International Journal of Applied and Natural Sciences (IJANS)
ISSN (P): 2319–4014; ISSN (E): 2319–4022
Vol. 9, Issue 1, Dec–Jan 2020; 93–104

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

GAMMA UNFOLDING FOR POLY-BORON (PB), Pb SINGLE SHIELDS AND MULTILAYERS CONTAINING PB SHIELD

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ABSTRACT

Gamma ray transport and shielding properties of Lead (Pb) and some multilayers and their reversed combinations have been investigated using a 3.7 x 10^4 Bq ^{252}Cf point source. NaI (Tl) scintillation detector has been used for the detection. The unfolded dose spectra of the fission gamma ray spectrum for some specific shield thicknesses were also studied. Three dimensional Monte Carlo computer code MCNP have been used for theoretical calculations to study the characteristics of the above mentioned shielding setups for fission gamma rays. Experimentally obtained values are then compared, effectiveness of the materials are satisfactory. It has been found that the materials (single layer and multilayer) studied are very effective as the shield for gamma rays.

KEYWORDS: *PB Shield, Gamma Unfolding, Poly-Boron*

Article History

Received: *14 Nov 2019* | ***Revised:*** *17 Dec 2019* | ***Accepted:*** *31 Jan 2020*

INTRODUCTION

All penetrating radiations from radioactive substances and their harmful effects has been a matter of concern and study. The most significant radiation fields are the combinations of [1], fast neutrons, thermal neutrons, primary gamma rays, and secondary gamma rays. In shielding design an important factor that is required to be considered is the choice of most suitable material from which the main part of the shield should be built. It also satisfies all other requirements like the density, the weight, and the amount of the material needed for shielding purpose. The primary gamma rays is the main radiation of interest which can best be shielded with lead or other high density materials [2]. And the last one - the secondary gamma rays with an energy of 2.2 MeV are produced as a result of the capture of thermal neutrons by hydrogen.

The combination of the suitable component shielding materials together is required for increasing the effectiveness of the shield. The combination of shielding components into a most effective single homogeneous composite has now become a recognized standard method of developing shielding materials. The composites so developed are given variety of shapes or forms such as bricks, blocks, slabs, sheets, cylinders, pellets, casks etc. according to the requirements [1]. An alternative method is to form suitable multilayers. Such type of heterogeneous mixers [3] can also be developed by forming multilayers of the composite shielding materials.

In shielding gamma rays traditionally theoretical as well as experimental investigations have been considered. The theoretical approach considers the interaction cross section of different materials with a view to developing the required shield specifications. The experimental method generally yields gross results and is concerned only with the total effect on half value thicknesses and build up factors.

In reviewing the present trend of studies, it is found that among all the applied radiation sources, diagnostic x-ray machines got the priority [4]. Shielding experiments have been performed on a few shields; the results are then compared with those obtained through calculations using MCNP code for neutron and gamma ray transmission. The gamma-ray spectrum is obtained in the present work from a ^{252}Cf source. It was necessary to identify the components of the gamma rays, and a part of the present work is devoted to this aspect of unfolding study of gamma rays as it simultaneously emits neutrons and gamma rays and the source have different energies and intensities. The total dose due to 25, 50 and 100 keV gamma rays unfolded was evaluated.

THE CONCEPT OF UNFOLDING

The differential pulse height spectrum N(H) observed from any radiation detector is given by.

$$N(H) = \int R(H,E)S(E)dE \quad (1)$$

Where, R(H,E) is the response function of the detector, and S(E) is the energy distribution of the incident radiation. The response function usually is dependent on [5] (i) the operating conditions of the detector, (ii) the source detector geometry, and (iii) the detector counting rate.

We have a different discrete form of the recorded count in the channel (N_i) in the case of a multichannel analyzer,

$$N_i = \sum R_{ij}S_j \quad (2)$$

Here, R_{ij} is the response matrix coupling the i^{th} pulse height interval with the jth energy interval. S_j is the radiation intensity in the jth energy interval.

At times we become interested in deducing the energy distribution of the incident radiation. As the recorded spectrum is made up of M values of N_i we may write M simultaneous equations like the equation (2). Assuming that the response matrix R_{ij} is known, the process solving the equation for all the S_j elements for $M \geq L$ is known as spectrum unfolding. Unfolding methods have been thoroughly developed for application area, of spectra recorded by gamma ray spectrometers employing either NaI(Tl) scientillators or Ge(Li) detectors.

Unfolding Method

- **Mathematical Formulation**

The conversion is achieved in accordance with the following relation:

$$S(E_i)\,\Delta E_i = \sum_{j=1}^{J} R_{ij}^{-1} N(E_j)\,\Delta E_j \quad (3)$$

Here $N(E_j)$ = The number of counts per sec unit pulse height in bin j

R_{ji}^{-1} =The inverted response elements

J =The maximum energy bin converted

Now from the equation (2) the operation

$$S = R^{-1}N \quad (4)$$

Should give the required photon strength, S; but it has a number of disadvantages: (i) direct matrix inversion amplifies small statistical fluctuations resulting in violent oscillations and (ii) sometimes negative strengths of photons in the unfolded spectrum [6] is observed. These disadvantages are avoided by adopting Gold's iterative technique [7].

- **The Dose Rate**

The dose rate D now can be expressed as [8]

$$D = \int_{Ei=0}^{Ei=max} K(E_i)\, E_i S(E_i)\, \mu_a(E_i)\, dE_i \quad (5)$$

Where, $K(E_i)$ = a conversion factor,

E_i =Photon energy,

$S(E_i)$ = Number of photons calculated per unit energy, per sec and per cm^2

$\mu_a(E_i)$ = energy absorption coefficient, defined as

$$\mu_a(E_i) = \frac{\bar{E}i}{Ej}\mu(E_i) \quad (6)$$

In terms of K_i and E_j the dose rate may be expressed as

$$D = \int_{Ei=0}^{Ei=max} K(E_i)\, \bar{E}_i S(E_i)\, \mu(E_i) dE_j \quad (7)$$

Here $\bar{E}_i$ = average energy transferred by photons per collision in the medium, and

$\mu(E_i)$ = linear absorption coefficient.

- **Calculation for R**

In the work the response matrix described in Eqn. (1) has been calculated. The following procedure was adopted for the purpose. The detector used was a 3"×3" NaI(Tl) detector with the following amplifier gains:

Coarse gain = 4

Fine gain = 1

Applied high voltage = 750 volts.

The amplifier used was the model 2012 with positive input polarity.

The output obtained from the NaI detector was fed to the input of a computerized multi channel analyzer (MCA). The MCA was calibrated using some known sources. Eight different known gamma sources (e.g., ^{241}Am, ^{109}Cd, ^{54}Mn, ^{57}Co, ^{133}Ba, ^{22}Na, ^{137}Cs, ^{60}Co) have been used for the purpose. Each of the sources were kept at a distance of 5 to 10 cm from the detector. The channels were selected before calibration and times were also preset. After this, the spectrum was collected for sources of different energy and source strengths keeping the distance between the source and the detector 5 to 10 cm and for a preset time. The spectrum was then stored in the hard disc of the computer. The energies together with the yield per cent of the sources [9] and their distances from the detector has been shown in Table 1.

The strength of the sources on the date of collecting the spectrum was calculated by using radiation decay formula. The number of gamma photons incident on the detector surface was found using the following formula:

$$S(E) = (A/4\pi)\times(a/r^2) \quad (8)$$

Where, A = Activity of the source on the date of experiment, (a/r^2) = solid angle subtended at the source point by the detector, a = surface area of the detector = πd^2 (d = detector radius), and r = source to detector distance.

Therefore, S(E) = number of photons incident per second on the detector = $(A/4) \times (d/r)^2$.

If the source is a multiple energy one then the number of photons incident on the detector per second for each energy had to be determined. For this the yield (%) had to be added up for all the energies. S(E) was then divided by the sum of these yield (%) and subsequently multiplied by the yield (%) of the expected energy. The sum of counts of 10 or 20 channels (sum count) was divided by S(E) × total time. This gives the efficiency of the detector per photon.

i.e. Efficiency = [Sum count] / [S(E) × time].

The channel number varies from source to source and for variation of their energy as well upto which the efficiency has to be determined. The final channel has to be considered as the one upto which the peak area starts. Then the efficiency versus energy curves are to be drawn listing different source energies for different range and efficiency. And from this, efficiencies are to be calculated for both energies and also for all cases. A matrix has to be made for efficiency versus energy from these calculations.

THE EXPERIMENT

The experiment was done at Atomic Energy Research Establishment, Savar, Bangladesh. The source used in the work was a ^{252}Cf source of strength measured on the date of performance of the experiment. Gamma particles coming out of the source was detected by a NaI(Tl) detector placed at 105 cm away from the source. Different shielding arrangements were placed in between the source and the detector. Spectra were then taken for different shields and different thickness values for a preset time.

RESULTS AND DISCUSSIONS

Unfolding of Gamma Rays: Unfolded Dose Spectra for the Single Shields

- **PB**

In Fig. 1 all the four different thicknesses for unfolded dose spectra of fission gamma of the shield shows the same positions of the peaks between 150 to 450 keV. With increasing shield thickness the peak strength decreases. On the higher energy side the dose rate falls at a quicker rate and practically maximum 850 keV gammas also contributes to the total dose. On the lower energy side the extension occurs down to 50 keV. The dose rate between 50 to 150 keV is approximately one-third of that in between 150 to 250 keV. The total dose values for 4, 16.5, 33.8 and 54 cm shield thicknesses are respectively 12.13, 10.39, 7.58, 2.03 μSv/h. Compared to these 100 keV bin results the corresponding total dose values found for the 50 keV and 25 keV bins are observed to be the same approximately. The values are given in the legends. The peak positions of the main peak of the latter two cases (Figs. 2 and 3) are again found to be the same. This means that between 250 to 350 keV maximum numbers of gamma photons are found to possess energy. When the shield thicknesses are increased these energy limits does not changes.

- **Pb**

Figs. 4-6 show unfolded dose spectra of fission gamma after passing through the 5, 10.12, 19.66 and 24.57 cm shield thicknesses of Pb. Pb, being a very good gamma shield, reproduces suppressed peak of height 1.2 µSv/h for the 5 cm shield thickness for the 100 keV bin spectra. The peak position of the 50 keV bin shifts by about 25 keV towards the lower energy side.

No extra feature (Fig. 6) between 25 to 75 keV in the 50 keV bin spectra could be observed in the 100 keV bin spectra. As of the previous case the total dose values are found to remain approximately the same in all the different bin spectra. The suppression of the spectra for Pb is due to the high quality shielding effect of the shield.

Unfolding of Multilayers Containing PB

- **Unfolded Dose Spectra for the Shields PB+Pb and Pb+PB**

The presence of Pb in the multilayers PB+Pb and Pb+PB influences strongly (Figs. 6-7). Hence much depressed spectra than those of other multilayers could be observed. The peak position of the main peak is found to be the same as of the previous cases. On reversion and thus forming Pb+PB setup less values of dose rate and the total dose rate are obtained (please see the legends). The maximum energy gamma photons although very less in number are found to possess 850 keV energy. The common points mentioned previously are also found for the PB+Pb and Pb+PB multilayers.

CONCLUSIONS

In the present study five single layer shields e.g., PB and Pb and their multilayers e.g., PB+Pb, and Pb+PB and their reversed combination have been studied. Flux spectra and dose spectra for fission gamma rays shielding have been investigated for all the above setups. The fission gamma ray flux spectra of the PB-multilayer shields shows some special features. These features include an initial peak at 0.3 MeV, a trough at 1 MeV, a second small peak observed at 1.5 MeV, a trough at 3 MeV, a third peak at 4 MeV and a constant photon flux between 5 to 10 MeV (Figs. 1-3). In all the shielding arrangements it is observed that the transmitted gamma photons unfolded by using three energy bins, contain maximum number of photons in the range between 250 to 350 keV. On reversing i.e., by forming a multilayer placing the heavier element first, the dose rate values are found to decrease. Beyond the 850 keV energy, practically no gamma photons were observed (Figs. 1-14). A multilayer containing more than two layers and having a heavy shield placed first is found to be a better gamma shield compared to its reversed setup. Multilayers are found to be more effective at larger thicknesses of the shields. Characteristics of PB-multilayers for fission gamma rays are found to be dependent on their uncommon component shields. On reversing the components the shielding characteristics change, but the relative characteristics of the uncommon components do not.

Among the single layers studied Pb is the best gamma ray shield. For practical purpose Pb is generally avoided because of its toxic effect and then BC naturally becomes the next choice for the whole range of thicknesses studied. For fission gamma ray shielding, for small thickness, Pb+PB multilayer shows equal shielding ability as a better choice for gamma ray shielding purpose and this is supported by experiments as well as theoretical (MCNP) calculations (Table 2). Once the choice is made about the suitable shielding arrangement, the results obtained from the present study in the form of polynomial fits can give the quantitative information about the exact value of the shield thickness necessary. This is one of the beauties of the present investigation.

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TABLES

Table 1: Half life, Source Strength, Energy, Yield Percent and The Distance of the Sources from the Detector used for the Unfolding Experiment

Name of Isotope	Half Life ($T_{1/2}$)	Source Strength	Gamma energy, E_γ (keV)	Yield Percent (%)	Source to Detector Distance (cm)
^{241}Am	458 years	373.7 kBq (on 1-7- 1983)	60	36%	5
^{109}Cd	453 days	37.37 kBq (on 4 -1 -1988)	88	3.7%	5
^{54}Mn	313 days	40.96 kBq (on 4 -1 -1988)	835	100%	5
^{57}Co	271 days	634.1 kBq (on 1-7-1983)	122 136	85.5% 11%	5
^{133}Ba	10.54 years	328.3 kBq (on 1-7-1983)	302 356	18.4% 62.2%	10
^{22}Na	2.62 years	337.1 kBq (on 1-7 -1983)	511 1275	180% 100%	10
^{137}Cs	30 years	416.5 kBq (on 1-7-1983)	662	100%	10
^{60}Co	5.25 years	408.6 kBq (on 1-7-1983)	1173 1332	100% 100%	10

Table 2: Gamma Half Value, 25% Transmission, Tenth Value and 5% Transmission Fission Gamma

Shielding Material	50% Transmission		25% Transmission		10% Transmission		5% Transmission	
	MCNP	Expt.	MCNP	Expt.	MCNP	Expt.	MCNP	Expt
PB	44	53.0	74.0	*	*	*	*	*
Pb	2.5	2.8	4.0	4.5	7.0	8.3	8.7	9.5
PB+Pb	7.7	7.3	9.2	9.4	16.0	16.3	18.4	18.6
Pb+PB	2.5	2.8	4.0	4.5	11.5	12.7	13.5	14.2

FIGURES

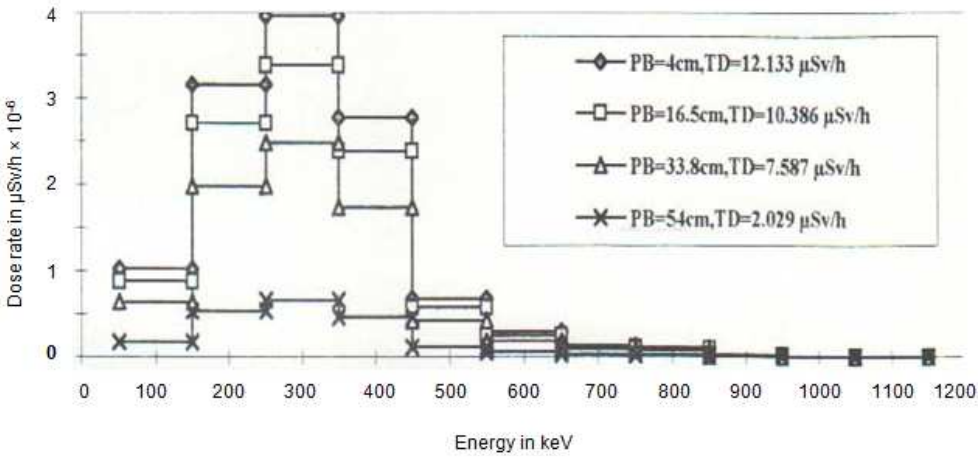

Figure 1: Unfolded dose Spectra (100 keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield PB.

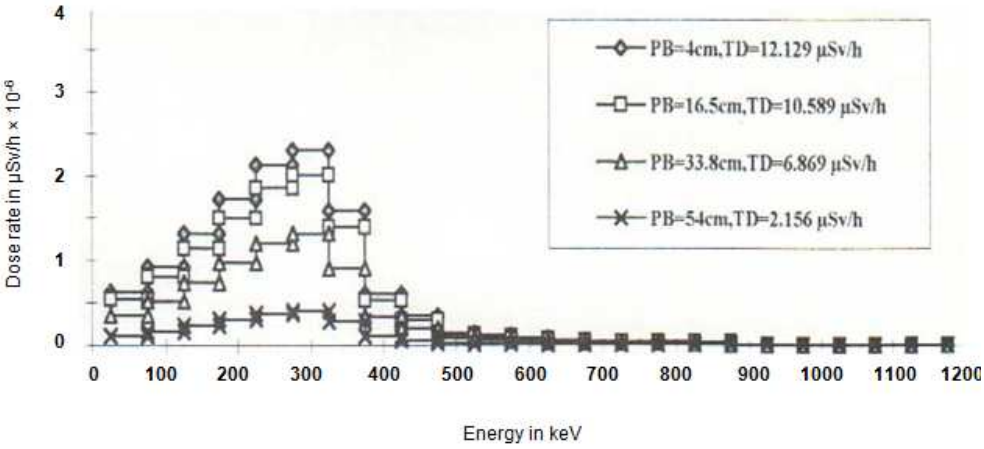

Figure 2: Unfolded dose spectra (50 keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield PB.

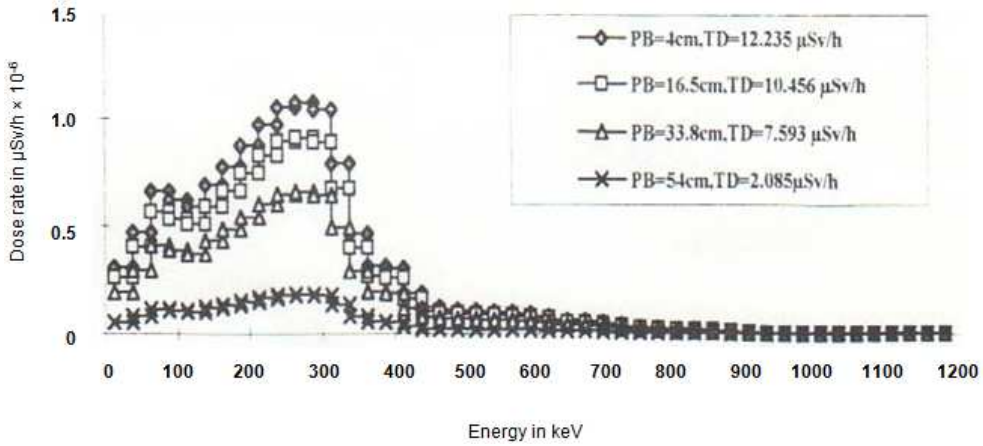

Figure 3: Unfolded Dose Spectra (25keV bin) of Fission Gamma after Passing through different thicknesses of the shield PB.

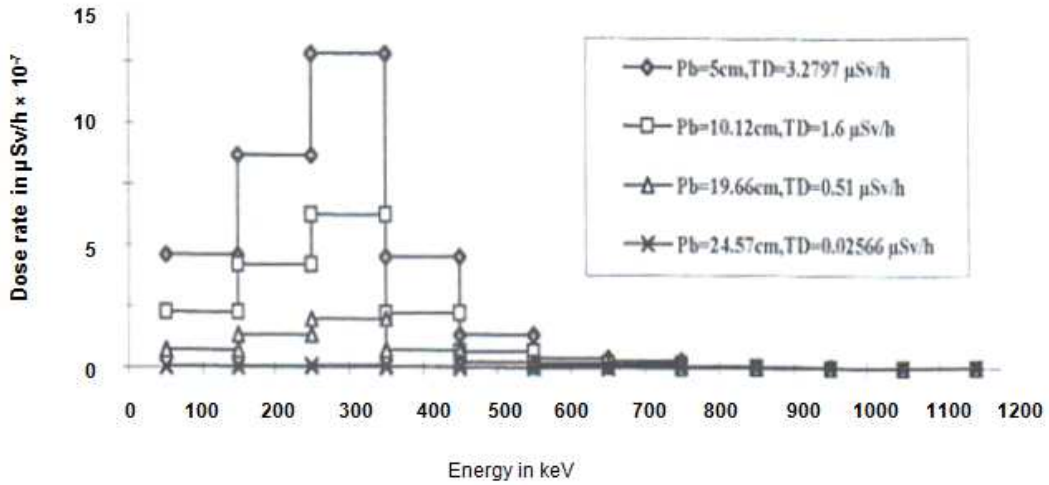

Figure 4: Unfolded Dose Spectra (100keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield Pb.

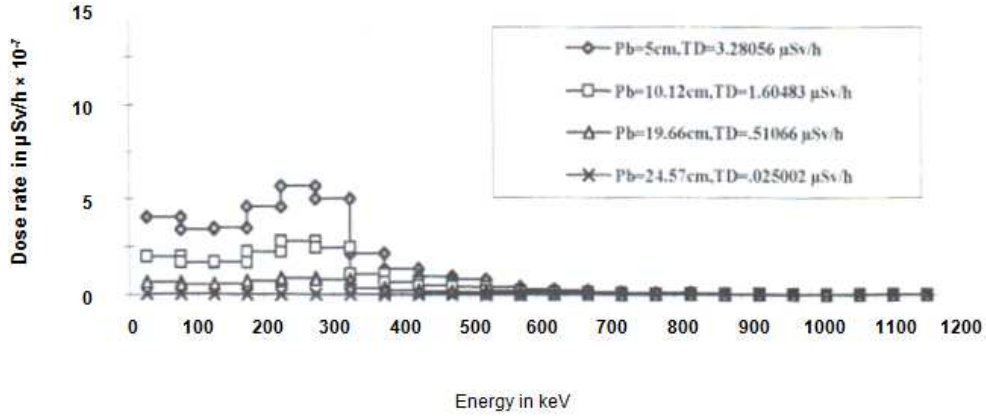

Figure 5: Unfolded Dose Spectra (50keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield Pb.

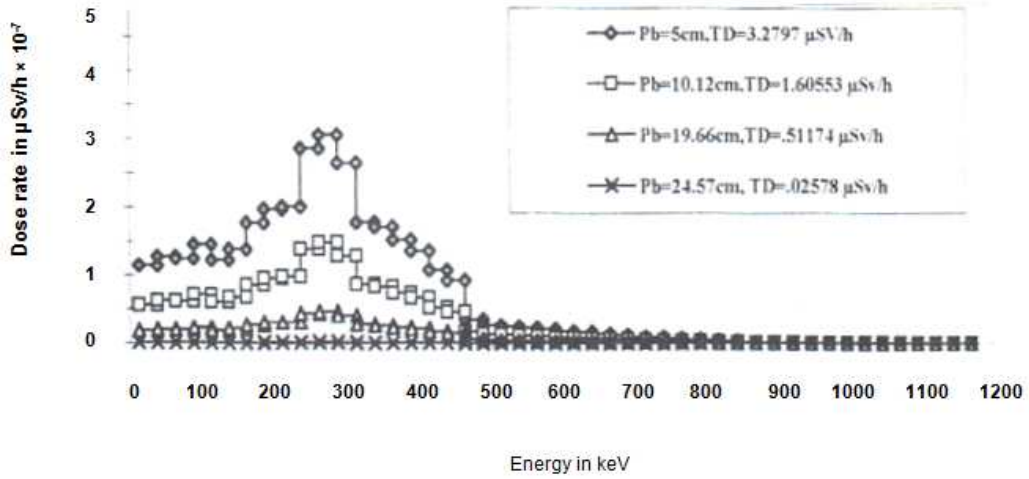

Figure 6: Unfolded Dose Spectra (25keV bin) of Fission Gamma after passing through different Thicknesses of the Shield Pb.

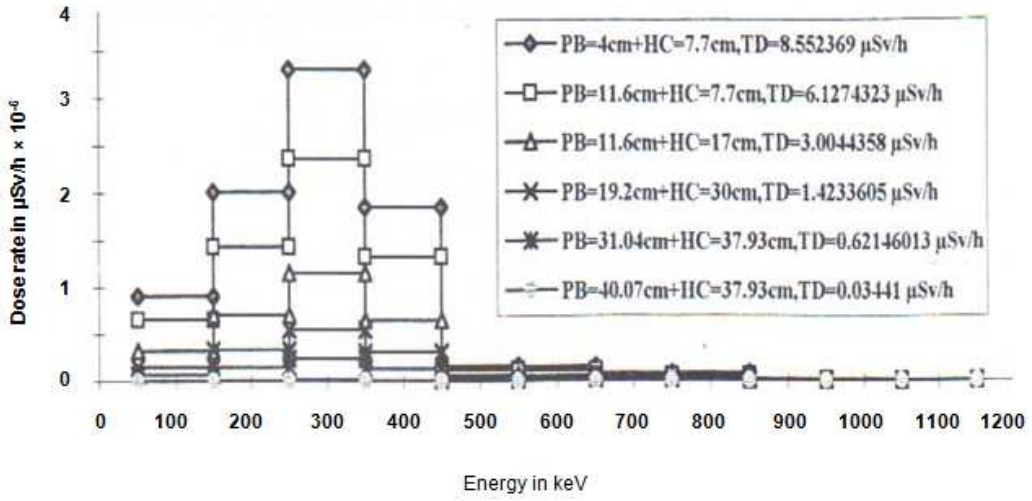

Figure 7: Unfolded Dose Spectra (100keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield PB+HC.

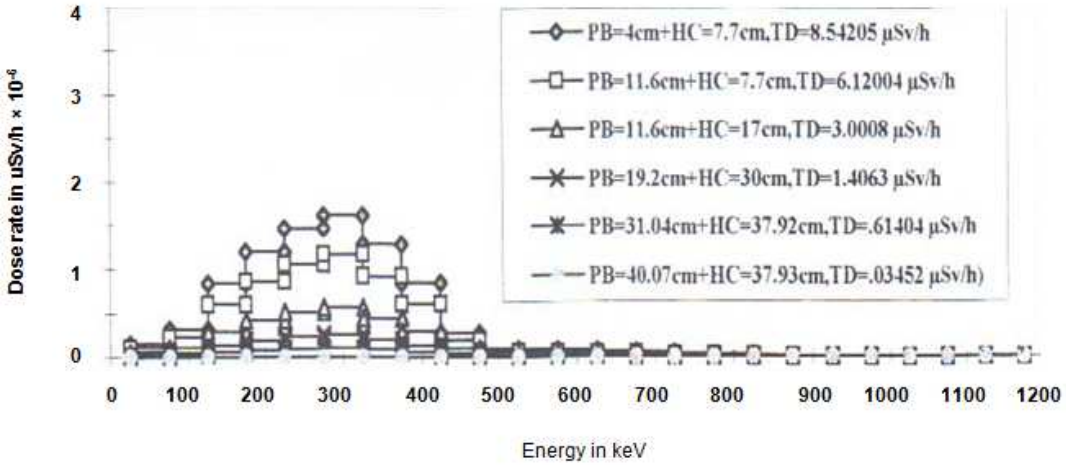

Figure 8: Unfolded Dose Spectra (50keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield PB+HC.

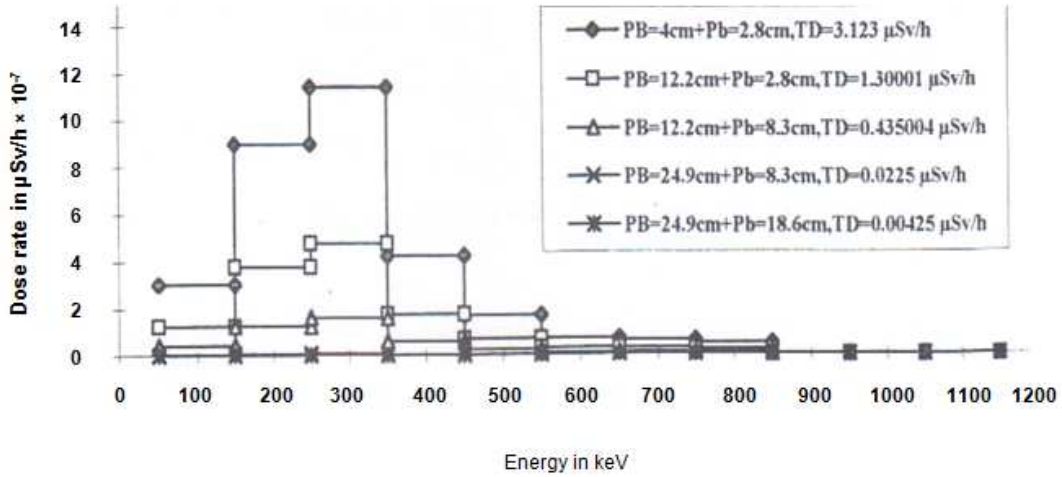

Figure 9: Unfolded Dose Spectra (100keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield PB+Pb.

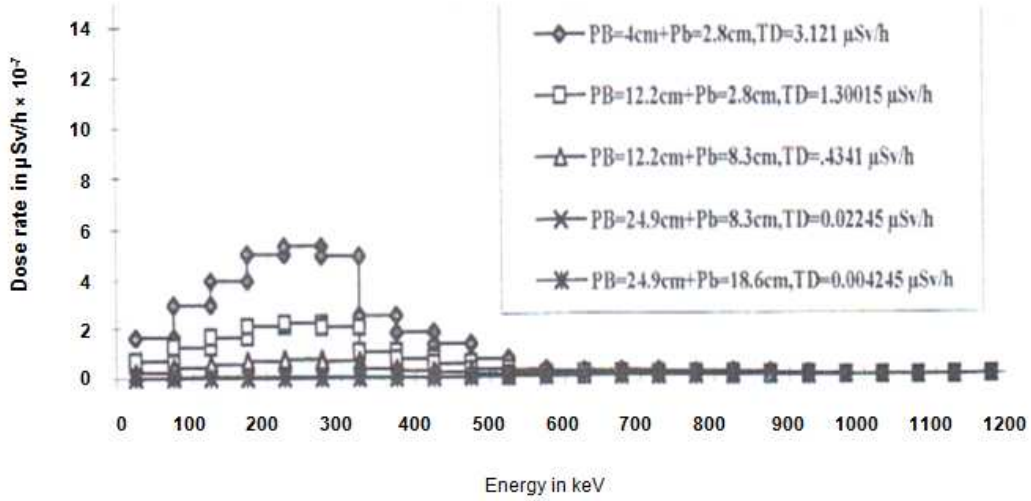

Figure 10: Unfolded Dose Spectra (50keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield PB+Pb.

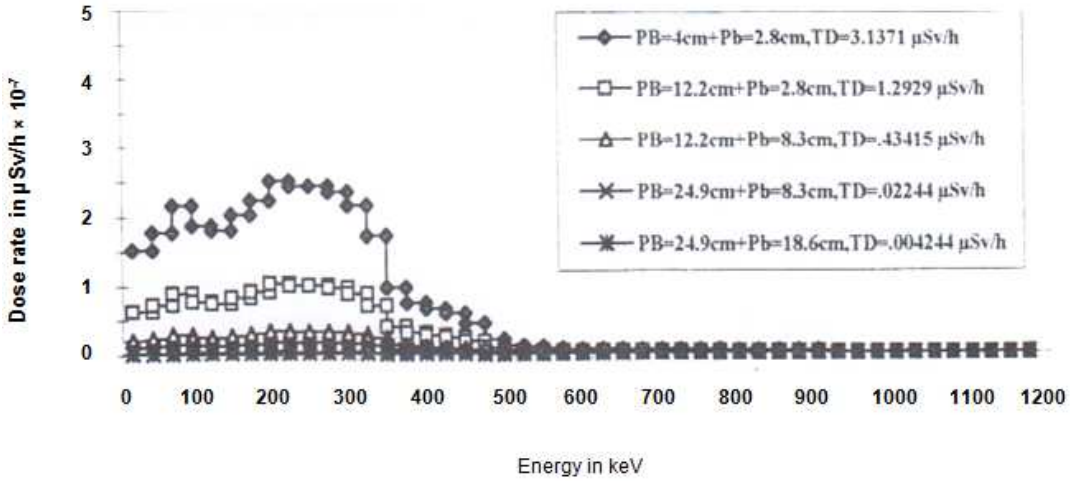

Figure 11: Unfolded Dose Spectra (25keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield PB+Pb.

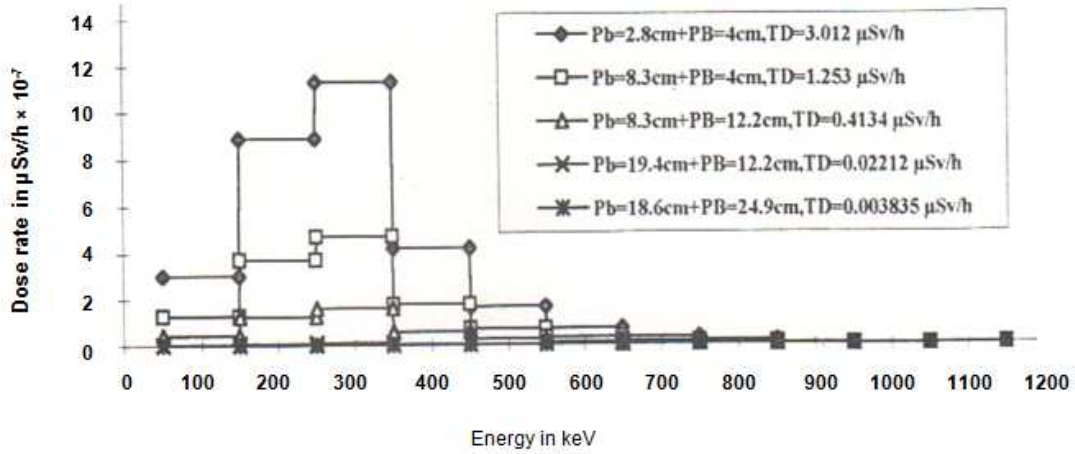

Figure 12: Unfolded Dose Spectra (100keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield Pb+PB.

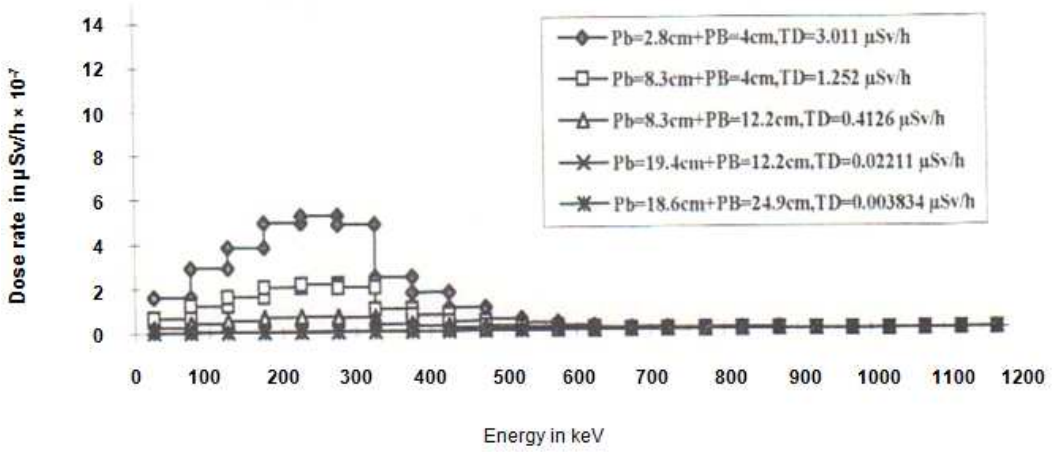

Figure 13: Unfolded Dose Spectra (50keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield Pb+PB.

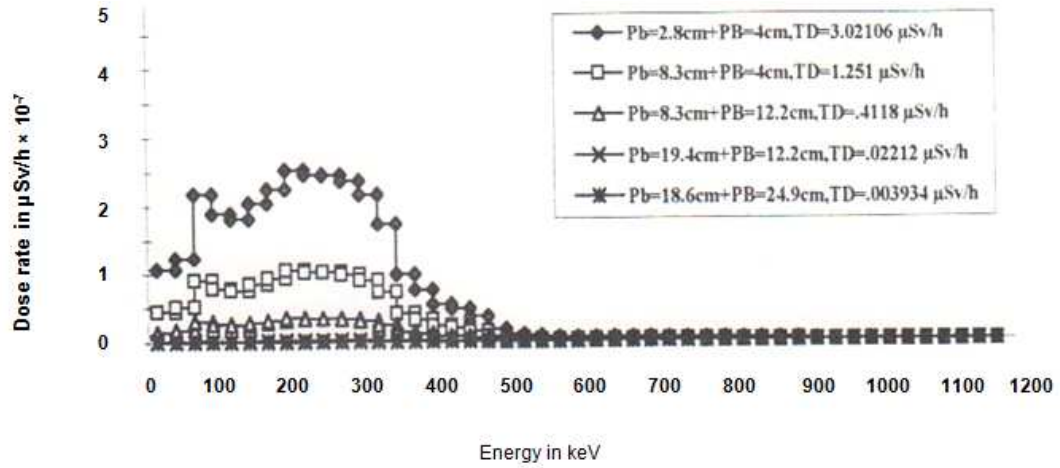

Figure 14: Unfolded Dose Spectra (25keV bin) of Fission Gamma after Passing through different Thicknesses of the Shield Pb+PB.