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AIR KERMA DISTRIBUTION IN AN IRRADIATION FACILITY - COMPARISON OF MONTE CARLO SIMULATIONS WITH PHYSICAL DOSIMETRY

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ABSTRACT

In order to evaluate the effectiveness of Monte Carlo methods applied to shielding calculations, an air kerma rate evaluation was performed in different locations of a ^{60}Co gamma irradiator, operated for industrial and research purposes in a state laboratory at Nuclear and Technological Institute near Lisbon. The MCNPX code was used to perform the radiation transport simulation along the facility. Variance reduction techniques were used by implementing, among others, the weight window generator to account for the air kerma rate in the access maze leading to the facility's irradiation chamber. Analog Monte Carlo simulations were also performed to test the correct implementation of the nonanalog techniques used and to evaluate the computational efficiency gain. The validation of the computational results is discussed by comparison with physical dosimetry measurements using ionization chambers. The results obtained show a good agreement between the simulations and the measurements for the positions in and the exit of the irradiation room. Discrepancies were found for the positions where the air kerma rate is lower resulting from the deeper penetration of radiation across the shields and scattering through the maze walls. Further insight must be gained to improve the results at these positions.

Key Words: ^{60}Co, air kerma, MCNPX, ionization chambers.

1. INTRODUCTION

The available state-of-the-art computational tools using Monte Carlo methods for particle transport simulation have proven its effectiveness to perform the assessment of dose distributions [1] in shielding calculations in industrial processing facilities [2].

Recent developments described by Booth [3] and Riper [4], such as weight window generators and automated variance reduction using deterministically generated importance functions greatly improved the computational efficiency for deep penetration problems [5].

Variance reduction methods have been traditionally categorized into four basic types, as follows: truncation, population control, modified sampling, and partially deterministic methods. It is rather consensual that thick shielding problems can require very long run times in order to achieve an acceptable level of uncertainty in the final results and the detection of particles in a location far away from the source requires a vast number of simulated histories.

For that reason, in this study, the population control method was applied by using the WWG, which keeps particle weight within certain bounds. This technique helps to keep the weight dispersion within reasonable bounds throughout the problem, which means that the user must define a weight window with lower and higher values of particle weights.

The efficiency of a Monte Carlo simulation may be quantified using the Figure of Merit (FOM), which is defined by the MCNPX code developers according to equation 1, where *R* is the tally relative error and *T* is the computing time.

$$\mathrm{FOM} = \frac{1}{\mathrm{R}^2\mathrm{T}} \tag{1}$$

In order to evaluate the effectiveness of the variance reduction techniques for shielding design and dose assessment in complex concrete mazes, a comparative approach using MCNPX code [6] with and without WWG technique was done by evaluating the figure of merit (FOM).

2. MATERIALS AND METHODS

2.1. Experimental Setup

Figure 1 illustrates the layout of the Unit of Radiation Technologies (UTR) in operation at the Nuclear and Technological Institute (ITN), a state laboratory located nearby Lisbon, Portugal.

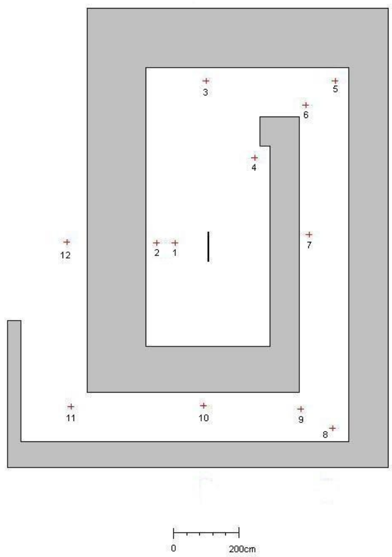

Figure 1. X-Y plant of the UTR irradiation facility, showing the entrance and the labyrinth that leads to the irradiation chamber, where the source is marked in black in the centre.

This installation operates with ^{60}Co sources with an overall activity of 161 KCi (as of May 2008, the initial activity of the source being of 300 KCi). The source is distributed in a lattice of cylinders placed in the centre of the irradiation chamber. The walls are made of concrete with a density of 2.23 g/cm^3 with thicknesses varying from 40 cm to 180 cm.

2.2. Physical Dosimetry Measurements

Air-kerma rate measurements were performed in different relevant positions of the facility as shown on figure 1, using ionization chambers from the Metrology Laboratory of Ionizing Radiation (LMRI) of ITN. A PTW ionization chamber type 23332 with an active volume of 0.3 cm^3 was placed in positions 1, 2, 3 and 4. For positions 5, 6 and 7 a PTW ionization chamber type 23361 with an active volume 30 cm^3 was used. Finally, for positions 8, 9, 10 and 11 was used a PTW ionization chamber type 32002 with an active volume of 1000 cm^3. The three different ionization chambers were used with different active volumes in order to increase the detection for those positions corresponding to greater distances from the source, along the maze. All the ionization chamber currents were measured with an electrometer type 10568 (LMRI, ITN, Lisbon).

For all measurements except for position 1, the ionization chambers were placed 1 m above the floor and 50 cm away from the walls resulting in the same irradiation conditions as for MCNPX calculations.

The ionization chambers used in the experiment were calibrated in the ^{60}Co photon reference beam available at the LMRI, allowing the calibration factor of the ionization chambers. The air kerma value K_{air} was obtained from equation (2)

$$K_{air} = M \times F_c \times C_{field} \times C_{energy} \tag{2}$$

where M is the measure obtained, F_c is the calibration coefficient, C_{field} is the correction for the field size (since the ionization chamber is calibrated with a 10x10 field) and C_{energy} is the correction for the energy (because the main contribution to the absorbed doses in some considered positions is secondary and terciary radiation). The relation between air kerma and absorbed dose in air is given by equation (3).

$$K_{air} = \frac{D_{air}}{1-g} \tag{3}$$

where D_{air} is the absorbed dose in air and g is the fraction of energy of secondary charged particles converted to bremsstrahlung in air.

2.3. Monte Carlo Calculations

Key issues in Monte Carlo simulations are, amongst other parameters, the accuracy of the source description and its geometry and the composition and density of the irradiated materials. Moreover, in deep penetration problems, it is usually necessary to implement nonanalog particle transport in order to obtain good statistical results.

The characteristics of the installation, with long and complex maze geometry and very thick concrete walls, thus define a typical deep penetration problem for the simulated radiation.

To solve it, the WWG card was implemented to generate adequate weights for the photon transport through a superimposed weight window mesh in the geometry. To establish the weight window, the ratio between higher and lower weight bounds equal to 5 was defined. Both energy-dependent and energy-independent weight windows were implemented; however for both cases similar computational results as well as FOM were obtained. In this study it was decided to use an energy-independent weight window and at least two iterations were simulated in order to refine the weight bounds.

Additionally, for positions 5 through 11 the iterative generations of the weights was made in the presence of point detectors (Tally F5) to which air kerma rate values are deterministically estimated. It must be highlighted that for positions 1 to 4 only the track length estimator (Tally F4) was used, due to the proximity of this positions to the source. For that reason, a comparison between analog and nonanalog is made for positions 5 to 11.

3. AIR KERMA EVALUATION AND RESULTS

3.1. Comparison of Results Performing Analog and Nonanalog Monte Carlo Simulations

In this study an analog simulation was performed for all positions using the tally F4 with the DE and DF cards according to the ICRP 74 photon flux to air kerma coefficients. The nonanalog method was implemented only for positions 5 to 11 using the variance reduction technique mentioned in section 2.3. Table I illustrates the results obtained with both methods.

From Table I and Figure 2 it can be concluded that the computational results obtained using analog and nonanalog methods are in good agreement (within 1σ) for nearly all positions, considering the quoted statistical uncertainties, except for position 9 where the discrepancies are at the level of 3σ.

Table I. Results obtained with Analog and Nonanalog MC methods

Position	*Analog MC*		*Nonanalog MC*	
	Air kerma rate (Gy/h)	*Relative Statistical Uncertainty (%)*	*Air kerma rate (Gy/h)*	*Relative Statistical Uncertainty (%)*
1	2.91E+03	1.5	-	-
2	9.24E+02	2.7	-	-
3	2.45E+01	4.5	-	-
4	4.54E+02	3.7	-	-
5	2.18E+00	4.1	2.08E+00	4.0
6	1.43E+00	4.3	1.32E+00	3.7
7	9.37E-02	6.4	9.47E-02	6.5
8	6.96E-03	10.0	6.33E-03	6.4
9	8.86E-03	9.2	7.07E-03	2.8
10	1.45E-04	30.7	1,17E-04	7,0
11	4.55E-05	57.1	2,44E-05	9,0

The ration between both methods is illustrated in Figure 2.

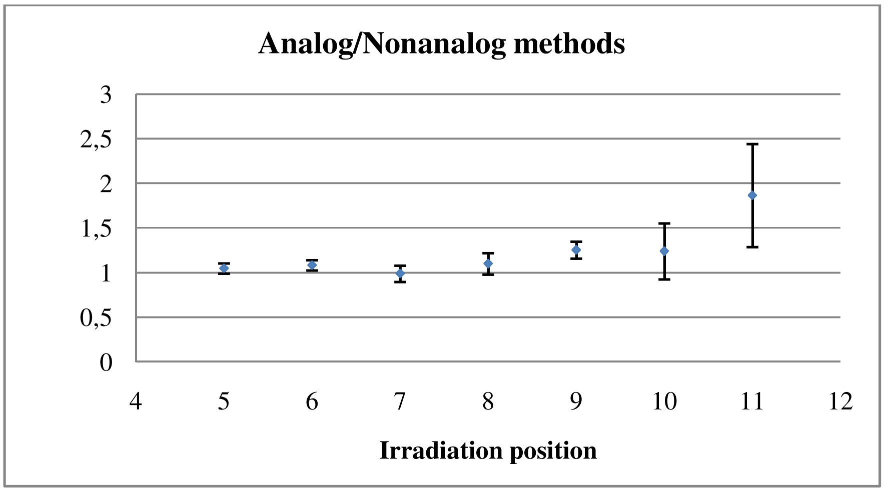

Figure 2. Ratio between analog and nonanalog methods.

Since positions 10 and 11 are located near the entrance of the labyrinth, the flux of particles is low and the statistical uncertainty affecting the air kerma results for those positions is higher and cannot be further decreased for the analog simulations.

3.2. Ionization Chamber Measurements and Monte Carlo Dosimetry

The results obtained with the measurements using the ionization chambers, corrected for the energy response function of the detectors (the incident spectrum was known from the Monte Carlo simulations) are shown in Table II, which displays the air kerma rate measurements and the computational values already shown in Section 3.1 obtained performing an analog Monte Carlo simulation.

Table II. Experimental and computational air kerma rate values obtained in different positions from figure 1.

Position	*Air kerma rate (Gy/h) Experimental*	*Uncertainty (%)*	*Air kerma rate (Gy/h) Computational*	*Relative Statistical Uncertainty (%)*
1	2,35E+03	0.86	2.91E+03	1.5
2	9,08E+02	0.86	9.24E+02	2.7
3	2,22E+01	0.86	2.45E+01	4.5
4	4,66E+02	0.86	4.54E+02	3.7
5	2,00E+00	0.95	2.08E+00	4.0
6	1,03E+00	0.95	1.32E+00	3.7
7	3,49E-02	0.95	3.64E-02	2.4
8	1,63E-03	0.95	6.33E-03	6.4
9	4,02E-03	1,70	7.57E-03	2.2
10	9,28E-06	1.40	1,17E-04	7,0
11	1,17E-06	1.40	2,44E-05	9,0

Table II shows a severe disagreement between the measurements performed and the computational results for the air kerma rate values for positions 10 and 11. However, considering the aforementioned deep penetration nature of the problem and the geometrical characteristics of the installation, reasonable agreement is obtained for positions 1 through 7 as shown in Figure 3. From the same Figure it can be seen that the agreement is poorer for both positions 8 and 9 most likely due to the fact that mainly scattered radiation in the walls is contributing to the radiation reaching these locations.

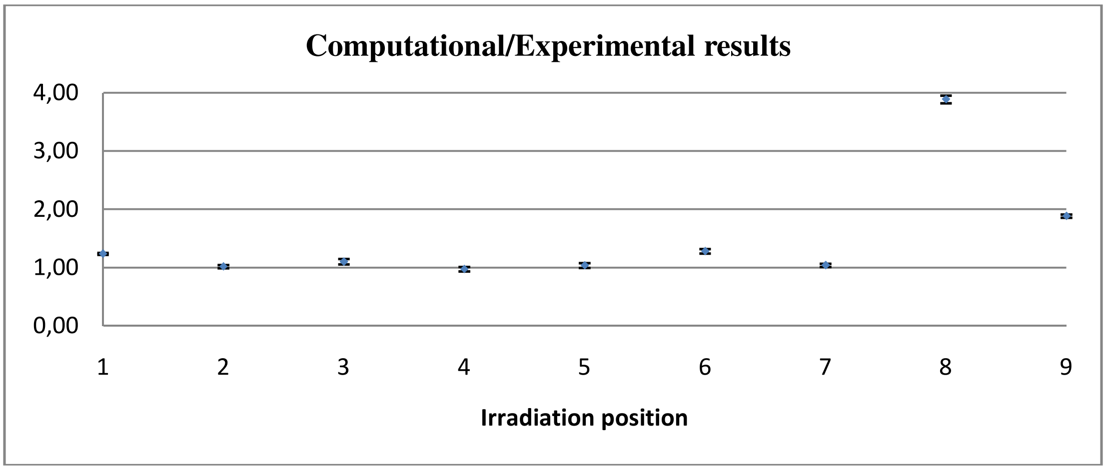

Figure 3. Ratio between the experimental and the computational values.

3.3. Effectiveness of the Variance Reduction Techniques Used

In this work, computational results were obtained for the aforementioned positions with and without applying variance reduction techniques. The purpose of this comparative study was to evaluate the gain in simulation efficiency and computational time. The measure of efficiency for MCNPX calculations is the figure of merit (FOM), which is calculated for one tally bin of each tally as function of the number of histories. Table III shows the values of FOM for both cases.

Table III. Values of FOM obtained in positions 5 to 11, by using analog and variance reduction techniques (VRT)

Irradiation Position	FOM	
	VRT	Analog
5	118	9.55E-02
6	134	8.80E-02
7	46	3.91E-02
8	2	1.60E-02
9	20	1.90E-02
10	0.18	3.18E-04
11	0.12	4,90E-04

It must be emphasized that, the more efficient a Monte Carlo calculation is, the larger the FOM will be and less computer time is required to reach a given value of relative standard deviation of mean. Regarding this and the values observable from Table III, the gain in computational efficiency with the methodology implemented is very high and allows not only for much faster simulation runs as for an improved statistical sampling of further positions.

4. CONCLUSIONS

In this work variance reduction techniques have been applied with the aim of reducing the computational time required for perfoming the accurate assessment of the kerma rate in the maze of a facility where a ^{60}Co irradiator is operated for industrial purposes. Due to the geometry, materials and the thickness of the shielding of the facility, the dose assessment using Monte Carlo computational tools becomes a typical deep penetration problem. At the same time, measurements have been performed using ionization chambers.

The simulation results obtained using purely analog computations or using variance reduction techniques are in good agreement for those points inside the irradiation chamber and for the majority of those points along the labyrinth.

As for the comparison between the measurements performed and the computational results, although inside the irradiation chamber the agreement between the measurements and the computational results is fairly good - what allows to infer that the modeling of the facility is correctly performed - significant discrepancies exist between the measurements and the computed results along a few points in the maze of the installation. These discrepancies are not fully understood.

The effectiveness of the MCNPX WWG variance reduction technique for solving deep penetration problems has been demonstrated, allowing to significantly improve the FOM of the Monte Carlo simulations performed.

Further insight must be gained in order to improve the agreement between measurements and the simulation results in those points along the maze which are located far away from the irradiation chamber and to which corresponds a longer flightpath for the scattered radiation reaching the corresponding locations.

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