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ESTIMATION OF ACCURACY AT DETERMINATION OF ELECTRON ENERGY BASED ON TWO PARAMETRIC MODEL OF ELECTRON BEAM

Accuracy of computational method for determining the energy of electron radiation, which was developed on the basis of two parametric electron beam models, is estimated for case when the electron source in the radiation-technological process has an energy spread. Accuracy is estimated with numerical methods using the electron spectra measured in different operating modes of the radiation-technological line.

Key words: parametric model of electron beam, electron spectrum, depth distribution of dose.

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ОЦІНКА ТОЧНОСТІ ВИЗНАЧЕННЯ ЕНЕРГІЇ ЕЛЕКТРОННОГО ВИПРОМІНЮВАННЯ НА ОСНОВІ ДВОПАРАМЕТРИЧНОЇ МОДЕЛІ ЕЛЕКТРОННОГО ПУЧКА

Оцінюється похибка обчислювального методу визначення енергії електронного випромінювання, який був розроблений на основі двопараметричної моделі електронного пучка, для випадку, коли джерело електронів в радіаційно-технологічному процесі має енергетичний розкид. Похибка оцінюється чисельними методами із використанням спектрів електронів, виміряних в різних режимах роботи радіаційно-технологічної лінії.

Ключові слова: параметрична модель електронного пучка, спектр електронів, глибинний розподіл дози.

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ОЦЕНКА ТОЧНОСТИ ОПРЕДЕЛЕНИЯ ЭНЕРГИИ ЭЛЕКТРОННОГО ИЗЛУЧЕНИЯ НА ОСНОВЕ ДВУХПАРАМЕТРИЧЕСКОЙ МОДЕЛИ ЭЛЕКТРОННОГО ПУЧКА

Оценивается погрешность вычислительного метода определения энергии электронного излучения, который был разработан на основе двухпараметрической модели электронного пучка, для случая, когда источник электронов в радиационно-технологическом процессе имеет энергетический разброс. Погрешность оценивается численными методами с использованием спектров электронов, измеренных в различных режимах работы радиационно-технологической линии.

Ключевые слова: параметрическая модель электронного пучка, спектр электронов, глубинное распределение дозы.

The problem formulation

At present, a large volume of products undergoes radiation treatment using electron beams [1]. At planning stage, the choice of optimal regime of the radiation-technological process can be performed on basis of computer modeling of the dose distribution of electron radiation in the objects undergoing processing [2,3]. At the stage of realization of the chosen mode of technological process, dosimetry methods of ionizing radiation are needed, which allow to determine with high accuracy the energy of electron radiation source in the process of radiation treatment. Certainly, today, there are methods and equipment capable of determining the characteristics of electron radiation with high accuracy. However, these methods are designed to solve scientific research problems and, as a rule, cannot be used to control the processes of irradiation in radiation technologies. Therefore, development of methods that allow with high accuracy to determine the electron beam energy of source is an actual task for realization of radiation technologies.

Analysis of recent investigations and publications

Influence of the energy spread of electron beam on the depth dose distribution was studied in [4]. To describe the energy spread of electrons, it was used the model of electron spectra in form of a triangular probability distribution. The depth distribution of the dose of electron radiation in an aluminum target was simulated by the Monte Carlo method in a detailed physical model using RT-Office software [5]. Obtained results of computer simulation were processed with standard computational methods of dosimetry electron radiation, which are used in processing the results of measurements of depth dose distributions performed by the dosimetric wedge or stack method [6]. The results of numerical studies show that the practical range of electrons R_p depends strongly on the energy spread of electrons and weakly correlates with the value of the most probable electron energy E_p for asymmetric electron spectra. Relatively the depths of half dose reduction R_{50}, it was shown that a correlation is observed between this value and the average electron energy in the beam E_{Av}, even for large values of the electron energy spread.

Thus, when the source of electrons has an energy spread, for dosimetry of electron radiation, along with the traditionally used value of the practical range of electrons R_p, the depth of half-reduction of the dose is important R_{50}. In this connection, the method of dosimetry of electron radiation based on two parametric electron beam models [7] is of interest, using which one can simultaneously determine R_p and R_{50} - standard characteristics of depth distributions of the electron radiation dose. It should be note that the main assumption that ensures agreement of the results obtained using this method with the results obtained on the basis of standard procedures for processing measurements, is the possibility of approximating the measurements results in a semi-empirical model of the depth distribution of the dose of monoenergetic electron radiation.

Since electron sources in radiation-technological processes can differ substantially from monoenergetic ones, it is necessary to estimates accuracy in determining the standard characteristics of the electron-beam energy obtained with method proposed in [7] for the cases when the electron sources have the energy spread.

Formulation of research objective

Accuracy of the computational method for determining the energy of electron radiation based on two parametric electron beam models, which was previously proposed and tested on the results of measurements, was studied. Accuracy was estimated by numerical methods using a set of electron spectra measured in various operating modes of the radiation-technological line of the Sterilization Center of the Institute of Nuclear Chemistry and Technology in Warsaw.

The errors in the method for determining of electron radiation energy in the presence of an electrons energy spread

The depth distribution of the electron radiation dose in case of a non-monoenergetic electron beam can be represented in the form

$$D_M(x) = \Phi_e \int_{E\min}^{E\max} D_M(x,E)\cdot S(E)dE \qquad (1)$$

Here $D_M(x)$ - depth-dose distribution of electrons radiation in the material M, $D_M(x,E)$ - depth-dose distribution in the material at irradiation with mono-energetic electron beam with fluency $\Phi_e = 1$ and energy electrons E, $S(E)$ - electron beam spectrum, Φ_e - electron fluency.

The main assumption of the two parametric model of the electron beam is fact that the results of measurements of the depth dose distributions of electron radiation can be well approximated by a function $D_M^*(x, X_0, E_0)$ that depends only on the distance x to the target boundary and contains three free parameters (Φ_0, X_0, E_0)

$$D_M^*(x, X_0, E_0) \equiv \Phi_0 \cdot D_M(x + X_0, E_0) \qquad (2)$$

Φ_0 - scale factor, X_0 - displacement and E_0 - effective energy of electrons.

At that the approximating function is superimposed on the condition, that provide the law of conservation of energy Q_{tot} transferred by the electron radiation to the target material in the depth interval from X_{min} to X_{max}.

$$Q_{tot} = \int_{X\min}^{X\max} D_M^*(x, X_0, E_0)dx \qquad (3)$$

The energy Q_{tot} transferred to the target material by electron radiation is determined on the basis of the dose distribution measured in the target in the depth interval from X_{min} to $X_{max.}$

$$Q_{tot} = \int_{X\,\min}^{X\,\max} D_M(x)dx$$

Condition (3) allows us to determine two independent parameters (X_0, E_0) of the approximating function by the method of least squares. In this case, the scale factor can be determined from equation

$$Q_{tot} = \Phi_0 \int_{X\,\min}^{X\,\max} D_M(x + X_0, E_0)dx \qquad (4)$$

Thus, the use of condition (3) makes it possible to realize a conservative computational method [8] for determining the values of three free parameters of function (2) on the basis of two parametric electron beam models. Software that implements the procedures for determining the parameters of the electron beam model from the measurement results is described in [9].

To estimate accuracy of the method for calculating the characteristics of the radiation energy, in the presence of an energy spread of electrons, the electron spectrum $S(E)$ of the radiation source was used. Based on the electron spectrum, the depth dose distributions of electron radiation in an aluminum target are simulated by the Monte Carlo method [5]. The results of computer modeling assume as the results of measurements of deep dose distributions performed by the method of dosimetric wedge or stack, and processed with standard methods of dosimetry of electron radiation [6]. Accuracy of values were obtained as values of the deviations of the results of calculating the practical ranges of electrons R_p and the depths of the half-reduction of the dose R_{50}, calculated using standard methods [6] and a method based on two parametric electron beam models [7].

Spectra of electrons from a radiation source

To estimate accuracy of the method for calculating the characteristics of radiation energy, we used the electron beam spectra from the linear electron accelerator Elektronika 10/10 with electron beam energy of 10 MeV at Institute of Nuclear Chemistry and Technology, Warsaw, Poland. The spectra of electrons are shown in Fig.1.

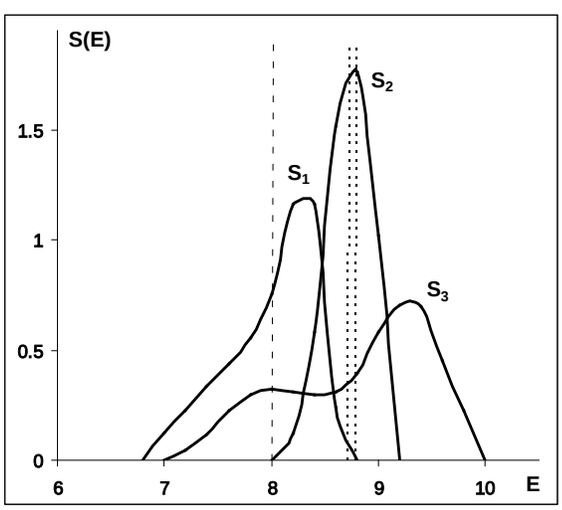

Fig. 1. Spectra of electrons $S(E)$ for different accelerator parameters (S_1 – magnetron RF source average current: 600 mA; pulse current of electron gun: 400 mA, and respectively: S_2 – 700 mA; 500 mA, S_3 – 550 mA; 300 mA)

Characteristics of spectra: E_p - is the maximum possible electron energy, E_{Av} - average electron energy, D - dispersion of the energy distribution of electrons, σ - root-mean-square deviation of electron energy (energy spread of electrons) calculated from the data presented in Figure 1 are shown in Table 1. In the figure, vertical dashed curves indicate values for each of the spectra.

As can be seen from the Fig. 1 - the spectra of electron beam 1 and 3 are asymmetric; the spectrum 2 is close to the symmetric one. The indicator of asymmetry can be the relative deviation of the average electron energy from the maximum probable electron energy. $K_{As} = (E_p - E_{Av})/E_{Av}$.

Table 1

Characteristics of spectra from the source of electrons radiation

Spectrum	E_p, [MeV]	E_{Av}, [MeV]	D, [MeV^2]	σ, [MeV]	σ / E_{Av}, [%]	K_{As}, [%]
S_3	8.30	8.01	0.17	0.41	5.14	3.62
S_2	8.80	8.72	0.05	0.23	2.59	0.92
S_1	9.30	8.79	0.46	0.68	7.75	5.78

As follows from the Table 1, the value of asymmetry index K_{As} for the spectrum of $\boldsymbol{S_2}$,is much smaller than the values for the spectra $\boldsymbol{S_1}$ and $\boldsymbol{S_3}$

The depth-dose distribution of electron radiation in an aluminum target

The depth-dose distribution of electron radiation in an aluminum target was simulated by the Monte Carlo method in a detailed physical model using RT-Office software [5]. Figure 2 shows the results of calculations for sources with different electron spectra.

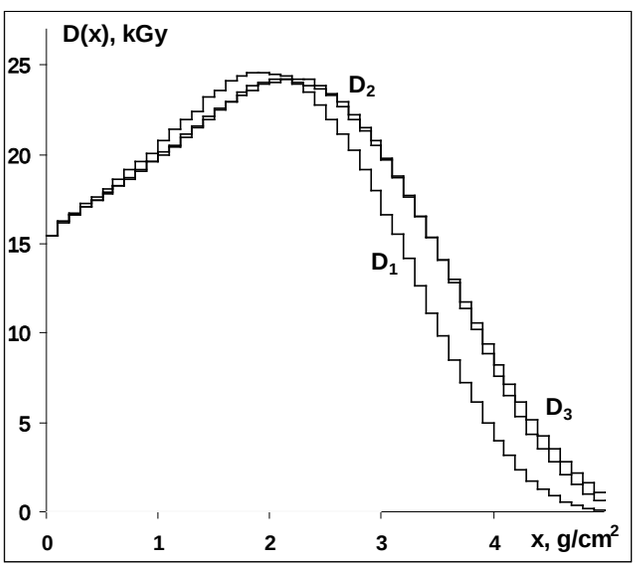

Fig. 2. Depth-dose distributions of the electron radiation in an aluminum target. Histogram D_1 - calculation of the dose for the source of electrons with the spectrum S_1, D_2 - spectrum of the source S_2, and D_3 - spectrum of the source S_3.

Note, that for the spectra of $\boldsymbol{S_2}$ and $\boldsymbol{S_3}$, all characteristics given in Table 1 differ greatly except for the quantities E_{Av} . As can be seen in Fig. 2, the depth distributions of dose $\boldsymbol{D_2}$ and $\boldsymbol{D_3}$ from electron sources with these spectra differ insignificantly. Otherwise, when characteristics of the spectra differ significantly (for example, for spectra $\boldsymbol{S_2}$ and $\boldsymbol{S_3}$), the differences in depth distributions of the dose $\boldsymbol{D_2}$ and $\boldsymbol{D_3}$ can be significant (see $\boldsymbol{D_2}$ and $\boldsymbol{D_3}$ in Fig. 2). Furthermore, we note, that difference in characteristic values for the spectra of S1 and S2 and for the spectra of $\boldsymbol{S_2}$ and $\boldsymbol{S_3}$ is close (about 0.5 MeV). However, this difference in values of the characteristics does not lead to significant differences in depth distributions of the dose $\boldsymbol{D_2}$ and $\boldsymbol{D_3}$ (electron sources with spectra $\boldsymbol{S_2}$ and $\boldsymbol{S_3}$). These facts confirm the conclusions of paper [4] about more important role of the spectrum characteristic E_{Av} with respect to the characteristic E_p in estimation of depth distributions of the electron radiation dose, in presence of an electron energy spread.

Processing results of computer modeling the depth-dose distributions

The results of computer simulation were processed with a method that was developed on the basis of two parametric electron beam models [7] and standard computational methods for radiation dosimetry [6]. The results of processing the depth dose distribution from sources with different electron spectra are presented in Table 2.

Table 2

Characteristics of the depth dose distributions, calculated using two parametric electron beam model (R_p, R_{50}) and standard methods (R^*_p, R^*_{50}) of electron radiation dosimetry.

Dose	E_0	X_0	R_p	R_{50}	R^*_p	R^*_{50}
D_1	8.01	-0.006	1.61	1.26	1.60	1.25
D_2	8.66	0.007	1.75	1.37	1.73	1.37
D_3	8.97	-0.091	1.78	1.39	1.77	1.38

As follows from a comparison of the practical range of electrons and the half-dose reduction depths presented in Table 2, accuracy of computational method, which was developed on the basis of two parametric electron beam models, does not exceed 1% relative to standard methods.

Results and conclusions

It is shown in the paper, that use of a computational method, developed on the basis of two parametric models of an electron beam, makes it possible to determine, with a small relative error, the energy characteristics of not monoenergetic electron radiation. The proposed computational method for dosimetry of electron radiation can be successfully applied also in the case of sufficiently large (<10%) energy spread of electrons in the beam.

An important advantage of the method is the ability, in a consistent calculation scheme, to determine simultaneously two standard characteristics of electrons depth dose distributions, such as the practical range of electrons R_p and the depth at which the dose equals half of the maximum dose R_{50}. The relative error in calculating these characteristics does not exceed 1%.

In the future, it is necessary to study the possibilities of using two parametric electron beam model for processing special data samples from a set of results of measurements of deep dose distributions made using the dosimetric wedge or stack methods. Such possibilities of computational method will make it possible to eliminate errors in the results of measurements that arise due to edge effects in construction of the dosimeter wedge and nonlinear response of dosimetric film to transferred energy of the electron radiation.

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