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DOSE MAPPING OF A GAMMA INDUSTRIAL RADIATION FACILITY USING A PRACTICAL AND COMPUTATIONAL DOSIMETRY

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Comparison results for absorbed dose mapping of the Co^{60} industrial radiation facility BULGAMMA of Sopharma PLC, Bulgaria using a practical and computational dosimetry are presented in the paper. The gamma radiation facility is based on JS-8500 Co^{60} irradiator produced by MDS Nordian, Canada. The absorbed dose distributions of gamma rays in an irradiated product on JS-8500 Co^{60} irradiator have been calculated using the ModeGR Monte Carlo software. The software ModeGR was designed specially for simulation of the absorbed dose distribution within multi-layer packages irradiated with gamma ray from flat panoramic Co^{60} source rack using a Monte Carlo method. Absorbed dose measurements into containers filled with material using Ethanol Chlorobenzene chemical dosimeters were carried out to validate the software ModeGR. The comparison results show that software ModeGR can be used as a predictive tool for detailed dose mapping in gamma irradiated product.
KEY WORDS: computational dosimetry, software ModeGR, Monte Carlo method, absorbed dose mapping, industrial gamma facility.

КАРТОГРАФИРОВАНИЕ ДОЗЫ ПРОМЫШЛЕННОГО ГАММА РАДИАЦИОННОГО ОБОРУДОВАНИЯ С ИСПОЛЬЗОВАНИЕМ ПРАКТИЧЕСКОЙ И КОМПЬЮТЕРНОЙ ДОЗИМЕТРИИ

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В работе рассматривается сравнение результатов картографирования поглощенной дозы гамма излучения Co^{60} на промышленном радиационном оборудовании БУЛГАММА, Софарма, София, Болгария с использованием практической и компьютерной дозиметрии. Гамма радиационное оборудование основано на излучателе JS-8500 Co^{60} производства фирмы MDS Nordian, Canada. Расчет распределение поглощенной дозы гамма излучения в облучаемой продукции на JS-8500 Co^{60} излучателе проводилось методом Монте Карло программой ModeGR. Программа ModeGR была специально разработана для моделирования распределение поглощенной дозы в многослойных мишенях, облучаемых гамма излучением на плоском панорамном излучателе Co^{60}. Измерение поглощенной дозы гамма излучения в контейнерах, заполненных материалом, проводилось химическими дозиметрами Ethanol Chlorobenzene для валидации программы ModeGR. Результаты сравнения экспериментальных и расчетных данных показали, что программа ModeGR может использоваться как инструментарий для предсказания детальной карты поглощенной дозы в гамма облученной продукции.
КЛЮЧЕВЫЕ СЛОВА: компьютерная дозиметрия, программа ModeGR, метод Монте Карло, картографирование дозы, промышленный гамма излучатель.

КАРТОГРАФУВАННЯ ДОЗИ ПРОМИСЛОВОГО ГАМА РАДІАЦІЙНОГО ОБЛАДНАННЯ З ВИКОРИСТАННЯМ ПРАКТИЧНОЇ Й КОМП'ЮТЕРНОЇ ДОЗИМЕТРІЇ

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У роботі розглядається порівняння результатів картографування поглиненої дози гама випромінювання Co^{60} на промисловому радіаційному обладнанні БУЛГАММА, Софарма, Софія, Болгарія з використанням практичної й комп'ютерної дозиметрії. Гама радіаційне обладнання базується на випромінювачі JS-8500 Co^{60} виробництва фірми MDS Nordian, Canada. Розрахунок розподілу поглиненої дози гама випромінювання в продукції, що опромінюється на JS-8500 Co^{60} випромінювачі, проводився методом Монте Карло програмою ModeGR. Програма ModeGR була спеціально розроблена для моделювання розподілу поглиненої дози в багатошарових мішенях, що опромінюються гама випромінюванням на плоскому панорамному випромінювачі Co^{60}. Вимірювання поглиненої дози гама випромінювання в контейнерах, заповнених матеріалом, проводилося хімічними дозиметрами Ethanol Chlorobenzene для валідації програми ModeGR. Результати порівняння експериментальних і розрахункових даних показали, що програма ModeGR може використовуватися як інструментарій для прогнозування детальної карти поглиненої дози в гама опроміненої продукції.
КЛЮЧОВІ СЛОВА: комп'ютерна дозиметрія, програма ModeGR, метод Монте Карло, картографування дози, промисловий гама випромінювач.

Gamma ray emitters like cobalt-60 became popular radiation sources for medical and industrial applications. More than 250 gamma ray irradiators are currently in operation in Member States of the International Atomic Energy Agency

(IAEA) [1]. The kinds of applications that use gamma radiation have steadily increased, from crosslinking, polymerization and sterilization of health care products to food irradiation and environmental applications such as flue gases, wastewater and sludge treatment. Emerging applications could be in the fields of nanomaterials, structure engineered materials (sorbents, composites, ordered polymers, etc.) and natural polymers.

To control these processes the routine dosimetry procedures must be carried out to identify the positions of minimum and maximum absorbed dose within the product containers and to establish gamma source operational parameters. A detailed dose mapping of the industrial gamma radiation facility, optimization of the gamma irradiator geometry can be performed using computer modeling (computational dosimetry), which allows to reduce significantly the routine dosimetric measurements [2, 3].

The Co^{60} industrial radiation facility BULGAMMA is used for sterilization of health care products, pharmaceuticals, drugs, cosmetics and food irradiation [4]. JS-850 gamma facility comprise a typical flat panoramic Co^{60} irradiator with overlapping product, a water filled storage pool and shuffle–dwell conveyer system [5].

Introduction success of radiation technologies into practice substantially depends on development of computational dosimetry which is based on verified and validated programs, capable effectively calculate absorbed dose distributions in processes of an irradiation [3, 6]. Authors have developed the software ModeGR specially for simulation of the absorbed dose distributions within multi-layer packages irradiated with gamma ray from flat panoramic Co^{60} source rack using a Monte Carlo (MC) method [6, 7]. The software ModeGR was used for simulation of some practical tasks in gamma radiation processing on the Co^{60} industrial radiation facility BULGAMMA.

The objective of this study was the performing of benchmarking (BM) experiments on gamma radiation facility to validate software ModeGR. BM experiments are based on comparison of simulation results against measurement results for the absorbed dose distributions in containers with product irradiated by gamma ray on the BULGAMMA industrial gamma radiation facility.

GAMMA RADIATION FACILITY AND DOSIMERTY SYSTEM

Experimental validation of theoretical predictions for absorbed dose distribution formation into containers with product 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. JS-850 replenishment was in 2007 with total irradiator activity 98.484 Ci after source reloading. JS-850 comprise a typical flat panoramic Co^{60} irradiator with overlapping product, a water filled storage pool and shuffle–dwell conveyer system. Co^{60} source rack consist of 15 modules in 5x3 array. Only 4 modules in 2 x 2 array comprise the 10 pencils with active cobalt-60 slugs encapsulated into stainless steel capsule.

Conveyor system provides the following regimes irradiation the product containers, such as static, one pass continuous, multipass continuous or multipass shuffle–dwell. The aluminum containers with product are pneumatic moved around the Co^{60} source rack on a conveyor in 4 parallel rows at two levels on each sides of the source rack. Two levels are characterized by horizontal and vertical movements of the product containers. There are 63 dwell positions for the product container at eight passages. Position on one corner is empty. As a result, the product container irradiated with gamma ray at two sided. The aluminum container size is 60cm (width), 50cm (depth), and 90cm (height) with wall thickness in 2mm.

The absorbed dose distributions were measured with Ethanol Chlorobenzene (ECB) routing dosimeters. ECB dosimeter consists of dosimetric solution encapsulated in glass ampoule with diameter 10.7mm and volume 2ml. This dosimeter comprises an aerated solution of Chlorobenzene and water in ethanol to which a small quantity of acetate is added. The absorbed dose was calculated from a calibration curve connecting it with the electric conductivity of the dosimetric solution measured with oscilotitrator.

The maximum of the combined uncertainty related to dose determination in the heterogeneous targets with ECB dosimeters did not exceed 7.6 % (for 2 standard deviations). The uncertainty is a combination of the uncertainties related with dosimetry system calibration, in reproducibility of the series of experiments, irradiated materials into container variability, oscillometric reader variability.

Two benchmarking (BM) experiments were planned and performed on the gamma facility to validate software ModeGR.

1. The comparison of measurement and simulation results for dose mapping in 4 aluminum (Al) containers filled with reference materials and routing dosimeters irradiated with gamma ray and located on the lower and top levels of the conveyer line was planned in the BM-1 task. Product containers were irradiated in static position near the center of gamma source rack. In this special case the big gradient in the ADDs along all axises of container with gamma irradiated product should be observed.

2. The comparison of measurement and simulation results for the dose uniformity ratio (DUR) in Al containers filled with medical devices such as hemodialyzers and routing dosimeters irradiated with gamma ray in all 63 dwell positions was planned in the BM-2 task. It is a typical task in the technology related with radiation sterilization of medical devices. In this case the gamma ADDs should be uniform in the irradiated product in the range which is characterized by value of DUR = D_{max}/D_{min}, where D_{max} and D_{min} - maximum and minimum absorbed dose in an irradiated product.

GEOMETRICAL MODELS OF GAMMA RADIATION FACILITY FOR MC SIMULATION

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. Panoramic irradiators are more suitable for industrial gamma ray processing.

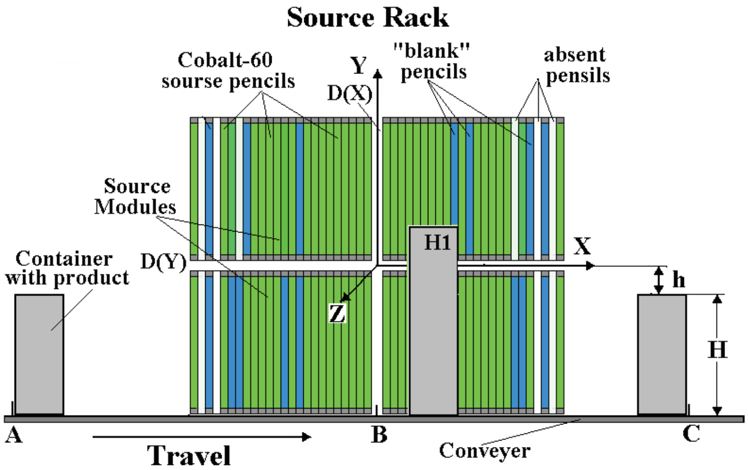

Fig.1. Geometrical arrangement of ^{60}Co source modules, conveyer and containers with product. The model of flat panoramic source rack comprises of four source modules, in 2 x 2 array.

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:

• static 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.1. 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.1. 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 2×10 array.

The schematic model of the flat panoramic source rack with arrangement of source modules, conveyer and irradiated containers with product is presented in Fig.1.

Distance D(X) and distance D(Y) characterize the displacement between modules along axis X and axis Y. Point A on Fig.1 characterize the entrance of back side of container with product into gamma radiation field (into irradiation room) in direction of conveyer movement.

Point C on Fig.1. characterize the exit of front face of container with product out gamma radiation field (out of irradiation room) in direction of conveyer movement. The container with product can continuously or discretely move on a conveyer platform in parallel with surface of source rack from the point A to the point C.

The computer model allows calculate:

• the transit dose - the dose received by the product in its movement into and out of the irradiation field (i.e. from the point A to first dwell position plus from end dwell position to the point C);

• the shuffle dose - the dose received by the product during its movement from one dwell position to the next.

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.2. The 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.

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 passes and 64 for the eight passes. As a result, the product irradiated with gamma ray at two sided.

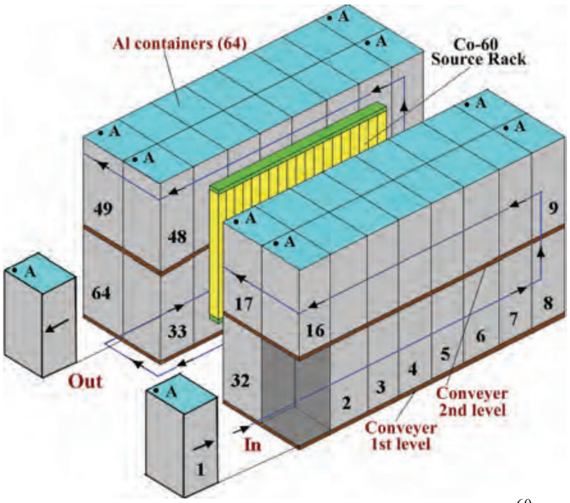

Fig.2. Sequence of irradiation in a flat panoramic Co^{60} source rack, multipass, two direction, multiposition.

The 64 aluminum containers with product are moved around the Co^{60} source rack on a conveyor 8 passes at two levels. "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, with four passes on each side of the source

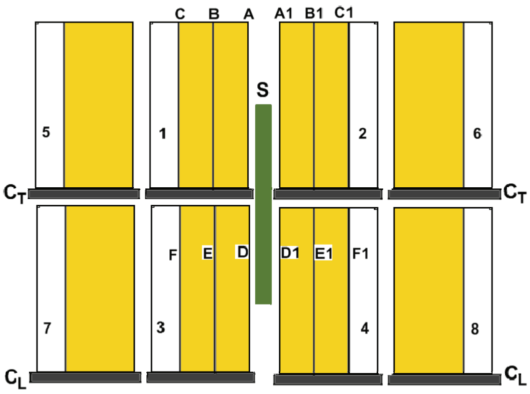

Fig.3. Experimental setup. S – gamma source rack, C_T – conveyer line on the top level, C_L – conveyer line on the lower level, 1, 2, 3, 4 –containers with reference materials and dosimeters, 5, 6, 7, 8 – containers with reference materials. A, B, C and A1, B1, C1 – positions of carton plates with dosimeters in two containers on the top level of conveyer line symmetrically from opposite side of source rack, D, E, F and D1, E1, F1 - positions of carton plates with dosimeters in two containers on the lower level of conveyer line symmetrically from opposite side of source rack.

DOSE MAPPING IN CONTAINERS WITH REFERANCE MATERIALS AND WITH MEDICAL DEVICES

In the first BM-1 experiment, four aluminum containers filled with reference materials and dosimeters were located near the center of source rack. Two containers were located on the lower level of conveyer line symmetrically from opposite side of source rack and two containers were located on the top level of conveyer line symmetrically from opposite side of source rack and symmetrically relatively two containers on the lower level. These containers were close surrounded from all side with the same containers filled with reference materials only without dosimeters. The package of gypsum-carton plates was used as reference material.

Fifteen ECB dosimeters were bonded to the specially made carton plate in different positions. Three carton plates with dosimeters were inserted between gypsum-carton plates on various distance from the entrance surface of Al containers.

1st carton plate with dosimeters was inserted between inner part of front side of aluminum container and the package of gypsum-carton plates.

2nd carton plate with dosimeters was inserted into the package center between gypsum-carton plates.

3d carton plate with dosimeters was inserted after the package of gypsum-carton plates.

Forty five dosimeters were located in each container with reference materials.

Full size of the package of gypsum-carton plates with dosimeter plates was 58x27x90cm, where:

the size 58cm located in parallel with source rack surface in direction of conveyer movement **(axis X),**

the size 90 cm - in parallel with source rack surface in direction of source rack height **(axis Y),**

the size 27cm is the package thickness of gypsum-carton plates with dosimeter plates and located perpendicular to source rack surface **(axis Z)** (See Fig. 3).

The grid of dosimeters in one container with reference materials is presented in Fig. 4a. The plates with 15 dosimeters in the first container are marked by A, B and C, in the second container – by A1, B1 and C1. Plates A and A1 are the entrance plates for gamma rays which are located from opposite sides of source rack. At that, all dosimeters with the same number in the two containers are symmetrically located from opposite side of source rack. Carton plates A and A1 with dosimeters were positioned on the distance 1cm from the entrance surface of Al containers. Carton plates B and B1 – on the distance 13cm, carton plates C and C1 – on the distance 27cm from the entrance surface of Al containers. The same dispositions of carton plates D, E, F and D1, E1, F1 with dosimeters are observed in two containers on the lower level.

The dispositions of 15 dosimeters on all carton plates along the height of source rack **(axis Y)** and along conveyer movement **(axis X)** are the same. An example dispositions of all 15 dosimeters on carton plate A1 is presented in Fig.4b. Counting of the dosimeter coordinates are carried out from right top corner of container side which is parallel to surface of source rack. All containers with reference materials and dosimeters were irradiated in static position 5400 s (90 min).

For the simulation of the absorbed dose in the gamma-irradiated product, accounting for the difference of gamma source activity in comparison with time of the source replenishment and time experiment was performed in accordance with the MDS-Nordian Table "Timer-Setting Table for Irradiator" by multiplication of the dwell time value by a coefficient 0.76.

This comparison experiment allows to investigate in detail the dose map structure in the reference materials in the positions of maximal activity of the gamma source rack. In these four positions all irradiated product obtained maximal value of the absorbed dose in comparison with the other 59 positions.

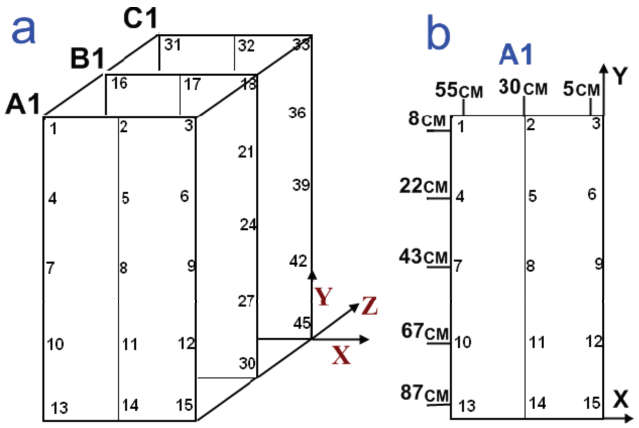

Fig.4. Dosimeters location in container.
a) Grid of dosimeters in container with reference materials.
b) The dispositions of 15 dosimeters on A1 carton plate along the height of source rack (axis Y) and along the conveyer movement (axis X), in cm.

In the process of experimental data handling of the absorbed dose map in 4 containers with reference product irradiated with gamma ray on two levels of conveyer system the following results were obtained for further analysis:

• The values of dose averaging over two dosimeters with the same number which are symmetrically located in two containers from opposite side of source rack on the lower and top levels. Dosimeters with the same number with symmetrically positions in two containers from opposite side of source rack are located in the pair sheets on the top level A-A1, B-B1, C-C1 and on the lower level – D-D1, E-E1, F-F1 (See Fig. 3).

• The absolute values for difference of absorbed dose values between two dosimeters with the same number which are symmetrically located in two containers from opposite side of source rack.

In the second BM-2 experiment a some aluminum containers filled with medical devices such as hemodialyzers were irradiated with gamma ray at two sided due to eight passes at two levels in all 63 dwell positions. 4 carton boxes with 20 hemodialyzers in each box were inserted in each aluminum container. Hemodialyzer construction mainly includes PE cylinder with diameter 3.8 cm and length 29cm which is filled with filter made of cellulose and closed from two sides with plastic cap. 4 carton boxes with size 38×29×35.5 cm were placed in 2(axis Y)x 2(axis X) array in each container. 20 hemodialyzers in 5(axis Z)×4(axis X) array were located in each carton box.

In one of container in each of four boxes 6 ECB dosimeters were bonded to 6 hemodialyzers at the center length of PE cylinders. ECB dosimeters in each box were bonded to the 1st , 3^{d} and 5th cylinders in the 1st row and to the 16th, 18th and 20th cylinders in the 4th row. All number of ECB dosimeters in the container was 24.

Container with dosimeters was located in the middle of containers group with hemodialyzers. Containers group with hemodialyzers was surrounded from all side with the containers filled with reference materials.

Container with hemodialyzers and with dosimeters was gamma irradiated in all 63 dwell positions with dwell time 2570 second. Bulk density of product in container was 0.054 g/cm^3.

RESULTS AND DISCUSSIONS

BM-1 experiment. Four aluminum containers filled with reference materials and dosimeters were irradiated in static positions near the center of source rack. Simulation of the gamma absorbed dose distribution in the containers filled with reference materials and dosimeters materials was carried out by the software ModeGR.

The irradiation method "Discrete mode" in the software ModeGR allows to simulate the product irradiation in a stationary regime. To do so, it has to be specified that the irradiation will be performed in 3 positions ("Number of positions" = 3), see Fig.1. Moreover, the left and right boundaries of irradiation must be set greater than source rack size (parameters "Left part of irradiation field" and "Right part of irradiation field"). For this case, the 1st and 3^{d} container positions will be located relatively to the source rack center on the distance values which are marked in the windows "Left part of irradiation field" (point A, Fig.1) and "Right part of irradiation field" (point C, Fig.1). The 2nd container position will be located in the point of conveyor line equal to the half of distance between the 1st and 3^{d} container positions. In the case when the values of "Left part of irradiation field" and "Right part of irradiation field" are equal, the container in 2nd position will be located near the center of gamma source rack (point B, Fig.1) and contributions from containers in the 1st and 3^{d} positions can be neglected.

The comparison of simulation and measurement results for dosimeters which are located on the pair carton sheets A-A1, B-B1, D-D1, D-D1, E-E1and F-F1 in two containers from opposite side of source rack on the conveyer top and lower levels as function of containers height (axis Y) are presented in the Fig.5. As it is seen from the Fig.5. the big gradient of the absorbed dose values in the containers are observed along 3 spatial axises (X, Y, Z). The values of absorbed dose in positions Z=1cm, Z=13cm and Z=27cm are characterized the behavior of the gamma dose distributions along container thickness, axis Z. The values of absorbed dose in positions X=5cm, X=30cm and X=55cm are characterized the behavior of the gamma dose distributions along container width, axis X.

The comparison of simulation and measurement results for dosimeters which are located on the pair carton sheets A-A1, B-B1, D-D1 in two containers from opposite side of source rack on the conveyer top level has the same behavior as in on the pair carton sheets D-D1, E-E1and F-F1 on the conveyer lower level.

Detailed analysis of experimental results into BM-1 experiment have shown that the maximal difference of absorbed doses for two dosimeters with the same number with symmetrically positions in two containers from opposite side of source rack for top level is 1 kGy, for lower layer - 0.8 kGy. Such difference is less than 7% of maximal value of the absorbed dose in an irradiated material.

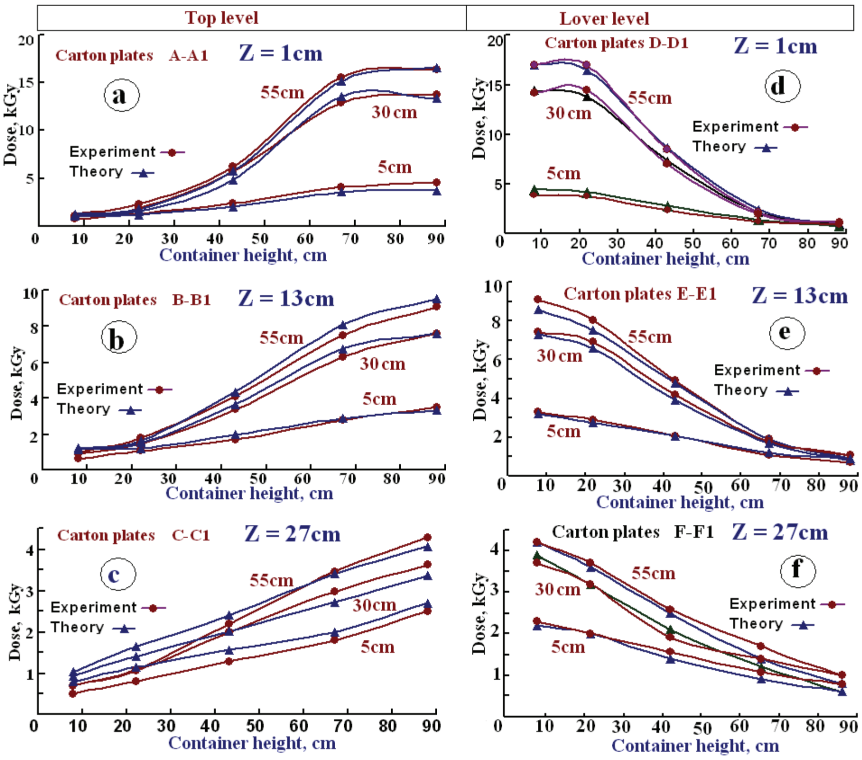

Fig.5. The absorbed dose distributions into dosimeters located on the pair carton sheets in two containers from opposite side of source rack as function of container height (axis Y). (a) Carton sheets A-A1, (b) B-B1, (c) C-C1 on the conveyer top level, and (d) carton sheets D-D1, (e) E-E1, (f) F-F1 on the conveyer lower level.

Maximal difference of the absorbed doses for two dosimeters with the same number with symmetrically positions in two containers from opposite side of source rack for top level is 1.4 kGy, for lower layer - 0.6 kGy.

Thus, it is possible to approve, that satisfactory agreement between results of computer modeling and dosimetric results in the main spatial areas of absorption of gamma ray energy is observed.

The differences which are observed in spatial points with small values of the absorbed dose from gamma radiation are related to the essential contribution to these points the gamma radiation scattered from walls of a room in which gamma source rack is located.

At computer simulation of the absorbed dose in materials irradiated with gamma ray, the influence of construction elements of radiation installation such as the rollers of conveyer system and other elements was not taken into account. It is necessary to carry out more precise experiments to estimate the influence of construction elements of radiation installation on formation of absorbed dose in gamma irradiated product. Such experiments will be carry out in a future.

On the basis of obtained data it is possible to estimate the value of the not taken into account the multiple scattered irradiation with the use of difference between calculated and measured values of the absorbed doses. For analyzed experiment this value can be estimated as value about 1 kGy.

BM-2 experiment. The comparison of simulation and measurement results for absorbed dose distributions in product container with hemodialyzers are presented in the Table.

The computer simulation with software RT-Office of the gamma dose map in product container loaded with hemodialyzers irradiated in regime of shuffle-dwell mode was performed in two stages:

• obtaining the data set for absorbed dose distributions in product container in each separate pass/level/side along gamma source rack (software ModeGR),

• building the dose map in an irradiated product on the base of the data set obtained for separate passes with variable parameters of irradiation (software RT-Builder).

It should be noted, that RT-Office is optimal for complicated radiation processes by using multi-stage simulation technology. In the 1st stage, the set of absorbed dose distributions in the product container will be calculated and stored for the following passes: top level - 1st row, top level – 2nd row, lover level - 1st row, lover level – 2nd row. The set of absorbed dose distributions were calculated with ModeGR. Let's assume that conveyor line is symmetrical relatively to the source rack and containers are homogeneously loaded with product. Then the dose distributions data into 8 passes can be obtained on the base of previously calculated dose distributions (at the 1st stage) for one pass by symmetry considerations.

RT-Builder was used at the 2nd stage. RT-Builder is the specialized tool of RT-Office for the calculation and analysis of the cumulative 3D dose distribution in product irradiated with various methods, such as multi-pass, multi-level, or multi-sided. The example below (see Table) is the simulation of a 3D dose distributions in a product container loaded with hemodialyzers.

Analysis of simulation and measurement results (see Table) into BM-2 experiment have shown that spatial dose distribution in the container with hemodialyzers is close to uniform. In this case the values of average dose (D_{av}) and dose uniformity ratio (DUR) may be used for performing comparison of simulation and experimental data. Analysis results: for experiment D_{av} =22.2 kGy, DUR =1.1, for simulation D_{av} = 22.3kGy, DUR =1.1. Such coincidence of comparison results indicates that satisfactory agreement between results of computer modeling and dosimetric results is observed.

Table

Comparison of Simulation and Experimental results

		Lower level	Experimental Data	
Y=72cm	1st box			2nd box
X, cm	56cm	36cm	24cm	4cm
Z=4cm	22.6	23.24	21.97	20.43
Z=20cm	20.43	21.04	21.35	23.24
Z=37cm	20.43	21.97	22.6	23.24
		Top level	Experimental Data	
Y=36cm	3d box		4th box	
	Dose, kGy	Dose, kGy	Dose, kGy	Dose, kGy
X, cm	56cm	36cm	24cm	4cm
Z=4cm	21.97	23.24	23.24	23.24
Z=20cm	21.66	21.97	22.6	21.97
Z=37cm	21.97	22.6	22.6	22.6
		Lower level	Simulation	Data
Y=72cm	1st box			2nd box
X, cm	56cm	36cm	24cm	4cm
Z=4cm	22.1	22.6	22.5	22.9
Z=20cm	22	21.6	21.6	21.9
Z=37cm	22.1	22.6	22.5	22.9
		Top level	Simulation	Data
Y=36cm	3d box			4th box
X, cm	56cm	36cm	24cm	4cm
Z=4cm	22.5	22.6	22.5	23.3
Z=20cm	21.8	21.6	21.5	21.6
Z=37cm	22.5	22.6	22.5	23.3

It should be note, statistical analysis of deviations of experimental from simulation data for absorbed doses have shown that the deviations have stochastic character and can be interpret as statistical errors of experiment and simulation.

CONCLUSION

In two BM experiments the measured absorbed dose of Co^{60} gamma rays in dosimeters located into product are in agreement with the results obtained with the ModeGR software. This agreement indicate that the developed mathematical model in the ModeGR software is reliable and can be used for simulation of gamma ray processing. The comparison of simulation and experimental results show that ModeGR software can be used as a predictive tool for detailed dose mapping in an irradiated product on the Co^{60} industrial radiation facility.

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