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Computer simulation of radiation processing on industrial gamma J-9600 Co^{60} irradiator

A. A. Abdel-Fattah*, A. M. Mohammed Bayomi*, G. Popov, Yu. Rogov

V.N.Karazin Kharkov National University, Kharkov, Ukraine

**National Center for Radiation Research and Technology, Cairo, Egypt*

Computer simulation of radiation processing on the industrial gamma facility of the National Center for Radiation Research and Technology, NCRRT, Cairo, Egypt are considered in the paper. Egypt's industrial Mega Gamma-1 facility is based on J-9600 Co^{60} flat panaramic wet source storage industrial irradiator with designed and produced by MDS Nordian, Canada. The absorbed dose distributions of gamma rays in an irradiated product on J-9600 Co^{60} flat panoramic source rack irradiator have been calculated with the ModeGR and RT-Builder softwares. Absorbed dose map in gamma irradiated product with various uniform density and characteristics such as dose uniformity ratio (DUR) and throughput were investigated. The features analysis of computer simulation results are discussed.

Keywords: *computer simulation, SW ModeGR, gamma radiation, absorbed dose distribution.*

У роботі приводяться результати комп'ютерного моделювання процесу опромінення на промисловій гама радіаційній установці Національного Центру Радіаційних Досліджень і Технологій, Каїр, Єгипет. Промислова Мега Гама-1 установка базується на плоскому панорамному гама випромінювачі J-9600 Co^{60} мокрого зберігання у басейні, який розроблено і виготовлено Канадською компанією MDS Nordian. Розподіл поглиненої дози гама випромінювання в продукції на плоскому панорамному гама випромінювачі J-9600 Co^{60} розраховувався програмами ModeGR і RT- Builder. Досліджено карту поглиненої дози гама випромінювання в продукції з однорідною густиною, неоднорідність поглиненої дози і продуктивність опромінюємої продукції. Обговорюється аналіз особливостей результатів комп'ютерного моделювання.

Ключові слова: *комп'ютерне моделювання, програма ModeGR, гама випромінювання, розподіл поглиненої дози.*

В работе приводятся результаты компьютерного моделирования процесса облучения на промышленной гамма радиационной установке Национального Центра Радиационных Исследований и Технологий, Каир, Египет. Промышленная Мега Гамма-1 установка базируется на плоском панорамном гамма излучателе J-9600 Co^{60} мокрого хранения в бассейне, которая разработана и изготовлена Канадской компанией MDS Nordian. Распределение поглощенной дозы гамма излучения в облучаемой продукции на плоском панорамном гамма излучателе J-9600 Co^{60} рассчитывалось программами ModeGR и RT-Builder. Исследовано карту поглощенной дозы гамма излучения в продукции с однородной плотностью, неоднородность поглощенной дозы и производительность облучаемой продукции. Обсуждается анализ особенностей результатов компьютерного моделирования.

Key words: *компьютерное моделирование, программа ModeGR, гамма излучение, распределение поглощенной дозы.*

1. Introduction

Gamma ray irradiator like 60Co became popular radiation sources for medical and industrial applications. More than 250 gamma ray irradiators are currently in industrial 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 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].

Implementation 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 [4, 5, 6,7].

Results of detailed simulation with standard ITS Monte Carlo code and validation of irradiation process on industrial gamma facility are presented in the paper [5]. Simulation and validation of irradiation process were performed only in some positions of product container relatively to the flat panoramic gamma source rack. At that, the significant operational parameters for gamma irradiation process such as Dmin, Dmax, dose uniformity ratio (DUR) and throughput, that are used for quality control of process irradiation and profitability of gamma processing cannot be obtained. Utilization of standard package of ITS Monte Carlo code makes it difficult an obtaining the simulation results for absorbed dose distribution of gamma rays into irradiated product with good three-dimensional resolution and small statistical uncertainties. Point Kernel code that was used at simulation, do not allow to obtain correct values for absorbed dose distribution of gamma rays near the boundary of contacting materials with big difference of density and atomic numbers.

Authors have developed the softwares ModeGR and RT-Builder specially for simulation of the 3D absorbed dose distributions (ADD) within multi-layer packages irradiated with gamma ray from flat panoramic Co60 source rack using a Monte Carlo (MC) method [6, 7].

The software ModeGR was used for development of model for the Co60 industrial irradiator J-9600 and calculation of the 3D dose distributions in product on the industrial Mega Gamma-1 facility [8]. Software RT-Builder was used for calculation of the cumulative 3D dose distributions in product and analysis an effectiveness of gamma irradiation process with various methods, such as multi-pass, multi-level, or multi-sided.

Analysis of technical and operational parameters for Egypt's industrial Mega Gamma-1 facility in accordance with technical documents and selection of simulation parameters for approximation of complicated elements of radiation facility in the frame of simple geometrical models for Software ModeGR will be presented in the paper. Considerable attention has been given to the model of conveyer line, because the value of Dmin into irradiated product is located near the boundary with conveyor line in the area of big heterogeneity of construction elements.

2. Gamma radiation facility and simulation model of radiation processing
2.1.Gamma radiation facility

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.

The source rack in the Mega Gamma-1 facility designed and built by MDS Nordion comprise 6 modules with 60Co source pencils C-188 which were mounted by 3 modules in two levels [8]. Each module comprise various number of the active 60Co source pencils from 15 up to 37. Summarized gamma activity of all 160 active 60Co source pencils in 6 modules was 415901Ci of 60Co of average energy of 1.25MeV in October 2012. 60Co energy of 1.25MeV is the result of averaging two gamma lines of 1.17 and 1.33 MeV. The schematic model of the flat panoramic source rack with arrangement of source modules is presented in Fig.1.

Module 1 comprise 37 active pencils, module 2 - 36 active pencils, module 3 - 30 active pencils, module 4 - 27 active pencils, module 52 - 15 active pencils, module 6 - 15 active pencils. All active pencils have individual value of activity in the range from 778.6 Ci up to 4756 Ci.

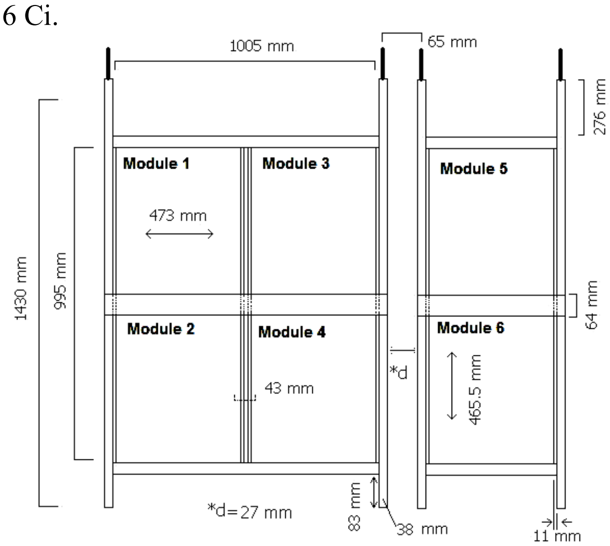

Fig.1. Arrangement of source modules in the NCRRT panoramic source rack with active cobalt-60 source pencils

In this irradiator product is loaded into aluminium totes with dimensions 52 cm long x 54 cm wide x 90 cm high. The totes are moved through the gamma irradiation field on a system of tracks and rollers by pneumatic cylinders and an elevator. The totes pass a rectangular source rack in four parallel rows; two on each side of the source rack at each of two levels. The totes first travel along four rows at the upper level. They are then lowered on an elevator and travel along the four rows at the lower level. The irradiator is shown in plan view in Fig.2.

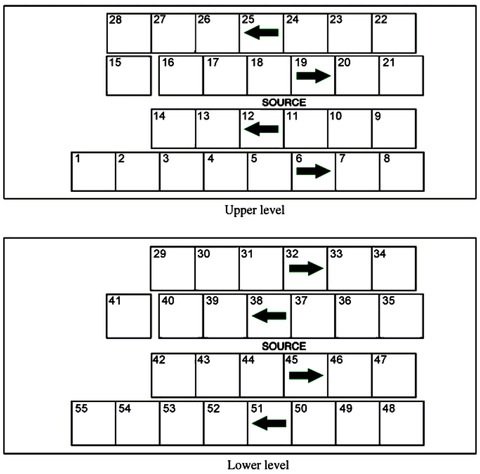

Fig. 2. The sequence of product totes movement at upper and lower levels

2.2. Simulation model for gamma radiation facility

Detailed 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 tote with homogeneous materials as well as of tote filled with stack of plates. The stack of plates can be interleaved with dosimetric films.

In the simulation 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 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. All pencils types have the same geometrical characteristics but they can have various activity the ^{60}Co.

The computer model allows calculate:

• the transit dose - the dose received by the product in its movement into and out of the irradiation field;

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

The software ModeGR allows calculate the absorbed dose distributions and dose uniformity within product irradiated on Co60 shuffle–dwell irradiator. The absorbed dose distribution can be calculated for various number totes with irradiated product in the row, various number passes of totes in front of gamma source rack, and various number dwell positions in the row.

As example, the schematic model of a typical Co60 multipass shuffle–dwell irradiator with overlapping product to gamma source configuration is presented in Fig.3. The totes with product are located on bottom and top horizontal conveyer lines. The 56 aluminum totes (containers) with product are moved around the Co60 source rack on a conveyor 8 passes at two levels. Two levels are characterized by horizontal and vertical movements of the product totes. This model is more close to the Co60 industrial irradiator J-9600. In this model each of 160 active pencils was individually modeled.

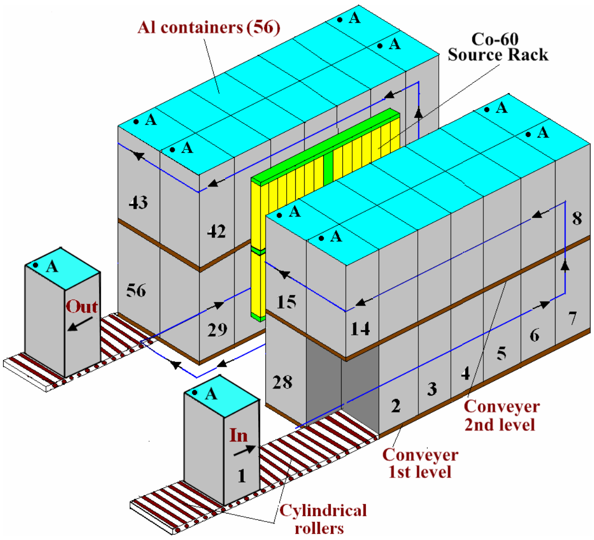

Fig.3. Sequence of irradiation in a flat panoramic Co^{60} source rack, multi-pass, two direction, multi-position. "A" is a fixed point on the side surface of the process load, which passes through the irradiation room on both sides of the Co^{60} source rack from position 1 to position 56, with four passes on each side of the source.

Conveyer line comprise cylindrical rollers made of steel. Diameter of rollers is 42mm, the cylindrical wall thickness of rollers is 2mm, the distance between rollers is about 10 cm. Cylindrical rollers of conveyer line can partly absorbed gamma flux from source rack. This effect can be influence on values of ADD, DUR and throughput in gamma irradiated product totes. Cylindrical rollers were modeled as steel layer with thickness of 42mm and density 0.5 g/cm^3.

In multipass shuffle–dwell mode of operation, the product totes 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 tote irradiated at each dwell position (in all loops around the source) before leaving the irradiation room. There are 7 dwell positions for each of the passes and 56 for the eight passes. As a result, the product totes irradiated with gamma ray at two sided.

It should be note that conveyor lines with product totes are symmetrically located relatively to the flat panoramic source rack, See Fig.3. Therefore we can simplify the Monte Carlo calculation process for the absorbed dose distributions in product tote. For that we should divide the process simulation on 3 stages.

1st stage, software ModeGR: Calculation of the absorbed dose distributions in product tote irradiated gamma only from one side of the Co^{60} source rack on the top conveyer lines with two passes product tote positions 1 - 14, and on the bottom conveyer lines with two passes product tote positions 15 - 28.

2nd stage, SW RT-Builder: Inversion of the obtained data relatively surface of the Co^{60} source rack.

3^{d} stage, SW RT-Builder: Summation the results from 1st and 2nd stages.

In some cases the totes with product can be also located and irradiated symmetrically on the bottom and top horizontal conveyer lines, See Fig.3. In this simplified variant the process simulation will be divided on 4 stages.

1st stage, software ModeGR: Calculation of the absorbed dose distributions in product tote irradiated gamma only from one side of the Co^{60} source rack on the top conveyer lines with two passes product tote from positions 1 to 14.

2nd stage, SW RT-Builder: Inversion of the obtained data relatively the top conveyer line of the 1st level.

3^{d} stage, SW RT-Builder: Inversion of the obtained data relatively surface of the Co^{60} source rack.

4th stage, SW RT-Builder: Summation the results from 1st, 2nd and 3^{d} stages.

3.Simulation results of operational parameters

3.1. Influence of material density on operational characteristics

Absorbed dose map formation in gamma irradiated product with various density and characteristics such as dose uniformity ratio (DUR) and throughput were investigated in the gamma irradiation process using computational dosimetry method with software ModeGR and RTBuilder.

The computer simulation of the gamma dose map in product container loaded with dummy materials gamma 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 such simulation method 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 tote will be calculated with software ModeGR and stored for the following passes: top level - 1st row, top level – 2nd row, lover level - 1st row, lover level – 2nd row. In the 2nd stage, the set of absorbed dose distributions will be calculated with software RT-Builder.

Polyethylene (PE) and carbon of various density from 0.05 to 1 g/cm3 were used as dummy materials in all computer experiments.

The following computational experiments were performed:

• Calculation of an absorbed dose map and identification the positions of minimum and maximum gamma absorbed dose within the product containers,

• ADD calculation as function of dummy material density (carbon and polyethylene) in the range from 0.05 to 1 g/cm3,

• analysis of influence of the metal (steel) rollers of the conveyer line on the ADD formation, steel density was tested in the range from 0.001 to 7 g/cm3.

• calculation of DUR and throughput as function of gamma irradiated material density in the range from 0.05 to 1 g/cm3 and the tote size.

• calculation of the isodose curves for dose map in the middle and near the surface of gamma irradiated containers with product.

Some results of computational experiments are presented in Figs. 4, 5, 6.

Comparison results for dependences of gamma dose uniformity ratio (DUR) in the product containers on product density for gamma radiation facilities designs by MDS Nordian, Canada are presented in Fig. 4. Curves 1 and 2 represent of DUR dependence on product (PE) density for two typical different irradiator designs by MDS Nordion, Canada [9]. Curves 3 and 4 represent simulation results for dependence of DUR on product (PE) density for tested gamma radiation facility.

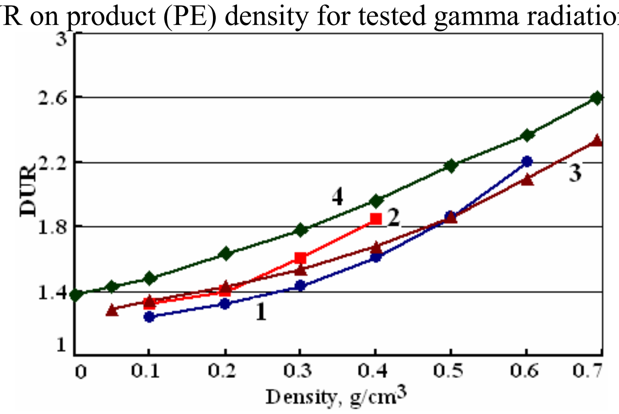

Fig.4. Curves 1 and 2 – Dependence of dose uniformity ratio (DUR) on product density for two different irradiator designs by MDS Nordion, Canada. Curves 3 and 4 – simulation results for dependence of DUR on product (PE) density for tested gamma radiation facility

Presented simulation results on Fig. 4. have shown:

• dependence DUR on product density in curves 3 and 4 has the same characters as in the curves 1 and 2, related with typical gamma irradiators designs by MDS Nordion, Canada [9];

• the value DUR depends on the product density;

• the value DUR increases with increasing density of the product and with increasing density of the conveyer line material. DUR is increased mainly due to decreasing the value of D_{min} with increasing density of the product and conveyer line material.

Results simulation of an ADD in form of isodose curves obtained in plane at the middle of the product container which is perpendicular to the source rack as function of the conveyer line material density are presented in the Fig.5. a, b. Conveyer line material made of steel with thickness 4.2 cm and various density: 0.001 g/cm^3 (Fig.5. a) and 7 g/cm^3 (Fig.5. b).

Analysis of simulation results for isodose curves in dose map near the middle and near the surface of gamma irradiated containers with product have shown that minimum dose locations were found in the center at the top and bottom and near the corners of the product container. The maximum dose locations were found near the product container surfaces which are parallel with the source rack.

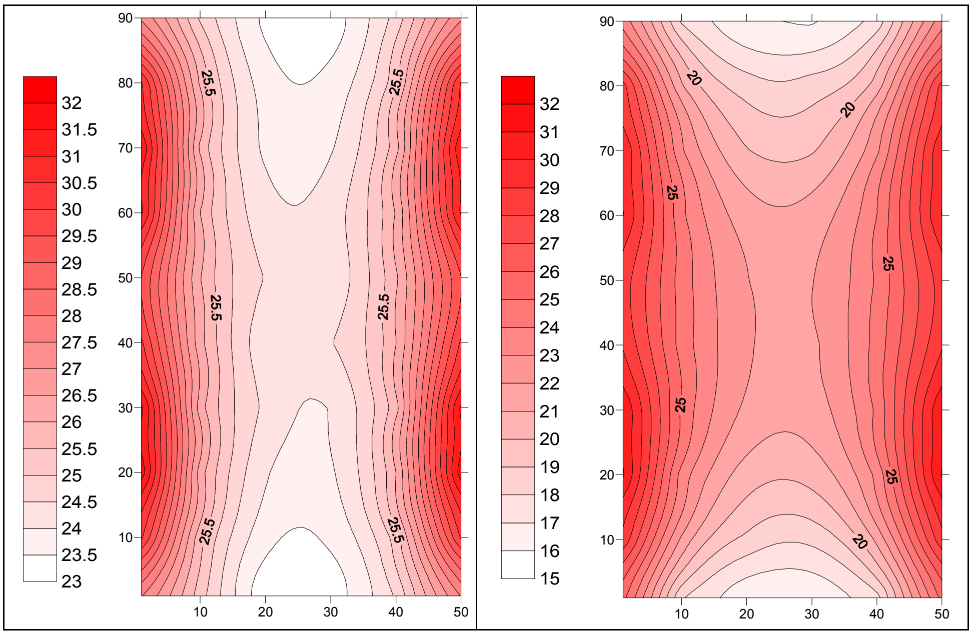

Fig. 5. Isodose curves in plane at the middle of the product container which is perpendicular to the source rack for 2 extreme cases. a) Metal density – 0.001 g/cm^3, DUR = 1.4, b) Metal density - 7 g/cm^3, DUR = 2.15

Fig. 6 illustrates how product density and metal density of conveyer line can affect on mass throughput. Radiation processing throughput is the amount (mass or volume) of product processed per unit time (such as, kg/h or m^3/h) and is determined by the radioactivity of the radiation source, product density and the product absorbed dose. Dependences of product mass throughput on product density (Curves 1 and 2) are presented for 2 typical gamma radiation facilities designs by MDS Nordian, Canada.

Curves 3 and 4 represent of simulation results for investigation of influence of the conveyer line material density on the mass throughput. Curve 3 was calculated at density 0.002g/cm3 of the steel layer, curve 4 - at density 1g/cm3 of the steel layer. Thickness of metal layer is 4.2 cm.

Presented results in the Figs. 3-6 have shown that irradiated product density and characteristics of conveyor line construction materials can essentially influence on an absorbed dose uniformity ratio and throughput of gamma irradiation process.

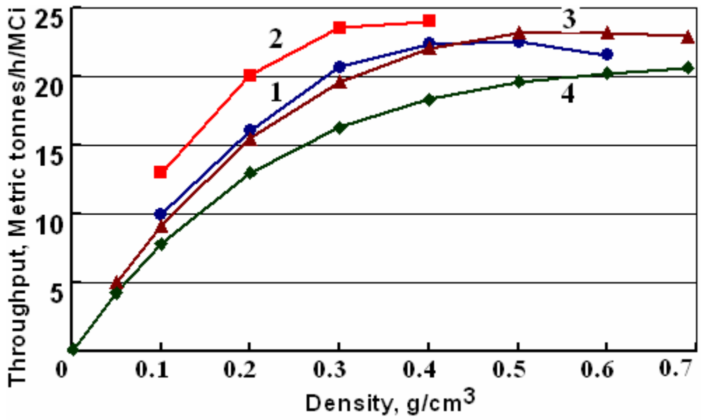

Fig.6. Curves 1 and 2 - dependence of product mass throughput at absorbed dose 1 kGy on product density for two irradiator designs by MDS Nordian, Canada. Curve 3 was calculated at density 0.002g/cm^3 of the metal layer, curve 4 - at density 1g/cm^3 of the metal layer

3.2. Estimation of uncertainties for simulation results

One of the basic questions for using theoretical predictions into practice is the question related with uncertainties for prediction results. Therefore the following computational experiments were performed:

• Investigation of an absorbed dose distribution (ADD) formation in gamma irradiated containers with product as function of containers number in the row - 7, 8 and 6&7 mixture containers in various rows. It was obtained that average absorbed dose and dose uniformity ratio into gamma irradiated product do not exceed 3-4%.

• ADD calculation as function of various distance between source rack and product container from 5 to 15 cm. Influence the distance between source rack and product container is more greater up to 8%. The distance should be controlled. The distance was taken into account from gamma facility documentation with accuracy 0.5cm.

• ADD calculation as function of displacement of product containers along axis Y in the range ± 10cm relatively irradiator central line (axis X). The same results as in previous point.

Obtained results made it possible to estimate some components of uncertainties for results simulation.

Conclusion

Technical and operational parameters for Egypt's industrial Mega Gamma-1 facility in accordance with technical documents were determined. The analysis of factors that determinative to the value of Dmin into gamma irradiated product was performed.

It was shown that value of Dmin into gamma irradiated product is located near the boundary with conveyor line in the area of big heterogeneity of construction elements. Therefore the model parameters of conveyer line should be selected on the base of dosimetric measurements.

Possibility of modeling parameters selection for approximation of conveyor line in the frame of simple geometrical model (layer of homogeneous material) for practical use of SW ModeGR was shown.

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