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HPGe Detector Efficiency Curve Evaluation for Low-Level Measurements

H.M. Diab
Nuclear and Radiological Regulatory Authority NRRA , Egypt

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ABSTRACT

HPGe detectors are currently being used in a wide range of applications ranging from basic and applied research to homeland security. The combination of large detection efficiency and the excellent energy resolution make the detector a good choice for measuring gamma rays to detect, identify, and quantify the amount of nuclear materials in the environment and specific samples. Therefore, it is necessary to have available, reliable and precise analytical methods to determine their bulk concentrations as well as their isotopic compositions. There are many methods used for calibration, one is the so-called relative method where Ra-226 point-source is used at a representative point (25 cm from the detector). Another method is the absolute full-energy peak (photopeak) efficiency where standard multisource including different radionuclides (U-238, Ra-226, Th-232, K-40, Cs-134, Cs-137, Am-241 and Pb-210) covering the energy range from 186 to 1860 KeV is used.

In this paper, the methods used in efficiency calibration for HPGe in Central Laboratory for Environmental Radioactivity Measurements Inter-comparison and Training (CLERMIT) are evaluated. It is important for laboratory accreditation according to the requirements of the standard ISO/17025: 2005 which is implied in the radioactive content measurement of samples collected from the environment, food chain or industrial products.

All the necessary calibration corrective actions were taken in consideration to improve the quality of the radioactivity measurements performed in the laboratory. Also, the effect of some regular matrices such as water, soil and sediment on the detector efficiency is investigated.

As a result, the detection efficiency curves are obtained and a remarkable agreement between the two methods is achieved with discrepancies less than 5%.

Key words: HPGe, Gamma-spectrometry, efficiency calibration.

INTRODUCTION

The high purity germanium (HPGe) spectrometer is one of the most widely used procedures for the identification and quantification of unknown gamma-ray emitting radionuclides in environmental samples. It is a non-destructive technique that has the advantage of not requiring laborious sample preparation [(1)]. This technique, however, requires prior knowledge of the photo-peak efficiency of the detector in the counting geometry for each energy peak. This is usually obtained by an efficiency calibration using standard radioactive sources of very similar geometrical dimensions, density and chemical composition of the sample that is being studied [(2)]. However, in many cases these conditions cannot be fulfilled and standard radioactive samples, even if available, are costly and would need to be renewed, especially when the radionuclides have short half-lives.

The efficiency ε (E) is defined as the fraction of the photons of a particular energy emitted by a source, that contributes to the corresponding all energy peak observed in the pulse height spectrum[3], so that:

$$N = \varepsilon (E) Y.A \qquad (1)$$

Where:

N is the counting rate in the full-energy peak observed in the pulse height spectrum,

E is the counting efficiency;

Y is the photon yield (i.e. fraction of decay events that result in the emission of a photon of the relevant energy); and

A is the activity of the source in Bq.

The value of efficiency is dependent on the geometry of the sample size, density, and distance from the detector. Therefore, counting geometry requires an efficiency calibration, using known standard in the same geometry which includes multiple energies. The branching ratio (or yield) is used to correct the number of gamma rays observed to obtain the number of disintegrations of the source [4]. Taking these factors in consideration, the efficiency can be calculated as follow:

$$\varepsilon(E) = \frac{N}{A \Delta t I_{\gamma}} \cdot f, \qquad (2)$$

Where:

N is the net counts of the full energy absorption peak corresponding to the gamma-ray of energy E and emission probability per decay I.

Δt is the measuring time and A is the source disintegration rate.

Factor f takes into account corrections due to dead time, detection geometry, decay, summing effects and self absorption [5, 6].

The efficiency curve in the 59–2754 KeV range shows three regions of different behavior because distinct attenuation and absorption processes dominate [7]. At low energies the efficiency rises rapidly because of abrupt reduction in the attenuation in radioactive source, detector cap or inner dead layer. A maximum is reached for an energy value which depends on the detector and source characteristics [8]. Above a few hundreds KeV the efficiency decreases monotonically almost linearly in log-scale up to around 1200 KeV. For higher energies the curve continues to decrease but following a different pattern due to pair production interactions. Therefore three regions can be distinguished: at lower, intermediate and higher energies [9].

For efficiency calibration, one can use any source with known nuclide activity and gamma emission probability. But in this case, not only the accuracy of the activity was standardized, but also the uncertainties arising from the emission probability were evaluated with stamped percent dead time. To determine the energy dependence of the detector efficiency, a set of several reference gamma ray sources is needed to cover the energy ranges of interest [9].

This study is concerned with the evaluation of the methods used for the determination of relative and absolute peak efficiency using Ra-226 point-source and a multi-nuclides source under identical geometry in an HPGe detector.

EXPERIMENTAL WORK

N-type HPGe with Beryllium window gamma spectrometer system was used for absolute efficiency determination. The detector has a 40% relative efficiency and a resolution of 1.9 KeV for the ^{60}Co gamma ray at 1332 KeV. Because of the dependence of efficiency on the geometry of the sample size, density, and distance from detector, therefore, an absolute efficiency calibration of the HPGe gamma spectrometry was done using IAEA reference standard samples. The IAEA samples include multiple gamma energies were prepared in the same geometry (Marilli Beakers). To obtain reliable measurements of radionuclide activity, the knowledge of the detector absolute peak efficiency in the counting conditions is required. This becomes a complex problem whenever there are many types of matrices and geometries involved in the measurements because the count rate depends on the characteristics of the matrix, the source geometry and the source–detector configuration [10]. To investigate the effect of matrix on the photo-peak efficiency the IAEA standard reference samples in the density range of 0.5 – 1.6 g.cm^{-3}were used as shown in Table 1. The gamma spectra for each sample measured at a 25 cm distance from the detector was determined. Each sample was put into the shielded HPGe detector and measured under the same conditions. The background gamma radiation was determined by an empty Marinelli beaker at the same condition of the samples. The background spectrum that has been used to determine the absolute efficiencies is that of 100 ml tap water sample in a Marinelli beaker as shown in Fig. 1. The obtained spectrum of the background gamma radiation was subtracted from the measured gamma ray spectra of each sample.

Table (1): The IAEA Standard Reference Samples Used.

	IAEA Code	Sample type and density	Activity (Bq/kg)
K-40	IAEA RGK-1	Ore Rock, 1.34	14000.0
	IAEA-A14	Whey Powder, 0.68	527.0
	IAEA-152	Milk Powder, 0.58	539.0
	IAEA-375	Soil, 1.42	424.0
	IAEA-381	Irish Sea Water, 1.0	11.4.0
U-238	IAEA-RGU-1	Ore Rock, 1.51	4940.0
Ra-226	IAEA-313	Stream Sediment, 1.11	343.0
	IAEA-375	Soil, 1.42	20.0
	Soil-6	Soil, 1.08	79.9
	IAEA-375	Soil, 1.42	20.5
Cs-137	IAEA-A14	Whey Powder, 0.68	1.79
	IAEA-152	Milk Powder, 0.58	2129.0
	IAEA-375	Soil, 1.42	5280.0

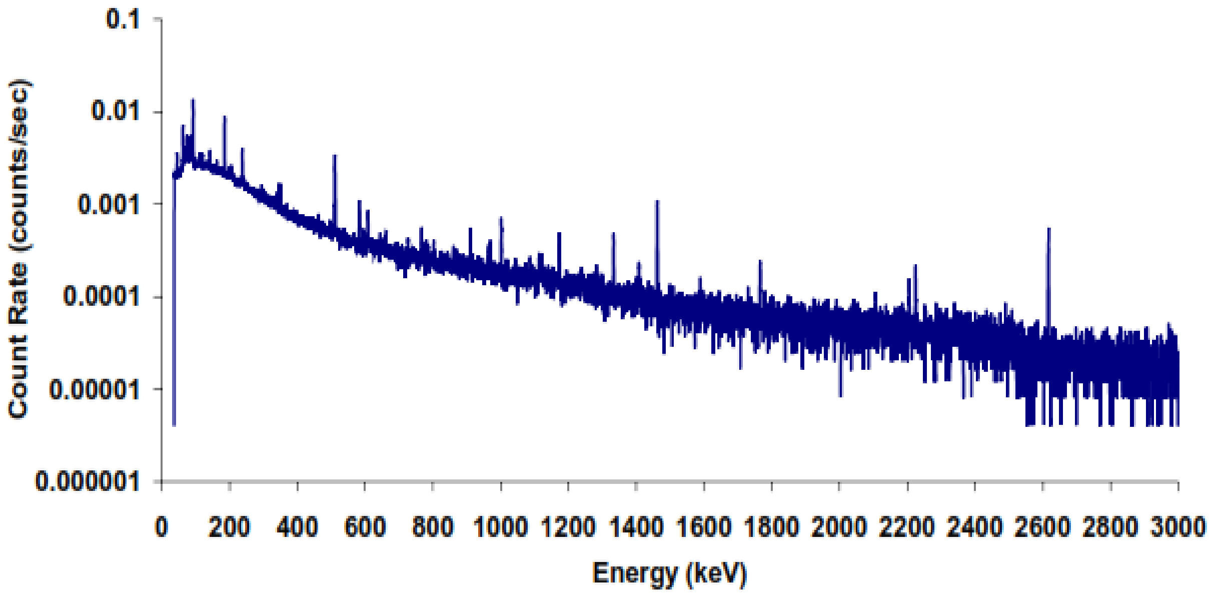

Fig. (1): Spectrum of 100 ml tap water sample used for background correction.

From the series of data pairs (E, ε) and by using a fitting program, a curve of efficiency versus energy is generated. From the obtained curve, the counting efficiency (ε) can be calculated at any energy in the calibrated energy range.

The experimental efficiency ε (*E*γ) as a function of energy at selected geometry with different densities can be obtained using the following equation:

$$\varepsilon(E_\gamma) = \frac{(CPS_{ref} - CPS_b)}{A_{ref} \times P_\gamma \times m_{ref}}$$

where: *A is* the radioactivity of radionuclide of interest in reference material; m_{ref} is mass of reference material, CPS_{ref} is the count per second of the reference sample and CPS_b is the count per second of the background. Because of using IAEA reference samples with different radionuclides (short and long half-life) [(12)], correction for source (reference sample) decay using the following formula is needed:

$$A\text{ (at count time)} = A\text{ (at certificate time) } e^{\frac{-\ln(2)*Decay\ time}{Half\ Life}} \qquad (3)$$

Where decay time and half-life are in the same units.

The value of ε (*E*γ) depends on the density of the sample for the same measuring conditions. In the laboratory we often deal with variable sample densities (from 0.5 to 1.5 gcm^{-}).

To investigate the effect of matrices on detection efficiency, three types of matrices: soil, water and milk powder were chosen. The volumes were the same with all types and the densities fall in the range 0.5- 1.5 gcm^{-3}.

RESULTS AND DISCUSSION

Fig. 2 illustrates the dependence of the photo peak efficiency on the gamma ray energy values in the energy region (186 – 1860). As shown in Fig. 2, it is obviously clear that as the density increases, the number of gamma rays that can reach the detector will decrease as a result of the attenuation effects causing a reduction of efficiency values. This can explain the difference between the efficiency values for soil, water and milk powder. Table 2 presents the calculated results obtained from the calculated experimental full-energy peak efficiency ε (%) against energy for different samples with energy E and density ρ. The obtained results show that the total error of calibration method is about ± 5% for the determined radioactivity of different radionuclides and about ± 10% for ^{40}K. The greatest experimental counting error for ^{40}K is related to its background measurement conditions, especially for small mass or low ^{40}K radioactivity.

The quality of the results of gamma spectrometry measurement depends directly on the accuracy of the detection efficiency in the specific measurement conditions. The relative efficiency measured with point sources is compared with the absolute efficiency measured using reference samples.

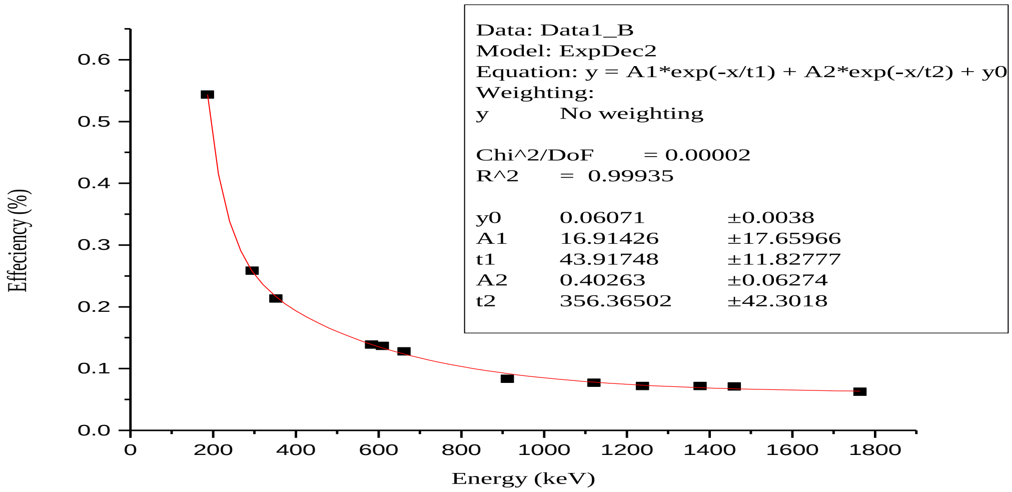

Fig. (2): Absolute Efficiency curve of soil samples as a function of energy (KeV).

Table 2: The calculated experimental full-energy peak efficiency ε (%) against energy for different sample density (ρ)

Isotopes	Energy (keV)	Branching Ratio	Density > 1	Density < 1	Average Efficiency
Ra-226	186.18	3.3	0.668982	0.417672311	0.5433272
Pb-212	238.85	43.6	0.219424302	0.137429469	0.2194243
Pb-214	241.92	7.5	0.279269537	0.256594612	0.2679321
Pb-214	295	19.2	0.260123192	0.256594612	0.2583589
Ac-228	338.56	12.4	0.179656427	0.043001689	0.1796564
Pb-214	351.99	37.1	0.164297824	0.213271566	0.1887847
TI-208	583.34	30.9	0.13891672	0.053210958	0.1389167
Bi-214	609.41	46.1	0.141852396	0.13166592	0.1367592
Cs-137	661.7	85.2	0.121838441	0.134080166	0.1279593
Bi-214	768.66	5	0.088421734	0.093676695	0.0910492
Cs-134	795.48	85.4	0.133210333	0.009188793	0.1332103
Ac-228	840.4	0.9	0.232627175	0.313668725	0.2731479
Ac-228	911.23	29	0.083448455	0.033688028	0.0834485
Bi-214	934.67	3.2	0.074804237	0.073333506	0.0740689
Ac-228	969.36	17.4	0.057669436	0.0331107	0.0576694
Bi-214	1120.53	15	0.075053392	0.07904857	0.077051
Bi-214	1238.14	5.9	0.071839724	0.067407208	0.0718397
Bi-214	1377.56	4	0.07253934	0.070881853	0.0717106
K-40	1460.6	10.7	0.073799857	0.068271556	0.0710357
Ac-228	1588.2	3.6	0.074618534	0.001539269	0.0746185
Bi-214	1764.5	15.9	0.06921958	0.055922578	0.0625711
Co-60	1173	100	0.070358721	0.094588464	0.0824736
Co-60	1332	100	0.047379273	0.080720476	0.0640499

Reliability and Precise Efficiency Calibration of HPGe Detector

It is important to take into consideration that the experimental efficiency curve is affected by various uncertainties. For instance, there is a standard uncertainty of up to 5% on the activity of the prepared standards Marinelli. Also geometry positioning and counting statistics affect the accuracy of the results. A further uncertainty can arise from the coincidence summing effect. So, to evaluate the results, both of the detection efficiency (absolute and relative) results are used for calculation of elemental concentration of certified reference materials IAEA-326. The comparison between the results and the certified values are presented in Fig.4. The obtained values show that the radioactivity concentrations are in good agreement with the certified values. Also, the results of multi-nuclides source are more consistent with the certified values than the point source. Generally the obtained results confirm the good applicability of the multi-nuclides standard source in the radioactivity evaluation of the volumetric environmental samples.

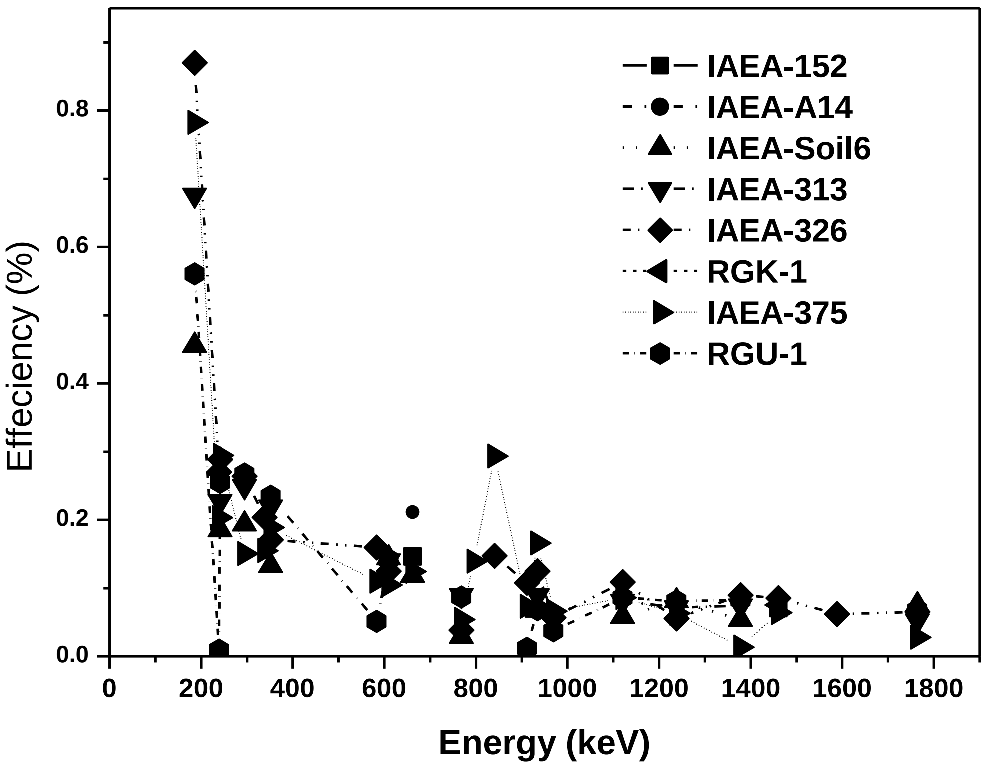

Fig. (3): The dependence of efficiency on energy and density of soil matrix

CONCLUSION

In this study, two simple methods for γ-ray efficiency calibration of HPGe detector system are evaluated. Reference standard multi-sources cover the energy range from 186 to 1860 KeV are used for absolute efficiency calibration and a single point source is used for relative efficiency calibration. The use of multi-sources in γ-ray spectrometry improves the sensitivity of detection thus enabling the measurement of low-activity environmental samples. Using multi-source for absolute efficiency could effectively predict the efficiency of a detector at any source-to detector distance. The statistical error of the efficiency curve can be improved by using a longer counting time. For the sake of the competence of the study, the absolute efficiency ε (E) at low energy region from 46 to 186 KeV has to be undertaken in a future work.

To summaries, the results of the present work clearly confirm the dependence of the efficiency on the gamma ray energy, geometry, density, height of soil sample and characterization of the detector.

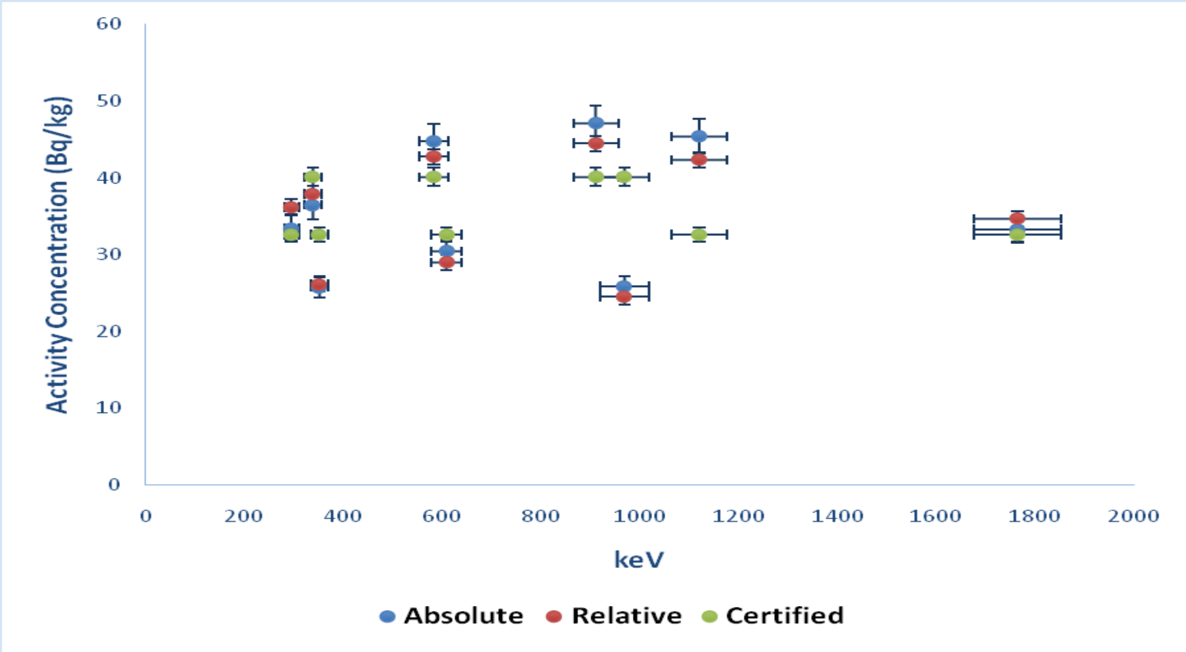

Fig. (4): The Comparison of IAEA-326 certified activity concentration using Absolute, Relative Efficiency.

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