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RECEIVED: *January 21, 2016*
ACCEPTED: *February 22, 2016*
PUBLISHED: *???, 2016*

Validation of Monte Carlo model of HPGe detector for field-station measurement of airborne radioactivity

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ABSTRACT: A Monte Carlo (MC) model of a mechanically-cooled High Purity Germanium detection system IDM-200-V™ manufactured by ORTEC® was created, optimized and validated within the scope of the Joint Research Project ENV57 "Metrology for radiological early warning networks in Europe". The validation was performed for a planar source homogeneously distributed on a filter placed on top of the detector end cap and for point sources positioned farther from the detector by comparing simulated full-energy peak (FEP) detection efficiencies with the ones measured with two or three different pieces of the IDM detector. True coincidence summing correction factors were applied to the measured FEP efficiencies. Relative differences of FEP efficiencies laid within 8% that is fully satisfactory for the intended use of the detectors as instruments for airborne radioactivity measurement in field-stations. The validated MC model of the IDM-200-V™ detector is now available for further MC calculations planned in the ENV57 project.

KEYWORDS: Models and simulations; Dosimetry concepts and apparatus

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doi:xxxxxxx

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1 Introduction

In a radiological emergency, early and reliable knowledge of radioactivity concentrations in the air and the subsequent assessment of contamination levels of land and of dose rate levels in urban areas are of key importance in order to organise appropriate measurements for the protection of the general public against dangers arising both from direct external irradiation and from intake of radioactivity from food and air. The aim of the Joint Research Project ENV57 "Metrology for radiological early warning networks in Europe" (MetroERM) is to harmonise the radiological early warning networks in Europe by optimisation of the measuring devices and methods for monitoring airborne radioactivity, resulting from incidents at nuclear facilities or other industrial releases, and to introduce pan-European harmonisation in data reliability for input to the European Radiological Data Exchange Platform (EURDEP) and other monitoring networks. The uncertainties should be reduced to less than 20% for gamma-ray emitting radionuclides.

In nuclear accidents a complex mixture of radionuclides is present and high resolution gamma-spectrometric detectors should be used for identification of different radionuclides. The Interchangeable Detector Module (IDM) mechanically cooled High Purity Germanium (HPGe) semiconductor detector IDM-200-V™ manufactured by ORTEC®, U.S.A., (hereafter IDM detector) investigated in this work is very suitable for this purpose because of its high energy resolution and compact field-use design.

The aim of this work is to develop and validate a Monte Carlo (MC) model of the IDM detector. In particular, the model is intended to be used for calculation of detector pulse-height spectra of naturally occurring radionuclides. These spectra will be subtracted from the total measured pulse-height spectrum with the aim to decrease the minimum detectable activity of artificial radionuclides in air. Validation of the MC model is based on the comparison of measured and simulated full-energy peak detection efficiencies (FEP DE) for several geometries including close geometry with the filter that will be used for the real field measurement.

2 Materials and methods

2.1 Experiment

The aim of the experiments was to provide measured data for validation of the MC model of the IDM detector in geometries same or similar to the detector's intended use in field-station measurement of airborne radioactivity. Three experimental determinations of full-energy peak detection efficiencies (FEP efficiencies) were performed — one with a surface source and two with point-like sources positioned at different distances from the detector.

2.1.1 Point sources

FEP efficiencies for point sources were initially measured for three pieces of the same type of the IDM-200-V™ detector available at that time at the Czech Metrology Institute (CMI). Five point-like sources of the EFS type (CMI, Czech Republic) were prepared, each one with a different radionuclide (Am-241, Co-57, Co-60, Cr-51, Cs-137). The activity of the sources ranged from 30 to 160 kBq. The sources were positioned on the detector rotational axis at the distance of 25 cm from the detector end cap.

Later, an additional measurement with point-like sources was performed at CMI for two IDM detectors. The third detector was not temporarily available at CMI. FEP efficiencies were measured for Am-241, Eu-152, and Co-60 sources of the EFS type at a distance of 5 cm from the detector end cap, on the detector rotational axis. The activity of the sources ranged from 30 to 60 kBq. The goal was to check the detectors stability and to test coincidence probabilities and methods for calculation of corrections to the true coincidence summing effect needed later for corrections of measured efficiencies for a source on the filter.

2.1.2 Surface source on filter

A surface source was realized by using Eu-152 radionuclide spiked on a GA-100 fibreglass filter (Chromservis, Czech Republic [1]). The activity was deposited on the filter in 24 drops distributed on the filter in such a way to uniformly cover the whole area of the filter. The source had the nominal activity of 100 Bq and it was prepared and standardized at CMI. Detection efficiencies for this source were determined in a close geometry for two pieces of the IDM detector.

Corrections to the true coincidence summing effect were applied to the measured FEP efficiencies by using the MC calculated detection efficiencies and Eu-152 summing-out and summing-in coincidence probabilities published in [2]. The MCNPX code does not contain routines for correct calculation of true coincidences from radionuclide decay schemes that is why the final value of

TCSC factors had to be determined outside MC simulations. The surface source was divided into nine annular segments so that it was possible to expect constant detection efficiency in the whole area of each segment. For each segment, the FEP and total detection efficiencies were calculated for energies between 40 and 2100 keV. The overall TCSC factor was then determined as a sum of products of individual efficiencies and areas of corresponding segments as described in more detail in [3]. Although this method is primarily intended to account for the influence of photon attenuation in material of the source, in this case the purpose was to account for different detection efficiencies across the whole source radius which is relatively large compared to the radius of the Ge crystal. The correction is necessary because in such close measurement geometry the TCSC factors may reach up to tens of percent for some radionuclides.

2.2 Monte Carlo simulations

Monte Carlo simulations were performed by using the code MCNPX in version 2.7.E [4]. MCNPX is a well-known general-purpose Monte Carlo code for radiation transport simulations validated by many benchmarks and, in the photon and electron energy range of interest of this work, i.e. from tens of keV to a few MeV, provides reliable results. In the simulations, continuous-energy photoatomic data library MCPLIB84 [5] and electron data library el03 were used. Photons were transported over the whole modelled geometry while electrons were transported only in Ge crystal and its close proximity. Photon and electron cut-off energy was set to 2 keV and 5 keV, respectively. The calculated quantity was a full-energy peak detection efficiency and total detection efficiency determined by an F8-type tally. The calculations were stopped when the statistical uncertainty of the result fell below 0.2%.

2.2.1 IDM detector

The IDM-200-V™ HPGe detector MC model was created based on information obtained from 1) IDM detector datasheet containing general information [6], 2) IDM detector diagram with detailed specifications of Ge crystal dimensions (confidential), and 3) radiogram of one piece of the IDM detector taken at CMI. The IDM detector model consisted of the Detector Assembly and the Detector Box (figure 1).

The detector assembly was modelled in all details provided on the detector diagram or visible on the radiogram including a mount cup ring, contact pin, and skewed edges of the germanium crystal. The thickness of germanium crystal window dead layer was later modified from 200 μm (manufacturer's data) to 325 μm based on the initial comparison of measured and simulated FEP efficiencies for point-like sources positioned 25 cm from the detector end cap.

The detector box contains a power supply, electronics, and cooling mechanism. The box has outer dimensions of 21.2 cm $\times$ 30.0 cm $\times$ 30.0 cm and a 0.2 cm thick steel wall. The internal structure of the detector box was modelled as a homogeneous material composed of a mix of epoxy resin, duralumin, and steel. The density of this material was chosen in such a way that the total weight of the IDM detector model was the same as of the real one, i.e. 17.7 kg [6].

2.2.2 Experimental room

The close geometry of the measurement of activity on the filter raised the necessity to correct the measured FEP efficiencies to true coincidence summing effects. For this reason the experimental

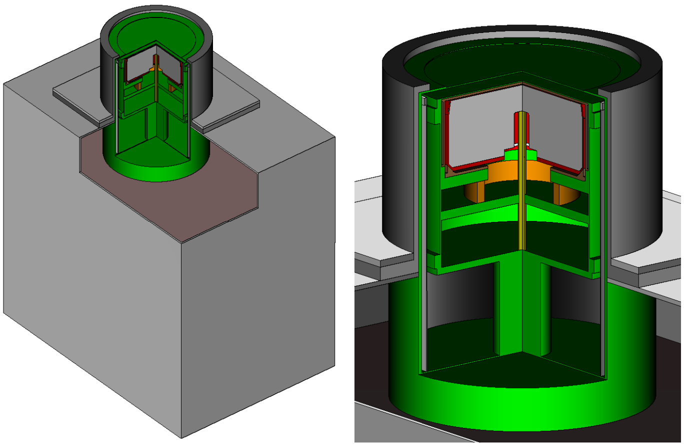

Figure 1. MC model of the IDM-200-V™ detector. Colours distinguish materials. Left — partial cut through detector assembly and detector box. Right — detail of the detector assembly.

room was added into the IDM detector model in order to include the contribution of scattered photons into the detector response. The rectangular room had inner dimensions of 300 cm × 200 cm × 250 cm and the walls, floor and ceiling were made of 3 cm thick steel and 70 cm thick concrete. No other significant scattering objects were present in the room therefore no other objects were added into the MC model.

2.2.3 Definition of sources

Three different sources were modelled. The first two sources were point-like sources positioned above the detector at the same distance as in the measurements. Construction of the sources was neglected in the model. The third source was a planar cylindrical source homogeneously distributed in the whole filter volume. The filter was modelled as 0.44 mm thick fiberglass [1] with the density of 0.25 g/cm^3 enclosed into a duralumin ring with an inner diameter of 8.2 cm. The filter was positioned above the detector end cap with its rotational axis matching the detector axis. The distance between the detector end cap and upper surface of the filter was the same as in the measurement, i.e. 0.30 cm (corresponding to the total distance of 0.94 cm to the front face of the Ge crystal). Validation of the IDM detector MC model for this source is important because such geometry will be used in field-station measurements due to low activities of environmental samples.

Generated particles were emitted isotropically and no variance reduction method was used. The calculated quantities were the FEP and total detection efficiencies for a set of 32 monoenergetic photons in the energy range from 30 keV to 2.1 MeV. Some of these energies were selected to correspond to the main photons emitted by radionuclides used in measurements, i.e. Am-241 (59.5 keV), Co-57 (122.1 keV, 136.5 keV), Co-60 (1173.2 keV, 1332.5 keV), Cr-51 (320.1 keV), Cs-137 (661.7 keV), and Eu-152 (121.8 keV, 344.3 keV, 778.9 keV, 964.1 keV, 1408.0 keV). The calculated total detection efficiencies were used to determine the true coincidence summing correction (TCSC) factors applied to the measured data.

3 Results and discussion

3.1 Validation for point sources at 25 cm

The simulated FEP efficiencies and relative differences to the values measured by all three IDM detectors and their mean are summarized in table 1. Relative differences are also depicted in figure 2. The uncertainty of the measurement was kept below 1.0% except for Co-57 at 136.5 keV peak where it reached up to 2.1%. No TCSC factors were applied to the measured data.

Table 1. Results of validation for point-like sources positioned 25 cm from the detector end cap.

Radionuclide	Photon energy (keV)	MC simulation	Relative difference of FEP DE[a]			
		FEP DE[b]	IDM #1[c]	IDM #2[c]	IDM #3[c]	Mean
Am-241	59.5	3.648E-03	(1.6 ± 0.6)%	(−8.4 ± 0.9)%	(1.8 ± 1.0)%	(−1.7 ± 1.5)%
Co-57	122.1	4.769E-03	(−2.6 ± 0.6)%	(−0.6 ± 0.3)%	(5.0 ± 0.7)%	(0.6 ± 1.0)%
Co-57	136.5	4.651E-03	(0.1 ± 1.8)%	(1.7 ± 1.1)%	(5.5 ± 2.1)%	(2.4 ± 3.0)%
Cr-51	320.1	2.351E-03	(2.5 ± 0.8)%	(−0.4 ± 0.7)%	(−2.2 ± 0.9)%	(0.0 ± 1.4)%
Cs-137	661.7	1.132E-03	(2.8 ± 0.8)%	(−3.7 ± 0.7)%	(4.3 ± 1.1)%	(1.1 ± 1.5)%
Co-60	1173.2	6.745E-04	(1.6 ± 0.8)%	(0.4 ± 0.7)%	(−4.3 ± 0.8)%	(−0.8 ± 1.4)%
Co-60	1332.5	5.992E-04	(2.2 ± 0.8)%	(−0.8 ± 0.7)%	(−2.3 ± 0.9)%	(−0.3 ± 1.4)%

[a] 1-FEP_{EX}/FEP_{MC}; FEP_{EX} — measured FEP DE, FEP_{MC} — simulated FEP DE.
[b] Statistical uncertainty of the simulation is 0.2%.
[c] The uncertainty (k=1) is composed of uncertainty of simulation, source activity, and spectrometric measurement.

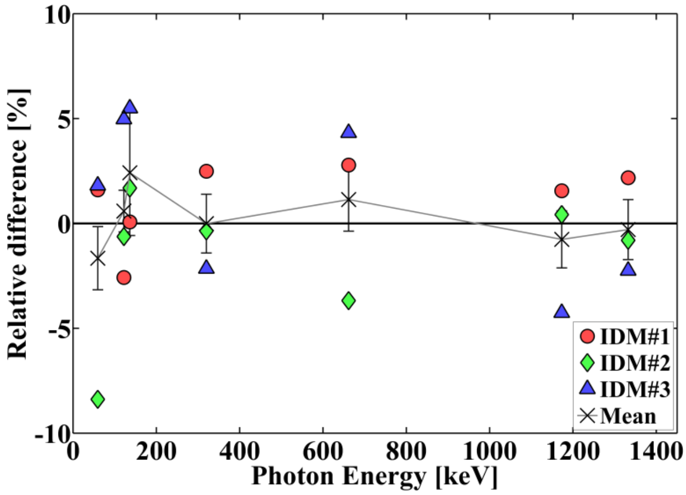

Figure 2. Relative difference between FEP efficiencies for point-like sources positioned 25 cm above detector end cap obtained from MC simulations and measured with three different IDM detectors. Error bars are shown for mean values only for better readability. The line between data points is displayed as a visual guide.

The comparison of measured and simulated FEP efficiencies shows that even when the IDM detectors are of the same type and the manufacturer declares the same nominal dimensions and 50% relative detection efficiency [6], the measured FEP efficiencies differ between studied IDM detectors by up to 10%. For example, the FEP efficiency of the IDM #2 for 59 keV photons higher by 10% compared to the other two IDM detectors implies that the front Ge dead layer is thinner than of the other two detectors. Also, the higher detection efficiency of IDM #2 at high energies implies that the Ge crystal in this detector is larger compared to IDM #1.

The mean value of FEP efficiencies of the three IDM detectors matches the simulated FEP efficiencies within 2% in the energy range from 59 keV to 1408 keV. This is a satisfactory agreement showing that the dimensions and shape of the germanium crystal is modelled very close to reality.

3.2 Validation for point sources at 5 cm

Simulated FEP efficiencies and relative differences to the values measured by two IDM detectors and their mean are summarized in table 3. Relative differences are also visualized in figure 4. TCSC factors between 1.04 and 1.08 were applied to FEP efficiencies measured for Co-60 and Eu-152 radionuclides.

FEP efficiencies measured with IDM#1 are lower than the ones of IDM#2 practically in the whole examined energy range. This is in agreement with the measurements performed for the distance of 25 cm (see figure 2).

The mean value of the relative difference between simulated and measured FEP efficiencies is very close to zero in the whole energy range resulting in confirmation of the correctness of the IDM detector model. And more, it also proves that coincidence probabilities and the method for calculation of TCSC factors for Co-60 and Eu-152 in this measurement geometry gives reliable results.

3.3 Validation for surface source at 0.3 cm

Simulated FEP detection efficiencies and relative differences to the values measured by two IDM detectors are summarized in table 2. Relative differences are also presented in figure 3. TCSC factors applied to the measured FEP efficiencies reached up to 1.32 due to very close distance between the source and the detector.

The comparison shows quite a good match between the measured and simulated FEP efficiencies with a maximum difference of 7.4%. Such agreement is fully satisfactory for the intended use of the detectors in field-stations measurements of airborne radioactivity. The uncertainty of the mean value presented in table 2 is a combination of total uncertainties for each IDM detector and they consist of the uncertainty of simulation, source activity, TCSC factors, and counting statistics of spectrometric measurements.

In the summary, the Monte Carlo model of the IDM-200-V™ HPGe detector is validated for measurement geometries with gamma-ray emitting sources positioned in front of the detector, including a geometry of thin surface source located very close (0.3 cm) above the detector end cap. The latter geometry is intended to be exploited for spectrometric measurement of airborne radioactivity with IDM detectors.

4 Conclusions

In the framework of the Joint Research Project ENV57 “Metrology for radiological early warning networks in Europe”, portable HPGe gamma-spectrometric detectors IDM-200-V™ are supposed

Table 2. Results of validation for Eu-152 surface source positioned 0.3 cm from the detector end cap.

Photon energy (keV)	MC simulation	Relative difference of FEP DE[a]			
	FEP DE[a]	IDM #1[b]	IDM #2[b]	Mean	TCSC[b]
121.8	0.2029	(5.0 ± 1.7)%	(3.0 ± 2.0)%	(4.0 ± 2.7)%	1.32
344.3	0.0987	(2.7 ± 2.0)%	(−5.1 ± 1.9)%	(−1.2 ± 2.8)%	1.17
778.9	0.0463	(−0.4 ± 3.8)%	(−1.6 ± 4.8)%	(−1.0 ± 6.1)%	1.26
964.1	0.0386	(3.4 ± 4.1)%	(5.4 ± 5.4)%	(4.4 ± 6.8)%	1.25
1408.0	0.0279	(7.4 ± 3.9)%	(4.6 ± 5.0)%	(6.0 ± 6.3)%	1.19

[a]See table 1.
[b]See table 3.

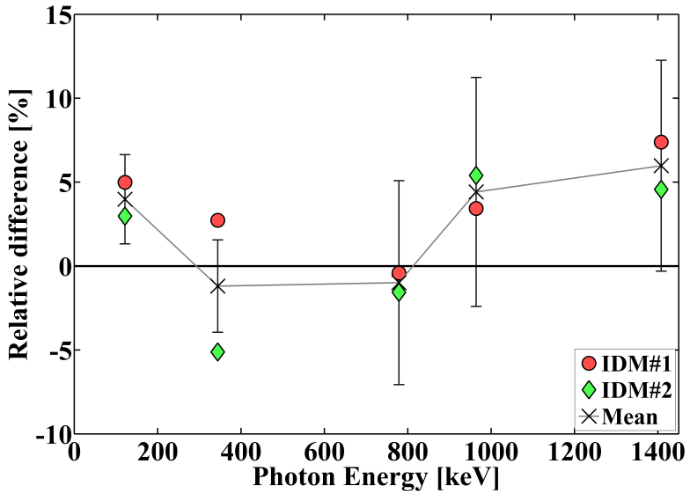

Figure 3. Relative difference between FEP efficiencies obtained from MC simulations and measured with two IDM detectors, for Eu-152 surface source positioned 0.3 cm above the detector end cap. Error bars are shown for mean values only. The line between data points is displayed as a visual guide.

to be suitable for operational measurement of airborne radioactivity in field-stations throughout Europe. The aim of the presented work was a validation of the Monte Carlo model of the IDM detector in the expected measurement geometry. The validation was performed in consecutive steps, beginning with the comparison of measured and simulated FEP efficiencies for point-like sources at 25 cm distance, and ending with the close measurement geometry with a surface source on a filter. The final MC model of the IDM detector provides reliable results for all tested geometries, with the relative differences within 2.5% for point sources at 5 and 25 cm and within 7.5% for a surface source at 0.3 cm above the detector end cap. Such deviations are fully acceptable for intended use of the detectors therefore the IDM detector model is considered as validated.

In future work within the MetroERM project, the MC model will be used for calculation of detector pulse-height spectra of naturally occurring radionuclides deposited on the filter with the aim to subtract them from the total measured pulse-height spectrum resulting in significantly decreased minimum detectable volume activity of artificial radionuclides in the air. Subsequently,

Table 3. Results of validation for point-like sources positioned 5 cm from the detector end cap.

Radionuclide	Photon energy (keV)	MC simulation	Relative difference of FEP DE[a]			
		FEP DE[a]	IDM #1[b]	IDM #2[b]	Mean	TCSC[c]
Am-241	59.5	5.426E-02	(6.3 ± 0.8)%	(−7.4 ± 0.8)%	(−0.5 ± 1.1)%	1.000
Eu-152	121.8	6.850E-02	(1.5 ± 0.9)%	(−1.5 ± 0.9)%	(0.0 ± 1.3)%	1.080
Eu-152	344.3	2.928E-02	(3.8 ± 1.0)%	(−1.4 ± 1.0)%	(1.2 ± 1.4)%	1.041
Eu-152	778.9	1.306E-02	(2.5 ± 1.4)%	(−2.9 ± 1.5)%	(−0.2 ± 2.0)%	1.061
Eu-152	964.1	1.075E-02	(1.2 ± 1.4)%	(1.1 ± 1.5)%	(1.1 ± 2.1)%	1.075
Co-60	1173.2	9.002E-03	(2.5 ± 1.0)%	(−1.9 ± 1.1)%	(0.3 ± 1.5)%	1.044
Co-60	1332.5	8.007E-03	(2.8 ± 1.1)%	(−2.2 ± 1.1)%	(0.3 ± 1.5)%	1.046
Eu-152	1408.0	7.600E-03	(3.9 ± 1.4)%	(0.7 ± 1.5)%	(2.3 ± 2.1)%	1.063

[a] See table 1.

[b] The uncertainty (k=1) is composed of uncertainty of simulation, source activity, spectrometric measurement, and TCSC factors.

[c] The true coincidence summing correction factor applied to measured FEP efficiencies.

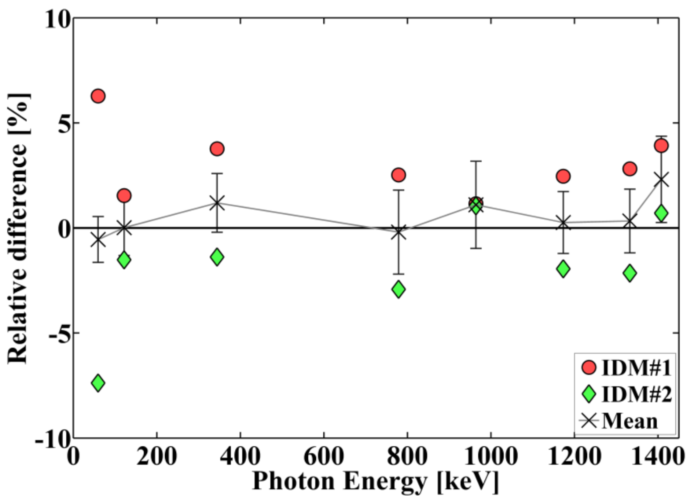

Figure 4. Relative difference between FEP efficiencies for point-like sources positioned 5 cm above the detector end cap obtained from MC simulations and measured with two different IDM detectors. Error bars are shown for mean values only. The line between data points is displayed as a visual guide.

the detector response matrix will be calculated allowing the conversion of measured radionuclide-specific pulse-height spectra of radionuclides in the air into effective dose from external irradiation. Following the similar approach, calculated detector response matrix for geometries of an infinite planar source (surface contamination) and a hemispheric source (radionuclides in ground) will allow to estimate the contribution to effective dose from such sources. At the end, the total effective dose from external irradiation will be assessed from the detector pulse-height spectrum measured outside field-station and, if needed, may be separated into contributions from different radionuclides and sources. It is expected that this estimation of effective dose will deliver lower uncertainty than current methods considering low uncertainty on gamma-spectrometric measurement of activity.

Acknowledgments

This work was supported by the EMRP Joint Research Project ENV57 "Metrology for radiological early warning networks in Europe " under funding from the European Union on the basis of Decision No. 912/2009/EC. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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