CHAPTER 1- Introduction

1.1 Theoretical Fundamentals

Ionising radiation of gamma ray interacts with matter mainly in three ways; that is through photoelectric absorption, Compton scattering and pair production. Radiation is reduced in intensity when passing through material with density,ρ. The combination of absorption and scattering processes leads to a decrease in flux density of the beam when passed through matter. These interaction mechanisms involve the transfer of gamma ray photon energy to electron energy. In photoelectric absorption, an incident gamma ray will interact with a bound electron in the absorber material and dislodges the electron. The electron absorbs the photon energy, becomes excited and may de-excite by redistribution of the excitation energy between the remaining electrons in the atom. Or a higher energy electron may fill the vacancy left by the excited electron. With high atomic number (Z), materials such as lead (Pb-82) will give good gamma ray interaction and will attenuate gamma ray.

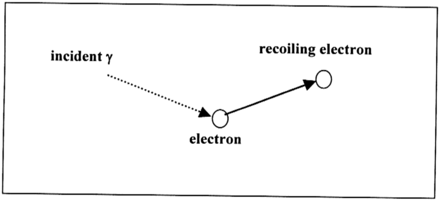

Fig.1. Interaction by photoelectric absorption

Photoelectric absorption is the dominant process for gamma ray absorption up to energies of 50keV. It is also dominant for atoms of high atomic numbers.

In Compton scattering, the incident gamma ray collides with an electron and deposits partially its photon energy to the electron. From this event, the electron acquires kinetic energy and may, in-turn deposit its energy to other electrons in the material. An ionised atom and a photon of a lesser energy than the incident shall result from this type of interaction. In the energy range 0.5 MeV to about 2.5MeV; it is Compton scattering which is the dominant process whereby photons transfer their energy to matter. The physical form of the medium through which is the gamma rays are passing is not very important. It is the electron density, which is related to the bulk density of the medium, which is the important factor.

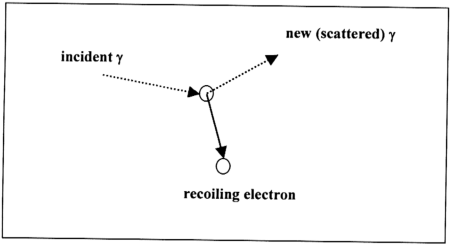

Fig.2. Interaction by Compton scattering

Pair production occurs when a photon (high energy radiation) interacts with the electromagnetic field of an atomic nucleus to create an electron-positron pair of particles. The particles are created out of the energy that the photon originally possessed, i.e. the energy of the incident photon is spontaneously converted into the mass of an electron positron pair. Therefore, pair production occurs only when it is more than the rest mass energy of the pair, that is 1.022 MeV. This interaction is dominant in high-energy range, such as in the interaction of Co-60 (1.332MeV) gamma ray with matter.

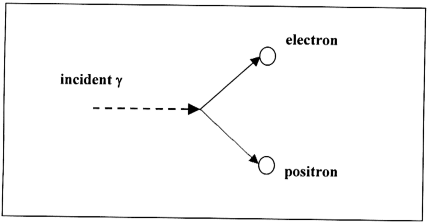

Fig.3. Interaction by pair production

Other known interactions that lead to the attenuation of a photon beam, for energies below the threshold for pair production is in elastic scattering. Elastic scattering from atoms is called Rayleigh or coherent scattering when it involves strongly bound electrons. Photons of radiation are reflected and bounce off the atoms and molecules without any change of energy. It is only a minor contributor to the absorption coefficient.

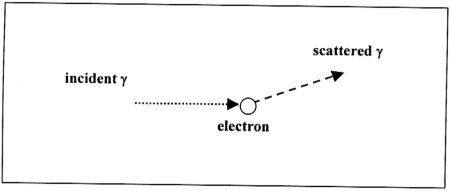

Fig 4. Interaction by Rayleigh scattering

Thomson scattering occurs when the atomic electrons can be regarded as free in the low energy limit. Scattering of free charged particles occurs when the photon energy is small compared with the energy equivalent to the rest mass of the charged particles.

In the interaction between gamma radiation and matter, the three dominant processes observed, ultimately results in an attenuation of the incident photon passing through matter. Thus, it is made up of contributions from each mode of photon interaction.(See Equation 5) The gamma ray photons is characterised by their mean free path λ, defined as the average distance travelled in the absorber before an interaction takes place. This value can be obtained from the equation $\lambda = 1/\mu$. The sum of the probability of occurrence per unit length that the gamma ray photon is removed from the beam is actually the linear attenuation, μ. The use of the linear attenuation coefficient is limited by the fact that it varies with the density of the absorber, even though the absorber material is the same. Therefore, the mass attenuation coefficient is much more widely used and is defined as μ/ρ. Each of the interaction process removes the gamma ray photon from the beam either by absorption or scattering away from the detector direction and can be characterised by a fixed probability of occurrence per unit length in the absorber.

$$\mu/\rho = \mu/\rho(\textbf{Photoelectric}) + \mu/\rho(\textbf{Compton}) + \mu/\rho(\textbf{Pair Production}) \quad \text{------------} \quad \textbf{(5)}$$

In this project report, the theory of gamma ray interaction with matter is treated as the fundamentals of the experimental mass attenuation coefficient measurements. The attenuation coefficient is a measure of the reduction in the gamma ray intensity at a particular energy caused by an absorber. It measures the photon absorption or scatter probability per unit length while interacting within the sample, and is proportional to the cross-section per electron κ_ε (cm^2 / electron), therefore it can be expressed as

$$(\mu / \rho) = \kappa_\varepsilon \, Z \, N_{adv} / A \qquad \text{(1)}$$

where Z is the atomic number, N_{adv} Avogadro's number, and A the atomic mass of the material. Both solid and liquid physical states of the absorber (material) are considered. When the material is a composition of multiple materials, the mass attenuation coefficient can be found approximately as the sum of the coefficients for its constituent elements. w_i is the proportion by weight of the *i*th elemental constituent mass attenuation coefficient (μ/ρ)

$$(\mu / \rho)_c = \sum_i w_i \, (\mu / \rho)_i \qquad \text{(2)}$$

$$I = I_o \exp(-\mu/\rho . \, x) \qquad \text{(3)}$$

Equation (3) relates the intensity of gamma ray, attenuation coefficient and the absorber thickness. I_o and I represent intensity of an incident photon and intensity of the transmitted photon respectively. x represents the mass per unit area, with μ/ρ (cm^2/g) as mass attenuation coefficient. Re-arranging equation (3), the mass attenuation coefficient μ/ρ (in cm^2/g) for samples were obtained using equation (4) and taking the bulk densities (ρ = measured densities) of the respective samples.

$$\mu/\rho = 1/x \ln(I_o / I) \qquad \text{(4)}$$

Shown in Fig.5, the intensity of the gamma ray passing through an absorber will be attenuated exponentially as the absorber thickness increases.

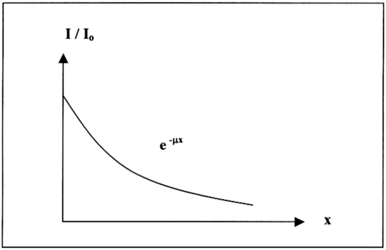

Fig. 5. Gamma ray attenuation through material with thickness

With broad beam condition, the effects of radiation scattering modify equation (3) to include the 'Build-up' factor, B. The scattering effects increases the amount of transmitted radiation above that predicted by equation (3). With the addition of build-up factor, equation (6) takes into account gamma ray that is scattered through any medium with diminishing energy.

$$I = I_0 \, B \exp(-\mu/\rho . \, x) \qquad \text{.......} \qquad (6)$$

If equation (6) is used, additional demand is placed on the design of experiment and can complicate the experimental result. Hence it is best that the experiment design follows a good geometry configuration. Utilising a collimated source, the build-up factor can be reduced to unity and equation (4) is conveniently used for practical measurement and the experiment calculations.

1.2 Objective

This study aims to collect measurements of mass attenuation coefficient, $\mu/\rho(cm^2/g)$ to be used as a guide for applications of nuclear gauges in the local industry. The motivation for this work lies in the lack of specific μ/ρ values for use in the estimation of the amount of build-up found in petroleum processing production pipelines. In many instances, pipelines lose efficiency throughput when pipelines are plugged and this results in extreme cost of lost production and replacement of pipelines. The values from the project work could be used in gamma ray measurements, for example in calculation of deposition of paraffin in the inner walls of pipelines, thickness measurements, calibration of a pipe scanner[16] and investigations of compounds and composite materials[2].

1.3 Radiation Gauges

Nuclear gauging is the term that describes the use of radiation or emitted nuclear particles for the measurement of particular properties of a system. The basic components of a nuclear gauge are a radiation source, detector and its electronics unit. Nuclear gauge has found many uses in various industries and applications. There are three ways these gauges are used i.e. permanent and fixed gauges e.g. level gauges, portable gauges e.g. moisture and density gauge and laboratory nuclear instrument module (NIM system). The use of radioisotope in nucleonic gauges and system have been of outstanding success because of the following advantages:

i) Contactless, continuous and on-line measurement and monitoring of product and process parameters

ii) Sealed and well shielded small radioactive sources in fixed installations ensure radiological safety

iii) Measurement is independent of pressure, temperature, chemical composition and physical condition of the medium to be measured

iv) High reliability and accuracy

When making measurements with a nuclear instrument, it is clear that a relation between the readout or response of that instrument and the parameter being measured must be made. The relation can be expressed by $R = f(x)$ where R is instrument response and x is the measured parameter. The only requirement is that R be a single-valued function of x over the range encountered. In general, the readout from any measuring device, for example the ratemeter, is a relative reading; i.e., the device has a readout that is relative to a standard or an accepted value. Thus, the measuring device must be calibrated initially. Calibration of a measuring device is simplified when the readout has a known functionality in the variable being measured. Once this functionality is established, only one or two calibration points are required. However, the higher the precision demanded of an instrument, the more calibration points along the scale is required. In many cases it is possible to design an instrument so that the readout is a linear function of the variable being measured. In other cases, particularly where the characteristics being measured is a function of several variables, a calibration curve must be determined from a series of standards or accepted values. The calibration curves can then be used to measure an unknown variable, where we re-write $R = f(x)$ to be $x = F(R)$ and F is the inverse function of f. So, in a simple transmission type gauge, instrument response can be expressed as, $I = I_o \exp(-\mu x)$.

In the study of gamma ray interaction with matter, we are invariably drawn to its absorption and attenuation outcome of the transmitted ray. From its theory, techniques are formulated based on gamma ray absorption and they are extensively used in plant and process investigation. The basic technique involves positioning a gamma ray source and a radiation detector on opposite sides of the medium of interest and relating changes in the transmitted intensity to changes in the mass per unit area of the material. With material of constant thickness, the attenuation of the beam provides information about the density of the material. This radioisotope application is increasingly used in petrochemical plants for rapidly identifying problems in distillation columns and is known as gamma ray scanning[3,19].

The attenuation coefficient can also be used to determine amount of deposit or sludge present in pipelines in an oleo chemical plant[16]. This is true for material of constant density and the attenuation of the beam provides information about the thickness of the material. In tomographic investigations, a map of linear attenuation coefficient is correlated to density of material where in turn these data is transform into useful information as a reconstructed image of the material studied[1,2,20]. Values of the attenuation coefficient in gamma ray computed tomography (CT) can be associated with tomographic units and in turn are used in investigation of compaction on sewage-sludge-treated soil[32]. Other measurements for photon linear attenuation coefficients were performed to study attenuation properties for soft tissues and tissue substitute materials[5].

An extensive database for photon mass attenuation has been tabulated by Hubbell[3] for elements hydrogen (Z=1) to Uranium (Z=92) for photon energies 1keV to 20MeV. Theoretical calculations are made using this data and relative difference percentage between experimental value and theory are tabulated. Colgate[13] and

Conner[14] performed exploratory works on gamma ray absorption and gamma ray attenuation measurements for the contribution of Compton scattering, Rayleigh scattering and sources of errors to the final measurements. Various works by G.J. Baldha[7], L.M. Chaudhari[12], Ali İsahkoğlu[23] are referred to for their investigation methods and findings of the validity of exponential absorption law in liquids. Attenuation measurements in solids performed by M.N. Alam[17] showed a linear relationship with sample density. Reports by Gurdeep S Sidhu[34] and K.M. Varier[38] demonstrated the effect of absorber dimensions on gamma ray attenuation thickness for solid and liquid respectively. Investigation by Bassam Z. Shakhreet[33] explored a simple and direct method based on paraxial sphere transmission and discussed effects of nonparaxiality and of finite sample thickness. G.S. Bhandal[8,9] performed detailed study of variation of mass attenuation coefficients with photon energy for photoelectric absorption, coherent scattering, incoherent scattering and pair production. This studies revealed the variation found in cement and multielement composite material. Formulation that is more recent is described in linear attenuation coefficient measurements performed that uses a particular method incorporating two media for odd-shape samples[15,25]. This method can be particularly useful in applications of archaeological investigations.