

Article

A Simplified Method for HPGe Detector Efficiency Calibration Using Certified Reference Materials Containing Natural Radionuclides

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Abstract

Multinuclide calibration sources, consisting of mixtures of gamma-emitting radionuclides, are commonly used for detector efficiency calibration in gamma-ray spectrometry. While they enable fast and accurate calibration, they have certain drawbacks, such as high cost and relatively short usable lifespans. This paper presents a simplified and cost-effective method for the efficiency calibration of cylindrical high-purity germanium (HPGe) detectors, which relies on the use of certified reference materials containing natural radionuclides. The method is based on selected gamma lines from natural radionuclides that are practically unaffected by the true coincidence summing (TCS) effect, enabling reasonably accurate calibration for multiple measurement geometries at energies above 200 keV. The main limitation of the method is its applicability only to energies higher than 200 keV; however, this range is sufficient for most routine environmental measurements. Verification measurements conducted for cylindrical geometry showed that detector efficiency values obtained using the proposed method (with IAEA RGK, RGU, and RGTh certified reference materials) differed by less than approximately 4% from those obtained using a commercial multinuclide calibration source.



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1. Introduction

A calibration sources consisting of a mixture of gamma-emitting radionuclides (also known as multinuclide sources) are typically used for efficiency calibration of HPGe detectors in gamma-ray spectrometry. However, this method has a number of limitations:

- a relatively short half-life (ranging from several tens to several hundreds of days) of most radionuclides included in the calibration source, which means that the source becomes of limited use after approximately one year,
- the epoxy resin matrix source can only be used to calibrate the detector in a single measurement geometry; an alternative is the purchase of a liquid source, which enables the preparation of standards for several measurement geometries; however, this approach introduces issues related to the dilution of standard solutions and the homogeneity of calibration sources, both of which may constitute additional sources of uncertainty,

- high cost; for calibration sources with epoxy resin matrix this disadvantage is amplified by the need to purchase a separate source for each geometry and the short useful lifespan of the source.

One alternative to the use of multinuclide calibration sources is the use of natural radioactive nuclides for calibration. In recent years, Certified Reference Materials (CRMs) containing natural radionuclides with known activity have been increasingly used. Most commonly, authors [1–5] determine efficiencies for selected gamma lines of several natural radionuclides (e.g., Tl-208, Pb-212, Pb-214, Bi-214, Ra-226, Pa-234m), and then use these to determine the activity concentration of these nuclides in samples (a method known as nuclide-specific calibration).

Some authors, based on these efficiency measurements, derive a continuous dependence of efficiency on energy, $\epsilon(E)$, which allows them to calculate the detector efficiency for any energy and thus determine the activity of any radionuclide in a sample. In the latter case, the main challenge is the need to correct for true coincidence summing (TCS) effect. Natural radionuclides typically have very complex decay schemes, which lead to significant TCS corrections—for cylindrical detectors, these corrections can reach twenty percent or more. Since determining TCS corrections requires knowledge of the detector's characteristics and typically specialised software, only some authors (e.g., [6–11]) apply these corrections and thus obtain an accurate $\epsilon(E)$ dependence. In other cases, the resulting efficiency function may be significantly biased.

The main goal of this work is to propose a simplified and cost-effective efficiency calibration method for HPGe detectors, using only selected natural radionuclide lines that are practically unaffected by TCS effect. This method is intended for a limited subset of laboratories conducting routine measurements of radionuclide activity that do not have the resources to implement TCS corrections and for which measurement accuracy of approximately 5% is acceptable. The method uses IAEA certified reference materials RGK-1, RGU-1 and RGTh-1, which have guaranteed radioactive equilibrium and activity certified with standard uncertainty below 5.5%. However, any reference material with significant activity concentration and guaranteed equilibrium may be used. The only limitation of the proposed method is that its scope of application is limited to energies above 200 keV. Nonetheless, for most routine environmental measurements, this energy range is entirely sufficient.

2. Materials and Methods

2.1. Gamma-Ray Spectrometer

A n-type coaxial HPGe detector GX4020 (Mirion Technologies (Canberra), Inc., Meriden, CT, USA), featuring an epoxy resin window, energy resolution of 1.9 keV (at the 1.33 MeV Co-60 gamma line), an energy range above 3 keV, and a relative efficiency of 42%, was used in the gamma-ray measurements. The detector crystal was a cylinder with the diameter 6.1 cm and the height 6.0 cm. The setup was operated with an integrated spectrometric system DeskTop InSpector (Mirion Technologies (Canberra), Inc., Meriden, CT, USA). Gamma-ray spectra were acquired and analysed using the Genie 2000 software (version 3.2.1). The detector was housed in a shielding made of lead bricks, with an inner lining of 1 mm cadmium and 1 mm copper. The upper and side walls were 10 cm thick, and the bottom wall was 15 cm thick. A detailed description of the setup is presented elsewhere [12].

2.2. Calibration Sources

The following certified reference materials (RG series) provided by the International Atomic Energy Agency (IAEA) were used as calibration sources:

- RGK-1—high-purity potassium sulphate (K_2SO_4), used as a calibration source for K-40.
- RGU-1—a mixture of certified uranium ore and silica, serving as a calibration source for radionuclides of the uranium series. This material is characterised by secular equilibrium between U-238 and its progeny, including Ra-226 and Pb-210.
- RGTh-1—a mixture of certified thorium ore and silica, used as a calibration source for thorium series radionuclides, with confirmed equilibrium between Th-232 and its decay products, including Ra-228 and Th-228.

Detailed specifications of these reference materials can be found in [13–16]. Selected information is presented in Table 1.

Table 1. Selected data on RG series Certified Reference Materials [13–16].

Reference Material	Activity Concentration ¹			Radioactive Substance	Bulk Density ³ [g/cm ³]
	K-40 [Bq/kg]	U-238 [Bq/kg]	Th-232 [Bq/kg]		
RGK-1	14,180 (160) ⁴	<0.01	<0.04	99.8% K_2SO_4	1.680
RGU-1	<0.6	4950 (100)	<4	BL-5 U ore ²	1.505
RGTh-1	6.3 (16)	78 (3)	3250 (180)	OKA-2 Th ore ²	1.390

¹ Activity concentration is reported in Bq/kg of dry mass. ² Matrix SiO_2 . ³ Present work. ⁴ Standard uncertainties ($k = 1$) in parentheses.

Three calibration sources (RGK, RGU, and RGTh) were prepared. The reference material (RGK-1, RGU-1, RGTh-1, respectively) was dried at 105 °C to constant weight and then placed in an aluminium vessel with a volume of 121 cm³ (sample diameter 70.0 mm, height 31.5 mm, Al wall thickness 1 mm). The material was lightly compacted to prevent subsequent settling and geometry changes. Each vessel was closed with a 1 mm thick aluminium lid and sealed with epoxy resin. Approximately one month after sealing, secular equilibrium was re-established in the RGU and RGTh sources (between Ra-226 or Th-228 and their progeny). These calibration sources exhibited high stability in key parameters, including geometry and moisture content. The estimated standard uncertainty in these parameters, based on repeated count rate measurements, was below 0.5% [12].

For validation purposes, a commercial multinuclide calibration source manufactured by Polatom (National Centre for Nuclear Research Radioisotope Centre POLATOM, Otwock, Poland) was used [17]. It contained Cr-51, Co-57, Mn-54, Co-60, Zn-65, Sr-85, Cd-109, Sn-113, Cs-137 and Am-241, with initial activities ranging from about 200 to 4300 Bq and activity standard uncertainties below 3%. The source had the same dimensions as the RG series sources and used an epoxy resin matrix with a density of approximately 1.15 g/cm³. The radionuclide composition of the source is shown in Table 2.

Table 2. Radionuclide composition of the Polatom multinuclide source ¹ [17,18].

Nuclide	Activity ² [Bq]	$T_{1/2}$	E [keV]	I_γ ³ [%]
Am-241	1094 (19) ⁴	432.6 a ⁴	59.5	35.92 (17)
Cd-109	4222 (95)	461.9 d ⁴	88.0	3.66 (5)
Co-57	233 (3)	271.81 d	122.1	85.49 (14)
Co-57	233 (3)	271.81 d	136.5	10.71 (15)
Cr-51	4275 (87)	27.704 d	320.1	9.89 (2)
Sn-113	849 (19)	115.09 d	255.1	2.11 (8)
Sn-113	849 (19)	115.09 d	391.7	64.97 (17)
Sr-85	583 (9)	64.850 d	514.0	98.5 (4)

Table 2. Cont.

Nuclide	Activity ² [Bq]	$T_{1/2}$	E [keV]	I_γ ³ [%]
Cs-137	828 (22)	30.018 a	661.7	85.01 (20)
Mn-54	1316 (24)	312.19 d	834.8	99.9752 (5)
Zn-65	2381 (37)	244.01 d	1115.5	50.22 (11)
Co-60	2291 (32)	5.2711 a	1173.2	99.85 (3)
Co-60	2291 (32)	5.2711 a	1332.5	99.9826 (6)

¹ Multinuclide source was placed in aluminium vessel with a volume of 121 cm³ (sample diameter 70 mm, height 31.5 mm, Al wall thickness 1 mm). ² Activity at calibration date. ³ Emission probability, standard uncertainties ($k = 1$) in parentheses. ⁴ a—years, d—days.

2.3. Calculations of Efficiency, C_s and C_c Corrections

Full-energy peak efficiency (FEPE), $\varepsilon(E)$, was calculated using the equation:

$$\varepsilon = \frac{N}{A \cdot I_\gamma \cdot t} \cdot C_s \cdot C_c \quad (1)$$

where N is the net peak area (counts), A is the calibration source activity, I_γ is the emission probability, t is the acquisition time, C_s is the self-attenuation correction and C_c is the TCS correction.

Determining the detector efficiency, according to Equation (1), requires knowledge of the self-attenuation correction C_s and true coincidence summing correction C_c .

The self-attenuation correction C_s for the sample relative to the calibration source, accounting for differences in self-attenuation between them, was determined using two methods: the Monte Carlo approach and the method proposed by Debertin and Helmer [19]. The latter is suitable for laboratories without Monte Carlo simulation software.

In the first approach, the self-attenuation correction was determined using Monte Carlo simulations, a technique widely applied in the determination of spectrometer efficiency. In this method, code tracks (simulates) the history of each photon from the moment of its emission by the source until the complete dissipation of its energy or its escape from the modelled geometry. Repeating this process hundreds of thousands or even millions of times yields, among other results, the simulated counts in the full-energy peak and the total counts in the spectrum. From these quantities, the photopeak efficiency ε and the total efficiency ε_t of the spectrometer can be calculated.

The efficiencies were computed using MCNP6 code (version 1.0) [20] based on a detailed model of the HPGe detector. This model included the detector, the sample, and the shielding, and incorporated accurate dimensions and material specifications. The calculations were performed using the nominal detector dimensions provided by the manufacturer. The simulation time was selected to ensure that the type A standard uncertainty of the results remained below 0.1%.

For the calculation of C_s for the sample relative to the calibration source, the detector efficiency was evaluated for both the calibration source ε_c and the sample ε_s , and the correction is then obtained according to:

$$C_s = \frac{\varepsilon_c}{\varepsilon_s} \quad (2)$$

The second method, proposed by Debertin and Helmer [19], assumes a point-detector model, in which the detector efficiency for a given geometry is proportional to the weighted sum of photons emitted from infinitesimal volume elements of the sample. The weight of each volume element is determined by the corresponding solid angle (inversely proportional to the square of the distance from the detector) and by the attenuation of photons

within the sample material along their path to the detector. The efficiency is obtained by integrating the contributions from all volume elements over the sample volume. Efficiencies calculated for both the sample and the calibration source yield C_s value via Equation (2). The point-like detector is assumed to be located at the geometric centre of the actual detector.

The required input parameters are the sample dimensions (e.g., diameter and height for cylindrical samples), the distance between the point-like detector and the sample, and the linear attenuation coefficient of the sample material. The method's standard uncertainty is approximately 1–2% [21]. A detailed description of the method is also provided in [22].

In the present study, considering additional sources of uncertainty and the negligible magnitude of the correction ($C_s \approx 1.00$), the standard uncertainty of the C_s values was assumed not to exceed 0.5%.

The true coincidence summing correction C_c must be considered when the measured radionuclide emits photons in cascade and when a highly efficient measurement geometry is employed, for instance, in cases where the source is positioned close to the detector—this being almost the rule in environmental radioactivity measurements. For a volume sample, the TCS correction C_c value depends on the nuclear data of the radionuclide and on the dependencies $\varepsilon(E)$ and $\varepsilon_t(E)$, for specific locations within the sample [19].

The true coincidence summing corrections C_c were calculated using the ETNA software (Efficiency Transfer for Nuclide Activity measurements, version 2017) [23,24]. ETNA is designed to transfer photopeak efficiency ε and total efficiency ε_t from one measurement geometry to another (known as efficiency transfer) and to determine true coincidence summing corrections C_c for both point and volume sources. In these calculations, the effective solid angle concept is applied, which assumes that the change in efficiency between two geometries depends on the change in the ratio of their respective “effective solid angles”. The “effective solid angle” accounts for radiation attenuation between the emission point and the detector, as well as for the detection probability.

The input data for ETNA include:

- a precise description of the measurement geometry (detector, sample, etc.), including the dimensions and material specifications of all components,
- the energy dependencies $\varepsilon(E)$ and $\varepsilon_t(E)$,
- the nuclear data of the nuclide under investigation, as well as the attenuation coefficients of the materials used; these data are contained in the program's internal database.

In the present work, the C_c corrections were determined for two geometries: the cylindrical geometry used for efficiency calibration, and the point geometry (see Section 2.4, Table 3) [12,25]. For both geometries, the dependencies $\varepsilon(E)$ and $\varepsilon_t(E)$ were known, so the efficiency transfer option, which introduces additional uncertainty, was not required. For the cylindrical geometry, $\varepsilon(E)$ and $\varepsilon_t(E)$, were determined experimentally using certified reference materials containing artificial radionuclides (see [12]), while for the point geometry, they were obtained using the MCNP6 code and subsequently validated experimentally. The standard uncertainty of the C_c values was estimated using the formula: $unc(C_c) = 0.1 \cdot |(1 - C_c)|$.

Table 3. TCS correction for gamma lines from K-40 and uranium- and thorium-series nuclides with a negligible true coincidence summing effect. Stronger lines corresponding to energies above 150 keV were selected.

Energy [keV]	Nuclide	Decay Series	Present Work ¹ Cylindrical Source	Xhixha ² et al. [11]	Present Work ³ Point Source
186.2	Ra-226	uranium	1.000 (1) ⁴	No data	1.000 (1)
238.6	Pb-212	thorium	1.000 (1)	No data	1.001 (1)
241.0	Ra-224	thorium	1.000 (1)	No data	1.001 (1)
242.0	Pb-214	uranium	1.008 (1)	1.0020 (2)	1.026 (3)
295.2	Pb-214	uranium	0.998 (1)	0.9993 (1)	0.990 (1)
351.9	Pb-214	uranium	1.001 (1)	1.0017 (2)	1.002 (1)
1001.0	Pa-234m	uranium	0.995 (1)	No data	0.984 (2)
1460.8	K-40	-	1.000 (1)	No data	1.000 (1)
1764.5	Bi-214	uranium	0.999 (1)	0.9970 (1)	0.994 (1)
2204.2	Bi-214	uranium	0.998 (1)	0.9950 (1)	0.993 (1)

¹ Cylindrical HPGe n-type detector (42%), cylindrical sample: diameter 70 mm and 31.5 mm height, placed directly on the detector. ² Cylindrical HPGe p-type detector (67%), cylindrical vessel: 75 mm diameter and 45 mm height, placed close to the detector. ³ Cylindrical HPGe n-type detector (42%), point source placed directly on the detector. ⁴ Standard uncertainties ($k = 1$) in parentheses.

2.4. Selection of Calibration Lines

Prior to calibration, all relatively intense gamma lines (above 150 keV) from uranium and thorium series radionuclides were reviewed. Lines with negligible true coincidence summing effects were selected. Nuclear data from the Decay Data Evaluation Project (DDEP) were used [18].

First, decay schemes were analysed to identify gamma lines with negligible true coincidence summing effects. Then, TCS corrections were calculated using the ETNA software [23], with $\varepsilon(E)$ and $\varepsilon_t(E)$ dependencies for a silica (SiO₂) matrix as input.

Results are presented in Table 3. For comparison, Table 3 also includes TCS correction values reported by Xhixha et al. [11] for a different cylindrical measurement geometry. Furthermore, C_c correction determined using the ETNA software were presented for a point source placed directly on the detector used in this study (see Section 2.1). For this geometry, the detector efficiencies (ε , ε_t), and consequently the C_c correction, are higher than for any volume source. Even for this geometry, the C_c corrections are negligible, except for the 242.0 keV line of Pb-214.

The analysis revealed several strong gamma lines (emission probability $I_\gamma > 3\%$) between 186 and 352 keV and between 1461 and 2204 keV, for which the TCS effect is negligible. In the intermediate range (352–1461 keV), only the 1001.0 keV weak line of Pa-234m ($I_\gamma = 0.847\%$) meets the criteria of negligible TCS correction and sufficient emission probability. Lines at 241.0 keV and 242.0 keV were excluded due to their interference, while the 186.2 keV line was excluded due to interference with the U-235 line at 185.7 keV. However, the 295.2 keV line was excluded due to its proximity to the 351.9 keV line, to avoid overweighting of lines within the 200–400 keV range in the calibration. Ultimately, the following lines were selected for calibration: 238.6 keV, 351.9 keV, 1001.0 keV, 1460.8 keV, 1764.5 keV, and 2204.2 keV. All selected lines are practically unaffected by TCS effect for cylindrical detectors and by spectral interferences, with the exception of a weak Bi-211 line near 351.9 keV.

3. Results

3.1. Efficiency Calibration

Efficiency calibration was carried out using the RGK, RGU, and RGTh sources. Measurement times were chosen such that the statistical standard uncertainty in count rates

was below 0.5% for all lines except the 1001 keV line. Measurements lasted 20 h for RGK and RGTh, and about 100 h for RGU. Calibration was performed for a silica matrix with a bulk density of 1.505 g/cm^3 , matching the RGU source. For RGK and RGTh sources, self-attenuation corrections C_s were applied in relation to silica; these were determined using two independent approaches: Monte Carlo simulations and the method proposed by Debertin and Helmer. These corrections did not exceed 2%, meaning that even if omitted, their impact on calibration quality would be minor.

Full-energy peak efficiency (FEPE), $\varepsilon(E)$, was determined using Equation (1). For the calibration with the RGK and RGTh sources, the C_s correction was determined relative to a SiO_2 matrix with a density of 1.505 g/cm^3 , while C_c was approximately 1.00.

A continuous efficiency function $\varepsilon(E)$ was fitted to the six measured values. Due to the limited number of data points and an acceptable uncertainty level of several percent, a second-degree polynomial in natural logarithm scale was chosen. Table 4 presents the efficiency data and fit residuals; Figure 1 illustrates the fitted $\varepsilon(E)$ curve. The experimental efficiency standard uncertainty ranged from 1.5% to 5.7%, primarily due to standard uncertainties in activity concentrations (1.1–5.5%), emission probabilities (<1.5%), and counting statistics (<0.5%; 1.2% for the 1001 keV line). The standard uncertainty of the obtained efficiency function $\varepsilon(E)$ was estimated to be 3.0%. This includes the uncertainty of the experimental efficiency values and the residuals from the curve fitting procedure (ranging from 0.1% to 2.0%, with an average of 1.1%).

Table 4. Detector calibration for energies above 200 keV, performed with RG series calibration sources for a SiO_2 matrix of density 1.505 g/cm^3 ; input data and calibration results.

Energy [keV]	Calibration Source	Nuclide	I_γ [%]	Activity Concentration [Bq/kg]	C_s ¹	$\varepsilon(E)$ [%]	Fit Residuals [%]
238.6	RGTh	Pb-212	43.6 (5) ²	3250	0.982 (5)	4.73 (27)	−1.1
351.9	RGU	Pb-214	35.60 (7)	4950	N/A	3.637 (75)	1.8
1001.0	RGU	Pa-234m	0.847 (8)	4950	N/A	1.581 (40)	−0.9
1460.8	RGK	K-40	10.55 (11)	14180	1.011 (5)	1.169 (18)	−1.2
1764.5	RGU	Bi-214	15.31 (5)	4950	N/A	1.034 (21)	1.6
2204.2	RGU	Bi-214	4.913 (23)	4950	N/A	0.851 (18)	−0.1

¹ Self-attenuation correction relative to the SiO_2 matrix of density 1.505 g/cm^3 ; for both applied methods, the results were consistent within the uncertainty limit. ² Standard uncertainties ($k = 1$) in parentheses.

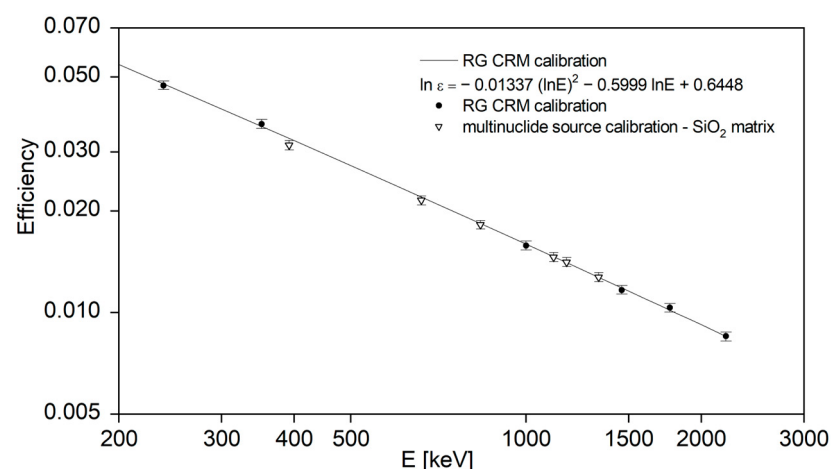


Figure 1. The calibration curve obtained using RG CRM calibration sources and its comparison with the efficiency values obtained using a multinuclide calibration source.

3.2. Validation of Calibration

To validate the proposed method, the $\varepsilon(E)$ dependence obtained above was compared with that derived from a standard efficiency calibration procedure using a multinuclide calibration source.

The measurements were performed using a multinuclide source produced by Polatom (see Section 2.2). The measurement time was approximately 220 h, and statistical standard uncertainties remained below 0.5%. In the efficiency calculations, the C_c correction for Co-60 was taken into account, as determined using the ETNA software; the TCS effect is absent for the remaining lines. A second-degree polynomial in natural logarithm scale was also fitted to calculated efficiencies [26] (see Table 5, Figure 2).

Table 5. Detector calibration using Polatom multinuclide calibration source.

Energy [keV]	I_γ [%]	Activity ¹ [Bq]	C_c	$\varepsilon(E)$ [%] Resin ²	Fit Residuals [%]	C_s ³	$\varepsilon(E)$ [%] SiO ₂ ²
391.7	64.97 (17) ⁴	196 (4)	1.000	3.267 (74)	0.2	0.965 (5)	3.159 (72)
661.7	85.01 (20)	815 (22)	1.000	2.269 (61)	−1.1	0.972 (5)	2.182 (59)
834.8	99.9752 (5)	767 (14)	1.000	1.869 (34)	1.0	0.975 (5)	1.840 (33)
1115.5	50.22 (11)	1193 (19)	1.000	1.512 (24)	0.2	0.976 (5)	1.481 (23)
1173.2	99.85 (3)	2099 (29)	1.098 (10)	1.456 (20)	0.1	0.978 (5)	1.425 (19)
1332.5	99.9826 (6)	2099 (29)	1.103 (10)	1.325 (19)	−0.4	0.978 (5)	1.292 (18)

¹ Activity at measurement date. ² Efficiency for the resin (density 1.15 g/cm³) and SiO₂ (density 1.505 g/cm³) matrices, respectively. ³ Self-attenuation correction for the resin relative to the SiO₂. ⁴ Standard uncertainties (k = 1) in parentheses.

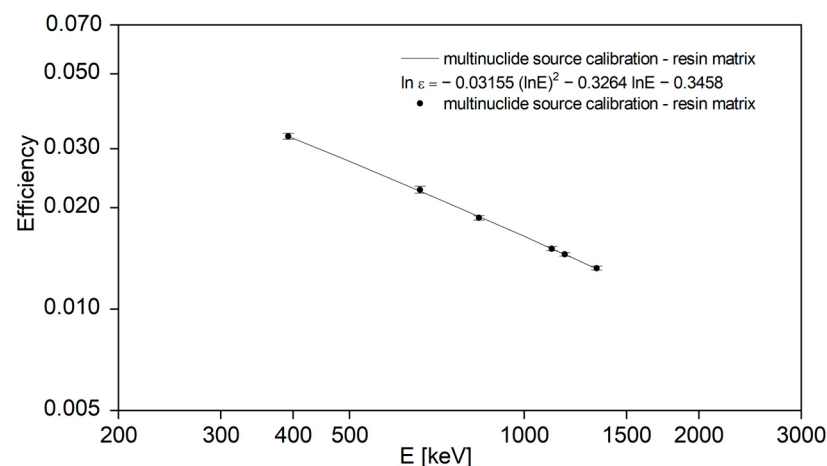


Figure 2. The calibration curve obtained using Polatom multinuclide calibration source.

Because the multinuclide source has an epoxy resin matrix, whereas the efficiency function derived in this work applies to silica with a density of 1.505 g/cm³, the measured efficiencies were converted to the silica matrix using a self-attenuation correction C_s determined by the Monte Carlo approach (see Section 2.3). The correction ranged from 0.96 to 0.98, depending on energy.

Subsequently, for several energies within the analysed range, the efficiency values obtained by both methods were compared (see Table 6 and Figure 1). The relative bias ranged from 0% to 4.1%, with an average bias of 1.5%. These results confirm that the proposed method yields results consistent with those obtained using multinuclide calibration sources.

Table 6. Comparison of $\varepsilon(E)$ values obtained using the proposed method and that obtained with a multinuclide calibration source.

Energy [keV]	Nuclide	$\varepsilon(E)$		Relative Bias [%]
		RG CRM Source [%]	Multinuclide Source [%]	
391.7	Sn-113	3.293 (99) ¹	3.159 (95)	−4.1
661.7	Cs-137	2.203 (66)	2.182 (65)	−0.9
834.8	Mn-54	1.839 (55)	1.840 (55)	0.0
1115.5	Zn-65	1.465 (44)	1.481 (44)	1.0
1173.2	Co-60	1.408 (42)	1.425 (43)	1.2
1332.5	Co-60	1.273 (38)	1.292 (39)	1.4

¹ Standard uncertainties ($k = 1$) in parentheses.

4. Discussion

The main advantage of the proposed method lies in the selection of gamma lines with negligible TCS effects. This eliminates the need for complex TCS corrections calculations and enables laboratories without access to specialised software or expertise to perform reliable calibration. Moreover, certified reference materials exhibit long-term stability and are available. Despite the limited number of gamma lines used, the resulting efficiency function $\varepsilon(E)$ showed very good agreement with the function derived from a commercial multinuclide source—relative deviations did not exceed approximately 4%. This level of agreement is acceptable for most routine analyses of environmental samples and building materials.

The primary limitation of the method is that it applies only to energies above 200 keV, due to the limited number of suitable gamma lines from natural radionuclides at lower energies. However, this energy range is rarely required in environmental and building material analyses. Exceptions include the determination of Pb-210 and Th-234 activities using the 46 keV line and the 63 keV/93 keV lines, respectively. Nonetheless, the activity of these radionuclides can still be determined using the same CRMs applied to establish the $\varepsilon(E)$ function, by applying nuclide-specific calibration approach [19].

Another drawback of the proposed method is the absence of calibration lines in the 352–1000 keV range. However, this issue does not appear to have a significant impact on the quality of the calibration, since it is generally accepted that the $\ln \varepsilon(\ln E)$ dependence is approximately linear between 200 and 2000 keV [19]. Consequently, the lack of lines within 352–1000 keV range, combined with the presence of two lines in the 200–352 keV range and four lines in the 1000–2200 keV range, should not substantially affect the shape of the resulting efficiency calibration curve.

Another issue is the use of the very weak 1001.0 keV line in the calibration, which requires a time-consuming (several tens of hours) measurement of the RGU reference source. Although this extends the detector calibration procedure, it should not have a significant impact on the routine operation of the laboratory, considering that such calibrations are performed infrequently.

5. Conclusions

This study demonstrates that, for gamma-ray energies above 200 keV, the efficiency calibration of cylindrical HPGe detectors can be performed using certified reference materials (CRMs) containing natural radionuclides, without the need to estimate true coincidence summing corrections.

This simplified approach, despite certain limitations (restricted energy range, absence of calibration points between 352 and 1001 keV, and the long measurement time of calibration sources), represents, for a specific group of laboratories, a practical and cost-

effective alternative to calibration using commercial multinuclide sources while providing comparable accuracy.

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References

1. Alharbi, S.H.; Akber, R.A. Broad-energy germanium detector for routine and rapid analysis of naturally occurring radioactive materials. *J. Radioanal. Nucl. Chem.* **2017**, *311*, 59–75. [\[CrossRef\]](#)
2. Hanfi, M.Y.; Abd El Rahman, R.M.; Alqahtani, M.S. Assessment of environmental hazard impacts in building materials (Marble), Gabal El-Galala El-Bahariya, Northeastern Desert, Egypt. *Nucl. Eng. Technol.* **2024**, *56*, 4966–4974. [\[CrossRef\]](#)
3. Mantero, J.; Thomas, R.; Isaksson, M.; Forssell-Aronsson, E.; Holm, E.; Garcia-Tenorio, R. Quality assurance via internal tests in a newly setup laboratory for environmental radioactivity. *J. Radioanal. Nucl. Chem.* **2019**, *322*, 891–900. [\[CrossRef\]](#)
4. Martínez-Ruiz, F.; Borrego, E.; Miguel, E.G.S.; Bolívar, J.P. An efficiency calibration for ²¹⁰Pb and ⁷Be measurements by gamma-ray spectrometry in atmospheric filters. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2007**, *580*, 663–666. [\[CrossRef\]](#)
5. Ramsiya, M.; Joseph, A.; Eappen, K.P.; Visnuprasad, A.K. Activity concentrations of radionuclides in soil samples along the coastal areas of Kerala, India and the assessment of radiation hazard indices. *J. Radioanal. Nucl. Chem.* **2019**, *320*, 291–298. [\[CrossRef\]](#)
6. Barba-Lobo, A.; Bolivar, J.P. A practical and general methodology for efficiency calibration of coaxial Ge detectors. *Measurement* **2022**, *197*, 111295. [\[CrossRef\]](#)
7. Eleftheriou, G.; Tsabaris, C.; Androulakaki, E.G.; Pappa, F.K.; Patiris, D.L. High resolution gamma-ray spectrometry for routine measurements of environmental samples. *Appl. Radiat. Isot.* **2024**, *206*, 111234. [\[CrossRef\]](#) [\[PubMed\]](#)
8. 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.* **2014**, *94*, 82–88. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Iurian, A.R.; Cosma, C. A practical experimental approach for the determination of gamma-emitting radionuclides in environmental samples. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2014**, *763*, 132–136. [\[CrossRef\]](#)
10. Tedjani, A.; Mavon, C.; Belafrites, A.; Degrelle, D.; Boumala, D.; Rius, D.; Groetz, J.-E. Well GeHP detector calibration for environmental measurements using reference materials. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2016**, *838*, 12–17. [\[CrossRef\]](#)
11. Xhixha, G.; Alberi, M.; Baldoncini, M.; Bode, K.; Bylyku, E.; Cfarku, F.; Callegari, I.; Hasani, F.; Landsberger, S.; Mantovani, F.; et al. Calibration of HPGe detectors using certified reference materials of natural origin. *J. Radioanal. Nucl. Chem.* **2016**, *307*, 1507–1517. [\[CrossRef\]](#)
12. Jodłowski, P.; Kalita, S.J. Gamma-Ray Spectrometry Laboratory for high-precision measurements of radionuclide concentrations in environmental samples. *Nukleonika* **2010**, *55*, 143–148.
13. IAEA. *Preparation of Gamma-Ray Spectrometry Reference Materials RGK-1, RGTh-1, and RGK-1*; Report, IAEA/RL/148; International Atomic Energy Agency: Vienna, Austria, 1987.
14. IAEA. *Certificate*; Certified Reference Material IAEA-RGK-1; Potassium Sulphure; IAEA-RGK-1_Rev.01; International Atomic Energy Agency: Vienna, Austria, 2024. Available online: https://nucleus.iaea.org/sites/AnalyticalReferenceMaterials/Shared%20Documents/ReferenceMaterials/Radionuclides/IAEA-RGK-1/IAEA-RGK-1_Certificate.pdf (accessed on 29 July 2025).
15. IAEA. *Reference Sheet*; Certified Reference Material IAEA-RGU-1; Uranium Ore; RS_IAEA-RGU-1; International Atomic Energy Agency: Vienna, Austria, 2016. Available online: https://nucleus.iaea.org/sites/AnalyticalReferenceMaterials/Shared%20Documents/ReferenceMaterials/Radionuclides/IAEA-RGU-1/RS_IAEA-RGU-1.pdf (accessed on 29 July 2025).

16. IAEA. *Reference Sheet*; Certified Reference Material IAEA-RGTh-1; Thorium Ore; RS_IAEA-RGTH-1; International Atomic Energy Agency: Vienna, Austria, 2016. Available online: https://nucleus.iaea.org/sites/AnalyticalReferenceMaterials/Shared%20Documents/ReferenceMaterials/Radionuclides/IAEA-RGTh-1/RS_IAEA-RGTh-1.pdf (accessed on 29 July 2025).
17. Polatom. Multigamma Sources. Available online: <https://www.polatom.pl/kategoria-produktu/radioactivity-standards/multigamma-sources/> (accessed on 29 July 2025).
18. DDEP Webpage. Available online: <http://www.lnhb.fr/accueil/donnees-nucleaires/donnees-nucleaires-tableau/> (accessed on 29 July 2025).
19. Debertin, K.; Helmer, R.G. *Gamma- and X-Ray Spectrometry with Semiconductor Detectors*; North-Holland: Amsterdam, The Netherlands, 1988.
20. Pelowitz, D.B.; Goorley, J.T.; James, M.R.; Booth, T.E.; Brown, F.B.; Bull, J.S.; Zukaitis, A.J. *MCNP6 User's Manual*; Tech. Rep. LA-CP-13-00634; Los Alamos National Laboratory: Los Alamos, NM, USA, 2013.
21. Debertin, K.; Ren, J. Measurement of the activity of radioactive samples in Marinelli beakers. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **1989**, *278*, 541–549. [[CrossRef](#)]
22. Jodłowski, P. Self-absorption correction in gamma-ray spectrometry of environmental samples—An overview of methods and correction values obtained for the selected geometries. *Nukleonika* **2006**, *51*, S21–S25.
23. Lépy, M.-C.; Bé, M.-M.; Piton, F. *ETNA (Efficiency Transfer for Nuclide Activity Measurements): Software for Efficiency Transfer and Coincidence Summing Corrections in Gamma-Ray Spectrometry*; Note Technique LNHB 01/09/A; Laboratoire National Henri Becquerel: Saclay, France, 2004.
24. Lepy, M.-C.; Ferreux, L.; Pierre, S. Coincidence summing corrections applied to volume sources. *Appl. Radiat. Isot.* **2012**, *70*, 2137–2140. [[CrossRef](#)] [[PubMed](#)]
25. Fedasz, E. Determination of Coincidence-Summing Corrections for Gamma-Ray Spectrometer. Bachelor's Thesis, Faculty of Physics and Applied Computer Science, AGH University of Krakow, Krakow, Poland, January 2012. (In Polish)
26. Gorzkiewicz, K. Efficiency Calibration of Gamma-Ray Spectrometer for Selected Measurement Geometries. Bachelor's Thesis, Faculty of Physics and Applied Computer Science, AGH University of Krakow, Krakow, Poland, February 2014. (In Polish)

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