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Modeling of processes of an irradiation for industrial radiation technologies

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Today, the industrial radiation technologies represent the systems with high integration of scientific and technical solutions from various data domains of production activity of a society. Success of the use of ionizing radiation in various radiation technologies depends largely on development of mathematical models and computer codes for simulation of irradiation processing on radiation facility. The features of modeling methods of complicated variants of an irradiation by electrons and photons beams of heterogeneous objects in industrial radiation technologies are considered in the report.

Keywords: *radiation processing, mathematical models, computer simulation, RT-Office.*

Сьогодні промислові радіаційні технології представляють собою системи із високою інтеграцією науково-технічних рішень із різних областей виробничої діяльності суспільства. Успіх використання іонізуючого випромінювання в радіаційних технологіях в значній мірі залежить від розвитку математичних методів і комп'ютерних програм для моделювання процесів опромінення на радіаційно-технологічних лініях. Розглядаються особливості моделювання складних методів опромінення гетерогенних об'єктів пучками електронів і фотонів у промислових радіаційних технологіях.

Ключові слова*: радіаційні технології, математичні методи, комп'ютерне моделювання, РТ-Офіс*

Сегодня промышленные радиационные технологии представляют собой системы с высокой интеграцией научно-технических решений из различных предметных областей производственной деятельности общества. Успех применения ионизирующих излучений в радиационных технологиях в значительной степени зависит от развития математических методов и компьютерных программ для моделирования процессов облучения на радиационно-технологических линиях. Рассматриваютсяособености моделирование сложных методов облучения гетерогенных объектов пучками электронов и фотонов в промышленных радиационных технологиях.

Ключевые слова*: радиационные технологии, математические методы, компьютерное моделирование, РТ-Офис*

1. Introduction

At present the electron beam (EB), breamsstrahlung radiation (X-ray) and gamma ray from radionuclide sources 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 ionizing radiation, development of new methods of radiation processing [1, 2]. The above radiation technologies solve different industrial tasks in various spheres of a society activity, but all of them contain as the functional element the processes of an irradiation which are based on the effects of transport and interaction of radiation with matter.

An usage of radiation technologies generates a number of the complicated scientific and technical problems which depend from type of the radiation processing and irradiated objects.

Thus, first of all, for each radiation processing, for everyone radiation facility it is necessary to solve tasks of support of safe operating modes and a reliable quality control methods of an irradiation process.

Besides it is required to determine an optimum operating modes of the functional elements of radiation facility from the point of view of quality assurance and quality control of radiation processing, as well as of temporary and financial expenditures on their execution. And at last, it is required to formulate a scientifically based proofs, that the radiation processing is carried out according to operating international and regional standards.

Solution of these tasks by experimental methods demand a big material, temporary and labour expenditures and cannot, even today, to provide an effective utilization of existing radiation facilities.

Scientific researches in the area of simulation of radiation processing which were started in the middle of the last century are actively continued up today. Because the computer simulation of radiation processing is the main tool for:

• scheduling of irradiation process,
• prediction and calculation of the 3-dimensional (3D) distributions of the absorbed dose in heterogeneous targets irradiated on the radiation facility:
• searching of optimum and safe operating modes,
• development of new methods irradiation for radiation processing and
• interpretation of experimental results.

For development and establishment of standard procedures as well as harmonization in process validation and in process control for the radiation technologies, authors propose to use the comprehensive approach in form of Information System for modeling of industrial radiation processing [3,4].

The **Information System** includes the following main components: the Radiation-Technological Office (RT-Office) software; trainer courses for education of broad audience of end-users and students to modeling of industrial radiation processing.

The RT-Office software is intended for simulation of wide range of practical tasks in an industrial electron beam, X-ray and gamma ray processing in the irradiation energy range from 0.02 to 50 MeV. **The RT-Office** software comprise: application program package with specialized codes for simulation of EB, X-ray and γ-ray processing; databases with information related to radiation facilities and features of different radiation technologies.

Application program package with specialized codes for simulation EB, X-ray, and gamma ray processing was developed on the basis of simulation and calculation modules of the RT-Office. The codes were designed specially for simulation and optimization of industrial radiation processes, calculation of the absorbed dose, sterility assurance level, temperature and charge distribution within irradiated products.

The processing technologies database stores all characteristics of typical irradiators of electron, X-Ray and gamma ray beams, geometrical and operational characteristics radiation facility, detailed description and characteristics of radiation processing, the calibration data for monitoring equipment, the parameters of irradiated materials, the material and size of the package for irradiated products, and others.

Trainer courses were developed for EB, X-ray and gamma ray processing. They are intended for training and education of practical skills, accelerated accumulation of professional experience in the fields of basic knowledge of industrial radiation processing, practical and computational dosimetry, methods of experimental validation of simulation predictions, the use of simulation methods for quality control of radiation processing.

The trainer courses include the following training aids:

• the interactive tutorials with basic terminology and knowledge in the field of transport ionizing radiation through matter, radiation technology realization, practical and computational dosimetry for control of radiation processing, optimization methods;

• the specialized codes for simulation of EB, X-ray and gamma ray processing;

• the user guides containing the detailed description of the code architecture, which allows end-users successfully to work with all modulus for each codes;

• handbook -"How to get results", which comprise the rules and instruction for end-users to calculation of different characteristics for radiation processing;

• examples and the book of simulation problems to control of theoretical knowledge and modeling methods;

• the methods of solution of practical tasks in radiation processing.

The complex approach to computer modeling methods of the 3D absorbed dose distributions in an irradiated products for complicated variants of an irradiation with electrons and photons beams which are realized in the version RT-Office-3, are considered in the report**.**

2. Methods of computer modeling of complicated variants of products irradiation with electrons and photons beams

In practice on radiation facility with big power irradiators the multipass, multilevel and multisided methods irradiation of product are used for improvement of quality and dose uniformity in product irradiated with EB, X-ray and gamma ray. The complex approach to computer modeling methods of the 3D absorbed dose distributions in an irradiated products for complicated variants of an irradiation with electrons and photons beams was developed and realized by authors in RT-Office-3.

The RT-Office 3 with software package is intended for simulation of wide range of practical tasks in an industrial electron beam, X-ray and gamma ray processing in the energy range from 0.02 to 50 MeV. The functional modules of the RT-Office 3 were used as the basis for design of the programs for decision of special practical tasks in various industrial EB, X-ray and gamma ray processing.

The RT-Office 3 comprise the following specialized programs for simulation EB, X-ray and gamma ray processing:

• The program **ModeStEB (Modelling of EB processing in multi-layer flat objects)** was designed specially for simulation and optimization of industrial radiation processes, calculation of the 3D absorbed dose within multi-layer packages irradiated with scanned EB on industrial radiation facility that is based on the pulsed or continuous type of electron accelerators in the electron energy range from 0.02 to 25 MeV [5].

• The program **ModeSXR (Modelling of X-ray processing in multi-layer flat objects)** was designed specially for simulation of the 3D absorbed dose distribution within multi-layer packages irradiated with scanned X-ray (bremsstrahlung) beams on industrial radiation facility that is based on the pulsed or continuous type of electron accelerators with X-ray converter in the energy range from 0.1 to 50 MeV.

• The program **ModeGR (Modelling of gamma ray processing)** was designed specially for simulation of the **a**bsorbed dose distribution within 3D multi-layer packages irradiated with gamma ray from flat panoramic ^{60}Co source. Conveyor system provides the following regimes irradiation the product containers, such as stationary, one pass continuous, multipass continuous or multipass shuffle–dwell. The product containers can be multi-sided irradiated: at one-, two-, or four sided.

The ModeStEB, ModeSXR and ModeGR programs calculate the 3D absorbed dose profile for one pass of product in front of EB, X-ray or gamma ray irradiators. These programs are the data producers of 3D absorbed dose distributions at one pass irradiated product with EB, X-ray or gamma ray.

The data of 3D absorbed dose profile obtained at one pass of product irradiation are used for phased integration of radiation processing at simulation of practical tasks in an industrial EB, X-ray and gamma ray processing. The program **RT-Builder** perform the arrangement of radiation processing on the base of data of 3D absorbed dose profile obtained at one pass of product irradiation.

The program **RT-Builder** is the special module of RT-Office 3 which is used for calculation and analysis of the summarized 3D absorbed dose distributions in product irradiated by EB, X-ray or gamma ray with various methods, such as multipass, multilevel, multisided and others. RT-Builder summarizes the absorbed doses obtained with software ModeStEB, ModeSXR and ModeGR in the 3D product irradiated with EB, X-ray or gamma ray for one pass/side/level irradiation, for two pass/side/level irradiation and so on.

RT-Office 3 comprise in form of special modules the comprehensive built-in tools for processing and analyzing of output data:

• comparative analysis of output data in graphical and tabular forms;
• cognitive visualization of results simulation;
• for dose volume histogram analysis to summarize 3D dose distributions in a graphical 2D format;
• for 3D absorbed dose analysis with spokes method;
• for statistical analysis;
• for uncertainties estimation of results simulation due to uncertainties of input data for radiation facility;
• for estimation of uncertainties for physical models;
• comparison modulus for decision of optimization tasks in radiation processing;
• dosimetry module for preparing of experimental data to comparison with simulated results.

RT-Office 3 comprise the special modules for simulation and analysis of some practical problems in radiation processing: sterility assurance level (SAL) and sterilizing dose for process of radiation sterilization [6]; radiation-induced heating of irradiated objects and calorimetry of absorbed dose; computer modeling of dosimetric devices.

Main problem tasks in radiation processing which can be decided with RT-Office:

• Computational dosimetry tasks.

Prediction and calculation of the 3-dimensional (3D) distributions of the absorbed dose in heterogeneous targets irradiated on the radiation facility:

- for various types of irradiation: electron beams (EB), bremsstrahlung radiation (X-ray) and gamma rays from radionuclide sources;
- for product irradiated in the stationary regime or on a moving conveyer at one-, two-, four-sided irradiation, or rotation product in front of the irradiator;
- for product irradiated by EB, X-ray or gamma ray with various methods, such as one pass, multipass, multilevel, multisided and others.

Dose mapping studies to identify the zones with maximum and minimum doses in an irradiated product.

• Optimization tasks of irradiation process.

- Optimal arrangement of irradiated product with packaging, optimal installation of radiation facility, methods and parameters irradiation for obtaining of predicted profile of the absorbed dose distribution into irradiated product.
- Selection of optimal parameters for process of product irradiation which provides for various types irradiation (EB, X-ray and γ-ray) and methods irradiation the following basic principals for specific radiation processing: radiation facility and radiation processing should provide the maximum of the radiation energy utilization, acceptable level for dose uniformity in an irradiated product and maximum throughput of irradiated product.

• Calculation and analysis of characteristics of various radiation-induced effects in the irradiation process.

On the base of obtained profile of the absorbed dose distribution into irradiated product the characteristics of the following effects can be calculated and analyzed:

- spatial distribution of radiation-induced heating of an irradiated product and estimation of the integral characteristics of the heat transmission for cooling process of an irradiated product into thermostable environment, calorimetry of an absorbed dose.
- radiation-induced charge depositions in an irradiated product,
- sterility assurance level and sterilized dose for process of radiation sterilization.

• Representation, analysis and interpretation of the simulation results, comparison results of computational and practical dosimetry.

• Optimization tasks at the design and commissioning of new EB, X-ray and gamma ray radiation facility and new radiation processing, radiation facility qualification, process validation and routine process control.

3. Geometrical models and operational parameters of radiation facility

3.1. Influence of geometrical models on dose map formation in an irradiated product

RT-Office software can be used to optimize the configuration of radiation facility with taking into account the basic principles for irradiators design. These principles are as follows: radiation facility and radiation processing should provide the maximum of the radiation energy utilization, acceptable level for dose uniformity in an irradiated product and maximum throughput of irradiated product.

Factors which influence on formation of the absorbed dose distribution in targets at radiation processing are as follows:

• Geometrical arrangement of irradiation source and irradiated target and spatial distribution of irradiation intensity which interact with target.

In case for EB and X-ray processing, geometrical arrangement and spatial distribution of electrons and X-ray which interact with product are mainly determined with EB scanning and conveyer movement.

Continuously moving conveyer is used for improvement the lateral dose distribution uniformity in the direction of product motion.

Process of EB scanning influence on dose distribution and dose uniformity in an irradiated product in the lateral direction perpendicular to the direction of the conveyer motion.

For gamma ray processing, these factors are determined by geometrical arrangement of Co^{60} source pencils into gamma source rack, mutual arrangement of source rack with irradiated target and methods irradiation.

• Geometrical form, size of irradiated target and its construction elements, density, composition of the target material and weight concentrations of component; heterogeneity, geometrical form and size of the container for irradiated product.

For example:

- targets with a simple geometry such as container filled with homogeneous materials,
- targets with complex geometry like multi-layer cylindrical targets in form of cable and tube, as well as a set of cables or tubes,
- multi-layer targets consists of flat sheets of contacting materials with different density and/or atomic number, and others.

• Methods of target irradiation:

- one-, two- or four sided irradiation, or rotation target in front of the irradiator,
- multilayer target can be located on a conveyer platform under arbitrary angle relatively direction of incident irradiation,
- for gamma ray processing the product on a conveyer platform can be irradiated in stationary, continuous or shuffle-dwell modes, and others.

Methods of target irradiation are directly related with geometry irradiation. For example, variation dose with depth and variation dose in the lateral direction depends on the geometry irradiation.

• Types and characteristics of irradiation which are used in radiation processing: EB, X-ray or gamma ray.

• Factors which influence on modeling of the absorbed dose distribution in targets irradiated with EB, X-ray and gamma ray directly related with physical processes of interaction of electrons and photons with material which were included in the physical model. For example: Compton scattering, photoelectric effect, fluorescent emission, pair production, positron annihilation; electrons lost energy due to inelastic collision with atomic electrons or X-ray, emission of secondary electrons and others.

Authors analysis have shown that at fixed parameters of irradiation source above geometrical factors are determinative in process of absorbed dose distribution formation in targets irradiated with EB, X-ray and gamma ray. Therefore the development of correct geometrical models of radiation facility, mutual arrangement of irradiation source and irradiated target, geometrical models of irradiated targets, geometrical models of methods irradiation are actual task at simulation of radiation processing. Fixed parameters of irradiation are as follows: electron energy spectrum and electron beam current – for EB and X-ray processing; activity of Co^{60} in pencils of gamma source – for gamma ray processing.

All RT-Office programs for simulation of EB, X-ray and gamma ray processing are based on self-consistent geometrical and physical models [7]. It is meant that determination of geometrical and physical factors which influence on formation of absorbed dose and dose uniformity in irradiated targets are necessary to perform with the same accuracy.

3.2. Models of radiation facility

EB and X-Ray radiation facility

Analysis of typical irradiation facility generated an electron and X-Ray beams which are used in industrial radiation processing was made in the paper [7].

The developed geometrical, physical and mathematical models for EB, X-ray and gamma ray irradiators, complicated 2D and 3D heterogeneous target such as packages with multilayer flat sheets, thin dosimetric films, multilayer tubes and cables, multilayer cylinders with limited length were used as basis in the RT-Office programs.

The physical model of an irradiation process for EB and X-ray radiation processing includes the following principal elements: EB irradiator characteristics, parameters of the X-ray converter with cooling system, the systems parameters which provide the necessary spatial characteristics in radiation processing, and radiation and physical characteristics of irradiated product and packaging.

Besides, the set of processes of interaction of ionizing radiation with product which are necessary for description of results with the given accuracy are included in physical model at the theoretical analysis and/or computer modeling of ionizing radiation expose on product.

The following processes of interaction of electrons with substance and their modeling conceptions were included in the physical model:

• electrons lost energy by two basic processes an inelastic collision with atomic electrons and bremsstrahlung;

• inelastic electron collision with atomic electrons lead to excitation and ionization of the atoms along the path of the particles (model of grouping of the transferred energy);

• emission of the secondary electrons (model of the threshold energy);

• electrons participated in elastic collisions with atomic nuclear lead to changes in the electron direction (model of grouping of transferred pulse).

Transport of photons are attended with: Compton scattering, photoelectric effect, fluorescence emission, pair production, emission of photons in process of bremsstrahlung.

All physical processes which assure obtaining of results with predetermined accuracy are taken into account at simulation.

For example, for EB radiation processing in the energy range of incident electrons from 100keV to 10 MeV and irradiated materials with atomic number $Z \leq 30$, the model uncertainty is less than 5% for calculated dose distribution in the field of the basic EB energy absorption.

Gamma ray installation

Various types of gamma irradiators and methods of product container irradiation with gamma ray are used to reduce the dose uniformity ratio in an irradiated product and to maximize gamma radiation energy utilization [8]. Panoramic irradiators are more suitable for industrial gamma ray processing.

Detailed description of geometrical model of gamma ray facility with irradiated targets was made for panoramic planar ^{60}Co source rack which is used as gamma source in the software ModeGR. In the computer model, the ^{60}Co source rack is represented as a rectangular planar frame with number of modules from 4 up to 20, which should be mounted in two levels, with uniform/non uniform distribution of ^{60}Co strength. General number of ^{60}Co source pencils in the source rack can be in the range from 1 up to 800.

Irradiated product can be represented in form of container with homogeneous materials as well as of container filled with stack of plates. The stack of plates can be interleaved with dosimetric films.

The product on a conveyer platform can be irradiated in tree modes:

• stationary mode - the container with product will irradiated in stationary regime;

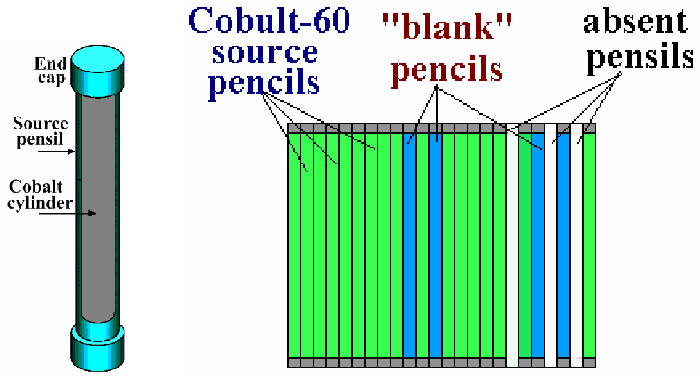
• continuous mode - the container with product will continuously move on a conveyer platform in parallel with surface of source rack;

• shuffle-dwell mode - the container with product will discontinuously move on a conveyer platform in parallel with surface of source rack to a new irradiation position and then remaining at rest for a dwell time at that position. The dwell time is the time interval during which a process load is at rest at an irradiation position.

There are two types of source pencils which are used in the gamma source model: active cobalt-60 slugs encapsulated into stainless steel capsule, and a “blank,” inactive stainless steel cylinder. Typical source pencil constructions is presented in Fig.2a. All pencils types have the same geometrical characteristics but they can have various activity the ^{60}Co.

Typical source modules manufactured by firm MDS Nordian, Canada comprises 40-48 of the above cobalt-60 source pencils. The model of source module with pencils arrangement is presented in Fig.2b. In this model the number of pencils in the source module can be in the range from 0 to 200. It is allows one source module to present as 1-5 typical source modules. As a result, we can represent source rack with 20 typical source modules, in 2 x 10 array.

The computer model allows calculate the absorbed dose distribution and optimize dose uniformity within product irradiated on Co^{60} multipass shuffle–dwell irradiator. The schematic model of a typical Co^{60} multipass shuffle–dwell irradiator with overlapping product to gamma source configuration is presented in Fig.3. 64 Aluminum containers with product are moved around the Co^{60} source rack on a conveyor 8 passes at two levels. Two levels are characterized by horizontal and vertical movements of the product containers.



Figs.2. (a) and (b). (a) Source pencil constructions.
(b) Scheme of arrangement of sours pencils in the source module.

In multipass shuffle–dwell mode of operation, the product containers stay at the designated irradiation positions around the radiation source for a certain dwell time, and then they all move to the next positions, such that each container irradiated at each dwell position before leaving the irradiation room. There are 8 dwell positions for each of the 8 passes and 64 for the all 8 passes (See Fig.3). As a result, the product irradiated with gamma ray at two sided.

3.3. Methods of product irradiation

The methods of product irradiation essentially influence on absorbed dose and dose uniformity formation in the product irradiated with EB, X-ray and gamma ray. Methods of the product irradiation are directly related with geometry irradiation.

RT-Office software provides simulation of the following methods of product container irradiation with EB, X-ray or gamma ray:

1. EB and X-ray processing.

• The moving conveyer is used for improvement of the lateral dose distribution uniformity in the direction of product motion.

• EB is scanned to improve the dose uniformity in an irradiated product across the width of the conveyer.

• The special form of beam current in scan magnet can be used for improvement of the lateral dose distribution uniformity near the interface of irradiated target with container materials or with air in direction of EB scanning, as well as for realization of asymmetric scanning to maximize utilization of EB.

• Multilayer target can be located on a conveyer platform under arbitrary angle relatively direction of incident irradiation.

• Irradiation of product can be performed at one-, two- and four sided.

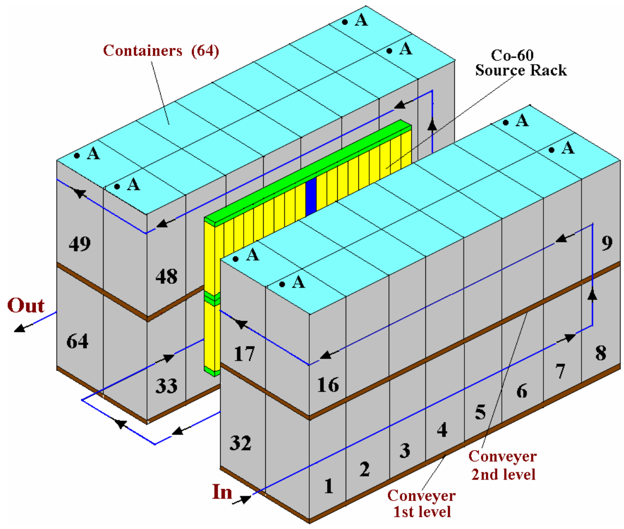


Fig.3. Sequence of irradiation in a flat panoramic Co^{60} source rack, multipass, two direction, multiposition. The 64 aluminum containers with product are moved around the Co^{60} source rack on a conveyor 8 passes at two levels. Point “A” is a fixed point on the side surface of the process load, which passes through the irradiation room on both sides of the Co^{60} source rack from position 1 to position 64.

• Additionally for X-ray processing, the rotation method of the product container in front of the X-ray irradiator is used.
• Irradiation of product can be performed with non-divergent or triangular scanned EB/X-ray.
2. Gamma ray processing.
• The product containers are moved around a radiation source on a conveyor a few times (generally, from 2 to 8 passes), and may also travel at different levels. Two and more levels are characterized by horizontal and vertical movements of the product containers.
• Conveyor system provides the following regimes irradiation the product containers, such as stationary, one pass continuous, multipass continuous or multipass shuffle–dwell.
In multipass shuffle–dwell mode of operation, the product containers stay (dwell) at the designated irradiation positions around the radiation source for a certain dwell time (usually a few minutes), and then they all move (shuffle) to the next positions, such that each container eventually resides at each position (in all loops around the source) before leaving the irradiation room.
• The product containers can be multi-sided irradiated: at one-, two-, or four sided.
• There are two types of irradiation geometry: product overlap irradiators and source overlap product.
For product-overlap arrangement, the combined height of two containers is more than the height of the source rack and each container travels around the source at two levels.

For source-overlap arrangement, the height of the source rack is more than that of the product container and each container travels at one level only.
• The lateral dose variation in gamma irradiated product can be reduced including placing the higher-activity source pencils near the periphery of the source rack, so called source activity augmentation method.

4. Built-in tools for representation of simulation results

Representation of results simulation for absorbed dose distributions and their analysis are unified for all simulation modules of the RT-Office 3. The features of all simulation modules of the RT-Office are the presence of the built-in tools for representation and analysis of simulation results such as follows:

• Presentation of physical and operational characteristics for radiation processing.
• Cognitive visualization of results simulation.
• Comprehensive comparative analysis of results simulation in graphical and tabular forms.
• Comparison Modulus for visual and a numerical analysis of calculated and experimental data which can be used for decision of optimization tasks in radiation processing.
• Built-in tools for decision of optimization problems with using dynamic and statistical databases.
• RT-Office programs represent the following additional information related to EB, X-ray and gamma ray processing: average dose, dose minimum, dose maximum, dose uniformity ratio, extrapolated and CSDA ranges for electrons, part of beam use, effectiveness, statistical uncertainties.

5. Built-in tools for analysing of results simulation

RT-Office 3 programs for simulation of absorbed dose in targets irradiated with EB, X-ray and gamma ray comprise the built-in tools for comprehensive output data analysing and processing.

The built-in tools for analyzing and processing of output data are as follows:

• Tools for dose volume histogram (DVH) analysis.
• Tools for 3D absorbed dose analysis with spokes method.
• Comparison module for scientific analysis and comparison calculated with experimental dosimetric data.
• Dosimetry module for preparing of experimental data for comparison between themselves or between simulated and experimental data. This module allows to load experimental data files, invert and move each experimental curve, cut and scale, transform to format of Comparison module.

Dose volume histogram (DVH) analysis.

The purpose of a DVH analysis is to summarize 3D dose distributions in a graphical 2D format. DVHs can be visualized in either of two ways: differential “pdf” or cumulative (integral) “cdf”. DVH analysis is used in the following RT-Office programs: ModePEB, ModeGR, ModeStEB, ModeSXR, ModeSAL and RT-Builder.

DVH analysis will be demonstrated on example of 5th layer target irradiated with gamma ray from ^{60}Co source rack, Software ModeGR (See Fig.4).

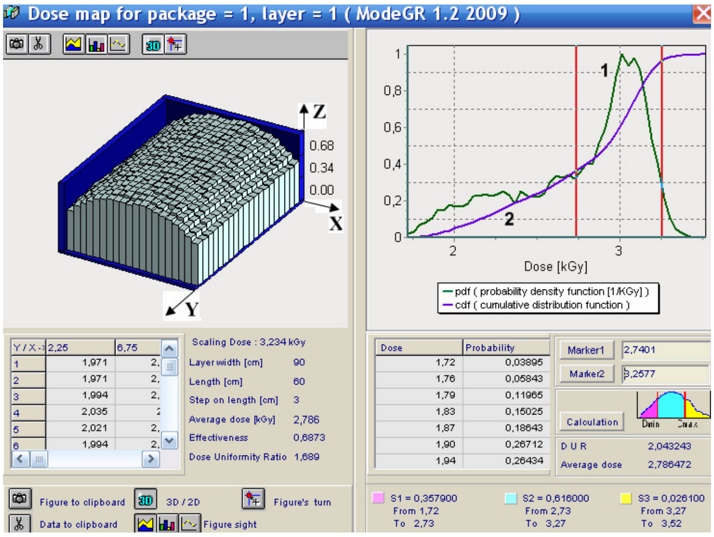


Fig.4. Left Graph: 3D view of the depth dose distributions of Gamma ray (Dose Map, along layer length (axis Y) and along layer width (axis X)) in graphical and tubular forms for the 1st layer in 1st package. The dose value is integrated along layer thickness (axis Z). Right graphs: Cumulative distribution function – cdf (curve 2), and Probability density function in 1/kGy – pdf (curve 1).

In "cdf" type of DVH, the vertical axis represent the relative value of total target volume that receives a dose less than a specified dose selected with markers. The plot was separated with markers on three parts accordingly with scheme near the button "Calculation". The integral of function "pdf " for the three parts divided Markers is located in the right downside of the "Dose map" form. (see Fig.4 – Right part). In a such way you can made DVH analysis step by step for each of 5 selected for calculation layers.

Spokes method for 3D absorbed dose analysis

3D absorbed dose distribution of gamma ray for any layers of 3D multilayer target can be analysed with "spokes method". The "spokes method" analysis is used in the following RT-Office programs: ModeGR, ModeStEB, ModeSXR, and RT-Builder.

The method includes the following operations:

• the layer volume is splitted by 3D grid with bin (cell) size $\Delta V = \Delta X \bullet \Delta Y \bullet \Delta Z$. Where ΔX=Width/ N(x), ΔY=Length/N(y), ΔZ = Thickness/ N(z). N(x), N(y), N(z) – the number of splitting along the Layer Width (axis X), Length (axis Y) and Thickness (axis Z) respectively. (See Fig.5).

• the "spokes" can intercross the layer in any point of its surface in directions of axis X, axis Y, or axis Z perpendicularly to planes of a layer .

• at calculation the dose distribution along spokes, the absorbed dose averaging in each splitting point along spoke is realized in volume $\Delta V = \Delta X \bullet \Delta Y \bullet \Delta Z$.

Example of target layer with grid and spokes is presented in Fig.5. Layer is located on a conveyer platform. Spoke A cross a layer thickness along axis Z. Spoke B cross a layer length along axis Y. Spoke C cross a layer width along axis X.

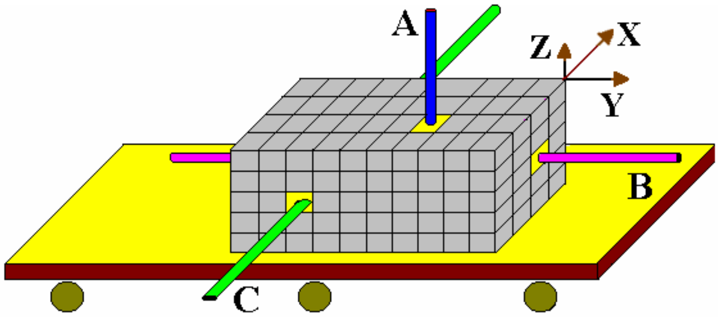


Fig.5. Target layer with grid and spokes located on a conveyer platform.

Results of the spokes method for 3D absorbed dose analysis in the 5th layer target irradiated with gamma ray from ^{60}Co source rack (Software ModeGR) are shown in the Fig.6 - Right part. In a such way you can made spokes method analysis step by step for each of 5 selected for calculation layers.

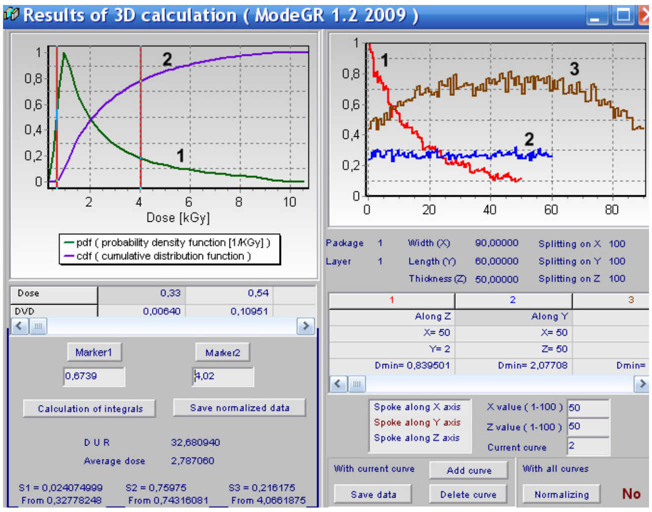


Fig.6. The form of "Results of 3D calculation" for analysis of 3D absorbed dose distribution of gamma rays for the 1st layer in 1st package. Left graphs-DVH analysis, Right graphs – spokes method analysis. 1st curve on the right graphs is the absorbed dose distribution along axis Z (layer thickness), 2nd curve - the absorbed dose distribution along axis Y, 3d curve - the absorbed dose distribution along axis X.

6. RT-Office applications

RT-Office 3 comprise the special modules for simulation and analysis of some practical problems in radiation processing, such as: sterility assurance level (SAL) and sterilizing dose for process of radiation sterilization; radiation-induced heating of irradiated objects and calorimetry of absorbed dose; computer modeling of dosimetric devices.

6.1. Simulation of sterility assurance level and sterilization dose

The computer technology for simulation of practical tasks in radiation sterilization process in accordance with Method 1, "Standard ISO 11137" [9] and "IAEA Code of Practice for the Radiation Sterilization of Tissue Allografts" [10] was developed [11]. The technology was realized on the base of the RT-Office modules for modeling by Monte Carlo method of an absorbed dose map in an irradiated heterogeneous targets with electron beam (EB), X-ray and gamma-ray and specialized software ModeSAL.

The software ModeSAL [11] is intended for calculation and comparative analysis of a sterility assurance level (SAL) and a sterilizing dose for bioburden to achieve a required SAL in an irradiated product.

The mathematical approach of the technology is based on the detailed and precise consideration of a self-consistent physical and geometrical models of calculation an EB, X-ray and gamma-ray dose maps in an irradiated product, a SAL, a sterilizing dose and the spatial and time uncertainties for dose provided to an irradiated product.

The features of mathematical model of the software ModeSAL are the following:

• The generalized stochastic model of radiation sterilization process is developed.

• The basic stochastic parameters proper in the modern radiation technologies are taken into account.

• To such stochastic parameters refer to: the bioburden in a product and in its separate parts; a spatial distribution of microbes in a product; a spatial dose distribution in an irradiated product; uncertainties because of nonstability of radiation facility parameters in time of irradiation; operational characteristics of radiation facility required to achieve a given SAL.

The feature of the theoretical approach at development of the generalized stochastic model of radiation sterilization process is introduction of the scale factor (SF). SF is the basic characteristic of change of an irradiation process for the analysis of dose map uncertainties effect.

Analysis and solution of problem tasks in radiation sterilization technology are performed as follows:

• The RT-Office modules for specific EB, X-ray and gamma-ray radiation facility and irradiated products optimize a thickness of irradiated products, a configuration of package for the product, the method of irradiation as one- or two-sided types, the choice of irradiation regimes.

• The RT-Office modules simulate a profile of an absorbed dose map in an irradiated product for optimal irradiation regimes.

• Simulation prediction for the dose map should be periodically verified in special dosimetric experiments.

• The output results for EB, X-ray and gamma-ray processing simulated with the RT-Office modules for an absorbed dose in forms of probability distribution and space distribution (dose map) are used directly as input data for the software ModeSAL;

• The software ModeSAL determines the sterilization dose and scale factor for parameters of radiation facility to achieve a required SAL for microbial population on/in an irradiated product in accordance with Method 1 ISO 11137 or IAEA Code. The software ModeSAL decides as well known and established tasks, so the specific

practical tasks in radiation sterilization technology.
• The RT-Office modules optimize the operational parameters of radiation facility on the base of scale factor data.

Such execution sequence of work provides a computer technology for sterilization process in accordance with Method 1 ISO 11137 and IAEA Code with regard to the spatial and time uncertainties for dose delivery to irradiated product.

6.2. Computer modeling of dosimetric devices

Programs for modeling by Monte Carlo method the dosimetric devices such as dosimetric wedge (ModeDW) and stack (ModeStEB) irradiated with scanned electron beam (EB) on moving conveyer were developed on the base of RT-Office 3 modules.

International standards determine the measuring procedure for the depth-dose distributions with usage of the dosimetric wedge and stack, experimental data treatment and an interpretation of observed results [12]. Practical use of a procedure of the dosimetric wedge and stack is related with utilization of a standard construction of the devices that ensures determination and control of the most probable energy, E_p, and the average energy, E_a, of an EB.

Software ModeDW is intended for modeling an EB dose distribution in dosimetric film placed along the sloping surface between the two wedges made of an arbitrary materials. Software ModeStEB is intended for modeling an EB dose distribution in a stack of plates of an arbitrary materials interleaved with dosimetric films or a stack of dosimetric films alone.

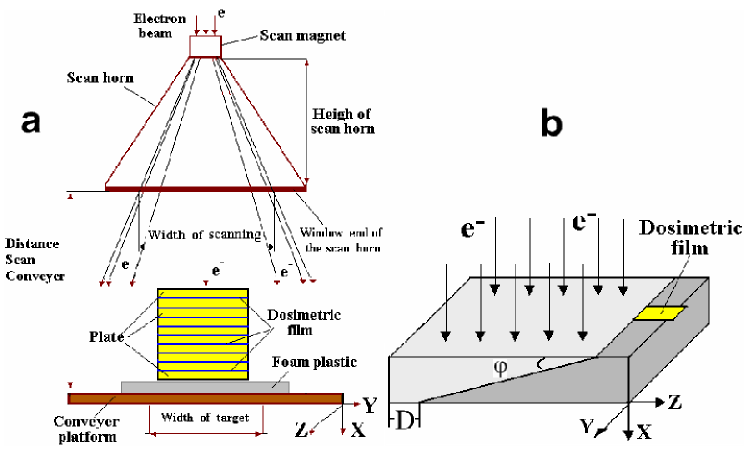
Fig.7b demonstrates the geometrical model of dosimetric wedge irradiated with non-diverging EB on moving conveyor. In the Fig.7b two wedges are stacking together to form a rectangular block. Dosimetric film is inserted along the sloping surface between the two wedges made of an arbitrary materials. The rectangular block can be located under arbitrary angles relatively incident electron beam axis.

Dosimetric stack consists of a set of plates made of an arbitrary materials interleaved with dosimetric films or a stack of dosimetric films alone. The number of plates with dosimetric films in the stack are in the range from 1 to 60. The plates of stack with dosimetric films should be located on the conveyer platform perpendicular relatively incident EB axis.

The total thickness of the stack should be chosen about 1.5 R_p, where R_p is practical range of electrons in the stack materials. A wedge thickness in direction of EB incidence should be chosen greater than anticipated range R_p of the EB in the wedge materials.

The developed programs essentially expand opportunities of the further development and usage of a procedure of the dosimetric wedge and the stack, because it remove the restrictions on obtaining of experimental data only in conditions when the flat one-dimensional case of an EB irradiation is realized.

1. Programs allow to develop optimum constructions of the dosimetric wedge and stack for monitoring of operational characteristics for EB. (on the basis of the analysis of sensitivity procedure of the dosimetric wedge and stack).
2. Programs allow to extract the maximal possible information on characteristics of the irradiation process with scanned EB on the basis of the comparative analysis of calculated and experimental results.



Figs.7a,b. a) Electron beam and irradiated dosimetric stack geometry. Arrangement of a stack plates interleaved with dosimetric films on moving conveyor irradiated with EB and triangular scanning. Axis X - direction of EB incidence, axis Y - direction of EB scanning, axis Z - direction of conveyer motion.
b) Model of the dosimetric wedge with dosimetric film irradiated by scanned EB. Axis X - direction of EB incidence, axis Y - direction of EB scanning, axis Z – direction of conveyer motion

3. Programs allow to develop the optimum phantom of an object irradiated with EB for the experimental testing of selected modes of an irradiation.
4. Programs allow to determine a dose map in an irradiated materials, a dose uniformity ratio, 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 the programs can be used for commissioning of EB facility, EB facility qualification, process validation and routine process control.

7. Integration of computer modeling methods into International Standards which are used in area of radiation processing

Integration of computer modeling methods into International Standards which are used in radiation processing is a perspective direction for development of Information Technology.

Today on the base of the RT-Office 3 modules the computer support was developed for calculation and operational functions of the following international standards:

• EN/ISO 11137:2006. Sterilization of health care products.
Part 1:Requirement for development, validation and routine control of a sterilization process for medical devices.
Part 2: Establishing the sterilization dose.
Part 3: Guidance on dosimetric aspects.
• A Code of Practice. “Radiation Sterilization of Tissue Allografts: Requirements for Validation and Routine Control.”// IAEA, VIENA, 2007.

• ISO/ASTM 51649:2002 “Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies Between 300 keV and 25 MeV”.
• ISO/ASTM 51608, Practice for Dosimetry in an X-ray (Bremsstrahlung) Facility for Radiation Processing.
• ISO/ASTM 51702, Practice for Dosimetry in a Gamma Irradiation Facility for Radiation Processing.
• ASTM 2303:2003. Standard Guide for Absorbed-Dose Mapping in Radiation Processing Facilities.

An integration of the developed computational methods into International Standards expands possibility and enhances quality assurance and quality control of the use of the Standards for decision of problem tasks in various radiation processing and in dosimetry of EBs, X-rays and gamma rays.

Conclusion

Benchmarking experiments for developed software were carried out on EB and X-ray radiation facility and certified dosimetric system in the Institute of Nuclear Chemistry and Technology, INCT, Warsaw, Poland [4, 5, 6, 7, 9, 12, 13]. Benchmarking experiments were performed for: EB processing of packages with multilayer flat sheets/thin films; EB processing of packages with multilayer cylinders; X-ray processing of package with thin films.

Experimental verification of theoretical predictions for absorbed dose distribution formation into targets irradiated with gamma ray was carried out on the radiation facility BULGAMMA based on JS-850 Co^{60} type gamma irradiator of Sopharma PLC, Bulgaria. JS-850 Co^{60} gamma irradiator is a wet storage, tote-box irradiator produced by MDS Nordian, Canada.

The measured absorbed dose distributions of 10 MeV electrons, 2.2 MeV X-rays and Co^{60} gamma rays in dosimetric films located into 3D multilayer targets are in agreement by the shape and absolute value with the results obtained by simulation of an absorbed dose distributions with calculation programs of the RT-Office 3. This agreement indicate that the developed physical and mathematical models in the programs ModeStEB, ModeSXR and ModeGR, are reliable and correct, and the program adequately reproduces the observed dose distributions even at positions with a high gradient dose.

Developed programs for simulation EB, X-ray and gamma ray processing were used :

• on stage of commissioning of new EB and X-ray radiation facility based on EB accelerator;

• on stage of optimization of radiation facility parameters and regimes irradiation in EB, X-ray and gamma ray processing;

• at interpretation of predictions for processing results of dosimetric data;

• at performance of actions and procedures prescribed with dosimetric standards and the standards for process of radiation sterilization.

• as basis in the training courses "The use simulation methods for quality control of EB, X-ray and gamma ray processing".

• for advanced training and educating of the qualified specialists and students in the fields of the transport of ionizing radiation through heterogeneous objects, in the industrial EB, X-ray, and gamma radiation technologies and in the practical and computational dosimetry.

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