RADIATION SHIELDING OF THE STERILIZATION INSTALLATION BASED ON GAMMA-RADIATING EUROPIUM ISITOPES

B.N. Razsukovanyj, A.A. Mazilov, A.V. Mazilov

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
e-mail: Mazilov@kipt.kharkov.ua

The method of calculation of a radiation protection from a source of a gamma radiation including isotopes of europium-152 and europium-154 by activity 1.5 MCi everyone is presented. As a material of protection the iron, concrete and homogeneous mixture of iron ore and concrete was used. The way of computation of radiation parameters necessary for performance of calculation of protection from nontraditional materials is shown.

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INTRODUCTION

Among the methods used for radiation treatment (sterilization) of diverse products there is application of a radionuclide gamma-source with ultra-high activity as a radiating means. In the process of realization of similar projects one of the most important stages is the selection of material and performing of calculations on radiation shield providing the radiological protection of personnel and population. The specialists of the NSC KIPT are developing, under STCU support, physical fundamentals of radiation technologies with the use of gamma-sources on the base of europium isotopes. As a radiation-protective material it is suggested to use in one case iron, and in another case – homogeneous mixture of iron ore and concrete (further: reinforced concrete) of a density ρ = 4.0 g/cm^3. In the world practice a similar material for protection from photon irradiation is used rather often due to the increased value of an effective atomic number, as compared with conventional concrete. However, up to the present, there are not any universal data on radiation parameters constituting the algorithm of calculation of a radiation shield made from a similar material. It is explained by the variety of the weight content of iron in the protective material.

The present work is continuation and supplement of work [1] and gives the calculation of the radiation shield and equivalent dose rate around the shield of a gamma-source with defined geometrical dimensions composed of isotopes europium-152 and europium-154, every having an activity of 1.5 MCi. We consider two variants of the upper shield: one from iron, and another from the mixture of iron ore and concrete.

Besides, the side face and the side frontal shields from the reinforced concrete-iron ore mixture are considered. For calculations we have used the interpolation of known literature data on radiation parameters of iron and concrete as applied to the offered project of the radiation shield geometry and design.

1. RADIATION SOURCE AND SHIELD GEOMETRY

A gamma-radiation source represents two rectangular plates of a height H=200 cm and a length L=400 cm with the activity uniformly distributed over the plane of every plate. It is conditioned by the isotopes *Eu*-152 and *Eu*-154 each of which has the activity Q=1.5·10^6 Ci. Thus, every plate acts as a radiation source with the total energy spectrum of isotopes *Eu*-152 and *Eu*-154 and corresponding partial gamma-constants K_{ji}. The total gamma-constant is equal to the sum of total gamma-constants of *Eu*-152 and *Eu*-154 and the surface density of the activity is

$$\sigma = \frac{Q}{2LH} = 1{,}9\cdot 10^4\, mCi/cm^2.$$

In Table 1 given are the main energy gamma-lines of the source E_i (MeV), partial gamma-constants K_{ji} *(mrem·cm²)/(g·mCi)* and the contribution of the partial gamma-constant into the full gamma-constant $n_i(\%)=(K_{ji}/\sum K_{ji})\cdot 100$.

Generally speaking K_{ji} has the dimensionality *(R·cm²)/(h·mCi)*. We have assumed that the exposition dose of gamma-radiation equal to 1 R corresponds to the equivalent dose equal to 1 rem, though in the different literature data this coefficient is varying from 0.64 to 1.0.

Table 1. *The energy spectrum and gamma-constants of the source [2]*

E_i	1.405	1.277	1.210	1.110	1.085	1.007	0.998	0.963	0.875	0.866	0.725	0.720
K_{ji}	1772	2772	127	709	754	926	757	736	630	288	857	41
n_i	15.75	24.64	1.13	6.30	6.70	8.23	6.73	6.54	5.60	2.56	7.62	0.36

E_i	0.593	0.550	0.442	0.248	0.244	0.123	0.122	
K_{ji}	136	16	127	80	118	78	327	$\sum$ = 11251
n_i	1.21	0.14	1.13	0.71	1.05	0.69	2.91	$\sum$ = 100

The geometry of the shield has the following form. The sources, arranged in-series in the one plane at a distance L_1=300 cm from each other, are closed at the top, in one case, by the iron plate of a thickness Δ=45 cm (Fig. 1), and, in another case, by the reinforced concrete plate of a thickness Δ=150 cm (Fig. 2) in the arc form.

The lateral wall on the face side of plates (Fig. 3) and on the frontal side (Fig. 4) is made from reinforced concrete of a thickness Δ=150 cm.

All linear dimensions necessary for calculations are indicated on the below-given figures.

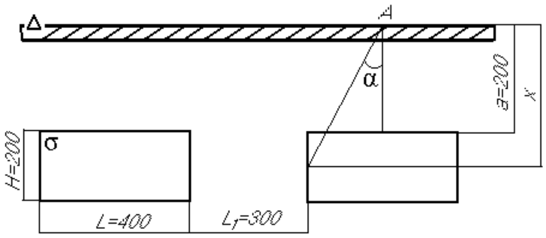

Fig. 1. *Upper shield from iron*

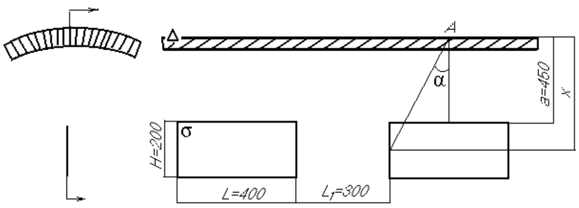

Fig. 2. *Upper arc-like shield from reinforced concrete*

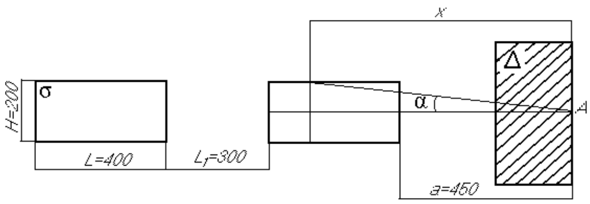

Fig. 3. *Lateral face shield from reinforced concrete*

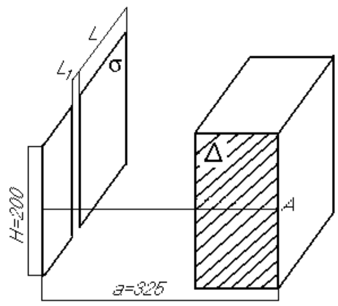

Fig. 4. *Lateral frontal shield from reinforced concrete*

2. RADIATION PARAMETERS

In the general case of an extended source the dose rate P at point A on the outside of the shield (Fig. 5) is proportional to the integral (without taking into account the self-absorption in the source):

$$P = C\int \frac{e^{-b(r)}}{|\vec{r}|^2} B(b(r))d\vec{r}, \qquad (1)$$

where C is the proportionality coefficient; $b=\mu x$ is the dimensionless value equal to the length x (cm) of radiation passage from the source element to the observation point A in the shielding material and expressed in lengths of a free path in this material; μ (cm^{-1}) is the linear factor of gamma-radiation attenuation in the shielding material depending on the atomic number of the shielding material Z and on the radiation energy E; $B(E,b,Z)$ is the dose factor of accumulation taking into account the diffuse radiation in the shielding material depending on the shield thickness b, as well as, on the radiation energy and shielding material Z; r is the radius-vector from the point A into the source element (elementary volume, surface element, length). Integration in Eq. (1) is performed over the whole source.

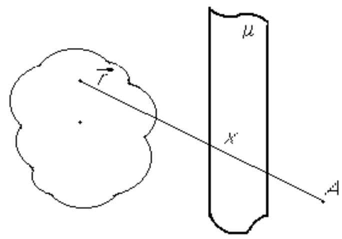

Fig. 5. *Geometry of the extended source and of the shield*

The dose factor $B(b(r))$ is a slowly changing function as compared to the function $e^{-b(r)}/|r|^2$ and therefore for practical calculations it is removed from the sign of integration, however, we take into account only its dependence on *E, b, Z*.

For conventional shielding materials, e.g. iron and concrete used in the project, in the literature one widely presents the table data on the radiation parameters of the linear attenuation coefficient of γ-radiation $\mu(E,Z)$ and on the dose factor of accumulation $B(E,b,Z)$. The values of these data, in general, slightly differ from each other. We have used for the parameter $\mu(E,Z)$ the data of [2] , and for the parameter $B(E,b,Z)$ the data of [3].

Table 2 gives the values of gamma-lines of the source energy-spectrum and the values of the parameter μ (cm^{-1}) interpolated by the energy for iron and concrete.

Table 2. *Values of the linear coefficient of attenuation for the source energy spectrum*

E_i	1.405	1.277	1.210	1.110	1.085	1.007	0.998	0.963	0.875	0.866	0.725	0.720
$\mu_{(ir)}$	0.398	0.419	0.431	0.448	0.452	0.466	0.468	0.477	0.500	0.503	0.549	0.551
$\mu_{(concr.)}$	0.126	0.131	0.135	0.142	0.143	0.149	0.149	0.152	0.160	0.160	0.174	0.175

E_i	0.593	0.550	0.442	0.248	0.244	0.123	0.122
$\mu_{(ir.)}$	0.600	0.622	0.689	0.952	0.962	2.061	2.085
$\mu_{(concr.)}$	0.190	0.196	0.215	0.269	0.272	0.362	0.364

Comparison of the radiation parameters given in Tables 1 and 2 shows that the major contribution into the dose rate on the outside of the shield is made by two gamma-lines of the spectrum: E_1=1.405 MeV and E_2=1.277 MeV. Indeed, the linear coefficient of attenuation μ increases considerably with energy decreasing, and it means significant decrease of the function $e^{-b(E)}$ at characteristic thicknesses of the shield designed. Besides, gamma-lines of lower energies make a lesser contribution into the dose rate at the expense of low values of partial gamma-constants. At the same time, the value of the dose factor of accumulation *B* in the range of the energy spectrum of source gamma-radiation increases much slowly than the decrease of the first two factors (μ and $e^{-b(E)}$) [3].

So, in calculations of the dose rate on the outside of the shield we will take into account only the first two lines of the spectrum with energies E_1=1.405 MeV and E_2=1.277 MeV and the radiation values and parameters with indexes *1* and *2*, used for calculations, will, respectively, refer to these energies.

To determine the radiation parameters of reinforced concrete it is necessary to know its effective atomic number Z_{ef}. Let us consider reinforced concrete with a density ρ=3.5 g/cm^3 as a homogeneous mixture of two components, namely, of iron (ρ_I=7.89 g/cm^3) and concrete (ρ_C=2.35 g/cm^3), which, in turn, is a homogeneous mixture of some elements with proper effective atomic number Z_C. The weight composition of concrete (%) is taken [4] so: 0.56*H*; 40.83*O*; 1.71*Na*; 0.24*Mg*; 4.56*Al*; 31.58*Si*; 0.12*S*; 1.93*K*; 8.26*Ca*; 1.22*Fe*. The weight composition of reinforced concrete is determined from the relation: $(1-x)\rho_I+x\rho_C=\rho$, from where we determine that the reinforced concrete contains 79.2% of concrete and 20.8% of iron.

At our energies (E_1 and E_2) the main processes of gamma-quantum interaction with material will be photo-effect and Compton-scattering at which the effective atomic number Z is determined by the formula of [3]:

$$Z=\left(\sum a_i\cdot Z_i^4/\sum a_i\cdot Z_i^4\right)^{1/3} \tag{2}$$

where a_i is the weight fraction of the element (material) with the effective atomic number Z_i. Applying this formula to concrete and reinforced concrete, we obtain Z_C=15; Z_{IC}=20 respectively.

Using the data for $\mu_1$and μ_2 from table 2 and interpolating by the atomic number in the range Z_C=15 and Z_I=26 we obtain for concrete: μ_1=0.182 cm^{-1} and μ^2=0.191 cm^{-1}. We have interpolated not the linear coefficients of attenuation, but the values independent on the material density, i.e. the mass coefficient of attenuation $\bar{\mu}=\mu/\rho$.

To obtain the values of accumulation factors $B_1(b)$ and $B_2(b)$ for reinforced concrete, the data of [3] for iron and concrete were, at first, interpolated by the energy, thus $B_{1I}(b)$ and $B_{2C}(b)$ were obtained. Then these values were interpolated by the atomic number and the values $B_1(b)$ and $B_2(b)$ were obtained. The results are given in Table 3 where besides values $B_{1I}(b)$, $B_{2I}(b)$, $B_{1C}(b)$, $B_{2C}(b)$, $B_1(b)$ and $B_2(b)$ shown are the values of accumulation factors for the design thicknesses of the shield: B_{1I} and B_{2I} at $b_I=\mu_{11}\Delta_1$=17.9; $b_2=\mu_{21}\Delta_1$=18.9, as well as, B_1 and B_2 at $b_1=\mu_1\Delta_2$=27.3 and $b_2=\mu_2\Delta_2$=28.65.

Table 3. *Dose factors B for iron, concrete and reinforced concrete for energies E_1=1.405 MeV and E_2=1.277 MeV*

B	Material	*b*=10	*b*=15	*b*=17.9	*b*=18.9	*b*=20	*b*=25	*b*=27.13	*b*=28.65	*b*=30
B_1	Iron	13.2	22.0	27.8	-	32.0	43.2	-	-	55.2
	reinforced concrete	14.6	24.0	-	-	36.0	48.8	55.2	-	62.7
	concrete	15.8	25.6	-	-	39.4	53.5	-	-	68.9
B_2	Iron	14.0	23.7	-	32.5	34.9	47.4	-	-	61.4
	reinforced concrete	15.8	27.1	-	-	40.4	55.2	-	67.2	71.7
	concrete	17.3	30.0	-	-	44.9	61.7	-	-	80.3

3. DOSE RATE ON THE OUTSIDE OF THE SHIELD DESIGNED

It is absolutely clear, that the maximum dose rate on the outside of the shield designed (see Fig. 1-4) is expected at points *A* located on the shield surface above the middle of the length of every plate (Fig. 1, 2), at a level of the half-height of plates (Fig. 3) and against the center of each of plates (Fig. 4).

It is important to note that the contribution of the plates distant from the point A into the dose rate is negligibly small as compared to the dose rate created by the nearest plate. It is connected with that the radiation from the distant plate must pass in the shield an effective distance being larger approximately by a factor of 1.4 than the distance passed by the radiation from the nearest-to- point A plate. From Eq (1) it follows that at characteristic values of shield thicknesses of the order of *b*=20, the contribution of the distant plate will, at least, less by a factor of $e^{0.4b}=3\cdot10^3$ than that of the nearest one. This affirmation is valid for the cases of the upper shield (Fig. 1, 2) and the lateral frontal shield (Fig. 4). In the case of lateral face shield (Fig. 3), of course, the contribution of both plates should be taken into account.

Besides below-given calculations of dose rates on the outside of the shield designed, we have calculated the shield thickness *d* providing the dose rate decreasing up to the value not exceeding the limit established by the normative documents of Ukraine in the field of radiation protection [5,6]. In accordance with normative documents, when designing the shield from the external irradiation for places of probable personnel situation (independently on the time of stay) it is necessary to take into account the safety factor equal to 2. Thus, the permissible dose rate behind the shield should be not higher than the value P_d=0.6 mrem/h for the personnel of category *A*.

Calculation of the shield thickness *d* for all four cases was performed by the method of "competitive" lines [7] that consists in the following. For every line of the energy spectrum, the shield thickness providing a required multiplicity of dose rate attenuation is calculated. Among defined thicknesses the maximum thickness d_m (corresponding to the "main" energy line) and the next one d_k (corresponding to the "competitive" energy line) are selected. For each of these thicknesses the layer of half-attenuation $\Delta_{1/2}=d/\log_2 K=d\ln 2/\ln K$ is determined, where *K* is the multiplicity of dose rate attenuation equal to the relation of the dose rate, created by the corresponding energy line in the absence of the protection P_o, to the permissible dose rate P_d: $K=P_0/P_d$. From two obtained values of layers of half-attenuation, $\Delta_{1/2m}$ and $\Delta_{1/2k}$, the higher value is selected. Then with a good approximation the final thickness should be found from the relationships:

if $d_m - d_k = 0$, then $d = d_m + \Delta_{1/2}$; (3a)
if $d_m - d_k < \Delta_{1/2}$, then $d = d_k + \Delta_{1/2}$; (3b)
if $d_m - d_k > \Delta_{1/2}$, then $d = d_m$. (3c)

In the energy spectrum of the source (Table 1) without any calculations one can see that the "competitive" lines are the lines E_1=1.405 MeV and E_2=1.277 MeV. It still remains to calculate only the corresponding values d_1 and d_2 and to determine which of them is "main" and which is "competitive" in every particular case of shielding.

3.1. UPPER SHIELD MADE FROM IRON (FIG. 1)

Integration over the plane of the plate (by one of coordinates) in (1) leads to the expression for the dose rate on the outside of the shield at point *A*:

$$P = 2B(b)K_\gamma \cdot \sigma \int_a^{a+H} \frac{F[\alpha(x),b]}{x} dx, \quad (4)$$

where $F[\alpha(x),b] = \int_o^{\alpha(x)} e^{\frac{b}{\cos\alpha}} d\alpha$ is the integral cosine, $\alpha(x)=arctg(\alpha(x))=arctg(L/2x)$. Substituting in this expression the numerical values of constants $b_1=\Delta_1\mu_{11}$=17.9 (see Table 2); B_1=27.8 (see Table 3); $K_{\gamma 1} = 1772 \frac{mrem \cdot cm^2}{h \cdot mCi}$ (see Table 1); b^2=18.9; B^2=32.5; $K_{\gamma 2} = 2772 \frac{mrem \cdot cm^2}{h \cdot mCi}$; $\sigma=1.9\cdot10^4$ mCi/cm^2; a=200 cm; H=200 cm and L=400 cm, we obtain after numerical integration: $P_1(\Delta_1)$=5.84 mrem/h, $P_2(\Delta_1)$=3.80 mrem/h and in the sum of two energy lines E_1 and E_2 $P(\Delta_1)$=9.64 mrem/h=16.1 P_d.

So, the shield from iron of a thickness Δ_1=45 cm is insufficient for decrease of the dose rate to the permissible one. Applying the above-described method of "competitive" lines and changing in Eq. (4) *P* by P_d, we obtain the equations for determination of d_k and d_m:

$$8{,}9 \cdot 10^{-9} = B_1\left(b\int_{200}^{400} \frac{F[\alpha(x),b]}{x}dx\right)$$

and

$$5{,}7 \cdot 10^{-9} = B_2(b)\int_{200}^{400} \frac{F[\alpha(x)b]}{x}dx, \quad (5)$$

the solutions of which are b_1=20.4 or d_1=51.3 cm (B_1(20.4)=32.9); b_2=21.0 or d_2=50.0 cm (at B_2(21.0)=37.5). The "main" line is E_1 and d_c=51,3 cm, the "competitive" line is E_2 and d_k=50.0 cm. Thus, in the absence of a shield the dose rate at point A is:

$$P_0 = 2K_\gamma \delta \int_a^{a+H} \frac{1}{x} arctg\frac{L}{2x}dx, \quad (6)$$

or $P_{01}=2.63\cdot10^7$ mrem/h, from where $K_1=P_{01}/P=4.38\cdot10^7$; $\Delta_{1/2(1)}=d_1\ln_2/\ln K_1$=2.0 cm;
$P_{02}=4.12\cdot10^7$ mrem/h, from where $K_2=P_{02}/P=6.87\cdot10^7$; $\Delta_{1/2(2)}=d_2\ln_2/\ln K_2$=1.9 cm. It means that $\Delta_{1/2}$=2.0 cm.

As d_m-d_k=1.3 cm < $\Delta_{1/2}$=2.0 cm, then, according to Eq. (3b), $d=d_k+\Delta_{1/2}$, i.e. d=52.1 cm.

At d=52.1; b_1=20.7; B_1=33.6; b_2=21.8; B_2=39.5, by Eq. (4) we find: $P_1(d)$=0,41 mrem/h; $P_2(d)$=0,24 mrem/h; $P(d)$=0.65 mrem/h.

3.2. UPPER SHIELD FROM REINFORCED CONCRETE (FIG. 2)

In this case in Eq (4) we should change the constants: $b_1=\Delta\mu_1$=27.3; B_1=55.2; $b_2=\Delta\mu_2$=28.65; B_2=67.2; a=450. After numerical integration we obtain: $P_1(\Delta)=4.0\cdot10^4$ mrem/h; $P_2(\Delta)=2.0\cdot10^4$ mrem/h, and the summary dose rate from two lines E_1 and E_2: $P=6.0\cdot10^{-4}$ mrem/h=10^3 P_d.

To determine a required thickness *d* we solve two equations Eq. (5) (with a=450 cm and $a+H$=650 cm) relatively to *b*, from which we obtain: b_1=19.5; d_1=107 cm (at B_1(19.5) =34.8) and b_2=20.4; d_2=107 cm (at B_2(20.4)=41.6), i.e. $d_m=d_k$=107 cm. In this case in the absence of the shield the dose rate at point *A* is determined by Eq. (6):

$P_{01}=8.1\cdot10^6$ mrem/h, from where $K_1=1.35\cdot10^7$ and $\Delta_{1/2(1)}$=4,5 cm;

$P_{02}=1.27\cdot10^7$ mrem/h, from where $K_2=2.11\cdot10^7$ and $\Delta_{1/2(2)}$=4.4 cm, i.e. $\Delta_{1/2}$=4.5 cm.

Then according to Eq. (3a): $d=d_m+\Delta_{1/2}$ or d=111.5 cm.

At d=111.5 cm; b_1=20.3; B_1(20.3)=36.8; b_2=21.3; B_2(21,3)=44.2, by Eq. (4) we find: $P_1(d)$=0,37 mrem/h; $P_2(d)$=0.25 mrem/h, i.e. $P(d)$=0.62 mrem/h.

3.3. LATERAL FACE SHIELD FROM REINFORCED CONCRETE (FIG. 3)

The dose rate on the outsideside of the shield at point *A* is determined by the equation:

$$P = 2B(b)K_\gamma \sigma \cdot \left[\int_a^{a+L} \frac{F[\alpha(x),b]}{x}dx + \int_{a+L+L_1}^{a+2L+L_1} \frac{F[\alpha(x),b]}{x}dx\right], \quad (7)$$

where $\alpha(x)=arctg(H/2x)$, and the radial parameters are the same as in section 3.2. After numerical integration we obtain $P_1(\Delta)=5.8\cdot10^{-4}$ mrem/h and $P_2(\Delta)=2.9\cdot10^4$ mrem/h, and the total dose rate created by the energy gamma-lines E_1 and E_2 is:

$$P(\Delta) = 8{,}7\cdot10^{-4}\ mrem/h = 1{,}5\cdot10^{-3}\ P_o\,.$$

To determine the required thickness d we have two equations relatively to b:

$$8{,}9\cdot10^{-9} = B_1(b)\cdot\left[\int_{450}^{850}\frac{F[\alpha(x),b]}{x}dx + \int_{1150}^{1550}\frac{F[\alpha(x),b]}{x}dx\right],$$

$$5{,}7\cdot10^{-9} = B_2(b)\cdot\left[\int_{450}^{850}\frac{F[\alpha(x),b]}{x}dx + \int_{1150}^{1550}\frac{F[\alpha(x),b]}{x}dx\right],\quad(8)$$

from which we obtain: b_1=20.0 or d_1=110 cm (B_1(20.0)=36.0) and b_2=20.6 or d_2=108 cm (B_2(20.6)=42.1), i.e. the "main" line is E_1 with d_m=110 cm, and the "competitive" one is E_2 with d_k=108 cm. In the absence of the shield the rate dose at point A is:

$$P_0 = 2K_\gamma\sigma\cdot\left[\int_{\alpha}^{\alpha+L}\frac{1}{x}arctg\frac{H}{2x}dx + \int_{\alpha+L}^{\alpha+2L+L_1}\frac{1}{x}arctg\frac{H}{2x}dx\right],(9)$$

or P_{01}=7.4·10^6 mrem/h, from where K_1=1,23·10^7 and $\Delta_{1/2(1)}$=4.7 cm; P_{02}=1,16·10^7 mrem/h, from where K_2=1,93·10^7 and $\Delta_{1/2(2)}$=4.5 cm, i.e. $\Delta_{1/2}$=4.7 cm. According to (3b), $d=d_k+\Delta_{1/2}$ or d=112.7 cm. In this case at d=112.7 cm; b_1=20.5; B_1(20.5)=37.3; b_2=21.5; B_2(21.5)=44.8 by Eq. (7) we find: $P_1(d)$=0.32 mrem/h and $P_2(d)$=0.22 mrem/h, i.e. $P(d)$=0.54 mrem/h.

3.4. LATERAL FRONTAL SHIELD MADE FROM REINFORCED CONCRETE (FIG. 4)

The dose rate behind the shield at point A is determined by the equation:

$$P = 4B(b)K_\gamma\sigma\cdot\left\{\frac{\pi}{2}E_1(b) - \int_o^{arctg\,H/L}E_1\left(b\sqrt{1+\frac{L^2}{4a^2\cos^2\alpha}}\right)d\alpha - \right.$$

$$\left. - \int_{arctg H/L}^{\pi/2}E_1\left(b\sqrt{1+\frac{H^2}{4a^2\sin^2\alpha}}\right)d\alpha\right\},\quad(10)$$

where a=325 cm; $E_1(b) = \int_b^\infty L^{-t}/t\,dt$ is the exponential integral function, and the radiation parameters are the same as in sections 3.2 and 3.3. After numerical integration we obtain: $P_1(\Delta)$=5.1·10^{-4} mrem/h; $P_2(\Delta)$=2.5·10^{-4} mrem/h, and the total dose rate from the energy lines E_1 and E_2: $P(\Delta)$=7.6·10^4 mrem/h= 1.3·10$^{-3}P_d$. For the numerical integration we used the approximations: $F(\alpha,b) = \alpha L^{-b}$ at small α; $F(\alpha,b) \approx F\left(\frac{\pi}{2},b\right) = 1{,}2\frac{L^{-b}}{\sqrt{b}}$ at large α; $E_1(b) = \frac{L^{-b}}{1+b}\left[1+\frac{1}{(1+b)^2}\right]$ at b>10. These approximations overvalued the calculated dose rates not more than by 15% and practically had no effect on the calculated thicknesses of the shield. To determine a required thickness α of the shield we have two equations relatively to b:

$$4{,}4\cdot10^{-9} = B_1(b)\cdot\left\{\frac{\pi}{2}E_1(b) - \int_0^{0,46}E_1\left(b\sqrt{1+\frac{0{,}38}{\cos^2\alpha}}\right)d\alpha - \right.$$

$$\left. - \int_{0,46}^{\pi/2}E_1\left(b\sqrt{1+\frac{0{,}095}{\sin^2\alpha}}\right)d\alpha\right\}\ \text{and}$$

$$2{,}8\cdot10^{-9} = B_1(b)\cdot\left\{\frac{\pi}{2}E_1(b) - \int_0^{0,46}E_1\left(b\sqrt{1+\frac{0{,}38}{\cos^2\alpha}}\right)d\alpha - \right.$$

$$\left. - \int_{0,46}^{\pi/2}E_1\left(b\sqrt{1+\frac{0{,}095}{\sin^2\alpha}}\right)d\alpha\right\},\quad(11)$$

from which we obtain: b_1=20.2 or d_1=111.0 cm (at B_1(20.2)=36.5); b_2=20.7 or d_2=108.4 cm (at B_2(20.7)=42.5).

It means, that the "main" line is E_1 with d_m=111.0 cm and the "competitive" one is E_1 with d_k=108.4 cm. In the absence of the shield the dose rate at point A is:

$$P_0 = 4K_\gamma\sigma\int_0^{H/L}\frac{arctg\frac{1}{\sqrt{\alpha^2+\left(a/2L\right)^2}}}{\sqrt{\alpha^2+\left(a/2L\right)^2}}d\alpha\,,\quad(12)$$

or P_{01}=2,0·10^7 mrem/h, from where K_1=3.3·10^7 and $\Delta_{1/2(1)}$=4.4 cm;

P_{02}=3,1·10^7 mrem/h, from where K_2=5,2·10^7 and $\Delta_{1/2(2)}$=4.2 cm, ie. $\Delta_{1/2}$=4.4 cm.

According to Eq. (3b) $d=d_k+\Delta_{1/2}$ or d=112.8 cm.

At d=112.8 cm; b_1=20.5; B_1(20.5)=37.3; b_2=21.5; B_2(21,5)=44.8 by Eq. (10) we find: $P_1(d)$=0.40 mrem/h; $P_2(d)$=0.26 mrem/h, i.e. $P(d)$=0.66 mrem/h.

It is easy to see that with the required thicknesses d, calculated by the above method, the total dose rate on the outside of the shield P is defined by two energy lines E_1 and E_2 differs from the permissible dose rate P_d: $P=\eta\cdot P_d$, where just η determines the error of the method of "competitive" lines related with the approximations Eq. (3a, b, c).

It is possible to avoid this error, changing the required thickness d by some correcting value δ that leads to the equality $P(d+\delta)=P_d$. It is easy to show that δ is related with the layer of half-attenuation $\Delta_{1/2}$ by the relationship $\delta=\Delta_{1/2}\cdot\ln\eta/\ln2$.

In our calculations for four variants of the shield (values of η equal to 1.083; 1.033; 0.9; 1.1) the corresponding values of the correcting thickness: δ =+0.2; +0.2; -0.7; +0.6 cm are determined.

Below in Table 4 presented are the main results of the above-described calculations: required thickness of the radiation shield d, dose rate on the outside of the shield P_1 and P_2, defined by the energy gamma-lines E_1 and E_2, their sum in the units of P_d, layer of half-attenuation $\Delta_{1/2}$ and correcting thickness δ.

Table 4. *Main results of calculations*

Type and material of a shield	d, cm	$P_1, \frac{mrem}{h}$	$P_2, \frac{mrem}{h}$	P/P_d	$\Delta_{1/2}$, cm	δ, cm
Upper, iron	52.1	0.41	0.24	1.083	2.0	+0.2
Upper, reinforced concrete	111.5	0.37	0.25	1.033	4.4	+0.2
Lateral face, reinforced concrete	112.7	0.32	0.22	0.9	4.7	-0.7
Frontal, concrete	112.8	0.40	0.26	1.1	4.4	+0.6

CONCLUSIONS

The paper presented the method offered for calculation of radiation parameters necessary for designing a shield from unconventional materials. For solution of this problem one can have very restricted quantity of initial data - only the density and weight composition of radiation shielding material. Operating with these and known literature data, using the interpolation method it is possible to obtain all the parameters necessary for carrying out of the calculation.

It should be noted, that during execution of the work we used the normative documents: Radiation Safety Standards of Ukraine (НРБУ-97) and Main Sanitary Rules of Radiation Protection of Ukraine (ОСПУ-2000). The calculation results show that the use of iron ore and concrete, as a photon radiation shielding material, is of great practical significance due to the availability of material components, possibility to vary the percentage composition of these components, and possibility to decrease the shield overall dimensions as compared to conventional concrete.

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REFERENCES

1. A.V. Mazilov, B.N. Razsukovanyj, V.V. Kolosenko et al. *Radiation shield design for the gamma-irradiation source of europium with the activity of 6·10⁶ Ki:* Preprint KIPT 2003-1, Kharkov, 2003, p. 11 (in Russian).
2. L.R. Kimel', V.P. Mashkovich. *Ionizing Radiation Protection Guide*. M., Atomizdat, 1972 (in Russian).
3. V.P. Mashkovich, A.V. Kudryavtseva. *Ionizing Radiation Protection Guide*. 4-d issue, M.: "Energoatomizdat", 1995 (in Russian).
4. V.F. Kozlov. *Radiation Protection Guide*. M.: "Atomizdat", 1977 (in Russian).
5. Main Sanitary Rules of Radiation Protection of Ukraine. Kiev, 2001
6. Radiation Safety Standards of Ukraine. Kiev, 1997.
7. *Ionizing Radiation Protection*. Ed. N.G. Gusev. M.: "Atomizdat", 1969, v. 1; 1973, v. 2 (in Russian).

РАДИАЦИОННАЯ ЗАЩИТА УСТАНОВКИ СТЕРИЛИЗАЦИИ НА БАЗЕ ГАММА-ИЗЛУЧАЮЩИХ ИЗОТОПОВ ЕВРОПИЯ

Б.Н. Разсукованный, А.А. Мазилов, А.В. Мазилов

Представлен способ расчёта радиационной защиты от источника гамма-излучения, включающего в себя изотопы европий-152 и европий-154 активностью 1.5 МКи каждый. В качестве материала защиты использованы железо, бетон и гомогенная смесь железной руды и бетона. Показан способ вычисления радиационных параметров, необходимых для выполнения расчёта защиты из нетрадиционных материалов.

РАДІАЦІЙНИЙ ЗАХИСТ УСТАНОВКИ СТЕРИЛІЗАЦІЇ НА БАЗІ ГАММА-ВИПРОМІНЮЮЧИХ ІЗОТОПІВ ЄВРОПІЮ

Б.М. Разсукованний, О.О. Мазілов, О.В. Мазілов

Представлено спосіб розрахунку радіаційного захисту від джерела гамма-випромінювання, що включає в себе ізотопи європій-152 і європій-154 активністю 1.5 МКи кожний. Як матеріал захисту використано залізо, бетон і гомогенна суміш залізної руди і бетону. Показано спосіб обчислення радіаційних параметрів, необхідних для виконання розрахунку захисту з нетрадиційних матеріалів.