Calculation of the Gamma Radiation Dose Produced by a Cylindrical Radioactive Source

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The dose rate produced by a gamma photons source with cylindrical shape having the radius R_0 and height h was calculated. The calculations are complicated (laborious) because it involves many variables changes followed by application of the corresponding integration methods. The final expression of the dose contains both the source characteristic parameters and the two variable parameters R and z , defining the point of interest Q where the dose is calculated. Obtaining the four particular situations of the dose rate calculation is a proof that (26) final expression is general.

Keywords: gamma rays, absorbed dose, attenuation, point of interest, self absorption

Radioactive sources of gamma rays are increasingly utilized in various social and economical fields and more specifically for medical uses [1-4]. The management of these radioactive material sources necessitates the control of radiation exposure to these sources with compliance of the regulation issued annually by IAEA [5].

Many methods have been developed for evaluating gamma dose and gamma dose rates. The paper presents the particular example of the calculation of the dose rate produced by a gamma cylindrical source.

Dose rate calculation in the exterior point of cylinder shape source is more complicated than in the case of simple geometrical shape sources. The most common forms of sources theoretically studied are: point, linear, plan-circular, spherical and empty-cylinder. In the literature [6-7] the dose calculation in a point situated outside the cylindrical radioactive source is treated in the following situations:

- the point is located on the radioactive cylinder surface or in the plane passing through its axis. In this case there are not given the dose calculation steps, it is presented a formula specifying that the integral from the dose expression can be graphically calculated;

- dose calculation formula is rigorously demonstrated but are considered only the simplest possible situations, namely: the point calculation is disposed on the vertical passing through the source center. The final formula contains the two characteristic parameters of the source: the radius and the height of the cylinder. Dose rate expression obtained for this source type can be easy customized for the case of disposition the point at a higher distance than the source sizes. In this way it can be founded dose formulas for a punctate and filiform radioactive source. Dose calculation in a point outside the cylindrical source presented in this paper is more general than the other known from the literature because the dose calculation point has not particular layout. To facilitate the understanding of dose calculation in a cylindrical source external point we analyzed in a previous work two sources having simple geometric shapes in that occur fewer variables [8]. As it can be seen from the theoretical treatment performed in this paper there are mathematical difficulties related to numerous variables changes followed by integration. Self absorbtion is an important factor that should be taken in to account regarding this volumic source but it is neglected because gamma radiations unlike the corpuscular ones have high penetration capacity. Radiation attenuation in the space between the source and the interest point is also neglected because the absorbant environment is considered to be the air.

Dose rate calculation

The Q point where is calculated the gamma rays dose produced by the cylindrical source having Ë activity is defined in figure 1.

The radioactive cylinder has R0 radius, h height and it is considered to consist of a sum of point sources. Specific activity of the source is defined by $\Lambda_v = \Lambda / \pi R_0^2 h$. For calculations a point O are fixed as the origin in the middle of the cylinder axis. This point is at the cylinder axis intersection with the XOY horizontal plane which sections the cylinder at the half of its height.

It is considered an arbitrary P point located inside the cylinder at r_0 distance from its axis and z_0 from horizontal plane. The two r_0 and z_0 variables determine a vertical plane performing φ_0 angle with OY axis.

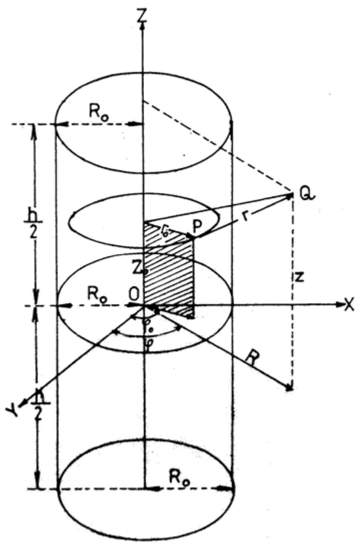

Fig.1. The displacement of the interest point Q to the cylindrical radioactive source where gamma radiations debit dose is calculated.

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The Q point where dose is calculated is disposed outside the cylinder at the r distance from P. A gamma photon emitted from the cylinder P point get in to the Q point from the source outside after goes the r distance both through source material and air. Projecting the Q point in the XOY horizontal plane, a point situated at the R distance from the origin axis is obtained. Dose calculation point Q is located at the z distance from the horizontal plane passing through the O center of the cylinder and at the R distance from its axis. The two parameters z and R determines a vertical plane passing through the axis origin and performs the φ angle with the OY axis of the horizontal plane. The r distance between the point P inside the source and the external point Q is given by the expression:

$$r^2 = (z - z_0)^2 + R^2 + r_0^2 - 2r_0R\cos(\varphi_0 - \varphi) \tag{1}$$

The volume element in the cylindrical coordinates is written:

$$dV = r_0 dr_0 d\varphi_0 dz_0 \tag{2}$$

The debit dose created by the cylindrical radioactive source having the specific activity Λ_v at the r distance has the expression [9]

$$D = k_\gamma \Lambda_v \int_v \frac{dV}{r^2} \tag{3}$$

In the relation (3) the expressions (1) and (2) are introduced and also the limits of the three variables φ_0, r_0, z_0. For the φ angle is taking into account the fact that the integrant is a periodical function having the period 2π. Having these specifications the integral from the debit dose formula is written:

$$I = \int_v \frac{dV}{r^2} = \int_{-\frac{h}{2}}^{+\frac{h}{2}} \int_0^{R_0} \int_\varphi^{2\pi+\varphi} \frac{r_0 dr_0 d\varphi_0 dz_0}{(z - z_0)^2 + r_0^2 + R^2 - 2r_0R\cos(\varphi_0 - \varphi)} \tag{4}$$

For integrating the expression (4) in relation to φ_0, the following changes of variables are performed:

$$\varphi_0 - \varphi = t,\ tg\frac{t}{2} = x \text{ respectively } dt = \frac{2dx}{1+x^2},\ \cos t = \frac{1-x^2}{1+x^2} \tag{5}$$

Because in a previous work [8] was performed the calculation of the integral (4) in relation to φ_0, now except that the z variable must be replaced with $z\text{-}z_0$ only the result is presented:

$$I_{\varphi_0} = \frac{2\pi}{\sqrt{\left[(z - z_0)^2 + (R_0 + R)^2\right]\left[(z - z_0)^2 + (r_0 - R)^2\right]}} \tag{6}$$

After calculating relation (6), the integral in relation to r_0 variable is written:

$$I_{r_0} = 2\pi \int_0^{R_0} \frac{r_0 dr_0}{\sqrt{\left[(z - z_0)^2 + R^2 + r_0^2\right]^2 - 4r_0^2R^2}} \tag{7}$$

In relation (7) the following variable change is used:

$$(z - z_0)^2 + R^2 + r_0^2 = t \tag{8}$$

Substituting relation (8) in (7) the I_{r0} integral becomes:

$$I_{r_0} = \pi \int_{(z-z_0)^2+R^2}^{(z-z_0)^2+R_0^2+R^2} \frac{dt}{\sqrt{(t - 2R^2)^2 + 4R^2(z - z_0)^2}} \tag{9}$$

Integrating expression (9) followed by limits introduction and performing calculations,results:

$$I_{r_0}(z_0, z, R, R_0) = \pi\left[-\ln 2 - 2\ln(z - z_0) + \ln\left|\sqrt{\left[(z - z_0)^2 + R_0^2 - R^2\right]^2 + 4R^2(z - z_0)^2} + (z - z_0)^2 + R_0^2 - R^2\right|\right] \tag{10}$$

Expression (10) must be integrated in relation to z_0 variable between –h/2 and + h/2 . Is observed that this expression consists of a sum of three terms notated I_1, I_2, I_3, and that to simplify the work will be integrated separately.

$$I_{r_0} = \int_{-\frac{h}{2}}^{+\frac{h}{2}} I_{r_0}(z_0, z, R_0, R)dz_0 = I_1 + I_2 + I_3 \tag{11}$$

where:

$$I_1 = -\pi \int_{-\frac{h}{2}}^{+\frac{h}{2}} \ln 2 dz_0 = -\pi h \ln 2 \tag{12}$$

$$I_2 = -2\pi \int_{-\frac{h}{2}}^{+\frac{h}{2}} \ln(z - z_0)dz_0 \tag{13}$$

$$I_3 = \pi\left[\int_{-\frac{h}{2}}^{+\frac{h}{2}} \ln\left|\sqrt{\left[(z - z_0)^2 + R_0^2 - R^2\right]^2 + 4R^2(z - z_0)^2} + (z - z_0)^2 + R_0^2 - R^2\right|dz_0\right] \tag{14}$$

Regarding I_2 integral (13), the $z_0\text{-}z=t$ substitution is performed. After by parts integration and introducing the corresponding limits the following result is obtained:

$$I_2 = \pi\left[2h - 2\left(\frac{h}{2} - z\right)\ln\left(\frac{h}{2} - z\right) - 2\left(\frac{h}{2} + z\right)\ln\left(\frac{h}{2} + z\right)\right] \tag{15}$$

Solving I_3 integral requires variable change (8). Calculation of the I_3 integral requires a complex series of mathematical operations. In order to simplify this work, only the final result will be presented.

$$I_3 = \pi\left\{\left(\frac{h}{2} - z\right)\ln\left[\sqrt{\left[\left(\frac{h}{2} - z\right)^2 + R_0^2 - R^2\right]^2 + 4R^2\left(\frac{h}{2} - z\right)^2} + \left(\frac{h}{2} - z\right)^2 + R_0^2 - R^2\right] + \left(\frac{h}{2} + z\right)\ln\left[\sqrt{\left[\left(\frac{h}{2} + z\right)^2 + R_0^2 - R^2\right]^2 + 4R^2\left(\frac{h}{2} + z\right)^2} + \left(\frac{h}{2} + z\right)^2 + R_0^2 - R^2\right] - h - \right\} - \int_{-\frac{h}{2}-z}^{\frac{h}{2}-z} \frac{t^2 + R^2 - R_0^2}{\sqrt{(t^2 + R_0^2 - R^2)^2 + 4R^2t^2}} dt\} \tag{16}$$

In (16) formula the last integral noted by i will be calculated.

$$i = \pi \int_{-\frac{h}{2}-z}^{\frac{h}{2}-z} \frac{t^2 + R^2 - R_0^2}{\sqrt{(t^2 + R_0^2 - R^2)^2 + 4R^2t^2}} dt \tag{17}$$

For calculating the integral noted by (17) it can be considered three distinct situations that express vertical variation of the Q point position where dose to the (h/2) height of the cylindrical radioactive source is calculated.

$$\begin{aligned}&a)\ z\langle -\frac{h}{2} \rightarrow -z-\frac{h}{2}\rangle 0 \qquad \frac{h}{2}-z\rangle 0\\&b)\ -\frac{h}{2}\le z\le \frac{h}{2} \rightarrow -z-\frac{h}{2}\langle 0 \qquad \frac{h}{2}-z\rangle 0\\&c)\ z\rangle \frac{h}{2} \rightarrow \frac{h}{2}-z\langle 0 \qquad -\frac{h}{2}-z\langle 0\end{aligned} \tag{18}$$

The three situations (18) are reduced to solving a single integral separately presented in this paper. In the mathematical treatment of the previous cases (18), the (19) notation is used. The calculation result of each case is expressed using **Φ** function whose meaning is given in the appendix.

$$\frac{t^2+R^2-R_0^2}{\sqrt{\left(t^2+R_0^2-R^2\right)^2+4R^2t^2}}=A(t,R,R_0) \tag{19}$$

$$i_a=\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}A(t,R,R_0)dt=\int_0^{\frac{h}{2}-z}A(t,R,R_0)dt-\int_0^{-\frac{h}{2}-z}A(t,R,R_0)dt=\Phi\left(\frac{h}{2}-z\right)-\Phi\left(-\frac{h}{2}-z\right) \tag{20}$$

<u>Case b</u>

$$i_b=\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}A(t,R,R_0)dt=\int_0^{\frac{h}{2}-z}A(t,R,R_0)dt+\int_{-\frac{h}{2}-z}^{0}A(t,R,R_0)dt \tag{21}$$

In the second integral from (21) expression, t is changed to –t, results:

$$i_b=\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}A(t,R,R_0)dt=\int_0^{\frac{h}{2}-z}A(t,R,R_0)dt+\int_0^{\frac{h}{2}+z}A(t,R,R_0)dt=\Phi\left(\frac{h}{2}-z\right)+\Phi\left(\frac{h}{2}+z\right) \tag{22}$$

Case c

Solving integral (19) involves t to –t substitution resulting:

$$i_c=\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}A(t,R,R_0)=\int_0^{z+\frac{h}{2}}A(t,R,R_0)dt-\int_0^{z-\frac{h}{2}}A(t,R,R_0)dt=\Phi\left(\frac{h}{2}+z\right)-\Phi\left(-\frac{h}{2}+z\right) \tag{23}$$

Using I1, I2, I3, integral expressions and also the obtained result in the general form given in the appendix, the final form of the integral (4) calculating dose is written:

$$\begin{aligned}I=\pi\{&h-h\ln 2-2\left(\frac{h}{2}-z\right)\ln\left(\frac{h}{2}-z\right)-2\left(\frac{h}{2}+z\right)\ln\left(\frac{h}{2}+z\right)+\left(\frac{h}{2}-z\right)\ln\left[\sqrt{\left[\left(\frac{h}{2}-z\right)^2+R_0^2-R^2\right]^2+4R^2\left(\frac{h}{2}-z\right)^2}+\left(\frac{h}{2}-z\right)^2+R_0^2-R^2\right]\\&+\left(\frac{h}{2}+z\right)\ln\left[\sqrt{\left[\left(\frac{h}{2}+z\right)^2+R_0^2-R^2\right]^2+4R^2\left(\frac{h}{2}+z\right)^2}+\left(\frac{h}{2}+z\right)^2+R_0^2-R^2\right]-\Psi(\alpha)\}\end{aligned} \tag{24}$$

where:

$$\left.\begin{aligned}&\Psi(\alpha)=\Phi\left(\frac{h}{2}-z\right)-\Phi\left(-\frac{h}{2}-z\right) \quad \text{for } z<-\frac{h}{2}\\&\Psi(\alpha)=\Phi\left(\frac{h}{2}-z\right)+\Phi\left(\frac{h}{2}+z\right) \quad \text{for } -\frac{h}{2}\le z\le\frac{h}{2}\\&\Psi(\alpha)=\Phi\left(\frac{h}{2}+z\right)-\Phi\left(-\frac{h}{2}+z\right) \quad \text{for } z>\frac{h}{2}\end{aligned}\right\} \tag{25}$$

The final form of the debit dose produced by a cylindrical source in an external Q point is given by:

$$\begin{aligned}D=k_\gamma\frac{\Lambda}{R_0^2h}\{&h-h\ln 2-2\left(\frac{h}{2}-z\right)\ln\left(\frac{h}{2}-z\right)-2\left(\frac{h}{2}+z\right)\ln\left(\frac{h}{2}+z\right)\\&+\left(\frac{h}{2}-z\right)\ln\left[\sqrt{\left[\left(\frac{h}{2}-z\right)^2+R_0^2-R^2\right]^2+4R^2\left(\frac{h}{2}-z\right)^2}+\left(\frac{h}{2}-z\right)^2+R_0^2-R^2\right]\end{aligned}$$

$$+\left(\frac{h}{2}+z\right)\ln\left[\sqrt{\left[\left(\frac{h}{2}+z\right)^2+R_0^2-R^2\right]^2+4R^2\left(\frac{h}{2}+z\right)^2}+\left(\frac{h}{2}+z\right)^2+R_0^2-R^2\right]-\Psi(\alpha)\} \tag{26}$$

Particular cases

1) The interest point is located on the vertical which passes through the center of the source at the z distance from the center. In this case R=0, expression (26) become:

$$D=k_\gamma\frac{\Lambda}{R_0^2h}\left[h-h\ln 2-\left(\frac{h}{2}-z\right)\ln\left(\frac{h}{2}-z\right)^2-\left(\frac{h}{2}+z\right)\ln\left(\frac{h}{2}+z\right)^2\right]+\left(\frac{h}{2}-z\right)\ln 2+\left(\frac{h}{2}-z\right)\ln\left[\left(\frac{h}{2}-z\right)^2+R_0^2\right]$$
$$+\left(\frac{h}{2}+z\right)\ln 2+\left(\frac{h}{2}+z\right)\ln\left[\left(\frac{h}{2}+z\right)^2+R_0^2\right]-\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}\frac{t^2-R_0^2}{t^2+R_0^2}dt \tag{27}$$

The last integral from expression (27) is calculated:

$$I=\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}\frac{t^2}{t^2+R_0^2}dt-R_0^2\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}\frac{dt}{t^2+R_0^2}=\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}dt-2R_0^2\int_{-\frac{h}{2}-z}^{\frac{h}{2}-z}\frac{dt}{t^2+R_0^2}=h-2R_0\left[\operatorname{arctg}\frac{\frac{h}{2}-z}{R_0}+\operatorname{arctg}\frac{\frac{h}{2}+z}{R_0}\right] \tag{28}$$

Introducing expression (28) in the dose formula results:

$$D=k_\gamma\frac{\Lambda}{R_0^2h}=\{h-h\ln 2+h\ln 2-h+\left(\frac{h}{2}-z\right)\left[\ln\left|\left(\frac{h}{2}-z\right)^2+R_0^2\right|-\ln\left(\frac{h}{2}-z\right)^2\right]+\left(\frac{h}{2}+z\right)\left[\ln\left|\left(\frac{h}{2}+z\right)^2+R_0^2\right|-\ln\left(\frac{h}{2}+z\right)^2\right]$$
$$+2R_0\left[\operatorname{arctg}\frac{\frac{h}{2}-z}{R_0}+\operatorname{arctg}\frac{\frac{h}{2}+z}{R_0}\right]\}= \tag{29}$$
$$k_\gamma\frac{\Lambda}{R_0^2h}\{\left(\frac{h}{2}-z\right)\ln\left[1+\frac{R_0^2}{\left(\frac{h}{2}-z\right)^2}\right]+\left(\frac{h}{2}+z\right)\ln\left[1+\frac{R_0^2}{\left(\frac{h}{2}+z\right)^2}\right]+2R_0\left[\operatorname{arctg}\frac{\frac{h}{2}-z}{R_0}+\operatorname{arctg}\frac{\frac{h}{2}+z}{R_0}\right]\}$$

Expression (29) become:

$$D=k_\gamma\frac{\Lambda}{R_0^2h}\{\left(\frac{h}{2}+z\right)\ln\left[1+\frac{R_0^2}{\left(\frac{h}{2}+z\right)^2}\right]-\left(z-\frac{h}{2}\right)\ln\left[1+\frac{R_0^2}{\left(z-\frac{h}{2}\right)^2}\right]+2R_0\left[\operatorname{arctg}\frac{\frac{h}{2}+z}{R_0}-\operatorname{arctg}\frac{z-\frac{h}{2}}{R_0}\right]\} \tag{30}$$

2) Customize expression (30) for the case : $z>>R_0$ and $h>>R_0$, the cylindrical source become filiform; the following approximations are performed:

$$\left(\frac{h}{2}+z\right)\ln\left[1+\frac{R_0^2}{\left(\frac{h}{2}+z\right)^2}\right]\cong\frac{R_0^2}{\frac{h}{2}+z}$$
$$\left[z-\frac{h}{2}\right]\ln\left[1+\frac{R_0^2}{\left(z-\frac{h}{2}\right)^2}\right]\cong\frac{R_0^2}{z-\frac{h}{2}} \tag{31}$$
$$\left[\operatorname{arctg}\frac{\frac{h}{2}+z}{R_0}-\operatorname{arctg}\frac{z-\frac{h}{2}}{R_0}\right]\cong\frac{R_0h}{z^2-\frac{h^2}{4}}$$

Using approximations from (31), expression (30) become

$$D=k_\gamma\frac{\Lambda}{R_0^2h}\left[\frac{2R_0^2h}{z^2-\frac{h^2}{4}}-\frac{R_0^2h}{z^2-\frac{h^2}{4}}\right]=k_\gamma\frac{\Lambda}{z^2}\frac{1}{1-\left(\frac{h}{2z}\right)^2} \tag{32}$$

Expression (32) is identical to the dose rate created by a filiform source in the Q point located on the source axis [8,10].

3) If the dose calculation point Q is at the z distance sufficiently large from the cylindrical source, the formula for the point source is obtained. In this case $z >> R_0$ and $z >> h$, (32) formula become:

$$D = k_\gamma \frac{\Lambda}{z^2} \tag{33}$$

expression identical to the photon fluency rate of the radioactive point source.

4) Dose calculation point is located in the XOY plane. For this, in expression (26) z=0, results:

$$D = k_\gamma \frac{\Lambda}{R_0^2 h}\left[h + h\ln 2 - 2h\ln h + h\ln\left|\sqrt{\left(\frac{h^2}{4} + R_0^2 - R^2\right)^2 + R^2h^2} + \frac{h^2}{4} + R_0^2 - R^2\right| - \Phi(\alpha)\right] \tag{34}$$

If the Q point is located in the XOY plane and at $R=R_0$ distance from the cylinder axis, from the previous expression results: R_0-R=0 and $\Phi(\alpha) = 0$

$$D = k_\gamma \frac{\Lambda}{R_0^2}\left[1 + \ln 2 - 2\ln h + \ln\left|\sqrt{\left(\frac{h^2}{4}\right)^2 + R_0^2h^2} + \frac{h^2}{4}\right|\right] \tag{35}$$

If we consider in expression (35) the approximation : $\sqrt{\left(\frac{h^2}{4}\right)^2 + R_0^2h^2} \cong \frac{h^2}{4}$ then the dose calculation formula for the point source is obtained, when the point is located in the XOY horizontal plane at the R_0 distance from the source:

$$D = k_\gamma \frac{\Lambda}{R_0^2}$$

The obtaining of the four particular cases previous presented is a proof that dose rate expression (26) has general character. The dose rate formulas for this particular cases were directly obtained and are presented in literature [10,11].

Annex

The integral must be solved:

$$\Phi(\alpha) = \int_0^\alpha \frac{t^2 + R^2 - R_0^2}{\sqrt{\left(t^2 + R_0^2 - R^2\right)^2 + 4R^2t^2}}dt \quad \text{where } \alpha = \frac{h}{2} \tag{36}$$

In expression (36) $t^2=v$ substitution is performed, results:

$$\Phi(\alpha) = \frac{1}{2}\int_0^{\alpha^2} \frac{\left(v + R^2 - R_0^2\right)dv}{\sqrt{v\left[v + (R_0 + R)^2\right]\left[v + (R_0 - R)^2\right]}} \tag{37}$$

In (37) integral a new substitution : $v = (R - R_0)^2 \mathrm{tg}^2\varphi$ is performed, results:

$$\Phi(\alpha) = \frac{1}{2}\int_0^{\mathrm{arctg}\frac{\alpha}{|R-R_0|}} \frac{2\left[(R - R_0)^2\mathrm{tg}^2\varphi + R^2 - R_0^2\right]d\varphi}{(R_0 + R)\sqrt{1 - \frac{4RR_0}{(R + R_0)^2}\sin^2\varphi}}$$

$$= \frac{(R - R_0)^2}{R + R_0}\int_0^{\mathrm{arctg}\frac{\alpha}{|R-R_0|}} \frac{\mathrm{tg}^2\varphi d\varphi}{\sqrt{1 - \frac{4RR_0}{(R + R_0)^2}\sin^2\varphi}} + \frac{(R - R_0)^2}{R + R_0}\int_0^{\mathrm{arctg}\frac{\alpha}{|R-R_0|}} \frac{d\varphi}{\sqrt{1 - \frac{4RR_0}{(R + R_0)^2}\sin^2\varphi}} \tag{38}$$

For solving (29) integral expressions the following three integrals are necessary [12]:

$$\int_0^\beta \sqrt{1 - k^2\sin^2\varphi}\, d\varphi = E(\beta, k) \tag{39}$$

$$\int_0^\beta \frac{d\varphi}{\sqrt{1 - k^2\sin^2\varphi}} = F(\beta, k) \tag{40}$$

$$\int_0^\beta \frac{\mathrm{tg}^2\varphi d\varphi}{\sqrt{1 - k^2\sin^2\varphi}} = \frac{\sqrt{1 - k^2\sin^2\beta}\,\mathrm{tg}\beta - \int_0^\beta \sqrt{1 - k^2\sin^2\varphi}d\varphi}{k'^2} \tag{41}$$

where: $F(\beta, k)$ and $E(\beta, k)$are elliptic functions of first and second degree [13-14] of β argument and k module $\left(k'^2 = 1 - k^2\right)$ is k complementary module, and

$$k = \frac{2\sqrt{RR_0}}{R + R_0} \quad (42)$$

using notation $\beta = \mathrm{arctg}\,\frac{\alpha}{|R - R_0|}$ (43)

the (36) integral has the following final expression:

$$\Phi(\alpha) = (R + R_0)\left[\sqrt{1 - \frac{4RR_0}{(R + R_0)^2}\sin^2\beta}\,\mathrm{tg}\beta - E(\beta, k)\right] +$$

$$+ (R - R_0)F(\beta, k) \quad (44)$$

Conclusions

Dose rate formula calculated considering a cylindrical radioactive source leads to the following conclusions:

- calculating the integrals in relation to the three variables φ_o, r_o, z_0 defining an arbitrary point P inside the source means that the dose to the point of interest Q located at distance r from P is determined by the all point sources contribution that perform the cylindrical source of R_0 radius and h height;

- in the final formula of the dose rate, the variable parameters remain those characterizing the position of the Q point: the R distance from the cylinder axis and z height to the XOY horizontal plane respectively. For determined values R_0,h it can calculate and plotted the dose rate variation versus R and z;

- fhe formula contains many logarithmic terms proving that the dose created by the cylindrical source show a logarithmic dependence from the R and z variable parameters defining the Q point position outside the source.

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