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THE COMPTON NEUTRON HAFNIUM DETECTOR: ELECTRIC CHARGE GENERATION RATE

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The properties of a Compton neutron detector with the emitter of metallic Hf were studying in this work. Using the previously calculated the emitter material nuclide composition during reactor irradiation, the dependence of the emitter signal value on the irradiation time was obtained with a step of 1 year for 5 years. It is shown that the composition modification due to nuclear transmutations changes the rate of an electric charge generation in the emitter.

INTRODUCTION

The safety and reliability of nuclear power plants are the most important factors in modern nuclear power engineering. The desire to enlarge the efficiency of the reactor by increasing the temperature in the core, as well as by enhancing the radiation dose on materials, by default leads to the safety level decrease. In such conditions, high requirements appear for measuring and diagnostic systems, as well as for the control and protection systems. In particular, the thermal neutron fields measurement accuracy and speed become more important to maintain the needed safety level.

The energy release and density of neutron fluxes in the nuclear reactor core are controlled using detectors of various designs and operating principles. They are β-emissive (or activation) and Compton (prompt response) detectors (these two types are also called Self Powered Neutron Detectors or SPND), fission chambers, gas chambers, etc.) [1–5].

Hundreds of activation SPNDs are used in WWER reactors [6]. Their reliability has been proven over time. These SPNDs have a high sensitivity to neutrons, they also have excellent signal linearity, and their production technology is well developed. And yet, on the background of existing trends in increasing the radiation dose and operating temperature of the used in the core materials, the signal delay of the activation SPNDs and their relatively short service life [7–10] put the question: is it enough to use only inertial detectors from the point of the safety view?

Compton SPNDs, like β-emission detectors, have a quite simple and stable design under reactor core conditions, and also don't need an external electrical source. Compton SPNDs have clear advantages: an absence of inertia, a relatively low burn up rate (for the majority of the emitter materials).

The efficiency and reliability of an in-core detector are determined by its design, composition and properties of materials, sensitivity to radiation fluxes in the core, signal level, and service life.

This work is devoted to further investigation of metallic Hf as an emitter material for the Compton SPND. The unique nuclear-physical characteristics of Hf, as well as its relatively low cost, are the factors that make it as advanced material for SPND.

This article is a continuation of the work [11], in which attention was focused primarily on the study of the nuclear-physical characteristics of the detector (induced activity, change in the nuclide composition, burn-up rate, and change in absorbing capacity). In this work, using the MCNPX program, we study the processes of electric charge generation. Previously obtained results for the nuclide composition modification under reactor irradiation made it possible to estimate how the electric charge generation will change with time.

1. RESEARCH METHODS

1.1. THE DETECTOR DESCRIPTION

The subject of the study is the Compton neutron detector, which is shown on Fig. 1. The emitter of the detector is made of nuclear-pure natural composition metallic Hf (rod with radius $r_{\mathrm{Em}} = 0.075$ cm); the insulator is MgO (the layer thickness[1] is $d_{\mathrm{Ins}} = 0.0414$ cm, the density is $\rho = 2.21$ g/cm^3, the specific electrical resistance is $R_{\mathrm{spec}} = 2.7 \cdot 10^5$ Ω·m); the collector is the Inconel-600 tube with wall thickness[2] of $d_{\mathrm{Col}} = 0.02$ cm. The detector length is $L_{\mathrm{SPND}} = 25$ cm. The detector has a standard coaxial geometry for such types of devices, in which an insulator fills the space between the emitter and the collector. This detector was made as part of the study [12]. It is important to note that the insulator is formed by liquid-phase deposition, and has a relatively high density, as well as a good value of the electrical resistance (for the finished SPND under normal conditions, the resistance is at the level of $R \sim 10^{11}$ Ω).

[1] According to the sources of information, the insulator thickness should be into the range of 0.025…0.050 cm.

[2] According to the sources of information, the insulator thickness should be into the range of 0.015…0.025 cm.

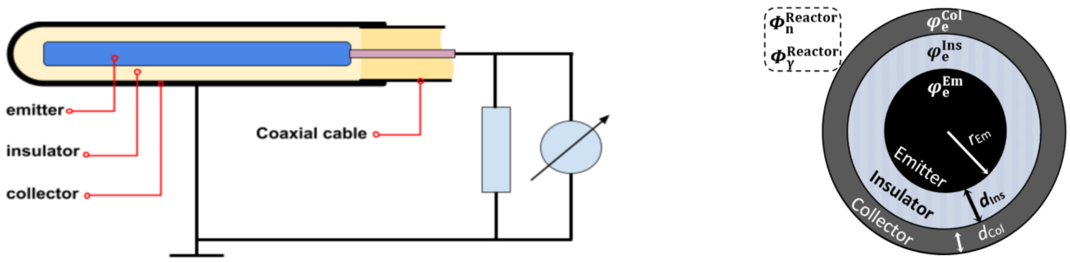

Fig. 1. Scheme of the detector (connection and cross-section view)

In the reactor core conditions, the SPND undergoes the neutron and γ-quanta irradiation with fluxes $\Phi_{\mathrm{n}}^{\mathrm{Reactor}}$ and $\Phi_{\gamma}^{\mathrm{Reactor}}$. As the result of the neutron absorption by the nuclei of emitter material and (n, γ)-reactions the γ-quanta flux $\Phi_{\gamma}^{\mathrm{Em}}$ appears. This photons together with $\Phi_{\gamma}^{\mathrm{Reactor}}$ are attenuated within the detector materials and generate the electron flux in the emitter $\varphi_{\mathrm{e}}^{\mathrm{Em}}$, the collector $\varphi_{\mathrm{e}}^{\mathrm{Col}}$, and the insulator $\varphi_{\mathrm{e}}^{\mathrm{Ins}}$. The electrons deceleration leads to the charge accumulation and then the conduction currents arise in the dielectric. All these processes determine the behavior of the device in the reactor core at last.

The collector is electrically grounded, so the main source of the potential difference in the circuit is the emitter.

Given the above, it is necessary to determine what amount of the electric charge is generated in the emitter. One needs to use only the charge distribution tally in the MCNPX program for that. Two situations should be considered:

- the effect of irradiation with neutrons n and γ-quanta from the (n, γ)-reaction in the detector is taken into account, as well as irradiation with γ-quanta formed outside the detector (the γ-quanta of reactor origin – delayed and instantaneous);
- the effect of irradiation with neutrons n and γ-quanta from the (n, γ)-reaction only in the detector itself is taken into account.

Such a separation will help to find out what part of the electric charge is generated due to the emitter, and what role plays the reactor γ-radiation in this process.

To speed up the calculation, some model simplifications were also adopted:

- only 1 detector was taken, instead of 7 standard ones, placed along the height of the reactor core;
- the real detector geometry in the lower and upper parts was ignored; instead of the detector end and the area of the connection with the contact wire, planes were used that limit the length of the SPND;
- the sheath where the detector is placed was ignored, only the wall of the neutron measurement channel is taken into account.

1.2. THE EMITTER NUCLIDE COMPOSITION

In addition to the main task of studying the process of the detector charge rate generation, it is also extremely important to find out how this property will change with time. To do this, one needs to carry out the calculation described above with compositions of materials changed under irradiation. The nuclide composition of the emitter was studied earlier in [11]. On Fig. 2 it is shown diagrams of changing the Hf composition under neutron irradiation during 5 years with a step of 1 year. The accounting of the nuclide composition is important from following points:

- the influence on the ability to absorb neutrons (macroscopic cross-section);
- the influence on the γ-quanta attenuation;
- the change of the γ-quanta number that are emitted at the neutron capture.

Macroscopic absorption cross-section for Hf

$$\Sigma_a = \sum_{\mathrm{k}} \sigma_{\mathrm{k}}^{a} \cdot N_{\mathrm{k}} \qquad (1)$$

(σ_{k}^{a} is the microscopic cross-section for neutron absorption ("*a*" is for "*absorption*"); N_{k} is the concentration of the k$^{\mathrm{th}}$ kind of atom nuclei), and the attenuation coefficient μ of γ-radiation already were considered in [11] work. When evaluating these characteristics, the change of the emitter material nuclide composition and the appearance/accumulation of transmutants were taken into account. The macroscopic cross-section Σ_a decreases noticeably over 5 years, and the attenuation coefficient μ of γ-quanta remains almost unchanged.

1.3. THE REACTOR FACTORS SEPARATION

In addition to the reactor γ-radiation, other γ-quanta also affect on the emitter:

- photons from the (n, γ)-reaction of the neutrons radiative capture by the atoms nuclei that make up the emitter (these are the nuclides of the initial Hf, and the nuclides of transmutants appearing at the neutron irradiation);
- photons that are emitted by radioactive transmutants.

Estimating the contribution of each individual "kind" of photons is the task of further research. The main purpose of this study is to find out how the generation of electric charge in the detector will be changed, and what is the contribution to this process intensity of reactor factors, and the neutron detector itself.

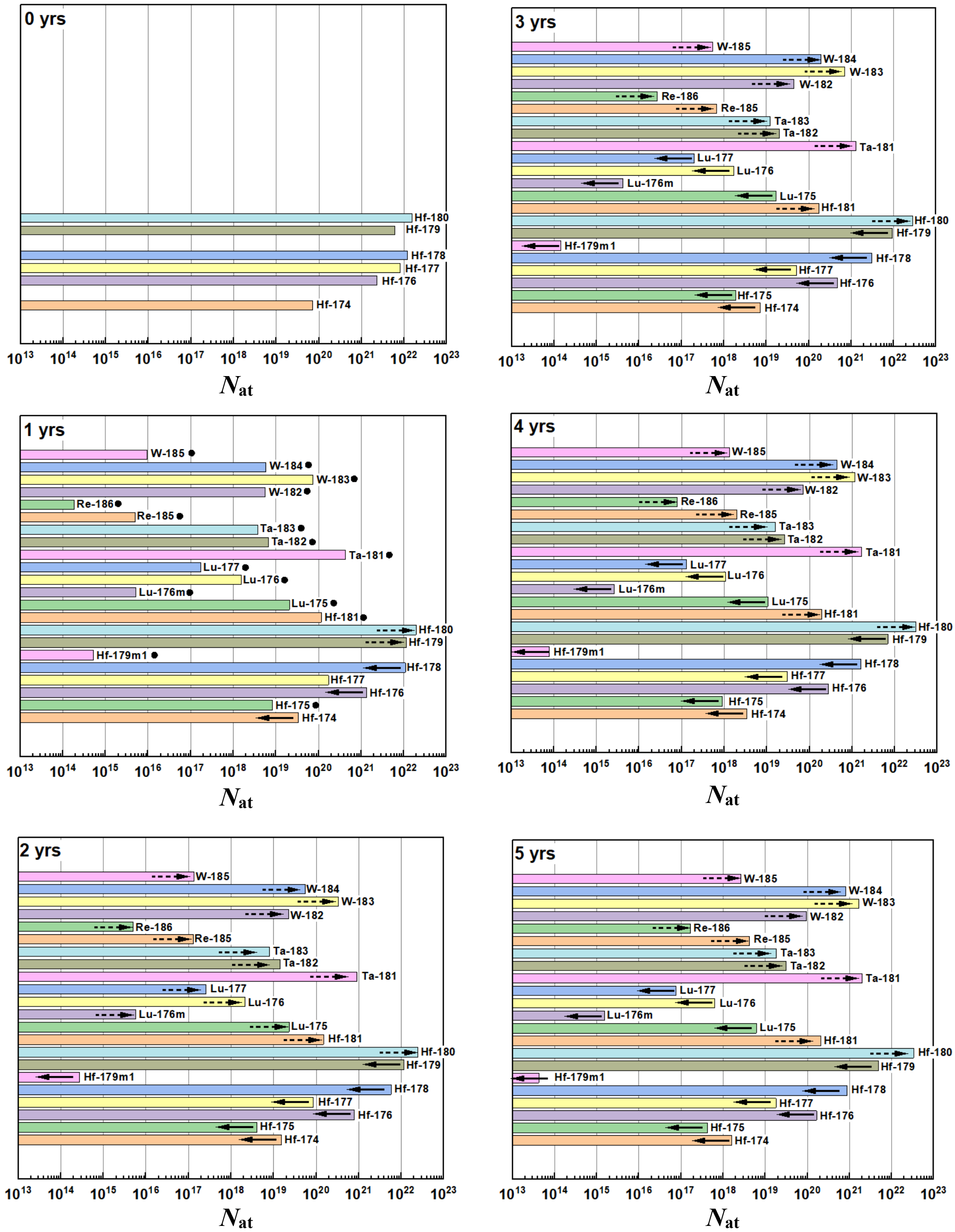

Fig. 2. Hf nuclide composition changes under the neutron irradiation
"Arrows" show trends in the atoms number increase/decrease in comparison with the values on the previous points. The "dots" mark the nuclides that didn't exist on the previous step

Thus it is necessary to estimate the γ-quanta fluxes Φ_γ and the electric charge generation rate R_Q within the emitter in the different combinations[3] Table.

The combination 1 in the table allows to estimate the total charge generation, taking into account all the selected factors. In combination 2 the reactor γ-radiation is disabled, and the generation of electric charge occurs only due to the attenuation of photons from the (n, γ)-reaction in the detector.

[3] "+" and "–" indicate if the factor was chosen or not.

The factor combinations that were used in the calculations

№	Reactor γ-quanta	Reactor neutrons	γ-Quanta from (n, γ) within the detector
1	+	+	+
2	–	+	+
3	+	–	–

The combination 3 corresponds to the conditions when photons originated outside the detector are taken into account only. At the same time, in order to exclude photons from the (n, γ)-reaction, the neutron irradiation should be eliminated. However, because of the MCNPX program features, it isn't possible to do this explicitly (without the occurrence of a "fatal error"). That is why; it was decided to make the calculation in combination of factors 1, but with another emitter material. It means here that for the calculation, a material is artificially assigned, which has a low neutron capture cross-section, and the density of the electron cloud is the same as for Hf.

Pb is well suited for the role of an "artificial" material, its absorbing properties are significantly lower than Hf, and the electron density is easy to correct. For this, one just needs to use a correction that takes into account the density of the material, as well as its *A* and *Z* (the density is used in the calculation Pb, equal $\rho_{Pb} = 13.48$ g/cm^3 instead of 11.34). The macroscopic cross-sections values for Pb and Hf are very different: $\Sigma_a^{Pb} << \Sigma_a^{Hf}$ ($\Sigma_a^{Pb} \approx 1.08 \cdot 10^{-2}\,\text{cm}^{-1}$; $\Sigma_a^{Hf} \approx 41.06\,\text{cm}^{-1}$)[4]. Thus the neutron capture cross-section for Pb is so low that the reaction (n, γ) can be neglected and the number of photons produced in this process can be considered negligible too. In this case, the reactor γ-quanta are minimally distorted by the radiation that is generated within the detector. On the other hand, the corrected electron density provides the same attenuation coefficients for the processes of the photoelectric effect, Compton scattering, and electron-positron pairing as in the case of Hf, and makes it possible to obtain the electric charge generation rate that corresponds to this metal.

2. RESULTS AND DISCUSSION

The solution of the problem was under the following conditions:

- external parameters (the number and power of n- and γ-radiation sources, as well as the temperature of the medium) are unchanged;
- only the change of the emitter material composition is taken into account, modifications of other materials compositions are ignored.

Such conditions were adopted in order to see the "pure" effect of the emitter material nuclide composition, excluding all possible external factors.

The purpose of all calculations was to determine the electric charge generation rate in the detector for given fluxes of reactor neutrons and γ-quanta.

The curves on Fig. 3 show the dependence of γ-quanta flux through the emitter on time. The red color curve corresponds to the case described above (Pb is taken as the emitter) and reflects the situation when it is considered that there are only γ-quanta of reactor origin. It is clearly seen that reactor photons have the largest fraction in the total γ-radiation that affects the detector. The portion of photons that are appeared in the detector (the blue curve) is small. It can also be seen that if we sum up the fluxes of reactor photons (Pb emitter) and those that arose in the Hf emitter itself due to the (n, γ)-reaction, we obtain values that are very close to the total flux (curves for $\Phi_\gamma^{\text{total}}$ and $\Phi_\gamma^{\text{Hf}} + \Phi_\gamma^{\text{Pb}}$ practically coincide). As a result, the γ-quanta total flux changes slightly, but this change is determined by the emitter material photons generation.

γ-quanta, passing through the material, are attenuated in independent processes: photoelectric effect, Compton scattering, generation of electron-positron pairs. Electrons with enough energy to leave the emitter encounter an insulator on their way to the collector. Some of the electrons are decelerated in it, creating a space charge and an electric field. The potential of the electric field during the operation of the SPND in the "short circuit" mode is located inside the insulator. If an electron, when moving through an insulator, loses its energy up to the maximum potential, then its charge returns to the emitter. When crossing the surface of the maximum, the charge enters the collector [13].

On Fig. 4 the results of the electric charge generation rate calculation are given. Each point along the abscissa corresponds to its own nuclide composition (see Fig. 2).

The figure shows that for the case when the reactor γ radiation is not taken into account, the charge rate is several times lower. This means that the total charge is formed mainly due to reactor γ-quanta. It can also be seen that the charge generation rate is constantly changing. And if to talk about the R_Q^{Hf} that arise due to the (n, γ)-reaction photons in the emitter, then it corresponds to the Φ_γ^{Hf}, that takes place in the current case. If we talk about the total electric charge generation rate R_Q^{total}, then it doesn't correspond to the sum $R_Q^{\text{Hf}} + R_Q^{\text{Pb}}$ and deviates more and more in time.

[4] In the (1) formula the cross-section were used that take into account [5, 12, 14] the resonant absorption and the neutron spectrum hardness $k_{\text{th/res}}$ for the WWER-1000 conditions. The atoms number was chosen for 1 cm^3.

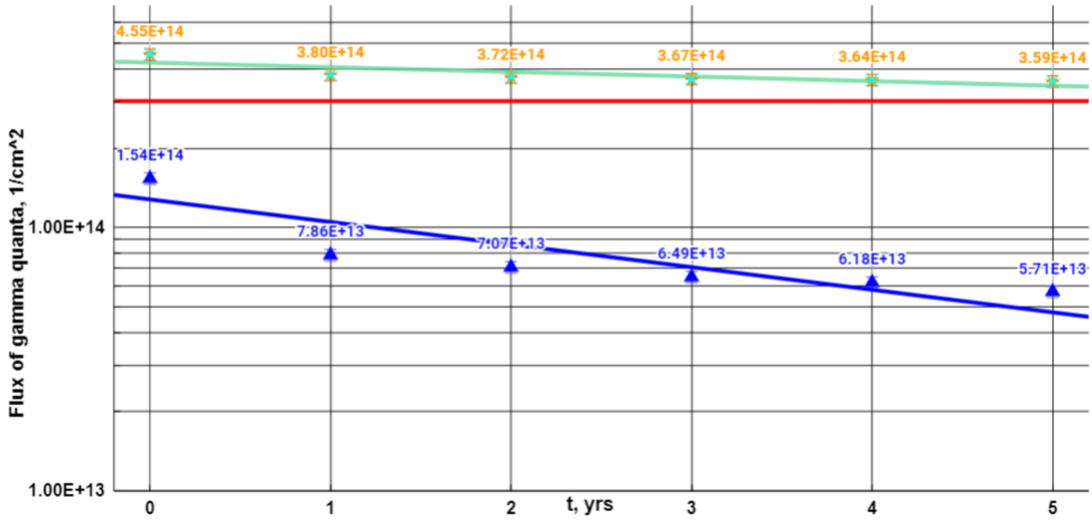

Fig. 3. The γ-quanta flux through the emitter in time

$\Phi_\gamma^{\mathrm{Hf}}$ *is the flux of γ-quanta which appear in the Hf emitter due to the (n, γ)-reaction*

$\Phi_\gamma^{\mathrm{total}}$ *is the total flux of γ-quanta which includes the photons that appear in the Hf emitter due to the (n, γ)-reaction, and photons that have the reactor origination*

$\Phi_\gamma^{\mathrm{Pb}}$ *is the flux of γ-quanta which appear in the Pb emitter due to the (n, γ)-reaction*

$\Phi_\gamma^{\mathrm{Hf}} + \Phi_\gamma^{\mathrm{Pb}}$ *is the sum of the photons that appear in the Hf emitter, and those that are formed in the case of the Pb emitter*

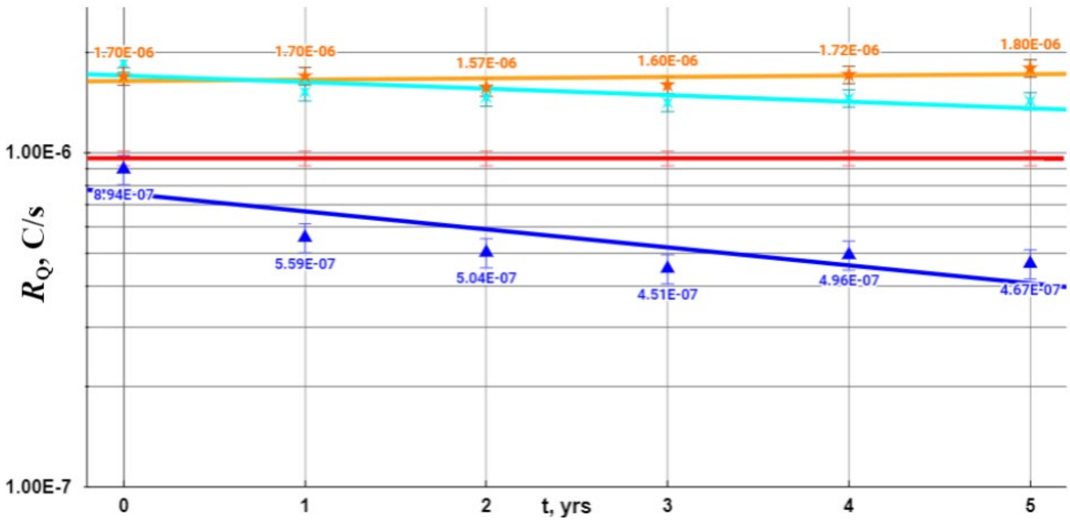

Fig. 4. The rate of the electric charge generation in time

R_Q^{Hf} *is the rate of the electric charge generation in the case when only γ-quanta from the (n, γ)-reaction within Hf emitter were accounted*

R_Q^{total} *is the rate of the electric charge generation in the case when γ-quanta from the (n, γ)-reaction within Hf emitter, and the photons that have the reactor origination were accounted*

R_Q^{Pb} *is the rate of the electric charge generation in the case of the Pb emitter*

$R_Q^{\mathrm{Hf}} + R_Q^{\mathrm{Pb}}$ *is the sum of the charge generation rate for Hf emitter without external photons influence and the rate for the Pb emitter case*

Each of the nuclides, when capturing a neutron, emits a specific number of γ-quanta with a certain energy. As a result, a constant change in the composition of the material leads to the fact that the energy spectrum of the emitted photons also changes, which, in turn, inevitably leads to changes in the attenuation coefficient μ for γ-radiation. The point is that μ is the sum of the partial attenuation coefficients for the photoelectric effect, Compton scattering, and the formation of electron-positron pairs

$$\mu = \mu_{\text{photo}} + \mu_{\text{Compton}} + \mu_{\text{el.-pos.}}, \quad (2)$$

and the cross-sections of each of the listed processes have completely different dependences on the energy of the γ-quantum and atomic number Z

$$\sigma_{\text{Compton}} \sim Z / E_\gamma, \quad (3)$$

$$\sigma_{\text{photo}} \sim Z^5 / E_\gamma^{3.5}, \quad (4)$$

$$\sigma_{\text{el.-pos.}} \sim Z^2 \cdot \ln(2E_\gamma). \quad (5)$$

Based on the nature of the cross-sections dependences, it can be concluded that the photoelectric effect prevails in the region of low energies area, Compton scattering dominates in the range of medium values, and the generation of electron–positron pairs mostly occurs at high the values of the E_γ. However, it is important to understand that the ratio of energy ranges of γ-quanta for each Z is its own. As a result, any changes in the energy spectrum of γ-quanta are equal to an imbalance between the individual processes of their attenuation, as well as a different number of electrons that are appeared in these processes [15–18]. In this work, estimates of how the energy spectrum of γ-quanta changes and how this affects the ratio among μ_{photo}, μ_{Compton} и $\mu_{\text{el.–pos.}}$, were not carried out. It's enough bulky task and it deserves a separate study, which will be carried out at the next stage of the research. It also remains to be investigated what is the role of prompt and delayed reactor photons in changing the R_Q of the detector.

3. CONCLUSIONS

The nuclide composition modification of the Hf emitter influence on the ability to generate an electric charge was studied. This was implemented using the MCNPX program in 1-year increments over 5 years, and the problem setting was such that the only factor that changed over time was only the emitter material nuclide composition. The fluxes of n and γ which have the reactor origination remained constant in order to evaluate the role of the emitter.

The results of the calculations show the following:

- reactor photons have the largest fraction in the total γ-radiation that affects the detector;
- the portion of photons that are appeared in the detector is small, but it is this fraction that determines the change in the total flux of γ-quanta;
- the electric charge generation rate is mainly determined by photons of reactor origin.

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КОМПТОНІВСКИЙ НЕЙТРОННИЙ ДЕТЕКТОР ІЗ ГАФНІЮ: ШВИДКІСТЬ ГЕНЕРАЦІЇ ЕЛЕКТРИЧНОГО ЗАРЯДУ

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Досліджувалися властивості комптонівського нейтронного детектора з емітером із металічного Hf. Використовуючи розрахований раніше нуклідний склад матеріалу емітера в умовах реакторного опромінення, отримано залежність значення сигналу емітера від часу опромінення з кроком 1 рік протягом 5 років. Показано, що модифікація складу внаслідок ядерних трансмутацій змінює швидкість генерації електричного заряду в емітері.

КОМПТОНОВСКИЙ НЕЙТРОННЫЙ ДЕТЕКТОР ИЗ ГАФНИЯ: СКОРОСТЬ ГЕНЕРАЦИИ ЭЛЕКТРИЧЕСКОГО ЗАРЯДА

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Изучались свойства комптоновского детектора нейтронов с эмиттером из металлического Hf. Используя ранее рассчитанный нуклидный состав материала эмиттера при облучении реактора, была получена зависимость величины сигнала эмиттера от времени облучения с шагом 1 год в течение 5 лет. Показано, что модификация состава за счет ядерных трансмутаций изменяет скорость генерации электрического заряда в эмиттере.