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Investigation of a HPGe Detector's Geometry Using X-Ray Computed Tomography in Collaboration with Monte Carlo Method

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Abstract— **Reliable, accurate information about the detector geometry specifications are required to determine the detector full energy peak efficiency, using the general Monte Carlo simulation code (MC). Due to the incomplete detector geometry specifications given by the manufacturer a CT scanner (X-ray Computed Tomography) has been used to illustrate the physical dimensions, housing and placement of the detector crystal. Also, HPGe detector has been scanned using a collimated reference source (137Cs) to estimate the dead-layer as well as inner hole of the crystal. Obtained information and available manufacturer data are used to generate MCNP5 input file. Estimated dead-layer was a round 0.6 mm for the front facet and about 0.4 mm for the side. To validate MCNP5 model activity of reference point source (137Cs, 60Co and 133Ba) has been estimated. Calculated activity was in agreement with the reference value within relative difference less than 2%. Mass of 235U contents in a reference volume sources has been estimated with relative different less 1%.**

Index Terms— **Dead-layer, Full energy peak efficiency, HPGe detector, Monte Carlo simulation, Source activity, X-ray Computed Tomography**

I. INTRODUCTION

Verification of radioactive sources considers an essential problem in the absent of standard source (with the same shape and matrix). In order to overcome this problem a suitable measurement or calculation of the efficiency for particular source-detector geometry is require [1]. The essential requirement for utilize gamma ray detector in quantitative analysis of radioactive sources is measure or calculate of full energy peak efficiency for particular source-detector geometry. Accurate determination of the full-energy peak efficiency for a high-purity germanium (HPGe) detector with numerical simulation methods requires the precise dimensions of the detector to be known [2]. Material composition and thickness of the housing of the crystal, crystal position inside the housing and crystal dead-layer are included among requisite parameters.

Monte Carlo simulation using MCNP5 code is considered one of the effective procedures for efficiency calibration of the detector. This method methodology is depending on using the means of random number to obtain the solution of mathematical problems [3]. During calculation of the efficiency, the photon and the particles producing from its interaction inside the detector are tracked until all its energies are dissipated. The characteristics of the detector and the measurement geometry are taking into account in the peak efficiencies calculation using Monte Carlo method.

One of the ways to overcome the absence of an accurate characterization of the detector is utilizing X-ray equipment (CT: x-ray computed tomography) to produce 2D or 3D image of the internally components of the detector [4, 5].

This work aims to generate an accurate MC model using X-ray computed tomography (CT) in collaboration with the manufacturer datasheet, which could be used for nuclear safeguards characterization and verification activities.

II. METHOD AND EXPERIMENT

A. Equipment

- *HPGe detector specification*

Detector under investigation is a Canberra commercial Cryo-Pulse®5 HPGe detector (Model GC6020) [6], it is shown in Fig. 1. In accordance with manufacturer datasheet, the detector has a germanium crystal with 67.70 mm diameter and 71.1 mm length. It has been placed at 5.32 mm away from the front window of the detector. Detector front window is made of carbon composite (0.6 mm thick). Recommended bias voltage is (+) 3800 V. Data acquisition system involves a pre-amplifier (Model 2002CSL) and Genie-2000 software. The full power of Genie-2000 analysis is available in the Cryo-Pulse®5 detector.

Fig. 1: Cryo-Pulse®5 HPGe detector.

- *CT scanner*

CT (X-ray computed tomography) scanner is a Toshiba Medical X-ray Computed Tomography System, Aquilion

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ONE™ CT system, with the following specifications [7]:

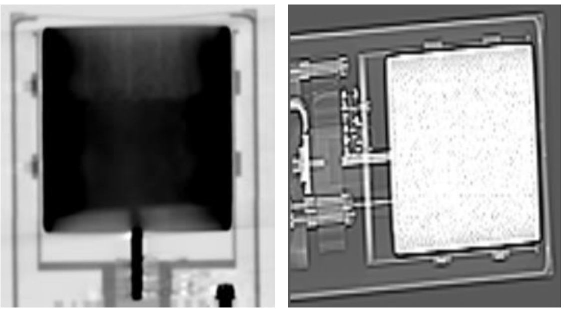
- Aquilion ONE 320
  - 0.5 mm x 160 detector
  - 320* slices every rotation
  - 8 cm of coverage every rotation
  - 0.35 sec rotation
  - 72 kW generator
  - 78 cm bore
  - AIDR 3D Enhanced
  - PUREVISION CT Detector
  - SEMAR metal artifact reduction

B. *Detector scanning*

Available information (manufacturer datasheet information provided for the detector) about the physical dimensions of the detector was not enough to construct the MCNP5 input file. The physical dimensions of the detector, such as the thick of aluminum housing, the thickness of gap between the aluminum and the crystal, dead-layer, crystal inner hole diameter or depth…etc, are required to construct the input file. To obtain these dimensions the detector has been placed inside the CT scanner.

CT scanning produced an image of the internal components of the detector. Obtained image was helpful in determination of the components, and its dimensions, inside aluminum housing, the position and outer dimensions of the crystal. Fig. 2 shows X-ray image of the internal components of the detector aluminum housing which obtained from CT scanning.

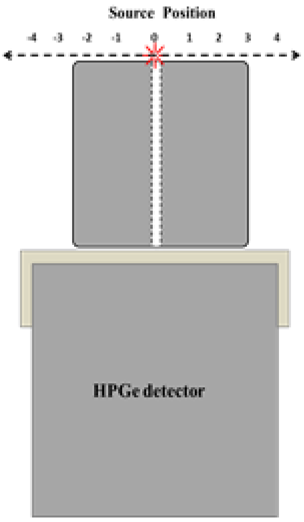
2D image



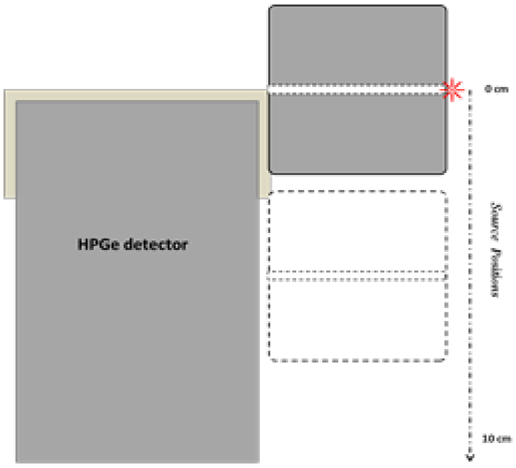
3D image

Fig. 2: Detector structures images (2D & 3D) obtained from CT scanning (X-ray image).

Due to a fully absorption of X-rays, after penetrating a few millimeters into the crystal of the detector, the obtained image from CT scanning could not produce any information about the dimensions of the crystal inner hole as well as the thickness of the dead-layer of the crystal. In order to estimate this dimensions the front facet and lateral of the detector has been scanned with a collimated reference radioactive point source (^{137}Cs, with 38.6 kBq activity). Lead collimator with 6.1 cm length, 6 cm diameter and a central aperture with 0.28 cm diameter and 6.1 cm length has been used. ^{137}Cs source has been placed behind the collimator aperture to generate a narrow beam of gamma-ray. This system was employed to scan the detector with 5 mm step along the diameter on the front facet and the central line along the lateral surface. Count rate (net peak count) due to the 661.7 keV gamma-ray energy line has been recorded at each position during the scanning process. Fig. 3 shows the experimental setup arrangements to measure the count rate at different displacements for point source.



(a) Front facet scan



(b) *Lateral scan*

Fig. 3: Experimental setup arrangements to measure the count rate at different displacements for point source.

Also, NaI detector has been employed to lateral scan of the detector. In this case HPGe detector has been placed (as a gamma-ray shield) between NaI detector and ^{137}Cs source. Count rates due to 661.7 KeV energy line recorded using NaI detector and HPGe at each position for horizontal displacement of ^{137}Cs source and NaI detector. The displacement was parallel to the lateral of the detector by regular steps (step=1 cm) in both sides. Fig. 4 shows the experimental setup arrangement to measure the count rate.

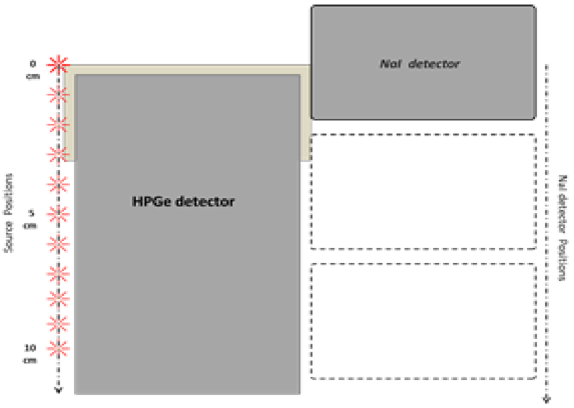


Fig. 4: Experimental setup arrangements to measure the count rate using NaI detector.

C. Monte Carlo modeling

MCNP5 input file contains the input information necessary to describe the problem. Problem specification (describe geometry, materials, tallies… etc.) is required to prepare input file for the code [8]. MCNP5 code has many tally cards, which are used to specify what you want to learn from the Monte Carlo calculation. One of them (tally F8) is used to estimate the energy distribution of pulses (pulse height) created in a detector [9, 10].

At first, available information of the detector (manufacturer datasheet information and information obtained from CT scanning) and the problem geometry specification (radiation source location to the detector and collimator specification) have been used to construct MCNP5 input files, the tally F8 has been used to determine pulse height. For most of the calculations, the number of histories was selected so as to keep the relative standard deviation due to MCNP5 calculations less than 1%. MCNP5 calculations were performed using a computer with a 2.66 GHz processor. The calculation times were about 10 min (10^7 histories). Peak efficiency of the detector has been determined from MCNP5 calculation at 661.7 keV gamma line. Count rate due to 661.7 keV gamma-ray energy line has been calculated. A big different between calculated and measured values of count rate has been noted. MCNP5 input files have been reconstructed by adjusting crystal inner hole dimensions (height & diameter) and dead-layer thickness to minimize the difference between calculation and measurement values of count rate. The average relative difference between measured and calculated values was less than 2%. Fig. 5 shows the characteristics of the simulated detector as drawn by MCNP5 visual editor.

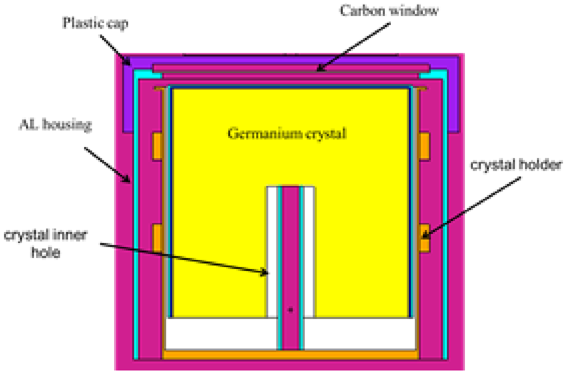


Fig. 5: Detector model as drawn by MCNP visual editor.

D. Validation of Monte Carlo model

After generation MCNP5 model of the detector it was necessary to examine the validity of this model for radiation measurements. Point and volume reference sources have been used. Experimental measurements with three reference point sources (Cs-137, Co-60 and Ba-133) were carried out. The parameters of each source are listed in Table 1.

Table 1: Specification of the reference point sources [11]

Source	Activity (KBq)	Production date	Gamma ray energy (KeV)	Iγ %
Ba-133	37.8 ± 5%	1st Dec.1995	80.9971	34.06
			356.017	62.05
Co-60	40.2 ± 4%		1173.23	99.97
			1332.5	99.98
Cs-137	38.6 ± 4%		661.7	85.1

Ba-133 reference point source has been located at a distance equal to 5 cm from the center of the front facet of the detector. Count rates due to 356.017 KeV energy line has been counted by the detector. Cs-137 and Co-60 have been located at a distance equal to 10 and 2 cm from the center of the front facet of the detector, respectively. HPGe detector has been employed to record the count rates due to the investigated energy lines. Fig. 6 shows the experimental setup arrangement to measure the count rate (net count rate).

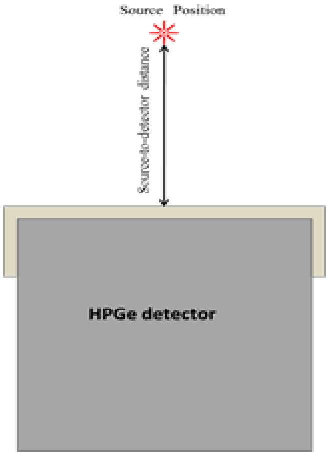


Fig. 6: Experimental setup arrangements to measure the count rate for point source.

To examine the validation of MCNP5 model with volume source a set of reference nuclear material (NM) with cylindrical shapes (volume source) and different enrichment percentage has been used to perform some experimental measurements.

The specifications and characteristics of the NM samples are given in Table 2. The reference samples contain different quantities of U-235 isotope.

Table 2: Specifications of the certified NM standards [12]

Sample	Enrichment %	U-235 mass (g)	U-238 mass (g)
1	4.46	7.572	162.109
2	2.95	5.004	164.677
3	1.94	3.295	166.386
4	0.71	1.208	168.473
5	0.31	0.537	169.144

The sample has been placed in front of the detector as shown in Fig. 7, the sample-to-detector cap distance has been adjusted and optimized in such a way to obtain the maximum count rate mean while the counting losses due to pile up and dead time were minimized.

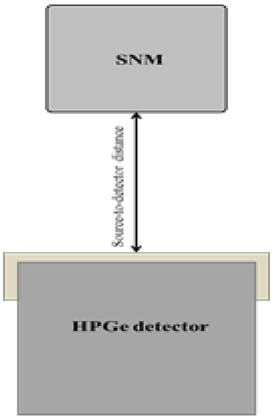
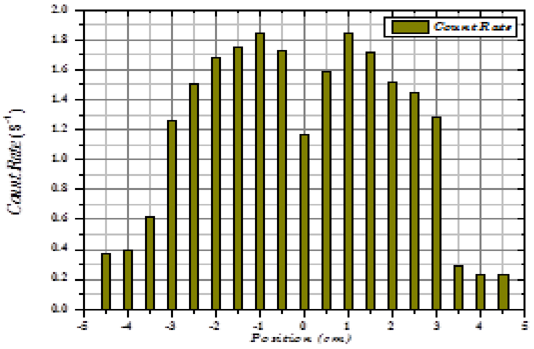


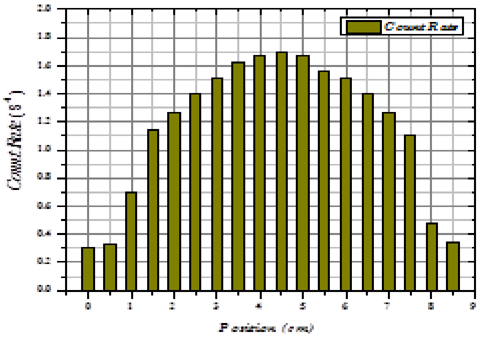
Fig. 7: Experimental setup arrangements to measure the count rate for NM samples.

III. RESULTS AND DISCUSSION

Count rate (net peak count) due to the 661.7 keV gamma ray energy line, recorded at each position during the scanning process with collimated source, is showing in Fig. 8. The front facet scan produces a non-uniform distribution for count rate. This non-uniform distribution indicates the Germanium crystal has a coaxial configuration. The variation of the Germanium layer thickness has an effect on the absorbing of photons. Crystal inner hole diameter is 4.5 cm length and 1.4 cm diameter, approximately.



(a) Front facet scan

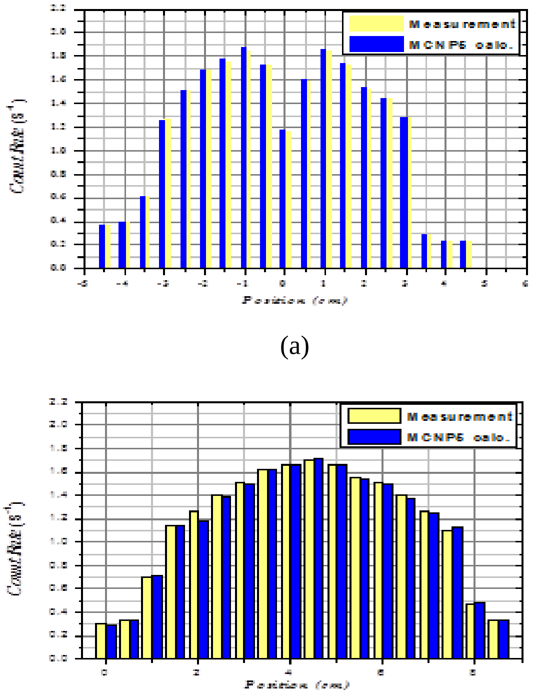


(b) Lateral scan

Fig. 8: Gamma-ray scanning results (a) front facet scanning, (b) lateral scanning.

Fig. 8 (b) indicates that Ge crystal active volume lay between 0.5 cm and 8 cm from the detector window, which is approximately agreed with the detector data sheet that provide by the manufacture.

Count rate due to the collimated reference source (^{137}Cs, at 661.7 keV) has been estimated from MCNP5 calculation at each displacement and compared with measured value. Fig. 9 shows a comparison between the count rates obtained from experimental measurement and those obtained from MCNP5 calculation. It is clear the agreement between experimental and calculated count rate values.



(a)

(b)

Fig. 9: Calculated count rate at different displacements in comparison with experimental measurement values (a) front facet scanning, (b) lateral surface scanning.

Fig. 10 shows count rate recorded using NaI and HPGe detector at each location of lateral scan of the detector. Due to the absorption of gamma-ray, into the HPGe crystal, the count rate of gamma-ray counting by NaI detector had decreased with increasing active volume of the crystal of HPGe detector. The obtained result indicates that Ge crystal active volume lay between 0.7 cm and 7.8 cm from the detector window, which is approximately agreed with the detector data sheet that provide by the manufacture.

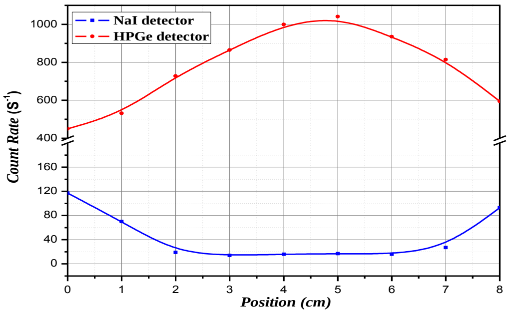


Fig. 10: Comparison of NaI and HPGe count rates

Table 3 presents sources activities that estimated for the point sources placed in front facet of the detector by divided the measured count rate at investigated gamma energy line by the calculated absolute full energy peak efficiency (by MCNP5 code at the same energy line) and the gamma emission probability of the measured gamma energy line.

Table 3: Estimated activity for the point sources

Point Source	Energy Line (KeV)	Estimated Activity based on MCNP (kBq)	Certified Activity (kBq)	diff. %
Ba-133	356.017	9.433894	9.465256	-0.33
Cs-137	661.7	20.43401	20.245622	0.93
Co-60	1173.23	2.550093	2.541667	0.33
	1332.5	2.590653	2.541922	1.91

For reference nuclear material (volume source) the measured count rate at 185.7 KeV gamma energy line has been divided by the calculated absolute full energy peak efficiency at this energy line and the specific activity of the measured gamma energy line to estimate ^{235}U mass contents in nuclear material sample. Table 4 presents estimated ^{235}U masses.

Table 4:^{235}U masses estimated based on MCNP5 calculation with the associated uncertainties

Sample	Enr. %	U-235 mass (g)	Estimated U-235 mass (g) ± RSD	diff.%
1	4.46	7.572	7.615± 0.231	-0.56
2	2.95	5.004	5.0127± 0.0768	-0.17
3	1.94	3.295	3.311± 0.0556	-0.48
4	0.71	1.208	1.2067± 0.0342	-0.11
5	0.31	0.537	0.541± 0.0134	-0.74

It is clear from the results, for point sources and volume sources, the agreement between experimental and MCNP5 calculations with difference less than 2%, which can be considered a good evidence of the reliability of the description of a HPGe Detector's Geometry.

IV. CONCLUSION

Physical dimensions of the radiation detector are a part of necessary information required to construct MCNP5 input file. For the shortage of information provided by the manufacturer, X-ray imaging (Computed Tomography scanning) has been used to overcome this problem. X-ray image produce a description for the internal structure of the detector cap, crystal position and outer parameter of the crystal. However, it can't produce any information about inner crystal hole dimensions and dead-layer thickness because of X-ray absorption inside a thin layer of the Ge crystal. Collimated gamma-ray reference source has been employed to estimate these parameters. Obtained geometry parameters (from the detector scanning) have been used to generate MCNP5 model for the detector. The final MCNP5 model of the HPGe detector has been obtained by adjusting the geometry parameters to achieve the agreement between experimental and MCNP5 calculations values. Point and volume sources have been used to examine the reliability of the obtained geometry specifications of the detector.

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REFERENCES

[1] Jonas Boson, Göran Ågren, Lennart Johansson (2008, March). A detailed investigation of HPGe detector response for improved Monte Carlo efficiency calculations. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume (587), Issues 2–3, Pages 304-314. https://doi.org/10.1016/j.nima.2008.01.062

[2] Steven J. Novotny, Dominic To (2015, January). Characterization of a high-purity germanium (HPGe) detector through Monte Carlo simulation and nonlinear least squares estimation. J Radioanal Nucl Chem, Volume (304), page 751-761. https://doi.org/10.1007/s10967-014-3902-7

[3] N. Stefanakis (2014, Nov.).Detection efficiency of a BEGe detector using the Monte Carlo method and a comparison to other calibration methods. arXiv:1411.4225v1 [physics.ins-det]. https://arxiv.org/abs/1411.4225v1

[4] Evans Ll. M., Margetts L., Casalegno, V., Lever L. M., Bushell J., Lowe T., Wallwork A., Young P., Lindemann A. (2015, Nov.). Transient thermal finite element analysis of CFC–Cu ITER monoblock using X-ray tomography data. Fusion Engineering and Design. Volume (100), page 100–111. https://doi.org/10.1016/j.fusengdes.2015.04.048

[5] Payne, Emma Marie (2013). Imaging Techniques in Conservation. Journal of Conservation and Museum Studies. Volume (10), Number 2, pp. 17-29. http://doi.org/10.5334/jcms.1021201

[6] Canberra (2012). Detector Specifications and Performance Datasheet (Model: GC6020).

[7] Toshiba Medical Systems manual, https://medical.toshiba.com/products/computed-tomography/aquilion-one-family/

[8] MCNP — A General Monte Carlo N-Particle Transport Code. Version (5) manual

[9] Giorgia Cinelli, Laura Tositti, Domiziano Mostacci, Jonathan Bare (2016, May). Calibration with MCNP of NaI detector for the determination of natural radioactivity levels in the field. Journal of Environmental Radioactivity. Volume (155-156), pages. 31-37. https://doi.org/10.1016/j.jenvrad.2016.02.009

[10] C.M. Salgado, L.E.B.Brandão, R.Schirru, C.M.N.A.Pereira, C.C.Conti, (2012, August).Validation of a NaI(Tl) detector's model developed with MCNP-X code, Progress in Nuclear Energy. Volume (59), pages.19 -25. https://doi.org/10.1016/j.pnucene.2012.03.006

[11] Measurement data of reference point sources, Amersham the health science group, set no.211, reference date 1 December 1995.

[12] NBS, Uranium Isotopic Standard Reference Material for Gamma Spectroscopy Measurements, 969, NBS-111, Gaithersburg, MD 20891, USA, (1985)