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## The Evaluation of Radon-Protective Characteristics in Engineered and Existing Buildings with the Radon Diffusive Entry from the Soil

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# The Evaluation of Radon-Protective Characteristics in Engineered and Existing Buildings with the Radon Diffusive Entry from the Soil

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**Abstract.** A human receives more than half of the annual individual radiation dose from the radon and its progeny contained in indoor air. Therefore, in order to limit domestic exposure of the population in the Russian Federation the national radon control levels have been established. The excess of these levels is not allowed in buildings with a long people's residence. Radon entry into the building through horizontal underground walling from the soil base and therefore, the restricting of the soil radon flux in the ground floor rooms indoor air is possible only with construction technologies and means. The effectiveness of radon-protective technologies directly depends on the understanding of the laws of radon transport in porous media, since this transport may occur through diffusion and/or convection (filtration). Each of these mechanisms may be dominant under the certain conditions and requires its own radon-protective measures. This article compares the density of diffusive and convective radon fluxes in the entire range of soils permeabilities. The range of underground walling and soils permeability was determined, in which the prediction of radon conditions in a building can be built exclusively on the patterns of diffusive radon transport in porous media. The approach to the underground walling design on the basis of the one-dimensional model of stationary diffusive radon transport in porous media is proposed.

## 1. Introduction

Radon is the only radioactive element that is in a gaseous state under the normal conditions. It is a radium decay product, there are three radon isotopes in the nature: <sup>222</sup>Rn (radon), <sup>220</sup>Rn (thoron) and <sup>219</sup>Rn (actinon), but the last two radionuclides have half-lives of less than 1 minute and therefore are not able to entry into buildings from the outside. Thus, by protection against radon we understand the entry restriction in indoor its main isotope radon-222. This isotope is formed in the uranium-238 family during the maternal radium-226 decay, it has a half-life of 3.8 days and itself decays with the gradual formation of four short-lived progeny that are dangerous to humans at the internal irradiation.

Uranium-238 is present in all types of soils and bedrocks, while its mass fraction can vary from 10<sup>-6</sup> in sandstones and limestones to 10<sup>-3</sup> in alumina and other uranium-bearing soils [1]. As a result,



the radon concentration in the soil air can also differ by several orders of magnitude. It is the increased content of uranium and radium is a cause of high radon levels in indoor air

It was found the underlying soil is the only significant source of radon entry into the building, its contribution in most cases is about 90% [1-7], no more the 10% falls on its exhalation from building materials [8; 9]. The radon entry with a water and a gas is negligible and does not require accounting. The radon concentration in the soil air increases with distance from the surface and, reaching a maximum value at a certain depth, then remains constant: its loss due to radioactive decay is compensated by the formation during the radium decay. The rate of radon generation rate  $G$  is determined by the soil physical and mechanical properties and is expressed by the formula

$$G = C_{Ra} \cdot \rho_s \cdot f \cdot \lambda \cdot \frac{1-\varepsilon}{\varepsilon}, \quad (1)$$

where  $C_{Ra}$  is the radium specific activity in the soil,  $\text{Bq} \cdot \text{kg}^{-1}$ ;  $\rho_s$  is the soil density,  $\text{kg} \cdot \text{m}^{-3}$ ;  $f$  is the radon emanation coefficient;  $\lambda = 2,1 \cdot 10^{-6} \text{ s}^{-1}$  is the radon decay constant;  $\varepsilon$  is the soil porosity.

Radon is transferred from the soil to the surface and underground walling of buildings by diffusion and convection. Therefore, it is of practical interest to compare the contributions of the diffusive and convective components to the total radon flux in order to substantiate the form of the equation for its transport from the soil to the indoor air.

The diffusion flux is caused by the difference in the radon concentrations in the soil and ambient (or indoor) air and is described by the Fick's law

$$q_{dif} = D \cdot \frac{\partial A}{\partial z}, \quad (2)$$

where  $D$  is the radon diffusion coefficient,  $\text{m}^2 \cdot \text{s}^{-1}$ ;  $A$  is the radon concentration in the soil air,  $\text{Bq} \cdot \text{m}^{-3}$ .

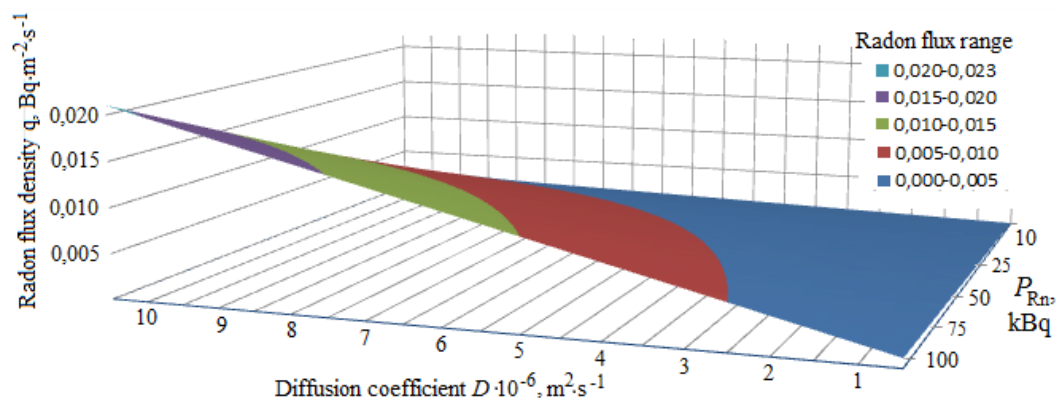
The maximum radon concentration is set at a depth of 3-5 meters (less often up to 10 m) and is called the soil radon potential  $P_{Rn}$

$$P_{Rn} = \frac{G}{\lambda} = C_{Ra} \cdot \rho_s \cdot f \cdot \frac{1-\varepsilon}{\varepsilon}. \quad (3)$$

Its average value is in the range from 20 to 50  $\text{kBq} \cdot \text{m}^{-3}$ , higher radon activities in the soil air are confined to uranium-bearing soils. At the same time, the radon concentration in the atmospheric air (no more than 10  $\text{Bq} \cdot \text{m}^{-3}$ ) is negligible compared to the soil radon potential and can be assumed to be equal to zero in the calculations. In Fig. 1 shows dependency

$$q_{dif} = f(D, \nabla A)$$

for a typical range of the radon diffusion coefficient in soils  $(0.5 \dots 5) \cdot 10^{-7} \text{ m} \cdot \text{s}^{-2}$  with a radon concentration gradient from 2 to 20  $\text{kBq} \cdot \text{m}^{-4}$ , which corresponds to the soil radon potential from 10 to 100  $\text{kBq} \cdot \text{m}^{-4}$  with the "active" power layer equal to 5 m [10-12].



**Figure 1.** The dependence of the diffusion flux density on the physical and mechanical characteristics of the soil.

The driving force of convective radon transport is the pressure gradient in the soil, its value is determined from Darcy's law

$$q_{con} = \frac{k}{\mu} \cdot \frac{\partial P}{\partial z} \cdot A, \quad (4)$$

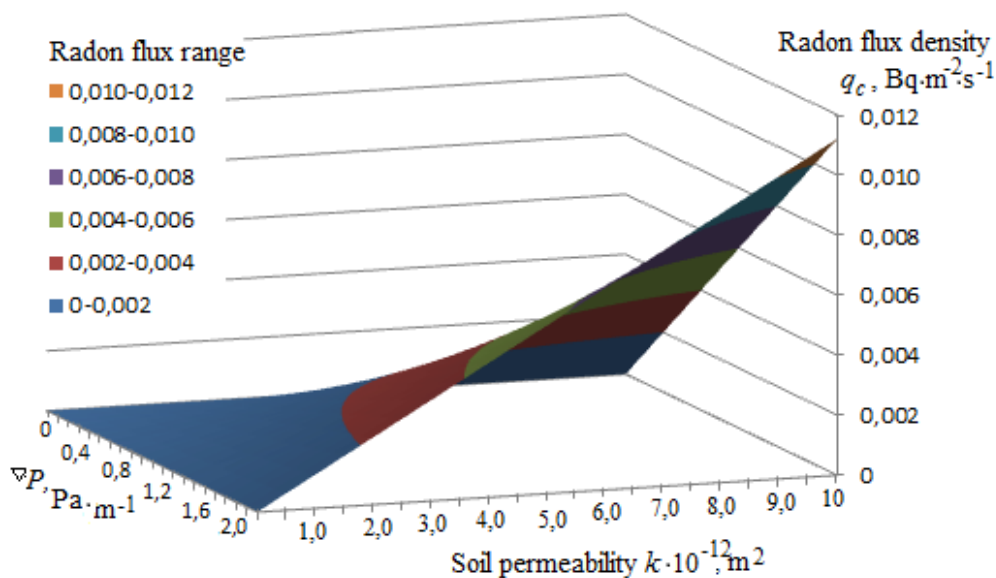
where  $k$  is the soil permeability,  $m^2$ ;  $\mu$  is the dynamic viscosity of air, Pa·s.

The pressure gradient presence caused by a lower temperature of the surface layers of the soil and its value does not exceed  $2 \text{ Pa} \cdot m^{-1}$  [13; 14]. Soil permeabilities are in the range of  $10^{-8} m^2$  for the well-graded gravel to  $10^{-15} m^2$  for sandy clays [15; 16], however, all soils containing clay have a permeability less than  $10^{-12} m^2$  [17].

In the Fig. 2 shows the dependence of the radon convective flux on the pressure gradient and soil permeability

$$q_{con} = f(k, \nabla P).$$

The dynamic viscosity of the soil air was assumed to be  $1.8 \cdot 10^{-5} \text{ Pa} \cdot s$  and the radon activity in it is the  $10\,000 \text{ Bq} \cdot m^{-3}$ .



**Figure 2.** Convective flow density dependence on soil permeability and pressure gradient.

There is no doubt the decisive influence of soil permeability on the radon transport character, since this value has the largest variations range (7 orders) from all the factors of radon situation formation at the soil base.

Comparison of the graphs at the Fig. 1 and Fig. 2, allows us to draw a number of conclusions regarding the patterns of radon transport in the soil:

- when the soil permeability less than  $10^{-12} m^2$  radon transport occurs by diffusion, the convection contribution is negligible and does not require consideration;
- when the soil permeability is the order of  $10^{-11} m^2$  the convective transport becomes dominant and with permeabilities above  $10^{-10} m^2$  convection is the only significant radon transport mechanism;
- in the range of the soil permeabilities from  $10^{-12}$  to  $10^{-11} m^2$  diffusion prevails, but convective transport can also play a significant role. In this range it is necessary to make a comparison of the diffusive and convective components of the radon flux for specific soil characteristics.

The underground walling materials of buildings also represent a porous medium with uniformly distributed radon sources; therefore, the radon transport in these materials occurs according to the same laws. Modern buildings have a monolithic slab at the base and the building materials permeability is in the range of  $10^{-12}$  to  $10^{-15} m^2$  with the most typical value  $10^{-14} m^2$  [18]. Therefore, the radon transport in the walling materials is possible by diffusion only.

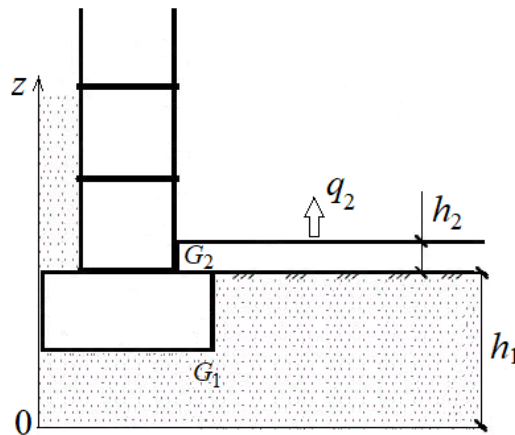
The most practical significant aspect of radiation safety in construction is the design building underground structures which perform the basic carrier functions and also be able to provide an acceptable radon entry from the soil. The process of radon situation forming in a building should be considered exclusively within the framework of the "soil-building". Due to the multifactorial character of this process, the development of a universal model describing the radon entry into a building in the entire range of possible system state parameters values is not possible. At present time it is advisable to develop a mathematical model that is adequate to real conditions in a limited range of soil permeability values and with a certain floor construction of the building.

## 2. Materials and methods

For buildings with a monolithic slab on the clay soils the estimate of radon entry into the building can be obtained from the equation of one-dimensional diffusive radon transport of in a two-layer environment. This task calculation scheme is shown in Fig. 3, the equations system of radon diffusive transport in the layers materials has the form

$$D_1 \cdot \partial^2 A_1(z) / \partial z^2 - \lambda \cdot A_1(z) \cdot \varepsilon_1 + \lambda \cdot \rho_{s1} \cdot C_{Ra1} \cdot f_1 = 0 \text{ if } 0 \leq z \leq h_1, \quad (5)$$

$$D_2 \cdot \partial^2 A_2(z) / \partial z^2 - \lambda \cdot A_2(z) \cdot \varepsilon_2 + \lambda \cdot \rho_{s2} \cdot C_{Ra2} \cdot f_2 = 0 \text{ if } h_1 < z \leq h_2, \quad (6)$$



**Figure 3.** The calculation scheme for the (5)-(6) equations.

The boundary conditions for this task are obtained from the conditions:

- equality of radon flows and activities at the «soil – walling» interface

$$D_1 \cdot \partial A_1(z) / \partial z = D_2 \cdot \partial A_2(z) / \partial z, A_1(z) = A_2(z) \text{ if } z = h_1; \quad (7)$$

- no radon flux from the below layers

$$D_1 \cdot \partial A_1(z) / \partial z = 0 \text{ if } z = 0; \quad (8)$$

- negligible radon activity in indoor air

$$A_2(h_1 + h_2) = A_u \approx 0 \text{ Bq} \cdot \text{m}^{-3}. \quad (9)$$

Solving a system of equations (5) - (6) subject to boundary conditions (7) - (9) allows to obtain the expression for the radon flux density from the upper surface of the underground horizontal walling [19]

$$q_2 = \left[ Q_2 + (Q_1 - Q_2) \cdot ch \frac{h_2}{L_2} \right] \cdot \frac{(D_1 / L_1) \cdot sh(h_1 / L_1)}{sh(h_1 / L_1) \cdot ch(h_2 / L_2) + (D_1 \cdot L_2 / D_2 \cdot L_1) \cdot ch(h_1 / L_1) \cdot sh(h_2 / L_2)}, \quad \text{if } x = h_1 + h_2. \quad (10)$$

In (10) are used the concepts of radon diffusion length in the layers materials

$$L_1 = (D_1 / \lambda)^{1/2} \text{ and } L_2 = (D_2 / \lambda)^{1/2}, \quad (11)$$

and the radon flows in the layers

$$Q_1 = C_{Ra1} \cdot \rho_{s1} \cdot f_1 / \varepsilon_1 \text{ and } Q_2 = C_{Ra2} \cdot \rho_{s2} \cdot f_2 / \varepsilon_2. \quad (12)$$

Thus, the radon flux density, which entry into the room from the soil base is a function of the soil and the walling materials physical and mechanical characteristics

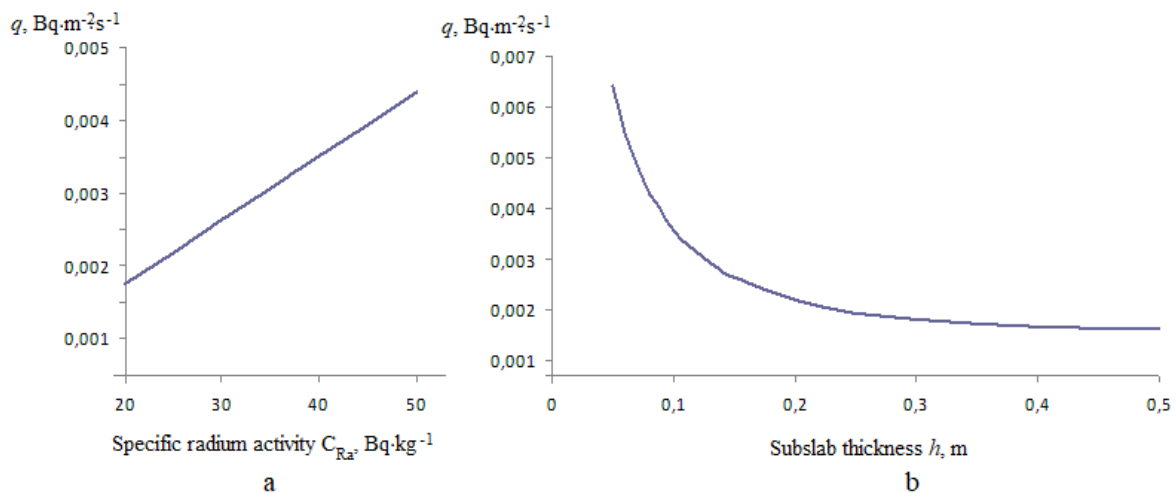
$$q_2 = f(C_{Ra1}, f_1, \rho_{s1}, \varepsilon_1, D_1, h_1, C_{Ra2}, f_2, \rho_{s2}, \varepsilon_2, D_2, h_2).$$

### 3. Results

At the design stage the radiation characteristics of the walling materials are not always known. Therefore, equation (10) can be simplified by excluding from consideration the radon formation of in the walling materials

$$q_2 = \frac{C_{Ra1} \cdot \rho_1 \cdot k_{\text{eml}}}{\varepsilon_1} \cdot \frac{(D_1 / L_1) \cdot sh(h_1 / L_1) \cdot ch(h_2 / L_2)}{sh(h_1 / L_1) \cdot ch(h_2 / L_2) + (D_1 \cdot L_2 / D_2 \cdot L_1) \cdot ch(h_1 / L_1) \cdot sh(h_2 / L_2)}. \quad (13)$$

In the Fig. 4a shows the dependence of the radon flux density into the building on the radium content. Soil block depth  $h_1 = 5$  m in the calculations has a density  $\rho_{s1} = 2000 \text{ kg} \cdot \text{m}^{-3}$ ; a porosity  $\varepsilon_1 = 0.5$ ; a radon diffusion coefficient  $D_1 = 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$  and emanation coefficient  $f = 0.3$ . The base slab thickness was taken to be  $h_2 = 0,15$  m with radon diffusion coefficient in concrete  $D_2 = 10^{-7} \text{ m}^2 \cdot \text{s}^{-1}$ . In the Fig. 4b shows the dependence of the radon flux density on the base plate thickness  $h_2$  when it changes from 0.05 to 0.5 m when the radium content in the soil  $C_{Ra1} = 30 \text{ Bq} \cdot \text{kg}^{-1}$ .



**Figure 4.** The dependence of the radon flux density into the building on the specific radium activity in the soil (a) and on the base slab thickness (b).

Thus, the radon flux density into the building through the underground horizontal walling can be determined at the design stage using the formula (10) or (13) depending on the available source data. Further a transition from the radon flux density to the equivalent equilibrium radon concentration (EERC) in the indoor air is possible [20]

$$q_2 = EERC \cdot (\lambda + n) \cdot V / (F \cdot S), \quad (14)$$

when  $n$  is the air exchange rate in the room,  $\text{s}^{-1}$ ;  $F$  is the equilibrium factor;  $S$  is the floor construction area in contact with the soil base,  $\text{m}^2$ ;  $V$  is the room volume,  $\text{m}^3$ .

The proposed method also allows us to solve the inverse task: for a given value of EERC in indoor air after the building construction it is possible to determine the maximum permissible radon flux density through the underground walling. Then, using the formula (10) or (13) calculate the base slab thickness at which this limit value will not be exceeded.

### 4. Conclusions

The conducted research allows to draw the following conclusions:

1. The radon transport in the soil can be carried out by diffusion and convection. The main parameter, which determines the dominant transport mechanism, is the soil permeability.

2. At the permeabilities less than  $10^{-12} \text{ m}^2$  the radon transport in soils and underground walling materials described with sufficient accuracy by the stationary diffusion equation.

3. The proposed method of calculation allows, in the first approximation, to determine the base slab thickness, which will ensure the radon safety of the building. Further refinement of the calculation results is possible when taking into account the building width and using the equation of two-dimensional stationary diffusive transport.

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