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Modeling of processes of an irradiation for industrial technologies

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The conception for design of the Radiation-Technological Office (RT-Office) was developed by authors. RT-Office realize computer technologies at all basic stages of works execution on the radiation-technological lines (RTL) using irradiators of electron beam (EB), X-ray and γ-ray. RT Office is the common program shell which provides flexible intellectual interaction between specialized modules and databases for optimal planning of the process of an irradiating and control of its realization. RT-Office is accessible to a broad audience of users without a special knowledge in the field of transport of ionizing radiation and computer technologies. The descriptions of the specialized programs developed by authors ModeRTL, XR-Soft and γ-ray-Soft which are based RT-Office modules and intended for simulation of EB, X-ray, and γ-ray processing respectively are considered in the paper.

1. Introduction

At present the electron beam (EB), X-ray (bremsstrahlung) and γ-ray processing are widely used in different industrial radiation technologies, such as sterilization of medical devices, in particular, for mail sterilization; foodstuffs irradiation; advanced composites modification; cable cross-linking; bulk polymer modification; polymerization of monomers and grafting on monomer onto polymers; tire and rubber pre-cure treatment; decontamination of clinical waste; purification of water and gas wasters, and others. An implementation of radiation technologies in various fields of industry is accompanied by magnification of amount of industrial radiation facilities, expansion of assortment of products treated by an ionizing radiation, development of new methods of radiation processing [1, 2, 3]. Success of the use of ionizing radiation in different radiation technologies depends largely on development of theoretical notions, semiempirical models and computer codes for simulation of irradiation processes on the radiation-technological lines [4, 5, 6, 7].

Now there is no a set of consistent simulation methods for radiation processes which allow to fulfil correct and agreed simulation at all stages of radiation-technological process realization. It is beginning from the expertise of the original characteristics of irradiated product, the characteristics of radiation facility, a control and execution of irradiation process, and ending by accounting documentation about final products with a given range of an absorbed dose.

It is difficult to correctly fulfil a simulation of all sequence of radiation-technological stages, because the availability of many physical models, many stages and many factors should be taken into account in actual processes.

There are the powerful universal packages as ITS, EGS, GEANT, MARS, PENELOPE and others for simulation of electron and photon transport through arbitrary multielement constructions, which allow to fulfil simulation at separate stages of radiation-technological process [8,9,10,11]. These packages permit obtaining by Monte Carlo method numerical data sets to solve practical problems. The development of the programs for specific radiation-technological processes on basis these packages demands a lot of time, and calculation are carried out long enough.

These packages are just the sets of program blocks accelerating notable coding of Monte Carlo methods for simulation of transport of ionizing radiation through construction. To realize a computer experiment, that one could interpret as the physical one, the scientific elaboration of the physical experiment model is necessary, as well as model error evaluation of results of computer simulation.

With these universal programs only experienced personnel of physicists - the experts in the field of transport of an ionizing radiation through matter, mathematicians, programmers and interpreters of calculations results can work.

There are the fast analytical and semiempirical methods for simulation of radiation processes, which utilize a simplified model for radiation transport. These programs are narrowly specialized and can not give away results of calculations with necessary accuracy for a wide range of problems in the field of radiation technologies. With these programs the experienced personnel can also work only.

It is difficult to carry out scientific validation of obtained results for known calculation packages and procedures. Because the comparisons of prediction within the framework of calculation procedures for simulation results with experimental results at all stages of radiation-technological process are not enough or completely are absent. The problem related with validation and verification of obtained simulation results by the use of various physical models and software packages is one of the key moments for use in practice the simulation methods for radiation-technological processes.

The conception for design of the Radiation-Technological Office (RT-Office) - software tools for EB, X-ray and γ-ray processing was developed by authors [7, 12]. RT-Office is intended for realization of computer technologies at all basic stages of execution of works on radiation-technological lines (RTL). It is beginning from the computer expertise of the original characteristics of irradiated product and radiation facility; a choice of optimum parameters of irradiation regimes and permissible values of a level deviations for automatic control system; a control and execution of irradiation process; and ending by a preparation of a scientifically – justified report on the fulfilled work.

RT-Office is completely correspond to basic positions of the international Standard E2322-02 - "Standard Guide for Selection and Use of Mathematical Methods for Calculating Absorbed Dose in Radiation Processing Applications" [13].

The modules structure, geometrical and physical models of the electron beam (EB), X-ray, and γ-ray irradiators for the programs ModeRTL, XR-Soft, and γ-ray-Soft which were constructed on the base of developed by authors RT-Office modules are considered in the paper more closely.

2. RT-Office consideration

Developed RT-Office is the common program shell, which provides flexible and intellectual interaction between specialized modules and databases for optimum planning of process of an irradiation and control of its realization.

The wide opportunities of the RT-Office are based on the authors developments of last years [7, 12, 14, 15, 16]:

- semiempirical models for dose distribution of an ionizing radiation in spatially non-uniform objects irradiated by electron, X-ray and γ-ray;
- high effective programs for simulating by Monte Carlo method of the irradiation processes in heterogeneous objects;
- models of irradiation processes on industrial radiation facility which includes self-consistent geometrical and physical models of the main functional elements and regimes irradiation for real radiation facility;
- databases for the equipment characteristics and objects used in radiation technologies;
- computer methods of expertise and control of conditions for an irradiation realization;
- the methods validation of theoretical predictions on the basis of comparison of calculation data obtained by different independent simulation methods and/or comparison with experimental results.

The RT-Office includes the list of the following functional modules and databases developed by authors:

- **Module of Monte Carlo simulation** of dose distribution for scanning electron beam into heterogeneous targets.
- ***Module of MC simulation*** of dose distribution for electron beam into heterogeneous targets irradiated by EB in stationary regimes via scatterer.
- **Module of Monte Carlo simulation** of dose distribution for electron beam into thin dosimetric films.
- **Module for calculation** by special developed semiempirical model of 2-D dose distribution for targets irradiated by scanning electron beam on moving conveyer.
- **Module of Monte Carlo simulation** of charge deposition into heterogeneous targets irradiated by scanning electron beam on moving conveyer.
- **Module of Monte Carlo simulation** of conversion of electron energy to X-ray (bremsstrahlung) energy.
- **Module of Monte Carlo simulation** of dose distribution into heterogeneous targets irradiated by scanning X-ray beam on moving conveyer.
- **Module of Monte Carlo simulation** of dose distribution for cylindrical turntable target irradiated by scanning X-ray beam.
- **Module of Monte Carlo simulation** of γ-ray intensity from distributed source with radionuclides.
- **Module of Monte Carlo simulation** of dose distribution from distributed source with radionuclides in an environment.
- **Calorimetry Module.** Calculation of spatial distribution of radiation-induced temperature and analytical estimations of integral characteristics of a heat transmission for process of cooling of the irradiated products in a thermostable environment.

- **Comparison module.** Methods of mathematical physics for handling and comparative analysis of depth dose curves obtained by different calculation and experimental methods.
- **Dosimetry module.** Specialized tool for entering and processing of experimental dosimetry data and their transmission to the Comparison module.
- **RTL configuration module.** Entering and saving of the operational characteristics for all construction elements of RTL.
- **Wizard for control and validation** of input data for working regimes of RTL.
- **Module for cognitive visualization** of results for 2-D and 3-D view of dose distribution.
- **The processing technologies database** for equipment characteristics and objects used in radiation technologies.
- **Set of service blocks** which provides the interaction between functional modules and databases.
- **Module for the choice of geometrical model for irradiated objects.** This module will be designed in the form of a Database with different geometrical model of irradiated objects, such as tube, tubes package, box with bottles, box with syringes, box with Petry cups, and others. This module is under development.

Simulation and calculation modules of the RT-Office are the basis for construction of the specialized software for EB, X-ray and γ-ray processing [7, 12, 15, 16].

3. Description of the ModeRTL and XR-Soft Programs

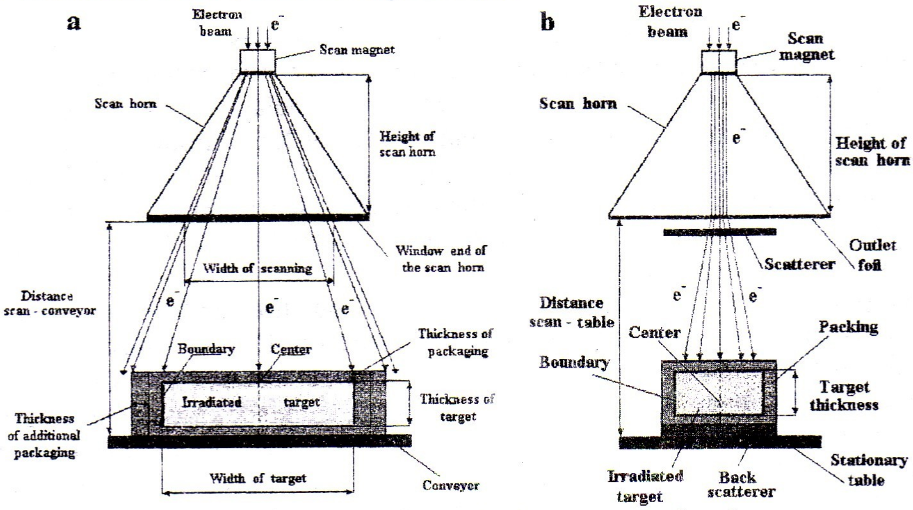
An electron accelerator, a scanner of electron beam, a conveyor line, an irradiated product and a package are the major components of the radiation-technological lines (RTL) for EB irradiator. An additional element of RTL for X-ray irradiator is an X-ray converter with cooling system. The detailed physical and geometrical models of the EB and X-ray irradiators were realized on the base of RT-Office modules in the form of new mathematical software: the program ModeRTL for EB and the program XR-Soft for X-ray processing respectively.

These programs were designed specially for simulation and optimization of industrial radiation processes, calculation of the absorbed dose, temperature and charge distribution within products irradiated by scanning electron and X-ray beams on industrial RTL that is based on the pulsed or continuous type of electron accelerators in the electron energy range from 0.1 to 25 MeV and for X-ray energy range from 0.1 to 50 MeV.

Geometrical models of the EB radiation facility that were used for simulation of EB processing by the program ModeRTL are shown in Figs.1 (a) and (b). Fig. 1 (a) represents EB irradiator which forms a dose field by a scanning EB into heterogeneous target placed on moving conveyer. EB irradiator includes an electron accelerator, a scanner of electron beam, an irradiated product with packaging, and moving conveyor. Fig. 1 (b) represents EB irradiator which forms a dose field in an irradiated target placed on the stationary table by EB via scatterer and back scatterer. The construction elements for this EB irradiator which scatter EB and affect on the dose distribution in an irradiated target are the following: a foil of outlet window of accelerator, an air gap between the foil and a target, scatterer plate placed between the foil and a target, and back scatterer plate placed on the bottom of a target. Two different functional modules of RT-Office are used for simulation of EB dose mapping in each geometrical model of EB irradiator.

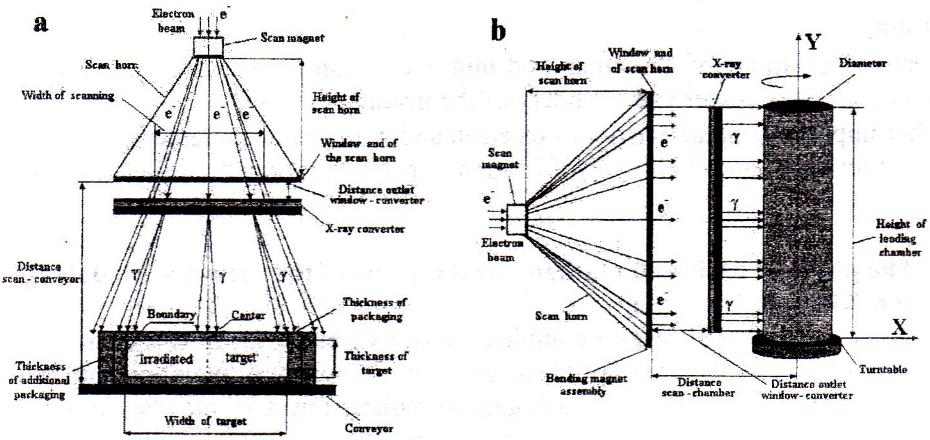
Two geometrical models for X-ray irradiators that were used for simulation of X-ray processing by the program XR-Soft are shown in Figs. 2 (a) and (b). The first X-ray irradiator includes an electron accelerator, a scanner of electron beam, an X-ray converter with cooling system, and an irradiated product with packaging on moving conveyor (Fig.2(a)). The second one includes an irradiated product placed in turntable cylindrical chamber that is rotating in front of the X-ray beam (Fig.2(b)) like Palletron installation [6].

The programs ModeRTL and XR-Soft take into account in detail a construction of the RTL and requirements to regimes of irradiation in each specific radiation-technological process. The programs ModeRTL and XR-Soft use in the unified calculation scheme of the transport of electron and gamma radiation in materials of different calculation methods, such as analytical, semiempirical and precise - method Monte Carlo (MC). Simulation of EB dose mapping in irradiated target materials was conducted by MC and Analytical methods, for X-ray dose mapping - by MC in 2-dimensional model (2-D). The 2-D dose distribution in the target is represented as function of two coordinates - of the target depth (axis X) and the target width along scan direction (axis Y). Conveyer moves along axis Z. (See Fig.6). Such conditions are realized in many cases for EB and X-ray processing when the target is irradiated at one- and double-sided on the moving conveyer.



Figs. 1 (a) and (b). Schemes of EB radiation facility for target placed on moving conveyor and irradiated by triangular scanning of EB (a) and for targets irradiated by EB in stationary regimes via scatterer (b).

The processing rate and EB and X-ray absorbed dose distribution within of the irradiated materials depend on a lot of parameters for the radiation facility of RTL and characteristics of target material.



Figs. 2 (a) and (b). Schemes of radiation facility with X-ray converter, cooling system and moving conveyor for triangular EB (a) and turntable loading chamber for non-diverging (parallel ray) EB (b).

Input data for the programs ModeRTL and XR-Soft are the following:

Parameters of electron beam: average beam current, or pulse duration and repetition frequency in pulsed accelerators, electron energy spectrum, beam diameter and spatial distribution of the beam intensity.

Parameters of scanning system: modes of operation - the triangular or non-diverging irradiation treatment field in target material; height of scan horn and width of scanning; distance scan - conveyer; form of current in magnet of scanning system; repetition frequency of scanning.

Parameters of the X-ray converter with cooling system: geometrical characteristics of the X-ray converter with cooling system, thickness of plates and cooling agent, materials composition.

Parameters of scatterer: geometrical characteristics and elemental composition of the scatterer materials.

Parameters of conveyer line: speed and geometrical characteristics.

Parameters of irradiated product: geometrical characteristics of the irradiated product; elemental composition of the target; material and size of the covering for irradiated product.

Regimes of target irradiation: one- and two-sided irradiation on moving conveyer by electron or X-Ray beams; irradiation of turning target by X-ray beams; EB irradiation of target which is stationary in the irradiated zone.

Output data. For searching optimum solutions, the programs ModeRTL and XR-Soft calculates and represent via "Module for cognitive visualization" the following parameters:

- in convenient for comparative analysis graphic and tabular forms, the spatial distributions of an absorbed dose, charge and temperature in an irradiated targets;
- maximum, minimum and average values of an absorbed dose;
- total energy transmitted to the irradiated targets;
- factor of utilization of beams power;
- electron ranges;
- the conversion efficiency from electron beam to X-ray for converter and X-ray

spectrum;

- relative deviations of maximum and minimum values from the average value for dose profiles at center and boundary of the irradiated target,
- other important characteristics of electron and X-ray beams interaction with product for economic evaluation of EB and X-ray processings.

4. The physical basis and mathematical aspects of the software ModeRTL and XR-Soft

The program ModeRTL uses a combination of two methods for calculation of dose field in an object irradiated by electrons: the formulas of analytical models and simulation of transport of electron and gamma radiation by a Monte-Carlo method.

Analytic calculation. The principles [14, 16].

It is supposed, that the process of scanning ensures a quite high uniformity of the electrons flux on all surface of the target. It is achieved in a case, when the scan frequency f, the target driving velocity V and effective beam diameter d satisfy the following condition $V << d \cdot f$ and the width of a scanning zone W_S exceeds the width of the target W_T on magnitude, more than on $2d$ i.e. $W_S > W_T + 2d$. Within the framework of this supposition, the spatial dose distribution in the target does not depend on scan frequency and beam diameter. Besides, the model does not take into account boundary and edge effects at description of the spatial dose distribution.

The semiempirical model.

In semiempirical model, the analytical relations for dependence of dose $D(x,E)$ on depth x in a semi-infinite target uniformly irradiated with the normally incident beam of monoenergetic electrons with energy E are used [17]. The computational scheme for an one-dimensional spatial dose distribution $D(x,E)$ was implemented in the program EMID [14]. The comparison of results of analytical calculations with results of simulation by the Monte Carlo method by the program ITS shows a small data discrepancy (less than 3 %) for energies of electrons E from 0.1 MeV up to 20 MeV and materials of a target with the atomic numbers Z from 4 up to 92 [14]. The generalization of one-dimensional model is carried out in the supposition of a smallness of an electron cross deviation in comparison with its path length in substance.

The analytical expressions for calculation of two-dimensional spatial dose distribution can be submitted in a form

$$D(x,y,E) = \frac{10^3 I}{W_S V} \frac{W_T \cdot K_S(y)}{(W_T + 2x \cdot tg\theta_M)} \frac{D(x/\cos\theta, E)}{\cos\theta}, \qquad (1)$$

$$\cos\theta = \sqrt{\frac{W_T^2}{W_T^2 + 4y^2 tg^2\theta_M}},$$

where I is the beam current (μA), V - the conveyor velocity (cm/sec), W_S - the width of scanning (cm), W_T - the target width (cm), θ_M - the maximum angle of incidence of the beam on the target (radian), $K_S(y)$ - the- normalized electron flux intensity on target surface $(x=0)$ in point y, defined by the mode of operations of a scanning system.

As it is supposed in the formula (1), the target is located in area $0 \leq x < \infty$ and scanning is executed along axis Y symmetrically in relation to a point $y=0$ within interval $-\frac{W_S}{2} < y < \frac{W_S}{2}$.

At the sawtooth shape of a time dependence of a current in deflecting magnets of the scanner and small angles of the beam deflection, the function $K_S(y)$ looks like:

$$K_S(y) = \frac{W_T W_S \cdot tg\theta_M}{W_T^2 + 4y^2 tg^2\theta_M}\left(arctg\left(\frac{W_S \cdot tg\theta_M}{W_T}\right)\right)^{-1}. \qquad (2)$$

The absorbed dose within the irradiated target with account the cover box thickness *h*, the energy spectrum ΔE and angular $\Delta\theta$ distributions of electrons in the beam $D(x,y,E,h,\Delta E,\Delta\theta)$ is calculated by formula [15, 16]:

$$D(x,y,E,h,\Delta E,\Delta\theta) = \frac{1}{4\Delta E\Delta\theta}\int_{E-\Delta E}^{E+\Delta E} dE' \int_{\theta-\Delta\theta}^{\theta+\Delta\theta} D(x,y',E',h)d\theta', \qquad (3)$$

where $x_h = h\rho_s/\rho$, ρ_s, ρ - density of substance of object and cover, correspondingly, the variables y, y' are related to variables θ, θ' by equation (1).

The atomic number $\boldsymbol{Z}^*$ and the atomic weight $\boldsymbol{A}^*$ to be used for compounds and mixtures are given by the following formulas:

$$Z^* = \left(\sum_{i=1}^{M}\frac{w_i Z_i^2}{A_i}\right) \Bigg/ \left(\sum_{i=1}^{M}\frac{Z_i}{A_i}\right), \qquad A^* = \left(\sum_{i=1}^{M}\frac{w_i Z_i^2}{A_i}\right) \Bigg/ \left(\sum_{i=1}^{M}\frac{Z_i}{A_i}\right)^2, \qquad (4)$$

where w_i denotes the fraction by weight of the i-th constituent element with atomic number Z_i and atomic weight A_i.

Monte Carlo simulation. The principles [15, 16].

It is supposed, that the scanning process ensures sufficient uniformity of dose distribution in the target along direction of the conveyor moving. It is valid, when the scan frequency f is sufficiently great, so $f >> \frac{V}{d}$. Here V is the conveyor velocity, d - effective diameter of the beam. In this case, dose distribution in the target can be represented as function of two coordinates (two-dimensional spatial distribution) – of depth in the target (X axis) and of displacement along direction of scanning (Y axis).

Physical model.

This is a few decades as the Monte Carlo method applies successfully to calculate spatial electron dose distributions in various objects, therefore physical models of calculation are well known today. The following elementary processes are traditionally taken into account: elastic scattering of electron on atom, inelastic collision of electron with atomic structure, generation of electron and generation of bremsstrahlung quantum. For realization of computer experiment on transition electrons through matter, a scheme of grouping of collisions is used.

A basis of this scheme of construction of branching trajectories (i.e. with accounting of secondary particles) is the separation of electron interactions on two classes: "close" and "far" collisions. Last are defined as collisions with small energy transmissions and small deflection angles of electrons. They are grouped, i.e. are described in the approximation of multiple scattering. The collisions with considerable energy transmissions or with considerable deflection angles are featured as separate events (the "close" collisions) [18, 19].

Free parameters of the accepted scheme to be determining separation of collisions are the critical energy E_C and the critical scattering angle θ_C,. The limiting case $E_C \to 0$ and $\theta_C \to 0$ corresponds to a scheme of individual collisions. This scheme allows obtaining results with small model error, but requires huge expenditures of machine time for obtaining of an acceptable statistical error. Other limiting case $E_C \to E$ and $\theta_C \to 2\pi$ corresponds to the scheme of the condensed collisions. This scheme allows quickly receiving statistically valid results, but has several essential errors.

On the basis of equations for description of elementary processes, the algorithm of simulation of electron transition through matter is created. A scheme of grouping of collisions is implemented with the following parameters: the critical energy E_e of electron formation, the critical energy E_p of bremsstrahlung quantum formation and critical angle θ_C of elastic scattering of electron on atoms. For construction of the electron trajectory, a free parameter E_S of the scheme is specified. This parameter - energy of stopping of electron - is determined by field of applicability of used descriptions of elementary processes.

The necessity of introducing of the averaging domain for calculation of spatial distributions of physical quantities is the feature of the Monte Carlo method. For calculation of the spatial dose distribution, sizes of a domain of averaging of energy, which is transmitted in the act of electron-matter interaction, are specified. (The set of free parameters Δh_i).

The features of the MC method.

The specially designed analytical interrelations are used for the reasonable choice of free parameters of the physical model for adjusting statistical and model errors of computer experiment and minimizing time of calculation for obtaining of data with a given accuracy.

The feature of implemented statistical estimation of the dose distribution is the use of the method of translations in some spatial domains of the object. This method is used in regions, where variation of magnitude and direction of the electron flux leads to dose variation to be smaller than the established model error. The sizes of these regions are determined according to expert equations, on the basis of parameters of irradiation process and the established model error for obtained results.

A feature of sampling of initial values of electron parameters is randomization of the scanning process. It simplifies procedure of generation of random values of parameters and allows correctly estimating required time for realization of statistical experiment.

Features of realization of a physical model for X-ray processing are the following:

- The use of a forced method for process of producing X-ray on each step of design of electron track in a construction of the X-ray converter.
- The automatic choice of self-consistent parameters is used for simulation of an electron - photon shower. The choice is based on determination a minimum machine time for obtaining given accuracy. These parameters are the following: cutoff energy for modeling of an electron track, threshold energy of catastrophic electron-electron collisions, cutoff energy for modeling of a photon track, threshold angle of grouping electron collisions for modeling of scattering.
- The use of both a simple estimation (collision method) and the special estimation (method of crossing area) for the dose calculation.

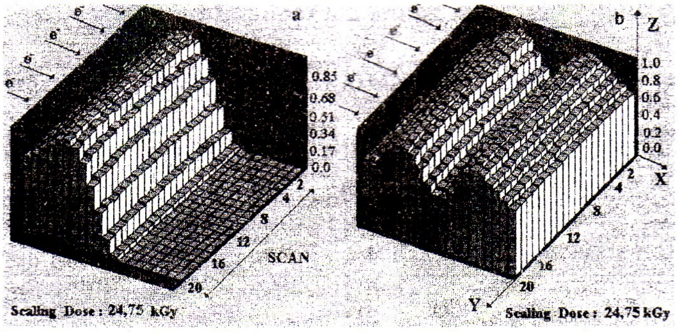
At implementation of the simulation MC methods the specially designed schemes which allow to reduce a running time for receiving of the end results in about hundreds time were applied.

5. Simulation of industrial EB processing by the program ModeRTL

One of the most important characteristics for all radiation-technological processes is the absorbed dose in an irradiated materials. For each product to be treated in the EB and X-ray irradiation facility, there will usually be a minimum dose limit $D_{min\text{-}lim}$ to obtain the desired effect and a maximum dose limit $D_{max\text{-}lim}$ to avoid product degradation. Value of an absorbed dose necessary for realization of the EB and X-ray processing, the required level of uniformity of an absorbed dose in volume of the irradiated product determine efficiency and productivity of the technological process.

The examples of simulation of a dose field formation in polymer modified wood (PMW) irradiated by electron and X-ray beams are considered in chapters 5 and 6. PMW is a new type of composite materials manufactured by impregnation of inexpensive soft kinds of wood with synthetic monomers or oligomers and subsequent radiation polymerization [3]. All given below figures are captured directly from the interface of the programs ModeRTL, XR-Soft, and γ-ray-Soft.

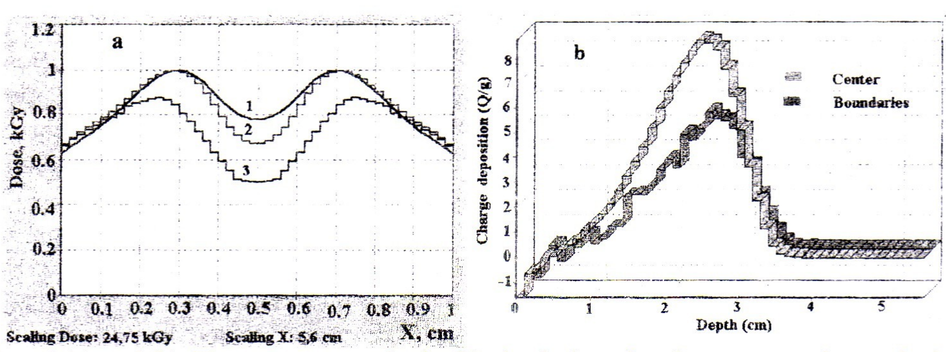
EB dose mapping within compound at one-sided irradiation and for optimal target thickness at double-sided irradiation are shown in Figs. 3 (a) and (b) respectively. Regimes irradiation: electron beam energy - 5 MeV; beam current – 1 mA; triangular scanning; target - compound with density 0.8 g/cm^3 (wood of aspen + 70% polymethylmethacrylate); width of target - 100cm; width of scanning -100cm; conveyer speed -1cm/s. Target has not cover box. A current in magnet of scanning system has the saw-tooth form. This current form is often used in scan magnet of industrial electron accelerator. The optimal thickness for maximum dose uniformity for electron beam in compound is 5.6 cm relatively of dose distribution at the center of a target.



Figs. 3 (a) and (b). 3D-view of the EB dose mapping within compound at one-sided irradiation (a) and for optimal targets thickness at double-sided irradiation (b). Statistical deviations: in the center target - 0.3% and in the boundaries - 2,5%. (Running time is about 7 minutes on PC AMD-K7, 750 MHz).

The compare results for EB depth-dose distributions in a plane, which cross the center (curves 1, 2) in the direction of moving conveyer, and the boundaries (curve 3) of an irradiated target at the end of scan beam direction (see Fig. 3 (b)) at double-sided irradiation are shown in Fig. 4 (a). Curves 2 and 3 simulated by MC method, curve 1 - by Analytical method. As is seen from Fig. 4 (a), the good agreement between depth-dose distributions in a plane, which cross the center calculated by Analytical method (curves 1) and simulated by MC method (curve 2) is observed. It allows to use Analytical method for fast optimization of irradiation regimes and integrate it in control system of radiation facility [15, 16].

The simulation results by MC method of the charge deposition in the center and the boundaries of compound irradiated by 5 MeV electron beam are presented in Fig.4(b).



Figs. 4 (a) and (b). The compare results for EB depth-dose distributions in a plane, which cross the center (curves 1, 2) in the direction of moving conveyer, and the boundaries (curve 3) of an irradiated target at the end of scan beam direction at double-sided irradiation (a). Charge depositions in the center and the boundaries of compound irradiated by 5 MeV electron beam (b).

As it is seen from Figs. 3(a) and (b) and Fig.4 (a), the EB depth-dose distribution within compound has minimal value on the boundaries of a target along direction of the scanning electron beam and maximal value at plane that cross the target center in direction of moving conveyer.

From standpoint of the dose limits, the minimum dose limit $D_{min\text{-}lim}$ must be chosen as a minimum dose value $D_{min\text{-}bound}$ on the boundaries of an irradiated target, the maximum dose limit $D_{max\text{-}lim}$ - as a maximum dose value $D_{max\text{-}center}$ in the target center. In this case the dose uniformity ratio will be determined for all irradiated volume as $DUR_V = D_{max\text{-}center}/D_{min\text{-}bound}$.

As evident from simulation results and Figs. 3 (a) and (b) and Fig. 4 (a) for the center of a target the EB dose uniformity ratio $DUR = D_{max}/D_{min}$ is 1.51. For the target boundaries at the end of scan beam direction the DUR is 2.12. As a result, the dose uniformity for all irradiated volume DUR_V is 2.7. This value is greater than $DUR = D_{max}/D_{min}$ for the targets center. EB dose uniformity ratio DUR_V can be decrease by decreasing of the optimal target thickness, or by the choice of the special shape of current in scan magnet, or with help of special filters [15, 20].

The anomalies of depth-dose distribution on boundary of two materials at orientation in parallel with incident electron beam were predicted by computer simulation with use ModeRTL software [21]. Experiments were conducted on radiation-technological line LAE 13/9 to validate computer simulation results. Cellulose Triacetate (CTA) dosimetric film (FTR-125) in form of strips were inserted between two blocks at various combinations of materials (Al, wood, PE). Such heterogeneous targets were irradiated by scanned electron beam on moving conveyer.

Validation of computer simulation predictions of an irradiation process with use of the software ModeRTL was fulfilled by comparison with results of CTA films measurements. The anomalies predicted by simulation methods on curves of depth-dose distribution near to boundary of two materials with different densities were experimentally confirmed. Both used materials (Al, PE, wood, CTA film) and radiation facility on basis of the LAE 13/9 are typical for a series of radiation technologies. It was established, that the boundary anomalies of a dose can be realized at radiation processing of heterogeneous materials. Investigation of those anomalies can be used to estimate the quality of an irradiation fulfilled on RTL. It is shown that an application of designed software ModeRTL for planning of irradiation on RTL and interpretation of results obtained by dosimetric film is correct, useful and in a series of cases, it is necessary in practical activity.

6. Simulation of industrial X-ray processing by the program XR-Soft

X-ray beam was generated by scanning electron beam with electron energy 5 MeV in a tantalum converter. Fig.5 represents the X-ray spectrum for 5 MeV electron beam in tantalum converter. Converter construction includes the tantalum target plate with thickness 1.2 mm, the cooling water channel - 2mm, and the aluminum backing plate - 5.0 mm. The X-ray yield in the forward direction for 5 MeV electron is 8.62%.

X-ray dose mapping within compound (wood of aspen + 70% PMMA) with density 0.8 g/cm3 for optimal target thickness at double-sided irradiation for saw-tooth and special forms of current in scan magnet are shown in Figs. 6 (a) and (b) respectively. The optimal thickness of compound for maximum X-ray power utilization is 38.5cm relatively of dose distribution at the center of a target. X-ray beam power utilization in this case is 58%.

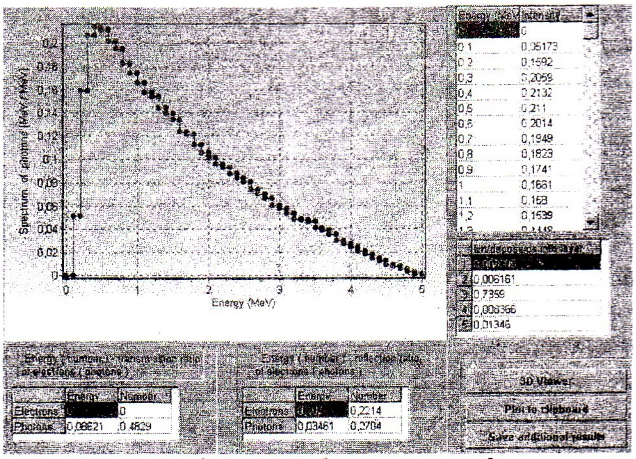
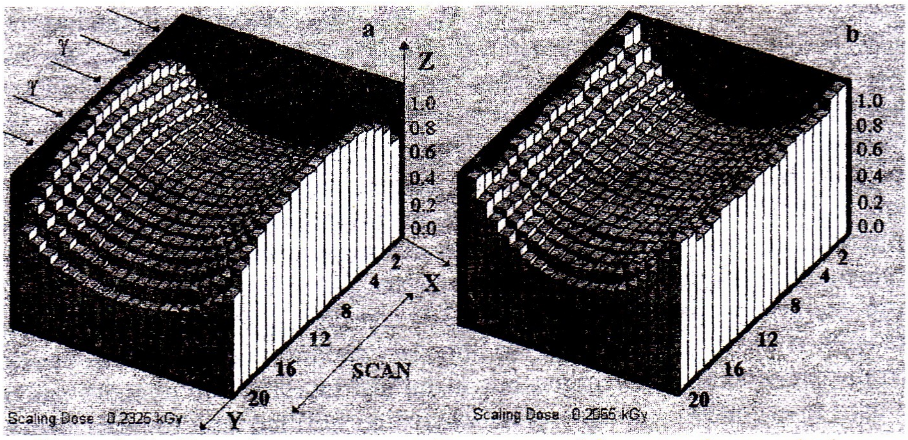


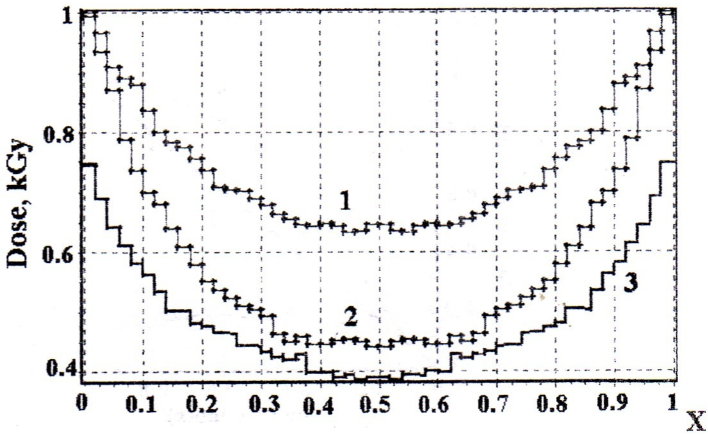
Fig. 5. X-ray spectrum for 5 MeV electron in tantalum converter.



Figs. 6(a) and (b). X-ray dose mapping within compound for optimal target thickness and for the saw-tooth form of current (a) and the special form of current (b) in scan magnet. Statistical deviations: 2.2 % for center target and 2.5% for boundary target along direction of the scanning X-ray beam. (Running time is about 8 minutes on PC AMD-K7, 750 MHz).

The compare results for X-ray depth-dose distributions in a plane, which cross the center (curve 1) in the direction of moving conveyer, and the boundaries of an irradiated target at the end of scan beam direction (see Fig. 6 (a) and (b)) at double-sided irradiation for saw-tooth (curve 3) and special forms (curve 2) of current in scan magnet are shown in Fig. 7.

As is seen from Figs. 6(a) and (b) and Fig. 7, the X-ray depth-dose distribution within compound has minimal value on the boundaries of a target along direction of the scanning X-ray beam and maximal value at plane that cross the target center. For the center of a target the dose uniformity ratio DUR = D_{max}/D_{min} is 1.53. For the target boundaries the DUR is 1.94. As a result, the X-ray dose uniformity for all irradiated volume of compound DUR_V is 2.91.



Scaling Dose: 0,2063 kGy **Scaling X: 38,5 cm**

Fig. 7. 2D-view of the X-ray depth-dose distributions in the center (curve 1) and in the boundaries of a target at the end of scan beam direction for saw-tooth (curve 3) and special forms (curve 2) of current in scan magnet.

Significant dose gradient in volume of irradiated target can be decrease by the choice of the special shape of current in scan magnet. Changing of the current shape in scan magnet results in change a time dependence for electrons intensity along a direction of scanning in front of an X-ray converter [15, 16, 22]. By the use the program XR-Soft, the special shape of current in scan magnet which provide the maximum uniformity for X-ray dose distribution in the irradiated compound was determined.

Fig. 8 represent the time dependencies of current in scan magnet for the saw-tooth shape of current (curve1) and the special shape of current (curve 2). The X-ray dose distribution determined by the special current shape (curve 2) is shown in Fig. 6 (b). X-ray beam power utilization in this case is 53%, the value DUR_V is 2.1 and also is greater than DUR in the target center. Further decreasing of the target thickness at double side X-ray treatment results in decreasing both the value DUR_V and the X-ray power utilization. For example, for compound thickness h=30cm the DUR_V is 2.0 for saw-tooth shape of current (curve1) and the DUR_V is 1.6 for the special shape of current (curve 2). In this case the X-ray power utilization is 48%.

Most effectively X-ray processing can be realized by treatment of turning loading chamber with irradiated materials which is placed in front of scanning X-ray beams (see Fig. 2(b)). In this case at given value DUR_V an optimal material thickness for X-ray processing will be greater than for double-sided irradiation. The program XR-Soft allows to simulate a dose mapping in turning cylinder chamber with materials irradiated by scanning X-ray beam. The direction of scanning X-ray beam is in parallel with a cylinder axis. For above compound with density 0.8 g/cm^3 and X-ray parameters, for the value DUR_V = 1.54, the optimum diameter D_{max} for the treated material is 60 cm.

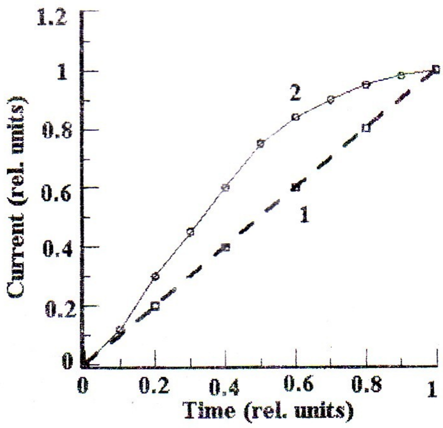


Fig. 8. Time dependencies of current for the saw-tooth (curve1) and the special shape of current (curve 2) in scan magnet. One-quarter of current time period.

As this takes place, a non-uniformity equalization for X-ray dose distribution along a direction of scanning on the ends (boundaries) of a turning cylinder chamber was conducted by the choice of the special shape of current in scan magnet. It is was done by the same method that was used above for double-sided irradiation. Without usage this method, the DUR_V is 2.2 because of the non-uniformity effects on the cylinder boundaries for the X-ray dose distribution.

Therefore the analysis of X-ray dose mapping must be conducted with consideration of the dose non-uniformity not only in the target center but also on the boundaries of an irradiated target.

As a minimum, the 2-D simulation model for EB and X-ray dose mapping must be used for correct analysis of the optimum product thickness, power utilization, max/min dose ratio, and processing capacity.

The validation and verification of the results simulated by the programs ModeRTL and XR-Soft were carried out in compare with theoretical calculated data, with results obtained by the universal packages such as ITS, EGS, GEANT and PENELOPE, and some experimental data of authors and data in published work [4, 20, 23]. The comparison investigations indicated that the developed physical and mathematical models are reliable and correct, and the programs ModeRTL and XR-Soft are accurate and easily accessible for users.

7. Program γ-ray-Soft for simulation of γ-ray irradiator

The special problem for the program γ-ray-Soft is the shielding analysis from a source with a radioactive wastage. Simulation of γ-ray characteristics from a large source with distributed radionuclides and simulation of spectrum and dose distribution from a distributed source in an environment was performed by Monte Carlo method.

Fig. 9 represents a geometrical scheme of γ-ray irradiator. Fig. 10 (a) represents the spectrum γ-ray from barrel with radionuclide 60Co ($E\gamma$ = 1.25 MeV). Fig. 10 (b) represents the dose map in an air around the barrel with radionuclides.

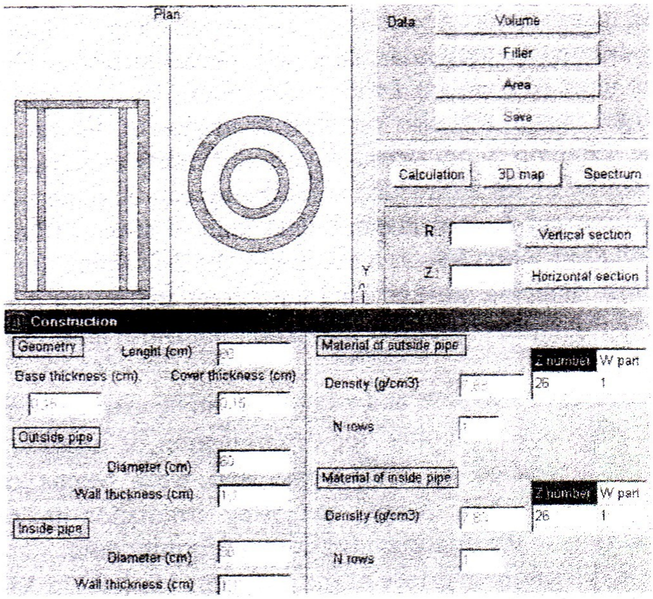
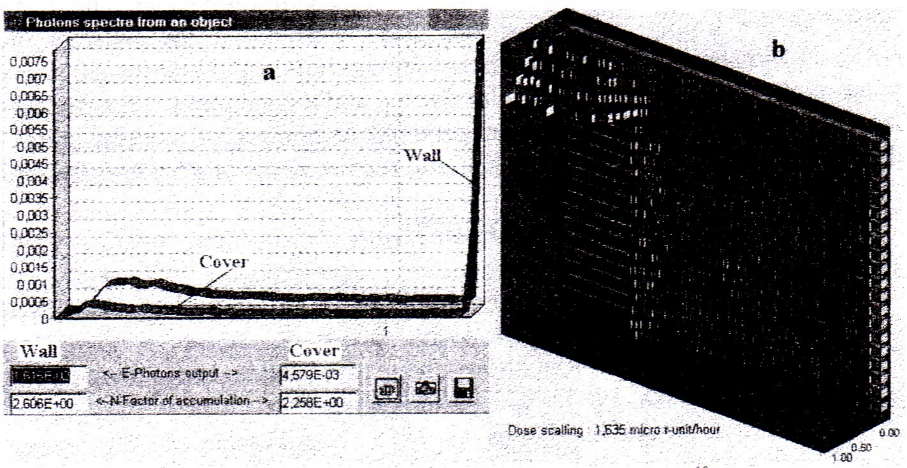


Fig. 9. Geometrical model of the γ-ray irradiator.



Figs. 10 (a) and (b). Spectrum of γ-ray from barrel with radionuclide ^{60}Co (a). Dose Map in an air around the barrel filled with radionuclide ^{60}Co (b).

The program γ-ray-Soft can be used for the dose distribution mapping in γ-ray processing of medical device or foodstuff in the multi-pencil type of γ-ray irradiator.

7. Conclusion

The functional modules of the RT-Office can be used as the basis for designing of the software for decision of special tasks in different radiation-technological processes. Specialized software for EB, X-ray, and γ-ray processing in the form of the programs ModeRTL, XR-Soft and γ-ray-Soft were developed on the basis of simulation and calculation modules of the RT-Office.

The results of some examples of simulation of radiation processing show, that programs ModeRTL and XR-Soft are very useful for the simulation analysis of EB and X-ray dose mapping for objects irradiated at one- and double-sided by scanning EB and X-ray beams. In particular, it is was determined that EB and X-ray dose uniformity ratio must be conducted with consideration of the dose non-uniformity not only in the target center but also on the boundaries of an irradiated target along direction of the scanning X-ray beam. A non-uniformity equalization for EB and X-ray dose distribution along a direction of scanning can be done by the choice of the special shape of current in scan magnet, with help of special filters, or with special methods of irradiation. Therefore as a minimum, the 2-D simulation model for EB, X-ray, and γ-ray dose mapping must be used for correct analysis of the optimum product thickness, EB, X-ray and γ-ray power utilization, max/min dose ratio, and processing capacity.

Programs ModeRTL, XR-Soft, and γ-ray-Soft can be used as predictive tools for of EB, X-ray and γ-ray dose mapping, for determination of location $\boldsymbol{D_{min}}$ and $\boldsymbol{D_{max}}$ in volume of target irradiated by EB, X-ray, and γ-ray beams on RTL, and for optimization of regimes EB, X-ray, and γ-ray irradiation to receive maximum processing capacity with the minimum for dose uniformity ratio.

The flexible and friendly interface of the programs ModeRTL, XR-Soft and γ-ray-Soft is realized in the Windows environment. It allows effectively to use these programs to a broad audience of users without a special knowledge. These programs can serve as the trainer course for end users working in the field of radiation technologies, transport of ionizing radiation in materials with heterogeneous structure, computer modeling of systems and technologies, and a good manual for students.

The RT-Office can be installed on personal computers of a mean power under Windows 98/NT/Me/XP, there are no specific requirements of a basic software.

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