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New source models to represent the irradiation process in panoramic gamma irradiator

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HIGHLIGHTS

- Gamma radiation generates a number of technical problems.
- New methodologies have been proposed for irradiation simulation in a panoramic irradiator.
- Validation was performed by MCNPX calculations and experimental measurements.
- Results showed that the proposed methodologies well represent the irradiation process.

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ABSTRACT

The use of gamma irradiation technologies generates a number of complex scientific and technical problems; for example, the target is manually loaded onto turntables and is rotated during the entire irradiation process and the MCNPX three-dimensional geometry simulation is kept static. For this, it is necessary to introduce additional approaches. In this paper, two new methodologies are proposed for the simulation of irradiation process in panoramic gamma irradiator. The study was performed at the gamma irradiation facility at the Nuclear Technology Development Center of the National Nuclear Energy Commission, Brazil. The source can be reproduced with a homogenized geometry. Validation of MCNPX calculations of gamma doses were performed by thorough comparison with the experimental measurements. The contribution of this proposed source models has opened new lines of research. The results of this study showed that the proposed source models effectively represent the irradiation process.

1. Introduction

Presently, gamma irradiation technologies need to be studied in detail, because the results can vary considerably within different targets (density), exposure time (doses), and geometry (dose uniformity). The Nuclear Technology Development Center (CDTN), in Belo Horizonte, Brazil, has one GammaBeam – 127 (GB-127) gamma irradiation facility installed at the Gamma Irradiation Laboratory (LIG). This panoramic irradiator was manufactured by the MDS Nordion and has been in operation since 2002 (MDS Nordion, 2002). The source of the gamma irradiation facility has a maximum activity of 2.220 TBq (60.000Ci). The GB-127 is a dry storage gamma panoramic irradiator that uses Nordion's F-127 shipping container (Gual Maritza et al., 2015) for source storage and operation. Products to be irradiated are placed inside the biological shield, either on turntables or directly on the floor. The source is raised by a pneumatic system for a prescribed amount of time and then returned to the safe position inside the container. The source-to-product distance can be varied easily. The irradiator is a box chamber with high-density concrete walls. Fig. 1 shows the photo of the gamma irradiation facility with turntables and source shroud of the GB-127.

This irradiator has been used in a wide range of applications (Soares et al., 2009; Souza et al., 2011; Batista et al., 2013; Silva and Lameiras, 2014;Medeiros et al., 2015; Kadri et al., 2005; Ladeira et al. 2015).

Results of detailed simulation of the GB-127 gamma irradiator with Monte Carlo MCNPX v 2.6.0 code (Hendricks et al., 2008) and validation of simulation are presented in this paper. The calculated and measured doses were compared to validate the MCNPX model. In addition, the dose distribution calculations were compared in terms of isodose contours, and the resulting isodose curves were compared for

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Fig. 1. Gamma irradiation facility at the CDTN.

Table 1
Basic GB-127 parameters used in the MCNPX modeling.

Parameters Pencils	
Source model	C-198
Maximum height (mm)	209.9
Shape	Cylinder
Radionuclide	Co-60 solid
Active height (mm)	196.3
Maximum diameter (mm)	9.73
Encapsulation sources	
Inner encapsulation material	Ni
Thickness of Ni (mm)	5.0
Outer encapsulation material	316L stainless steel
Thickness of SS (mm)	63.5
Source in radiated position	
Radius source centerline to product centerline (mm)	1254
Radius source centerline to product edge (mm)	1000
Distance from the floor to the source centerline (mm)	575.0
Source shroud	
External radius (mm)	135.0
Material	Al
Thickness (mm)	20.0
Spacer rings of the sources racks	
Material	Al
Number	3
Geometry	Disk
Number of holes in the rings	24
Thickness (cm)	0.68
Inner diameter (cm)	11.9
Outer diameter (cm)	21.4
Plugin	
External radius (cm)	24.8
Height (cm)	23.8
Material	Pb
Plugin tube	
Inner diameter (cm)	5.6
Height (cm)	14.3
Material	316L stainless steel

the cylindrical irradiated target.

The target on turntables installed at the LIG can be irradiated in stationary, continuous, shuffle-dwell, or other modes. Two new methodologies are proposed for the simulation of the irradiation process.

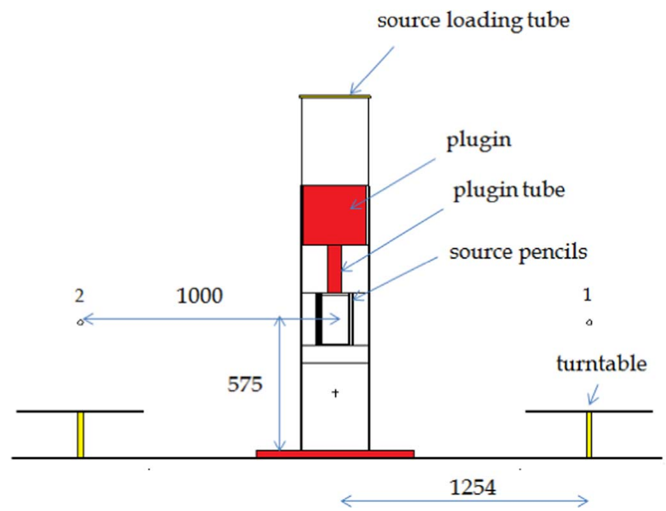

Fig. 2. Axial view of the GB-127 source MCNPX model. Plane XZ. Dimensions are given in millimeters.

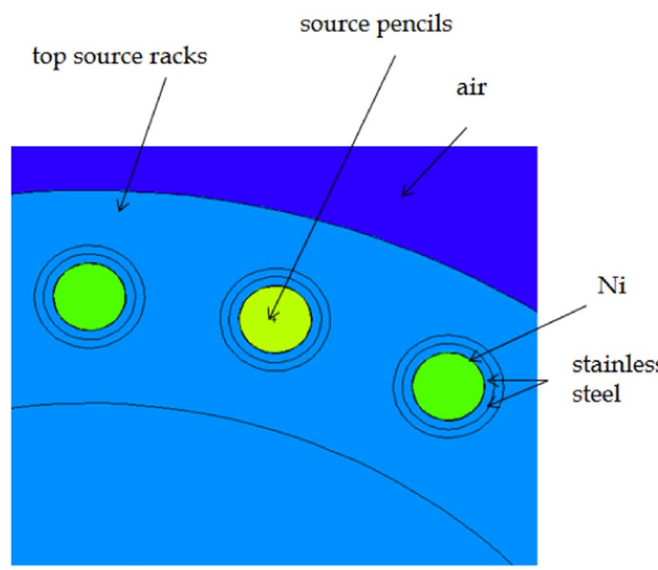

Fig. 3. Pencil source details in the simulation. Plane XY.

2. Materials and methods

The calculation is divided into the following stages:

1. Simulation of the irradiator room.
2. Validation of the irradiator MCNPX model by comparison with experimental measurements.
3. Implementation of the two new methodologies of dose calculation in MCNPX simulation: annular and cylindrical homogenized source.
4. Application of the proposed new homogenized source models on Dose Map Formation in an irradiated target.

2.1. Geometrical parameters of the irradiator

The source of the gamma irradiation facility is doubly encapsulated and contains either a Co-60 slug or Co-60 pellets. Co-60 slugs (small cylinders) are loaded into source elements in the form of "pencils," which are stored in dry conditions in a cylindrical aluminum shroud. One important simplification in this simulation was to consider the pencils as homogenized sources. The distribution of the source's activities is not homogeneous.

The Monte Carlo simulation considered several details of the

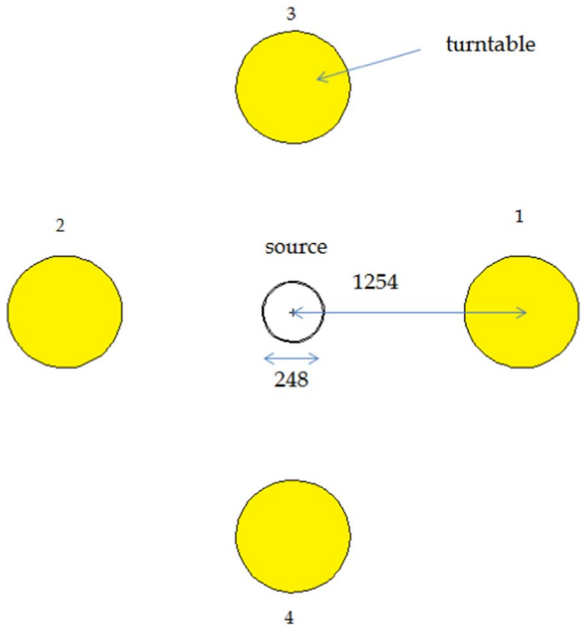

Fig. 4. MCNPX model of the GB-127 room with turntables. Plane XY. Dimensions are given in millimeters.

geometry and material structures of the GB-127 gamma irradiator as follows:

- The dimensions of F-127 aluminum shroud.
- The ^{60}Co source (formed by the circular arrangement of 16C-198 source model assemblies).
- The double encapsulation material of the sources, which has a stainless steel outer capsule.
- The radioactive contents in the form of ^{60}Co pellets.

Table 1 summarizes the main design parameters of the GB-127, which were used in the MCNPX modeling. All components of the irradiator were simulated.

The source was simulated using the Source Definition card SDEF, which defines a cylindrical source with diameter and length equal to the length of all the Co-60 pencils and parallel to the Z-axis with a distance of 63.5 mm (according to Fig. 1). The two ^{60}Co energy peaks of 1.1732 and 1.3325 MeV with emission probabilities of 0.9986 and 0.9998, respectively, were also considered in the simulation. The source was defined to be an isotropic source emitting gamma rays.

The MCNP option used for this problem was the energy deposition (tally mnemonic F6, in MeV/g/starting particle) for absorbed dose calculation (kerma approximation) in water. For photons, a conversion factor of 1 MeV/g = 1.602 E^{-07}J/kg was used to convert the F6 tally results from MeV/g/s/starting particle to the conventional units of absorbed dose in J/kg/starting particle, in mGy/starting particle. The source activity and the total photon emission from the source was multiplied to obtain the dose rate in mGy/h. The absorbed dose and the kerma practically coincide in the transient equilibrium region for Co-60 (Nilsson and Brahme, 1983).

The isodose curves will be obtained from "TMESH" mesh type 3 tally using "total" option to superimpose a rectangular mesh grid over the simulation geometry. The "total" contains energy deposition from all particles from the source, in units of MeV/cm^3 normalized by the source particle. A rectangular mesh is defined with 0.5 mm resolution. MATLAB software was used to generate the dose projection in different planes. The target material used in the analysis was water.

Table 2
Comparison between the values of the dose rates at a distance of 1 m in air from the source center for each position obtained from simulation and reference values.

Position	**MCNPX** **Absorbed dose rate** (Gy/h)	**MDS Nordion-supplied Fricke** **Absorbed dose rate** (Gy/h)	% Error
1	586.63	543.00	−8.03
2	589.61	556.00	−6.04
3	575.64	546.00	−5.43
4	573.40	556.00	−3.13

3. Results and discussion

3.1. MCNPX simulation

Fig. 2 shows the MCNPX XZ view of the source of the panoramic irradiator GB-127.

Fig. 3 shows the MCNPX XY view of the pencil source details of the panoramic irradiator GB-127.

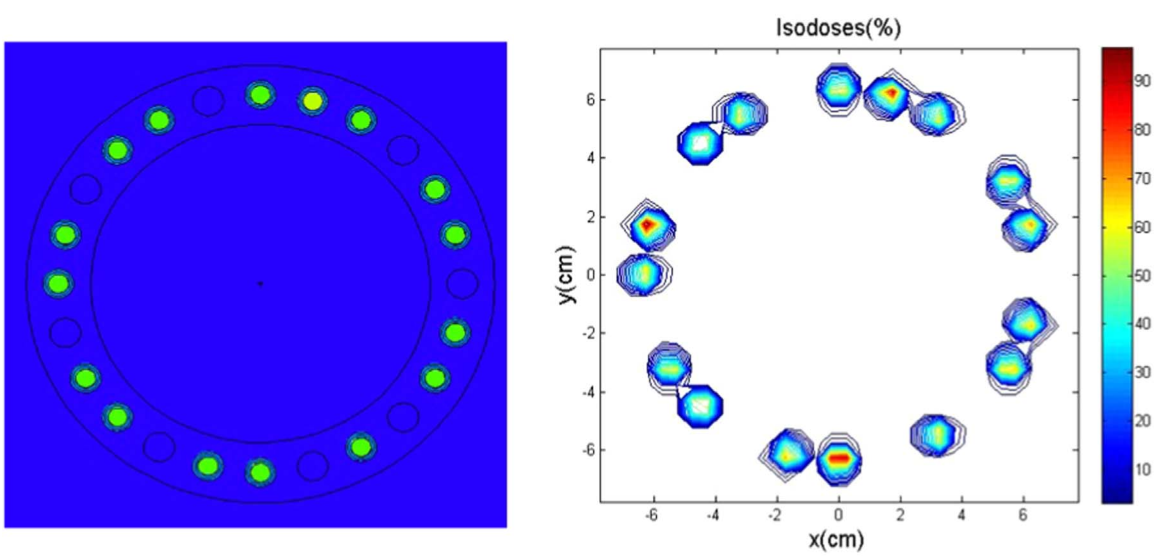

Fig. 5. The MCNPX model of C-198 source arrangement of Co-60 source pencils into gamma source rack (left) and isodose curve in % representation of XY view of the gamma dose rate distribution using MATLAB (right).

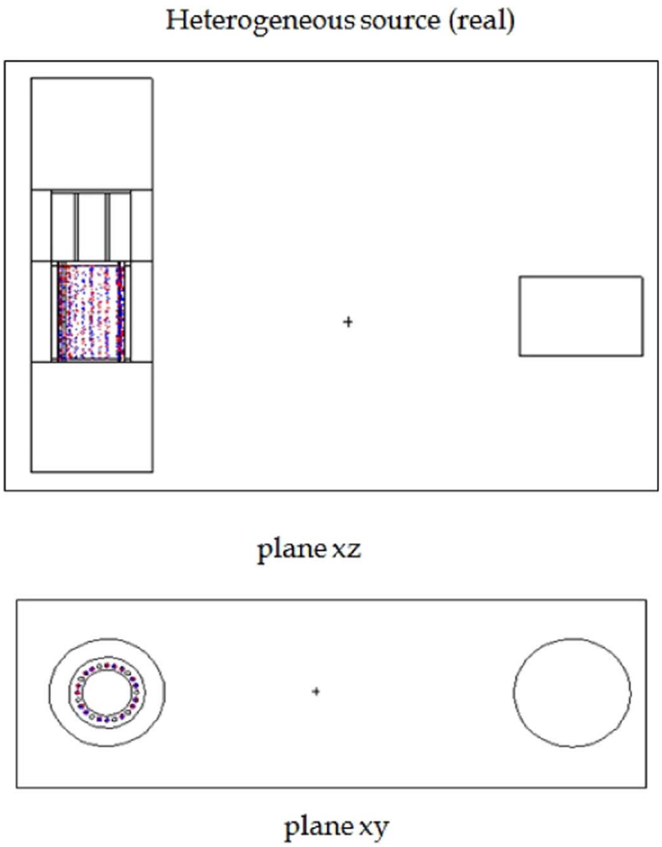

Fig. 6. Schematic representation of the real source (heterogeneous) used in the MCNPX simulation with spatial distribution of the particle tracks.

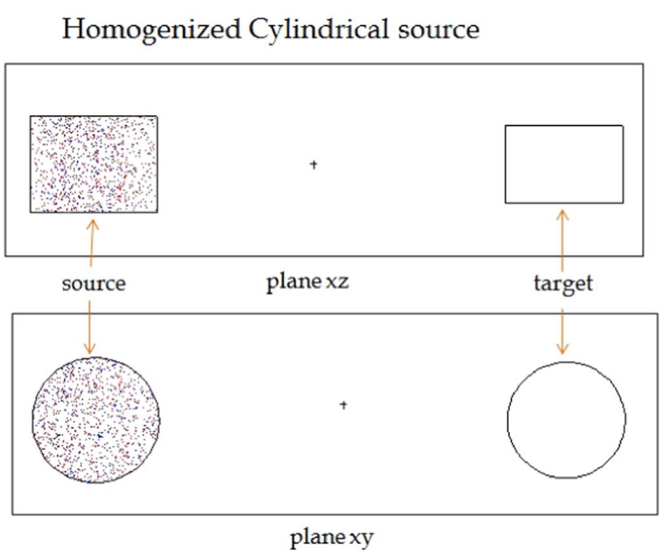

Fig. 7. Schematic representation of the homogenized cylindrical source used in the MCNPX simulation with spatial distribution of the particle tracks.

3.2. Validation of the MCNPX Model

The simulation for validation was performed considering that the detector was positioned in the source mid-height, at 1 m from the source. Figs. 4 and 5 illustrate the MCNPX model of the GB-127 room with the detector position.

Fig. 4 shows the four turntables arranged around the source. Note that 1, 2, 3, and 4 represent the points of calculations located at a distance of 1 m from the source center. The points are radially positioned and are at equal distances from one another.

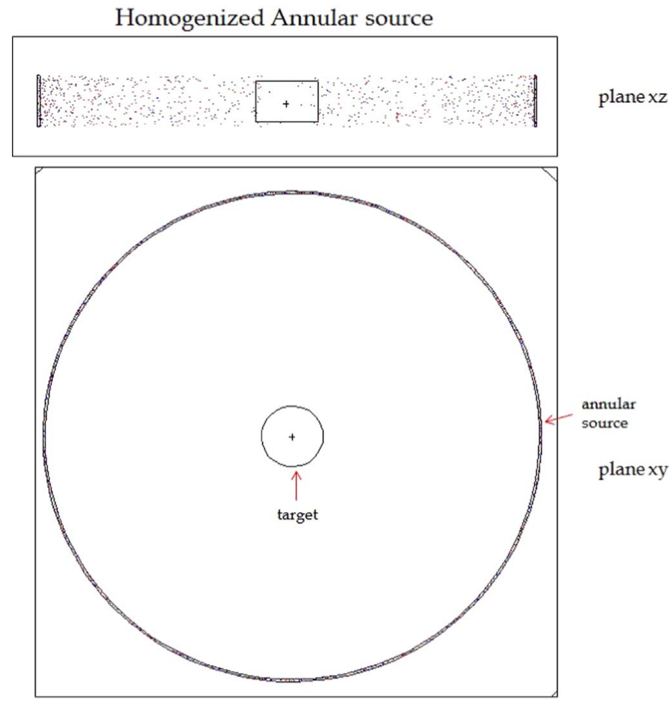

Fig. 8. Schematic representation of the homogenized annular source used in the MCNPX simulation with spatial distribution of the particle tracks.

The left panel in Fig. 5 shows an MCNPX model of C-198 source arrangement of Co-60 source pencils into gamma source rack, and the figure on the right shows an isodose curve in % representation of XY view of the gamma dose rate distribution using MATLAB.

To validate the simulation, dose rates were measured by MDS Nordion-supplied Fricke dosimeters at a distance of 1 m from the source center, near each of the turntables on August 30, 2002 (MDS Nordion, 2002). In this year, the source activity was 1924 TBq (52,021 Ci). The original configuration provided by the manufacturer in 2002 was considered during the validation. Table 2 presents the comparison between values of the dose rates at a distance of 1 m from the source center for each position, which were obtained from simulation using the MDS Nordion.

The MCNPX option used for validation was the energy fluence (tally Mnemonic *F5, in MeV/cm^2) for absorbed dose calculation. MCNP dose energy card (DEn) and dose function card (DFn) were used to introduce the conversion factors from energy fluence into the kerma in air. These factors are ($\mu_{en}(E)/\rho$) tabulated in Attix (2004). In the calculation using MCNPX *F5 tally, the relative error associated with the results were kept lower than 5% for all points of interest.

As shown in the table, error values were lower than 9% between MCNPX and measurement values. This confirmed that the geometric simulation, the source definition, and the calculation procedure of dose rates were satisfactory.

The success of simulation using the Monte Carlo code depends on the best parameters chosen for the simulation: atomic compositions of materials, details of the geometry, the physical model, transport methods, the correct choice of tally option, and cross-sectional libraries used by the codes representing each type of interaction of radiation with matter. These parameters are more crucial in the whole process of simulation and are necessary to better estimate dose values with greater accuracy.

Another source of discrepancies comes from the different flux-to-dose rate conversion coefficients used in the calculations. Clouvas et al. (2000) compared the dose rate conversion factors for external gamma exposure to photon emitters obtained by the three codes with the

Table 3
Data on the GB-127 source (9 zones).

Zone	Isotope	Composition (weight fraction)	Density (g/cm^3)	Mass (g)	Total Mass (g)
Co-60	Co-60	1	5	531.7888	531.7888
Ni	Ni	1	8.9	30.0485	30.0485
air	N	0.79	0.001205	0.1189	0.1505
(in the hole)	O-16	0.21		0.0316	
steel	Ni	0,1400	8.02	73.0242	521.2260
(pencil	Fe	0.61995		323.3669	
encapsulation)	Cr	0.18		93.8883	
	Mo	0.03		15.6480	
	C-12	0.00008		0.0417	
	Si-29	0.0075		3.9120	
	Mn	0.02		10.4320	
	P	0.00045		0.2347	
	S	0.0003		0.1565	
	N	0.001		0.5216	
Steel 2	Ni	0.1400	8.02	84.1485	600.6280
	Fe	0.61995		372.6276	
	Cr	0,18		108,1909	
	Mo	0,03		18,0318	
	C-12	0,00008		0,0481	
	Si-29	0,0075		4,5080	
	Mn	0,02		12,0212	
	P	0,00045		0,2705	
	S	0.0003		0.1803	
	N	0.001		0.6011	
Source holder	Ni	0.1400	8.02	330.1133	2356.2545
	Fe	0.61995		1461.8125	
	Cr	0.18		424.4314	
	Mo	0.03		70.7386	
	C-12	0.00008		0.1886	
	Si-29	0.0075		17.6846	
	Mn	0.02		47.1590	
	P	0.00045		1.0611	
	S	0.0003		0.7074	
	N	0.001		2.3580	
Air	N	0.79	0.001205	1.6740	2.1190
(in the center)	O-16	0.21		0.4450	
Air	N	0.79	0.001205	7.2083	9.1244
(inner sourceholder)	O-16	0.21		1.9161	
Air	N	0.79	0.001205	1.2346	1.5628
(between the source pencils)	O-16	0.21		0.3282	

results obtained previously by other authors; they concluded that there was a good agreement (less than 15% of difference) for photon energies above 1500 keV. However, the results did not agree well (difference of 20–30%) for low-energy photons (e.g., 200 keV). In the present study, the MCNPX-calculated gamma dose rates are in agreement with the measured values to $\leq$ 15%. In fact, the conversion factors used affect the calculation/measurement ratios (C/M) in each simulation.

3.3. Description of new models proposed: cylindrical and annular homogenized source models

When the data of the source supplied by the provider are unavailable, the use of homogenous models is justified. These models attempt to simplify the geometry by homogenizations to equivalent heterogeneous systems. Here, two models are proposed to simplify the geometry: the cylindrical and annular homogenized source models.

For irradiation by the GB-127 irradiator, the target is manually

Table 4
Homogenized source model with one zone.

Zone	Isotope	Mass (g)	Composition (weight fraction)	Volume (cm^3)	Density (g/cm^3)	Equivalent radius (cm)
1	Co-60	531.789	0.1312	11996.4394	0.3378	13.49
	Ni	517.335	0.1276			
	N	13.7164	0.0034			
	O-16	2.7209	0.000671			
	Fe	2157.8070	0.5324			
	Cr	626.5106	0.1546			
	Mo	104.4184	0.0258			
	C-12	0.2784	0.000069			
	Si-29	26.1046	0.0064			
	Mn	69.6123	0.0172			
	P	1.5663	0.0004			
	S	1.0442	0.0003			

Table 5
Homogenized source model with 2 zones.

Zone	Isotope	Mass (g)	Composition (weight fraction)	Volume (cm^3)	Density (g/cm^3)	Equivalent radius (cm)
1	Co-60	531.789	1.0000	5998.2197	0.0887	100.4540
2	Ni	517.335	0.1469	5998.2197	0.5870	100.9060
	N	13.7164	0.0039			
	O − 16	2.3927	0.00068			
	Fe	2157.8070	0.6129			
	Cr	626.5106	0.1779			
	Mo	104.4184	0.0297			
	C − 12	0.2784	0.0001			
	Si − 29	26.1046	0.0074			
	Mn	69.6123	0.0198			
	P	1.5663	0.0004			
	S	1.0442	0.0003			

Table 6
Comparison between the values of the MCNPX absorbed dose rate (Gy/h) in the cylindrical irradiated target of water for three homogenized source models and real source.

	CPU time (min)	Homogenized	GB-127	Difference (%)
Annular one zone	0.18	529.63	513.13	−3.2
Annular two zones	0.20	522.52	513.13	−1.8
Cylindrical zone	0.42	495.84	513.13	3.4

loaded onto turntables and is rotated during the entire irradiation process at a constant angular velocity *w*, and the MCNPX simulation geometry is kept static. The target was irradiated in an annular region with the width equal to the source height because of samples holder movement. To produce the same effect, we propose the annular homogenized source model. In this case, table movement was replaced by a static annular source (ring in Fig. 3), covering all positions through which the target passes; in addition, as *w* is constant, the probability of particle emission at each point will be the same.

The developed calculation models of the GB-127 source used in the MCNPX simulation reproduced with Vised 22S (Schwarz et al., 2008) are schematically presented in Figs. 6–8.

The equivalent source radius was calculated considering that the volume and height were the same. In all cases, the mass of all constituents was conserved. The height was set as 20.98 cm. When a cylindrical homogenized source was considered, the source was placed at the center, and when an annular homogenized source was considered, the source was placed at a distance of 1 m from the center. In both the cases, the distance between the source and the irradiated target was 100 cm. The irradiated target was considered a cylinder with a height of 16.67 cm and a radius of 12.5 cm in comparison between the proposed models. The composition of the GB-127 source is shown in Table 3.

The proposed homogenized models are given in Tables 4, 5. Two annular homogenized models were studied: model with one zone and model with two zones (see Table 5).

- One zone: smeared with Co-60, the source pencil encapsulation and the source holder are made of steel, surrounded by air.
- Two zones: the internal zone comprises Co-60 and the external zone is smeared with air, with the source pencil encapsulation and the source holder made of steel.

A comparison between the values of the MCNPX absorbed dose rate (Gy/h) with f6 tally in the cylindrical irradiated target of water for three homogenized source models and real source is presented in Table 6.

As shown in the table, error values were lower than 10% between MCNPX simulation and measurement values. It can be concluded that

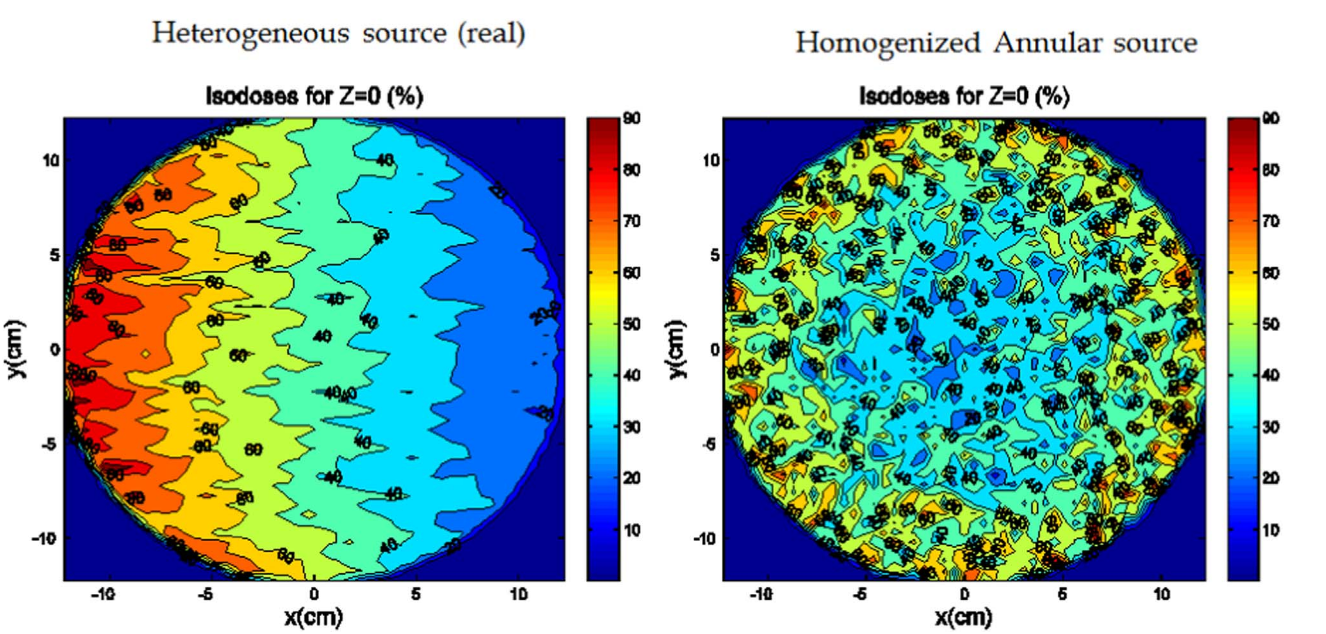

Fig. 9. Comparison of dose projection in plane xy of the gamma isodose distribution of the two models for a cylindrical target.

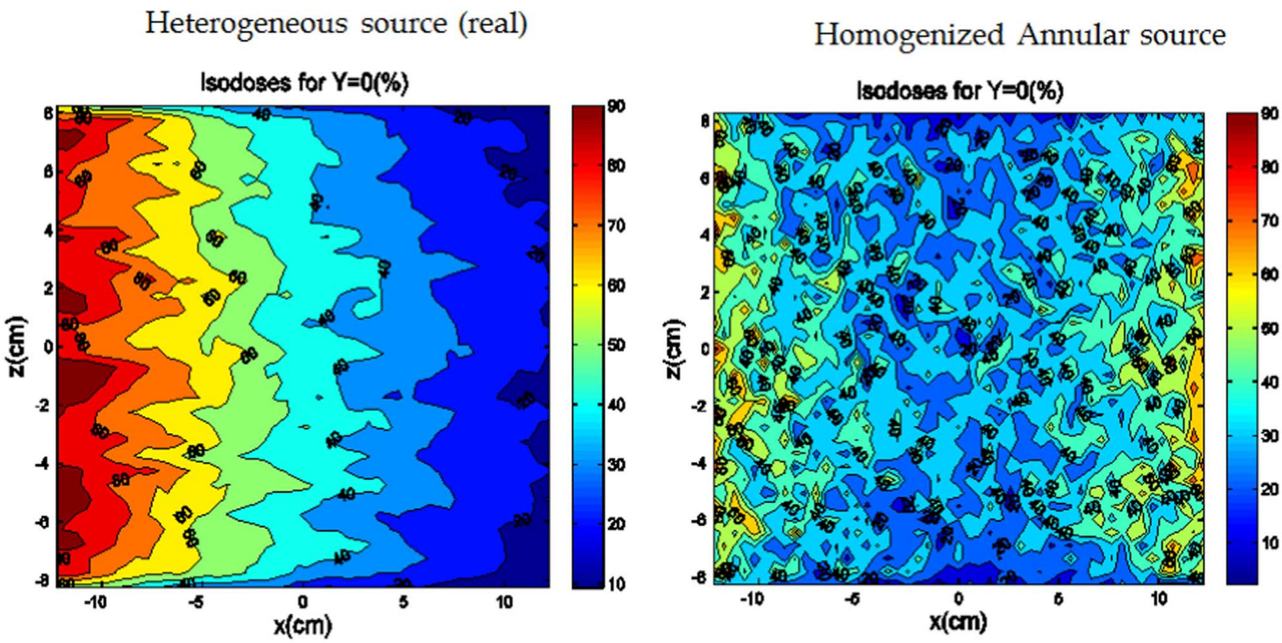

Fig. 10. Comparison of dose projection in plane xz of the gamma isodose distribution of the two models for a cylindrical target.

annular homogenized model with two zones is the most efficient source model. The advantages of using homogenized models is that they require extremely lower calculation time in real model (heterogeneous) equal to 2.57 h for 1×10^6 histories simulated in the Intel Core CPU with 3.3 GHz and 4 GB RAM.

3.4. Application of the proposed new homogenized source models on Dose Map Formation in an Irradiated Target

One of the major contributions of the paper is that it allows to study the effect of geometrical shape of the container of irradiated target on dose map formation in an irradiated target.

Figs. 9 and 10 show the comparison of isodoses for the homogenized annular source model including the xy and xz view for a cylindrical target. The image was reconstructed using $49 \times 49 \times 17$ pixel matrix by using MATLAB. The error associated with the TMESH was lower than 5%.

Results showed that when the proposed homogenized annular source model was used instead of the real source model, the irradiation process (rotational effects) was better represented. The annular source around the target replaced the mechanical rotation of the target.

This new proposed homogenized annular source model is very important when blood is irradiated because the objective is to inactivate pathogenic microorganisms in infected blood target and prevent graft-versus-host disease in immunosuppressed patients. Therefore, it is necessary to assess the dose uniformity for appropriate application of the irradiation process to the blood components.

In addition, this study can answer any questions about the nature of perception of different colors in the gemstones also, the chemical composition influence.

4. Conclusions

The proposed new methodologies effectively represent the irradiation process and can be used to conduct quantitative studies of spatial distribution of doses in the irradiated target.

Among the simulated models, the annular source model was found to be more similar to representation of the real dose distribution. The simulation can be used to determine the dose distribution in the irradiated samples or to certify that the target has received appropriate irradiation doses in all parts.

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