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REDUCING OF RADIATION EXPOSURE THROUGH OPTIMAL ACTIVITY DISTRIBUTION OF RADIATION SOURCES

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At permanent or temporary storage of radioactive waste (RAW) one of the major challenges is to reduce radiation exposure. The questions about layout of model tanks with a fixed total number of RAW along the line are considered. It has been shown that when radiation sources with the same activity are placed at a specified distance from the line, the dose rate depends on the number of sources. The methodology of determining activities of N sources providing minimum dose rate at a specified distance from the distribution line has been developed. It has been shown that there is an optimal number of sources with a certain activity, as well as their layout at which the exposure dose is minimal at a specified distance from the source disposal line.
KEY WORDS: radiation, gamma radiation, dose rate, activity, source radiation, minimum dose rate.

ЗМЕНШЕННЯ РАДІАЦІЙНОЇ ДІЇ ПРИ ОПТИМАЛЬНОМУ РОЗПОДІЛІ АКТИВНОСТЕЙ ДЖЕРЕЛ ВИПРОМІНЮВАННЯ

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При постійному або тимчасовому зберіганні радіоактивних відходів (РАВ) однією з головних проблем є зменшення радіаційної впливу. Розглядаються питання розміщення уздовж лінії модельних ємностей з фіксованою сумарною кількістю РАВ. Показано, що при розставлянні джерел випромінювань однакової активності, потужність дози на заданій від лінії відстані залежить від кількості джерел. Розроблена методика визначення розподілу активністей N джерел, що забезпечують мінімальну потужність дози на заданій відстані від лінії розміщення. Показано, що існує оптимальне число джерел з певною активністю, а також порядок їх розставляння, при якому потужність дози мінімальна на заданому видаленні від лінії розміщення.
КЛЮЧОВІ СЛОВА: випромінювання, гама-кванти, потужність дози, активність, джерело випромінювання, мінімальна потужність дози.

УМЕНЬШЕНИЕ РАДИАЦИОННОГО ВОЗДЕЙСТВИЯ ПРИ ОПТИМАЛЬНОМ РАСПРЕДЕЛЕНИИ АКТИВНОСТЕЙ ИСТОЧНИКОВ ИЗЛУЧЕНИЯ

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При постоянном или временном хранении радиоактивных отходов (РАО) одной из главных проблем является уменьшение радиационного воздействия. Рассматриваются вопросы размещения вдоль линии модельных емкостей с фиксированным суммарным количеством РАО. Показано, что при расстановке источников излучений одинаковой активности мощность дозы на заданном от линии расстояния зависит от распределения количества источников. Разработана методика определения активностей N источников, обеспечивающих минимальную мощность дозы на заданном расстоянии от линии размещения. Показано, что существует оптимальное число источников с определенной активностью, а также порядок их расстановки при котором мощность дозы минимальна на заданном удалении от линии размещения.
КЛЮЧЕВЫЕ СЛОВА: излучение, гамма-кванты, мощность дозы, активность, источник излучения, минимальная мощность дозы.

When dealing with radioactive waste (RAW) a problem raises as to their permanent or temporary storage. Generally RAW are stored in containers, barrels and tanks of various shapes, which are placed either on the floors of storage or in warehouses. In all cases, in accordance with the norms of radiation safety, it is necessary to ensure limitation of radiation exposure to the personnel and to the environment. Particularly, the exposure dose should be minimized along the borders of either the site of storage or the warehouses. The sources of radiation, arranged along these borders give the greatest contribution to the dose.

The aim of this work is to study the possibility of optimal layout of radiation sources to provide minimal dose rate at a fixed distance from the boundary of the storage floor or the wall of a warehouse.

The sources of ionizing radiation are generally represented by containers in the form of barrels of different sizes filled with RAW of low and medium intensity [1-3], as well as by ventilated storage containers employed in the dry storage of spent nuclear fuel (DSSNF) at Zaporozhye NPP (Nuclear Power Plant) [4-5]. In the first case they are three-dimensional cylindrical sources, and in the second case they are surface cylindrical sources.

The amount of the radiation exposure induced by tanks filled with RAW depends on many factors: radionuclide and elemental composition and density of RAW, thickness of the containers walls and their material, and finally, on the containers' geometric parameters. The dependence between the dose rate and the distance is generally determined by geometrical characteristics of containers (when radiation shielding is absent). A variety of methods is used for calculation of the radiation dose characteristics: Monte-Carlo simulation, integration of point sources from all the volume, etc. [1-3]. It is well known that γ-quanta flux and, accordingly, the dose rate at the distance r from the source to the detector: for the point source is proportional to $1/r^2$, and for the linear source it is ≈ $1/r$. These dependencies are slightly different for cylindrical sources. Fig. 1 shows an example of radial distribution of the dose rate induced by a single storage container filled with RAW whose burnout is 41.5 Mw · day/kg U and dwell time 5 years [4]. At the same figure the dose distribution effects are given for comparison, that decrease as r^{-n} , where r is the distance from the surface to the point of detection, for n = 1.1 and n = 1.2. Fig.2. shows the radial distribution from radiation source having the form of a standard barrel of 200 liters, filled with RAW (construction waste with a density of 1.2 g/cm^3, radioactive nuclide ^{137}Cs). For comparison the dose distribution effects decreasing as r^{-n}, where n = 1,0 and n = 1,1 are also given.

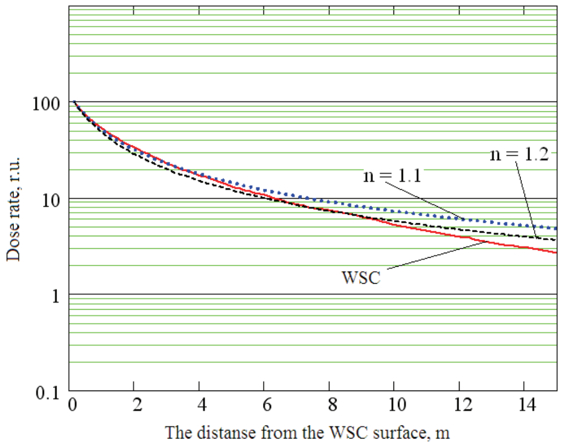


Fig. 1. Radial distribution of dose rate for the VSC WWER.

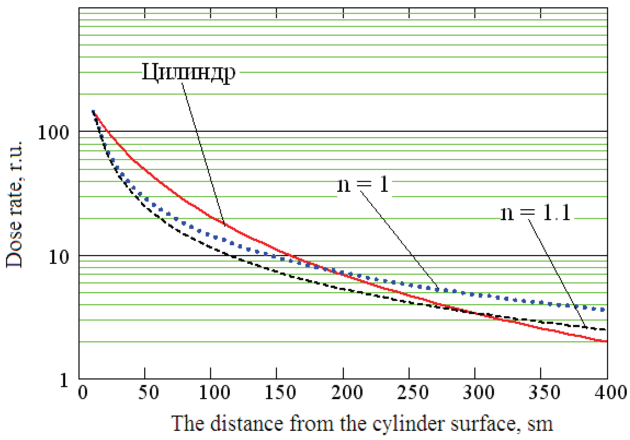


Fig. 2. Radial distribution of dose rate for the cylindrical source volume of 200 liters.

SIMULATION METHODS

Let's use a dependence of $1/r$ type as a model approximation of radiation for 3-d radiation sources. Let's consider that N sources emitting q_i gamma-quanta are arranged evenly along the x-axis where xs_i – the position of i-source. Then γ -quanta flux induced by i-source at the point having X and Y coordinates is determined by expression:

$$n_\gamma(X,Y)_i = \frac{q_i}{4\pi \cdot \sqrt{(xs_i - X)^2 + Y^2}} . \qquad (1)$$

The dose rate induced by N sources at the point having X,Y coordinates is determined by the expression:

$$D(X,Y) = \sum_{i=1}^{N} C_\lambda(E) \cdot n_\gamma(X,Y)_i , \qquad (2)$$

where $C_\gamma(E)$ is a gamma constant, depending on the energy of γ -quanta E.

Then we examine dose fields generated by N sources evenly placed over the range 0 ÷ 1. Thus the coordinate of source number 1 is $xs_1 = 0$, and the coordinate of source number N is $xs_N = 1$. The amount of activities for all the sources is constant, so $\sum_{i=1}^{N} q_i = 1$. Dependence of the dose rate on Y for different number of sources is shown on Fig. 3

The data presented in Fig. 3 show that the type of dose rate distributions at different distances from the sources depends on the number of sources N. Besides, the number of sources defines the type of dose dependencies. The maximum dose rate distributions are also determined by the number of sources N. The dose rate is the highest for N = 2 at short distances from the sources disposal line (Y ≤ 0.1) (see Fig. 3a). With increasing Y the maximum value is composed of larger number of sources (see Figs. 3b, c, d). It should be noted that the amount of the sources' activity is constant. The position of maximum dose distributions is obtained when X = 0.5 for all values of N at large distances comparable with the length of line that accommodates the sources (Y = 0.8, Fig. 3c).

The above figures indicate that, at different distances Y the maximum dose rate depends on the number of sources (the amount of sources' activity is constant). It is evident, that for each value of Y, there is some optimal number of sources N_{opt}, providing minimum value for the maximum dose rate – PD_{min}^{max}. Optimal values for number of sources N_{opt} producing the minimal dose rate at different distances from the source disposal line Y, when the radiation sources' total activity is constant, are given in Table 1.

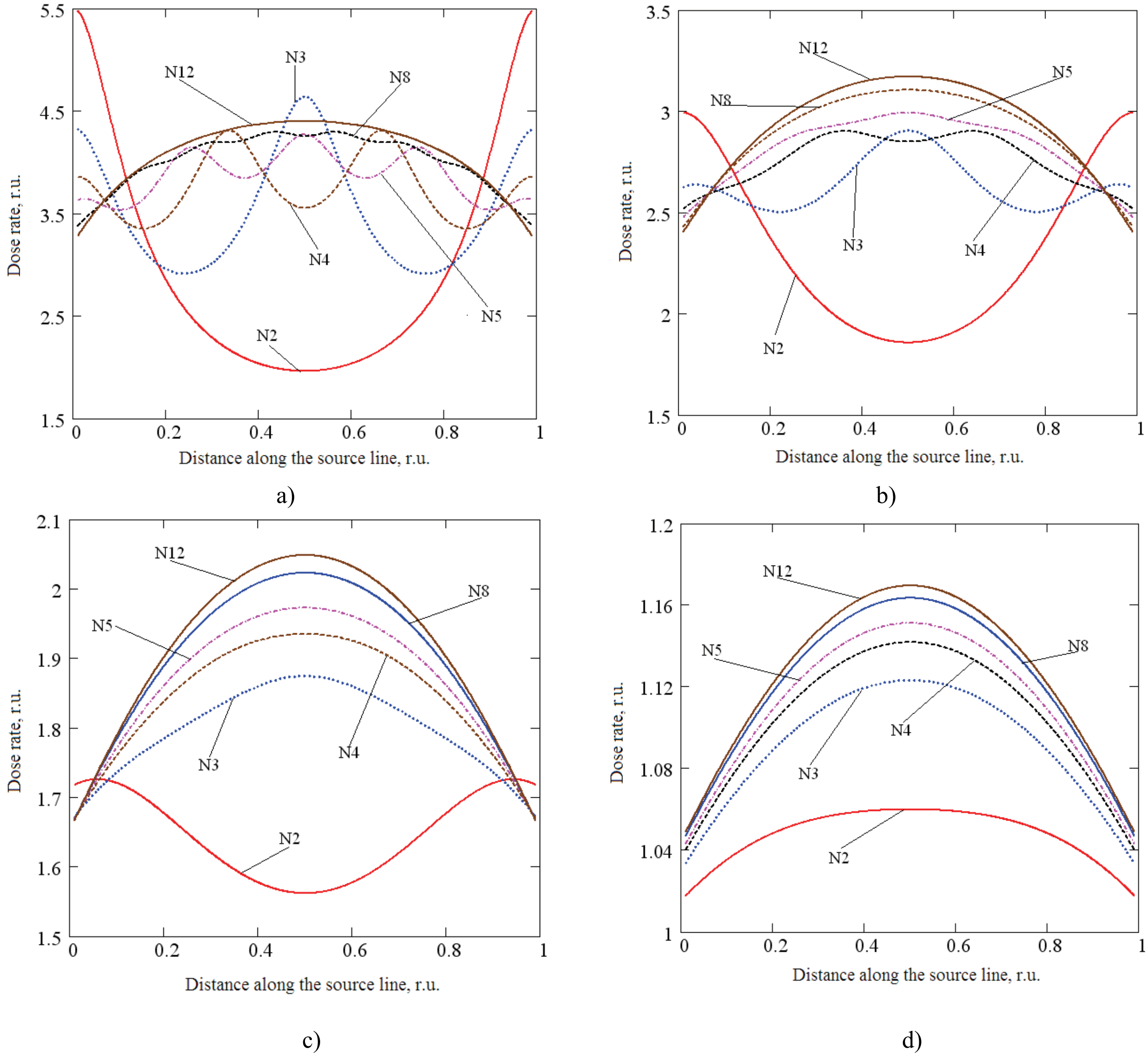


Fig. 3. Dependence of dose rate
a) for Y=0. 1, b) for Y=0.2, c) for Y=0.4, d) for Y=0.8.

Table 1

Optimal values of a number of sources producing the minimal dose at different distances from the source disposal line

Y	0,05	0.1	0.2	0.3	0.4	≥ 0.4
N_{opt}	≥ 12	6	3	2	2	2

The data presented in Table 1. and Fig. 3 illustrate the fact that two point sources produce maximum dose rate over short distances, for example,Y = 0.05 and $q_1 = q_2 = 0.5$. Therefore, to reduce the dose rate for such cases, it is necessary to distribute the sources' activity along the source disposal line. With increasing Y the dependence of the maximum dose rate from the number of sources is ambiguous. Data from Fig. 3c,d show that, at reasonable distance (Y ≥ 0.4) the increase in the number of sources would entail increase in the dose rate. In a large number of versions the dependence of dose rate on the evenly distributed sources with similar activity has maximum at X = 0.5. It is obvious, that if the activity of the central sources is decreased and activity at the edges is increased, then the dose rate at the centre will decrease and at the edges will increase, and integrally the maximum dose rate will reduce.

Therefore, one must define values q_i (for $N > 2$ since when $N = 2$, it is obvious that $q_1 = q_2 = 0.5$) that provide the least value of maximal dose rate at a distance Y for the interval $0 \le X \le 1$. So, we believe that the amount of activity of all the sources is constant and equals to 1, and that the sources are evenly placed in the interval (0 ÷ 1).

Expression for dose rate (2), depends on the position of the observation point (X,Y), as well as on the sources' activity q_i and the number of sources N. Let's rewrite expression (2) like this:

$$D(X,Y,f(q_i),N)=\sum_{i=1}^{N} q_i / R(n_i,X,Y), \quad (3)$$

where $R(xs_i,X,Y)=\sqrt{(xs_i-X)^2+Y^2}$ in our case, but may be different, for example, for the point source $R(xs_i,X,Y)=(xs_i-X)^2+Y^2$, $xs_i=(i-1)/(N-1)$, i=1… *N*. Some other dependence, determined according to geometry and, consequently, to some other characteristics of the source, is possible.

It's necessary to find the activities' distribution for *N* sources q_i , which provide at a distance Y the least value of maximum dose rate , 0 ≤X ≤ 1. This is a typical extremum task, but it can't be solved with variation methods. Here the method of the least squares to determine the optimal values of q_i may be applied.

Let's determine the average dose rate depending on *Y* in the interval, where sources 0 ≤ X ≤ 1 are placed, as follows:

$$D_{AV}(Y,f(q_i),N)=\sum_{i=1}^{N} q_i \int_0^1 \frac{dX}{\sqrt{(xs_i-X)^2+Y^2}}. \quad (4)$$

Then the dose rate standard deviation from its average value in the interval 0 ≤X ≤ 1 will be determined by the ratio:

$$\delta(Y,f(q_i),N)=\int_0^1 \left[D(X,Y,f(q_i),N)-D_{AV}(Y,f(q_i),N)\right]^2 dX \cdot \quad (5)$$

Minimum value $\delta(Y,q,N)$ will reach the minimum of q_i that satisfy the following system of equations:

$$d\delta[Y,f(q_i),N]/dq_i=0. \quad (6)$$

Substituting (3), (4) and (5) into (6) and setting transformations we get:

$$\sum_{i=1}^{N} q_i(C_{ji}-B_{ji)}=0, \quad (7)$$

where $C_{ji}=\int_0^1 \frac{dX}{R(n_j,X,Y)\cdot R(n_i,X,Y)}$, · $B_{ji}=\int_0^1 \frac{dX}{R(n_j,X,Y)}\cdot\int_0^1 \frac{dX}{R(n_i,X,Y)}$.

Designating $A_{ji}=(C_{ji}-B_{ji)}$ we'll rewrite (7) in the following form:

$$\begin{aligned} &q_1A_{11}+q_2A_{12}+q_3A_{13}+\cdots+q_NA_{1N}=0\\ &q_1A_{21}+q_2A_{22}+q_3A_{23}+\cdots+q_NA_{2N}=0\\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\ &q_1A_{N1}+q_2A_{N2}+q_3A_{N3}+\cdots+q_NA_{NN}=0. \end{aligned} \quad (8)$$

System of homogeneous equations (8) has a trivial solution $q_i = 0$. However we have another equation binding the intensity of the sources

$$q_1+q_2+q_3+\cdots+q_N=1. \quad (9)$$

Then, excluding one of the equations of the system (8) and substituting (9) we'll receive a heterogeneous equation system having non-trivial solution. In the system of equations (8) the 1st equation is replaced.

$$\begin{aligned} &q_1+q_2+q_3+\cdots+q_N=1\\ &q_1A_{21}+q_2A_{22}+q_3A_{23}+\cdots+q_NA_{2N}=0\\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\ &q_1A_{N1}+q_2A_{N2}+q_3A_{N3}+\cdots+q_NA_{NN}=0. \end{aligned} \quad (10)$$

In the system of equations (8) 2nd equation is replaced.

$$\begin{aligned} &q_1A_{11}+q_2A_{12}+q_3A_{13}+\cdots+q_NA_{1N}=0\\ &q_1+q_2+q_3+\cdots+q_N=1\\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\ &q_1A_{N1}+q_2A_{N2}+q_3A_{N3}+\cdots+q_NA_{NN}=0 \end{aligned} \quad (11)$$

RESULTS AND DISCUTION

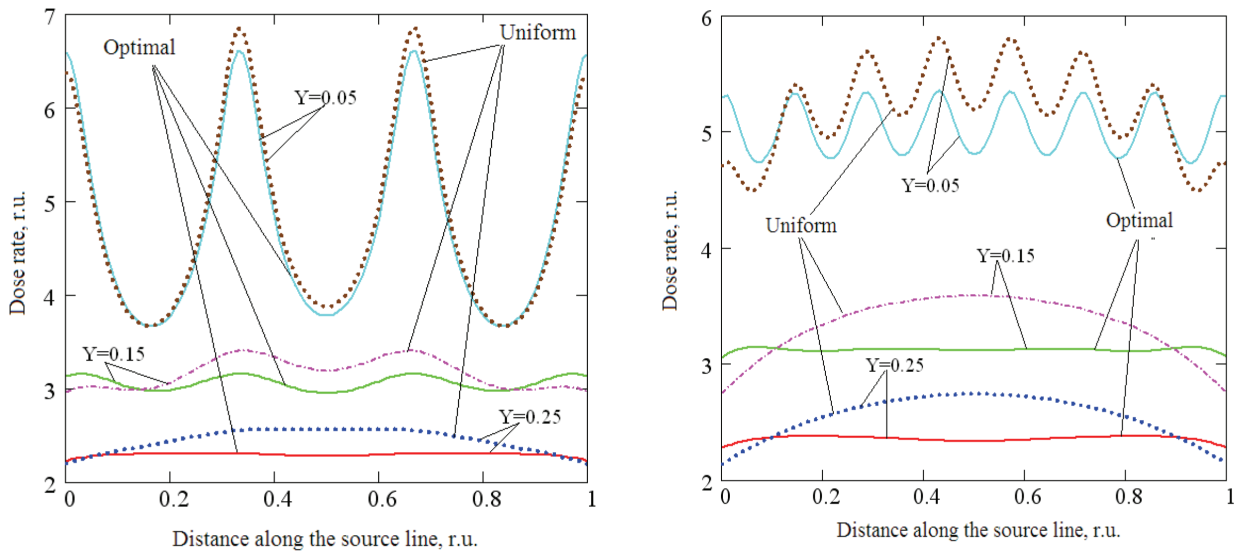
Thus, we receive *N* systems with *N* equations with nonzero determinant. Accordingly we receive solution matrix *N* × *N*. We will use average values for all systems as the optimal values of sources' activity. Table 2 shows an example of determination of optimal activities for 5 sources.

Table 2.

Optimal activities for 5 sourcesat a distance Y = 0.1 of the distribution line

	$(q)_1$	$(q)_2$	$(q)_3$	$(q)_4$	$(q)_5$
Equation 1	0.253	0.166	0.168	0.173	0.241
Equation 2	0.232	0.188	0.161	0.176	0.242
Equation 3	0.244	0.167	0.179	0.167	0.244
Equation 4	0.242	0.176	0.161	0.188	0.232
Equation 5	0.241	0.173	0.168	0.166	0.253
Average	0.2424	0.174	0.1674	0.174	0.2424

Fig. 4 shows the dependence of dose rate at different distances for the optimal activity values for 4 and 8 sources. To compare, the dose dependencies according to the uniform distribution of sources $q_N = 4 = 0.25$ and $q_N = 8 = 0.125$ are also presented. The results of the calculations shown in Fig. 4 reveal that with the even distribution of sources activities the maximum dose is greater than in the case with the optimal source activities distribution.

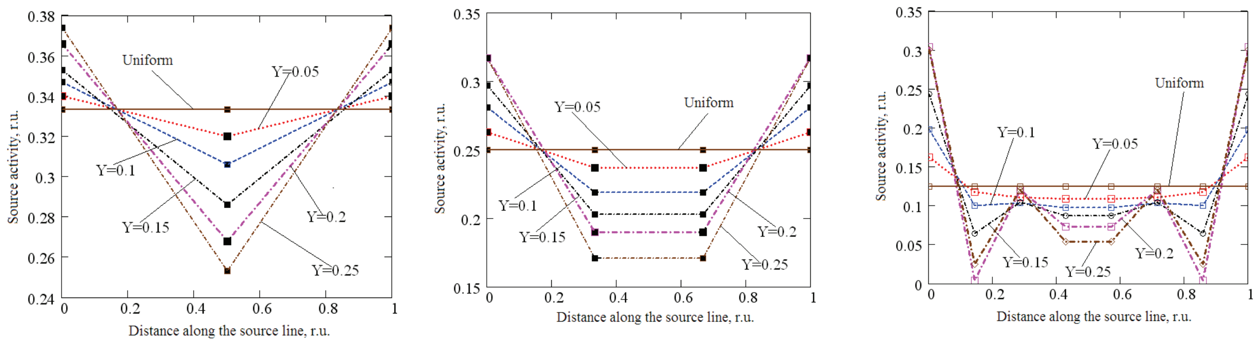


a) b)

Fig. 4. The dependence of dose rate.

a) with N of sources = 4, b) with N of sources = 8

Fig. 5 illustrates the degree of optimal activities deviation from their uniform values.



a) b) c)

Fig. 5. Optimal distribution of source activity

a) N = 3, b) N = 4, c) N = 8.

At small values of *Y* ($Y \leq 0.1$) the optimal activity values q_{opt} are slightly different from the uniform distribution

q_{gom}. With increasing Y the optimal activities q_{opt} for the sources placed at the edges of the interval 0 and 1 grow as compared to the uniform values of q_{gom}.

The studies to determine the optimal number of sources (total source activity is constant), which creates the minimum dose rate at the specified distance have been conducted. Presented in Fig. 6 data show that the dose rate raises at short distances (Y = 0.1) when the activities are divided into 2 sources as well as when the number of sources is large. Anyway optimal number of division exists, which provides the minimum dose rate. For Y = 0.1 division of the activities into 5-6 sources provides the minimal dose rate. With grow of Y the increase in the number of sources (divisions) results in a slow increase of the dose rate. But in the case of large distances (Y > 1.5) the dose rates actually do not depend on the number of the sources.

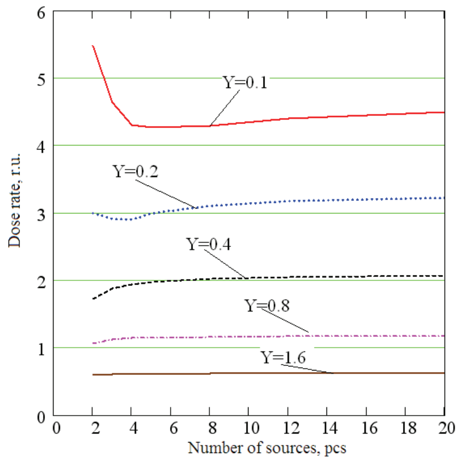


Fig.6. The dependence of maximum dose rate on the number of sources at different distances (dose rate dependence $d(r) \approx r^{-1}$)

CONCLUSION

For constant total sources activity (i.e. the number of RAW to be located is constant):

1. It is shown that for a linear arrangement of radiation sources with the same activity the dose rate at a specified distance along the distribution line depends on the number of sources.
2. Methodology aimed to determine activities of N radiation sources arranged along the line and providing the minimum dose rate at a specified distance from the accommodation line has been worked out.
3. When carrying out calculations aimed at optimizing the sources an inversely proportional dependence of dose rate on the distance was used. Our methodology allows using any dependency.
4. It has been shown that for any distance along the distribution line there is an optimal number of sources N_{opt} with a specific activity, as well as their layout at which the dose rate is minimal.

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