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Influence of boundary effects on electron beam dose distribution formation in multilayer targets

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Abstract. Computational dosimetry play a significant role in an industrial radiation processing at dose measurements in the product irradiated with electron beams (EB), X-ray and gamma ray from radionuclide sources. Accurate and validated programs for absorbed dose calculations are required for computational dosimetry. The program ModeStEB (modelling of EB processing in a three-dimensional (3D) multilayer flat targets) was designed specially for simulation and optimization of industrial radiation processing, calculation of the 3D absorbed dose distribution within multilayer packages. The package is irradiated with scanned EB on an industrial radiation facility that is based on the pulsed or continuous type of electron accelerators in the electron energy range from 0.1 to 25 MeV. Simulation of EB dose distributions in the multilayer targets was accomplished using the Monte Carlo (MC) method. Experimental verification of MC simulation prediction for EB dose distribution formation in a stack of plates interleaved with polyvinylchloride (PVC) dosimetric films (DF), within a packing box, and irradiated with a scanned 10 MeV EB on a moving conveyer is discussed.

Key words: absorbed dose • electron beam • simulation • Monte Carlo • software ModeStEB • dosimetry

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Introduction

Comparison of accurate measurements and calculations of the EB absorbed dose distributions in the heterogeneous targets with boundary conditions and with a high dose gradient is a good test for validation of software that intended for simulation of EB radiation processing. In our last investigations, the boundary anomalies of the absorbed dose distributions in heterogeneous targets irradiated with EB were used for verification of software ModeRTL, ModePEB intended for simulation of the EB absorbed dose distributions in flat targets, and ModeCEB intended for simulation of the EB absorbed dose distributions in multilayer cylindrical targets like tubes and cables [1–3]. The transport and interaction of primary and secondary electrons with target material was simulated by the MC method in a two-dimensional (2D) geometrical model. The experimental verification of the obtained theoretical predictions for absorbed dose distributions of 10 MeV electrons was performed with film dosimetry. It has been established that boundary anomalies in an absorbed dose distribution appear in radiation processing of materials and influence the quality of radiation technology applications.

In this paper, to validate the program ModeStEB intended for calculation of the EB dose distributions in 3D multilayer flat targets, a comparison between MC simulation prediction and film dosimetry for dose distributions formation in heterogeneous targets irradiated with EB was made. The target in the form of

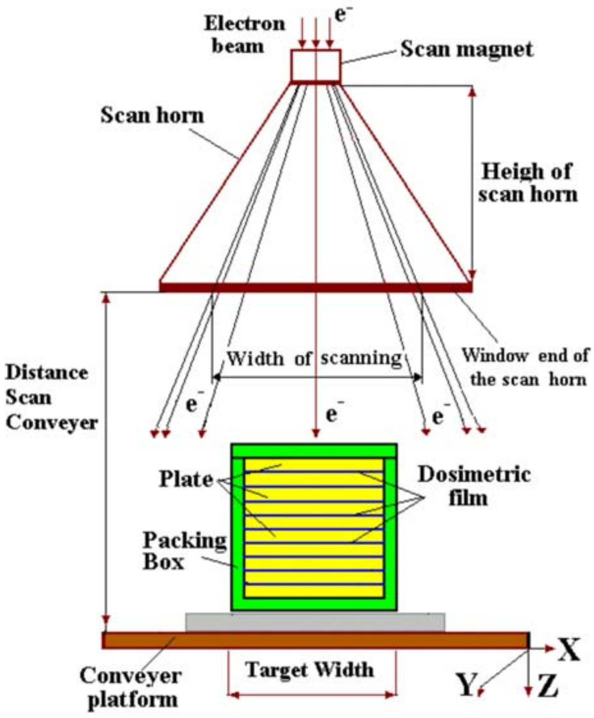


Fig. 1. EB and irradiated dosimetric stack geometry. Arrangement of a stack plates interleaved with dosimetric films on moving conveyer irradiated with triangular scanned EB. The stack with dosimetric films located in closed packing box. Axis *Z* – direction of EB incidence, axis *X* – direction of EB scanning, axis *Y* – direction of conveyer motion.

a stack comprise a set of plates interleaved with thin PVC dosimetric films. The stack with its packing box was irradiated with a scanned EB on moving conveyer. The stack plates were located on the conveyer platform normally to the incident EB direction.

Detailed investigations of boundary anomalies which appear in the stack of plates near the interface of the plates with the enclosing box and near stack sides oriented in direction of EB scanning and in direction of conveyer travel were performed.

Geometrical and simulation models of EB facility and irradiated product

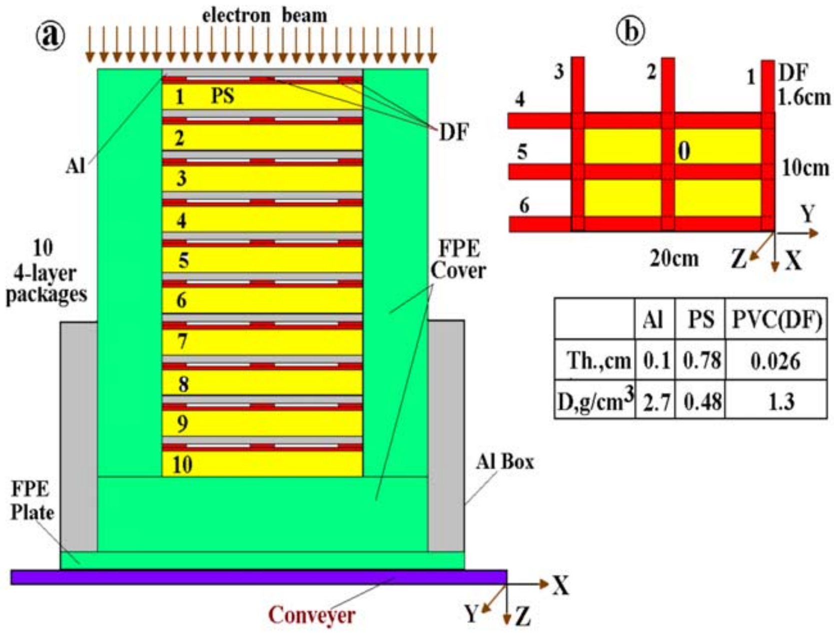
A schematic representation of the EB facility used for measurement of the electron depth-dose distributions in the stack with dosimetric films irradiated with scanned EB and on moving conveyer is shown in Fig. 1.

The dosimetric stack consists of a set of plates interleaved with dosimetric films or a stack of dosimetric films alone. The number of plates with dosimetric films in the stack is in the range 1 to 60. The stack with dosimetric films in the open or closed packing box can be located on the conveyer platform perpendicular or parallel to the incident EB axis.

Simulation of the EB dose distributions in irradiated films located in the stack was accomplished by the MC method in a 3D geometrical model using the program ModeStEB. ModeStEB was designed specifically for the simulation and optimization of industrial radiation processes, and calculates the absorbed dose within multilayer packages on moving conveyer irradiated with scanned EB in an industrial radiation facility that is based on the pulsed or continuous type of electron accelerators in the electron energy range from 0.1 to 25 MeV.

In accordance with the schematic representation of the electron beam facility and multilayer target presented in Fig. 1, a model was built for ModeStEB comprising an electron beam source including spectral characteristics, a scanner, a conveyer line and an irradiated target, all included as a uniform self-consistent geometrical and physical model.

Calculational and experimental investigations of EB dose field formation performed in the stack consisted of 10 identical packages. Each package included 4 layers. 1st layer: aluminum plate with a thickness of 0.1 cm and size 20 × 10 cm (density 2.7 g/cm^3). 2nd and 3rd layers: PVC film in the form of strips with a thickness of 0.026 cm, 1.6 cm – width, 10 and 20 cm length (density 1.3 g/cm^3), and a polystyrene plate with a thickness of 0.78 cm and size 20 × 10 cm (density 0.48 g/cm^3).



	Al	PS	PVC(DF)
Th.,cm	0.1	0.78	0.026
D,g/cm^3	2.7	0.48	1.3

Fig. 2. (a) Arrangement of a stack of plates with dosimetric films in form of strips on moving conveyer irradiated with triangular scanned EB. Surface of plates is located transversely to EB axis. The stack consists of 10 identical 4 layer packages. (b) Location of PVC dosimetric films in the 2nd and 3rd layers. 3 DF of 10 cm length are located in 2nd layer, number 1, 2, 3. 1 DF (number 1) is located on the center of 20 cm plates, and 2 DF (number 1 and 3) are located on the boundary of 20 cm plates with ethafoam box. 3 DF of 20 cm length are located in 3rd layer, number 4, 5, 6. 1 DF (number 5) is located on the center of 10 cm plates, and 2 DF (number 4 and 6) are located in the boundary of 10 cm plates with ethafoam box. The DFs, 10 cm in length are transversely placed above the DFs of 20 cm length. Center intercrossing of strips with lengths 20 cm and 10 cm is marked by point 0.

The stack was inserted in an open ethafoam box with a density of 0.1 g/cm^3 and wall thickness 5 cm from all sides of the stack. The height of stacks with dosimetric films along the EB axis (7.12 g/cm^2) was greater than the electron range with energy 10 MeV.

The setup for a multilayer target in the form of stack of plates with dosimetric films on a conveyer platform, is shown in Figs. 2a and 2b.

The stack of plates with dosimetric films was placed on a foam plate (thickness 5 cm) in the center of a standard aluminum box (580 × 460 × 200 mm) and a wall thickness of 1 mm. The aluminum box with the stack of plates with dosimetric films was placed into the central line of the conveyer platform. Two series of experiments were carried out: in the 1st series, the stack was located on a conveyer platform in such a way that the plate dimension 20 cm was oriented in direction of EB scanning (see Fig. 3, position 1). In the 2nd series irradiation the plate dimension 10 cm was oriented in the EB scan direction (see Fig. 3, position 2).

The proposed simulation models and experimental measurements with the stacks of plates using dosimetric films, allows calculation of the complete EB dose distribution in the multilayer target, and also to examine the EB dose distribution in the dosimetric films located between plates of the stack.

Theoretical predictions for EB dose distribution in stack of plates with thin films

ModeStEB was used for the investigation and analysis of EB dose distribution formation in the thin films located between the plates of the stack presented in Fig. 2 [4]. In the simulation the stack was located on moving conveyer in two positions in accordance with Fig. 3, and irradiated by scanned EB with energy 9.7 MeV. 2D and 3D dose distributions in the PVC films were simulated by MC methods for each of the films located in the 2nd and 3rd layers from 1st to 10th packages. 2D dose distributions were calculated in the center of plates and near the interface of the stack plates with the ethafoam cover. The EB dose distribution in the irradiated DF located in the stack is represented as a function of two coordinates: the scan direction (axis X), and the conveyer motion (axis Y). The calculated dose value in the PVC DF was averaged along the film thickness (axis Z). In the graphical presentation of results from the simulation of 3D dose distributions in DF, the bin size is 1/20 of the film width in the direction of EB scanning (axis X) and 1/20 of the film length in the direction of conveyer motion (axis Y).

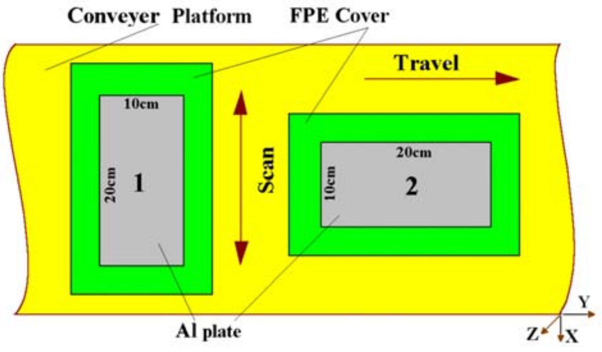


Fig. 3. Top view of two arrangements of a stack of plates with dosimetric films on moving conveyer. Position 1 – side of plates in the stack of size 20 cm is oriented in direction of EB scanning. Position 2 – side of plates in the stack of size 10 cm is oriented in direction of EB scanning.

Modeling of the electron beam transport from the exit window of the accelerator to the incident surface of the irradiated target takes into account such effects as scattering of electrons in the air gap.

The results of the MC simulation of 3D dose distributions in the PVC films with a length of 10 cm (row X = 10 cm) and 20 cm (row X = 20 cm) located in the 2nd and 3rd layers, respectively along the scan direction for the 5th, 6th, 7th, 8th and 10th packages are shown in Fig. 4.

The EB absorbed dose distributions calculated for the PVC films from 5th to 10th packages for stack positions 1 and 2 on a conveyer platform are observed in Fig. 4. Significant differences in the EB absorbed dose distribution in the PVC films for the 8th and 10th packages are observed between stack positions 1 and 2.

Simulation results for the EB absorbed dose distribution in the multilayer structure of the stack irradiated with the scanned EB with energy 9.7 MeV on a moving conveyer have shown the following features:

- Starting with 2nd package, the value of absorbed dose in the PVC dosimetric films near the interface of the package with the ethafoam packing box is reduced by about 10–40% over about a 4 cm zone inwards from the package side. $D_{\max}$ – dose maximum is located in the center of PVC DF (center stack). $D_{\min}$ – dose minimum is located near the interface of PVC DF with cover made of ethafoam. This effect is explained by the lack of electron equilibrium near the interface of stack plates with the ethafoam cover.
- Starting with 5th package, there are "shadows" in the absorbed dose distribution for PVC strips with 20 cm length, from the 10 cm PVC strips, which were placed above the 20 cm PVC strips and crossed each other in the center of plate plane (see point 0 in Fig. 2b).
- For the 9th and 10th packages, the absorbed dose in the center of the PVC DF plates approaches 0 with increasing layer number. This tendency is observed because the total thickness of the stack plates with dosimetric films in packages 9 and 10 along the EB axis is greater than EB range for energy 9.7 MeV.
- Beginning with the 8th PVC DF layer, the appearance of a local maximum for the dose distribution near the interface of DF with an ethafoam cover is observed near all package sides, both for sides located in the direction of EB scanning and those in the direction of conveyer travel. $D_{\max}$ for these layers is located near the interface of PVC DF with cover made of ethafoam. $D_{\min}$ is located in the center of PVC DF (center stack). The appearance of these local maxima can be explained by inscattering of secondary and primary electrons scattered within the ethafoam cover into the DF.
- Local maxima for the EB dose distribution near the interface of the DF with the ethafoam cover in the 9th and 10th packages are observed at depths (along axis Z) greater than the EB range in the stack materials.

- The values of local maxima for the EB dose distribution near the interface of DF with an ethafoam cover in the strips with a length of 20 cm, and in a length of 10 cm in the 8th, 9th and 10th packages are essentially dependent on their orientation on the conveyer platform – either in the direction of EB scanning or in the direction of conveyer travel. The ratios of local maxima in the EB dose distributions in the strips with a length of 20 cm are approximately 2.5, and in the strips with a length of 10 cm approximately 1.5, for the 8th, 9th and 10th packages; this is greater for strips located in direction of conveyer travel in comparison with strips located in direction of EB scanning.

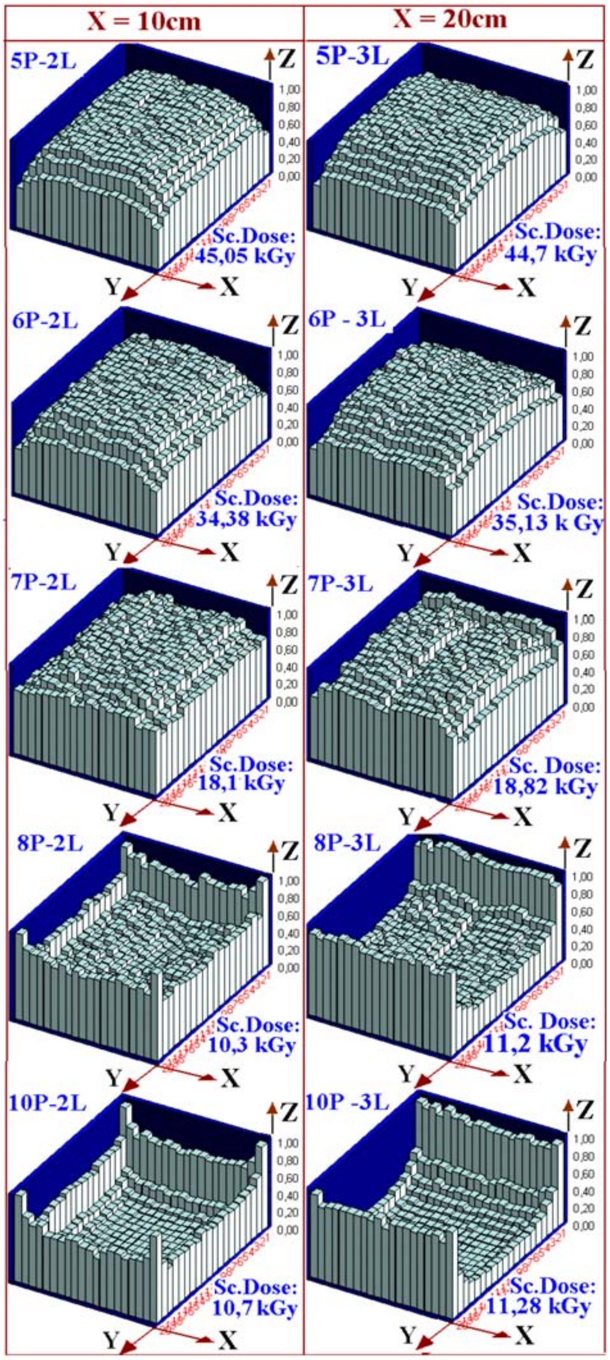


Fig. 4. Results of MC simulation of 3D dose distributions of 9.7 MeV electrons in the PVC films located between plates of the stack. Row $X = 10$ cm, PVC films of length 10 cm located between plates of the stack along scan direction for the 5th, 6th, 7th, 8th and 10th packages, respectively. Stack located on conveyer platform in accordance with position 2 in Fig. 3. Row $X = 20$ cm, PVC films of length 20 cm located between plates of the stack along scan direction for the 5th, 6th, 7th, 8th and 10th packages, respectively. Stack located on conveyer platform in accordance with position 1 in Fig. 3.

- The value of local maxima for the EB dose distribution near the interface of the DF with the ethafoam cover in the strips with a length of 20 cm in the 8th, 9th and 10th packages in direction of EB scanning is less than about half the value of the local maxima in the strips of length 10 cm for the same packages.
- The values of local maxima for the EB dose distribution near the interface of DF with the ethafoam cover in direction of conveyer travel are approximately equal for dosimetric strips with lengths 10 and 20 cm.

Experiments were performed for confirmation of the MC predictions for EB dose distributions in the thin films located between plates of the stack irradiated with scanned EB on the moving conveyer, in accordance with geometrical model presented in Fig. 2.

Comparison of MC simulation with film dosimetry

Irradiation of a multilayer target in the form of stack of plates with dosimetric films was performed on an electron linear accelerator Elektronika 10/10 at the Institute of Nuclear Chemistry and Technology (INCT), Warsaw with an EB energy of 10 MeV [6].

The stack was irradiated with a scanned EB of energy 9.7 MeV, pulse duration 5.6 μs, pulse frequency 370 Hz, average beam current 1.04 mA, scan width 58 cm, conveyer speed was in the range 1–0.1 m/min, scan frequency 5 Hz, angular spread 6 degree. The EB energy was measured with a standard Al wedge. Control of dose delivered to the target during the irradiation was performed with RISØ polystyrene calorimeters [5].

The maximum of combined uncertainty related to dose determination in the heterogeneous target with PVC dosimetric film for values of doses greater than 5 kGy did not exceed 8% ($k = 2$). The uncertainty is a combination of the uncertainties related with dosimetric film calibration, in reproducibility of a series of experiments, the dose given at electron accelerator, spectrophotometer reader variability. The uncertainty of the length value measurement of dosimetric strips is 0.1 cm.

The PVC dosimetric film calibration was traceable via the mail-order alanine reference dosimetry service operated by the National Physical Laboratory, Teddington, Middlesex, UK (www.npl.co.uk).

In the two series of experiments the stack was irradiated twice (see Fig. 3, positions 1 and 2). In the first irradiation, an absorbed dose was delivered to the PVC strips located in the 2nd and 3rd layers along the scan direction in the 1st, 2nd, 3rd, 4th, 5th, 6th and 7th packages in the range of 5–80 kGy. In the second, an absorbed dose was delivered to the PVC strips located in the 2nd and 3rd layers along the scan direction in the 7th, 8th, 9th and 10th packages in the range of 5–80 kGy. Normalization of all curves of absorbed dose distribution along scan direction from the 1st up to 10th package in each series was performed on the maximal value of the absorbed dose in the PVC dosimetric films located in the 2nd and 3rd layers of the 7th package.

A comparison of the results from the MC simulations and experimental measurements of the dose distributions of 9.7 MeV electrons in the PVC films located in the 3rd layer along scan direction for the 5th, 6th, 7th, 8th, 9th and 10th packages is shown in Fig. 5. PVC strips are located in the center of the plate along the travel direction; see position 5 in Fig. 2b. Computer modeling was chosen so that in the selected range of absorbed doses the relative root-mean-square statistical error was less than 1%.

The bin size of the 2D view of dose distributions is 1/50 of the film length (axis X). The uncertainty of the length value of all curves for dosimetric strips is 0.1 cm and the average size in each point is 0.1 cm. As is seen from Fig. 5, in the 5th, 6th and 7th packages the value of absorbed dose in the PVC dosimetric films near the interface of the package with the ethafoam packing box is reduced by about 30–40% over the distance from the interface to 4 cm inwards, in comparison with the dose recorded at the package center.

As is seen from Fig. 5, beginning with the 5th package, there are “shadows” in the absorbed dose distribution for PVC strips of 20 cm length from 10 cm PVC strips, which were placed above 20 cm PVC strips and crossed each other in the center of plate plane. For the 8th, 9th and 10th packages, the values of the EB absorbed dose in the center of the PVC DF plates approaches 0 with increasing layer number. For the 8th, 9th and 10th packages, the appearance of the local maximum for dose distribution near the interface of DF with the ethafoam cover in direction of EB scanning is observed.

A comparison of the results of the MC simulation of 3D dose distributions of 9.7 MeV electrons in the PVC films of length 20 cm located in the 3rd layer along scan direction for the 5th, 6th, 7th, 8th and 10th packages is shown in Fig. 4 (row $X = 20$ cm).

A comparison of the results of MC simulation and experimental measurements of dose distributions of 9.7 MeV electrons in the PVC films of length 10 cm located in the 2nd layer along the scan direction for the 6th, 7th, 8th, 9th and 10th packages is shown in Fig. 6. PVC strips are located in the center of the plate along the travel direction, as shown in position 2 in Fig. 2b.

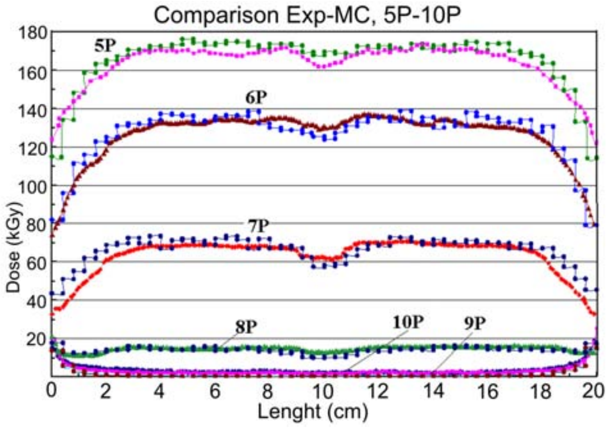


Fig. 5. Absorbed dose distribution in PVC strips of length 20 cm located in the 3rd layers along scan direction for the 5th, 6th, 7th, 8th, 9th and 10th packages, respectively. Round points – results of MC simulation.

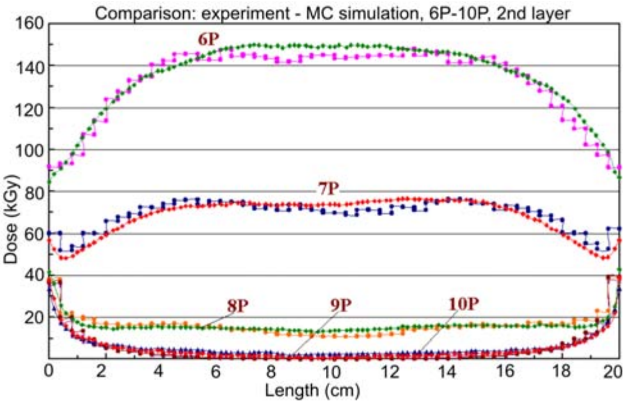


Fig. 6. Absorbed dose distribution in PVC strips of length 10 cm located in the 2nd layers along scan direction for the 6th, 7th, 8th, 9th and 10th packages, respectively. Round points – results of MC simulation.

As may be seen from Fig. 6 for the 8th, 9th and 10th packages, a local maximum for the dose distribution near the interface of DF with an ethafoam cover in direction of EB scanning is observed. The value of the local maximum for the EB dose distribution near the interface of DF with an ethafoam cover in the strips with a length of 10 cm in the 8th, 9th and 10th packages in direction of EB scanning is more than twice the value of the local maximum in the strips of length 20 cm for the same packages. For the 9th and 10th packages, the values of the EB absorbed dose in the center of the PVC DF strips approaches 0 with increasing layer number.

Experimental results have shown that the local maxima for the dose distribution near the interface of DF with an ethafoam cover, appear in the PVC DF strips of length 10 and 20 cm in the 8th, 9th and 10th packages located in the direction of conveyer travel. A difference is observed in absolute values of the local maxima in the dose distributions in PVC DF strips for different orientations on the conveyer platform.

On comparing the simulation and measurement results, it was established that:

- For strips of length 20 cm, the ratio of the value of local maximum for the EB dose distribution near the interface of DF with an ethafoam cover for the 8th, 9th and 10th packages in the direction of conveyer travel $D_{\max}$ (20 cm, Tr) to the value of local maximum for the EB dose distribution near the interface of DF with an ethafoam cover in the direction of EB scanning $D_{\max}$ (20 cm, Sc) is about $D_{\max}$ (20 cm, Tr)/$D_{\max}$ (20 cm, Sc) ≈ 2.5.
- For strips (length 10 cm), the ratio $D_{\max}$ (10 cm, Tr)/$D_{\max}$ (10 cm, Sc) ≈ 1.5.

These results have shown that changing the stack plates orientation on a conveyer platform will strongly influence the boundary effects on EB dose field formation near the interface of the stack plates with the ethafoam cover box.

Conclusion

The measured absorbed dose distributions of 9.7 MeV electrons in PVC films located between plates of stack are in agreement, concerning the shape and absolute value, with the results obtained by simulation of an EB dose distribution in the stack of plates with thin films using the MC method in 3D model with the program ModeStEB.

This agreement indicate that the developed physical and mathematical models in the program ModeStEB are reliable and correct, and the program adequately reproduces the observed dose distributions even at positions with a high gradient dose.

It was established theoretically and experimentally that a maximum for the EB dose distribution near the interface of DF with a wall of the ethafoam box is observed at a depth greater than the electrons range in the stack materials. The appearance of a maximum in the EB dose distribution can be explained by scattering of the flux of primary and secondary electrons from the ethafoam cover into DF.

The program ModeStEB can be used: as a research tool for investigating the features of the EB absorbed dose distribution formation in multilayer targets; for dose mapping studies to identify the zones with maximum and minimum doses in an irradiated product; as computational dosimetric device for determination an energy of incident electrons, an EB ranges, prediction and analysis of the EB absorbed dose characteristics related with parameters of EB radiation facility, as well as an interpretation of experimental dosimetry results. In the field of EB radiation processing to reduce dosimetric measurements the program can be used for commissioning of EB facility, EB facility qualification, process validation and routine process control.

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