ANALYSIS AND OPTIMIZATION OF A MODE OF INDUSTRIAL PRODUCT PROCESSING AT AN ELECTRON ACCELERATOR

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By means of computer simulation, the factors determinating non-uniformity of the volume distribution of the absorbed dose at product processing by scanned electron beam, namely, the energy spectrum and scanning mode, product density and homogeneity of its distribution, as well as the distance between the objects moving through the irradiation zone, are studied. On the basis of the PENELOPE-2008 package, a code for calculating the dose distribution and its non-uniformity coefficient with due regard to the beam characteristics, surface density and velocity of the object, has been developed. Verification of the code was carried out by comparison of simulation results with the experimental data obtained using a reference polystyrene calorimeter RISO as well as by dose mapping in a standard phantom.

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INTRODUCTION

One of basic criteria of quality at industrial radiation processing is ensuring the minimum value of the dose non- uniformity factor

$$k_D = \frac{D_{\max}}{D_{\min}}, \qquad (1)$$

where $D_{\min}$ and $D_{\max}$ – are respectively the minimum and maximum values of the dose throughout the processed product, where $D_{\min}$ and $D_{\max}$ are specified by a production schedule.

A widespread method of optimization of a processing mode is computer simulation (see, e.g., [1]). Commonly, a regime with uniform distribution of linear density of the scanned electron beam with conservation its energy spectrum in the course of scanning is considered. Such assumption is true for accelerators with narrow spectrum. In case of the machine having wide spectrum, it is necessary to consider its alteration with the angle of the beam deflection by magnetic field of the scanner device. Under such conditions, an additional parameter of optimization can be the form of the beam scan.

An actual industrial process includes also the passing of the processed objects with specified velocity through the irradiation zone. If product is packed in the boxes (e.g., at sterilization of medical devices [2]) the dose distribution along object edges differs sufficiently from one obtained in their central part.

Earlier, for calculating dose distribution in the immovable objects, the program modules “Beam”, “Transport” and “Dose” on the basis of the transport code PENELOPE-2008 have been developed and validated [3]. The modules describe respectively the spatial radiant distribution of particles in a primary beam, their transport to an object and interaction with it, in particular, distribution of the absorbed energy in the object. Later on, a modification of that package for calculating dose distribution in the movable objects was carried out [4].

In the work, the results of application of the modified code for analysis of main factors determining the dose distribution and for optimizing, in such a way, the regimes of the industrial processing are described.

1. EFFECT OF SCAN FORM

Study of influence of the beam scanning mode on dose distribution at a wide beam spectrum was carried out for the conditions corresponding to the accelerator LU-10 of NSC KIPT [5]. The center of the scanner electromagnet is positioned at a distance of 51 cm from a foil of the accelerator output window. A PC-driven control system of the scanner provides the possibility to set any form and amplitude of the beam sweep [6].

In calculations, it was supposed, that the axis Z coincides with the accelerator axis. Axis X is directed vertically and lays in a plane of the beam scanning. The axis Y is directed horizontally and coincides with the direction of moving of the processed object.

Fig. 1 presents an actual spectrum of the beam used in the simulation. The electron energy E in the maximum of the spectrum makes 9.3 MeV. A deflection angle α of the electrons in the scanner device was described by relationship

$$\alpha\,(E) \sim E^{-1}. \qquad (2)$$

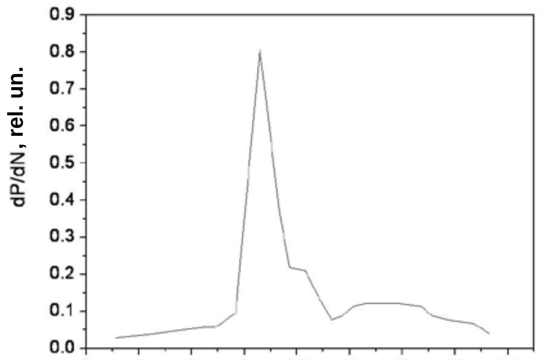


Fig.1. Spectrum of the LU-10 beam

As a standardized object, a parallelepiped from foamed polystyrene measuring 35 cm (thickness), 35 cm (height), and 70 cm (length) was considered. The object density makes 0.12 g/cm^3, that corresponds its surface density of 4.2 g/cm^2. It was considered also, that the object moves through the irradiation zone with velocity 2 cm/s at an average beam current of 800 mA.

The variants with linear mode of the sweep at both half-cycles of the beam scanning (LinLin), with linear mode in one half-cycle and cosine in the other (LinCos), as well as with the cosine-type sweep in the both half-cycles (CosCos) have been considered. In addition, the cases with direct representation of the specified spectrum of the electrons on the object (version A), and also with their distributions resulting from a law of changing the current in the scanner electromagnet with due regard to the change of the beam distribution at its deflection (version B) have been studied.

In the Table 1, the results of calculation of co-ordinates of the points in the object with minimum dose D_{min}, and also the value of the dose non-uniformity factor for each variant of the beam sweep are presented. It is seen, that in the case of double-linear sweep (LinLin) in the both versions the dose distribution preserves it appearance. In the variants LinCos and CosCos, it is essentially changed as to the co-ordinates of the area with minimum dose D_{min}, and in relation of the dose non- uniformity factor. So the variant LinCos provides essential decrease in this factor.

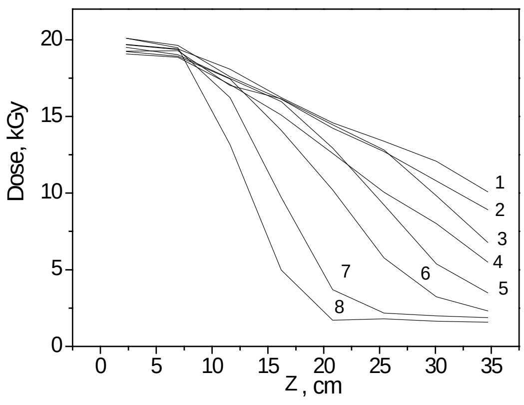
Table 1

Coordinates of the point with the minimum dose and dose non-uniformity factor in the reference object at different forms of the current in the scanner magnet

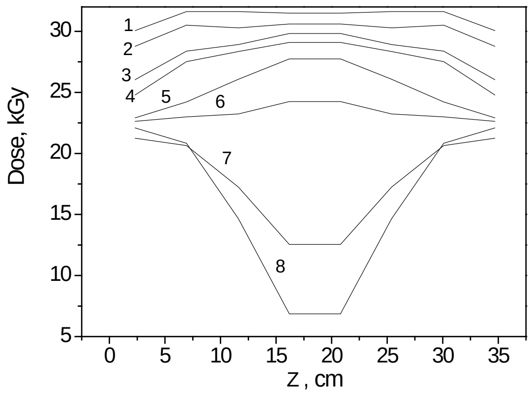
		A	B
LinLin	X_{MIN},Y_{MIN},Z_{MIN}	X= 17, Y=-33.5, Z= 0.5	X=-17, Y=-33.5, Z= 0.5
	D_{MAX}/D_{MIN}	2.88	2.87
LinCos	X_{MIN},Y_{MIN},Z_{MIN}	X= 17, Y=-34.5, Z= 15.5	X= 17, Y=-34.5, Z= 17.5
	D_{MAX}/D_{MIN}	2.51	2.23
CosCos	X_{MIN},Y_{MIN},Z_{MIN}	X=-17, Y=-34.5, Z= 13.5	X= 0.0, Y=-34.5, Z= 34.5
	D_{MAX}/D_{MIN}	2.41	2.62

2. EFFECT OF OBJECT DENSITY

Dependence of the dose distribution in a processed object from its density was analyzed for the LinCos sweep and conditions of the LU-10 Linac. This time as an object a parallelepiped from expanded polystyrene measuring 39×79×37 cm (X, Y, Z) has been considered. Those parameters are close to the characteristics of a phantom used for dose mapping at a procedure of the radiator qualification [4]. In calculations, it was supposed, that the object moves via the irradiation zone at a velocity of 1.2 cm/sec, the amplitude of the beam sweep at the accelerator output window makes 7.2 cm.



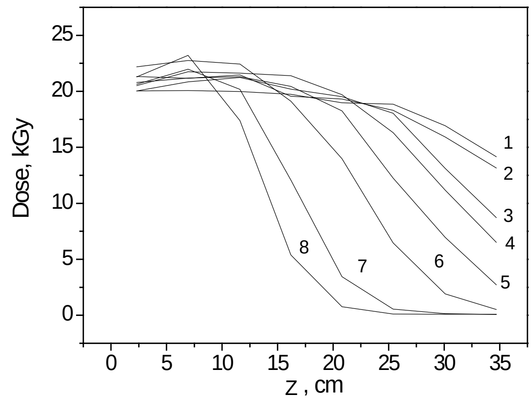
a



b

Fig. 2. Dose distribution along object's edge

In Figs. 2-4, the results of calculation of the dose distribution along the three spokes crossing the object with various surface density t (g/cm^2) in different places in parallel of the axis Z are plotted (*a* – one-sided irradiation, *b* – two-sided irradiation): 1 – t=3.33; 2 – t=3.70; 3 – t=4.44; 4 – t=4.81; 5 – t=5.55; 6 – t=6.66; 7 – t=9.25; 8 – t=11.1.



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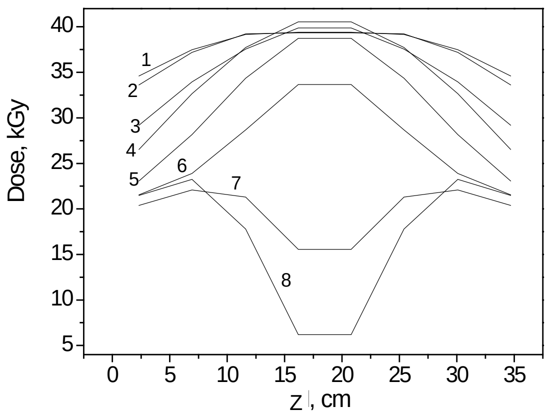

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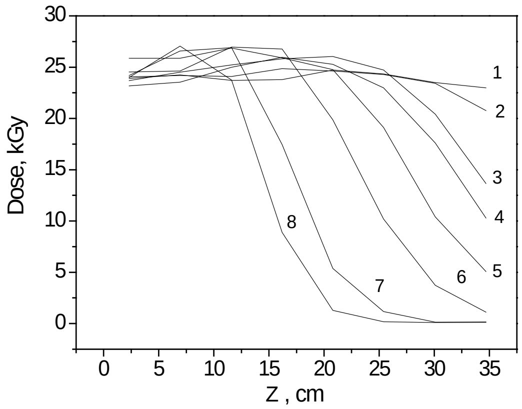
Fig. 3. Dose distribution along the central axes of the upper object's plane



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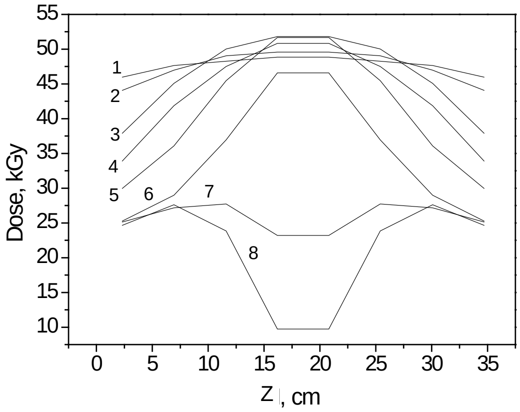

b

Fig. 4. Dose distribution along the central axis of the object

In Fig. 5, influence of distance between the objects moving through the irradiation zone on the dose non-uniformity factor is shown.

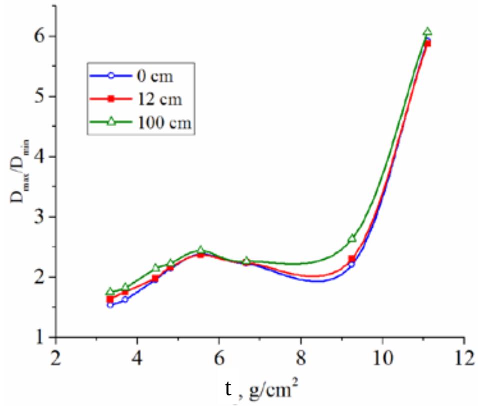

Fig. 5. Dependence of the dose non- uniformity factor from distance between objects

It is evident, that at an increase of the object density and interval between the irradiated objects the non-uniformity of the dose distribution increases.

3. EFFECT OF NON-UNIFORMITY OF THE OBJECT DENSITY DISTRIBUTION

As a rule, a processed object is not homogeneous. For example, at radiation sterilization of medical devices each unit is packed in the individual wrap. A certain quantity of the units is put up into a transport box, which is exposed to irradiation. If the transport box with volume V contains the n individual units of volume v_1 each, the estimation of the effective size of in homogeneity can be received from the expression

$$h_{ef} = \left(\frac{V}{n} - v_1\right)^{1/3}. \qquad (3)$$

In calculations, the four variants of the processed object inhomogeneity were considered:

- homogeneous object;
- object with effective size of the inhomogeneity h_{ef}=0.5 cm;
  h_{ef}=1.0 cm;
  h_{ef}=2.0 cm.

In every case the object corresponded a parallelepiped from cellulose measuring 36×108×36 cm (XxYxZ) with average surface density t=3.08 g/cm^2. Those characteristics are close to parameters of the boxes with bandaging material sterilized at the LU-10 plant. The actual distance between objects makes 12 cm (an interval between transport containers on the plant conveyor), at a velocity of their moving of 2.1 cm/s. In Fig. 6, the variants of the objects surface density distribution depending on the effective size of the inhomogeneity, and also the resulting dose distributions along the central axis of the object (Fig. 7) are shown.

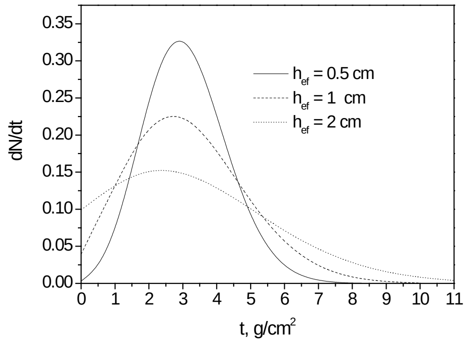

Fig. 6. Distribution of surface density of the object at different size of inhomogeneity

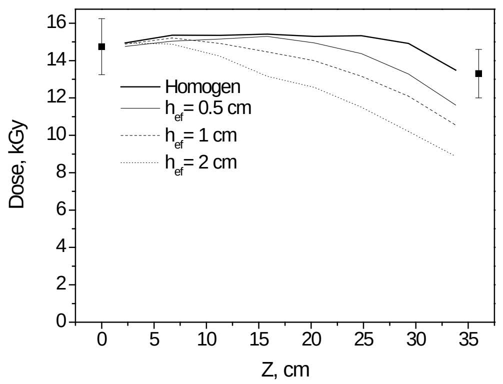

Fig. 7. Dose distribution along the central axis of the object, one-sided irradiation

4. BENCHMARKING

Experimental study was carried out with the use of a rectangular phantom from heavy expanded polystyrene (ρ =0.114 g/cm^3) measuring 39×79×37 cm (X, Y, Z). For dose mapping, the phantom contains a 3D net of the slots for placing the dosimeters (Fig. 8). The routine PMMA dosimeters (Harwell Red 4034) calibrated on-site with the use of reference polystyrene dosimeters were applied in the measurements. The phantom was two-side irradiated with the beam having the spectral maximum 9.3 MeV (see Fig. 1) at an average beam current of 0.8 mA and the LinCos sweep with frequency 3 Hz. A velocity of the phantom conveyance made 1.2 cm/s.

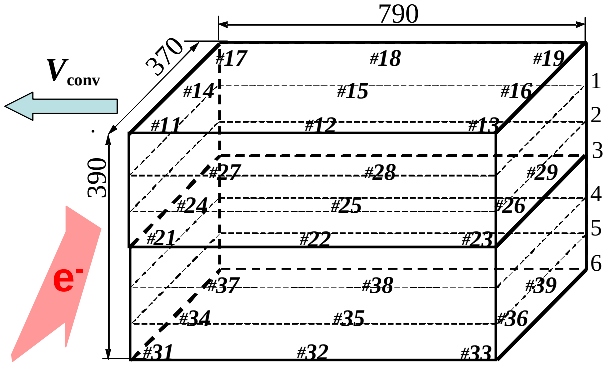

Fig. 8. 3D-phantom with slot numbering

In Fig. 9, the data of the dose mapping are given. It is obvious, that in point of definition of both the areas with D_{min} and D_{max}, and dose non-uniformity factor, the results received by the simulation and experimentally are satisfactory agreed.

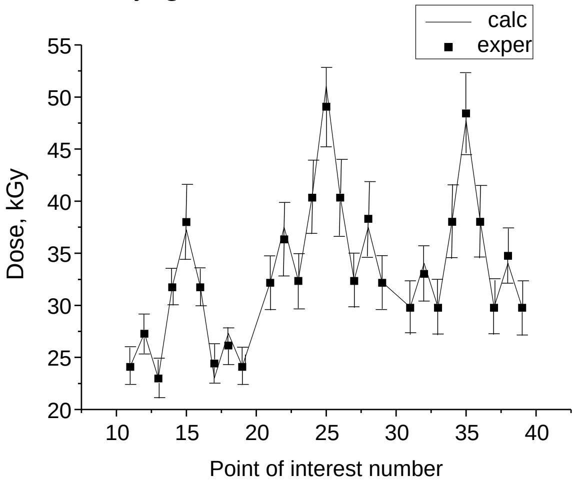

Fig. 9. Results of dose mapping

In the Table 2, the results of the dose measurement with the polystyrene calorimetric dosimeters RISO [7] at their passing with various velocity through the irradiation zone, and also calculated with the use of developed sw are listed. It can be seen, that both the data differ no more, than on 7%.

Table 2

Absorbed dose in the calorimetric dosimeters at a various velocity of the conveyor

Conveyor velocity, cm/s	Average beam current, mA	Calculated dose, kGy	Measured dose, kGy
4.88	0.816	6.9	6.5
3.65	0.808	9.1	9.2
2.43	0.801	13.5	13.4
1.82	0.804	18.1	17.9
1.22	0.809	27.2	26.5
0.92	0.804	36.1	38.8

CONCLUSIONS

Developed sw provides the possibility of analysis and optimization of a product processing mode at an electron accelerator with the scanned beam against all the key parameters determining the value of the absorbed dose and its spatial distribution within an irradiated object.

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АНАЛИЗ И ОПТИМИЗАЦИЯ РЕЖИМА ПРОМЫШЛЕННОЙ ОБРАБОТКИ ПРОДУКЦИИ НА УСКОРИТЕЛЕ ЭЛЕКТРОНОВ

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Методом моделирования исследованы факторы, определяющие неравномерность объемного распределения поглощенной дозы при обработке продукции сканирующим пучком электронов: энергетический спектр и форма развертки пучка, плотность объекта и однородность ее распределения, а также расстояние между объектами, перемещаемыми через зону облучения. На основе программной системы PENELOPE-2008 разработан код для расчета распределения дозы и коэффициента его неоднородности с учетом характеристик пучка, поверхностной плотности и скорости перемещения объекта. Выполнена верификация кода путем сравнения результатов моделирования с экспериментальными данными, полученными с помощью референтного полистирольного калориметра RISO, а также методом картографирования дозы в стандартном фантоме.

АНАЛІЗ ТА ОПТИМІЗАЦІЯ РЕЖИМУ ПРОМИСЛОВОЇ ОБРОБКИ ПРОДУКЦІЇ НА ПРИСКОРЮВАЧІ ЕЛЕКТРОНІВ

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Методом моделювання досліджені чинники, що визначають нерівномірність об'ємного розподілу поглинутої дози при обробці продукції скануючим пучком електронів: енергетичний спектр і форма розгортки пучка, щільність об'єкту та однорідність її розподілу, а також відстань між об'єктами, що переміщують через зону опромінювання. На основі програмної системи PENELOPE-2008 розроблений код для розрахунку розподілу дози і коефіцієнта його неоднорідності з урахуванням характеристик пучка, поверхневої щільності і швидкості переміщення об'єкту. Виконана верифікація коду шляхом порівняння результатів моделювання з експериментальними даними, отриманими за допомогою референтного калориметра з полістиролу RISO, а також методом картування дози в стандартному фантомі.