STOCHASTIC SIMULATION STUDY OF HPGe DETECTOR RESPONSE AND THE EFFECT OF DETECTOR AGING USING GEANT4

by

Hina TARIQ, Sikander M. MIRZA, Shakeel Ur REHMAN, and Nasir M. MIRZA*

Department of Physics & Applied Mathematics, Pakistan Institute of Engineering & Applied Sciences,
Nilore, Islamabad, Pakistan

Scientific paper
http://doi.org/10.2298/NTRP1701057T

In this study the effect of detector aging in terms of increased dead layer thickness on detector efficiency has been studied using the Geant4 toolkit. Variation of energy deposition in the detector dead layer with the dead layer thickness has been quantified for various values of incident γ-ray energy considering point isotropic as well as extended sources including the circular disk source and cylindrical volume sources. For the point isotropic source, the Geant4 computed values of energy loss per particle in the dead layer are found in good agreement with the corresponding published results with maximum deviation remaining below 2 %. New results for dependence of geometric, full-energy peak and total efficiency on dead layer thickness have been studied using Geant4 simulations for various values of γ-ray energy, and for point isotropic and extended sources at various axial and lateral positions. These simulations yield an exponentially decreasing profile of detector aging sensitivity with an increase in γ-ray energy for point isotropic, circular disk and cylindrical volume sources highlighting a larger decrease in efficiency due to aging for low energy photons.

Key words: HPGe, dead layer, detector aging, detection efficiency, Monte Carlo, Geant4

INTRODUCTION

HPGe detectors are widely used for quantification of radionuclides in environmental samples [1, 2] as well as neutron activation analysis [3]. These detectors offer high sensitivity along with excellent energy resolution which is essential for low activity measurements. Precise efficiency calibration is routinely needed for radio-assay of such samples. This is normally carried out experimentally. However, it typically entails various problems including unavailability of standard calibration sources covering the entire range of the γ-ray energy. Also, these sources must closely match the geometry of the samples to be analyzed. In the absence of such sources, the efficiency transfer method is commonly used [4] which is restrictive due to the various approximations involved. Empirical [5] and semi-empirical [6] approaches have been used in the past where availability of calibration sources is limited. In such cases, a few available sources are used for determination of parameters of the empirical fitting formula, which is then used for the estimation of detection efficiency for the sample by using the corresponding value of γ-ray energy and other parameters including source-to-detector distance etc. In such situations, the empirical or semi-empirical formulae serve as an interpolation procedure. Consequently, uncertainty is added to the value of efficiency due to the various approximations involved.

Exact analytical expressions have also been developed for direct computation of detector efficiency [7-9]. These formulae usually involve determination of the coupling solid angle between source and detector [10], while incorporating the exponential factor based interaction probability estimation utilizing a suitable, photoelectric- or total-attenuation coefficient. Such expressions prove highly useful due to the accuracy of the computed results and mostly "direct" use of formulae. However, for general cases of a practical nature, the computation of solid angles typically requires numerical evaluation of integrals which usually entails computational time and some limited numerical precision due to approximations while performing numerical integrations. Notably, the exact analytical formulae have been developed for a limited set of cases to-date. Their derivations tend to be tedious and extending the existing formulae to further geometries of practical interest generally involves enormous effort.

On the other hand, Monte Carlo methods offer a reliable way to determine detector efficiency for a

---

* Corresponding author; e-mail: nasirmm@yahoo.com
nmm@pieas.edu.pk

wide range of applications [11-13]. They belong to a general class of numerical methods called stochastic techniques in which detailed stochastic simulations of the processes are carried out. For detector efficiency estimation, the Monte Carlo method simulates radiation transport from the source to the detector and within the active volume of the detector. The simulation process tracks each radiation quanta from the source to the detector and then within the detector and along the track it simulates various interactions which the radiation quanta make within the detector and in the surrounding material. The tracking is terminated when either the radiation leaves the active volume of the detector or when the energy of the radiation falls below the preset threshold value.

This study discusses the effect of detector aging on its efficiency. The radiation detector efficiency has been observed to decrease/degrade with time. In this regard the detector dead layer has been identified as playing the dominant role. A thin dead layer has been reported to improve performance by 32 % for the Compton suppression spectrometer where two germanium detectors with 126 cm^3 volume and 1 mm thick dead layer, and with 90 cm^3 volume and 0.22 mm thick dead layer were compared [14]. Similarly Rodenas *et al.* [15] carried out Monte Carlo simulations to analyze the influence of the germanium dead layer on detector calibration involving environmental radioactivity. They identified the role played by a transition zone between the active and inactive regions of the detector. In another study electronic signals from the detector dead layer were analyzed experimentally and their contribution towards full-energy peak efficiency (FEPE) and total- efficiency was quantified [16].

Often sufficiently precise values of detector dead layer thickness and bulletization are not available from the manufacturer. Ashrafi *et al*. developed and applied a systematic iterative procedure for the coaxial HPGe detector to match the Geant4 estimated value of total absorption peak efficiency with the corresponding experimental data [17]. Improvements in the surface dead layer structure were suggested and the optimum value of dead layer thickness was found as 0.5 mm along with radial dead layer thickness starting with 0.7 mm at top to 1.1 mm at the bottom of the detector.

Strong discrepancies between calculated and measured efficiency values have been reported by using manufacturer provided data for detector modeling [15]. In addition, a transition zone has been identified between the dead layer and the detector sensitive region [18]. This zone behaves as an inactive region and must be treated as further extension of the dead layer with a thickness not precisely known. Using detailed sensitivity analysis, the authors have identified the γ-ray energy dependent inactive layer. Discrepancies in the 5 %-10 % range have been reported between Monte Carlo calculated values of efficiency and the corresponding experimental data [19] which are believed to be due to errors in the manufacturer's values of detector parameters. These include thickness of front dead-layer, crystal-to-Be window distance and effective detector radius. The authors carried out optimization of these parameters using stochastic simulations to match the estimated and experimental values. In a separate work, Dryak and Kovar [20] used a collimated photon beam of 59.5 keV from an Am-241 source from various incidence angles on the front face of an HPGe detector to determine the effective thickness of the dead layer. Likewise, many researchers found it necessary to optimize the dead layer thickness in order to remove discrepancies between experimental observations and corresponding Monte Carlo simulated values [21-31].

Efficiency degradation due to detector aging in the energy range of 50-170 keV was investigated by Huy [32] and an increase in the dead layer thickness was identified as the dominant cause of the degradation. The relative decrease of the detector's efficiency with an increase in dead layer thickness, for a point isotropic source, was calculated by MCNP5 simulations [33] and the values were compared with corresponding experimental measurements.While the previous studies explored the effect of the dead-layer thickness increase on detector efficiency for axially placed point isotropic sources, this work aims to assess detector aging induced dead-layer growth on detector efficiency for point isotropic, circular disk and cylindrical volumetric sources in axial as well as off-axial configurations.

MATERIALS AND METHOD

Geant4 toolkit

Geant4 [34] provides a state-of-the-art framework for simulation of transport of both charged and neutral particles. It uses the object oriented programming (OOP) approach and exploits classes with hierarchy for streamlining data handling and ensures data security through encapsulation. The user code assembles necessary modules from packages for problem definition. The Geant4 toolkit allows inclusion of user-defined new classes while the existing classes can be extended to handle a more complex scenario using inheritance.

The present work uses the Geant4 version 9.6 with the Standard Physics Library. Efforts have been made to implement a realistic detector model by incorporating all the necessary geometry details. One million photon histories have been generated for each measurement value and the simulations were repeated thrice with different random seed for better statistics. In some cases, source biasing has also been implemented for improving computational efficiency.

Geometry

A coaxial HPGe detector of radius *R* and height *H* with the inner hole of radius *Ri* and height *Hi* has been considered in this work. The source is taken at *h* axial distance and ρ off-axial distance. For extended sources, these distances are taken with reference to the geometric center of the source. All extended sources were assumed to be uniform and homogeneous.

Detector and source modeling

A detailed Geant4 model of the HPGe detector has been developed with the detector sensitive region, dead layer, front window and axial sleeve with materials and dimensions as given in tab. 1, and shown in fig. 1. Point isotropic and extended mono-energetic sources have been considered in this study. For extended sources such as the Petri dish and Marinelli beaker, water was chosen as the fill material with the γ-ray source distributed uniformly in it. Self-attenuation of emitted radiations within the source has been incorporated in the simulations. All major physics processes including photo-electric effect, coherent- and incoherent scatterings, pair production, Auger effect *etc.*, have been simulated using the Standard Physics Model in Geant4 for the energy range covering 0.001 MeV to 10 MeV. Energy cut off values of 30 keV for electrons and 1 keV for photons have been employed in the simulations.

RESULTS AND DISCUSSION

Geant4 model validation

Efficiency comparison with MCNP4C data

In order to validate the Geant4 detector model, simulated values of detector efficiency for point and Marinelli disk sources have been compared in fig. 2, with the corresponding published data using MCNP4C [35]. An HPGe detector of 60 mm length, 60 mm diameter, 40 mm core depth, 10 mm core diameter with 1 mm aluminum cover has been considered.

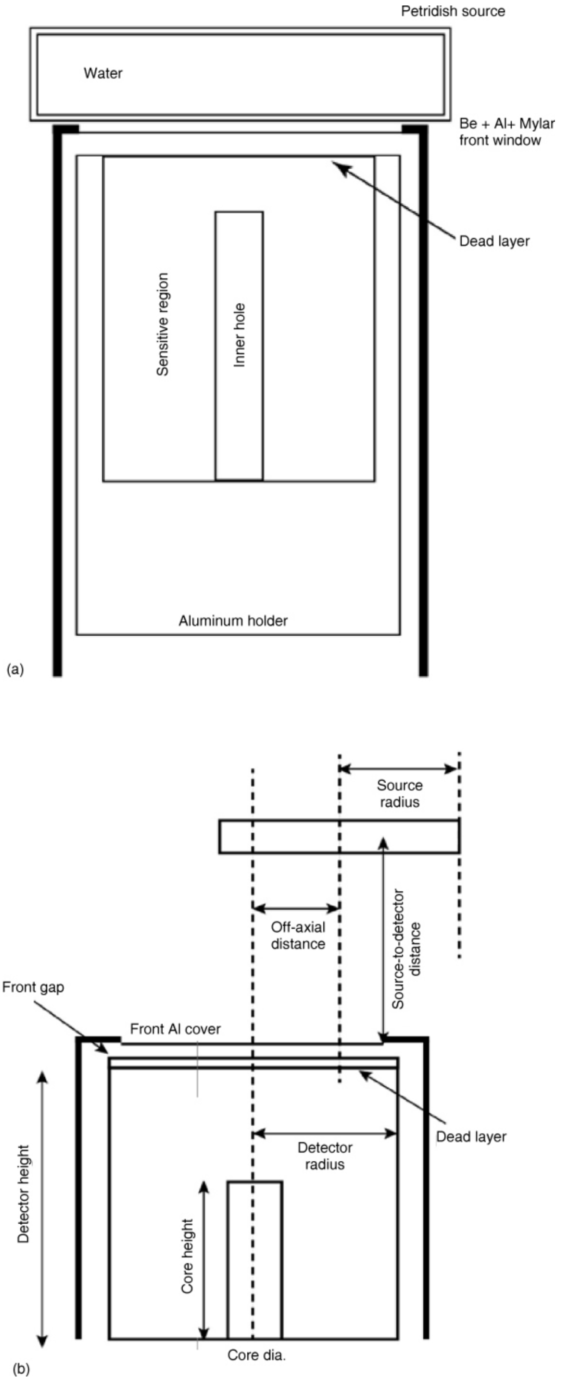

Figure 1. Schematic diagram of the HPGe detector geometry model used in Geant4 simulations (a) Petri dish source and (b) cylindrical volume source

Table 1. Summary of reference detector dimensions used in various Geant4 simulations carried out in this work

Parameter	Reported values				
	Liye *et al.*, [37]	Hurtato *et al.*, [19]	Querol *et al.*, [36]	Diaz *et al.*, (point source) [35]	Diaz *et al.*, (disk source) [35]
Ge crystal diameter [mm]	70	54	30	60	48
Ge crystal length [mm]	21	5	71.1	60	57.0
Ge dead layer [μm]	0.3	300	0.3	1	1
Core diameter [mm]	–	0.5	9.0	5.0	12
Core depth [mm]	–	41	63.1	40	45
Distance from windows to crystal [mm]	5.5	5.0	4	4	5.5
Window thickness [mm]	0.5	0.5	0.8	1	0.5

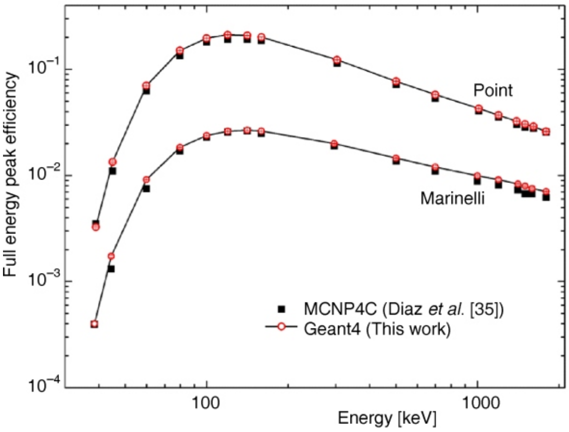

Figure 2. Comparison of Geant4 computed full energy peak efficiency values with the corresponding data obtained by using MCNP4C simulations for point isotropic source, circular disk source, and cylindrical volume source, placed axially at indicated distances from the HPGe detector

All sources have been placed axially at a 5 mm distance from the detector surface. It is clear from fig. 2 that Geant4 computed values of efficiency are in good agreement with the corresponding MCNP4C results having maximum error below 2 %, and 3 % for point, and the Marinelli disk sources respectively.

Energy deposition comparison with MCNP5 data

The energy deposition studies in the dead layer have been carried out using Geant4. A 71.1 mm long co-axial germanium crystal having a 60 mm diameter with a 63.1 mm deep core with 9 mm diameter has been considered in these simulations with the end-cap to crystal distance as 4 mm. The detector window has been taken as 8 mm thick aluminum and 0.03 mm Mylar. A 100 cm^3 polyethylene Petri dish filled with water has been used as the radiation source. Figure 3 shows the comparison of Geant4 computed values of the average energy deposition per particle with the MCNP5 calculated data for various values of dead layer thickness [36]. These results are in fairly good agreement with the corresponding MCNP5 data especially for the higher energy range. Some deviations between the corresponding values are observed for low energy photons but the maximum deviation remains below 5 %.

Detector efficiency dependence on detector aging

The detector aging results in increase of its effective dead layer thickness and consequently has its impact on detector efficiency values especially in the low energy range. In order to quantify the impact of increasing dead layer thickness on efficiency values, Geant4 simulations have been carried out for point isotropic, circular disk and cylindrical volume sources placed axially at a distance of h = 3.4 cm from the detector using γ-ray energies of Am-241 (59.54 keV), Cd-109 (87.90 keV), Co-57 (122.06 keV), Cs-137 (661.59 keV) and Zn-65 (1115.52 keV). Standard detector dimensions taken from literature (Querol *et al*., 2015) for the *n*-type HPGe detector have been used in these simulations. It has been observed that the efficiency decreases with the increase in dead layer thickness (figs. 4-6). It can be seen from the figures that the decreasing trend is more prominent for lower energies. This higher aging sensitivity of low energy photons stems from the fact that lower energy photons have greater value of photoelectric cross section and consequently, even small changes in effective dead layer thickness results in substantial attenuation of these photons within the detector dead layer and a corresponding decrease in detector efficiency.

The effective dead layer thickness for photons incident on the detector face from various directions depends on the angle of incidence of photon relative to

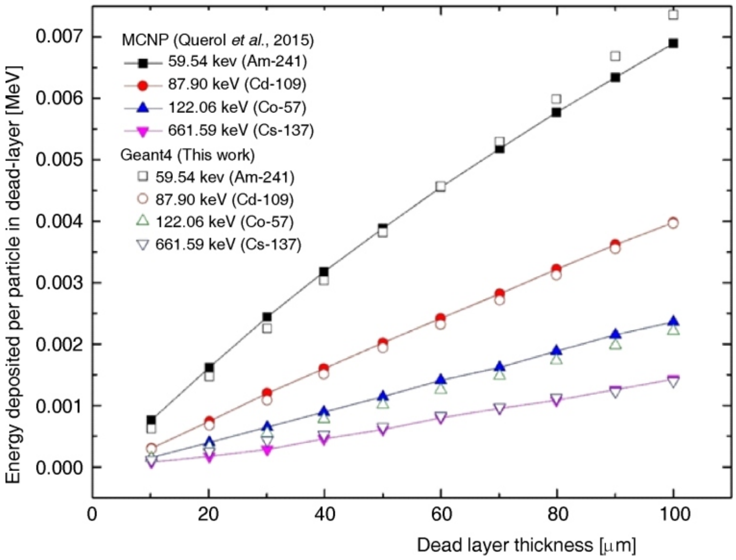

Figure 3. Comparison of Geant4 computed values and corresponding published data of the average energy deposition per particle with detector dead layer thickness for various indicated values of γ-ray energy for point isotropic source placed axially at 3.4 cm from the HPGe detector face

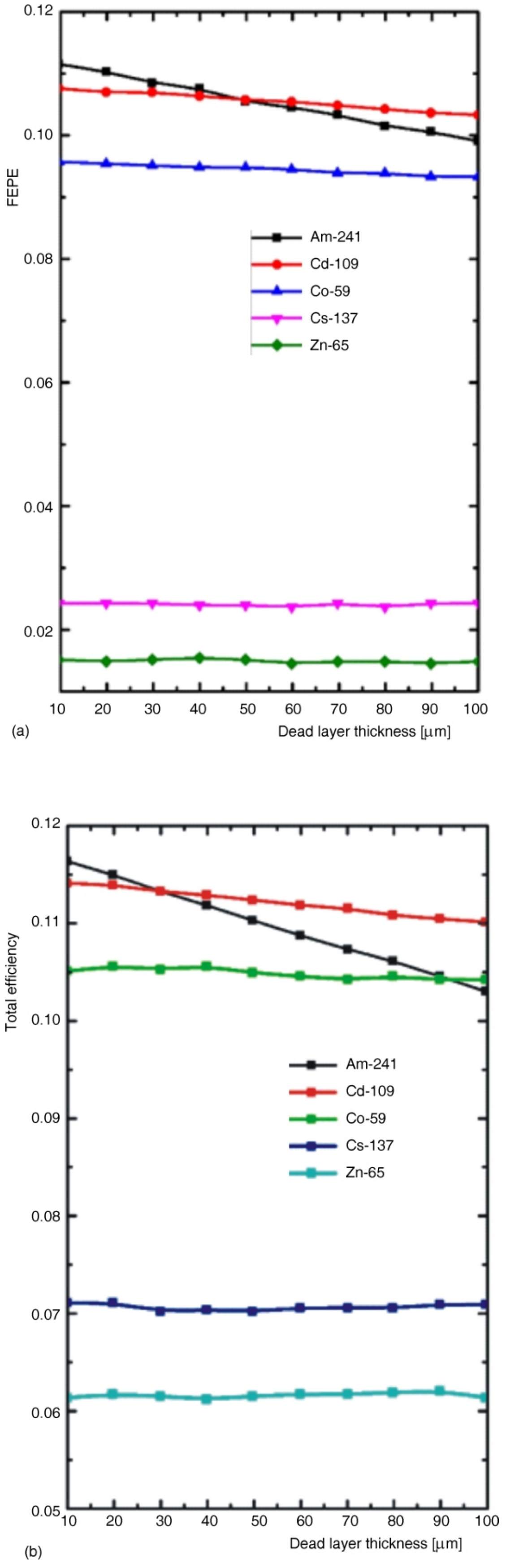

Figure 4. Variation of Geant4 computed values of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for point isotropic source placed axially at 3.4 cm from the HPGe detector face

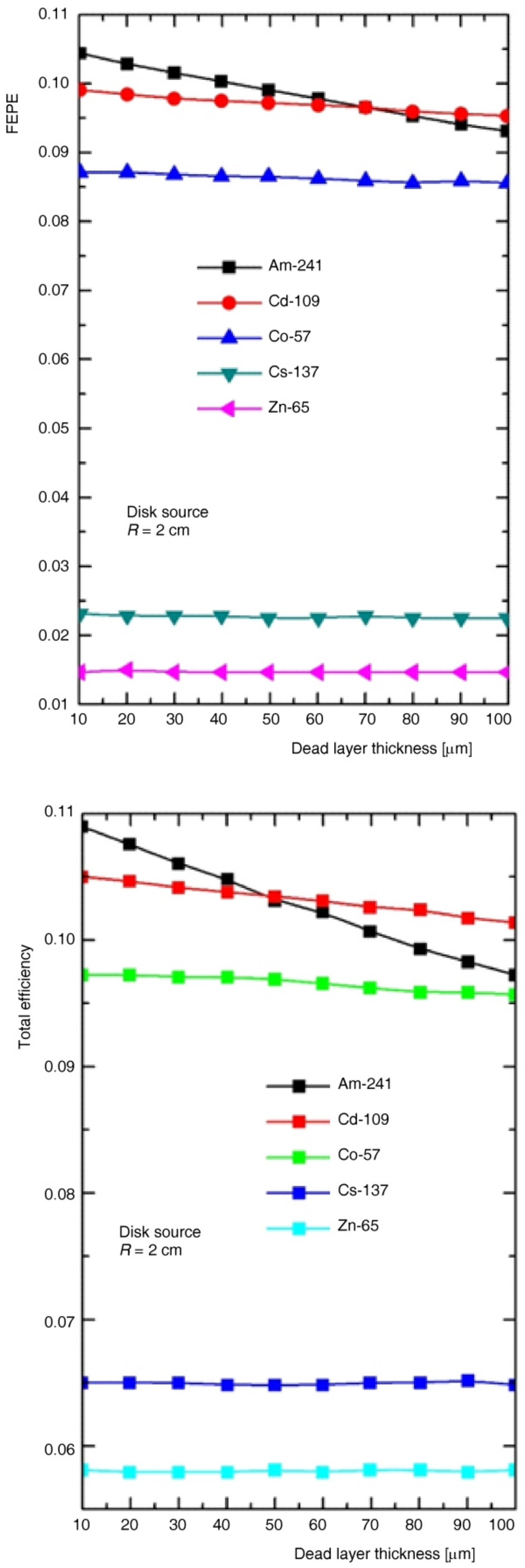

Figure 5. Variation of Geant4 computed value of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for disk source placed axially at 3.4 cm from HPGe detector face

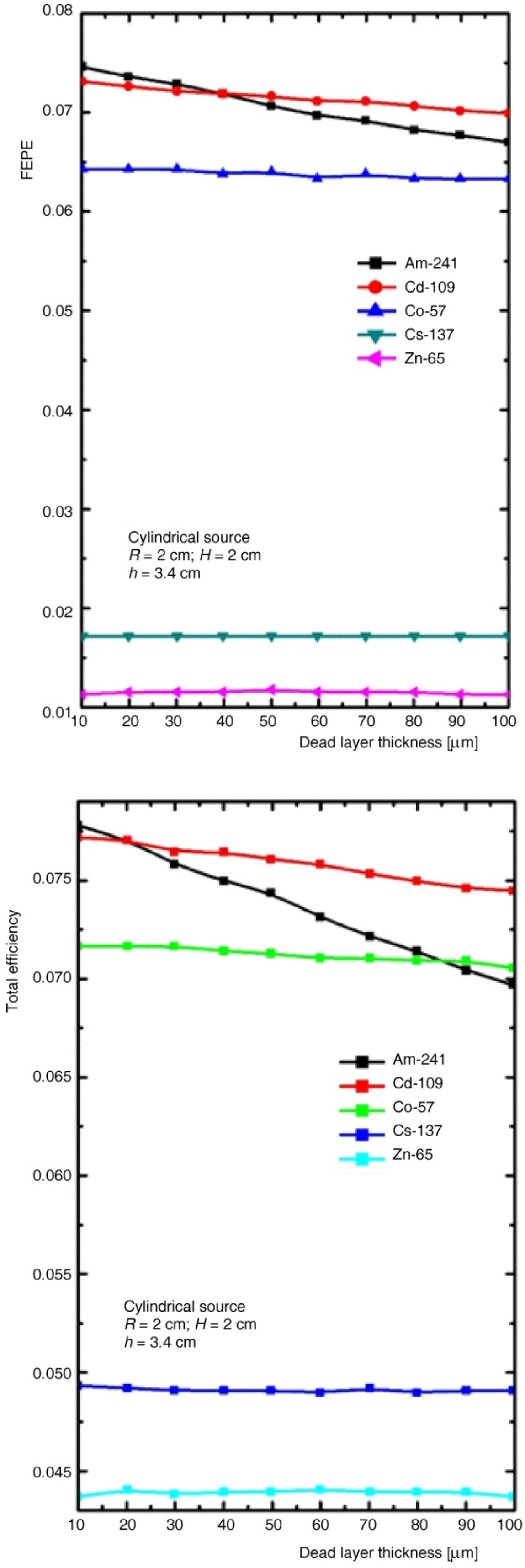

Figure 6. Variation of the Geant4 computed value of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for volume source placed axially at 3.4 cm from the HPGe detector face

the detector face, the larger the angle the larger will be the effective dead layer thickness. The distribution of the angle of incidences depends upon the source position relative to the detector. Therefore, the sensitivity of the detector in terms of detector efficiency has been studied for variation in the effective dead layer with the axial and off-axial position of the γ-ray source.

Effect of axial displacement of the source

For this a point isotropic source, a disk source with a radius $R = 2$ cm and a volume source of having a radius $R = 2$ cm and height $H = 2$ cm have been considered in Geant4 simulations. The axial distances of these sources from the detector h have been varied in the 2 to 5 cm range and the effect on FEPE and total efficiency have been studied for various γ-ray energies.

Since generally the average effective distance covered through the detector dead layer is larger for a source closer to the detector face, therefore, detector efficiency is expected to exhibit higher sensitivity to dead-layer thickness for sources closer to the detector. The corresponding results for point isotropic, disk and volume sources are shown in figs. 7-9. Consistent with the expectations, Am-241 emitting low energy photon placed axially closer ($h = 2$ cm) to the detector yields a higher value of aging sensitivity compared with the source placed at axial distance of $h = 4$ cm. With increasing γ-ray energy, the sensitivity decreases which is in agreement with the expected behavior.

Effect of off-axial displacement of the source

The off-axial movement of the source relative to the detector causes greater change in the average effective distance covered through the detector dead layer compared with axial configuration. Consequently, a larger variation in the detector efficiency has to be expected. Geant4 simulations have been carried out considering the same point, disk and volume sources, mentioned earlier. The off-axial position (ρ) of the sources has been varied from 2 cm to 4 cm while the axial distance (h) has been kept constant at $h = 3.2$ cm and the corresponding effect on detector efficiency has been quantified. The results are shown in figs. 10-12. Both FEPE and total efficiency values show a linear decrease with an increase in dead layer thickness with aging. As can be seen in the plots of total efficiency values, the relative decrease in the efficiency with the increase in dead layer thickness is greater at the higher off-axial position than the source position near the axis. The same trend can be seen for disk and volume sources. Again due to a higher value of the photo-electric cross section of lower energy photons, the variation in the detector efficiency with the off-axial position and dead layer thickness is more promi-

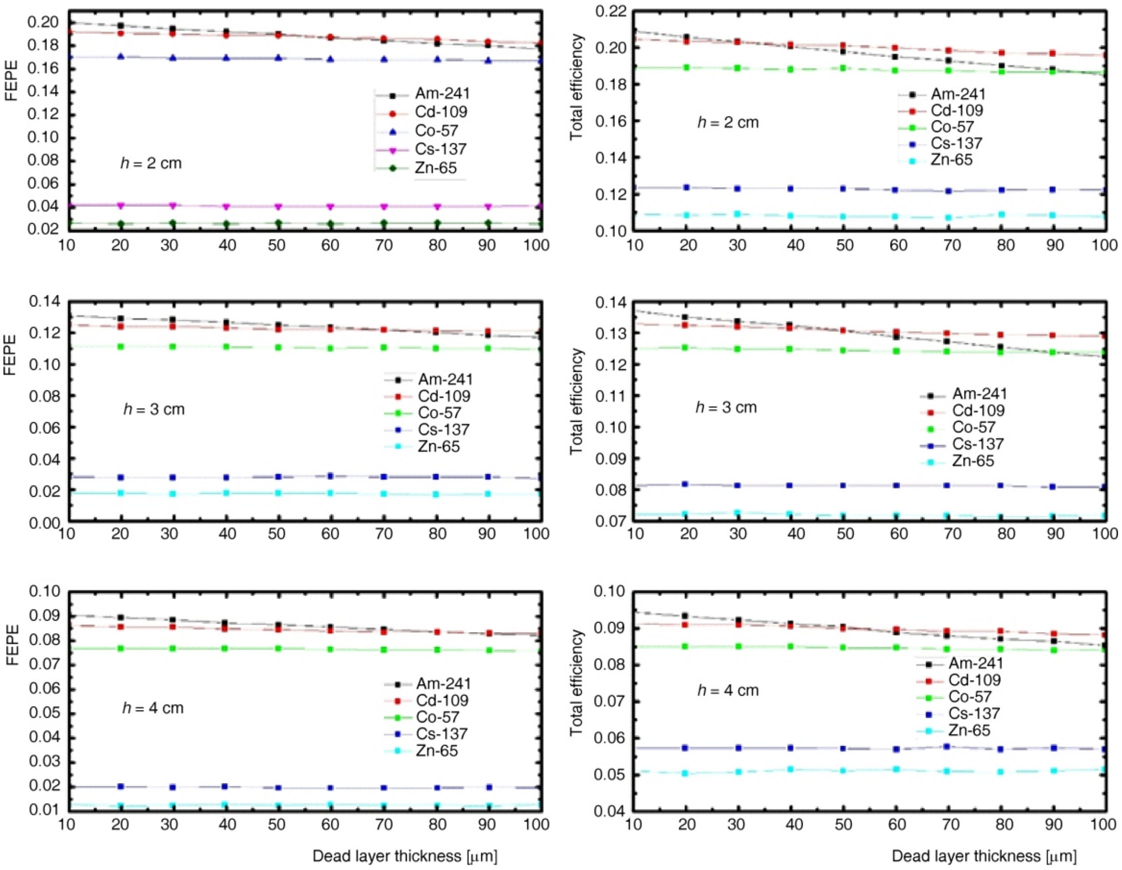

Figure 7. Effect of change in the axial source to detector distance (*h*) on Geant4 computed values of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for the point isotropic source

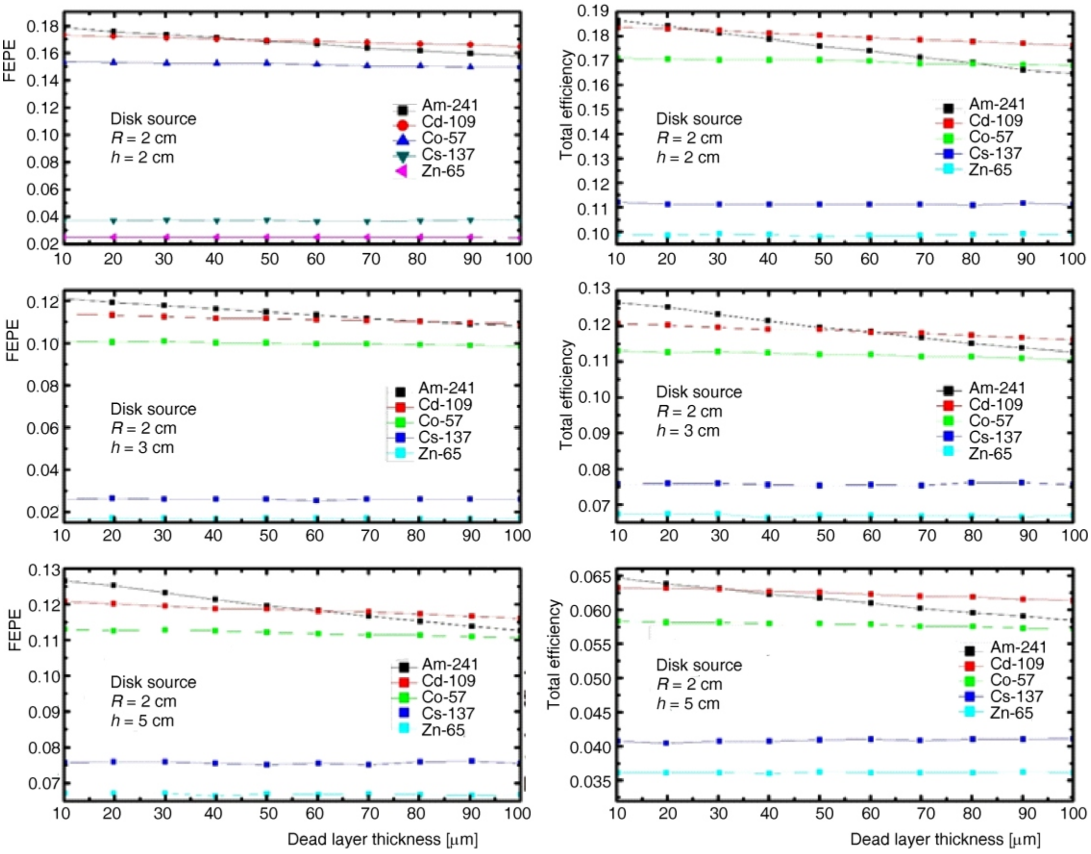

Figure 8. Effect of change in axial source to detector distance (*h*) on Geant4 computed values of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for disk source of 2 cm radius

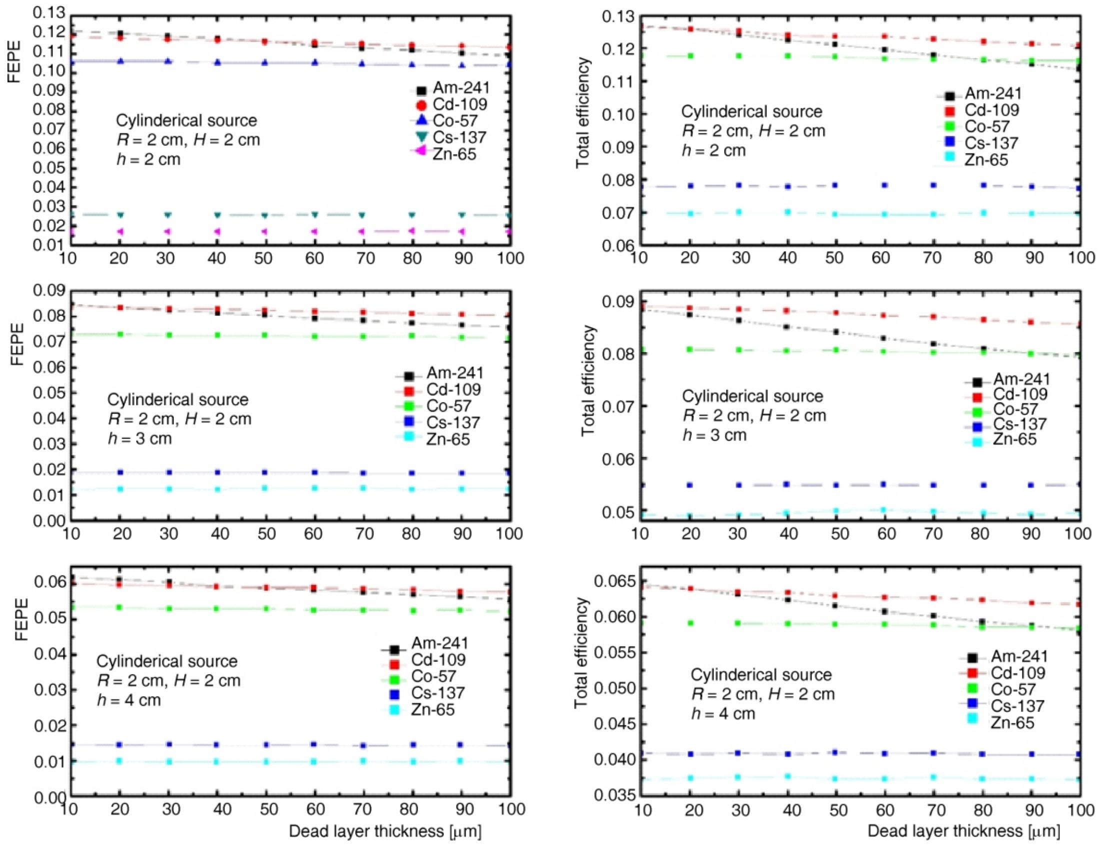

Figure 9. Effect of change in axial source to detector distance (h) on Geant4 computed values of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for volume source of 2 cm radius and 2 cm height

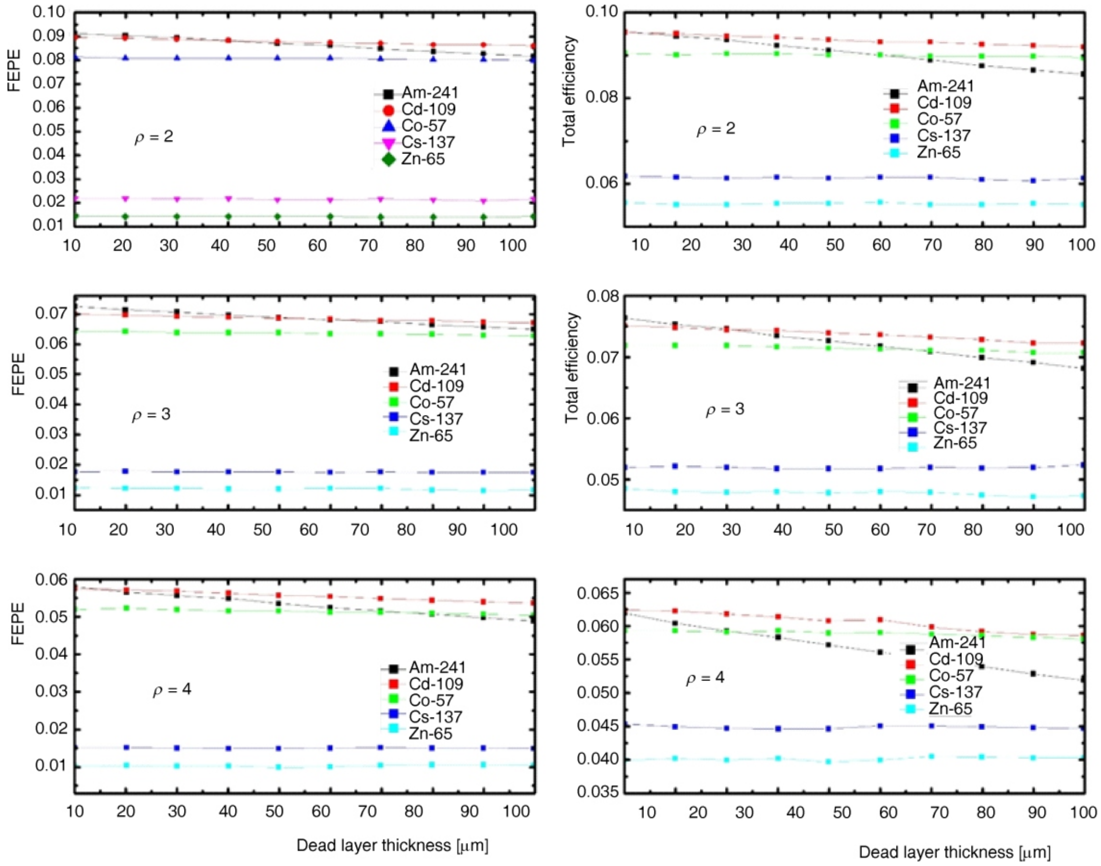

Figure 10. Geant4 computed values of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for various indicated off-axial positions (ρ) of the point isotropic source

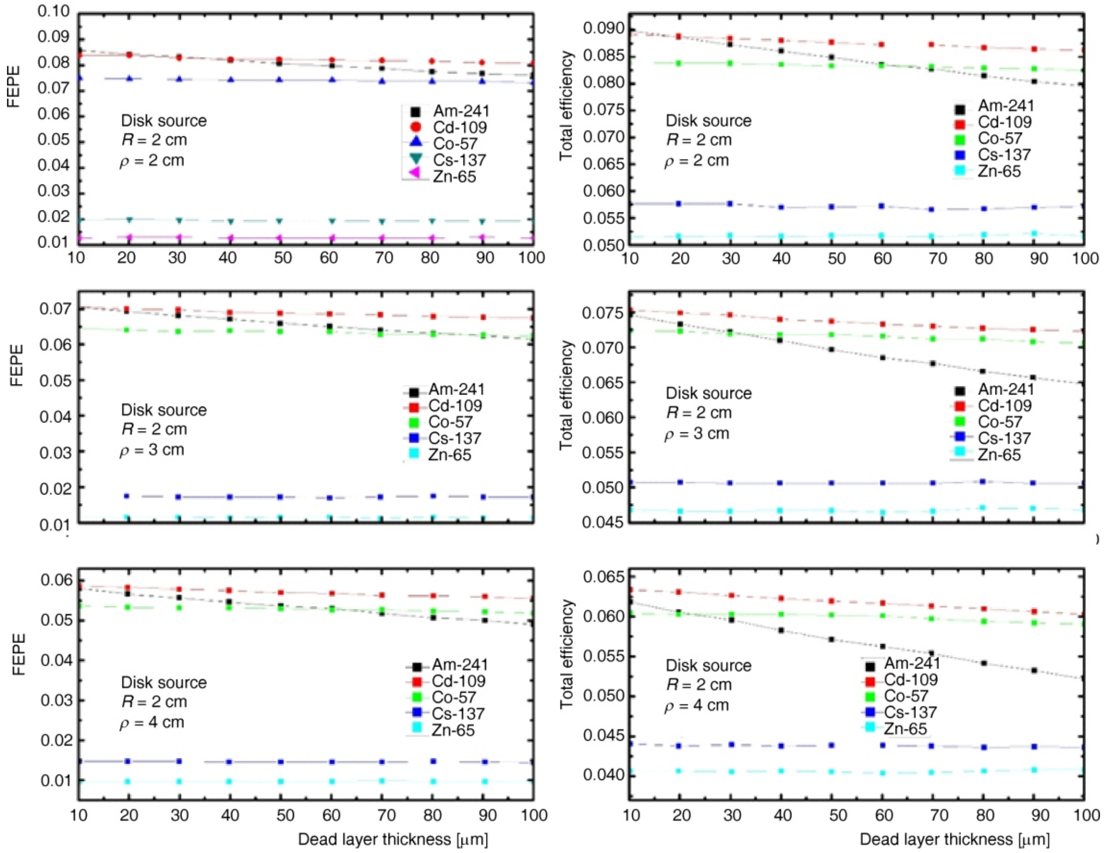

Figure 11. Geant4 computed values of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for various indicated off-axial positions (ρ) of the disk source

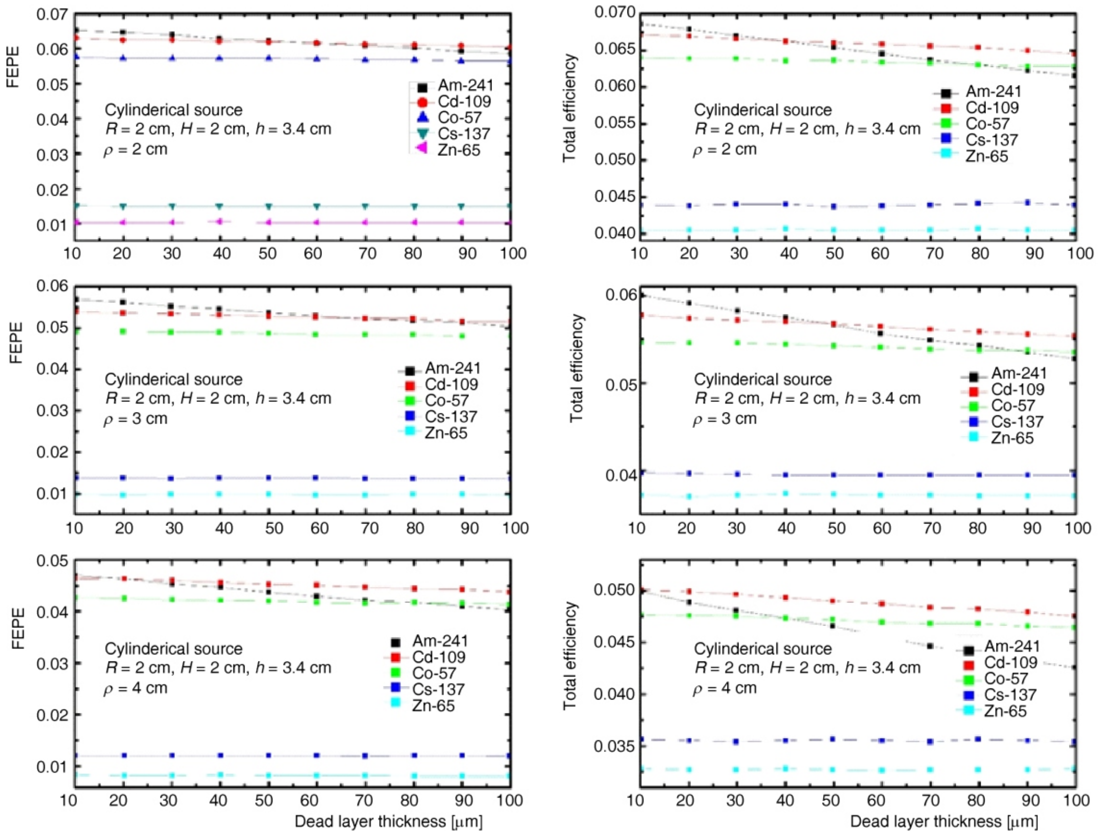

Figure 12. Geant4 computed values of FEPE and total efficiency with detector dead layer thickness for various values of γ-ray energy for various indicated off-axial positions (ρ) of the volume source

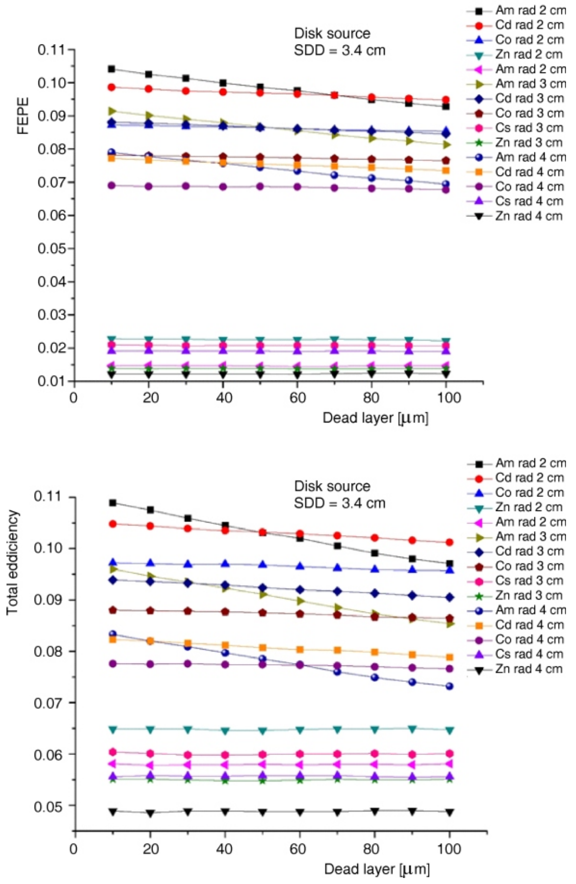

Figure 13. Effect of disk source radius (*R*) variation on values of FEPE and total efficiency with detector dead layer thickness for various indicated values of *γ*-ray energies

nent than the corresponding variation for higher energy photons.

Effect of the source dimensions

Next Monte Carlo simulations have been run to study the effect of *γ*-ray source dimensions such as the radius and length of the source. In order to investigate the effect of disk source radius on the sensitivity of the detector with aging, Geant4 simulations have been carried out for variation of disk source radius from $R = 2$ cm to $R = 4$ cm. The axial distance of the source from the detector face were kept at $h = 3.4$ cm. FEPE and total efficiency values for increasing values of dead layer thickness and various values of *γ*-ray energies were estimated. The corresponding results are shown in fig. 13. It can be seen in the figure that as the radius of the source is increased the value of FEPE and total efficiency at any particular dead layer thickness decreases. Also at larger values of the source radius the sensitivity of the detector for increasing the dead layer reduces.

Geant4 simulations have also been carried out for estimation for FEPE and total efficiency values of the detector with increasing dead layer thickness for

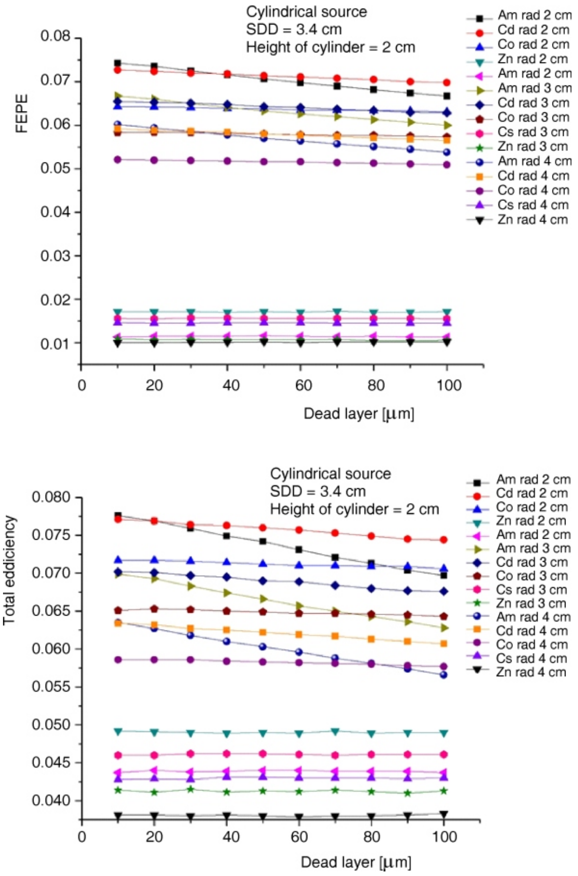

Figure 14. Effect of volume source radius (*R*) variation on values of FEPE and total efficiency with detector dead layer thickness for various indicated values of *γ*-ray energies

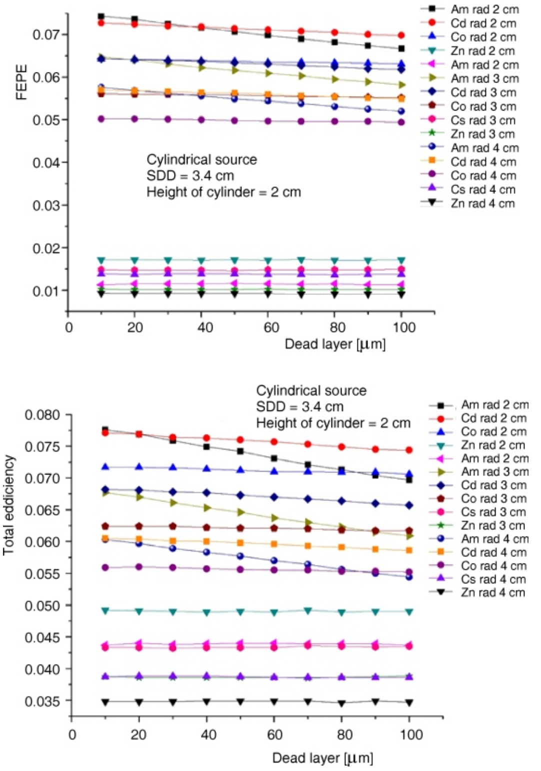

Figure 15. Effect of volume source height (*H*) variation on values of FEPE and total efficiency with detector dead layer thickness for various indicated values of *γ*-ray energies

Table 2. Comparison of Geant4 computed full-energy peak efficiency values for Petri dish source with the corresponding experimental data and results obtained by using MCNP simulations

Nuclide	Energy [keV]	Rodenas *et al*, [29]			This work	
		Exp. [%]	MCNP [%]	MCNP/Exp.	Geant4 [%]	Geant4/Exp.
Am-241	59.54	1.3562	1.3503	0.99565	1.39	1.0251
Cd-109	88.03	4.2463	4.3484	1.024044	4.22	0.9938
Co-57	122.06	5.7082	5.8236	1.020217	5.71	1.0004
Ce-139	165.85	5.8184	5.7716	0.991957	5.54	0.9522
Hg-203	279.19	4.0476	4.1428	1.02352	4.00	0.9881
Sn-113	391.45	2.9256	3.0912	1.056604	2.84	0.9706
Sr-85	514.01	2.3369	2.4472	1.047199	2.20	0.9413
Cs-137	661.33	1.8801	1.9871	1.056912	1.91	1.0159
Y-88	898.02	1.4794	1.5567	1.052251	1.44	0.9736
Co-60	1173.24	1.1836	1.2621	1.066323	1.12	0.9459
Co-60	1332.2	1.0502	1.1164	1.063036	1.00	0.9523
Y-88	1835.48	8.1958	8.7563	1.068389	0.79	0.9634

various values of source radius and source length. In this regard first a volume γ-ray source placed at an axial distance of $h = 2$ cm having a length of 2 cm was considered in the simulations. The radius of the source was varied from $R = 2$ cm to $R = 4$ cm. The results are given in fig. 14. Then the same source was considered again, this time the radius of the source has been fixed as $R = 2$ cm and the length was varied from $H = 2$ cm to $H = 4$ cm. The results are shown in fig. 15. In both, radius and length variation of the source, a similar trend, as reported earlier for radius of disk source variation, has been observed showing that increasing dimensions of the source reducing the absolute values of the FEPE and total efficiency values as well the sensitivity of the detector for increasing dead layer thickness.

CONCLUSIONS

In this work the effect of detector aging on the detector efficiency has been studied using Geant4 Monte Carlo simulations. The detector aging has been modeled by time proportionate increase in the detector dead layer. Validation of the Geant4 detector model developed in this work has been carried out by comparison of Monte Carlo simulations estimated values of detector efficiencies for point, cylindrical and Marinelli sources with the corresponding published results. The results are found in good agreement with each other. The Geant4 computed values of energy deposition per particle within the dead layer for increasing values of dead layer thickness and for various values of γ-ray energy, have been found in good agreement with the corresponding published data obtained by MCNP4C simulations. The values of detector aging sensitivity exhibit a sharp decrease with an increase in γ-ray energy. The sensitivity of the detector with aging has been extensively studied for point isotropic, disk and volume γ-ray sources. The values of aging sensitivity have been found as larger for point sources while the disk and cylindrical sources have smaller values. The effects of the source to detector axial distance and off-axial position of various sources has also been considered. The results show that detector efficiency is more sensitive to dead layer thickness for lower energy photons and less sensitive for higher energy photons. Besides increasing the source to detector axial and non-axial distance reduces the sensitivity of detector efficiency to detector dead layer thickness. Lastly the effects of γ-ray source dimensions on the sensitivity of the detector with detector aging have been investigated. The results show that the increase in radius and length of the γ-ray sources causes the sensitivity to reduce but beyond a certain limit the change in dimensions of the source has a negligible effect on the sensitivity of the detector.

AUTHORS' CONTRIBUTIONS

The computational models were developed by H. Tariq, S. M. Mirza and S. U. Rehman while the computer simulations were performed by H. Tariq. All authors were involved in the analysis and discussion on the results. The manuscript was written by H. Tariq and S. M. Mirza while figures and tables were prepared by H. Tariq and S. U. Rehman. All the authors participated in the preparation of the final version of the manuscript.

REFERENCES

[1] Harb, S., *et al.*, Study of Efficiency Calibrations of HPGe Detectors for Radioactivity Measurements of environmental Samples, *Proceedings*, 3rd Environmental Physics Conference, Aswan, Egypt, Feb. 19-23, 2008, pp. 207-218

[2] Nikolić, J., *et al.*, Calculation of HPGe Efficiency for Environmental Samples: Comparison of EFFTRAN

and GEANT4, *Nuclear Instruments and Methods-A. 763* (2014), Nov., pp. 347-353

[3] Abou Mandour, M. A., *et al*., Towards a Methodology for Bulk Sample Neutron Activation Analysis, *Journal of Taibah University for Science*, *10* (2016), 2, pp. 235-241

[4] Morera-Gomez, Y., *et al*., Application of the Monte Carlo Efficiency Transfer Method to an HPGe Detector with the Purpose of Environmental Samples Measurement, *Appl Radiat Isot., 97* (2015), Dec., pp. 59-62

[5] Peng, N., *et al*., An Empirical Formula for HPGe γ Detector Efficiency Calibration for Bulky Sources, *Radiation Physics and Chemistry, 81* (2012), 1, pp. 9-11

[6] Huy, N. Q., Binh, D. Q., A Semi-Empirical Approach to Analyze the Activities of Cylindrical Radioactive Samples Using Gamma Energies from 185 to 1764 keV, *Appl Radiat Isot., 94* (2014), Dec., pp. 82-88

[7] Abbas, M. I., Direct Mathematical Method for Calculating Full-Energy Peak Efficiency and Coincidence Corrections of HPGe Detectors for Extended Sources, Nuclear Instruments and Methods in Physics Research Section B: *Beam Interactions with Materials and Atoms., 256* (2007), 1, pp. 554-557

[8] Abbas, M. I., *et al*., A Simple Mathematical Method to Determine the Efficiencies of Log-Conical Detectors, *Radiation Physics and Chemistry, 75* (2006), 7, pp. 729-736

[9] Abbasa, M. I., *et al*., HPGe Detector Photopeak Efficiency Calculation Including Self-Absorption and Coincidence Corrections for Cylindrical Sources Using Compact Analytical Expressions, *Radiation Physics and Chemistry, 61* (2001), 3-6, pp. 429-431

[10] Abbas, M. I., *et al*., Analytical Formulae to Calculate the Solid Angle Subtended at an Arbitrarily Positioned Point Source by an Elliptical Radiation Detector, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 771* (2015), Jan., pp. 121-125

[11] Belgin, E. E., Aycik, G. A., Derivation of an Efficiency-Calibration Simulation for a Well-Type HPGe Detector Using the Monte Carlo Approach and Analytical Techniques, *Radiation Measurements, 73* (2015), Feb., pp. 36-45

[12] Cabal, F. P., *et al*., Monte Carlo Based Geometrical Model for Efficiency Calculation of an n-Type HPGe Detector, *Appl Radiat Isot., 68* (2010), 12, pp. 2403-8

[13] Carrazana Gonzalez, J., *et al*., Application of the Monte Carlo Code DETEFF to Efficiency Calibrations for in Situ Gamma-Ray Spectrometry, *Appl Radiat Isot., 70* (2012), 5, pp. 868-871

[14] Aarts, H. J. M., *et al*., Improvement of the Performance of a Compton Suppression Spectrometer by Minimizing the Dead Layer of the Central Ge Detector, *Nuclear Instruments and Methods, 172* (1980), 3, pp. 439-446

[15] Rodenas, J., *et al*., Analysis of the Influence of Germanium Dead Layer on Detector Calibration Simulation for Environmental Radioactive Samples Using the Monte Carlo Method, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 496* (2003), 2-3, pp. 390-399

[16] Dryak, P., *et al*., Total Efficiency of GE Detectors-Dead Layer Signal Effect, *Appl Radiat Isot., 68* (2010), 7-8, pp. 1451-3453

[17] Ashrafi, S., *et al*., Precise Modeling of a Coaxial HPGe Detector, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 438* (1999), 2-3, pp. 421-428

[18] Clouvas, A., *et al*., Monte-Carlo Based Method for Conversion of *in-situ* Gamma Ray Spectra Obtained with a Portable Ge Detector to an Incident Photon Flux Energy Distribution, *Health Physics, 74* (1998), 2, pp. 216-230

[19] Hurtado, S., *et al*., Monte Carlo Simulation of the Response of a Germanium Detector for low-Level Spectrometry Measurements Using GEANT4, *Appl Radiat Isot., 61* (2004), 2-3, pp. 139-143

[20] Dryak, P., Kovar, P., Experimental and MC Determination of HPGe Detector Efficiency in the 40-2754 keV Energy Range for Measuring Point Source Geometry with the Source-To-Detector Distance of 25 cm, *Appl Radiat Isot., 64* (2006), 10-11, pp. 1346-1349

[21] Agrafiotis, K., *et al*., Calibration of an *in-situ* BEGe Detector Using Semi-Empirical and Monte Carlo Techniques, *Appl Radiat Isot., 69* (2011), 8, pp. 1151-1155

[22] Andreotti, E., *et al*., Determination of Dead-Layer Variation in HPGe Detectors, *Appl Radiat Isot., 87* (2014), May, pp. 331-335

[23] Chham, E., *et al*., Monte Carlo Analysis of the Influence of Germanium Dead Layer Thickness on the HPGe Gamma Detector Experimental Efficiency Measured by Use of Extended Sources, *Appl Radiat Isot., 95C* (2014), Jan., pp. 30-35

[24] Ferreux, L., *et al*., Validation of Efficiency Transfer for Marinelli Geometries, *Appl Radiat Isot., 81* (2013), Nov., pp. 67-70

[25] Gallardo, S., *et al*., Uncertainty Analysis in Environmental Radioactivity Measurements Using the Monte Carlo Code MCNP5, *Radiation Physics and Chemistry, 116* (2015), Nov., pp. 214-218

[26] Hurtado, S., Villa, M., An Intercomparison of Monte Carlo Codes Used for In-Situ Gamma-Ray Spectrometry, *Radiation Measurements, 45* (2010), 8, pp. 923-927

[27] Huy, N. Q., *et al*., Study on the Increase of Inactive Germanium Layer in a High-Purity Germanium Detector After a Long Time Operation Applying MCNP Code, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 573* (2007), 3, pp. 384-388

[28] Marzocchi, O., Leone, D., Iterative Optimisation of Monte Carlo Detector Models Using Measurements and Simulations, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 779* (2015), Apr., pp. 47-51

[29] Rodenas, J., *et al*., Application of the Monte Carlo Method to the Analysis of Measurement Geometries for the Calibration of a HP Ge Detector in an Environmental Radioactivity Laboratory, *Nuclear Instruments and Methods in Physics Research Section B*: *Beam Interactions with Materials and Atoms, 263* (2007), 1, pp. 144-148

[30] Santo, A. S. E., *et al*., HPGe Well Detector Calibration Procedure by MCNP5 Monte Carlo Computer Code, *Annals of Nuclear Energy, 46* (2012), Aug., pp. 213-217

[31] Schlager, M., Precise Modelling of Coaxial Germanium Detectors in Preparation for a Mathematical Calibration, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 580* (2007), 1, pp. 137-140

[32] Huy, N. Q., Dead-layer Thickness Effect for Gamma Spectra Measured in an HPGe p-Type Detector, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, *Detectors and Associated Equipment, 64*1 (2011), 1, pp. 101-104

[33] ***, X-5 MONTE CARLO TEAM, MCNP – A General Monte Carlo N particle Transport Code, Version 5, 2003: Los Alamos National Laboratory (LA-UR-03-1987), Los Alamos, N. Mex., USA

[34] Agostinelli, S., *et al*., Geant4-a Simulation Toolkit, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 506* (2003), 3, pp. 250-303

[35] Diaz, N. C., Vargas, M. J., DETEFF: An Improved Monte Carlo Computer Program for Evaluating the Efficiency in Coaxial Gamma-Ray Detectors, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 586* (2008), 2, pp. 204-210

[36] Querol, A., *et al*., Using Lattice Tools and Unfolding Methods for Hpge Detector Efficiency Simulation with the Monte Carlo Code MCNP5, *Radiation Physics and Chemistry, 116* (2015), Nov., pp. 219-225

[37] Liye, L., *et al*., Monte Carlo efficiency Transfer Method for Full Energy Peak Efficiency Calibration of Three Type HPGe Detectors: A Coaxial N-Type, a Coaxial P-Type and four BEGe Detectors, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 564* (2006), 1, pp. 608-613

Received on November 18, 2016
Accepted on February 6, 2017

Хина ТАРИК, Сикандер М. МИРЗА, Шакил Ур РЕХМАН, Насир М. МИРЗА

СТУДИЈА СТОХАСТИЧКЕ СИМУЛАЦИЈЕ ОДЗИВА HPGe ДЕТЕКТОРА И УТИЦАЈА СТАРЕЊЕ ДЕТЕКТОРА ПРИМЕНОМ GEANT4 ПРОГРАМСКОГ ПАКЕТА

Применом програмског пакета Geant4 испитан је утицај старења детектора на ефикасност детектора кроз повећање дебљине мртвог слоја. Квантификована је промена депоноване енергије у мртвом слоју детектора са повећањем дебљине мртвог слоја при различитим енергијама упадног гама зрачења, узимајући у разматрање тачкасти изотропни извор, изворе у облику диска и цилиндричне запреминске изворе. У случају тачкастог изотропног извора, прорачунате вредности губитка енергије по симулираној честици у мртвом слоју сагласне су са одговарајућим објављеним резултатима, са максималним одступањем испод 2 %. Нови резултати зависности геометријске ефикасности, ефикасности детекције пика при пуној енергији и укупне ефикасности од дебљине мрвог слоја, добијени су симулацијом за различите енергије упадног гама зрачења и за тачкасте и нетачкасте изворе при различитим аксијалним и латералним позицијама. Ове симулације дају експоненцијално опадајући профил осетљивости детектора при старењу са порастом енергија гама зрачења тачкастих извора, извора у облику диска и запреминских извора, указујући на веће опадање ефикасности услед старења детектора за фотоне ниских енергија.

Кључне речи: HPGe, мршав слој, сшарење дешекшора, ефикасносш дешекшора, Монше Карло, Geant4