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МОДЕЛИРОВАНИЕ ГАММА-СКАНИРУЮЩЕГО ДЕТЕКТОРА С КОЛЛИМАТОРОМ ДЛЯ ИССЛЕДОВАНИЯ ДИФФЕРЕНЦИАЛЬНОГО РАДИОАКТИВНОГО ЗАГРЯЗНЕНИЯ

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В настоящей работе описана разработанная модель радиационного состояния ядерной установки, излагается состав модели, рассмотрены проблемы формирования инженерно-радиационной модели ядерной установки на основе моделирования результатов радиационного контроля и расчетов гамма-излучения в зависимости от состава радионуклидов, активности источников излучения, а также их геометрических размеров и форм.

Методы расчета излучения, исходящего от загрязненных узлов элементов ядерной установки, требующих обслуживания или разборки, рассматривают их как источники фотонного излучения, обладающих определенными физическими характеристиками, такими как размеры и активность. Радиоактивные источники рассматриваются как изотропные излучатели. Геометрические размеры и форма таких источников могут быть очень разнообразными.

Исследуются существующие методы расчета дозовых полей, создаваемых радионуклидными источниками ионизирующего излучения различных геометрических форм.

Обсуждаемые методы основаны на аналогичных подходах и представляют собой математический расчет характеристики поля дозы в зависимости от формы источника, его активности и относительного пространственного расположения расчетной точки в поле и источнике. Поэтому были разработаны специальные методы расчета мощности дозы облучения от протяженных источников.

Ключевые слова: вывод из эксплуатации, радионуклиды, канонические, моноэнергетические, затухание, детектор, фантом, цилиндр, дезактивация, радиоактивность, гамма.

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1.0 INTRODUCTION

The era of atomic energy that began in the 1940s led to the creation of a large number of nuclear facilities, the operation of which has now been discontinued or involves the suspension of the operation of these facilities in the coming years.

Preparation for decommissioning of the atomic nuclear facility is a complex process involving several stages in which a local concept and decommissioning program is developed. A complete engineering and radiation review of the facility is conducted from operation, work is carried out to decontaminate and dismantle the equipment and structures of the facility, to handle radioactive waste, and so on.

One of the main tasks in decommissioning radiation-hazardous and complex facilities like atomic nuclear facility is to ensure the safety of personnel, the public and the environment.

The accumulated experience of designing and carrying out works on decommissioning of complex facilities (nuclear power plants, radiochemical plants, etc.), as well as mistakes made during the creation of decommissioning projects, led to the need to create tools that allow solving several tasks when developing a decommissioning project for nuclear facility, including reducing the time and cost of design, as well as exclude all kinds of collisions related to the mismatch of the real state of the facility with the project.

Such a tool should be the software and hardware system Digital Decommissioning, which includes various databases and models, an executive 3D model of the object combined with radiation characteristics, visualizing radiation fields and allowing to produce the necessary engineering, technological and radiation calculations in the development of the decommissioning project and the adoption of relevant design and technological solutions. Methods for calculating radiation emanating from contaminated assemblies of the nuclear facility elements requiring maintenance or disassembly are considered as radionuclide sources of photon radiation having certain physical characteristics, such as dimensions and activity. Sources based on radionuclides are isotropic radiators. The geometric dimensions and shape of such sources can be very diverse in form and size.

All sources can be divided into point and extended: linear, area and volumetric. In most cases, when calculating radiation, one has to deal with extended sources. The concept of an extended source covers all sources whose dimensions cannot be neglected in calculations. In contrast to point sources, the radiation field of extended sources depends on their shape and size, and in the case of bulk sources and on absorption processes (self-absorption) and scattering of radiation in the source material itself. Calculations from extended sources prove to be more complex and time-consuming than from point sources.

2.0 METHODOLOGY

The construction of the radiation model of the object is based on mathematical modeling of the radiation transport in the air and the substance from the elementary unit of technological objects that may have a complex geometric shape. In this case, inverse modeling is possible, when the activity of the source (object) is calculated on the basis of the measured field characteristics and the known ratio of radionuclide activity.

Application of Monte Carlo method to construct radiation fields in the hardware software digital decommissioning requires more hardware and time resources. Therefore, in order to calculate the density of gamma radiation, fluxes and the equivalent dose rate created by a complex extended source (technological object), it is possible to use simpler and sufficiently accurate methods for calculating a volumetric or extended source.

In the first stage, processing facilities should be provided in the form of simplified phantom objects such as sphere, cylinder, cube and cuboid. The most complex configuration of the radiation source is in the form of a set of individual arbitrarily defined bodies. Some objects, such as bundles of thin tubes, can be one object, tube surface area is equal to the total surface area of all the tubes and the wall thickness corresponds to the thickness of the tube walls.

Phantom object must correspond to the real technological object of the total surface area and wall thickness, since main circulation pump, MCP reactor may be presented in the radiation pattern in the form of three cylindrical objects according to Figure 1.

3.0 RADIATION MODEL OF THE PROCESS PIPE

Gamma quanta generated in a point source and moving in the direction of the detector move along a rectilinear trajectory connecting points s and D. Generally, gamma quanta are partially absorbed from the beginning in the air in the cavity of the tube, then in the material of the pipe wall and air outside the pipe. Accordingly, in order to account for the absorption of gamma quanta in different media, it is necessary to determine the lengths of sp_1, p_1p_2 and p_2D segments in accordance with Fig. 2. Consider the projection of the geometry of the problem onto the xOy.

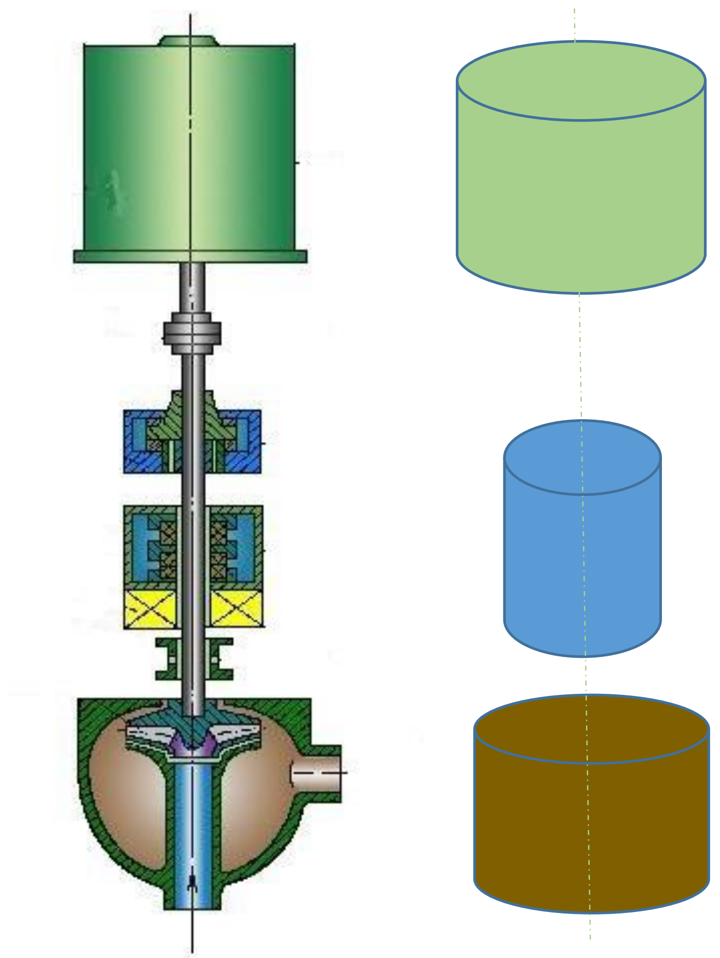

Fig.1. Presentation of MCP in phantom form

The outer and inner cylindrical surfaces of the tube in the projection will have the form of circles with centers lying at the origin. In rectangular Cartesian coordinates, the equations of these circles have the form:

$$x^2 + y^2 - r_{out.}^2 = 0, \tag{1}$$

$$x^2 + y^2 - r_{in.}^2 = 0. \tag{2}$$

Consider the outer circumference in order to determine the coordinates of intersection points with the segment of the circle sD i.e. the coordinates of p_2. Substitute coordinates of $s(x_s, y_s)$ in the equation of the circle

$$x_s^2 + y_s^2 - r_{out.}^2 = \text{ст}\, S. \tag{3}$$

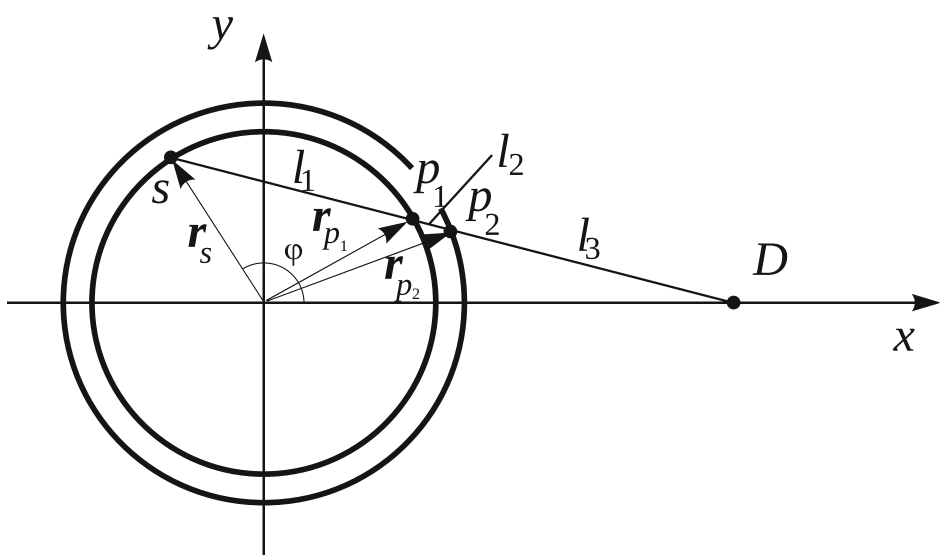

Fig. 2. Projection of a pipe on a plane

Since the point $s(x_s, y_s)$ does not lie on a circle, the number of item ст S is nonzero. Number item ст S is a power point s with respect to a given circumference. The degree of a point is negative if the point lies inside the circle and positive, if outside. It is obvious that for an inner circle ст S is equal to zero, since the point s belongs to the circle.

In vector form, the equation of a straight line passing through a point (in our case through the point s) has the form:

$$\boldsymbol{r} = \boldsymbol{r}_s + t\boldsymbol{a} \tag{4}$$

where $\boldsymbol{a}(l, m)$ is the directing vector of this line, l and m are the projections of the directing vector. If the vector $\boldsymbol{a}$ is an orthom, then $l^2 + m^2 = 1$. The vector equation in coordinates will have the form:

$$x = x_s + tl,\, y = y_s + tm. \tag{5}$$

Eliminating the parameter, t we obtain the equation of the line in the canonical form:

$$\frac{x - x_s}{l} = \frac{y - y_s}{m}, \tag{6}$$

from which we obtain the general equation of a straight line in the Cartesian coordinate system:

$$m(x - x_s) = l(y - y_s) \iff Ax + By = D, \tag{7}$$

where $A = m, B = -l, D = mx_s - ly_s$.

For a line passing through two points s and D, the vector parametric equation will have the form:

$$\boldsymbol{r} = \boldsymbol{r}_s + t(\boldsymbol{r}_D - \boldsymbol{r}_s), \tag{8}$$

or in the canonical form

$$\frac{x - x_s}{x_D - x_s} = \frac{y - y_s}{y_D - y_s}. \tag{9}$$

The differences in the denominators of the canonical equation and $(x_D - x_s)$ and $(y_D - y_s)$ are the projections of the segment sD onto the corresponding axis. If we divide each projection by the length of the segment sD, then we obtain the projections of the vector of the directing vector of a straight line passing through two points:

$$l = \frac{x_D - x_s}{\sqrt{(x_D - x_s)^2 + (y_D - y_s)^2}}, m = \frac{y_D - y_s}{\sqrt{(x_D - x_s)^2 + (y_D - y_s)^2}}. \quad (10)$$

$$(x_s + lt)^2 + (y_s + mt)^2 - r_{out.}^2 = 0. \quad (11)$$

After the expansion of the squares of the sums and the grouping of such terms, we obtain

$$(l^2 + m^2)^2 t^2 + 2(x_s l + y_s m)t + x_s^2 + y_s^2 - r_{out.}^2 = 0. \quad (12)$$

The expression in parentheses in the first term is 1, since l and m are the projections of the vector of the directing vector. The sum of the last three terms is equal to the degree of the point s relative to the outer circle. Correspondingly, we obtain the quadratic equation

$$t^2 + 2(x_s l + y_s m)t + \text{ст}\, S = 0, \quad (13)$$

whose roots t_1 and t_2 define two points of intersection of a straight line passing through points s and D, with an outer circle

$$x_1 = x_s + lt_1, y_1 = y_s + mt_1, \quad (14)$$

$$x_2 = x_s + lt_2, y_2 = y_s + mt_2 \quad (15)$$

For our problem from two points of intersection, we need to take the nearest point to the point D as the desired point p_2.

The search for points of intersection of a straight line passing through points s and D, with an inner circle is similar. Although it can be taken into account that the point s lies on the inner circle, respectively, the degree of the point s relative to the inner circle will be zero. Consequently, equation (13) takes the form:

$$t^2 + 2(x_s l + y_s m)t = t[t + 2(x_s l + y_s m)] = 0 \quad (16)$$

And one of the roots will always be zero, and the point s will be one of the intersection points. In a number of cases, when a point source is located on the tube wall near the detector, the points s and p_1 will coincide, respectively, the gamma rays emitted toward the detector will not be absorbed in the air filling the cavity of the tube.

To determine the coordinates z of the points of intersection of the straight line passing through the points s and D with the cylindrical surfaces forming the pipe, we consider the projection of the geometry of the problem onto the xOz plane in accordance with Fig. 3. Since the coordinates x_{p_1} and x_{p_2} are known, for the definitions of z_{p_1} and z_{p_2} must be substituted in the projection equation for the straight line passing through the points s and D.

$$z = z_s + \frac{x_D - z_s}{z_D - z_s}(x - z_s). \quad (17)$$

The total length of the gamma-ray trajectory will be

$$l = l_1 + l_2 + l_3 = \sqrt{(x_D - x_s)^2 + (y_D - y_s)^2 + (z_D - z_s)^2}. \quad (18)$$

The flow of monoenergetic gamma quanta, passing through a layer of matter of linear dimension, l loses part of the gamma quanta due to absorption in the direction of flow. The change in the flux density is determined by the thickness of the layer and by the absorbing properties of the medium

$$q(l) = q_0 \exp(-\mu l), \quad (19)$$

Where q_0 is the initial flux density, μ is the linear coefficient of attenuation of gamma quanta with energy E.

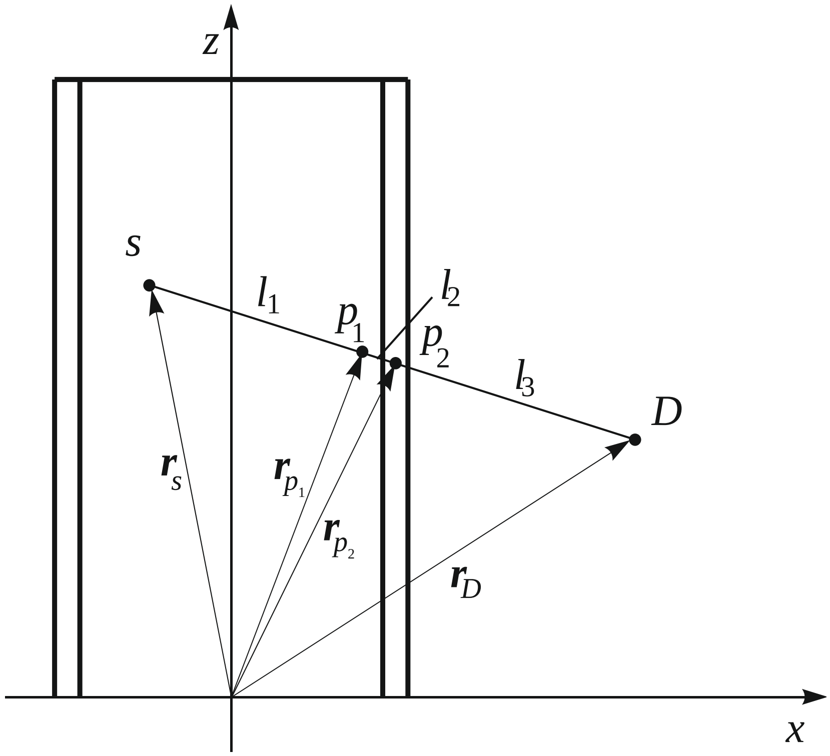

Fig. 3. Projection of a pipe on a plane *xOz*

On the entire trajectory of the motion, the flux of gamma quanta will change in accordance with Eq.

$$q(l) = q_0 \exp\left(-\sum_{k=1}^{3} \mu_k l_k\right), \tag{20}$$

where k - the index of the absorbing medium, which also corresponds to the linear length of the trajectory of the gamma-quantum within the given material.

In the general flow, the number of gamma quanta of each energy can be determined by the partial coefficient δ. If in a sequential list of gamma-quanta energies included in the total flow, each energy value is numbered by the index n $(n = 1,2 \ldots N_m)$, then the gamma-quantum energies will be denoted as E_n, the partial fractions of gamma quanta with energy E_n will be have the designation δ_n, linear attenuation coefficients -μ_{nk} ($n -$ is the energy index, and $k -$ is the index of the medium). Then the law of weakening the flux of gamma quanta with energy E_n in a multilayer medium will have the form.

$$q(E_n, l) = q_0 \delta_n exp\left(-\sum_{k=1}^{3} \mu_{nk} l_k\right). \tag{21}$$

In the general flow, when interacting with the medium, gamma quanta of different energies do not influence each other, respectively, the partial flux densities of monoenergetic gamma quanta can be added to the total flux density

$$q(l) = q_0 \sum_{n=1}^{N_m} \delta_n exp\left(-\sum_{k=1}^{3} \mu_{nk}\, l_k\right). \tag{22}$$

Taking into account the spherical geometry of the point source (see relation (38)

$$q(l) = \frac{Q}{4\pi l^2} \sum_{n=1}^{N_m} \delta_n exp\left(-\sum_{k=1}^{3} \mu_{nk}\, l_k\right). \tag{23}$$

To determine the gamma-ray flux density at point D, it is necessary to sum the gamma-ray flux densities of all energies entering the detector from each point source describing the radioactive contamination.

Knowing the flux density of gamma quanta of all energies at a given point D, one can obtain the absorbed dose rate in the detector and calculate the equivalent dose rate at point D.

CONCLUSION

Within the framework of this paper, the application of the nuclear radiation model to the construction of a spatially distributed radiation source for an object using atomic energy stopped for decommissioning work is considered. The structures of the created databases, their content and interrelations are described.

Proposed with mathematical calculations characteristics of ionizing radiation fields generated by the objects of complex geometry, to carry out substitution of the real objects in the engineering model, nuclear facilities phantom objects simple geometric shape with the surface area of the real object and its mass.

It is recommended for use are simpler and faster than the Monte Carlo method, and at the same time, accurate methods for calculating the density of gamma radiation fluxes and the equivalent dose rate from the model of a spatially distributed source of ionizing radiation, which is a set of graphic equivalents with a given for each of them activity (the so-called "phantom model"), as well as methods for solving the "inverse problem", i.e. calculation of the activity of the elements of the phantom model from the measurement of the dose rate of gamma radiation at points located in the space of the room.

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Modelling of Gamma-Scan Detector with Collimator for Investigating Differential Radioactive Contamination

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Abstract – In this paper, a description of the model of the radiation state of a nuclear facility is developed, the composition of the model is outlined, the problems of the formation of the engineering-radiation model of the nuclear facility are considered on the basis of the engineering model of radiation inspection and gamma radiation calculations depending on the radionuclide composition, the activity of radiation sources, and also their geometric sizes and shapes.

Methods for calculating radiation emanating from contaminated assemblies of the nuclear facility elements requiring maintenance or disassembly are considered as radionuclide sources of photon radiation having certain physical characteristics, such as dimensions and activity. Sources based on radionuclides are isotropic radiators. The geometric dimensions and shape of such sources can be very diverse in form and size.

The existing methods for calculating the dose fields created by radionuclide sources of ionizing radiation of various geometric shapes are investigated.

The methods considered are based on similar approaches and represent a mathematical calculation of the characteristics of the dose field depending on the shape of the source, its activity and the relative spatial location of the calculated point in the field and the source. Therefore, special methods for calculating exposure dose rate from extended sources have been developed.

Keywords: Decommissioning, radionuclide, canonical, monoenergetic, attenuation, detector, phantom, cylinder, decontaminate, radioactivity, gamma.