Monte Carlo simulation of extrapolation chamber for beta radiation dosimetry

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Abstract

The objective of the present work was to developed an extrapolation chamber type PTW model 23392 for standard beta radiation fields of $^{85}$Kr, $^{90}$Sr/$^{90}$Y and $^{147}$Pm using MCNPX code. The energy deposited at variable depths of the sensitive volume was calculated to study the chamber response and to calculate the absorbed dose rate in tissue (0.07) in μGy$^{-1}$. The dose rate resulted for $^{85}$Kr source was calculated using two equations published in literature. And to describe the spectrum used for the $^{90}$Sr/$^{90}$Y source it was considered two methods both are explaining in this paper. In the case of $^{147}$Pm source interesting and sensitive relation to the material and the geometry of the source model was observed, it may be due to the low energy of the beta particles emitted. Whereas for the dose rate calculations, up to 5% of variation was observed for all radionuclides when compared to literature results. Deviation up to 5% was observed for transmission factor calculations and approximately 15% deviation was observed in the case of $^{85}$Kr with respect to the literature. This work describes in detailed the main parameters and common issues seeing when modelling an extrapolation chamber and for three different sources.

**Keywords:** Nuclear instrumentation; Beta radiation; Computational modeling; MCNPX.
1.- INTRODUCTION

Extrapolation Chamber is a type plane-parallel ionization chambers with variable volume. The extrapolation chamber is useful for the detection of beta and X radiation of low energies, and is used to determine absorbed dose and absorbed dose rates. In addition, this chamber can be used as a standard primary or secondary system in dosimetry for beta and X radiation beams[Böhm 1986; Helmstädt and Böhm 1992; Antonio 2013].

The characterization of beta dosimetry systems involves the determination of the dose rates absorbed in air and/or tissues with small thicknesses of equivalent tissue materials[Caldas 1986; ISO 2004].

The mathematical method of Monte Carlo (MC) stands out in the area of radiation physics as a computational modeling technique[Pelowitz 2011]. Several computational codes exist for the simulation of the transport of particles[Fonseca et al. 2015; Seniwal et al. 2019; Fonseca et al. 2019; Mendes et al. 2019; Fonseca et al. 2019; Paixao et al. 2015].

The user develops an input-deck file containing all information of the case to be simulated. It has the dimensions of surface, the materials, the cross-section library, the characteristics of the radioactive source, and the tally which is the type of response desired.

This work presents the results of the computational modeling of a PTW model 23392 extrapolation chamber and different Beta Secondary Standard (BSS2) sources.

The validation of the computational model was performed by comparing the dose rate obtained for the beta sources such as, $^{85}$Kr, $^{90}$Sr/$^{90}$Y and $^{147}$Pm to the reference reported in literature[Faria et al. 2015; Polo et al. 2018].

The results obtained for the response of the chamber as a function of the depth of its sensitive volume, the transmission factor are reported.
2.- MATERIALS AND METHODS

2.1.- Monte Carlo model
The electron transport and photons were carried out using the Monte Carlo N-Particle eXtended (MCNPX), which allows to simulate the transport of particles in different geometries for different types of material. A 120-processor cluster from the Neutron Laboratory of the Institute of Radioprotection and Dosimetry-IRD / CNEN was used to simulate the dose rate for different beta radiation sources. The number of particles defined for the simulations was equal and above 5.0E+8. An optimum number of started particles is achieved if the MCNP statistical tests are satisfied[Pelowitz 2011]. This value allows statistical confidence in the results obtained up to 1%.

2.2.- Geometric of the Extrapolation Chamber PTW-23392
The PTW extrapolation chamber (EC) model 23392 was modeled according to the reference data [Faria et al. 2015, Benavente, 2011; Antonio et al. 2014]; the chamber instruction manual, additional information obtained from the manufacturer[PTW-Freiburg 2002]. A scheme of an extrapolation chamber [Pruitt et al. 1988] is shown in Figure 1.

![Scheme of an extrapolation chamber](image)

Figure 1.- Scheme of an extrapolation chamber[Pruitt et al. 1988].
The MC model is made of the acrylic body coating the entire main body of the chamber, the input window, the graphite coated electrodes, the absorption thickness and the sensitive volume containing air. Figure 2 shows the MC model of the EC. The geometry modeled is rotational with respect to the z axis and consists of cylinders formed by surface of macrobodies type RCC (Right Circular Cylinder) from MCNPx code.

![MC mode of the PTW-23392 Extrapolation Chamber three-dimensional diagram. 1 - Entrance Window of 3.5μm. 2 – Electrode coated with graphite of 0.35μm. 3 – PMMA Holder. 4 – PMMA Acrylic Body φ=140 mm. 5 – Air Sensitive Volume φ=30 mm. Absorption Thickness with φ=60.5 mm.](image)

**2.3.- Geometric of the filter**

The filter is made of Polyethylene Terephthalate (Hostaphan/Mylar) material and its geometries are made of circular sheets and are described in the manufacturer’s operating manual[BSS2 2000]. The filter was placed at 10 cm from the source[ISO 2004] and centered on the z-axis. The filters are paced at 30 cm from the $^{85}$Kr and $^{90}$Sr/$^{90}$Y sources and at 20 cm from the $^{147}$Pm source. Figure 3 shows the different forms and sizes of each filter.
2.4.- Geometric source

The sources reported in references [Faria et al. 2015, Polo 2018] consists of active material distributed in a cylindrical geometry covey of layers of different materials. The position of the source inside of the cylinder it is important due to its influence in the dose calculated as results. This may be explained and mainly seeing for the low energy beta source in which the material of the source cause the shield effect of the particles that surpass the exit of this source.

The geometric construction of this source is cataloged with its respective series [Nuclitec, 2019]. In order to obtain each sources geometry, it is needed to request directly to Nuclitec through email.

2.4.1.- Source of $^{85}$Kr

The MC model of the source of the $^{85}$Kr has a window made of material Titanium with surface density of 11.3 mg.cm$^{-2}$ [BSS2 2000] as show in Figure 4.
2.4.2.- Source of $^{90}$Sr/$^{90}$Y

The $^{90}$Sr/$^{90}$Y source has a window made of stainless steel with density of 79 mg.cm$^{-2}$ [BSS2 2000] as shown in Figure 5.

2.4.3.- Source of $^{147}$Pm

The $^{147}$Pm source has a window made of Titanium with surface density of 2 mg.cm$^{-2}$ [BSS2 2000]. In the simulations of this particular source geometry the beta particles, almost completely, are shielded in the material and very poor absorbed dose rate is computed in the sensitive volume as well as with a large relative error, even if a large
number of particles is set. Therefore, this window was not modelled even though it is known that the beta particles are emitted when the shutter is opened. Figure 6 shows the MC code along with the materials used in the simulation.

![Figure 6](image)

Figure 6.- (a) Scheme complete of two-dimensional geometric of the source $^{147}$Pm. (b) Source specific geometry with titanium window in front of the source. Illustration out of scale. Provide by author.

Table 1 shows the material compositions used in the MC model according to Behrens, et. al 2013.

Table 1.- Composition of the materials of the sources adopted in the simulations with their densities and their compositions in %.

<table>
<thead>
<tr>
<th>Material</th>
<th>Kr</th>
<th>Sr Carbonate</th>
<th>Pm$_2$O$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g.cm$^{-3}$]</td>
<td>0.0191</td>
<td>3.76</td>
<td>6.85</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>8.14</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td></td>
<td>32.51</td>
<td>14.03</td>
</tr>
<tr>
<td>Sr</td>
<td></td>
<td>59.35</td>
<td></td>
</tr>
<tr>
<td>Kr</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pm</td>
<td></td>
<td></td>
<td>85.97</td>
</tr>
</tbody>
</table>

The source card in MCNPx code allows to set the distance of the source to the extrapolation chamber. The beta particle beam was collimated in a cone toward the chamber with a half-angle around the z-axis[Shultis and Faw 2008]. The apex of the cone was immersed in
active material. Figure 7 shows in 3D illustrated through Vised[Schwarz, 2011] where the sources are located specifically in their respective geometries.

Figure 7.- Scheme 3D of the sources used in the simulations: (a) $^{85}$Kr (b) $^{90}$Sr/$^{90}$Y and (c)$^{147}$Pm. Illustration out of scale. Provide by author.

The simulations were performed at the standard calibration distance between the radiation source and the extrapolation chamber. The distance defined was 30 cm for the $^{85}$Kr, 20 cm for $^{147}$Pm and 30, 11, 20 e 50 cm for $^{90}$Sr/$^{90}$Y[ISO 2004]. The radionuclide energy spectra of the radionuclides $^{85}$Kr, $^{90}$Sr/$^{90}$Y and $^{147}$Pm were obtained in the ICRP 107[ICRP 2008].

2.5.- Spectra used in simulations

In the source card used in MCNPX, two types of source information (SI) were used, one was type L given for variable values of sources and another one was type H that describes the distribution of a source as histogram[Pelowitz 2011]. The type L of source information, has an energy threshold to be initiated for electrons of greater than 1 keV and a range of up to 1 GeV, for photons the energy threshold is greater than 1 keV and with a range of 100 keV[Hughes 2012].

Although these radionuclides are not just beta emitters, the emission rate of other radiations such as X-rays and gamma, internal conversion electrons, and Auger electrons are of the order of $10^4$ to $10^5$ lower than the beta emission rate[ICRP 2008] and, therefore, do not contribute to the simulation results.
Two methods were used to describe the beta spectra for type SI L and SI H respectively. Method I is defined by direct normalization in the parameter Y(E), which describes the probability of energy dependent emission through the beta spectrum obtained by ICRP 107 [ICRP 2008]. The spectra in question is cut off, stripping the bands of energies less than 1 keV and renormalized with these new energy bands and inserted into the SI L. For the beta spectrum defined in this method, energies below and equal to 1 keV have been removed. To $^{90}$Sr/$^{90}$Y, the following observations were made to actually define its spectrum.

Through literature [Silva et al. 2019; Carmona and Rizo 2009], it was observed that the sum of the spectrum $^{90}$Sr and $^{90}$Y, has an average behavior, that is, it was done in each energy range of the spectrum, an average of the probability of emission, which is shown in Figure 8. It is taken into account the secular equilibrium that is imposed to this spectrum, since the half-life of the parent radionuclide is much higher than the half-life of the son radionuclide [Knoll 2010].

![Figure 8.- Spectra $^{90}$Sr and $^{90}$Y. The junction of these spectra $^{90}$Sr/$^{90}$Y has a median behavior. [Carmona and Rizo 2009]](image)

The method I is imposed for the $^{85}$Kr and $^{90}$Sr/$^{90}$Y, in which both had ranges of energy cut and renormalized respectively as can be seen in Figure 9 and 10.
Figure 9.- Beta spectra of $^{85}$Kr with full energy ranges and energy ranges greater than 1keV. $E_{\text{max}} = 0.68740$ MeV. Provided by author.

Figure 10.- Beta spectra $^{90}$Sr/$^{90}$Y with full energy ranges and energy ranges greater than 1keV. $E_{\text{max}} = 2.28010$ MeV. Provided by author.
The Figure 11 shows the beta spectra of the $^{147}\text{Pm}$.

![Beta spectra of $^{147}\text{Pm}$](image)

*Figure 11.- Beta spectra of $^{147}\text{Pm}$. $E_{\text{max}} = 0.22460$ MeV. [ICRP 2008]*

MCNPx does not compute energies smaller than 1 keV for electrons. Then it is possible to observe that, with the removal of energies smaller than and equal to 1 keV and after that renormalizing them, there was an increase of probability of emission of particles with energy above 1 keV, in comparison with the spectrum covering all energy ranges. Thus, this type of spectrum was used for simulations in SI L.

Method II was defined through the following idea. The area of each surface section given by the beta spectrum which has a continuous behavior is defined between $[E, E+1] \times [Y(E), Y(E+1)]$. This area gives the probability of having a beta particle emission[Attix 1986]. The sum of all these areas has an approximation $\Delta E \times \overline{Y}$, where $\Delta E$ is the width of the bin of energy and $\overline{Y}$ is the average yield in the range. Summing this whole area of interval gives the total probability that should be equal to 1, accompanied by a common rounding error, after which it is renormalized and inserted along with the full energy range in SI H. This method was applied to the $^{90}\text{Sr}/^{90}\text{Y}$ for purposes of comparison with method I. The method
II was used for the \(^{90}\text{Sr}/^{90}\text{Y}\) source and added their respective \(\Delta E \times \bar{Y}\) following by its renormalization.

The geometry of the source, which was explained in the previous topic, \(^{90}\text{Sr}/^{90}\text{Y}\) which is positioned exactly 50, 30, 20 and 11 cm from the extrapolation chamber, has as its first component the Air Shutter that is in the initial position of the geometry itself, and with a difference of 0.13 cm is the active material of the source[Nuclitec], and later the window of the source and finally and more important, the source that is located at 50.13, 30.13, 20.13 and 11.13 cm in relation to the extrapolation chamber, this source has cylindrical format with height of 0.05 cm. For both methods, SI L and SI H, the positions of the sources, whereas the real situation, the sources fills all volume, therefore, a source will exhibit the characteristics of a point source if the measuring point for the distance from the source is greater than three times larger than the non-point source size[Moe et al. 1972; Merrick 2012], for the two methods, these have different positions as shown in Figure 12, but with approximate results, which will be seen later.

![Figure 12.- Point position of the sources, where P1 is the SI L spectrum, and P2 is the SI H spectrum for \(^{90}\text{Sr}/^{90}\text{Y}\). Provide by author.](image)

### 2.6.- Calculation to determine the transmission factor, \(T\)

The simulations for calculations of transmission factors with equivalent tissue thicknesses[Polo and Caldas 2018; Antonio et al. 2014] were performed with the source and calibration of the source-chamber distance with the depth of the chamber fixed to 4.0 mm. The absorption thicknesses were positioned in front of the entrance window. The transmission factor was defined according to the Equation (1):
where \( E_m(d) \) is the mean energy deposited on the sensitive volume of the chamber with an absorption thickness \( d \), \( E_m(0) \) is the average energy extrapolated to zero absorption thickness (representing the surface of the skin); \( a \) is the calibrated distance from the source-chamber and \( a_o \) is the thickness of absorption. The quadratic term in Equation (4) is a geometric correction factor[ISO 2006] and is a value very close to an unit.

2.7. Calculation to determine the dose rate in tissue, \( \dot{D} \)

Two equations were used to calculate the dose rate. Equation (2), from the reference work of Faria[Faria et al. 2015],

\[
\dot{D} = T_{(0.07)} A s_{t,a} \sum_{i=1}^{n} E_m r_i \\
M
\]

where \( T_{(0.07)} \) is the transmission factor with 0.07 mm thickness, which is related to the absorption thickness that is located in front of the entrance window of the chamber. \( A \) is the activity in \( Bq \) defined in BSS2[BSS2 2000], \( s_{t,a} \) is the electronic mass quotient of the fabric and air braking power reported by ISO[ISO 2004] in which, \( s_{t,a}=1.12 \) is to \( ^{85}Kr \), 1.10 to \( ^{90}Sr/^{90}Y \) and 1.124 to \( ^{147}Pm \), and \( r_i \) is the rate of particle production by nuclear decay, \( M \) is the mass of the sensitive chamber volume and \( E_m \) is the mean energy defined by tally *F8 which describes the mean energy deposition in the MCNPx in which it is deposited on the sensitive volume of the chamber.

The second Equation (3) from Polo/MIT 2004; Polo et al. 2017,

\[
\dot{D} = \frac{AE_m}{M}
\]
where $A/M$ is the activity of origin in $Bq/g$, $E_m$ is the average energy in MeV by disintegration. According to ISO[ISO 2004], the dose rate absorbed in the tissue within the sensing volume of the extrapolation chamber is calculated by Equation (4):

$$
\dot{D} = \dot{D}_{t,a}
$$

(4)

The value of mass M in both equations was $4.25882 \times 10^{-3} g$ with a chamber depth of 5.0 mm.

2.8.- Law of the Inverse of the Square of the Distance

Any point source that spreads its influence equally in all directions without spatial limitation will obey the law of the inverse of the square of the distance, this comes from strictly geometrical considerations[Nikolaos and Oikonomidis 2017]. The intensity of the influence on any radius $r$ is the intensity of the source divided by the area of the sphere. This law has several applications in several areas of physics, including radiation protection[Hoff 2014] that the intensity has a decay with the inverse of the square of the distance. Knowing this, it will be observed whether for distances to the source settings $^{90}\text{Sr}/^{90}\text{Y}$ will have this type of behavior.

3.- RESULTS

3.1.- Extrapolation Curve

The extrapolation response curve was obtained by the measurements of the energies deposited within the sensitive volume of the chamber as a function of the distance between the entry window and the collecting electrode, i.e. the depth of the chamber. For the variation of the sensitive volume of the chamber, different depths of the cylinder were also varied of 0.5 mm. This variation changes the sensitive volume of the chamber and allows to obtain the dose rate in relation to the volume. Figure 13 shows the linearity of the energy deposited relative to the depth of the sensitive volume for the $^{85}\text{Kr}$ and $^{90}\text{Sr}/^{90}\text{Y}$ source at distances of 30 cm and $^{147}\text{Pm}$ at distance of 20 cm. The value of the coefficient of determination $R^2$ of the linear regression is greater than 0.999.
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Figure 13.- Chamber Linear Response on the sources (a) $^{90}$Sr/$^{90}$Y without filter at 30 cm. (b) $^{90}$Sr/$^{90}$Y with filter at 30 cm, both (a) and (b) have both methods separately inserted into the source card. (c) $^{85}$Kr. (d) $^{147}$Pm.

3.2.- Transmission Factor, $T$

The following results were adopted only for the $^{85}$Kr with a standard distance of 30 cm and a filter 10 cm from the source. Table 2 summarizes the $T$ values obtained using Equation (1) for the source and source-chamber distance in the simulations $T_{Sim}$ performed in this work in relation to the reference simulation transmission factors[Faria et al. 2015] $T_{Ref}$ and calibration $T_{Cal}$. 
Table 2.- Comparison with Transmission factors for $^{85}$Kr. $\Delta$ is the difference in % compared to the simulated in this work.

<table>
<thead>
<tr>
<th>$a_o$ [mm]</th>
<th>$T_{Cal}$</th>
<th>$T_{Ref}$</th>
<th>$T_{Sim}$</th>
<th>$\Delta_{Cal}$ [%]</th>
<th>$\Delta_{Ref}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1.05</td>
<td>1.05 ± 0.010</td>
<td>1.00 ± 0.0033</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>0.02</td>
<td>1.04</td>
<td>1.03 ± 0.011</td>
<td>1.08 ± 0.0034</td>
<td>3.4</td>
<td>4.4</td>
</tr>
<tr>
<td>0.04</td>
<td>1.03</td>
<td>1.02 ± 0.011</td>
<td>1.08 ± 0.0034</td>
<td>4.9</td>
<td>5.9</td>
</tr>
<tr>
<td>0.05</td>
<td>1.02</td>
<td>1.01 ± 0.012</td>
<td>1.02 ± 0.0035</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>0.07</td>
<td>1.00</td>
<td>1.00 ± 0.013</td>
<td>1.03 ± 0.0036</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>0.1</td>
<td>0.98</td>
<td>0.98 ± 0.013</td>
<td>0.96 ± 0.0037</td>
<td>0.4</td>
<td>2.4</td>
</tr>
<tr>
<td>0.2</td>
<td>0.78</td>
<td>0.91 ± 0.013</td>
<td>0.75 ± 0.0041</td>
<td>3.3</td>
<td>17.1</td>
</tr>
</tbody>
</table>

3.3.- Tissue dose rate, $\dot{D}$

The absorbed dose rate in tissue $\dot{D}$, was estimated through the results found in the simulations for the source and source-chamber standard distance and compared with the results of $^{85}$Kr and $^{90}$Sr/$^{90}$Y for Faria[Faria et al. 2015] $\dot{D}_{Ref_1}$ and for $^{147}$Pm it was used the results published by Polo[Polo et al. 2018] $\dot{D}_{Ref_2}$.

For comparison purposes, the method I was used for $^{85}$Kr. The Equations (2) $\dot{D}_{Eq_2}$ and (4) $\dot{D}_{Eq_4}$ will be used for $^{85}$Kr, as shown in Table 3. The $\theta$ parameter represents the cone of half-angle, $f_{in}$ and $f_{out}$ are the fractions of the particles generated in and out of the cone respectively.

The difference between Equation 2 to 4 is about 3%, which can be differentiated by the transmission factor previous calculated. For the $^{90}$Sr/$^{90}$Y source only Equation (4) was used and the methods I and II. Tables 4 shows, respectively, the dose rates results for Method I of SI L spectra $\dot{D}_{Met.I}$ and Method II of SI H spectra $\dot{D}_{Met.II}$ to the reference dose rates $\dot{D}_{Ref_1}$[Faria et al. 2015].
Table 3.- Dose rate for $^{85}\text{Kr}$

<table>
<thead>
<tr>
<th>$A$ [GBq]</th>
<th>$\dot{D}_{\text{Ref1}}$ [µGy.s$^{-1}$]</th>
<th>$\dot{D}_{\text{Eq2}}$ [µGy.s$^{-1}$]</th>
<th>$\dot{D}_{\text{Eq4}}$ [µGy.s$^{-1}$]</th>
<th>$\Delta_{\text{Eq1to Eq3}}$</th>
<th>$\theta, f_{\text{in}}, f_{\text{out}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>43.37 ± 0.02</td>
<td>45.1 ± 0.37</td>
<td>43.7 ± 0.3</td>
<td>3.10%</td>
<td>10; 0.76; 0.24</td>
</tr>
</tbody>
</table>

*w for with and w/o for without

Table 4.- Dose Rate for $^{90}\text{Sr}^{90}\text{Y}$ compared to Equation 4 using the Methods I and II

<table>
<thead>
<tr>
<th>Method I</th>
<th>Distance [cm]</th>
<th>$A$ [GBq]</th>
<th>$\dot{D}_{\text{Ref1}}$ [µGy.s$^{-1}$]</th>
<th>$\dot{D}_{\text{Met1}}$ [µGy.s$^{-1}$]</th>
<th>$\Delta$ [%]</th>
<th>$\theta, f_{\text{in}}, f_{\text{out}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>0.46</td>
<td>130.2 ± 0.1</td>
<td>131.5 ± 0.2</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.46</td>
<td>38.03 ± 0.02</td>
<td>39.0 ± 0.1</td>
<td>2.48</td>
</tr>
<tr>
<td></td>
<td>30 w* filter</td>
<td>0.46</td>
<td>10.8 ± 0.2</td>
<td>11.02 ± 0.06</td>
<td>11.02 ± 0.06</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>30 w/o* filter</td>
<td>0.46</td>
<td>16.8 ± 0.1</td>
<td>16.87 ± 0.09</td>
<td>16.87 ± 0.09</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.46</td>
<td>6.1 ± 0.2</td>
<td>6.17 ± 0.04</td>
<td>6.17 ± 0.04</td>
<td>1.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method II</th>
<th>$\dot{D}_{\text{MetII}}$ [µGy.s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>0.46</td>
</tr>
<tr>
<td>20</td>
<td>0.46</td>
</tr>
<tr>
<td>30 w* filter</td>
<td>0.46</td>
</tr>
<tr>
<td>30 w/o* filter</td>
<td>0.46</td>
</tr>
<tr>
<td>50</td>
<td>0.46</td>
</tr>
</tbody>
</table>

In the case of $^{147}\text{Pm}$ source only method II was used. It was not specified in the work of Polo[Polo et al. 2018] the configuration used to achieve the dose rate value, then the method to calculate the dose rates propose by Faria[Faria et al. 2015]. Table 5 shows the dose rate results and the difference calculated.
Table 5.- Dose rate for $^{147}$Pm

<table>
<thead>
<tr>
<th>$A$ [GBq]</th>
<th>$\dot{D}_{Ref,2}$ [µGy.s$^{-1}$]</th>
<th>$\dot{D}_{Met,II}$ [µGy.s$^{-1}$]</th>
<th>$\Delta$</th>
<th>$\theta_{ins,rou}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>12.7 ± 1.8</td>
<td>12.23 ± 0.2</td>
<td>3.7%</td>
<td>1; 0.65; 0.35</td>
</tr>
</tbody>
</table>

3.4.- Validation of the inverse law of the distance square

With dose rates with different distances for the source $^{90}$Sr/$^{90}$Y, it can be observed if these values behave with the inverse law of the square of the distance, with the adaptation that using the intensity, the dose rate of methods I and II are used, in comparison with the values of simulated in reference to the distances of the source.

The line that characterizes this law in this work is illustrated in Figure 14, with the types of spectra studied SI L and SI H for the distances of $^{90}$Sr/$^{90}$Y.

![Figure 14.- Dose rate ratio for source $^{90}$Sr/$^{90}$Y with 11 cm dose rate defined as the nominal dose rate $DR_0$ as a function of the inverse of the square of the distance.](image-url)
4.- DISCUSSION

4.1.- Extrapolation Curve

The behavior of the curve obtained through the simulations presents an expected response. That is, the smaller the depth of the chamber the smaller the energy deposited.

It is observed for the $^{90}\text{Sr}/^{90}\text{Y}$ source in which the two methods used in their respective positions in the source cell, obtained a very close response in both configurations. The difference of the slopes obtained in each of the linearization in each one of methods I and II applied, was obtained a minimum difference. For the $^{90}\text{Sr}/^{90}\text{Y}$ source without filter the difference is de 0.766%, while for filtering, the difference is 0.139%.

4.2.- Transmission Factor, $T$

It is observed that the difference of the transmission factors simulated in this work approximate to values of the calibration, with difference up to 5% and for the reference simulations, the difference has a difference up to 17%. It is also observed the decreasing of the transmission factors along the growth of the absorption thickness, in which, the absorption thickness increases and even further the beta particles exceed this thickness, in which this type of behavior is expected.

4.3.- Tissue dose rate, $\dot{D}$

The response of the dose rates for both methods obtained an expected response, with a general difference of up to 5 %, which proves that in the validation of the computational model of this work. Various distances were simulated for the $^{90}\text{Sr}/^{90}\text{Y}$ source and with good response. Table 6 shows the difference in dose rates of the two types of methods used.

It is observed that as the source approximates the chamber, the method II obtains a decrease in its accuracy, and that by increasing this distance from the source to the chamber, the two methods have a near the equality in their dose rates.
4.4.- Inverse law of the distance square

It is observed, then, that the spectrum which behaved better in relation to the reference spectrum was the spectrum used of the method I, as shown in Figure 14, Tables 4. Although the spectrum used in method II develops the entire spectrum with all bands of energies while of the spectrum used in method I to arrive at the proposed result, it is necessary to cut lower energy bands.

5.- CONCLUSIONS

This work summarizes the simulations made based on the model of the extrapolation chamber PTW 23392 and different sources of radiation $^{85}$Kr, $^{90}$Sr/$^{90}$Y and $^{147}$Pm. The source configuration on MCNPx model has been adjusted with all requirements specified for the manufactures of the source.

It was observed that in relation to the chamber response, the energy deposited in the chamber volume shows a linearity over the extrapolated curve, which results in a good response in relation to the chamber for both methods with a difference minimum in the slope of its curves and an equal approximation of its results even in different configurations in relation to the position of the source in active material.
Regarding the transmission factor, it was observed that there was a difference with the calibration certification value around 5%, whereas the reference simulation had a difference of up to 17% already in thicker absorption thicknesses.

For dose rates, a positive result was observed in relation to the reference simulation. To $^{85}$Kr, source, in which only the method I was used but with the two equations differences of 3%, and a 3.9% from Equation (2) was also observed compared to the rate of dose simulated reference and from Equation (4) a difference of 0.91%.

The $^{90}$Sr/$^{90}$Y source dose rate the Equation (4) was used and comparisons were made to the types of spectra for the different distances. For method I, compared to the reference, a mean difference of 2.49% was obtained with a maximum difference of up to 4.13%. For method II, a mean difference of 2.67% was obtained compared to the reference simulation and with a maximum difference of up to 5.28%. It was also observed that the difference between the two methods, there is an increase in the difference according to the source approaching the extrapolation chamber, which leaves open with what despite the spectrum used in method II that have all the energy ranges, the method I maintains a consistent value, different from the method II, that the dose rate begins to decrease in value as it approaches the chamber.

For $^{147}$Pm, it was observed that by removing the source window made of titanium, it was possible to measure the expected dose rate compared to that of Polo[Polo et al. 2018], with a difference of %3. It was also observed that the material that is included in the source (Pm$_2$O$_3$) has a very high absorption also for the particles, since this radionuclide has the lowest maximum energy among the three studied in this work with the highest density material as well. Even with all this information, it still succeeded in transporting the beta particles to the sensitive volume.

The inverse square law validation had a good result with the two methods used for the reference simulation and may also observe that the slope of the method II differs somewhat from the reference.
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