ESTIMATION OF THE ESCAPE OF RADIONUCLIDES FROM HETEROGENEOUS MEDIA WITH A COMPLICATED STRUCTURE CONTAINING SOLID WASTES

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A mathematical model for estimating the escape of radionuclides from storage sites for radioactive wastes with an irregular arrangement of sources of contamination, for example, sources of ionizing radiation, piled on one another, is described. The model is tested for a particular case where the problem can be solved analytically. An example of the regularization of a heterogeneous medium with a complicated structure is given. Regularization makes it possible to simplify the initial problem and calculate the flow of radionuclides out of the volume containing the irregularly arranged sources of contamination.

When analyzing the safety of storage and burial of radioactive wastes, storage sites not only with a regular arrangement of sources of radioactive contamination (concrete and reinforced concrete containers, steel barrels, and others) but also an irregular arrangement are studied. These include storage sites containing radioactive garbage, soil contaminated with radioactive fallout, sources of ionizing radiation piled in containers, debris from metal structures with induced activity, and others. To simulate the propagation of radionuclides along such irregular heterogeneous media, the internal structure of the storage site must be simulated in each specific case. The simplest method of simulation is regularization of a heterogeneous medium.

In the present paper, an example of such regularization is studied. It makes it possible to simplify the initial problem and to calculate the flow of radionuclides out of a volume containing irregularly arranged sources of contamination. The calculations are based on the mathematical model of [1], which makes it possible to find the distribution of the radionuclide concentration in a volume filled in a regular manner with sources of contamination in the form of a square parallelepiped, a straight circular cylinder and a sphere, as well as outside the volume with sources.

The criteria for assessing the radiation safety of storage sites could be the maximum concentration of radionuclides inside and outside the storage site (for monofactor contamination), which is compared with a normative quantity – the intervention level when individual radionuclides are ingested for the population (IL_{water}) [2]. For simultaneous contamination with several radionuclides, the safety criterion could be the effective equivalent irradiation dose to an individual person ingesting contaminated water, calculated according to the specific concentration of radionuclides in the water.

Mathematical Formulation of the Problem. A regular, uniform block-type medium with voids (channels) between the blocks is studied. The blocks in such a medium are sources of contamination. The voids between the blocks can be free or filled with a filler material – gravel, sand, bentonite. This medium can be filled with standing water or ground or infiltrating waters with filtration rate \( U_0 \) can pass through the medium. In the absence of water in the voids between the blocks the radionuclides can be transferred along the medium only by diffusion through the zone of contact (touching) between blocks or between blocks and the filler material. For an option of storage in standing water, diffusion along contact zones will be...
negligibly small compared with diffusion in the water between the blocks. Blocks containing radionuclides with known initial concentration can have an initially uncontaminated surface layer of thickness \( z_0 \).

The escape of radionuclides from blocks and transport along the filler between blocks are described by a system of one-dimensional equations with boundary and initial conditions [1]:

\[
R_f \frac{\partial C_f}{\partial t} = - \frac{\partial}{\partial x} \left( U_f C_f - D_f \frac{\partial C_f}{\partial x} \right) - \lambda R_f C_f + \frac{A_f \partial C_p}{\varepsilon_b \partial z} \bigg|_{z=0} ;
\]

\[
R_p \frac{\partial C_p}{\partial t} = D_i \left( \frac{\partial^2 C_p}{\partial z^2} + \frac{\beta}{z} \frac{\partial C_p}{\partial z} \right) - \lambda R_p C_p ,
\]

where \( R_f \) and \( R_p \) are the coefficients of retention of a radionuclide in the filler between the blocks and the material of the blocks, respectively; \( R_f = 1 + \rho_p K_b / \rho_f \); \( \rho_f \) is the volume density of the filler; \( K_b \) is the coefficient of interphase distribution in the filler; \( \varepsilon_b \) is the porosity of the filler; \( R_p = \varepsilon_p + \rho_p K_p \); \( \varepsilon_p \) is the porosity of the block material; \( \rho_p \) is the volume density of the block material; \( K_p \) is the coefficient of interphase distribution in the block material; \( C_f(x, t) \) and \( C_p(x, t) \) are, respectively, the concentrations of the radionuclide in the filler and in the block material; \( U_f \) is the real velocity of motion of the water in the filler, equal to \( U_0 / (\varepsilon_b \varepsilon_f) \); \( \varepsilon \) is the porosity of the block medium, equal to the ratio of volume of the voids between blocks to the total volume of the medium; \( D_i \) is the coefficient of internal diffusion of a radionuclide in the block material; \( D_f = \alpha_f U_f + D_b \) is the coefficient of dispersion in the filler between the blocks with water present in the filler; \( \alpha_f \) is the dispersity of the block medium; \( D_b \) is the coefficient of internal diffusion of a radionuclide in the filler; \( \lambda \) is the decay constant of the radionuclide; and \( A_s \) is the specific surface area of the block medium – ratio of the area of the surface of the blocks in a typical macroelement of the volume of the medium to the volume of the voids in this element.

In the absence of the filler and water between the blocks of a composite irregular medium, the coefficient \( D_f \) is replaced by an effective coefficient of molecular diffusion \( D_{\text{eff}} \), which characterizes the diffusion of the radionuclide in the block medium through the contact zone between the blocks. The parameter \( \beta \) depends on the shape of the blocks in the medium: \( \beta = 0 \) – cubic blocks, \( \beta = 1 \) – cylindrical blocks, \( \beta = 2 \) – blocks in the form of spheres.

**Testing of the Model.** To check the workability of the model, the escape of \(^{137}\text{Cs} \) out of cubic containers with edge length 1.2 m, which are arranged in a storage facility on the ground surface and contain cemented wastes with specific concentration equal to 1 initially, is studied. The diffusion escape of \(^{137}\text{Cs} \) results in gradual contamination of the space between the containers. Pure infiltrating waters flows with a fixed velocity through the top cover; this flow carries a radionuclide which has escaped from the containers outside the confines the storage site through its base. The following parameter values were assumed in the calculations: \( U_f = 600 \text{ m/yr} \), \( R_f = 5000 \), \( R_p = 230 \), \( D_f = 0 \text{ m}^2/\text{yr} \), \( D_b = 3.15 \times 10^{-5} \text{ m}^2/\text{yr} \), and \( A_s = 4000 \text{ m}^{-1} \).

In the present paper, the results of the solution of problem (1), (2), which were obtained using the mathematical model considered above, are compared with the results of an analytical solution of the same problem, which are presented in [1]. The change in \(^{137}\text{Cs} \) concentration in water in the intercontainer space at distances 0.5, 1, and 2 m from the top cover of the storage site over a period of 0–20 yr is compared. The analytical solution is sought for a semi-infinite interval, and the numerical solution refers to a finite region. It is assumed that the containers holding the wastes initially do not have clean walls, i.e., \( z_0 = 0 \) (Fig. 1). The maximum relative error in calculating the \(^{137}\text{Cs} \) concentration in water with respect to the analytical solution is \(-3.8\% \), which is acceptable for problems of this kind.

**Some Aspects of the Regularization of the Medium.** The concept of regularity of a medium plays a large role in the simulation of mass transfer in heterogeneous media. This concept is associated with the possibility of separating from the volume of the medium being studied a typical and representative block and representing the entire space being studied as a collection of such typical blocks. If the material of the blocks, along which the transfer of radionuclides is described by Eq. (2), meets the requirement of regularity, then the block medium as a whole, where transport of radionuclides is described by Eq. (1), in general may not possess this property. One consequence of this fact is that it is necessary to make a preliminary interpretation of the actually existing medium as a regular block structure, after which it becomes possible to apply Eq. (1). The solution of the regularization problem depends on the parameters of the object and must be obtained individually in each specific case.