EXPERIMENTAL METHODS AND PROCESSING OF DATA

https://doi.org/10.46813/2021-136-149

VALIDATION OF THE GEIGER-MULLER COUNTER MODEL OF BDMG-04-02 USING THE MONTE-CARLO TECHNIQUE

Yu. Fylonych, V. Zaporozhan, O. Balashevskyi
The Department of the Scientific and Technical Support in Odesa SS “Scientific and Technical Support” of SE “NNEGC “Energoatom”, Odesa, Ukraine
E-mail: yuraenergy@i.ua

The model of the Geiger-Muller counter as the internal part of BDMG-04-02 detection unit in the calibration facility UPGD-2 was developedin MCNP6.2. The different methods are used for the determination of the Geiger-Muller counter response. The F1 and F8 tally applicability is briefly described. BDMG-04-02 model was validated by comparative analysis of the calculated results and experimental values of the counter responses that obtained on the UPGD-2 calibration facility. Additionally, the absolute, geometric and intrinsic registration efficiency of BDMG-04-02 was determined. The paper has been emphasized the disadvantages of using the method of direct counting of the electrons on the surface of the Geiger-Muller counter (F1).

PACS: 29.40Cs, 29.40-n

INTRODUCTION

NPPs require the utilization of a sufficient number of detectors, which differ by design features, operation principles, and registration efficiency of alpha, beta, gamma particles from various sources of ionizing radiation [1]. In practice, the detectors or dosimeters are calibrated using one or several radionuclides before being installed in the instrument workplace. Commonly, the radiation spectrum from various isotopes in the area of the contaminated equipment at NPP may differ significantly from that used for calibration. Furthermore, between the detectors and the radioactive medium could be installed various barriers in the form of the protective shield, additional equipment, etc. Its mean that all additional obstacles cause the changing of the initial particle spectrum.

In reality, reproduction of a large number of radioisotopes and spatial obstacles experimentally is to complicated and expensive process. Therefore, analytical prediction of the radiation dose rate by tabular and graphical data leads to overestimation/underestimation of the ionizing radiation compare to detector response at the place of the radiation monitoring. Especially this is inherent in non-proportional devices that could not determine the exact ionization energy.

The alternative method for solving such tasks is the development of detailed detector models with subsequent validation in computational programs designed for the registration of ionizing radiation (reconstruction of real conditions in the workplace).

GOALS

Develop model of the built-in Geiger-Muller counter of the detection unit BDMG-04-02 that could be used for prediction of detector response from different types of ionizing radiation sources using Monte-Carlo technique, implemented in the MCNP6.2. Validate Geiger-Mueller counter model based on the obtained experimental data in the calibration facility (UPGD-2), as well as using the passport characteristics of device.

METHODS

The Monte-Carlo technique is used for tracking random particle histories in the model using interaction cross-section libraries that contain the event probabilities [2]. Each simulated history is counted until the particle ceases to exist or leaves the computational model boundaries. The number of particle histories has to be large enough to achieve a statistically valid (precise) result. Consequently, that requires significant computational time.

The MCNP (Monte-Carlo N-Particle Transport Code [3]) code, which is based on the Monte-Carlo method, is used to simulate the transport and interaction of particles with a multi-component medium and provides the possibility to determine the absolute, geometric, intrinsic registration efficiency, as well as the precise value of detector response.

Version 6.2 of MCNP code is state-of-the-art software for modeling interaction between particles and their transport by using the appropriate cross-section data for simulating the transport of neutrons, photons and electrons. MCNP also contains a lot of options that enable/disable to activate photon and electron interactions, including Doppler broadening, which is necessary to take into account the of bound electrons affection on photon scattering.

MCNP code allows performing calculation analysis of the efficiency of different types of radiation detectors such as semiconductors, scintillation detectors, ionization chambers etc.

DESCRIPTION OF THE EXPERIMENT

The experiment was carried out at the Rovno NPP [4]. Encapsulated source of radiation was placed inside to collimator of the UPGD-2 facility. The detector was fixed in the movable carriage. ^{60}Co and ^{137}Cs were used as sources. The distance between the source and the side surface of BDMG-04-02 were changed in the range from 700 to 2500 mm. In all cases shielding between the source and BDMG-04-02 was absent.

The first source. ^{137}Cs undergoes beta decay with a half-life ($T_{1/2}$) of $9.51 \cdot 10^8$ s. As a result, a stable isotope of ^{137}Ba is formed. In 94.43% of cases, the decay occurs with the formation of the intermediate nuclear isomer ^{137m}Ba ($T_{1/2}$ = 153 s). This isotope passes to the ground state with the emission of a γ particle with an energy of 661.6 keV (probability of this event is 90.1%) and a conversion electron with an energy of 661.6 keV yet reduced by the value of the binding energy of the electron.

The second source. ^{60}Co also undergoes beta decay with $T_{1/2}$ $1.66 \cdot 10^8$ s and stable isotope of ^{60}Ni is formed. In this case, the source of ionizing radiation more probable emits photons with energies of 1.1732 and 1.3325 MeV.

Discrete γ- and x-ray spectra of ^{137m}Ba and ^{60}Co were used from the National Nuclear Data Center data bases [5].

The initial activity of ^{137}Cs in January 1991 was $9.43 \cdot 10^9$ Bq and ^{60}Co – $7.0 \cdot 10^{10}$ Bq in May 1987. Accordingly, the activities at the time of calibration are determined by the next expression:

$$A = A_0 \cdot \exp(-\lambda t), \quad (1)$$

where λ is decay constant, s^{-1}; A_0 is initial activity, Bq; t is time between two calibrations, s.

Thereby, the obtained results of activities are presented in Table 1.

Table 1

The initial and experimental activity of radioactive sources

Radioactive source	Calibration data	A_0, Bq	A, Bq
^{60}Co	28.09.2020	$7.0 \cdot 10^{10}$	$8.72 \cdot 10^8$
^{137}Cs	18.09.2020	$9.43 \cdot 10^9$	$4.76 \cdot 10^9$

The Geiger-Muller counter is used to detect and measure different types of radiation such as beta and gamma. It consists of a pair of electrodes surrounded by an inert gas. A high voltage is applied to the electrodes to create a potential difference. Knocked out electrons from gas atoms are moved to the anode, and positively charged ions – to the cathode. This creates a current in the electrodes (pulses). It is impotent to note that the counter requires a certain time to measure and record one pulse. During that time the counter unable to “correctly” reprocess the next signal. This effect is called the detector dead time [6, 7].

Three different detection units BDMG-04-02 were used during the experiments to obtain satisfactory precision in terms of count rates. Technical characteristics of BDMG-04-02 are taken from [8]. The encapsules sources of ^{60}Co and ^{137}Cs were separately installed in the movable carriage of the UPGD-2 and located at distances from 700 to 2500 mm to the front side of BDMG-04-02. Each experiment with one configuration was repeated 10 times to achieve the reliable statistics.

MCNP MODEL OF THE GEIGER-MULLER COUNTER

The calculation model of the experiments include: high-sensitivity Geiger-Muller counter of the detection unit BDMG-04-02; a lead protective shield; the source ^{137}Cs or ^{60}Co; collimator of calibrated facility UPGD-2, environment is air at normal pressure.

The main geometric and material characteristics for BDMG04-02 modeling are used from specification [9] that provided by manufacturer of the device. Three-dimensional model of the BDMG-04-02 in the MCNP6.2 code are shown at Fig. 1. The density of the sensitive gas was chosen arbitrarily and equal to $8.39 \cdot 10^{-5}$ g/cm^3 (rarefied Ne at 1/10 atmospheric pressure). The following materials with appropriate mass concentrations were used in the calculation: cathode – Cr 28.47 wt.%, Si 0.47 wt.%, V 0.08 wt.%, Mn 0.37 wt.%, Fe 70.43 wt.%, Ni 0.18 wt.%; anode – Cr 28.4 wt.%, Ni 1.4 wt.%, Fe 70.2 wt.%; inert gas with halogen impurities – Ne 99.4 wt.%, Br 0.5 wt.%, Ar0.1 wt.%; correction filter – Sn 100 wt.%; cladding – Al; protective shield and collimator – Pb.

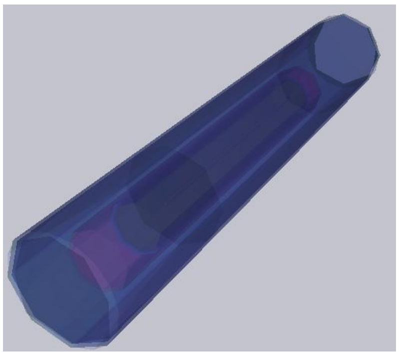

Fig. 1. Three-dimensional model of the high-sensitive Geiger-Muller counter of BDMG-04-02 in MCNP6.2

The volumetric source modeled as a cylinder medium including the appropriate spatial, energetic, and angular characteristics of the emitted radiation. The developed models contain all the main processes of secondary particle production for correct photons and electrons transport simulation. The models specified continuous moderation, which comprises positrons, k-rays, and bremsstrahlung radiation yet external or self-induced field were not taken into account.

In the developed models in MCNP6.2 were used two different methods to calculate the count rates of the Geiger-Muller tube. The first method was a particle current counting by F1 tally [10]. F1 determines the number of electrons that rich the sensitive region of BDMG-04-02 through the inner surface of the cathode, the surface of the anode, and the side (glass) surfaces. The particle counter was not used in combination with the "cosine" options in the models, as the transfer of all secondary electrons were forcibly stopped immediately after entering the gas cell. It means that all the secondary electrons create a pulse after reaching the sensitive region (the electron registration efficiency by the Geiger-Muller tube is almost 100%) [11]. Thus, the number of pulses in the counter is equal to the sum of all electrons obtained in F1 tallies from different surfaces surrounding the inert gas.

The second method is the calculation of the pulse height (F8 – Pulse Height Tally [12, 13]). The F8 is used to simulate the actual response of the Geiger-Muller counter and calculate the sum of the remaining energy in the sensitive gas from all possible interactions in the single event. Consequently, the correct number of pulses without electron efficiency assumption is determined [10].

The ambient equivalent dose rate in the detection region could be determined by calculating the photon flux (F4 tally, 1/cm^2) combined with the conversion coefficients that entered in DE (MeV) and DF (pSv·cm^2) cards in MCNP6.2 [14]. The empirical coefficients that used for conversion from the photon flux to the ambient dose equivalent are listed in the ICRP Publication 74 [15]. The F4 tally does not take into account the secondary ionization processes and, accordingly, not valid for calculation Geiger-Muller counter response.

Beta particles also emit from the source during the radioactive disintegration of ^{137}Cs, but due to the relatively short path length and the considerable distance from the source to the counter, the transport of these particles was not taken into account. It should be noted that the calculation was done to verify this statement. The obtained results confirmed the zero contribution to the F8 and F1 from beta particles during simulation of radioactive decay of ^{137}Cs at the distance of 700 mm to BDMG-04-02.

During the simulation, the energy range of the detector was arbitrary divided into 130 energy channels. The threshold energy required to form one electron-ion pair for ^{20}Ne gas is 36 eV [16]. As a result, the contribution of particles with energy below the threshold is not considered [17].

In all models were used libraries of estimated nuclear data for of photons (84p) and electrons (03e) transport simulation.

INTERPRETATION AND ANALYSIS OF RESULTS

In all calculation model of BDMG-04-0 25·10^9 decay histories were simulated, in which ^{137}Cs or ^{60}Co sources emit photons with characteristic energies. The obtained values of $F8_{mcnp}$ and $F1_{mcnp}$ are presented in Table 2.

Table 2

The results of the detector response (F1 and F8) in the model with the experimental facility and BDMG-04-02

Source	L, mm	700	1200	2500
^{60}Co	$F8_{mcnp}$	$1.58\cdot10^{-6}$	$5.33\cdot10^{-7}$	$1.22\cdot10^{-7}$
	$F1_{mcnp}$	$1.65\cdot10^{-6}$	$5.54\cdot10^{-7}$	$1.28\cdot10^{-7}$
^{137}Cs	$F8_{mcnp}$	$3.57\cdot10^{-6}$	$1.21\cdot10^{-6}$	$2.75\cdot10^{-7}$
	$F1_{mcnp}$	$3.84\cdot10^{-6}$	$1.29\cdot10^{-6}$	$2.93\cdot10^{-7}$

All values in the code MCNP6.2 are normalized to one released source particle. Accordingly, the number of registered pulses by the counter is described by the following equations [17]:

$$CPS^{F1}_{mcnp} = F1_{mcnp} \cdot A \cdot q, \quad (2)$$

$$CPS^{F8}_{mcnp} = F8_{mcnp} \cdot A \cdot q, \quad (3)$$

where q is the number of particles per isotope disintegration (for ^{137}Cs is equal to 0.851, and for ^{60}Co – 2); A is activity of the radiation source, Bq, CPS^{F1}_{mcnp} is the number of pulses created in the counter by the first method, cps; CPS^{F8}_{mcnp} – the number of pulses created in the counter by the second method, cps.

Photon tracks that contribute to the F1 and photon collisions in the computational model were shown in Fig. 2.

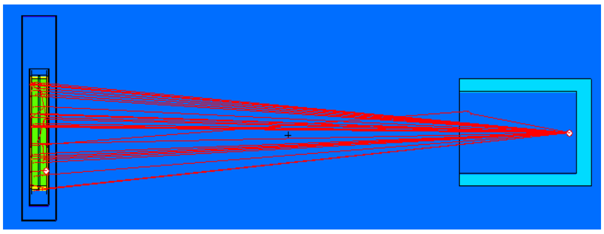

Fig. 2. Photon tracks from the source of ^{137}Cs in the model of the BDMG-04-02 with the experimental facility

The Geiger-Muller counter responses are determined by using the (1) and (2) equations. As a result, the summary Table 3 contains: calculated Geiger-Muller counter responses; detector responses of the ith BDMG-04-02 from the experiments (CPS^{Exp}_i); relative deviation of the calculated results to the experimental responses for the first detection unit (ε, %).

Table 3

Experimental and calculated values (F1 and F8) of the BDMG-04-02 response in the calibration facility

Source	^{60}Co			^{137}Cs		
L	700	1200	2500	700	1200	2500
CPS^{Exp}_1	6329	2115	482	6218	2063	459
CPS^{Exp}_2	6348	2082	471	6286	2099	474
CPS^{Exp}_3	6289	2050	470	6227	2043	455
CPS^{F1}_{mcnp}	6689	2251	510	6415	2161	494
ε, %	5.9	6.0	5.5	6.1	7.0	9.1
CPS^{F8}_{mcnp}	6227	2109	480	6672	2246	517
ε, %	-1.5	-0.8	-0.8	2.1	3.0	4.2

Due to the physical differences in the implemented approaches in MCNP6.2 for determination the F1 and F8, it is obvious that the results of F8 should be less than F1. The obtained results from Table 3 confirm that the significant overestimation of results was observed in the case of using the F1 tally relatively to the F8 for the determination of the counter responses from emitted photons of ^{60}Co and ^{137}Cs.

It is physically possible that the initial gamma-ray, with a certain probability, leads to the creation of more than one secondary electron after the chain of interactions. The formed electrons could reach the sensitive region of the gas. For instance, one photoelectron and one Auger electron or several recoil electrons could penetrate into the sensitive volume per one decay of the radioactive isotope [10]. In reality, the Geiger-Muller counter registers all electrons from one history as a single pulse. However, the results of the F1 indicates the greater number of pulses. Accordingly, for correct determination of the Geiger-Muller counter response it is appropriately to use the second method.

Comparative analysis of the calculated BDMG-04-02 (F8) responses has a good agreement regarding the experimental data and characterized with sufficient accuracy (ε<4.3%). Differences between the calculated Geiger-Muller counter responses and experimental data arise from the following reasons:

- statistical errors of the calculations in the code MCNP6.2 were less than 5%;

- increasing the size of the experimental facilities leads to higher deviation between the obtained experimental data and calculation results. This effect originates from the stochastic nature of radioactive decay;

- absence of structural components of the UPGD-2 facility in the simulation models. Detailed modeling of additional experimental elements allows to take into account the scattering effects. The secondary particles from scattering event could also reach the fill gas of the Geiger-Muller counter. Contrariwise, excessive specification significantly affects the calculation time that could be unreasonable;

- errors from determination of the exposure dose rate, that are listed in the passports of the radiation sources (± 10%).

In order to determine the intrinsic (ε_i), geometric (ε_g) and absolute (ε_{abs}) registration efficiency, the base models of the Geiger-Muller counter of the BDMG-04-02 and the collimator were modified. The point source of radiation was located inside the collimator at a distance of 700 mm from the counter. The sum of all photons that enter the sensitive region of the counter through the inner wall of the cathode, the outer wall of the anode and the inner side surfaces were determined using the F1 tally. Then, the ratio F8/F1 represents the ε_i of the counter. The internal, geometric and absolute registration efficiencies of the Geiger-Muller counter depend on the source energy in the model. To investigate this the photon energies were changed in range from 60 to 7500 keV. The obtained results are presented in Table 4.

Table 4

Absolute, intrinsic, geometric registration efficiency of the Geiger-Muller counter

Efficiency	Photon energy, MeV											
	0.06	0.10	0.20	0.30	0.40	0.50	0.66	1.00	1.25	3.0	6.13	7.5
ε_{abs}, 10^{-6}	0.2	0.25	0.37	0.52	0.77	1.06	1.60	2.79	3.66	9.01	18.19	21.76
ε_g, 10^{-4}	0.76	1.91	4.02	4.67	4.92	5.06	5.2	5.35	5.42	6.04	6.78	7.06
ε_i, 10^{-3}	2.70	1.31	0.93	1.12	1.56	2.10	3.08	5.22	6.75	14.9	26.8	30.8

The obtained results in Table 4 indicate that the highest photon energy corresponds the greater value of the ε_i of the BDMG-04-02. For the photon energy range provided by the manufacturer (up to 1.3 MeV) ε_i is less than 0.7%.

The reason for the low efficiency of the Geiger-Mueller counter BDMG-04-02 is utilization of the rarefied gas (in the range from 1 to 0.1 atm) that also used for energy absorption. Moreover, most of the primary γ-rays passes through the tube without any interactions due to the thin detector walls. On the other hand, the operation of the counter with the low density of the gas inside the tube makes it possible to significantly reduce the voltage applied on the electrodes [6]. Additionally, the small registration efficiency in the low energy region relative to other Geiger-Muller tubes can also be explained by the presence of the correction (flattering) filter, which is necessary to reduce the sensitivity at the low photon energies (from 30 to 250 keV).

For determination of the angular dependence of the Geiger-Muller counter response were used the previously developed model except of several modifications: collimator was absent; the distance from the source to the counter was invariant and equal to 400 mm. BDMG-04-02 responses (normalized to the counter response from ^{137}Cs photons at φ = 0) were determined using the F8 tally by changing the angle φ between the counter and the source in the range from -90 to +90°.

The obtained results were compared with the passport characteristics of the device due to the lack of experimental data regarding the angular dependence. The calculated angular dependence of the BDMG-04-02 has match with high precision with the passport characteristics when φ were changed in range from -80 to +80° (Fig. 3). The differences between the calculated and experimental results were within the statistical errors of the calculations for φ in the range from -45 to +45°. The statistical errors do not exceed 3% for all simulation models.

Significant deviations between the results are observed when placing the source on the same axis with the side surface of the counter. Such behavior could be explained by the absence in the models of the auxiliary equipment of BDMG-04-02, fasteners, maskworks as well as vectors of the electromagnetic field.

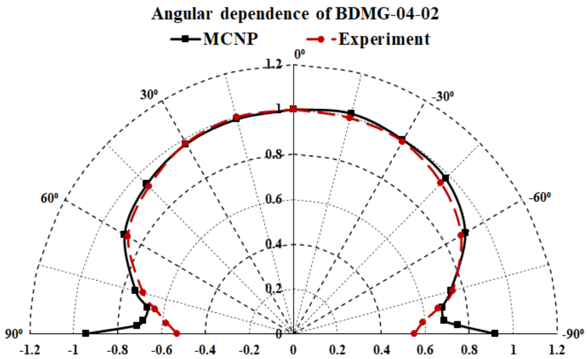

Fig. 3. Calculated angular response of BDMG-04-02 (normalized to ^{137}Cs at 0°)

The dependence of the dose sensitivity on the photon energy was recreated using experimental data, while the reference energy is 0.662 MeV. Therefore, a quantitative comparison of the calculated values of the dose sensitivity in the MCNP6.2 code and experimental data from [9] allows:

- to assess the correctness of the developed model and the reliability of the obtained results;

- predict the detector response when photons with energies above the energy range of the device reach the counter.

Firstly, ambient dose equivalent rates for different energies in range from 0.01 to 7.5 MeV were determined. It was assumed that the models do not include any structural components: the collimator, BDMG-04-02 and the encapsulated sources. The point source was located at a distance of 700 mm.

At the next step, the counter Geiger-Muller counter was placed in the registration area. Afterward, the detector responses were determined using the F1 and F8 tally. The obtained dependence of the dose sensitivity on the photon energy for BDMG-04-02 is shown in Fig. 4. Additionally, Fig. 4 includes the obtained results at the Rivne NPP.

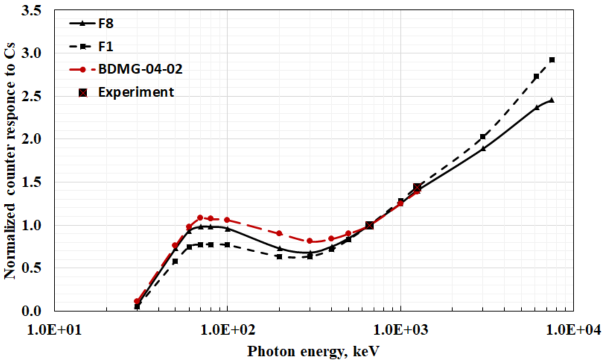

Fig. 4. Dependence of dose sensitivity on photon energy for BDMG-04-02

The calculated responses were indicated good convergence between the device specification in [9] and experimental data (at Rovno NPP) in the energy range from 0.5 to 1.25 MeV (the deviation were less than 5%). The ambient dose equivalent rate was overestimated by a factor of 2.4 for the 6.13 MeV photon energy. The calculated value is physically possible since other Geiger-Muller counters could overestimate the dose by a factor of 3 for ^{16}N photons energies [19 - 21]. The difference in obtained results in the energy range from 0.06 to 0.5 MeV could be associated with the applied coefficients to convert the photon flux to the ambient dose equivalent. Moreover, several completed experiments emphasized the presence of sufficient uncertainties regarding the experimental and theoretical determination of such coefficients [22]. At the same time, the comparative analysis in [22] indicated the deviations for the relatively low energies that could reach 14%.

It is important to note that the F8 tally results associated with better convergency with the experimental data for BDMG-04-02. Similar conclusions were obtained in [10, 23] for other types of Geiger-Muller counters.

CONCLUSIONS

The model of the detection unit BDMG-04-02 with build-in Geiger-Muller counter was developed and validated using the code MCNP6.2. ^{60}Co and ^{137}Cs radioisotopes were used as sources of ionizing radiation in the experimental facility UPGD-2.

For determination of the Geiger-Muller counter response, two different methods were utilized. During the comparative analysis of the calculated responses of BDMG-04-02 (using available in the MCNP6.2 code) with the experimental results, the following was clarified: the counter responses obtained using the F1 tally differ significantly from the experimental results; increasing the distance between the radiation source and the Geiger-Muller counter causes rapid deviations of the experimental with the calculated results obtained by the F1 tally (first method); the second method of calculating the pulse height tally (F8) is defined by a slight deviation from the measured data in the experimental facility UPGD-2 and the difference between the results do not exceed 4.3%.

As a result, for obtaining the most reliable results, it is better to use the second method of the pulses height tally. F8 more applicable for modeling counters with small sensitive volumes and under conditions with relatively high photon energies. However, it should be noted that the F8 tally compare to F1 require a significantly longer time of calculation. This comprises from the additional consideration of the electrons transport in the sensitive volume of BDMG-04-02. Therefore, the F1 tally could be used for a relatively faster assessment of the Geiger-Muller counter response.

According to the results of the analysis, the low intrinsic efficiency of the Geiger-Muller counter was emphasized, and does not exceed 0.7%. This value valid only for the energy range specified by the manufacturer of the device.

The obtained angular dependence confirms the correctness of the developed model for predicting the counter response for photons with energy 0.662 MeV, except in cases with perpendicular placement of the ionizing radiation source to the side surfaces of BDMG-04-02.

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Article received 29.06.2021

ВАЛИДАЦИЯ МОДЕЛИ СЧЕТЧИКА ГЕЙГЕРА-МЮЛЛЕРА БДМГ-04-02 С ИСПОЛЬЗОВАНИЕМ МЕТОДА МОНТЕ-КАРЛО

Ю. Фылоныч, В. Запорожан, А. Балашевский

С помощью метода Монте-Карло, реализованного в MCNP6.2, разработана модель счетчика Гейгера-Мюллера БДМГ-04-02 в калибровочной установке УПГД-2. Кратко описаны функционалы F1 и F8 программного средства MCNP6.2, используемые для определения отклика счетчика Гейгера-Мюллера. Валидация модели БДМГ-04-02 реализована путем сравнительного анализа расчетных значений откликов счетчиков с экспериментальными, полученными в калибровочной установке УПГД-2. Дополнительно были определены абсолютная, геометрическая и внутренняя эффективности регистрации БДМГ-04-02. Указаны недостатки использования метода прямого подсчета количества электронов на поверхности счетчика Гейгера-Мюллера (F1).

ВАЛІДАЦІЯ МОДЕЛІ ЛІЧИЛЬНИКА ГЕЙГЕРА-МЮЛЛЕРА БДМГ-04-02 ЗА ДОПОМОГОЮ МЕТОДУ МОНТЕ-КАРЛО

Ю. Филонич, В. Запорожан, О. Балашевський

За допомогою методу Монте-Карло, реалізованого в MCNP6.2, розроблено модель лічильника Гейгера-Мюллера БДМГ-04-02 у калібрувальній установці УПГД-2. Стисло описані функціонали F1 та F8 програмного засобу MCNP6.2, що використовуються для визначення відгуку лічильника Гейгера-Мюллера. Валідація моделі БДМГ-04-02 реалізована шляхом порівняльного аналізу розрахункових значень відгуків лічильників з експериментальними, отриманими в калібрувальній установці УПГД-2. Додатково визначено абсолютну, геометричну та внутрішню ефективності реєстрації БДМГ-04-02. Зазначено недоліки використання методу прямої лічби кількості електронів на поверхні лічильника Гейгера-Мюллера (F1).