser were calibrated using 1µCi, 2µCi and 5µCi calibrating source (obtained from the Nuclear Reactors Research Center) to ensure the optimum efficiency of the devices. Before irradiation, the background radiations were measured at different position of the Non-destructive testing laboratory where the experiment was performed. The Caesium source was obtained the Nuclear Reactors Research Center (NRRC) of the Ghana Atomic Energy Commission (GAEC).

The radiation source was picked from its shielding material with the help of a tong, and placed inside a carbon steel radiation source holder where radiation could be properly collimated for sample irradiation. The prepared samples were irradiated with a 30 mCi Caesium 137 source having energy of about 662 keV. The source, sample and detector distance were set in linear arrangement to ensure effective detection in measurement. Each of the petroleum products together with their containers were irradiated, a radiation path length or thickness of absorbers were varied between 5 cm to 10 cm based on different containers of the samples.

The initial intensities (I_0) coming from the collimated source were measured, by placing an empty sample container between the source and the detector, the transmitted intensities through the empty containers were determined. The incident and transmitted gamma-rays intensities for each sample were determined for a fixed preset time of 10 seconds in each experiment by recording the corresponding counts using NaI (Tl) detector having an energy resolution of 10.2% at 662 keV with a 0.2% statistical uncertainty at the fixed counting time. The transmitted intensities I through the petroleum products were determined by the expression below.

$$I = I_0 - (I_c + b + I_{c+s}) \tag{3.1}$$

I_0 is the average intensity of radiation source,

I_c is the average radiation intensities through empty container

b is the average background radiation and

I_{c+s} is the average intensities through both the container and the petroleum samples

3.5 Experimental determination of mass attenuation and energy absorption coefficient

A ray of gamma photon traversing through a medium is governed by the Beer Lambert Law. The initial photon intensity before irradiation of the samples is I_0 , μ is the linear attenuation coefficient measured in cm^{-1} and x is the thickness of the sample or the radiation path length through the sample. The mass attenuation coefficient form of the Beer Lambert Law is written in the form,

$$I = I_0 \exp[-(^{\mu}/_{\rho})\rho x] \tag{3.2}$$

The mass attenuation coefficient is $(^{\mu}/_{\rho})$, which is a better material property than the linear attenuation coefficient is a ratio of the linear attenuation coefficient to the density of the material. It has units of (cm^2/g). The product $\rho x = t$ is known as the *mass thickness* of the absorber. The mass thickness is a very essential property of any material because it determines a material's degree of attenuation. The thickness of material used in radiation measurements is often mass thickness rather than physical.

The mass thickness is the ratio of the mass of the material to its area. Additionally, it is the direct multiplication of the density of the product and its physical thickness. The mass attenuation coefficient was determined experimentally by the equation (3.5).

$$lnI = ln\, I_0 + \text{lnexp}\left[-\left({}^{\mu}/_{\rho}\right)\rho x\right] \quad (3.3)$$

Taking natural log of both sides of equation (3.2)

$$lnI = ln\, I_0 + \left[-\left({}^{\mu}/_{\rho}\right)\rho x\right] \quad (3.4)$$

$$lnI = \left[-\left({}^{\mu}/_{\rho}\right)t\right] + ln\, I_0 \quad (3.5)$$

In the experimental determination, linear plot of $\ln I$ to the mass thicknesses$t$ gives a gradient, which is the estimated value of the mass attenuation coefficient as used by Akca and Erzeneoglu, (2014).

3.5.1 Experimental mass energy absorption coefficient

Manjunathaguru and Umesh (2009) evaluated a simple parametrization of mass energy absorption coefficient as related to the mass attenuation coefficient by the following semi-empirical relation.

$$\left({}^{\mu_{en}}/_{\rho}\right) = 1.92 \times 10^{-4} \left({}^{\mu}/_{\rho}\right) E^{(1.983 - 0.125 \ln E)} \quad (3.6)$$

The experimental mass attenuation coefficients$\left({}^{\mu}/_{\rho}\right)$ and the energy of irradiation E were used as input parameters to estimate the experimental mass energy absorption coefficients of the samples as given in equation 3.6

3.6 Theoretical calculation of the mass attenuation coefficients and mass energy absorption coefficients.

Assumptions made in the theoretical calculation of the attenuation coefficients

- The petroleum products were assumed to be composed of only hydrocarbons (Carbon and Hydrogen)
- The general chemical equations of Kerosene, Gasoline and Diesel were used in the calculation. There is no known chemical formula for Aviation Turbine Kerosene (A.T.K)
- Kerosene has a range of $C_{12}H_{26}$ to $C_{15}H_{32}$as stated in literature, however the average of the above range was chosen for the theoretical consideration, i.e. $C_{13}H_{28}$
- Octane (C_8H_{18}) is usually used for chemical analysis of Gasoline (Dabelstein et al., 2007). So Octane is used in this work for the theoretical calculation of the Gasoline samples.
- Diesel has a range of hydrocarbons ranging from $C_{10}H_{20}$ to $C_{15}H_{28}$, however the average chemical formula for common diesel is $C_{12}H_{23}$(Anil, 2011).

Table 3.2 Petroleum samples used in the work for the theoretical considerations

Samples	General Molecular Formula	Average Formula used in the experiment
1. Kerosene	$C_{12}H_{26}$ to $C_{15}H_{32}$	$C_{13}H_{28}$
2. Gasoline	C_6H_{14} to $C_{12}H_{26}$	C_8H_{18}
3. Diesel	$C_{10}H_{20}$ to $C_{15}H_{28}$	$C_{12}H_{23}$
4. ATK	----	----

3.6.1 Theoretical mass attenuation coefficient

For compound materials composed of several elements, the total value of the (μ/ρ) is the sum of the $(\mu/\rho)\ i$ values of each constituent. The mass attenuation coefficient is given by Jackson and Hawker, (1981).

$$(\mu/\rho) = \sum w_i(\mu/\rho)i \qquad (3.7)$$

The value w_i is the weight fraction of the ith element in the compound and $(\mu/\rho)i$ is mass attenuation coefficient of the ith element. For multielement materials, the weight fraction or weight contribution is given by the relation;

$$w_i = \frac{n_i A_i}{\sum n_i A_i} \qquad (3.8)$$

A_i is the atomic weight of the ith element and n_i is the number of formula units. The values of the mass attenuation coefficient (μ/ρ) for Carbon and Hydrogen were obtained from the data of Hubbell and Seltzer, (1999) (Please refer to the Appendix III).

3.6.2 Theoretical mass energy absorption coefficient

The theoretical mass energy absorption coefficient values were calculated using the relation; $(\mu_{en}/\rho) = \sum w_i\,(\mu_{tr}/\rho)(1-g)$ (3.9)

The factor g represents the average kinetic energy of secondary charged particles (produced in all types of interactions), that is subsequently lost in radiative energy –loss processes as the particles slow to rest in the medium (Seltzer, 1993). The factor μ_{tr}/ρ is the mass energy transfer coefficient. The values of $(\mu_{tr}/\rho)(1-g)$ for photon energies have been tabulated and published by Hubbel and Seltzer (1999) (Please refer to Appendix III)

The percentage deviation of the mass attenuation coefficient is obtained by (Mitkar and Dongarge, 2012)

$$\text{Percentage error} = \frac{\left(\mu/\rho\right)_{th} - \left(\mu/\rho\right)_{exp}}{\left(\mu/\rho\right)_{th}} \times 100\% \qquad (3.91)$$

$\left(\mu/\rho\right)_{th}$ is the theoretical mass attenuation coefficient and $\left(\mu/\rho\right)_{exp}$ is the experimental mass attenuation coefficient.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Experimental mass attenuation coefficient

The transmitted radiation counts I through the samples were evaluated using equation (3.0) and the mass thicknesses$t = (\rho x)$ of the sample which is a product of the thicknesses of samples and their respective densities were also evaluated. (See Appendix II for details) The transmitted intensities through the petroleum samples were plotted against the mass thicknesses of the samples in order to estimate the experimental mass attenuation coefficients of each sample. Tables of values of all the plots can be obtained at the Appendix II

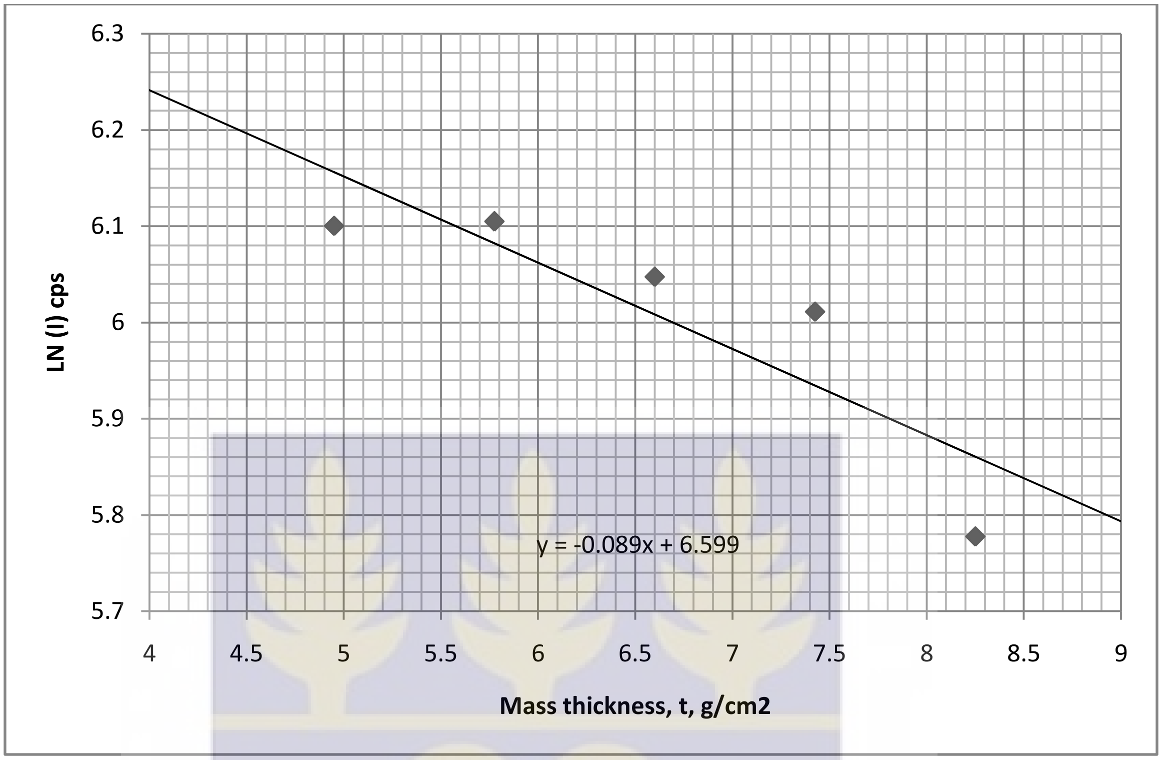

Figure 4.1 Graph of transmitted intensities versus mass thicknesses of Kerosene samples obtained at gamma photon energy of 662 keV.

The gradient of the graph is the mathematical estimation of the mass attenuation coefficient of the Kerosene samples as mention in equation (3.5).

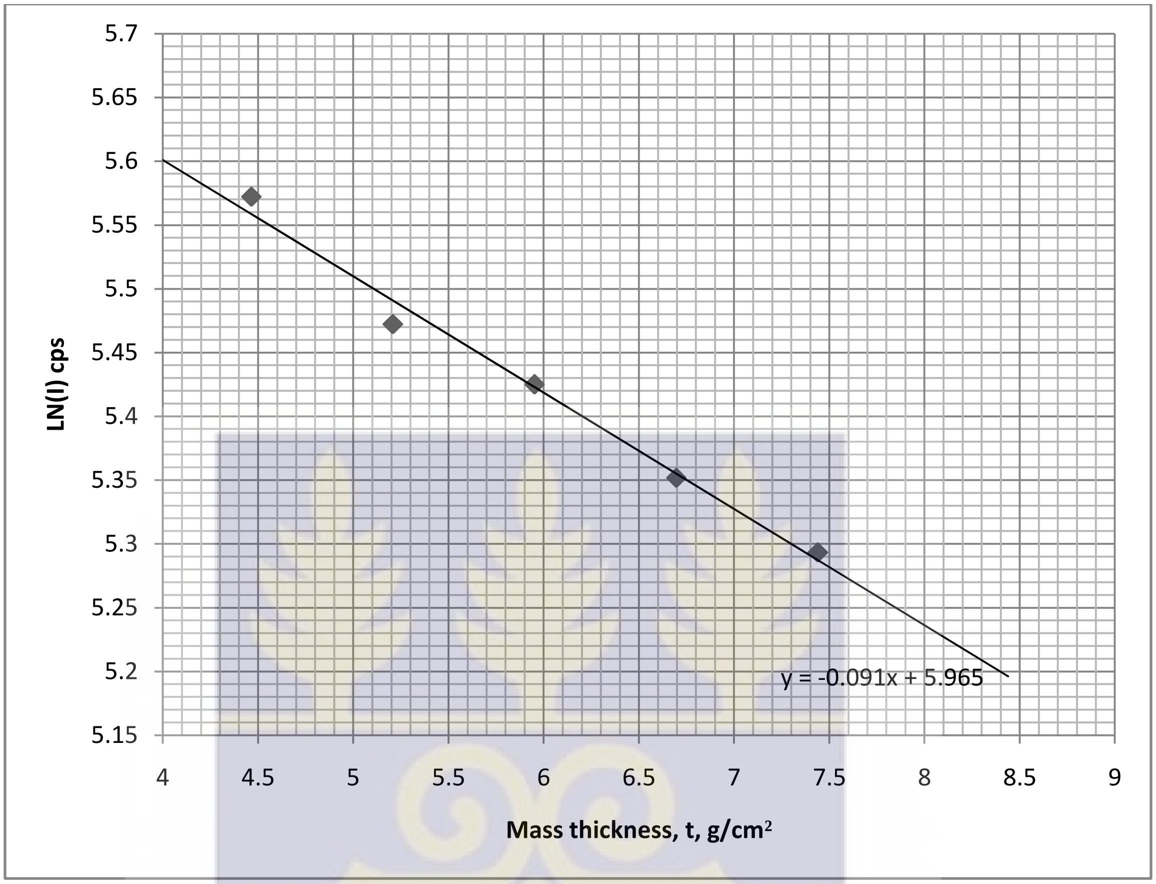

Figure 4.2 Graph of transmitted intensities versus mass thicknesses of Gasoline samples obtained at gamma photon energy of 662 keV.

The gradient displayed on the graph is the mathematical estimation of the mass attenuation coefficient of the Gasoline samples used.

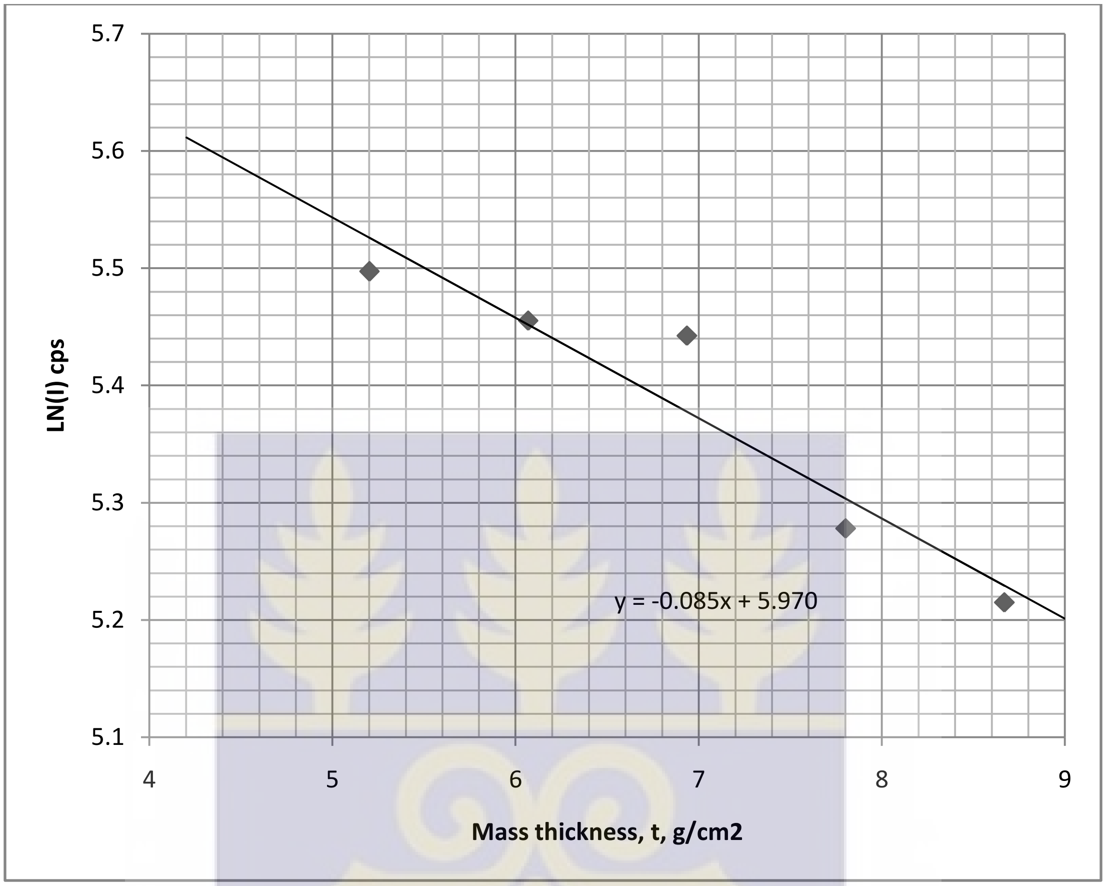

Figure 4.3 Graph of transmitted intensities versus mass thicknesses of Diesel samples obtained at gamma photon energy of 662 keV.

The gradient displayed on the graph is the mathematical estimation of the mass attenuation coefficient of the Diesel.

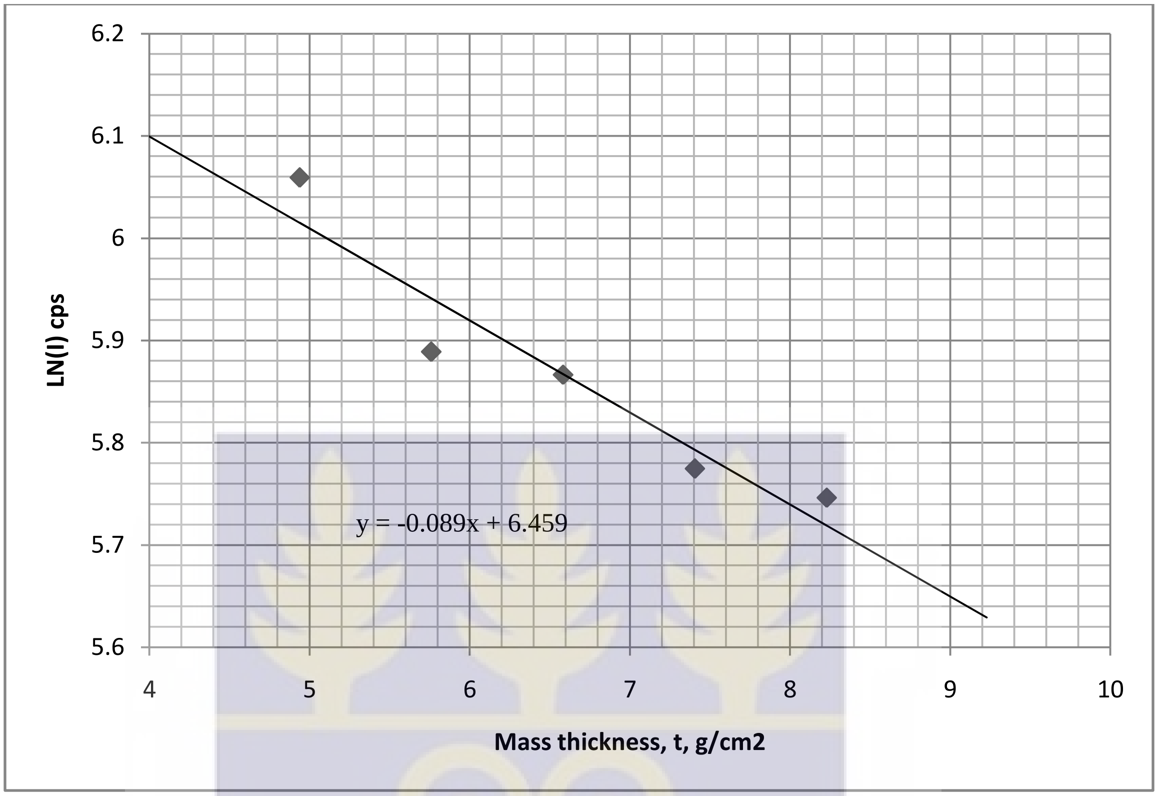

Figure 4.4 Graph of transmitted intensities versus mass thicknesses of Aviation Turbine Kerosene samples obtained at a gamma photon energy of 662 keV.

The gradient displayed on the graph is the mathematical estimation of the mass attenuation coefficient of the (A.T.K) samples.

The graphs in Figure 4.1 to Figure 4.4 show the intensities curve as a function of the sample thicknesses. From the graphs, it can be observed that the intensities decrease when the sample thicknesses are increased. The decreasing of the intensities when the thicknesses of the samples are increased is due to the attenuation of the incident photons as they traverse through the sample. The attenuation curves given in the graphs above confirm the attenuation law given in equation (3.1).

The fundamental law of gamma radiation attenuation is that, the transmitted radiation intensity depends on the composition of the absorber, the energy of the incident gamma photon and the thickness of the absorber. (Demir and Tursucu, 2012). The experimental values obtained agree with the inverse relation existing between the transmitted radiation intensity and the thickness of the material under investigation as given in the Beer Lambert law.

Table 4.1 Experimental mass attenuation coefficients of petroleum products obtained in the experiment.

Petroleum products used in the experiment.	Experimental mass attenuation coefficient, $(^{\mu}/_{\rho})$ in cm^2/g
Kerosene	0.0896
Gasoline	0.0911
Diesel	0.0855
Aviation Turbine Kerosene	0.0899

From the above table, it can be observed that, diesel samples recorded the least value of mass attenuation coefficient, and Gasoline had the highest value of the mass attenuation. Although the products used are mainly composed of hydrocarbons, they all recorded different values of the mass attenuation coefficient. This is because, although they are basically hydrocarbons, their chemical compositions are different. This means that, the attenuation properties take into consideration the chemical composition of compounds as observed by Demir and Tursucu, (2012). It was also observed that, for different materials, the mass attenuation coefficients were higher for less dense medium and lower for denser medium

.

Table 4.2 Experimental mass energy absorption coefficient of petroleum products used in the study.

Petroleum products used in the experiment.	Experimental mass energy absorption coefficient, $\left(\mu_{en}/\rho\right)$ in cm^2/g
Kerosene	0.0346
Gasoline	0.0352
Diesel	0.0330
Aviation Turbine Kerosene	0.0347

The values of the mass energy absorption coefficient of the petroleum products were calculated with the help of equation (3.6). The values show the quantity of photon energy deposited in each of the medium. It can also be observed that the mass energy absorptions are different for all the samples used. Higher value of the mass energy absorption coefficient means more energy is deposited in the material.

4.2 Theoretical Determination of the Mass Attenuation Coefficient and Mass Energy Absorption.

In the theoretical consideration, the weight percentages of each constituent (Carbon and Hydrogen) of the test samples were calculated using equation (3.7). The mass attenuation coefficients of the samples were evaluated using equation (3.6). The mass attenuation coefficient and the mass energy absorption coefficient of carbon and hydrogen were obtained from the values of attenuation coefficients tabulated and published by Hubbell and Seltzer, (1999) which can be obtained at Appendix III.

The mass attenuation coefficient and mass energy absorption coefficient of both Carbon and Hydrogen were obtained using energy of 662 keV on the data from Hubbell and Seltzer, (1999).

Table 4.3 Theoretical mass attenuation coefficients of samples at 662 keV photon energy

Products	General Chemical Equation	Mass Attenuation Coefficient of Carbon $(\mu/\rho)_c$	Mass Attenuation Coefficient of Hydrogen $(\mu/\rho)_H$	Weight Fraction of Carbon w_c	Weight Fraction of Hydrogen w_H	Mass Attenuation Coefficient of Product (μ/ρ) cm^2/g
Kerosene	$C_{13}H_{28}$	8.058E-02	1.599E-01	0.846914036	0.153085964	0.0927
Gasoline	C_8H_{18}	8.058E-02	1.599E-01	0.841165348	0.158834652	0.0932
Diesel	$C_{12}H_{23}$	8.058E-02	1.599E-01	0.861435846	0.138564154	0.0916
Aviation Turbine Kerosene	----	------	------	------	-----	------

From Table 4.3, Gasoline recorded the highest value of the mass attenuation coefficient and Diesel had the least value of the mass attenuation coefficient. A similar occurrence was recorded in the experimental results.

Table 4.4 Comparison between the theoretical and experimental values of the mass attenuation coefficients of samples

Petroleum Products	Experimental Mass Attenuation Coefficient $\left(\frac{\mu}{\rho}\right) exp$	Theoretical Mass Attenuation Coefficient $\left(\frac{\mu}{\rho}\right) th$	Percentage Deviation(%)
Kerosene	0. 0896	0.0927	3.344
Gasoline	0.0911	0.0932	2.253
Diesel	0.0855	0.0916	6.659
Aviation Turbine Kerosene (A.T.K)	0.0899	---------	-------

From Table 4.4, the theoretical and the experimental values of the mass attenuation coefficient agree fairly with each other. The error range between the experimental and the theoretical value is from 3% to 7%. The theoretical value of the mass attenuation coefficient was not calculated for Aviation Turbine Kerosene, this is because there is no known general chemical formula for A.T.K.

Table 4.5 Theoretical Mass Energy Absorption Coefficient of Samples at 662 keV

Products	General Chemical Equation	Mass Energy Absorption Coefficient of Carbon $(\mu_{en}/\rho)_C$	Mass Energy Absorption Coefficient of Hydrogen $(\mu_{en}/\rho)_H$	Weight Fraction of Carbon w_c	Weight Fraction of Hydrogen w_H	Mass Energy Absorption Coefficient of Product (μ_{en}/ρ)
Kerosene	$C_{13}H_{28}$	2.96E-02	5.88E-02	0.846914036	0.153085964	0.0340
Gasoline	C_8H_{18}	2.96E-02	5.88E-02	0.841165348	0.158834652	0.0342
Diesel	$C_{12}H_{23}$	2.96E-02	5.88E-02	0.861435846	0.138564154	0.0336
Aviation Turbine Kerosene	-----	-------	-------	------------	-----------	-------

From the table of Hubbel and Seltzer, (1999) which has been published by National Institute of Standard and Technology, the mass energy absorption coefficients of carbon and hydrogen were obtained, and together with their respective weight fractions, the total mass energy absorption coefficient of the compound were evaluated. (See Appendix III for details)

Table 4.6 Comparison between Experimental and Theoretical values of Mass Energy Absorption Coefficient of petroleum products at photon energy

Petroleum Products	Experimental Mass Energy Absorption Coefficient $(\mu_{en}/\rho)exp$	Theoretical Mass Energy Absorption Coefficient $(\mu_{en}/\rho)th$	Percentage Deviation (%)
Kerosene	0.0346	0.0340	1.765
Gasoline	0.0352	0.0342	2.934
Diesel	0.0330	0.0336	1.786
Aviation Turbine Kerosene (A.T.K)	0.0347	--------	-------

The values of the experimental and theoretical mass energy absorption coefficients as observed are very close. The lowest percentage deviation occurred in Kerosene and the highest percentage error was recorded for Diesel. From the table, the percentage error as provided by (Miktar and Dongarge, 2012) is within the range of 1% and 3%. The theoretical mass energy absorption of Aviation Turbine Kerosene could not be evaluated because there is no known general chemical formula for it.

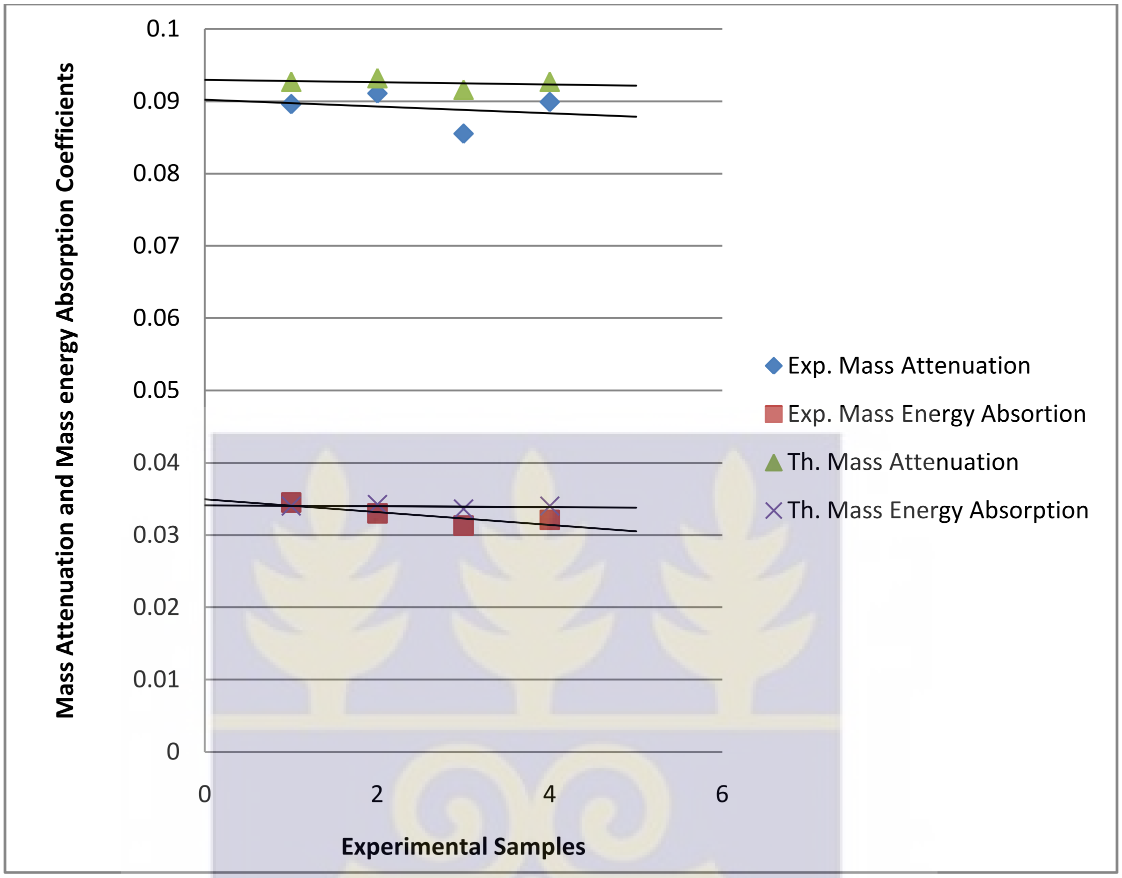

Figure 4.5 Comparison between the theoretical and experimental values of mass attenuation coefficients and mass energy absorption coefficients of the four samples used in the research.

From the figure above, it can be observed that, the experimental mass attenuation coefficients are in good agreement with the theoretical values of the mass attenuation coefficients. Furthermore, it can also be observed that, the experimental values obtained for the mass energy absorption coefficient are closer to the values of the same property obtained theoretically, with only a few percentage deviations.

4.3 Theoretical calculation of the Mass Attenuation Coefficient and Mass Energy Absorption Coefficient of Kerosene with gamma photon energy in the range of 10 keV to 2 MeV

The experimental data were obtained by using a Caesium source of photon energy 662 keV. However, since attenuation properties depend on the photon energies, the attenuation properties within a wide range of photon energies were theoretically evaluated to study the effect of different gamma energy on both mass attenuation coefficient and the mass energy attenuation coefficient. These values were estimated based on the values for the mass attenuation coefficient and mass energy absorption coefficient of Carbon and Hydrogen published by NIST by Hubbell and Seltzer, (1999) which is given in Appendix III.

The mass attenuation coefficients and the mass energy absorption coefficients of each petroleum product were plotted as a function of photon energies from 10 keV to 2 MeV. Two plots were obtained for each of the petroleum product, from 10 keV to 100 keV and from 150 keV to 2 MeV.

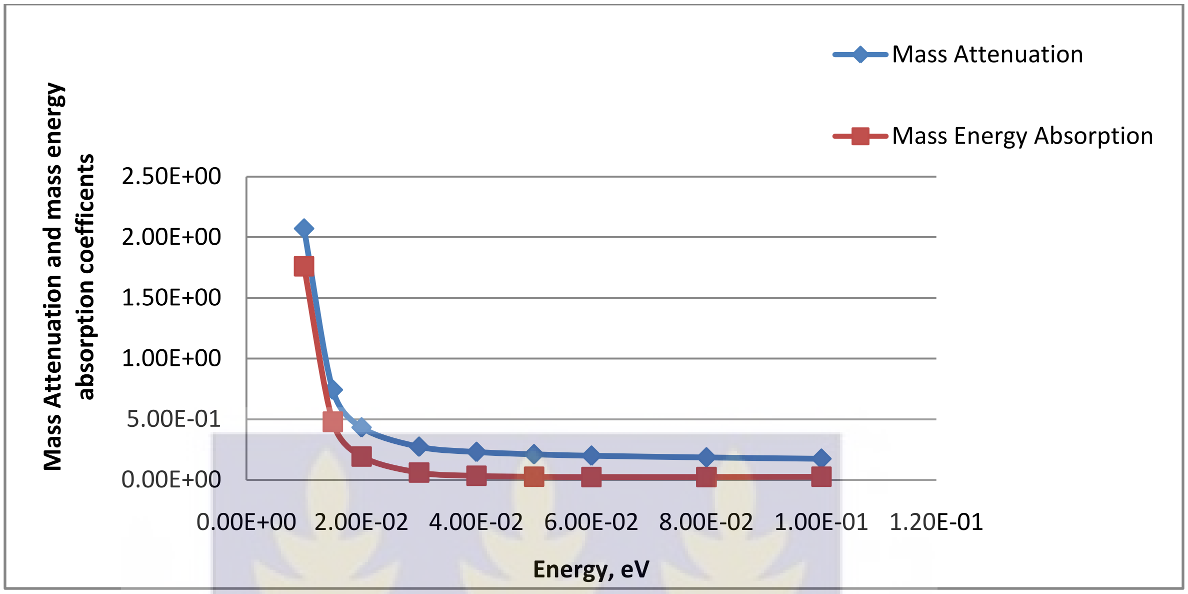

Figure 4.6.1 Comparison of theoretical values of mass attenuation coefficient and mass energy absorption coefficient of Kerosene from 10 keV to 100 keV

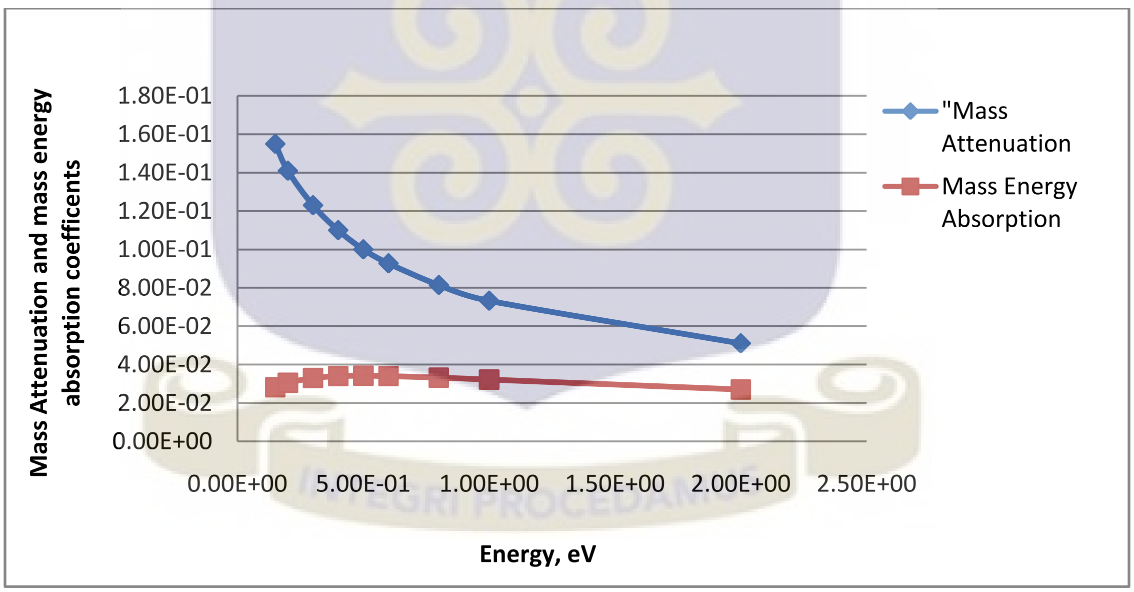

Figure 4.6.2 Comparison of theoretical values of mass attenuation coefficient and mass energy absorption coefficient of Kerosene from 150 keV to 2 MeV.

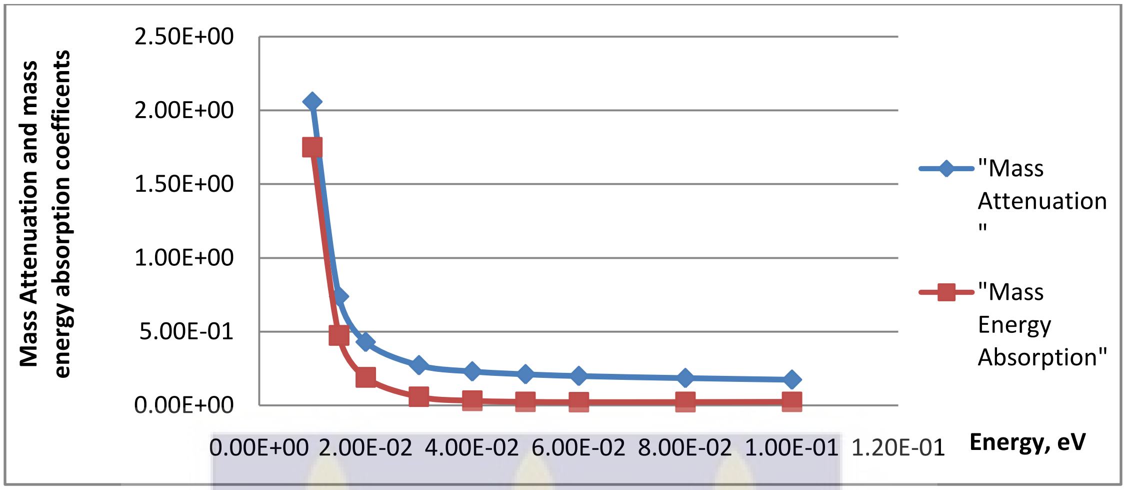

Figure 4.7.1 Comparison of theoretical values of mass attenuation coefficient and mass energy absorption coefficient of Gasoline from 10 keV to 100 keV

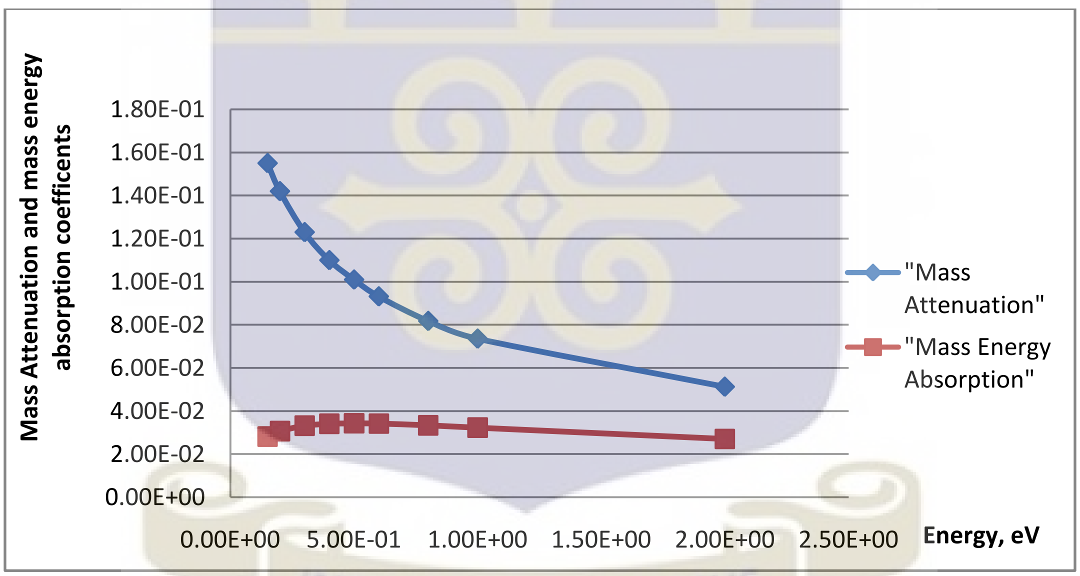

Figure 4.7.2 Comparison of theoretical values of mass attenuation coefficient and mass energy absorption coefficient of Gasoline from 150 keV to 2 MeV.

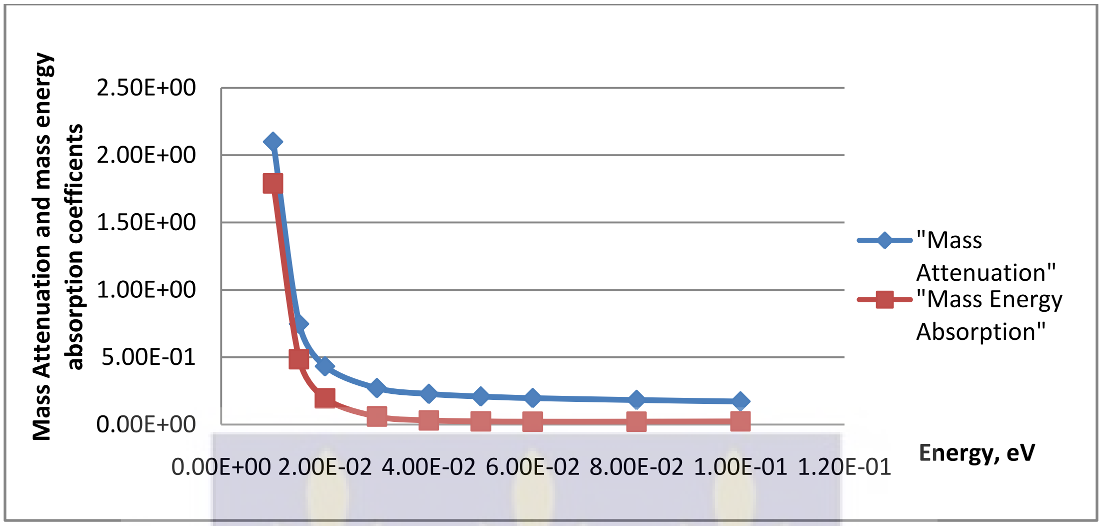

Figure 4.8.1 Comparison of theoretical values of mass attenuation coefficient and mass energy absorption coefficient of Diesel from 10 keV to 100 keV

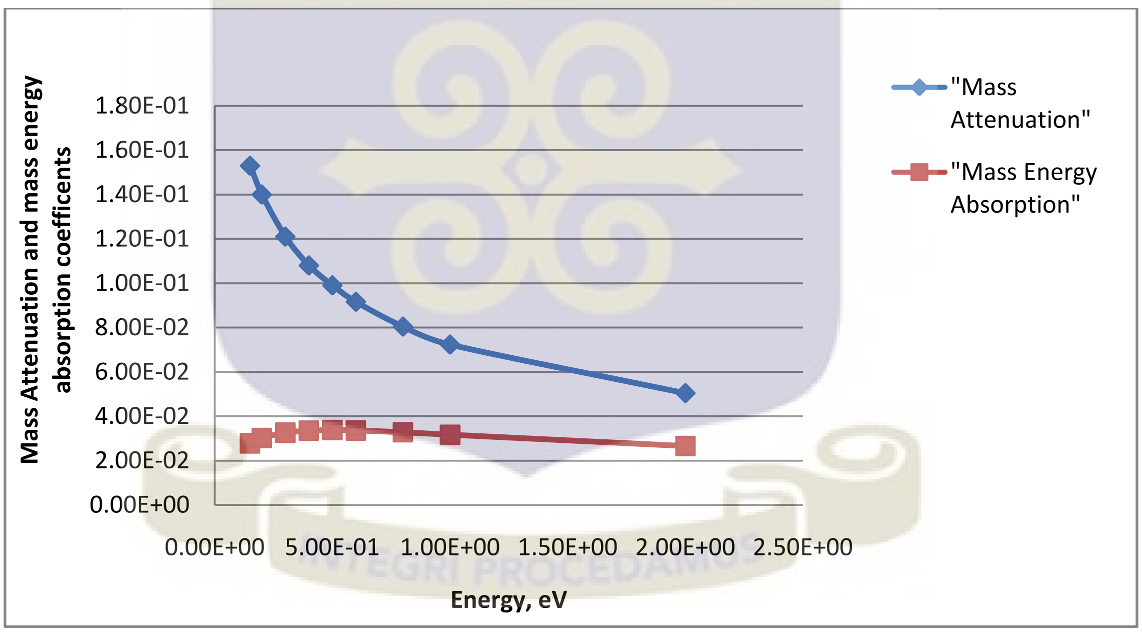

Figure 4.8.2 Comparison of theoretical values of mass attenuation coefficient and mass energy absorption coefficient of Diesel from 150 keV to 2 MeV.

Figures 4.6.0 to 4.8.1show the variation of the attenuation coefficients with the incident photon energy for all materials used in this study. It can be seen from these figures that the attenuation coefficients depend on the incident photon energy and the chemical composition of materials. We can also notice that the variation with the incident photon energy for all materials is almost identical. The dependence of the attenuation coefficient on incident photon energy can be explained by the dominance of partial processes of interaction of photons with material.

At low energies, attenuation is due to photoelectric effect, for intermediate energies, (100 keV and 1 MeV) the attenuation process is mainly due to Compton scattering, and for energies above 1 MeV, pair production is the most probable (Elmahroug *et al*., 2005)

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The Gamma ray absorption technique (GRAT) has been employed to determine the mass attenuation coefficients and the mass energy absorption coefficients of some petroleum products in Ghana (Kerosene, Diesel, Aviation Turbine Kerosene and Gasoline) using a photon energy of 662 keV. The theoretical values of the mass attenuation coefficients and the mass energy absorption coefficients have also been evaluated using data obtained from the publication of Hubbell and Seltzer, (1999). The following conclusions have been made;

1. The $\frac{\mu}{\rho}$ and $\frac{\mu_{en}}{\rho}$ were higher for less dense materials and lower for more dense materials.
2. The transmitted intensities through the samples increase when the material thicknesses decrease and also decrease with increment in material thicknesses.
3. The attenuation properties depend on chemical composition of the petroleum products.
4. The attenuation properties are also dependent on photon energy. High photon energies resulted in low attenuation and low photon energy resulted in high attenuation.
5. The experimental values of both the mass attenuation coefficients and the mass energy absorption coefficients agree fairly with their theoretical values.

This research provides a good approach to evaluate the gamma ray attenuation properties of petroleum products.

5.2 Recommendations

The experimental determination of the attenuation properties involved only one source of photon energy that is Caesium 137 with energy of 662 keV. The following recommendation will aide in future research.

1. Different photon energies can be used for further investigation in this area
2. The attenuation properties of petrochemical products in Ghana can also be evaluated
3. The attenuation properties obtained in this research can be used to evaluate adulterations in petroleum products used in future research.

REFERENCES

Akca, B. and Erzeneoglu, S.Z.(2014).The mass attenuation coefficients, electronic, atomic, and molecular cross sections, effective atomic, and electron densities for compounds of some Biomedically importance. vol 2014. Article ID 901465.

Akkurt, I., Basyigit, C., Akkas, A.S., Kilincarslan, B. and Mavi, K.G. (2012).Proceedings of the International Congress on Advances in Applied Physics and Material Science. Antalya. vol 121 No. 1

American Institute of Petroleum (September 2010). Kerosene/Jet Fuel Assessment Document (PDF). EPA. p. 8. Retrieved 2010

Anil D.W., (2011). Analytic Combustion: With Thermodynamics, Chemical Kinetics and Mass Transfer (Google eBook). *Cambridge University Press.* ISBN 1-107-00286-9. Retrieved 9 October 2014.

Bell Fuels."Lead-Free gasoline Material Safety Data Sheet".NOAA. Retrieved 6 July 2014

Bhandal, G. S., Singh, K., Rani, R. and Kumar, V. (1994). Energy absorption coefficients for 662 and 1115 keV gamma rays in some fatty acids. Applied Radiation. Volume. 45, 379–381.

Buesseler, K., Aoyama, M. and Fukasawa, M. (2011).Impacts of the Fukushima Nuclear Power Plants on Marine Radioactivity. Environmental Science Technology. 45, 9931

Bunting, R. L. (1975). Nuclear Data Sheets for A=137.Nuclear Data Sheets 15, 335.

Charles, H. (1961).CRC Handbook of Chemistry and Physics, 44th Ed. USA:Chemical Rubber Co.p. 2850

Chaudhari, L. M and Girase, S. B.(2013). Determination of Adulteration in Milk Samples by attenuation coefficient using nuclear technique.Archives of Applied Science Research, 5(2): pp255-260.

Chen, E. N., Cusatis, P. D., and Popiel, E. J. (1993).Validation of the aromatic ring distribution in diesel fuels refinery streams by supercritical fluid chromatography and mass spectrometry. *Journal of Chromatography A Volume 637*, pp 181-186.

Chernobyl: Assessment of Radiological and Health Impacts (OECD Nuclear Energy Agency, 2002).

Chitralekha, Kerur, B.R., Lagare, M.T., Nathuram, R. and Sharma, D.N. (2005). Mass attenuation coefficients of saccharides for low-energy X-rays. Radiation Physic and Chemistry. Volume 72, pp 1-5.

Chris, C., (2007). Implementing Phytoremediation of Petroleum Hydrocarbons.*Methods in Biotechnology* (Humana Press) (23): 99–108. ISBN 1-58829-541-9

Dabelstein, W., Reglitzky, A., Schütze, A., and Reders K., (2007). Automotive Fuels, *Ullmann's Encyclopedia of Industrial Chemistry*, p. 10-14.

Demir, D. and Tursucu A. (2012) Studies on mass attenuation coefficients, mass energy absorption coefficient and Kerma of some Vitamins. Annals of Nuclear Energy 48, pp 17-20

Dhillon, J. S., Singh, B. and Sidhu, G. S. (2012).IOSR Journal of Applied Physics (IOSRJAP). ISSN 2278-4681. Volume 1, Issue 6 (Sept-Oct 2012) pp 14-21.

Dukhin, A.S., and Goetz, P.J. (2002).Ultrasound for characterizing colloids. *Studies in Interface Science Elsevier*. Pp 425-475

Elmahroug, Y., Tellili, B., Souga, C. (2005). Determination of total mass attenuation coefficients, effective atomic numbers and electron densities for different shielding material" *Annals of Nuclear Energy* (75) pp 268 - 274

Ferraz, E. S. B. (195) "Gamma-ray attenuation technique for determining density and water content of wood samples", *IPEF, n.30*, pp.9-12.

Gary, J.H. and Handwerk, G.E. (1984). Petroleum Refining Technology and Economics (2nd Edition ed.). Marcel Dekker, Inc. ISBN 0-8247-7150-8.

Gordon G., Chap. 2 Interaction of gamma radiation with matter.

Gounhalli, S. G., Shantappa, A. and Hanagodimath, S. M. (2012).IOSR *Journal of Applied Physics* (IOSR-JAP) ISSN: 2278-4861. Volume 2, Issue 4 pp. 40-48

Holleman A. F. and Wiberg, E. (2001) Inorganic Chemistry (Academic Press, 2001), Ch. 28. Pp. 786-825

http://electrons.wikidot.com/pair-production-and-annihilation, retrieved on 15th May, 2015

http://en.wikipedia.org/w/index.php?title=Gamma_ray&oldid=6173720841retrieved on 5th May, 2015

https://en.wikipedia.org/wiki/Scintillation_counter#/media/File:Scintillation_Counter_Schematic.jpg

https://en.wikipedia.org/wiki/Kerosene. Webster's NewWorld College Dictionary.

https://myorganicchemistry.wokispaces.com/kerosene, retrieved on 15th May, 2015 http://www.epa.gov/radiation/radionuclides/cesium.html1retrieved on 25th May, 2015

https://www.integritytesting.net/faa.html."FAA Ethanol Safety Document". Retrieved 10 May 2015.

http://www.oilandgasiq.com/glossary/aviation-fuel."Aviation Fuel". Retrieved on 10 May 2014.

https://www.ndeed.org/educationresources/communitycollege/radiography/physics/attenuationcoefficient.html, retrieved on 4th February, 2015

http://patientsafetyauthority.org. Retrieved 2014.

http://www.wow.com/wiki/Scintillation_counter Retrieved July, 2015

Hubbell, J. H. (1996) Int. J. Applied Radiation. Vol. 33, pp. 12-69.

Hubbell, J.H., Seltzer, S.M., (1999). Tables of X-Ray Mass Attenuation Coefficients and Mass Energy Absorption Coefficients 1–20 MeV for Elements Z = 1 to 92 and 48 Additional Substances of Dosimetric Interest. NISTIR-5632.

Hodgman, C., (1961). CRC Handbook of Chemistry and Physics, *44th Edition*. p. 285.

IUPAC, (2006). Attenuation coefficient. *Compendum of chemical Terminology, 2nd ed*. Online corrected version. Retrieved on April, 2015

Jackson, D. F., Hawkers, J. D. (1981) X-ray attenuation coefficients of elements and mixtures. *Physics Reports.* Volume 70. Pp. 169–233.

Knothe, G., Sharp, C. A. and Ryan, T.W. (2006).Exhaust emissions of Biodiesel, Petrodiesel, Neat Methyl Esters and Alkanes in a new technology engine. *Energy Fuels*, 2006, 20 (1), pp 403–408

Kocherov, N., Lammer, M. and Schwerer, O, (1997).Handbook of Nuclear Data for Safeguards. *International Atomic Energy Agency*, INDC (NDS)-376.

Lamarsh, J. R. (1983). Introduction to Nuclear Engineering, Addison – Wesley Inc. pp 54-67

Lambert, J.H.(1760). Photometriasive de Mensura et Gradibus Luminis Colorumet Umbrae Augsburg, Germany.

Lilley, J., Prakash, S., Dendy, P. P. and Heaton, B. (2010) Nuclear Physics, Principles and applications,. R Nuclear Physics 2nd edition, p. 76.

Ludlum measurement, INC. Dimension configuration manager software manual. Version 1.0.0

Manjunathaguru, V. and Umesh, T.K. (2009).Simple parametrization of photon mass energy absorption coefficients of H-, C-, N- and O-based samples of biological interest in the energy range 200–1500 keV. *Pramana Journal of Science*. 72, pp 375–387.

Marashdeh, M.W., Bauk S., Tajuddin A.A. and Hashim R.(2012),Measurement of mass attenuation coefficients of Rhizophora spp. binderless particleboards in the 16.59-25.26 keV photon energy range and their density profile using x-ray computed tomography. *Applied Radiation and Isotopes*, 70(4): 656-662

Marion Brünglinghaus. Nuclear fission. European Nuclear Society. Retrieved 2013.

Maughan, R.L., Chuba, P., Porter, E., Ben-Josef, A.T., Lucas, D.R. and Bjarngard, B.E., (1999).Mass energy-absorption coefficients and mass collision stopping powers for electrons in tumors of various histologies. *Medical Physics*. Volume 26, 472–477.

Mitkar, S.R. and Dongarge, S.M. (2012). Study the linear and mass attenuation coefficient of alcohol soluble compound for gamma rays at energy 662 keV. *Journal Chemisty and Pharmacy*. Volume 4, pp 3944–3949.

Panno, J. (2005), CANCER: The Role of Genes, Lifestyle, and Environment.ISBN 0-8160-4950-5, pp 27-36.

Physics for Diagnostic Radiology. USA: CRC Press. (1999). ISBN 7503-0591-6. p 16

Podgorsak, E. B. (2005) Review of Radiation Oncology Physics: A Handbook for Teachers and Students. Chapter 6.

Radiation Safety Manual, Stanford University, 2010 Edition.

Rao, M. A. S., Narender K., Gopal K., Rao G. K., Krishna G. N., Marthy R. K. (2013), Mass attenuation coefficients, effective atomic and electron numbers of Alkali Halides for Multi-Energetic photons. *Research Journal of physical science*, ISSN 2320-4796 Vol 1(6), pp 11-16.

Seltzer, S.M. (1993).Calculation of photon mass energy-transfer and mass energy absorption coefficients.*Radiation Resorts*. 136, pp 147–170.

Shakhreet, B.Z, Chong, C.S., Bandyopadhey, T., Bradley, D.A., Tajuddin A.A. and Shukri A. (2003).Measurement of photon mass energy absorption coefficients of paraffin wax and gypsum at 662 keV. *Radiation Physics and Chemistry*, Volume 6, Issue 5, pp 757-764

Sidhu, G. S., Singh, B., Kumar, V. and Singh, S. (2011). *International Journal of latest research in Science and Technology*. Volume 2, Issue 5, pp 73-77

Singh, N., Singh, K. J., Singh, K. and Singh, H.(2012) Gamma-ray attenuation studies of PbO–BaO–B_2O_3 glass system. *Radiation Measurement*, Volume 41, Issue 1, pp 84-88.

Susan M. S. (2004). Determination of gamma ray mass attenuation coefficient of some industrial materials. Radiation Measurement Vol 130. Pp 56-67

Tema Oil Refinery Limited. http//:www.business.everythinghana.com. Retrieved on 4 August 2014.

Unterweger, M. P., Hoppes, D. D. and Schima, F. J. (1992), New and Revised Half-Life Measurements Results. *Nuclear Instrumentation.Methods*. Phys. Res. **A312**, p 349

Woods, J. R and Alexei K. Pikaev. (2001) Applied Radiation Chemistry: Radiation Processing. Volume 1. Pp 92-95.

APPENDICES

Appendix I

i. The weight percentage or fraction of Carbon and Hydrogen in the compound were evaluated using

$$C\% = \frac{m_C A_C}{m_C A_C + m_H A_C} \qquad (1a)$$

$$H\% = \frac{m_H A_H}{m_C A_C + m_H A_C} \qquad (2a)$$

ii. The theoretical mass attenuation the samples of were evaluated using the relation

$$\left({}^{\mu}/_{\rho}\right) = \frac{m_C A_C}{m_C A_C + m_H A_C}\left({}^{\mu}/_{\rho}\right)_c + \frac{m_H A_H}{m_C A_C + m_H A_C}\left({}^{\mu}/_{\rho}\right) \qquad (2a)$$

The theoretical mass energy absorption coefficient of samples were evaluated using the relation

$$\left({}^{\mu_{en}}/_{\rho}\right) = \frac{m_C A_C}{m_C A_C + m_H A_C}\left({}^{\mu_{en}}/_{\rho}\right)_C + \frac{m_H A_H}{m_C A_C + m_H A_C}\left({}^{\mu_{en}}/_{\rho}\right)_H \qquad (3a)$$

$m_C A_C$ = product of the molecular mass of Carbon and the Atomic mass of Carbon

$m_H A_C$ = product of the molecular mass of Hydrogen and the Atomic mass of Hydrogen

APPENDIX II

a. Table A. Transmitted intensity through Kerosene samples of density 0.825g/cm^3 with a gamma photon energy of 662 keV or 0.662 MeV.

Mass thickness(g/cm^2)	Initial Radiation count, I_0 (cps)	Transmitted radiation count I_{c+s}(cps)	Transmitted radiation count, I (cps)
8.250	1634	1311	323
7.425	1612	1204	408
6.600	1597	1174	423
5.775	1563	1115	448
4.950	1510	1064	446

b. Table B. Transmitted intensity through Gasoline samples of density 0. 744g/cm^3 a gamma photon energy of 662 keV or 0.662 MeV.

Mass thickness(g/cm^2)	Initial Radiation count, I_0 (cps)	Transmitted radiation count, I_{c+s} (cps)	Transmitted radiation count, I (cps)
7.44	1634	1435	199
6.696	1612	1401	211
5.952	1597	1370	227
5.208	1563	1325	238
4.464	1510	1247	263

c. Table C Transmitted intensity through Diesel samples of density 0.867g/cm^3 gamma photon energy of 662 keV or 0.662 MeV.

Mass thickness(g/cm^2)	Initial Radiation count, I_0 (cps)	Transmitted radiation count, I_{c+s} (cps)	Transmitted radiation count, I (cps)
8.67	1634	1450	184
7.803	1612	1416	196
6.936	1597	1366	231
6.069	1563	1329	234
5.202	1510	1266	244

d. Table D Transmitted intensity through Kerosene samples of density 0.823g/cm^{3}gamma photon energy of 662 keV or 0.662 MeV.

Mass thickness(g/cm^2)	Initial Radiation count, I_0 (cps)	Transmitted radiation count, I_{c+s} (cps)	Transmitted radiation count, I (cps)
7.44	1634	1321	313
6.696	1612	1290	322
5.952	1597	1244	353
5.208	1563	1202	361
4.464	1510	1082	428

e. Figure E. Weight fraction of Carbon and Hydrogen in the sample used

SAMPLE	AT.M.Carbon	AT.M. Hydrogen	Molar mass	C%	H%
$C_{13}H_{28}$	12.011	1.008	13 28	0.8469	0.15309
C_8H_{18}	12.011	1.008	8 18	0.8412	0.15883
$C_{12}H_{23}$	12.011	1.008	12 23	0.8614	0.13856

A T. M = Atomic mass

C% = Fraction of Carbon in the compound

H% = Fraction of Hydrogen in the compound

APPENDIX III

Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients from 1 keV to 20 MeV for Elements $Z = 1$ to 92 and 48 Additional Substances of Dosimetric Interest*

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Abstract

Tables and graphs of the photon mass attenuation coefficient μ/ρ and the mass energy-absorption coefficient μ_{en}/ρ are presented for all of the elements $Z = 1$ to 92, and for 48 compounds and mixtures of radiological interest. The tables cover energies of the photon (x-ray, gamma ray, bremsstrahlung) from 1 keV to 20 MeV. The μ/ρ values are taken from the current photon interaction database at the National Institute of Standards and Technology, and the μ_{en}/ρ values are based on the new calculations by Seltzer described in Radiation Research **136,** 147 (1993). These tables of μ/ρ and μ_{en}/ρ replace and extend the tables given by Hubbell in the International Journal of Applied Radiation and Isotopes **33,** 1269 (1982).

Carbon, Graphite
***Z* = 6**

HTML table format

Energy (MeV)	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)
1.00000E-03	2.211E+03	2.209E+03
1.50000E-03	7.002E+02	6.990E+02
2.00000E-03	3.026E+02	3.016E+02
3.00000E-03	9.033E+01	8.963E+01
4.00000E-03	3.778E+01	3.723E+01
5.00000E-03	1.912E+01	1.866E+01
6.00000E-03	1.095E+01	1.054E+01
8.00000E-03	4.576E+00	4.242E+00
1.00000E-02	2.373E+00	2.078E+00
1.50000E-02	8.071E-01	5.627E-01
2.00000E-02	4.420E-01	2.238E-01
3.00000E-02	2.562E-01	6.614E-02
4.00000E-02	2.076E-01	3.343E-02
5.00000E-02	1.871E-01	2.397E-02
6.00000E-02	1.753E-01	2.098E-02
8.00000E-02	1.610E-01	2.037E-02
1.00000E-01	1.514E-01	2.147E-02
1.50000E-01	1.347E-01	2.449E-02
2.00000E-01	1.229E-01	2.655E-02
3.00000E-01	1.066E-01	2.870E-02
4.00000E-01	9.546E-02	2.950E-02
5.00000E-01	8.715E-02	2.969E-02
6.00000E-01	8.058E-02	2.956E-02
8.00000E-01	7.076E-02	2.885E-02
1.00000E+00	6.361E-02	2.792E-02
1.25000E+00	5.690E-02	2.669E-02
1.50000E+00	5.179E-02	2.551E-02
2.00000E+00	4.442E-02	2.345E-02
3.00000E+00	3.562E-02	2.048E-02
4.00000E+00	3.047E-02	1.849E-02
5.00000E+00	2.708E-02	1.710E-02
6.00000E+00	2.469E-02	1.607E-02
8.00000E+00	2.154E-02	1.468E-02

1.00000E+01	1.959E-02	1.380E-02
1.50000E+01	1.698E-02	1.258E-02
2.00000E+01	1.575E-02	1.198E-02

Hydrogen
***Z* = 1**

HTML table format

Energy (MeV)	***μ*/*ρ*** (cm^2/g)	***μ*$_{en}$/*ρ*** (cm^2/g)
1.00000E-03	7.217E+00	6.820E+00
1.50000E-03	2.148E+00	1.752E+00
2.00000E-03	1.059E+00	6.643E-01
3.00000E-03	5.612E-01	1.693E-01
4.00000E-03	4.546E-01	6.549E-02
5.00000E-03	4.193E-01	3.278E-02
6.00000E-03	4.042E-01	1.996E-02
8.00000E-03	3.914E-01	1.160E-02
1.00000E-02	3.854E-01	9.849E-03
1.50000E-02	3.764E-01	1.102E-02
2.00000E-02	3.695E-01	1.355E-02
3.00000E-02	3.570E-01	1.863E-02
4.00000E-02	3.458E-01	2.315E-02
5.00000E-02	3.355E-01	2.709E-02
6.00000E-02	3.260E-01	3.053E-02
8.00000E-02	3.091E-01	3.620E-02
1.00000E-01	2.944E-01	4.063E-02
1.50000E-01	2.651E-01	4.813E-02
2.00000E-01	2.429E-01	5.254E-02
3.00000E-01	2.112E-01	5.695E-02
4.00000E-01	1.893E-01	5.860E-02
5.00000E-01	1.729E-01	5.900E-02
6.00000E-01	1.599E-01	5.875E-02
8.00000E-01	1.405E-01	5.739E-02
1.00000E+00	1.263E-01	5.556E-02
1.25000E+00	1.129E-01	5.311E-02
1.50000E+00	1.027E-01	5.075E-02
2.00000E+00	8.769E-02	4.650E-02

3.00000E+00	6.921E-02	3.992E-02
4.00000E+00	5.806E-02	3.523E-02
5.00000E+00	5.049E-02	3.174E-02
6.00000E+00	4.498E-02	2.905E-02
8.00000E+00	3.746E-02	2.515E-02
1.00000E+01	3.254E-02	2.247E-02
1.50000E+01	2.539E-02	1.837E-02
2.00000E+01	2.153E-02	1.606E-02

APPENDIX IV

a. Theoretical mass attenuation coefficient of Kerosene from 10 keV to 5 MeV

Kerosene	ENERGY	$(\mu/\rho)_c$	$(\mu/\rho)_H$	w_c	w_H	(μ/ρ)
	1.00E-02	2.37E+00	3.85E-01	0.847	0.153	2.07E+00
	1.50E-02	8.07E-01	3.76E-01	0.847	0.153	7.41E-01
	2.00E-02	4.42E-01	3.70E-01	0.847	0.153	4.31E-01
	3.00E-02	2.56E-01	3.57E-01	0.847	0.153	2.72E-01
	4.00E-02	2.08E-01	3.46E-01	0.847	0.153	2.29E-01
	5.00E-02	1.87E-01	3.36E-01	0.847	0.153	2.10E-01
	6.00E-02	1.75E-01	3.26E-01	0.847	0.153	1.98E-01
	8.00E-02	1.61E-01	3.09E-01	0.847	0.153	1.84E-01
	1.00E-01	1.51E-01	2.94E-01	0.847	0.153	1.73E-01
	1.50E-01	1.35E-01	2.65E-01	0.847	0.153	1.55E-01
	2.00E-01	1.23E-01	2.43E-01	0.847	0.153	1.41E-01
	3.00E-01	1.07E-01	2.11E-01	0.847	0.153	1.23E-01
	4.00E-01	9.55E-02	1.89E-01	0.847	0.153	1.10E-01
	5.00E-01	8.72E-02	1.73E-01	0.847	0.153	1.00E-01
	6.00E-01	8.06E-02	1.60E-01	0.847	0.153	9.27E-02
	8.00E-01	7.08E-02	1.41E-01	0.847	0.153	8.14E-02
	1.00E+00	6.36E-02	1.26E-01	0.847	0.153	7.32E-02
	1.25E+00	5.69E-02	1.13E-01	0.847	0.153	6.55E-02
	1.50E+00	5.18E-02	1.03E-01	0.847	0.153	5.96E-02
	2.00E+00	4.44E-02	8.77E-02	0.847	0.153	5.10E-02
	3.00E+00	3.56E-02	6.92E-02	0.847	0.153	4.07E-02
	4.00E+00	3.05E-02	5.81E-02	0.847	0.153	3.47E-02
	5.00E+00	2.71E-02	5.05E-02	0.847	0.153	3.07E-02

b. Theoretical mass attenuation coefficient of Gasoline from 10 keV to 5 MeV

Gasoline	ENERGY	$(^{\mu}/_{\rho})_c$	$(^{\mu}/_{\rho})_H$	w_c	w_H	$(^{\mu}/_{\rho})$
	1.00E-02	2.37E+00	3.85E-01	0.8412	0.1588	2.06E+00
	1.50E-02	8.07E-01	3.76E-01	0.8412	0.1588	7.39E-01
	2.00E-02	4.42E-01	3.70E-01	0.8412	0.1588	4.30E-01
	3.00E-02	2.56E-01	3.57E-01	0.8412	0.1588	2.72E-01
	4.00E-02	2.08E-01	3.46E-01	0.8412	0.1588	2.30E-01
	5.00E-02	1.87E-01	3.36E-01	0.8412	0.1588	2.11E-01
	6.00E-02	1.75E-01	3.26E-01	0.8412	0.1588	1.99E-01
	8.00E-02	1.61E-01	3.09E-01	0.8412	0.1588	1.85E-01
	1.00E-01	1.51E-01	2.94E-01	0.8412	0.1588	1.74E-01
	1.50E-01	1.35E-01	2.65E-01	0.8412	0.1588	1.55E-01
	2.00E-01	1.23E-01	2.43E-01	0.8412	0.1588	1.42E-01
	3.00E-01	1.07E-01	2.11E-01	0.8412	0.1588	1.23E-01
	4.00E-01	9.55E-02	1.89E-01	0.8412	0.1588	1.10E-01
	5.00E-01	8.72E-02	1.73E-01	0.8412	0.1588	1.01E-01
	6.00E-01	8.06E-02	1.60E-01	0.8412	0.1588	9.32E-02
	8.00E-01	7.08E-02	1.41E-01	0.8412	0.1588	8.18E-02
	1.00E+00	6.36E-02	1.26E-01	0.8412	0.1588	7.36E-02
	1.25E+00	5.69E-02	1.13E-01	0.8412	0.1588	6.58E-02
	1.50E+00	5.18E-02	1.03E-01	0.8412	0.1588	5.99E-02
	2.00E+00	4.44E-02	8.77E-02	0.8412	0.1588	5.13E-02
	3.00E+00	3.56E-02	6.92E-02	0.8412	0.1588	4.09E-02
	4.00E+00	3.05E-02	5.81E-02	0.8412	0.1588	3.49E-02
	5.00E+00	2.71E-02	5.05E-02	0.8412	0.1588	3.08E-02

c. Theoretical mass attenuation coefficient of Diesel from 10 keV to 5 MeV

DIESEL	ENERGY	$(\mu/\rho)_c$	$(\mu/\rho)_H$	w_c	w_H	(μ/ρ)
	1.00E-02	2.37E+00	3.85E-01	0.861	0.139	2.10E+00
	1.50E-02	8.07E-01	3.76E-01	0.861	0.139	7.47E-01
	2.00E-02	4.42E-01	3.70E-01	0.861	0.139	4.32E-01
	3.00E-02	2.56E-01	3.57E-01	0.861	0.139	2.70E-01
	4.00E-02	2.08E-01	3.46E-01	0.861	0.139	2.27E-01
	5.00E-02	1.87E-01	3.36E-01	0.861	0.139	2.08E-01
	6.00E-02	1.75E-01	3.26E-01	0.861	0.139	1.96E-01
	8.00E-02	1.61E-01	3.09E-01	0.861	0.139	1.82E-01
	1.00E-01	1.51E-01	2.94E-01	0.861	0.139	1.71E-01
	1.50E-01	1.35E-01	2.65E-01	0.861	0.139	1.53E-01
	2.00E-01	1.23E-01	2.43E-01	0.861	0.139	1.40E-01
	3.00E-01	1.07E-01	2.11E-01	0.861	0.139	1.21E-01
	4.00E-01	9.55E-02	1.89E-01	0.861	0.139	1.08E-01
	5.00E-01	8.72E-02	1.73E-01	0.861	0.139	9.90E-02
	6.00E-01	8.06E-02	1.60E-01	0.861	0.139	9.16E-02
	8.00E-01	7.08E-02	1.41E-01	0.861	0.139	8.04E-02
	1.00E+00	6.36E-02	1.26E-01	0.861	0.139	7.23E-02
	1.25E+00	5.69E-02	1.13E-01	0.861	0.139	6.47E-02
	1.50E+00	5.18E-02	1.03E-01	0.861	0.139	5.89E-02
	2.00E+00	4.44E-02	8.77E-02	0.861	0.139	5.04E-02
	3.00E+00	3.56E-02	6.92E-02	0.861	0.139	4.03E-02
	4.00E+00	3.05E-02	5.81E-02	0.861	0.139	3.43E-02
	5.00E+00	2.71E-02	5.05E-02	0.861	0.139	3.03E-02

APPENDIX V

a. Theoretical mass energy absorption coefficient of Kerosene from 10 keV to 5 MeV

Kerosene	ENERGY	$(\mu_{en}/\rho)_c$	$(\mu_{en}/\rho)_H$	w_c	w_H	(μ_{en}/ρ)
	1.00E-02	2.08E+00	9.85E-03	0.847	0.153	1.76E+00
	1.50E-02	5.63E-01	1.10E-02	0.847	0.153	4.78E-01
	2.00E-02	2.24E-01	1.36E-02	0.847	0.153	1.92E-01
	3.00E-02	6.61E-02	1.86E-02	0.847	0.153	5.89E-02
	4.00E-02	3.34E-02	2.32E-02	0.847	0.153	3.19E-02
	5.00E-02	2.40E-02	2.71E-02	0.847	0.153	2.44E-02
	6.00E-02	2.10E-02	3.05E-02	0.847	0.153	2.24E-02
	8.00E-02	2.04E-02	3.62E-02	0.847	0.153	2.28E-02
	1.00E-01	2.15E-02	4.06E-02	0.847	0.153	2.44E-02
	1.50E-01	2.45E-02	4.81E-02	0.847	0.153	2.81E-02
	2.00E-01	2.66E-02	5.25E-02	0.847	0.153	3.05E-02
	3.00E-01	2.87E-02	5.70E-02	0.847	0.153	3.30E-02
	4.00E-01	2.95E-02	5.86E-02	0.847	0.153	3.40E-02
	5.00E-01	2.97E-02	5.90E-02	0.847	0.153	3.42E-02
	6.00E-01	2.96E-02	5.88E-02	0.847	0.153	3.40E-02
	8.00E-01	2.89E-02	5.74E-02	0.847	0.153	3.32E-02
	1.00E+00	2.79E-02	5.56E-02	0.847	0.153	3.22E-02
	1.25E+00	2.67E-02	5.31E-02	0.847	0.153	3.07E-02
	1.50E+00	2.55E-02	5.08E-02	0.847	0.153	2.94E-02
	2.00E+00	2.35E-02	4.65E-02	0.847	0.153	2.70E-02
	3.00E+00	2.05E-02	3.99E-02	0.847	0.153	2.35E-02
	4.00E+00	1.85E-02	3.52E-02	0.847	0.153	2.11E-02
	5.00E+00	1.71E-02	3.17E-02	0.847	0.153	1.93E-02

b. Theoretical mass energy absorption coefficient of Gasoline from 10 keV to 5 MeV

GASOLINE	ENERGY	$\left(\mu_{en}/\rho\right)_c$	$\left(\mu_{en}/\rho\right)_H$	w_c	w_H	$\left(\mu_{en}/\rho\right)$
	1.00E-02	2.08E+00	9.85E-03	0.84117	0.159	1.75E+00
	1.50E-02	5.63E-01	1.10E-02	0.84117	0.159	4.75E-01
	2.00E-02	2.24E-01	1.36E-02	0.84117	0.159	1.90E-01
	3.00E-02	6.61E-02	1.86E-02	0.84117	0.159	5.86E-02
	4.00E-02	3.34E-02	2.32E-02	0.84117	0.159	3.18E-02
	5.00E-02	2.40E-02	2.71E-02	0.84117	0.159	2.45E-02
	6.00E-02	2.10E-02	3.05E-02	0.84117	0.159	2.25E-02
	8.00E-02	2.04E-02	3.62E-02	0.84117	0.159	2.29E-02
	1.00E-01	2.15E-02	4.06E-02	0.84117	0.159	2.45E-02
	1.50E-01	2.45E-02	4.81E-02	0.84117	0.159	2.82E-02
	2.00E-01	2.66E-02	5.25E-02	0.84117	0.159	3.07E-02
	3.00E-01	2.87E-02	5.70E-02	0.84117	0.159	3.32E-02
	4.00E-01	2.95E-02	5.86E-02	0.84117	0.159	3.41E-02
	5.00E-01	2.97E-02	5.90E-02	0.84117	0.159	3.43E-02
	6.00E-01	2.96E-02	5.88E-02	0.84117	0.159	3.42E-02
	8.00E-01	2.89E-02	5.74E-02	0.84117	0.159	3.34E-02
	1.00E+00	2.79E-02	5.56E-02	0.84117	0.159	3.23E-02
	1.25E+00	2.67E-02	5.31E-02	0.84117	0.159	3.09E-02
	1.50E+00	2.55E-02	5.08E-02	0.84117	0.159	2.95E-02
	2.00E+00	2.35E-02	4.65E-02	0.84117	0.159	2.71E-02
	3.00E+00	2.05E-02	3.99E-02	0.84117	0.159	2.36E-02
	4.00E+00	1.85E-02	3.52E-02	0.84117	0.159	2.11E-02
	5.00E+00	1.71E-02	3.17E-02	0.84117	0.159	1.94E-02

c. Theoretical mass energy absorption coefficient of Diesel from 10 keV to 5 MeV

DIESEL	ENERGY	$\left(\mu_{en}/\rho\right)_c$	$\left(\mu_{en}/\rho\right)_H$	w_c	w_H	$\left(\mu_{en}/\rho\right)$
	1.00E-02	2.08E+00	9.85E-03	0.861	0.1386	1.79E+00
	1.50E-02	5.63E-01	1.10E-02	0.861	0.1386	4.86E-01
	2.00E-02	2.24E-01	1.36E-02	0.861	0.1386	1.95E-01
	3.00E-02	6.61E-02	1.86E-02	0.861	0.1386	5.96E-02
	4.00E-02	3.34E-02	2.32E-02	0.861	0.1386	3.20E-02
	5.00E-02	2.40E-02	2.71E-02	0.861	0.1386	2.44E-02
	6.00E-02	2.10E-02	3.05E-02	0.861	0.1386	2.23E-02
	8.00E-02	2.04E-02	3.62E-02	0.861	0.1386	2.26E-02
	1.00E-01	2.15E-02	4.06E-02	0.861	0.1386	2.41E-02
	1.50E-01	2.45E-02	4.81E-02	0.861	0.1386	2.78E-02
	2.00E-01	2.66E-02	5.25E-02	0.861	0.1386	3.02E-02
	3.00E-01	2.87E-02	5.70E-02	0.861	0.1386	3.26E-02
	4.00E-01	2.95E-02	5.86E-02	0.861	0.1386	3.35E-02
	5.00E-01	2.97E-02	5.90E-02	0.861	0.1386	3.38E-02
	6.00E-01	2.96E-02	5.88E-02	0.861	0.1386	3.36E-02
	8.00E-01	2.89E-02	5.74E-02	0.861	0.1386	3.28E-02
	1.00E+00	2.79E-02	5.56E-02	0.861	0.1386	3.17E-02
	1.25E+00	2.67E-02	5.31E-02	0.861	0.1386	3.04E-02
	1.50E+00	2.55E-02	5.08E-02	0.861	0.1386	2.90E-02
	2.00E+00	2.35E-02	4.65E-02	0.861	0.1386	2.66E-02
	3.00E+00	2.05E-02	3.99E-02	0.861	0.1386	2.32E-02
	4.00E+00	1.85E-02	3.52E-02	0.861	0.1386	2.08E-02
	5.00E+00	1.71E-02	3.17E-02	0.861	0.1386	1.91E-02