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COMPARISON OF NUMERICALLY SIMULATED AND MEASURED DOSE RATES FOR GAMMA-IRRADIATION FACILITY[†]

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The article provides a description of steps which were made to make comparison between numerically simulated and measured dose rates in Izotop gamma-irradiation facility (Budapest, Hungary) Numerical simulation was carried out with the help of software toolkit GEANT4. Dose measurement were made by ethanol-chlorobenzene (ECB) dosimeters. The comparison shows a good agreement between simulated and measured values. Worst accuracy was 17.08%.
Keywords: absorbed dose, dose rate, numerical simulation, ECB.
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Radiation treatment are widely used for decision of big number of tasks which are important for the human life:

- sterilisation of medical goods and devices [1];
- food hygienization [2];
- flue gas purification from gaseous pollutants [3];
- sewage and sludge clean up [4];
- wire and plastic treatment [5];
- cultural heritage disinfestation, preservation and conservation [6];
- and many others.

Measurement of absorbed doses and dose rates is an important and indispensable task in radiation processing operations. The absorbed dose and dose rates are the main criteria for assessing the degree of radiation processing of materials [7].

This article provides a sequence of actions which were made to compare the numerically simulated and measured dose rates values.

DESCRIPTION OF THE NUMERICAL SIMULATION

In the course of this work, we used software toolkit GEANT4, a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science [8–10].

To use GEANT4 the following aspects should be defined:

– the geometry of the system;
– the materials involved;
– the fundamental particles of interest;
– the physical processes of interest;
– the generation of primary events;
– the response of sensitive detector components.

The geometry of the system

The geometry of the systems involves the dimensions of the objects and their location. The geometry of the system consists of the following items

– the maze and building of the gamma facilities;
– the ^{60}Co sources;
– the cover of the gamma sources;
– other constructional elements;
– dosimeters;
– conveyor system (if exists).

The above-mentioned items are shown on Fig. 1,2,3.

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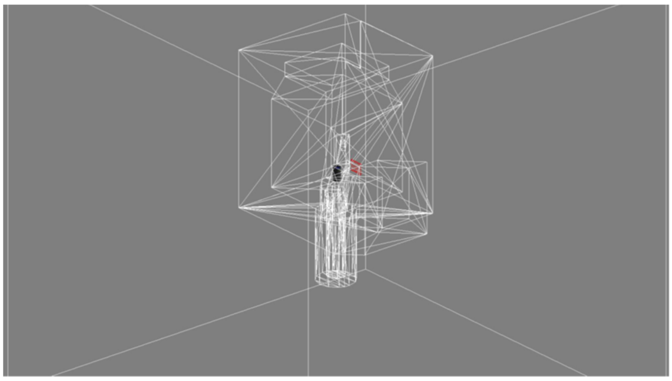

Figure 1. Building of gamma facility, Izotop (Budapest, Hungary)

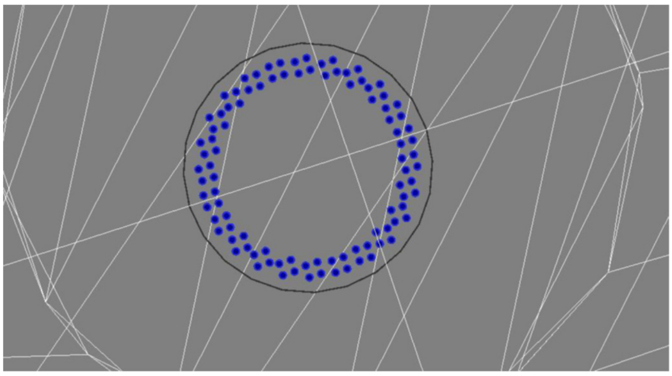

Figure 2. Gamma sources

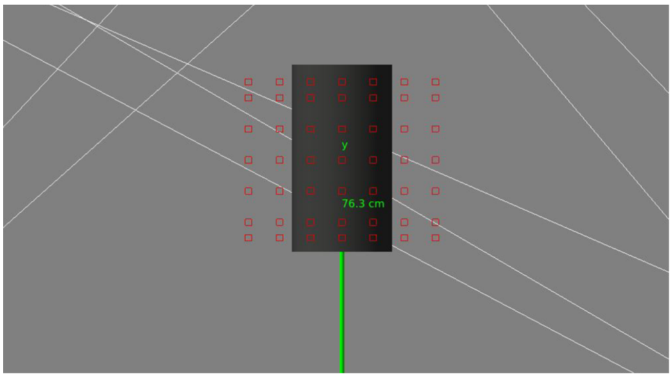

Figure 3. Array of dosimeters and cover of gamma sources

All geometrical objects are made as ".stl" files and were imported into simulations. Total view of facility geometry in simulation is given on Fig. 4.

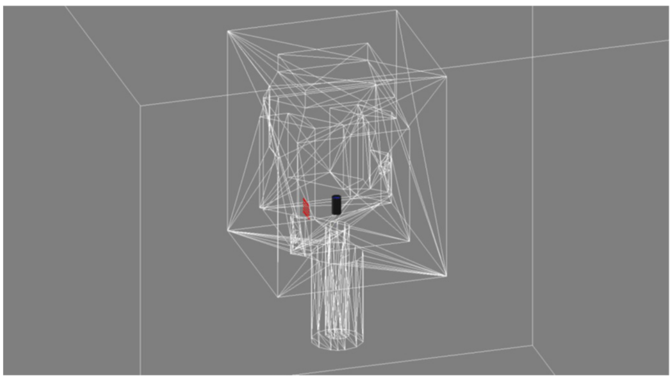

Figure 4. Total view of facility geometry in the simulation

The materials involved

The following materials are involved into the simulation:

– concrete;
– stainless steel;
– water (materials of doisemters);
– air.

These materials are standards ones and their composition can be found GEANT4 table of materials.

The fundamental particles of interest

According to the physical laws during gamma irradiation following elementary particles take part:

– gamma rays;
– X rays;
– electrons;
– positrons;
– anti-neutrinos.

Anti-neutrinos are not included into simulation because these particles can pass through the matter without any collisions with the matter.

The physical processes of interest

Seven major categories of processes are provided by GEANT4:

1. electromagnetic;
2. hadronic;
3. decay;
4. photolepton-hadron;
5. optical;
6. parameterization;
7. transportation.

In the simulation, the 1st, 3d and 7th processes were chosen.

The generation of primary events

Generation of initial gamma rays are generated from ^{60}Co isotropically (i.e. uniformly in all orientations) and along gamma sources (so-called "pencil"). Built-in GEANT4 General Particle Source (GPS) class is used for this purpose.

Data concerning activity of the gamma sources can be read from .csv file (one of the Excel formats).

Developed code arrange these gamma sources properly (See Fig. 2).

Also, the decay of gamma sources are taken into the account in the simulation.

The response of sensitive detector components

To record and output data from simulations, a process called "scoring", must be implemented, specifying what should be measured and where.

In the simulation array of dosimeters were used as shown on Fig. 3. The array of dosimeters consists of 49 dosimeters. All values of absorbed dose is referenced to the water.

SHORT DESCRIPTION OF GAMMA IRRADIATION FACILITY

The gamma-facility has following characteristics and parameters [11]. The γ-irradiation facility (Institute Izotop Co, Budapest, Hungary) is a ^{60}Co facility of SLL-01 type. The maximum amount of activity which can be loaded into the facility is 120 kCi.

The Co-60 gamma irradiator is a Category IV facility. It normally contains 20 Co-60 source capsules (so called torpedoes) each of them can be loaded with 4 ^{60}Co sources (type CoS-43 HH) of diameter 11 mm, height 451 mm, or other sources of the same size.

The Co-60 sources are stored in an underground water pool when not in use. The inner lining of the pool is made of 5-mm thick stainless steel. In storage position the radiation sources are kept (in fully shielded condition) in the source-cage. In this case there is 4.2-m water over the upper level of the sources, which gives adequate radiation protection in the direction of the irradiation chamber.

In order to reach the irradiation, position the torpedoes must be lifted from the storage position to the irradiation position. The sources in the cage are cylindrically arranged on a pitch-circle of 280-mm diameter.

The design of the tubes holding the sources allows after-loading of the sources. The torpedoes in the cage can be lifted up to irradiation position from the storage position by a hoist mechanism. In the irradiation position the symmetry level of the sources is 80 cm over the floor of the irradiation room.

The size of the irradiation chamber is 4 × 4 × 4 m; it is surrounded by walls made of 1.7 m normal concrete. Safe entrance to the irradiation chamber is ensured by a shielded maze with several turnings (breaks). The entrance door of the maze is made of steel. Access of personnel and transport of products are controlled by safety rules and technology to prevent accidental exposure of personnel or visitors. The irradiation process can be monitored from the control desk in the control room adjacent to the irradiation chamber. The irradiator is operated fully automatically, controlled by an electronic control unit. Irradiation during daytime-operation is performed in the presence of operators by manual or automatic control.

The radiation sources can be lifted to the irradiation position as required by the experimental or pilot-plant radiation treatment. The number of sources appropriate for the program can be manually chosen; the time required for irradiation can automatically be ensured. The goods, to be irradiated, can be placed either in the cylinder of 215-mm dia located in the middle of the cage irradiation position (inner irradiation field), or around the source-cage in the irradiation room (outer irradiation field).

Figure 5. Co-60 Gamma Irradiation Chamber

The distance of the horizontal plane of symmetry of the sources from the floor is 80 cm. This height makes it possible for regular pilot-scale radiation treatment of products placed in 40 × 60 × 75-cm boxes and also at larger distances from the sources. The radiation treatment of various products placed in aluminium containers (80 × 60 × 130 cm) of 0.5 m^3 volume can be carried out as well. In the space near the cage radiation treatment can be performed in small size e.g. 40 × 40 × 35-cm boxes (see the Fig 5).

The high dose intensity space within the cage can be regularly used for the radiation treatment of max. 9 litre samples (∅ I180×360). Owing to the relatively large volume of the irradiation chamber, up to 1.6 m height of the useful radiation field, products can be irradiated at very wide dose rates.

The irradiator is equipped with devices for water purification and exhaust air filters. The goods to be irradiated - before and after treatment - are transported into and out of the irradiation chamber through the maze manually or with the help of carriages made for this purpose.

RESULTS OF CALCULATION AND COMPARISON WITH ABSORBED DOSE MEASUREMENTS IN SITU

The dose measurements were performed by the ECB dosimeters according to “Practice for use of the ethanol-chlorobenzene dosimetry system” [12].

The dosimetry system at Institute of Izotop can be described as follows [11]. The ethanol-chlorobenzene dosimeter uses the hydrochloric acid formation. Dose range: 0.1 kGy – 1 MGy. The ethanol-chlorobenzene dosimeter (ECB) has got wide-spread application in gamma radiation processing and at (linear) electron accelerators. Its reliable performance was proved in a number of international and bilateral intercomparison programs, including the IAEA and several National Institutes of Standards. The method is in routine use in more than twenty countries.

The basic radiation chemical process, used for dosimetry, is the formation of HCl upon irradiation. Its concentration is a linear function of the dose absorbed in the solution in a wide dose range of 0.1 –100 kGy. At higher doses the reactions become more complicated.

The absorbed dose is determined by measuring the concentration of HCl(cHCl) formed during irradiation. Oscillometric titration is the most frequently used method. The irradiated dosimeter can be re-evaluated many times [13,14].

Calculations were performed on personal computer equipped with AMD Ryzen™9 3900xt (24 threads, 12 cores) processor, 48 GB RAM.

Amount of simulated events was 10^9. Calculation time was approximately about 72 hours. The results of absorbed dose rate measurement in situ, numerical calculations, and their comparison is given in the Tables 1, 2, 3 for distance 570, 820, 1700 mm from the center of γ-sources respectively.

Table 1. Absorbed dose measurement in situ, numerical calculations, and their comparison. Distance from the source – 570 mm

Distance Z, mm	Dose rates, kGy/h																				
	Y,mm																				
	-300			-200			-100			0			100			200			300		
	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m
250	1.08	0.99	**8.31**	1.16	1.05	**9.09**	1.24	1.17	**6.08**	1.27	1.18	**7.09**	1.24	1.14	**7.93**	1.14	1.06	**7.06**	1.08	1.03	**5.07**
200	1.11	1.14	**-3.25**	1.27	1.20	**5.83**	1.37	1.30	**5.55**	1.42	1.34	**5.36**	1.39	1.33	**4.07**	1.24	1.21	**2.53**	1.14	1.14	**0.16**
100	1.26	1.21	**3.72**	1.42	1.31	**7.41**	1.56	1.44	**7.96**	1.63	1.49	**8.53**	1.55	1.42	**8.48**	1.42	1.32	**6.91**	1.27	1.24	**2.76**
0	1.30	1.25	**3.46**	1.48	1.34	**9.84**	1.63	1.47	**10.00**	1.70	1.51	**11.08**	1.63	1.47	**9.88**	1.47	1.32	**9.68**	1.30	1.23	**5.00**
-100	1.30	1.21	**6.93**	1.47	1.28	**12.68**	1.58	1.42	**9.87**	1.61	1.50	**7.20**	1.55	1.43	**7.57**	1.42	1.30	**8.11**	1.28	1.23	**4.24**
-200	1.16	1.13	**2.53**	1.21	1.22	**-0.39**	1.42	1.31	**7.76**	1.45	1.33	**8.36**	1.40	1.30	**7.11**	1.28	1.20	**6.34**	1.17	1.13	**3.92**
-250	1.09	1.00	**8.06**	1.19	1.05	**11.44**	1.27	1.16	**9.06**	1.34	1.18	**12.45**	1.30	1.14	**12.16**	1.24	1.07	**13.65**	1.09	1.01	**7.14**

Table 2. Absorbed dose measurement in situ, numerical calculations, and their comparison. Distance from the source – 820 mm

Distance Z, mm	Dose rates, kGy/h																				
	Y,mm																				
	-300			-200			-100			0			100			200			300		
	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m
250	0.635	0.61	**3.35**	0.65	0.64	**1.92**	0.69	0.66	**4.64**	0.70	0.68	**2.97**	0.69	0.64	**7.52**	0.66	0.64	**4.39**	0.64	0.60	**5.24**
200	0.649	0.65	**0.08**	0.69	0.66	**4.79**	0.72	0.69	**3.39**	0.73	0.71	**2.64**	0.71	0.70	**2.05**	0.69	0.66	**4.64**	0.66	0.64	**2.41**
100	0.710	0.65	**8.68**	0.74	0.69	**7.54**	0.76	0.71	**6.06**	0.79	0.72	**9.05**	0.77	0.72	**6.86**	0.74	0.68	**7.68**	0.70	0.66	**6.11**
0	0.725	0.67	**7.05**	0.76	0.70	**7.25**	0.79	0.73	**8.16**	0.82	0.72	**12.38**	0.81	0.72	**10.18**	0.76	0.68	**10.02**	0.73	0.68	**6.91**
-100	0.710	0.66	**7.27**	0.76	0.67	**11.21**	0.79	0.72	**9.05**	0.79	0.72	**8.92**	0.78	0.72	**8.09**	0.75	0.69	**8.12**	0.72	0.66	**7.71**
-200	0.687	0.64	**6.65**	0.72	0.67	**6.32**	0.75	0.70	**7.19**	0.76	0.72	**5.40**	0.75	0.70	**6.26**	0.73	0.68	**6.22**	0.67	0.65	**3.07**
-250	0.638	0.61	**3.78**	0.71	0.61	**13.75**	0.71	0.65	**8.25**	0.73	0.67	**7.33**	0.75	0.67	**10.93**	0.72	0.62	**13.57**	0.64	0.62	**3.16**

Table 3. Absorbed dose measurement in situ, numerical calculations, and their comparison. Distance from the source – 1700 mm

Distance Z, mm	Dose rates, kGy/h																				
	Y,mm																				
	-300			-200			-100			0			100			200			300		
	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m	M	C	C_m
250	0.43	0.39	**10.15**	0.43	0.40	**5.31**	0.45	0.42	**5.98**	0.44	0.42	**6.36**	0.44	0.41	**5.86**	0.44	0.41	**6.32**	0.43	0.39	**10.15**
200	0.45	0.41	**7.08**	0.49	0.41	**15.69**	0.50	0.43	**15.51**	0.53	0.44	**17.07**	0.52	0.43	**17.09**	0.50	0.42	**16.91**	0.46	0.40	**12.60**
100	0.45	0.41	**8.91**	0.47	0.43	**7.94**	0.47	0.44	**5.37**	0.48	0.43	**11.30**	0.48	0.44	**7.69**	0.47	0.42	**9.45**	0.45	0.41	**8.87**
0	0.47	0.42	**9.45**	0.47	0.43	**9.93**	0.48	0.43	**12.13**	0.49	0.44	**9.33**	0.48	0.44	**9.03**	0.47	0.42	**11.62**	0.46	0.41	**10.48**
-100	0.45	0.41	**8.21**	0.47	0.42	**9.87**	0.47	0.43	**9.93**	0.48	0.44	**7.06**	0.48	0.44	**7.48**	0.47	0.42	**11.84**	0.45	0.42	**6.42**
-200	0.44	0.42	**4.72**	0.46	0.42	**8.09**	0.47	0.44	**6.01**	0.48	0.43	**10.62**	0.48	0.42	**11.25**	0.48	0.42	**12.71**	0.45	0.42	**7.31**
-250	0.44	0.40	**8.22**	0.46	0.41	**11.78**	0.48	0.42	**13.13**	0.47	0.43	**9.29**	0.47	0.41	**13.11**	0.47	0.40	**14.38**	0.44	0.40	**7.99**

CONCLUSION

The complex geometry of the Izotop irradiation facility was input into simulation. All proper physical processes and particles were included into the simulation and the numerical simulations were carry out.

The calculations were carried out for 109 events. Approximately time of calculations were 72 h. Comparison between measured and simulated results were done (Tables 1, 2, 3).

The accuracy of simulated results in comparison with measured ones is in the range 0.16 – 17.08 %. The accuracy can be improved by the increasing of the simulated events what will demands the using of the high-performance cluster (HPC).

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ПОРІВНЯННЯ МІЖ ЗМОДЕЛЬВАНИМИ ТА ВИМІРЯНИМИ ПОТУЖНЯСТОМИ ДОЗ НА ГАММА-ОБ'ЄКТІ

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У статті наведено опис кроків, які були зроблені для порівняння між чисельно змодельованими та виміряними потуж остями дози на гамма-об'єкті Ізотоп (Будапешт, Угорщина) Чисельне моделювання проводилося за допомогою програмного інструментарію GEANT4. Вимірювання дози проводили системою дозиметрів ECB. Порівняння показує хорошу відповідність між змодельованими та виміряними значеннями. Найгірша точність була 17,08%.

Ключові слова: поглинута доза, потужність дози, чисельне моделювання, ECB.